LEVERAGING FREE CARRIERS EFFECTS FOR INFRARED PHOTONIC
STRUCTURES AND DEVICES

BY

RUNYU LIU

DISSERTATION
Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Electrical and Computer Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2016

Urbana, Illinois

Doctoral Committee:
Associate Professor Daniel Wasserman, Chair
Professor Brian Cunningham
Professor Gary Eden
Professor Jianming Jin
Abstract

In this work, three types of novel photonic devices/structures were developed. The first one is a metal grating structure that combines the characters of ‘moth-eye’ structure and an extraordinary optical transmission grating. Therefore it has the capability to provide a uniform electrical distribution while simultaneously reducing the optical reflection loss. It can be applied to the active optoelectronic devices which require both optical and electrical access.

The second device is a slot waveguide made with a hybrid doped semiconductor/metal architecture. Our waveguide takes advantage of the doped semiconductor, which has highly controllable optical response as a designer plasmonic material in the mid-infrared. The local wavelength of the mode that propagates in the waveguide can be expanded at a selected frequency. Therefore the waveguide can function as a photonic wire, which potentially enables the design and fabrication of an integrated metatronic circuit.

The third device is a room-temperature photodetector based on a resonant RF circuit. It consists a microstrip busline and a split-ring resonator that is capacitively coupled to the busline; the RF circuit is built on a semiconductor substrate, with the great flexibility of changing the underlying material system by epitaxial growth. We experimentally investigated the responsivity of this type of detector and concluded that both the material and the geometry will have great impact on the detector response. This detector architecture offers the potential for multiplexing arrays of detectors on a single read-out line; it also can allow us to perform carrier dynamics characterization of semiconductor materials.
To my parents Dawei Liu and Mingfang Chen, my wife Xin Zhang and my son Nathan Liu
Acknowledgments

This work would not be finished without the help and support from the lovely people around me.

First of all, I would like to send my sincere thanks to my advisor, Professor Daniel Wasserman. I can’t remember how many times I have asked you to repeat the most simple sentence that I couldn’t get due to the language barrier, the most basic idea that I couldn’t understand due to background mismatch. But I do remember clearly how cheerful you were when I made any tiny achievement on the way towards my doctoral degree. Your patience, knowledge and trust helped me to continue the work I started when I knew nothing, and to complete it when I become more confident. Your spirit motivated me to do better, and I believe this spirit will help me in the future. In the summer of 2016, you were going to have a herniated disk surgery, but before the surgery, suffering the back pain, you still set up times to visit us in the lab and make sure everyone was on the right track, which motivates me to do my best job on the alignment of my optical setup. Fortunately, with the better focused beam, we discovered that our detector response is also spatially dependent, which is a process of quantitative change causing qualitative change. You probably haven’t noticed that you already set an example for me.

Next I want to thank my former advisor, Professor Catrina Coleman. Thank you for your kindness and all the encouragement you bring to me. Every time after I have a conversation with you, I will be more energetic and affirmative.

I also want to thank Professor Viktor Podolskiy and Dr. Christopher Roberts, for the all delightful times when theorists met experimentalists, and for all the amazing moments when the simulation data matched experimental results. Being able to visualize how the waves propagate, how the fields are distributed, is a gift for an experimentalist who has friends working on the
glorious theories.

Additionally, I want to thank Professor Gary Eden, Professor Jianming Jin, and Professor Brian Cunningham for serving on my committee. It is my great honor to have your signatures on my dissertation, and I am proud of presenting my research achievements in front of you.

Many fellow students and friends in MNTL have given me tremendous help during the past four and a half years. Thanks to Dr. Yujun Zhong, Dr. Daniel Zuo, Dr. Lan Yu, Dr. William Streyer, Narae Yoon, Sukrith Dev, Dr. Jui-Nung Liu, Dr. Hao Chen, Dr. Xin Miao, Dr. Chen Zhang, Dr. Mong-Kai Wu, Dr. Fei Tan, and Dr. Huiming Xu for their insightful discussions, great support and all the fun times we spent in the lab.

Finally, I would like to thank my family, my dear parents, and my lovely wife. It would take infinite pages to describe a small fraction of the love that you guys give to me, and at this moment, any word is powerless; all I want to say is, I love you!

To my son, Nathan, a gift from God, thank you buddy. Because of you, I become even stronger.
# Table of Contents

Chapter 1  Introduction .................................................. 1  
  1.1 The importance of the mid-infrared .......................... 1  
  1.2 Existing mid-infrared components - Sources ............. 2  
  1.3 Existing mid-infrared components - Detectors .......... 3  
  1.4 Existing mid-infrared components - Optics ............. 6  

Chapter 2  Enhanced Optical Transmission through MacEtch Fabrication Buried Metal Gratings ....................... 9  
  2.1 Trade-off between optical and electrical access ........ 9  
  2.2 Nanostructured dielectric surface .......................... 11  
  2.3 Traditional extraordinary optical transmission grating . 13  
  2.4 Buried EOT, a combination of moth-eye and EOT ....... 15  
  2.5 Device fabrication ................................................. 16  
  2.6 Optical characterization .......................................... 17  
  2.7 Modeling and simulation ......................................... 18  
  2.8 Results and discussion ........................................... 20  
  2.9 Conclusions ......................................................... 28  

Chapter 3  Epsilon-Near-Zero Photonic Wires ................. 29  
  3.1 Fundamental challenges to extend lumped circuits in optical frequencies ........................................... 30  
  3.2 Circuit elements at optical frequencies .................. 31  
  3.3 Optical nanocircuit board ........................................ 33  
  3.4 Experimental demonstration of a basic LC optical circuit .... 34  
  3.5 A missing part, the ‘photonic wire’ ......................... 36  
  3.6 ENZ-cladding, air-core photonic wires .................. 39  
  3.7 Device design ....................................................... 40  
  3.8 Device fabrication ............................................... 43  
  3.9 Experimental set-up and numerical calculations ......... 45  
  3.10 Results and discussion ......................................... 47  
  3.11 Future work on the photonic wires ....................... 51  
  3.12 Conclusions ....................................................... 53
<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>Multiplexed Infrared Photodetection using Resonant RF Circuits</th>
<th>54</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Background</td>
<td>54</td>
</tr>
<tr>
<td>4.2</td>
<td>Basic structure of the detector</td>
<td>57</td>
</tr>
<tr>
<td>4.3</td>
<td>Device design</td>
<td>59</td>
</tr>
<tr>
<td>4.4</td>
<td>Device fabrication</td>
<td>61</td>
</tr>
<tr>
<td>4.5</td>
<td>Device characterization-RF response</td>
<td>62</td>
</tr>
<tr>
<td>4.6</td>
<td>Device modeling</td>
<td>63</td>
</tr>
<tr>
<td>4.7</td>
<td>Device characterization-optical response</td>
<td>64</td>
</tr>
<tr>
<td>4.8</td>
<td>Conclusions</td>
<td>67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 5</th>
<th>Enhanced Responsivity Resonant RF Photodetectors (RRFPs)</th>
<th>69</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Sample preparation and experimental setup</td>
<td>70</td>
</tr>
<tr>
<td>5.2</td>
<td>Detector response-material dependence</td>
<td>73</td>
</tr>
<tr>
<td>5.3</td>
<td>Detector response-spatial dependence</td>
<td>75</td>
</tr>
<tr>
<td>5.4</td>
<td>Mapping field profiles</td>
<td>80</td>
</tr>
<tr>
<td>5.5</td>
<td>Conclusions</td>
<td>84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 6</th>
<th>Conclusions and Future Works</th>
<th>86</th>
</tr>
</thead>
</table>

| References |                                                             | 89 |
Chapter 1

Introduction

1.1 The importance of the mid-infrared

The mid-infrared spectral range (which in this thesis we will consider as spanning free-space wavelengths from 3 µm to 20 µm) is an important sub-domain of the electromagnetic spectrum for a wide variety of technological applications and fundamental investigations. Most notably, the mid-infrared is the spectral home for the vibrational and rotational absorption resonance signatures of a wide range of molecular species. Because of this, mid-infrared spectroscopy has extensive utility for chemical and even biological sensing applications, providing a powerful analytical tool for visualizing the chemical content of a sample without dyes or other destructive procedures. Mid-infrared spectroscopy thus has significant importance for security and defense, food and pharmaceutical quality control, and a host of additional applications requiring molecular sensing capabilities. In addition to being the wavelength range associated with a wide range of molecular resonances, the mid-infrared is also the spectral home to the peak wavelength of thermal (blackbody) radiation from objects with temperatures ranging between 200K and 1400K. For this reason, mid-infrared optical and optoelectronic components are essential for thermal imaging technologies, which have applications ranging from energy conservation to security and defense (countermeasures, night vision, etc.) The aforementioned applications require compact, low cost, and high efficiency light sources and detectors, as well as a range of optics and optical components which can generally be described as a mid-infrared optical infrastructure.
1.2 Existing mid-infrared components - Sources

The most common, and most cost-effective, light sources in the mid-infrared range are high-temperature blackbody sources. The Glo-bar is commonly used as the broadband light source in a Fourier transform infrared (FTIR) spectrometer; as we can see in Fig. 1.1, its radioactive profile covers almost the entire mid-infrared range. Such sources are nothing more than resistors, fabricated from high emissivity materials, and capable of operating at high temperatures. The power radiated from the surface of a hot object is given by Planck’s law of black-body radiation, and depends strongly on the temperature: the hotter the object, the more power emitted. The drawback of generating light in this manner is the extreme inefficiency inherent in the conversion of thermal to optical power. In addition to the energy lost to conduction and convection, a blackbody emitter will emit power across an extremely broad spectrum. Though this can be useful for certain applications (such as the aforementioned FTIR), most often mid-infrared light is only desired in a small fraction of the EM spectrum, and thus all other light can be thought of as nothing more than wasted energy.

Figure 1.1: Infrared sources [1].

In 1994, the quantum cascade laser (QCL) was first demonstrated by J.
Faist, F. Capasso and co-workers [2]. The QCL is a unipolar laser which emits low energy photons via optical transitions between intersubband states in complex semiconductor heterostructures. Over the decades since the first demonstration of the QCL, these semiconductor injection lasers have experienced tremendous developments in output power, wall plug efficiency, operating temperature, beam quality, wavelength coverage and wavelength tunability [3]. The QCL could well be described as a transformative technology, allowing for the replacement of bulky CO$_2$ gas lasers with a small-footprint semiconductor chip, and broadly extending the wavelength range of coherent mid-infrared sources. QCLs emit across almost the entire mid-infrared spectrum, with the capability of continuous wave, room temperature, single-mode, and high power operation. More recently, the interband cascade laser (ICL), a close analog of the QCL which emits light via type-II electron-hole recombination in complex heterostructures, has also emerged as a viable source for the 3 µm to 7 µm wavelength range [4, 5, 6]. Alternatively, the optical parametric oscillator (OPO) is another popular device to generate mid-infrared coherent light at wavelengths where lasers perform poorly or are unavailable. The OPO down-converts a pump signal into two tunable frequencies through a non-linear three-wave mixing process [7]. Depending on the material selected and the OPO architectures, these sources can offer: high power, continuous wave, wide wavelength coverage at 2 µm to 12 µm. However, such sources require high power pump sources, have significantly larger footprints than the QCL, and are quite expensive. The rapid development of mid-infrared sources such as the QCL, ICL, and the mid-infrared OPO have led to a surge of interest in the development of mid-infrared optical systems for a variety of applications. However, light sources form only a part of the mid-infrared optical infrastructure required for such systems.

1.3 Existing mid-infrared components - Detectors

Along with the development of mid-infrared sources listed above, the field of mid-infrared detectors has also experienced significant growth. Currently, the dominating mid-infrared detector material system is HgCdTe (MCT) [8], due to the impressive band gap tunability achieved by changing the Hg
and Cd ratio in these II-VI semiconductor alloys. As illustrated in Fig. 1.2, MCT detectors can cover a very wide range of the mid-infrared with commercially available detectors operating out beyond $\lambda=20$ µm. These detectors also boast very high sensitivity, can produce a large signal in a low photon flux measurement, and demonstrate a relatively constant signal versus data-collection speed, making them ideal for kinetic measurements. However, a limitation for MCTs is that they lose responsivity at high throughput (nonlinear response), which means that these detectors can saturate at high photon fluxes. In addition, there are significant difficulties associated with epitaxial crystal growth of HgCdTe, leading to spatial nonuniformity in the detector response, low yield and high cost. In contrast, the fully developed III-V compound semiconductor materials growth technologies can provide large area (>2” wafers) with accurate control of composition and layer thickness. The most representative candidate is the quantum well infrared photodetector (QWIP) [9], which uses intersubband or subband to continuum transitions in semiconductor quantum wells. Compared to HgCdTe detectors, however, QWIPs have a higher thermionic emission rate (charge escaping from the QW), which results in high dark currents. In addition, the polarization selection rule for electron-photon interactions for intersubband transitions in QWs prevents QWIPs from sensing the normal incidence light; therefore, QWIPs need additional process steps to create surface gratings to couple light to the intersubband transitions.

Recently, the growth of broken band type II superlattices (T2SLs) upon established substrates has attracted a great amount of research interest [10], due to the ability to design and control the absorption bandedge in the engineered superlattice material. T2SLs are considered promising candidates for the next generation of IR detection and imaging, resulting from both their wavelength flexibility and the potential for decreased dark current [11, 12]. However, the performance of the T2SL detector strongly depends on the ability to grow many periods of high quality type II superlattices, with minimal interface roughness and cross-contamination between wells and barriers. In addition, because the T2SL usually has slight lattice mismatches between alternating layers, significant effort is required to carefully compensate the residual strain that exists between the lattice mismatched layers. Alternatively, DTGS is one of the most commonly used thermal detectors in the mid-infrared (and extending well into the THz), giving moderate specific de-
tectivities ($D^*$) in high-flux environments, with a highly linear response over a very wide range of the IR spectrum. The DTGS is therefore beneficial in both qualitative and quantitative FTIR spectroscopy applications where light flux is not a concern. However, since the signal of a thermal detector is inversely proportional to the data collection speed, the DTGS and other detectors based on the same principles are less efficient for kinetic measurements. Unlike the DTGS detector, whose response comes from a change in the polarizability of the DTGS material as a function of temperature, the bolometer, another commonly used mid-infrared detector, offers a similar detection mechanism, where the change in conductivity of an absorbing medium is measured as a function of absorbed light (and therefore temperature change). Bolometers can be very sensitive to a broad spectral range of infrared signals. However, since the speed of the detector is set by the intrinsic thermal time constant, the bolometer faces a similar trade-off between speed and sensitivity when compared to the DTGS. For most practical iterations, bolometers tend to be quite slow.

Together, the new generation of mid-infrared sources and detectors offers significant opportunity for both the exploration of fundamental physical phenomena, and the design of mid-infrared optical systems. However, the optical
infrastructure required to enable these applications still lags well behind that of shorter wavelengths. In the next sub-section I will discuss the current state of the art for optical materials and components in the mid-infrared.

1.4 Existing mid-infrared components - Optics

As the need for IR applications grows and technology advances, manufacturers have begun to utilize IR materials in the design of planar optics such as windows, mirrors, polarizers, beamsplitters, and prisms; spherical lenses such as plano-concave/convex lenses; and aspherical lenses such as parabolic, hyperbolic, hybrid lenses. The candidate materials for mid-infrared optical components vary in their physical characteristics, and an optical system can always be optimized by using materials better suited to the end goal of the system. When choosing the correct material, there are some simple points to consider: thermal properties, transmission, hardness, index of refraction, dispersion, solubility, etc.

Semiconductors, such as those found in the III-V or II-VI material systems, normally have high refractive index as illustrated in Fig. 1.3, and according to Fresnel’s law, this high refractive index results in high reflection loss. Therefore many of these materials require anti-reflective coatings to enhance transmission. Additionally, free-carrier absorption in semiconductors can lead to significant absorption at longer wavelengths. However, as I will show later in this work, free carriers in semiconductors can also be used to develop a new class of ‘designer’ mid-infrared materials, leveraging the plasmonic response of high carrier concentrations to enable new physics and phenomena in the mid-infrared.

Zinc selenide (ZnSe), a II-VI material normally grown by chemical vapor deposition (CVD), is among the most commonly used optical materials in the mid-infrared. It has high transmission in a wide spectral range from the visible to the far IR (0.5 µm to 20 µm). ZnSe is also chemically inert; it is only soluble in strong acids and dissolves in HNO₃, has extremely low bulk loss and high thermal stability in virtually all environments, and is easily machined. The index of refraction of ZnSe is ~2.4 in the mid-infrared, which means a relatively high reflection loss (~17% per surface) compared to other visible optical materials with lower refractive index ~1.5, though not nearly
as high as most of the III-V semiconductors.

Potassium bromide (KBr) is another popular material that has been applied widely in the infrared range. KBr is commonly used for IR transmission windows on sample cells and beamsplitters for FTIR spectroscopy. It is transparent from 0.23 µm to 25 µm, and has a relatively low refractive index (around 1.524 at 11 µm), which leads to a ∼4.5% reflection loss per surface. The weak point of KBr is that it is hygroscopic and soluble in water, alcohol and glycerine. Table 1.1 lists several most commonly used window materials in the mid-infrared wavelength range.

Table 1.1: Infrared window materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Transmission</th>
<th>$n$ at 5 µm</th>
<th>Chemical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>2-17 µm</td>
<td>4.01</td>
<td>Soluble in hot H$_2$SO$_4$; insoluble in water</td>
</tr>
<tr>
<td>ZnSe</td>
<td>0.5-20 µm</td>
<td>2.43</td>
<td>Soluble in strong acids; dissolves in HNO$_3$</td>
</tr>
<tr>
<td>KBr</td>
<td>0.3-25 µm</td>
<td>1.54</td>
<td>Soluble in water, alcohol, and glycerine</td>
</tr>
<tr>
<td>KRS-5</td>
<td>0.6-60 µm</td>
<td>2.38</td>
<td>Soluble in warm water and base; insoluble in acids</td>
</tr>
<tr>
<td>CaF$_2$</td>
<td>0.15-8 µm</td>
<td>1.40</td>
<td>Soluble in NH$_4$ salts; insoluble in water</td>
</tr>
<tr>
<td>ZnS</td>
<td>0.45-13 µm</td>
<td>2.25</td>
<td>Soluble in acid; insoluble in water</td>
</tr>
</tbody>
</table>

Germanium (Ge) is the material of choice for systems operating in the
infrared wavelength. The resistivity of optical grade Ge is normally in the range of 3-40 Ω-cm at room temperature, and due to its great electrical specifications, Ge has very good transmission in the 2-15 µm, with a small absorption coefficient no greater than 0.035 cm⁻¹ at 10 µm. The Ge band gap of 0.67 eV is responsible for the increase in absorption in the short wavelength range, though this has little effect on its mid-infrared properties. As we indicated above, since Ge is a semiconductor, one of the most important properties is its high refractive index (∼4.01), resulting in very high reflection loss (∼36% per surface). We know that free carrier (both electron and hole) absorption and lattice absorption account for the IR absorption in the optical domain. For Ge, holes absorb more IR energy than electrons; in equilibrium Ge, the product of the hole and electron carrier concentrations is a constant. The great advantage for semiconductors is that we can engineer the material by doping, incorporating more electrons into Ge, suppressing the holes, and thereby tuning the absorption.

The relative paucity of optical materials in the mid-infrared, when compared to shorter wavelength ranges, can be a challenge to the optical engineer working in the mid-infrared, something we will discuss in the next chapter. However, it should be noted that the relative scarcity of optical materials also allows for a material’s ‘leapfrog’ effect, where new types of composite, plasmonic, or metamaterials may find purchase for a variety of mid-infrared applications. Fortunately, due to the free carriers’ unique response at different frequency range, we could manipulate the material’s optical property by leveraging the free carriers effect, which will be demonstrate explicitly in this thesis.
Chapter 2

Enhanced Optical Transmission through MacEtch Fabrication Buried Metal Gratings

This chapter describes the first device of this doctoral work. The focus of this experiment is the design, fabrication and characterization of a novel optical grating structure that has the capability to provide a uniform electrical distribution while also reducing the optical reflection loss for the active optoelectronic devices. The first part of this chapter will address the background; then we will discuss the fabrication, experimental testing, and lastly, the theoretical modeling results.

2.1 Trade-off between optical and electrical access

The integration of metallic components into optoelectronic devices is both essential (allowing electrical access) as well as of interest for a range of novel optical effects resulting from plasmonic, metamaterial, and subwavelength optical structures. A metal film can provide a near-uniform lateral voltage (current) distribution, which represents an ideal electrical contact for a wide range of electro-optical devices. However, it is the same free electrons which are responsible for the high DC conductivity of metals that dominate their optical properties. This can be observed in the wide and varied field of plasmonics, which is in large part geared toward leveraging the ability of metal/dielectric structures to confine light to subwavelength volumes, thus enhancing light-matter interaction, and potentially enabling next-generation nanophotonic devices. Unfortunately, the high conductivity and novel plasmonic effects associated with the free carriers in metals also cause metals to be highly reflective at optical frequencies and result in parasitic absorption of light through (ohmic) losses in plasmonic materials, limiting the functionality of many materials or devices with integrated metallic components, plasmonic or otherwise [14]. Thus, the integration of metal into any optical
or optoelectronic structure or device, while often providing very real benefits (subwavelength confinement, uniform electrical contact, etc.) is almost always accompanied by absorption and reflection losses compromising the ultimate performance of the optical structure or device.

Figure 2.1: Illustration of two extreme cases for either good optical access with poor electrical distribution, or good electrical distribution with poor optical access.

Figure 2.1 represents two extreme cases. Figure 2.1b is a detector with a top electrode that fully covers the entire mesa, which of course will provide the ideal uniform electrical distribution for the device, but it will block all the incident light. In the other case, where the detector in Figure 2.1a has an electrode that only contacts the edge of the mesa, almost all the area of the device has access to incident light, while the electrical distribution is poor compared to the right one.

Even for Fig. 2.1a, which has an almost fully opened area, it is impossible for all the light incident on the surface to transmit to the absorber, because the transmission behavior of light through the smooth interface between two materials can be related to the change of material permittivity via the Fresnel equations, which constitutes one of the most fundamental rules of classical optics.

Figure 2.2 demonstrates two simple classical examples. Example a) is the transmission and reflection from a simple air-GaAs interface. According to Fresnel’s law, without any metallic structures or patterns, 29% of the light incident on this surface will be reflected. In example b) when the light is generated inside the bulk GaAs, only a small percentage of the photons within the escape cone can be out-coupled; the rest will be reflected back into
2.2 Nanostructured dielectric surface

Nature routinely produces nanostructured surfaces with special properties, and the original anti-reflection (AR) surfaces were first discovered in nature while inspecting the eyes of night-flying moths by Bernhard in 1967. Since then, scientists and engineers have successfully created devices to reproduce these natural structures in the laboratory or real world applications by interference lithography technologies. Figure 2.3 is an example of the ‘moth-eye’ structure made in the lab [15].

The basic principle of a ‘moth-eye’ is that the interface between air and the dielectric is separated by a layer that consists of pillar arrays, normally of sub-wavelength height and spacing. The refractive index of this ‘buffer’ layer changes gradually from 1 (air) to n (substrate), thereby effectively suppressing the specular reflectance due to the abrupt change of the index of the two media [17, 18]. The principle can be conceived as the entire pillar array layer sliding into multiple layers with equal thickness, while the average effective refractive index gradually changes from top to bottom ($n_0 < n_1 < n_2 < n_3...$). Here the spacing between individual pillars should be sufficiently small to
Figure 2.3: Nanostructuring the dielectric surface to create a ‘Moth-eye’ structure [16].

prevent diffraction loss.

The dependence of the reflectance on the effective thickness \( h \) of the layer for a specific wavelength \( \lambda \) can be explained as follows: When \( d \ll \lambda \), the interface is relatively sharp (close to no pillar array). As \( d/\lambda \) starts to increase, the reflectance will first decrease to a minimum value at \( d/\lambda \approx 0.4 \). Further increase of the ratio between \( d \) and \( \lambda \) will introduce an oscillation in reflectance [17]. By designing the pillar height \( h \) and the spacing \( d \) of the arrays, the optimized broadband AR surface can be achieved. Figure 2.4 shows the relationship between reflectance and the \( d/\lambda \) ratio.

![Image](image.png)

Figure 2.4: Computed dependence of reflectance on \( d/\lambda \), [17].

Even without patterned nanostructuring of the surface, sometimes for nanostructuring, a simple ‘roughening’ of a surface can improve transmission. This is seen in semiconductor solar cells, where intentionally toughened
surface can efficiently scatter incident radiation, increasing the path length for light in the detector structure and acting as an antireflection coating [19, 20, 21].

However, for the development of active devices, structuring the dielectric interface does little to enable efficient electrical contact, which requires the integration of (often highly reflective) conducting material with the devices’ active dielectric components.

2.3 Traditional extraordinary optical transmission grating

The optical response of reflecting structured metallic films can be modified. The extraordinary optical transmission (EOT) grating, first reported by T. W. Ebessen [22], is a grating that consists of a periodic array of sub-wavelength apertures perforated into an optically thick metal film. What makes the EOT grating extraordinary is that, at the selected wavelength, the percentage of light transmitted through such a structured surface can exceed the percentage of open area of the film; in other words, it allows more light to pass through than is predicted by conventional aperture theory [23]. This extraordinary phenomenon is fundamentally interesting because of the challenge it poses to conventional optics; therefore, it has spurred a great amount of research interest, both theoretical and experimental, to explore the root of this enhanced transmission. It was first claimed that the incident optical radiation is coupled (through the grating vector) to a special type of highly confined electromagnetic wave supported by the metal film, so-called surface plasmon polaritons (SPPs), followed by the out-coupling of SPPs into dielectric on the other side of the film. More recent research, aimed at elucidation of the origin of EOT, has provided a number of complex coupled (and sometimes competing) mechanisms, related to the excitation, transmission, and out-coupling of (i) SPPs at the two metal-dielectric interfaces and (ii) cylindrical waveguide modes supported by the openings in the perforated metal films [24, 25, 26, 27, 28].

Due to its distinct characteristics, a metal film capable of providing a near-uniform lateral voltage/current distribution over the surface of a device, yet also capable of controlling and enhancing the coupling of incident
radiation into the device, has potential for a broad range of light-emitting and detecting optoelectronic devices. Such structures have been utilized for all-optical modulation of light-matter interaction [30], active control of thin film transmission [31, 32, 33], and to improve light absorption in underlying photodetector structures [34, 35, 36].

However, even without the losses from underlying active materials, passive EOT structures, from a purely light-filtering standpoint, typically demonstrate un-normalized peak transmission efficiencies well below 50%, never approaching the performance of traditional multilayer thin film filters, especially at optical frequencies. The reason for this poor peak transmission is twofold, resulting from both weak coupling to the plasmonic structure from free space, as well as losses in the metal itself (more problematic at shorter wavelengths, where the excited surface modes are more tightly bound, and thus interact more strongly with the metal film) [29]. It is worth noting that strong transmission (\(~ 90\%) through EOT arrays with apertures above cut-off, fabricated on glass, has been observed [37]. However, these structures demonstrate limited to no antireflection properties, as the low refractive index of glass already gives \(~ 96\%\) transmission without the patterned metal layer.
Until now, we are clear that, for an optoelectronic device, both electrical and optical access are required, and both of them need to be improved. For the optical part, the ‘moth-eye’ structure or other type of pattern could be applied for reducing the reflection loss per surface. For the electrical part, EOT gratings could provide uniform voltage/current distribution across the area of the device, while maintaining the possibility for light to get in, even though the total transmitted light in these structures is less than what would be transmitted through a bare surface. Is there a way to improve both the electrical and optical signal simultaneously? A simple and straightforward way would be to combine the two techniques together to achieve both functions.

2.4 Buried EOT, a combination of moth-eye and EOT

The following section will demonstrate an optical architecture which allows for the integration of a thin (\(\sim 10-30\) nm) nanostructured metal (gold) film into a high-index semiconductor (GaAs) material and which can exhibit transmission exceeding that of a smooth air-semiconductor interface. We dub such structures ‘buried’ EOT (B-EOT) gratings, and describe their fabrication using the metal-assisted chemical etching (MacEtch) process [38]. The resulting structures, which look similar to dielectric micro/nanopillars ‘extruded’ through an EOT grating can be fabricated with subwavelength, nanoscale pitch, and feature size, with etch depths equal to or greater than the grating pitch. Our structures are modeled using 3D rigorous coupled wave analysis (RCWA) and characterized experimentally by angle-dependent Fourier transform infrared (FTIR) transmission spectroscopy with good agreement between the theoretical predictions and experimental results. We present the protocols for fabrication of such structures and comprehensive experimental and theoretical analysis of their optical response. B-EOT structures not only show significantly enhanced peak transmission when normalized to the open area of the metal film, but more importantly, peak transmission greater than that observed from the bare semiconductor surface. In a sense, the B-EOT structure combines the benefits of both moth-eye antireflection coatings and EOT-inspired spectral selectivity. The structures demonstrated are of particular interest for potential optoelectronic applications, especially
for a range of integrated emitter and detector structures. Though we demonstrate passive structures in this work, the results presented offer the potential for efficient electrical and optical access to a range of active optoelectronic devices.

2.5 Device fabrication

The B-EOT structures characterized in this work were fabricated by MacEtch of double-side polished semi-insulating (SI) GaAs (100) substrates. MacEtch is a wet but directional semiconductor (e.g., Si, SiGe, GaAs, InP, GaN, etc.) etching technique which involves a thin layer of noble metal (e.g., Au, Pt, etc.) acting as a catalyst to guide the etch process in a solution that usually consists of an oxidant (to generate holes) and an acid (to remove the oxidized species) [39, 40, 41]. Under controlled etch conditions, only the semiconductor material directly underneath the catalyst metal is removed. This results in the catalyst metal being engraved or buried into the semiconductor, leaving behind a 3D semiconductor pattern that is complementary to the metal pattern. The sidewall roughness of MacEtch-produced semiconductor structures is largely determined by the catalyst metal pattern edge roughness. The sidewall verticality is affected by competing etching processes when mass transport of the oxidized species is limited. Details of the MacEtch mechanism, characteristics, and applications can be found elsewhere [39, 40].

In this work, all samples were initially cleaned with a diluted HCl solution to remove the native oxide in order to ensure an intimate contact between the deposited Au film and the underlying GaAs, critical to the uniformity and effectiveness of the MacEtch process. Following the oxide etch, a 30 nm thick Au film was deposited across the entire sample surface by e-beam evaporation, after which a layer of SU-8 (thickness ~ 5 µm) is spun over the Au. Polydimethylsiloxane (PDMS) stamps, consisting of a 2D array of holes with periodicities \( \wedge = 0.77 \, \mu\text{m} \) and \( \wedge = 1.75 \, \mu\text{m} \), were used to pattern the Au film by soft lithography. The periodic patterns on the PDMS stamps were transferred to the SU-8 coated samples by manually pressing the stamps against the samples, followed by a cure at 95 °C, leaving an SU-8 film with a 2D periodic array of apertures. After etching of the exposed Au film
using TFAC Au etchant through the SU-8 etch mask, the SU-8 was stripped from the sample leaving an Au film with a periodic hole array on the GaAs substrate.

Figure 2.6: Schematic of an extraordinary transmission grating (a) before and (b) after the MacEtch process. (c) 45° titled view scanning electron microscope (SEM) image of a MacEtch-fabricated buried-EOT grating with $\Lambda = 1.75 \, \mu m$.

The MacEtch process was then performed using a solution containing KMnO$_4$ (0.025 g) and HF (15 mL) diluted by de-ionized water (15 mL), etching only the material under the patterned Au film at an etch rate of $\sim 118 \pm 10 \, \text{nm/min}$ as measured by SEM. Controlling etch time effectively allows the Au to “descend” through the underlying semiconductor substrate, leaving the “extruded” GaAs pillars extending through the apertures in the Au film, as shown in Fig. 2.6c. The resulting diameter and period of the GaAs pillars are controlled by the geometry of the patterned Au hole array, now “buried” at the base of the GaAs pillars following the MacEtch process, with the height of the GaAs pillars determined by the duration of the MacEtch.

2.6 Optical characterization

Measurements of the interaction of broadband mid-infrared light with the B-EOT gratings were conducted in the following experiments. The transmission properties of the fabricated samples were characterized using a Bruker Vertex70 FTIR spectrometer in an experimental setup shown schematically in Figure 2.7d. Collimated light from the FTIR’s broadband internal glo-bar
was focused using an 8 inch focal length, 2 inch diameter ZnSe lens onto the sample, held outside the FTIR on a brass mount with a 2 mm diameter aperture, and with the aperture array’s principle axes in the horizontal (1,0) and vertical (0,1) directions, as shown in Fig. 2.7.

![Experimental setup for linearly polarized, angle-dependent transmission experiments.](image)

Figure 2.7: Experimental setup for linearly polarized, angle-dependent transmission experiments.

Light transmitted through the sample was collimated and refocused onto a liquid nitrogen-cooled HgCdTe (MCT) detector using a pair of 2 inch diameter, 3 inch focal length ZnSe lenses. The sample itself is mounted on a rotational stage with a principle axis of the 2D array aligned to the rotational axis of the stage to enable angular-dependent transmission measurements. A holographic wire grid polarizer was inserted between the first focusing lens and the sample, allowing for horizontally or vertically polarized incident radiation, corresponding to TM or TE polarization, respectively. Transmission spectra as a function of angle were taken for angles from 0° to 30° for both TM and TE polarized light. All transmission spectra are normalized to transmission through the experimental system with no sample on the mounting plate, providing absolute transmission spectra for the fabricated samples. Transmission spectra through an unpatterned SI GaAs wafer were also collected, and are shown for comparison.

2.7 Modeling and simulation

The fabricated structures were modeled using a 3D RCWA approach. This technique, originally introduced in [42] and further expanded in [43], takes explicit advantage of the periodicity of the B-EOT structure, imposing a Bloch-wave-periodicity condition on the fields. Explicitly, each planar region of the multilayer system (air, GaAs pillars in air, GaAs pillars in metal,
homogeneous GaAs) is considered separately. For the simulations presented in this thesis, the following material parameters were used: $\varepsilon_{GaAs} = 10.89$ and $\varepsilon_{Au} = \varepsilon_B - \frac{\omega_p^2}{\omega_{\text{p}}^2 - i\omega\Gamma}$, with $\varepsilon_B = 9.5$, $\omega_p = 1.3597 \times 10^{16}$ Hz, and $\Gamma = 1.0486 \times 10^{14}$ Hz.

The electromagnetic field inside each region is represented as

$$[E, H \propto E(x, y)e^{i\hat{q} \cdot \hat{x} + ik_z z}]$$

(2.1)

where $\hat{z}$ corresponds to the direction normal to the layered system. Substitution of equation (2.1) into Maxwell’s equations yields an eigenvalue-like problem. Each solution to this problem describes an individual electromagnetic mode, with an eigenvalue representing the mode’s propagation constant $k_z$, which describes the evolution of the field along the $\hat{z}$ direction, and the eigenvector representing the field distribution across the unit cell. The electromagnetic field inside the system is then represented as a linear combination of the modes. At the final stage of the RCWA process, the amplitudes of the modes in each layer are related to the amplitudes of the modes in the neighboring layers; implementation of RCWA [44] enforces the continuity of the tangential components of the $E$, $H$ fields to calculate modal amplitudes.

The 3D RCWA technique was used to analyze the transmission, reflection, and absorption of the B-EOT structures described in Section 2.5. The normal vector method was used to improve the convergence of in-plane components of the electric and displacement fields in the RCWA formalism [45]. The electromagnetic fields are represented a finite Fourier series of the fields’ modal amplitudes,

$$[\tilde{E}, \tilde{H}(x, y, z) = \sum_{n=-N}^{N} \sum_{m=-M}^{M} (\tilde{E}, \tilde{H})_{nm}(x, y)e^{i\vec{k}_{nm} \cdot \vec{x}}]$$

(2.2)

where $n$ and $m$ are the Bloch indices of the modes. The Fourier representation suffers from Gibbs’ phenomena at discontinuities in the permittivity. Lanczos’ $\sigma$-factors were introduced to attenuate Gibbs phenomena in the reconstruction of the fields and improve the convergence of the Fourier series. The addition of the Lanczos’ $\sigma$-factors alters the field reconstruction,
\[\vec{E}, \vec{H}(x, y, z) = \sum_{n=-N}^{N} \sum_{m=-M}^{M} \sigma_{nm}(\vec{E}, \vec{H})_{nm}(x, y)e^{i \vec{k}_{mn} \cdot \vec{x}} \]  
(2.3)

where \(\sigma_{nm} = \text{sinc}(\pi n/N)\text{sinc}(\pi m/M)\) are Lanczos’ \(\sigma\)-factors.

2.8 Results and discussion

Normal incidence transmission spectra for B-EOT samples with pillar heights ranging from \(h = 0\) to 1000 nm are summarized in Fig. 2.8. The fundamental phenomenon of interest is best seen in Fig. 2.8a, where we show the RCWA simulated transmission for pillars of fixed lateral geometry and varying heights. Here, we only consider transmission at the top surface of the sample (ignoring the losses in the substrate and at the substrate/air interface on the bottom of the sample), which best demonstrates the antireflective nature of the B-EOT structures. The transmission spectra corresponding to \(h = 0\) exhibit the Fano-type response characteristic of EOT gratings. \[46, 47, 48\]. The spectral positions of the (1, 0) and (1, 1) EOT resonances at \(\lambda_{1,0} = 5.76 \, \mu\text{m}, \lambda_{1,1} = 4.07 \, \mu\text{m}\) (Fig. 2.8a correspond to coupling of light into propagating SPPs at the GaAs-metal interface through the lowest diffraction orders of the grating formed by the B-EOT structure. As the pillar height \(h\) is increased (as the EOT grating is buried deeper into the substrate), the transmission spectrum changes dramatically, with a marked increase in the transmission peak’s long-wavelength tail. This effect is most clearly seen in Fig. 2.8a, with predicted peak transmission reaching 90% at \(\lambda \sim 7 \, \mu\text{m}\), an increase in transmission of almost 20% when compared to the bare, smooth GaAs-air surface. The experimental data show similar qualitative results, with a narrow transmission peak of 40% for the unetched EOT sample and a broader transmission peak, reaching 65% for the \(h = 650\) nm and \(h = 700\) nm samples. As in the numerical solutions of Maxwell’s equations, the peak experimental transmission through the B-EOT sample is larger than the transmission through the bare GaAs wafer at the same wavelength.

However, comparing our simulations of Fig. 2.8a to the experimental data of Fig. 2.8d, we see that while the qualitative behavior of the grating is repli-
Figure 2.8: 3D RCWA simulations of transmission for varying pillar heights for (a) top surface transmission, assuming fixed lateral geometry ($\Lambda = 1.75 \mu m$ and diameter $D = 1.2 \mu m$), (b) transmission through top and bottom interfaces, assuming the same fixed lateral geometry, and (c) transmission through top and bottom interfaces, with varying lateral geometries measured on fabricated samples using SEM. (d) Experimental normal incidence transmission spectra for B-EOT structures with designed $\Lambda = 1.75 \mu m$ and diameter $D = 1.2 \mu m$, for varying etch depths ($h$). The unetched sample ($h = 0$ nm), corresponding to a traditional EOT grating, is shown in black. Transmission through an unpatterned SI GaAs wafer is also shown for comparison (dashed gray). Scanning electron images of individual pillars from the samples with spectra shown in (d), having etch depths of (e) $h = 0$ nm, (f) $h = 200$ nm, (g) $h = 500$ nm, (h) $h = 650$ nm, (i) $h = 700$ nm, and (j) $h = 1000$ nm. All SEM images are taken at a 45° tilt.

In the RCWA simulations, minor adjustments are required to achieve a realistic simulation of our experimental parameters. First, in Fig. 2.8b, we consider the effect of the substrate on the transmission, by modeling the substrate as a thick, incoherent layer (where the RCWA code ignores the phase information of light transmitted into the substrate). We see that when the substrate effects are considered, the overall transmission of our simulations shows good agreement with our experimental results, most easily observed in the bare GaAs simulations, which show a drop in transmission from $\sim 70\%$ to $\sim 57\%$. More subtly, we also observe spectral shifts between the experimental data and the simulated transmission of Fig. 2.8a,b. The likely reason for this shift is the evolution of the sample geometry throughout the MacEtch
process. Most notably, a shift in the periodicity of the metal mesh is observed (from $\lambda = 1.65 \mu m$ to $\lambda = 1.75 \mu m$) between the unetched EOT sample and all of the MacEtched samples. This effect is a result of a resizing of the Au mesh upon initiation of the MacEtch process and has been observed in previous MacEtch work [49, 50]. For this reason, we also used measurements of the lateral geometry of our samples (from scanning electron microscope (SEM) measurements) to simulate the exact structure geometries (as well as the substrate effects) for each of the etch depths characterized experimentally. These simulations are shown in Fig. 2.8c, and show good spectral agreement with our experimental data.

Finally, the distinct spectral features observed in the simulated transmission spectra resulting from SPP coupling (i.e., the strong dip at 5.5 $\mu m$) are somewhat weaker in the experimental data for the deeper-etched samples, an effect possibly resulting from the nonuniformity in individual pillar width, and between pillar heights, associated with longer etch times. While we are able to achieve good agreement between our experimental and simulated transmission spectra, it is important to note that the observed spectral response is dominated by the front structured interface, as best depicted in the calculations that ignore substrate effects (2.8a), while the back interface of the system provides the overall spectrally flat correction to the results. Regardless of the back interface, our results demonstrate that the B-EOT structure, despite covering $\sim 50\%$ of the sample surface with metal, acts as an anti-reflection coating over a reasonably broad range of the mid-infrared.

Angular dependent transmission data for two different samples ( $\lambda = 0.77 \mu m$, diameter $D = 0.5 \mu m$ and pillar height $h = 0.5 \mu m$, and $\lambda = 1.75 \mu m$, diameter $D = 1.2 \mu m$ and pillar height $h = 0.7 \mu m$) are shown in Fig. 2.9 and Fig. 2.10 for both TE and TM polarized light, respectively. As can be seen in Fig. 2.9a and Fig. 2.10a, the TE polarized transmission peaks for each sample remain reasonably large and (spectrally) stationary for incidence angles up to $\theta = 30^\circ$, with the dips in the spectrum [associated with (0,1) SPP coupling] remaining fixed in position and magnitude (as would be expected for incident light with unchanging momentum in the direction of SPP propagation). Splitting in the (1,1) SPP-coupling feature is observed for the TE spectra, as non-normal incident TE-polarized light will have a varying momentum component in the (1,1) directions with increasing incidence angle.
Figure 2.9: Comparison of (a,b) TE and (c,d) TM transmission as a function of the incident angle for angles from \( \theta = 0^\circ \) to \( \theta = 30^\circ \). The sample under test has \( \Lambda = 0.77 \) µm, diameter \( D = 0.5 \) µm and pillar height \( h = 0.5 \) µm. (a,c) Experimental results and (b,d) simulation results (including substrate effects). The small minima at observed in some of the spectra in (a) and (b) results from small changes in CO\(_2\) absorption between background and sample spectra.

The TM polarized data (Fig. 2.9c and Fig. 2.10c) differs from the TE data in two significant regards. First, as the sample is rotated away from normal, we see a weakening in the transmission dips associated with SPP-coupling, as would be expected for incident light with momentum components in the direction of SPP propagation, which will lift the degeneracy in the of the positive and negative propagating (1,0) and (1,1) SPPs excited at the Au/GaAs interface. More interestingly, we see the appearance of a strong transmission dip in the center of the transmission peak, which grows in magnitude as the incidence angle increases. RCWA simulations for each sample for both TE-polarized (Figure 2.9b and Figure 2.10b) and TM-polarized (Figure 2.9d and Figure 2.10d) incident radiation, including substrate effects, show good agreement with experimental data.

The results from our 3D RCWA simulations of the fabricated B-EOT structures offer insight into both the primary finding of this work (namely, the strongly enhanced transmission seen with increasing pillar height) and the
Figure 2.10: Comparison of TE and TM transmission as a function of incident angle for angles from $\theta = 0^\circ$ to $\theta = 30^\circ$. The sample under test has $\Lambda = 1.75 \, \mu m$, diameter $D = 1.2 \, \mu m$ and pillar height $h = 0.7 \, \mu m$. (a,c) Experimental results, (b,d) simulation results (including substrate effects) for (a,b) TE and (c,d) TM polarized incident light. Contour plots of calculated local Poynting flux (not including substrate effects) for (e) $\theta = 0^\circ$ and (f) $\theta = 30^\circ$ at $\lambda_0 = 7.1 \, \mu m$, with lines showing Poynting vector field lines.

spectral anomalies observed in our angular-dependent transmission (strong dips in TM-polarized transmission with increasing angle). Our models suggest that the high reflectivity of the planar GaAs-air and metal-air interfaces is modulated through coupling of light into waveguide-type modes supported by the pillar arrays. Figure 2.10e shows the local Poynting flux (color scale) and Poynting vector field lines for normal incidence light at $\lambda_0 = 7.1 \, \mu m$, indicating strong transmission is associated with coupling into the dielectric pillar. Figure 2.10f illustrates the coupling of incident energy to the thin
metal film (note the Poynting vector field lines ending at the metal), giving
the transmission dip at oblique ($\theta = 30^\circ$) incidence at the same wavelength.
Both Fig. 2.10e and f are modeled without effects related to incoherent back
interface of the structure, as the purpose of these calculations is to elucidate
the behavior of our structures only in the near field of the B-EOT gratings.

Unlike a traditional EOT grating, where peak transmission can be thought
of as an interference maximum associated with light directly transmitted
through the arrayed apertures and light scattered from surface modes, the
transmission peak in our B-EOT samples results from efficient avoidance of
coupling to plasmonic modes. Indeed, transmission through a pillar structure
with no metal film shows broadband antireflection properties (Fig. 2.11).
Note that the simulations in Fig. 2.11 ignore absorption/reflection in the
substrate, so as to elucidate the optical properties of the top patterned sur-
face that dominates the spectral response of the structure. Such coupling
cannot be avoided for all wavelength/angle/polarization combinations. As
a result, the narrow-band angle-dependent transmission minima appear at
higher angles along with the broader anti-reflection (enhanced transmission)
background. These minima are associated with the coupling into, and absorp-
tion by, the thin metal film, as evidence by the inset in Fig. 2.10f showing the
local Poynting flux and vector field lines for $\theta = 30^\circ$ incidence angle light at
$\lambda_0 = 7.1 \mu m$. The spectral position of this minimum depends on the geomet-
rical parameters of B-EOT structures. In our simulations, we modeled the
nano-pillar cross section as a Lamé curve, $|X|^N + |Y|^N \leq R^N$ keeping the
ratio of pillar “diameter” to the unit cell size constant. When the pillars have
circular cross sections ($N = 2$), the spectral position of metal-transmission
minimum is well described by diffraction theory (Fig. 2.11b)

$$\lambda_{m,n}(\theta_i) = \frac{\sqrt{m^2 + n^2}}{m^2 + n^2} \left( \frac{\varepsilon_{Au} \varepsilon_{GaAs}}{\varepsilon_{Au} + \varepsilon_{GaAs}} \right) \approx \frac{\sqrt{n_{GaAs} \mp \sin(\theta_i)}}{\sqrt{m^2 + n^2}} \approx \sqrt{m^2 + n^2} (n_{GaAs} \mp \sin(\theta_i)) \quad (2.4)$$

where $m, n$ give the order of the diffracted mode in 2D and $\theta_i$ is the angle
of incidence, from normal. As the shape of the pillar becomes more square-
like ($N > 2$), and as a larger percentage of the unit cell is occupied by the
dielectric, the position of the broad metal-related minimum red-shifts and
becomes less dependent on the incident angle (Fig. 2.11f). Note that this
spectrally stationary absorption maximum splits off the weak (but spectrally
sharp) absorption peak that is still described by equation 2.4. Reproducing the sharp, square features of our lithography mask in our metal film becomes more difficult with decreasing feature size, an effect that turns squares into quasi-circles with decreasing $\Lambda$. Thus, our $\Lambda = 1.75 \mu m$ samples have almost

Figure 2.11: Comparison of (a,b,e,f,i,j) numerically calculated TE and TM specular and total transmission and (c,d,g,h) total absorption for BEOT samples as a function of incident angle and pillar cross section for angles from $\theta = 0^\circ$ to $\theta = 30^\circ$. The specular transmission (solid lines) corresponds to the transmission collected experimentally, while the total (dashed lines) also includes light coupled into transmitted diffracted orders. The sample has $\Lambda = 1.75 \mu m$, diameter $D = 1.2 \mu m$ and pillar height $h = 0.7 \mu m$. (a-d) A perfect circular pillar ($N = 2$), (e-h) simulations for an $N = 6$ Lamé curve pillar cross section, and (i,j) an $N = 6$ Lamé curve pillar cross section with no Au grating. The dotted vertical lines correspond to the spectral positions of the first order SPP coupling. No absorption is shown for the sample without Au, as the GaAs is modeled as a lossless dielectric. Insets in transmission plots show modeled pillar cross section.
square openings, approximated here as Lamé curve with $N \simeq 6$, while the $\Lambda = 0.77 \, \mu m$ samples have almost circular openings ($N = 2$). As expected, our larger period samples show TM-polarized transmission dips which remain nearly spectrally stationary with increasing angle (Fig. 2.10c) while the same dip in our smaller period sample shows a continuous red shift with increasing angle (Fig. 2.9c).

Figure 2.12: Numerically calculated peak transmission ($\lambda_0 = 7.1 \, \mu m$) through BEOT structure ($\Lambda = 1.75 \, \mu m$, diameter $D = 1.2 \, \mu m$) as a function of pillar height $h$ (including substrate effects). Insets show cross-sectional field profile inside the pillar for (left) the $z$ component of the Poynting vector and (right) the in plane (arrows) and $z$ (color) components of the magnetic field.

Figure 2.12 shows the calculated transmission, at normal incidence, for fixed wavelength $\Lambda = 1.75 \, \mu m$, as a function of pillar height. It is clearly seen that transmission oscillates with typical period $\Delta h = 1.9 \, \mu m$. Analysis of propagating modes supported by a layer of periodic dielectric pillars suggests that the transmission of light through this layer is dominated by modes with propagation constant $k_{zm}^m = 1.6 \, \mu m^{-1}$; note that $\Delta h \approx \pi/k_{zm}^m$. This fact further confirms that the observed transmission of light through the structured composite is in fact related to in-coupling of incident radiation into these modes. The insets of Fig. 2.12 illustrate the behavior of light in the above mode, showing the $z$-component of Poynting flux (color scale) and the distribution of magnetic field across the unit cell. Note that the latter is extremely similar to the field profile of the plane wave, explaining
the relatively easy coupling of light incident from free-space into the pillar array. On the other hand, the majority of energy flux is funneled into the dielectric pillar, thus assisting the transfer of this energy through the metal mesh at the interface between the pillar array and the homogeneous GaAs substrate.

2.9 Conclusions

The MacEtch process was used to fabricate buried extraordinary optical transmission gratings, metallic films with periodic arrays of subwavelength apertures buried into a high-index semiconductor material. The fabricated structures offer not only the uniform electrical contact expected from continuous metallic thin films, but perhaps more importantly, the potential for a significant enhancement of optical transmission, when compared to a bare, high-index semiconductor. B-EOT structures are fabricated and experimentally characterized using FTIR transmission spectroscopy, demonstrating transmission as great as 65% (uncorrected for substrate losses and scattering) from a structure where a metal film covers \( \approx 50\% \) of the sample surface. We model the fabricated structures using 3D RCWA with good agreement to our experimental data. In addition, our model allows for a fundamental understanding of the dielectric pillar-mediated transmission enhancement, as well as additional spectral features observed in the angle-dependent transmission experiments. Typically, the integration of metallic structures with semiconductor materials and/or optoelectronic devices requires a trade-off between efficient electrical contact (metal coverage) and optical coupling to free space (open, metal-free surface). The structures presented here, however, realize efficient, low-loss integration of metallic films with high-index semiconductor materials, offering the opportunity for next-generation optoelectronic sources and detectors with efficient electrical and optical access.
Chapter 3

Epsilon-Near-Zero Photonic Wires

In this chapter, we introduce the concept of Metatronics, a new optical circuit paradigm originally proposed by researchers from the University of Pennsylvania [51]. Metatronics can be thought of as an optical analogue of the familiar lumped element electronic circuitry which typically operates at radio frequencies. However, in the new paradigm of Metatronics, the electronic components are replaced by optical elements, which act as effective optical inductors, capacitors and resistors, ideally allowing for circuit operation at optical, not microwave, frequencies. One of the key requirements to build such a circuit would be the photonic equivalent of electrical wires. In a lumped element circuit, electrical wires carry signal between circuit elements, and because of the low operational frequency of the circuitry, and the relatively small size of the circuit, the signals on these wires are presumed to effectively propagate without phase shifts. The photonic equivalent of the electrical wire would be a waveguiding structure that can carry optical frequency signals to and from the optical lumped circuit elements. However, simply guiding the optical signal does not entirely produce the optical equivalent of electrical wires. Because of the high frequency of optical signals, significant phase shifts are of course expected for propagation of any distance on the order of an optical wavelength (which, depending on the wavelength, could be from 100’s of nm to several microns). Thus, the challenging aspect of developing photonic wires is achieving carrier signal wavelengths much larger than the size of the lumped circuit elements, while still operating at optical frequencies. In this chapter, we demonstrate the design, fabrication and characterization of hybrid metal/doped-semiconductor ‘photonic wires’ operating at mid-infrared frequencies, with effective indices approaching zero. Through polarization and angle-dependent reflection spectroscopy, we successfully prove the coupling of free space light into such a waveguide structure as well and demonstrate an extension of the local wavelength by an order of
magnitude when compared to the free space wavelength of our selected operational frequency. We will discuss the potential of such photonic wires, but also the very real challenges associated with the Metatronics paradigm.

3.1 Fundamental challenges to extend lumped circuits in optical frequencies

Metatronics has been proposed as a new paradigm for engineering optical circuits [51]. In this paradigm, light, instead of charge, functions as the information carrier, and interacts with small (subwavelength) components acting as optical lumped circuit elements. The most obvious advantage of an optical circuit is that it could potentially operate at frequencies orders of magnitude higher than the current electronic circuitry. If all of the basic lumped circuit elements that have been well developed in electronic circuitry could be successfully transferred into their optical counterparts on a single material platform, then the highly optimized apparatus for electronics can be applied to engineering optical circuits. However, extending the operating frequency to optical regimes such as terahertz, infrared or even visible wavelength does not mean simply scaling down the device dimension from microwave to optical wavelengths. Additional, significant challenges must be overcome.

The first of these is the reduction of the size of the optical structures (to subwavelength dimensions) in order that they may be treated with the lumped element formalism. Because of the small wavelengths associated with optical frequencies (compared to electronic), this will involve extremely expensive fabrication techniques in order to create components that have deep subwavelength dimensions. The second challenge is related to the metal’s optical properties, which change significantly as one moves to lower frequencies. Noble metals such as gold, silver and copper, are highly conductive at RF or microwave frequencies, whereas at optical frequencies, they behave differently: the real part of the metal’s permittivity is still negative, but it is on the order of surrounding dielectric’s positive permittivity, and thus these metals can support plasmonic excitation, which is a coupling of optical signal into collective oscillation at the surface of these metals. Hence, the traditional conduction current may not be the dominant current flowing in the system;
instead, the electric displacement current will be utilized as ‘flowing optical current’.

3.2 Circuit elements at optical frequencies

In this section I will discuss the optical equivalent of electronic lumped circuit elements. Professor Engheta’s group at UPenn has worked extensively on the optical wave interaction with metallic and nonmetallic nanoparticles [52], and has explored quantitatively how electronic circuit concepts and elements could potentially be extended to the optical domain. To do so, they have investigated the interaction of light with subwavelength particles, showing that such particles can be thought of as lumped optical elements for optical circuitry.

To illustrate this, let us consider a simple example: a nanosphere with radius R (much smaller than the wavelength), made of homogeneous material with dielectric function $\varepsilon(\omega)$, which in general should be considered to be a complex quantity. Now assume incident monochromatic light with harmonic dependence $e^{-i\omega t}$ and field amplitude $E_0$ impinges upon this sphere. The scattered electromagnetic (EM) fields in the vicinity of the sphere (both inside and outside) can be described using a quasi-static approximation (due to the subwavelength nature of the particle) [52]:

$$E_{\text{int}} = \frac{3\varepsilon_0 E_0}{\varepsilon + 2\varepsilon_0}$$  \hspace{1cm} (3.1)

$$E_{\text{ext}} = E_0 + E_{\text{dip}} = E_0 + \frac{3u(p \cdot u) - p}{4\pi\varepsilon_0 r^3}$$  \hspace{1cm} (3.2)

where $p = 4\pi\varepsilon_0 R^3(\varepsilon - \varepsilon_0)E_0/(\varepsilon + 2\varepsilon_0)$, $u = \hat{r}/r$, $r$ is the position vector from the sphere’s center to the observation point. The normal component of displacement current follows the boundary condition at the surface, which leads to [52]:

$$-i\omega(\varepsilon - \varepsilon_0)E_0 \cdot \hat{n} = -i\omega\varepsilon_0 E_{\text{dip}} \cdot \hat{n} + i\omega\varepsilon E_{\text{res}} \cdot \hat{n}$$  \hspace{1cm} (3.3)

where $\hat{n}$ is the local unit vector normal to the sphere surface. After integration Eq. 3.3 over the upper hemisphere, the “total” displacement current is
The left-hand side of Eq. 3.4 is defined as the impressed displacement current source, and the right-hand side consists of the displacement current circulating in the sphere and the displacement current of the fringe field respectively. Those various segments of the displacement current can be interpreted as the branch currents at a node in a circuit. The currents defined in Eq. 3.4 can obey Kirchhoff’s law; therefore, the equivalent impedance for the nanosphere and the fringe field branch can be calculated as an equivalent “average” potential drop, given as [52]

\[
\langle V_{\text{sph}} \rangle = \langle V_{\text{fringe}} \rangle = \frac{R(\varepsilon - \varepsilon_0)|E_0|}{\varepsilon + 2\varepsilon_0}
\]  

(3.5)

The ratio of the ‘average’ potential drop and the displacement current flowing into and out of the sphere can be defined as the optical ‘lumped impedance’, which we can write as:

\[
Z_{\text{sph}} = (-i\omega \varepsilon \pi R)^{-1}, \quad Z_{\text{fringe}} = (-i\omega 2\pi \varepsilon_0 R)^{-1}
\]  

(3.6)

Here, based on Eq. 3.6, we clearly see that the two parallel elements in the circuits shown in Fig. 3.1 may behave differently according to the sign of the nanosphere’s permittivity. For the case of a dielectric (nonmetallic) sphere, the \( Re[\varepsilon] \), and \( Z_{\text{sph}} \) in Eq. 3.6 is capacitive, as is the outside fringing field capacitance. Therefore the impedance of the equivalent nanocircuit for this dielectric nanosphere can be described as shown as Fig. 3.1a

In the case of a metallic sphere fabricated from a noble metal, at optical frequencies the metal will behave like a plasmonic material, where the real part of the permittivity will become negative, but of the approximate magnitude of the surrounding dielectric. Hence, the equivalent impedance of the particle can be ‘negatively capacitive’ in the frequency range when \( Re[\varepsilon] < 0 \), which corresponds to a ‘positive inductance’. So for the equivalent nanocircuit as shown in the bottom right of Fig. 3.1, the impedance for the sphere becomes: \( L_{\text{sph}} = (-i\omega^2 \pi R Re[\varepsilon])^{-1} \). Along with a fringing field capacitor in parallel, this combination will show a resonance. While in optics, this res-
onance is typically described as a localized plasmonic resonance associated with light interacting with a metallic nanosphere, the above formalism indicates that one can also describe such an interaction as an LC resonance of an optical nanocircuit comprised of optical lumped elements [51].

3.3 Optical nanocircuit board

After introducing the concept of optical lumped circuits, Professor Engheta’s group proposed the paradigm of an optical nanocircuit board, which consists of a layered metamaterial circuit board, leveraging materials/structures with effective epsilon-near-zero (ENZ) properties. This layer of novel material was proposed as the foundation for the optical circuit, and into which the nanocircuit traces can be carved out to form the channels that can guide the optical displacement current to “flow” between circuit elements [53].

In Fig. 3.2, the metamaterial of the substrate could potentially be formed by alternating thin layers of epsilon-positive (dielectric) and epsilon-negative (metallic) materials, as illustrated in the bottom right inset. The effective medium theory can be applied to such a layered material by simply averaging

![Figure 3.1: A basic nanoscale circuit in the optical regime. (a) A nonplasmonic sphere with \( \varepsilon > 0 \), which provides a nanocapacitor and a nanoresistor. (b) A plasmonic sphere with \( \varepsilon < 0 \), which gives a nanoinductor and a nanoresistor. Solid black arrows show the incident electric field, and the thinner field lines together with the gray arrows represent the fringe dipolar electric field from the nanosphere [52].](image-url)
Figure 3.2: A square loop nanocircuit channel carved in a low-permittivity (ENZ) metamaterial substrate. A layered metamaterial (bottom inset) constitutes the nanocircuit board over which specific grooves may be carved out. The channel may be excited by an optical source (left) and loaded by plasmonic (gray, darker) and nonplasmonic (green, lighter) nanorods. The transmission-line model for the field distribution along the channel is reported in the upper inset.

the permittivity in the plane of the layers (x-y plane), and an ‘averaged’ zero real part of permittivity could be obtained at a selected frequency. Due to the vanishingly small \( \text{Re}(\varepsilon_{\text{eff}}) \approx 0 \), the optical displacement current \( J_d = -i\omega \text{Re}(\varepsilon_{\text{eff}})E \) will be extremely small inside the materials, so the signal may be confined within the carved channel where [51]. Then, the nanoparticles can be embedded into the channels to form the desired circuit topology.

3.4 Experimental demonstration of a basic LC optical circuit

After theoretically proposing that subwavelength nanoparticles can behave in a similar manner to nanocapacitors, nanoinductors or nanoresistors, Professor Andrea Alu’s group at UT Austin successfully demonstrated the first modular assembly of optical nanocircuits, thereby experimentally verifying the full potential of the optical lumped circuit concept, potentially allowing for the design of complex optical lumped circuit architectures [54].
In their experiments, an atomic force microscope (AFM) nanomanipulation technique was applied to assemble the nanoparticles to form circuits, as shown in Fig. 3.3c. Due to the flexibility of this approach, the circuits can be arranged into various desired topologies [54].

The dark-field scattering technique was applied to investigate these composite optical elements. In this approach linearly polarized broadband light was focused on the nanocircuits, and the scattered signal was collected with a microscope objective, as illustrated in Fig. 3.3d. By comparing far-field scattering spectrum with full-wave simulations and a circuit model, they proved that the assembled nanocircuit indeed operates as an optical circuit with a rather intuitive topology [54].

Figure 3.4 shows a basic LC optical nanocircuit in their demonstration. Here the Au nanosphere with radius $a \approx 30$ nm was excited by a broadband white light source. The corresponding dark-field scattering spectrum is shown in Fig. 3.4b, where a distinct resonant peak was located at $\lambda_0 = 550$ nm.

Figure 3.3: Assembly and characterization of a modular optical nanocircuit. (a) AFM and (b) dark-field scattering images of plasmonic and dielectric nanoparticles (NPs) randomly distributed on a glass substrate. Only Au NPs yield strong scattering signals. Scale bar, 3 mm. The NPs enclosed in circles in (a) are missing in (b), thereby identifying them as dielectric NPs. (c) Illustration of AFM nanomanipulation as a way to dynamically assemble complex optical nanocircuits from independent optical inductors (plasmonic NPs, yellow) and capacitors (dielectric NPs, green). (d) Schematic representation of our dark-field scattering measurements. Light impinges at an incidence angle of 60° and the scattering signal is collected along the substrate normal [54].
The experimental result can be accurately predicted with nanocircuit theory model as shown in Fig. 3.4c. As aforementioned, the equivalent nanocircuit is the Au nanosphere $Z_{sph} = (-i\omega \varepsilon \pi a)^{-1}$, along with a fringing field capacitor $Z_{sph} = (-i\omega \varepsilon_0 2\pi a)^{-1}$, sourced by a voltage generator associated with the incident optical field. However, the above demonstration utilized a single lumped element, accessed using free space optics. To move the metatronic paradigm to full optical circuitry, all of the lumped components, sources, detectors will need to be integrated into a single board and connected by the optical equivalent of electrical wires.

3.5 A missing part, the ‘photonic wire’

The real advantages of the metatronics paradigm apply only at higher frequencies, inaccessible by current electronic circuitry. Extending the concept of lumped elements to the optical frequency regime, however, is not trivial and requires, among other things, the scaling of the size of the basic functional elements inside the optical circuits so that they can be treated as ‘lumped’, an issue we have address in the previous sections. Though doing so is not trivial, the fabrication of subwavelength elements is now reasonably mature, and could be applied to the metatronics paradigm. Linking these lumped elements with a signal-carrying structure where the wavelength of the signal far exceeds the size of the lumped elements, and ideally, the distance separating individual lumped elements, is far more difficult. In the original proposed two-dimensional paradigm of metatronics, the optical lumped elements are linked by a ‘photonic wire’, originally conceived as an air-filled guide with walls composed from hypothetical bulk material having vanishingly small permittivity, and thus having vanishingly small effective index.

Such materials are commonly referred to as epsilon near zero, or ENZ, materials, and have been predicted theoretically [55, 56, 57] as well as demonstrated experimentally, across a wide range of the electromagnetic (EM) spectrum [58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68]. Experimental realizations of ENZ materials have been demonstrated from visible to microwave frequencies, using composite materials designed to mimic bulk ENZ characteristics [58, 59, 60, 61, 62, 63, 64]. Alternatively, at optical frequencies, many plasmonic or phononic materials can be used as a homogeneous bulk
Before we detail the properties of photonic wire waveguides fabricated from ENZ materials, it is worth discussing the most common approach for achieving ENZ properties at optical frequencies. Traditional metals, for instance gold, silver, or other noble metals, can most easily be described using the Drude formalism, which models the optical response of the many free carriers in these metals by solving a simple Newton’s force law for the free carriers, assuming a harmonic driving field (the incident electric field of an electromagnetic wave) and a scattering time (τ) for the free carriers. Such metals are extensively used at visible or near infrared wavelengths in plasmonic applications, at wavelengths where the real part of their permittivity is negative and on the order of the surrounding dielectrics’ positive permittivity. Above these materials’ plasma frequency, they behave as lossy dielectrics (with positive real permittivity). Thus, at or near the plasma frequency, they have a permittivity which approaches zero, and thus conceivably, could be used as ENZ-like materials. However, many of the noble metals have an intrinsic disadvantage for ENZ applications. The noble metals (or intermetallics, essentially dilute metals fabricated by alloying metals with dielectric materials) often have strong interband absorption features near their plasma frequencies, which leads to large imaginary components of their permittivity, resulting in unacceptable losses at ENZ frequencies [68].

An alternative approach to achieving ENZ behavior involves the use of heavily doped semiconductors. Highly doped semiconductors have been demonstrated to be good candidates for plasmonic metals in the mid-infrared wavelength range (and for certain nitrides and oxides, the near-infrared as well [69]). The conduction band electrons in semiconductors behave as a free electron gas (just as we model the noble metals), and allow us to use a slightly revised Drude formalism which we write, similarly to the noble metal version, as:

$$\varepsilon(\omega) = \varepsilon_{\infty}(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}), \omega_p^2 = \frac{ne^2}{m^*\varepsilon_0\varepsilon_{\infty}} \tag{3.7}$$

where $\omega$ is the radial frequency of the incident radiation, $\Gamma$ is the damping constant, $\varepsilon_{\infty}$ is the high frequency permittivity of the semiconductor lattice, $\omega_p$ is the semiconductor plasma frequency, $n$ is the carrier concentration, and $m^*$ is the effective mass of the free electrons in the semiconductor.
Increasing the free carrier concentration while reducing the effective mass will push the plasma frequency towards shorter wavelength. Our group has been working on highly doped semiconductors as plasmonic materials for the mid-infrared for years, in particular focusing on InAs [70], and InSb [71]. As illustrated in Fig. 3.4, by carefully manage the doping level, the highly doped semiconductor’s plasma frequency, in this case InAs, can be tuned to wavelengths as short as 6 µm. In such a material system, the plasma frequency is well away from the semiconductor’s band gap energy. Thus, material loss resulting from interband absorption is not a concern in highly doped semiconductors. Compared to other types of ENZ materials, doped semiconductors often offer a reduced loss, high crystal quality, homogeneous bulk material platform tunable across the mid-infrared wavelength range. As one example, the utilization of doped semiconductor as a mid-infrared ENZ material was demonstrated to enhance the transmission of light through subwavelength apertures [65].

With such a material system, we began to design the ENZ-cladding/Air-core waveguide operating at mid-infrared wavelengths, to act as a photonic wire for metatronic circuit demonstration.

![Figure 3.4](image)

**Figure 3.4:** Wavelength-dependent (a) real and (b) imaginary parts of the permittivity of our five InAs epi-layers, calculated from the modeled fits of our experimental reflection data from the as-grown samples using the Drude model. The range of real and imaginary permittivity values results from the uncertainty in the fitted scattering rate, Γ [70].
3.6 ENZ-cladding, air-core photonic wires

The mode profiles for such waveguides, fabricated from highly doped semiconductor, operating at wavelengths where the permittivity of the doped semiconductor is nearest to zero $\varepsilon_{\text{InAs}}(\lambda_{\text{ENZ}} \approx 0)$, and using realistic losses extracted from the literature, are shown in Fig. 3.5, along with the variation in $n, \kappa$ for each waveguide as a function of geometry at ENZ wavelengths $\lambda_{\text{ENZ}}$. Both the 1D slot and 2D core/cladding waveguides are shown, each having operational lengths (defined as the propagation length of the optical mode, $\delta = \lambda_0/2\pi\kappa$) less than a free-space wavelength and local wavelengths (defined as $\lambda = \lambda_0/n$) of approximately $\lambda = 2\lambda_0$.

While these values are significant potential challenges to the use of ENZ-clad waveguides in metatronic applications, an additional challenge might be even more troubling. Even in the case of unrealistic (near lossless) materials, as soon as the 1D slot waveguide metatronic circuit (Fig. 3.5a) comes into contact with a dielectric, light would necessarily escape from the low-index

![Figure 3.5: Effective $n, \kappa$ for (a) 1D and (b) 2D ENZ cladding, air core waveguides as a function of (a) gap height $h$ and (b) core width $s$, modeled using realistic losses obtained from molecular beam epitaxial (MBE) grown n-doped InAs with $\varepsilon_{\text{InAs}}(\lambda = 6.9 \, \mu m = 0.0165 + 0.45i$. Insets show the basic structure used in our model. Normalized cross-sectional field profiles $|E_z|$ for c) 1D and (d) 2D waveguides with (c) $h = 2.7 \, \mu m$ and (d) $s = 3.7 \, \mu m$, at the wavelength where $\text{Im}\{\bar{n}\} = \text{Re}\{\bar{n}\}$. [72]
optical wires into the higher-index vacuum. An attempt to address these challenges was made in [73] where a photonic wire based on a plasmonic waveguide was proposed and experimentally demonstrated. However, the material platform of this wire does not allow straightforward integration with other metatronic components.

3.7 Device design

The discussion above provides the starting point for our efforts to develop photonic wires for metatronic applications. The ideal photonic wire should satisfy several important constraints. First, it should be isolated from the surroundings so as to minimize out-of-guide radiation leakage and parasitic coupling of signals to the surrounding optical environment. Second, the wire should be fabricated on a platform that would allow, in principle, fabrication of the other elements of photonic circuitry. Third, the structure (as well as the other optical elements) should be realizable with current fabrication protocols. Finally, the effective index (both real and imaginary) of the wire should be as low as possible. The latter condition results from the requirement that the ideal photonic wire not only demonstrates a dramatic extension of the local wavelength ($\lambda = \lambda_0/n \gg \lambda_0$) but also is able to propagate for distances longer than the free space wavelength ($\delta = \lambda_0/2\pi\kappa \gg \lambda_0$). Minimizing both $n$ and $\kappa$ provides the primary (significant) challenge to designing and demonstrating photonic wires for optical circuitry applications. The constraints outlined above virtually eliminate the possibility of all-dielectric photonic wires, such as the designs shown in Fig. 3.5, due to the sub-wavelength operational length ($\delta < \lambda_0$) and because the radiation to be guided will leak out of such structures into the surrounding environment, which have $n \sim 1$. However, were bound surface modes to be utilized, such leakage into the continuum could be prevented, or at least minimized. Furthermore, such modes would offer the opportunity to enhance the interaction between bound optical waves and any optical lumped circuitry integrated into the waveguide. While traditional polaritonic surface modes, such as the surface plasmon polaritons (SPPs) supported on semi-infinite planar metal/dielectric interfaces, do not offer dispersion relations with $n_{\text{eff}} \approx 0$ regimes, the addition of lateral confinement to the SPP mode results in a waveguide with a frequency cut-off
Figure 3.6: (a) Modeled $n, \kappa$ vs wavelength ($h = 6 \mu m$) and (b) value of $\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\}$ as a function of sidewall height $h$, for (c) all-Au (red), (d) all Au with Au cap (orange), (e) hybrid InAs/Au (blue), and (f) hybrid Au/InAs with Au cap (green) waveguides. Normalized mode profiles ($|E_z|$) at $\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\}$ are shown in (c-f). [72]

where $n_{eff} \approx 0$. Fig. 3.6 presents several designs of photonic wires based on surface modes and compares their performance as far as the extension of the quasi-static limit is concerned. As a figure of merit, we use the value of the real part of the effective index at the wavelength where $\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\}$, with smaller values of $\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\}$ corresponding to modes with lower losses, larger effective wavelength, and larger operational length. The optical properties of the modes in our waveguide designs are modeled using finite element method (FEM) using eigenvalue/eigenmode analysis offered by the commercially available COMSOL Multiphysics package.

Figure 3.6 presents the characteristics of four waveguide structures with the potential for serving as photonic wires at mid-infrared frequencies. The first two structures shown are waveguides fabricated entirely from Au: an open (Fig. 3.6c) and capped (Fig. 3.6d) Au slot waveguide with an Air gap, similar to the structure of [73]. The latter two waveguides represent the ‘hybrid’ slot waveguides proposed here, either open (Fig. 3.6e) or Au-capped (Fig. 3.6f) with a doped InAs base and Au sidewalls. At mid-
infrared wavelengths, the optical response of Au closely resembles that of a perfect electrical conductor (PEC), whereas the doped InAs represents a plasmonic material operating close to its plasma frequency. Therefore, the optical response of doped InAs at mid-infrared resembles the optical response of noble metals at visible frequencies \[29\]. While the all-Au structures (Fig. 3.6c,d) behave similarly to PEC waveguides, operating at cut-off, the hybrid waveguides presented here (Figs. 3.6e,f), take advantage of a SPP mode supported by the air-doped semiconductor interface that is brought to cut-off by two PEC vertical sidewalls. Figure 3.6a shows the dependence of \(n(\lambda), \kappa(\lambda)\), for each of the four waveguide structures, demonstrating that values of \(n \approx \kappa \leq 0.15\) are possible for all four designs presented, a marked improvement over the all-dielectric waveguide structures shown in Fig. 3.5.

Despite similar performance in the \(n(\lambda) \approx \kappa(\lambda)\) regime, the mode profiles of the all-Au and hybrid waveguides differ significantly. Figure 3.6b shows the dependence of the \(\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\}\) value for each of the four waveguides as a function of \(h\), the height of the waveguide sidewalls. The all-Au open waveguide (Fig. 3.6c) shows poor performance for small \(h\), a result of light leakage from the from the poorly bound Au/Air surface mode, as can be seen in the mode profile shown in Fig. 3.6c. For large values of \(h\), however, this waveguide gives low values, when the mode is more tightly bound by the \(\sim\)PEC sidewalls. However, the values required to achieve low losses are not only difficult to fabricate, but approach the cross-sectional length scales of quasi-plane waves, preventing strong interaction with subwavelength optical lumped elements. Not surprisingly, the open hybrid waveguide modeled shows the often-encountered plasmonic trade-off between mode confinement and propagation length. The hybrid waveguide shows slightly lower losses at small \(h\), due to the stronger confinement arising from the plasmonic nature of the doped semiconductor at long wavelengths. At larger \(h\), the hybrid waveguide shows higher losses than its all-Au counterpart, as confinement is provided by the plasmonic semiconductor, which results in a minimum \(n \approx \kappa\) value that is largely independent of sidewall height.

For realistic values of \(h\) \((h \leq \lambda_0/2)\), the uncapped hybrid waveguide slightly outperforms its all-Au counterpart. At the same time, the hybrid waveguide offers multiple additional design benefits. First, the dispersion of the hybrid mode can be controlled both by geometry (varying the width of the slot waveguide) and by material (control over the permittivity of the doped semi-
conductor during epitaxial growth) [70, 71]. Second, because our waveguide is fabricated on an epitaxially-grown semiconductor base, both bulk semiconductor (doped and undoped), as well as optoelectronic active regions, can be grown epitaxially in the waveguide region, offering the opportunity for future integration of passive optical lumped elements and/or optoelectronic emitters and detectors with the optical wires.

The addition of an Au-cap to the modeled waveguides significantly improves the performance of both the all-Au and hybrid designs. Figure 3.6e and f show the perspectives of designing completely encapsulated photonic wires. It is seen that these structures have even longer operational length, when compared to the open slot waveguides. Using such a design, the hybrid waveguide demonstrates $\text{Im}\{\tilde{n}\} = \text{Re}\{\tilde{n}\} < 0.08$ with $h \leq \lambda_0/2$, giving $\delta \approx 2\lambda_0$, wire lengths potentially compatible with optical lumped element circuit designs.

### 3.8 Device fabrication

Our waveguide structures were fabricated on epitaxially grown highly-doped InAs layers, grown in an SVT Associates molecular beam epitaxy (MBE) system using a growth process described in depth in previous work [71]. Figure 3.7 shows the growth structure of the epitaxial material, as well as the normal incidence reflection spectrum from the epitaxial surface. From this spectrum, using a transfer matrix method (TMM) approach, the plasma frequency and scattering rate of the doped InAs can be extracted, allowing for the determination of the complex permittivity of the InAs, using the Drude model.

The waveguide fabrication process for a single waveguide is shown in Fig. 3.8a. Upon the epitaxial surface, we first pattern an Au grating with stripe width 12 μm, period 18 μm and thickness 50 nm using a standard UV photolithography, metal deposition and lift-off process. Subsequently, a layer of SU-8 with thickness of ~ 6 μm is spin-coated over the surface of the sample. A second lithography step is used to pattern SU-8 stripes directly above the existing Au stripes. Next, a double angled metal evaporation is performed to coat the SU-8 stripe sidewalls, using the shadow effect to prevent metal deposition on the exposed semiconductor between the SU-8 stripes. A scanning
electron micrograph (SEM) of a waveguide cross-section, after the metal deposition step, is shown in Fig. 3.8b. The sample was then placed face down on an Au-coated silicon wafer, and the edge of the sample sealed with crystal bond wax. The GaAs substrate was removed using a selective wet etch (solution NH$_4$:H$_2$O$_2$:H$_2$O=8:24:128), and the thin GaSb buffer removed using a different selective wet etch (solution HCL:H$_2$O$_2$:H$_2$O=100:1:100), leaving the substrate side of the doped InAs layer exposed.

The result of the waveguide fabrication process is an array of hybrid slot waveguides with metal sidewalls and a doped InAs base. The metal sidewalls of the waveguides ensure that each waveguide is optically isolated from its neighboring waveguide structures, while the spatial density of the waveguides results in a stronger interaction of the waveguide modes with the large beam diameter of the mid-infrared probe beam. Figure 3.8a (viii) shows the final fabricated structure directly bonded to an Au-coated carrier wafer. It should be noted that due to bowing of the epi- and carrier wafers, it is likely that

![Figure 3.7](image-url)

**Figure 3.7:** a): TMM-modeled (solid red line) and experimental (red triangles) reflection spectra for as-grown epitaxial structure. Inset shows epitaxial layer structure. b): Extracted complex permittivity of the doped InAs layer. Fitting parameters: $\varepsilon_{\infty, \text{GaAs}} = 10.89$, $\varepsilon_{\infty, \text{GaSb}} = 14.45$, $\varepsilon_{\infty, \text{InAs}} = 12.3$, $\lambda_{p, \text{InAs}} = 6.9$ $\mu$m, and $\gamma_{\text{InAs}} = 1 \times 10^{13}$s$^{-1}$.[72]
an air-gap spacer exists between the two sample surfaces. The magnitude of this spacer gap most likely varies across the sample surface, an effect which would result in a broadening of our experimental data, as discussed below.

### 3.9 Experimental set-up and numerical calculations

Our structure was characterized by angle and polarization dependent FTIR spectroscopy using the experimental set-up shown in Fig. 3.9. Light from the internal source of the FTIR passes through two spatial filters designed to collimate and reduce the beam size of the light incident on the sample. A wire grid polarizer after the second spatial filter controls the polarization of the incident light. The sample is placed on a rotating stage to control the angle of the incident beam, and reflected light is collected by a parabolic mirror and focused onto an HgCdTe (MCT) detector mounted on a rotational stage concentric with the sample stage. Such a configuration is essentially the well-known Kretschmann configuration used to measure coupling to plasmonic modes on thin metal films, except in this case, we are coupling to hybrid waveguide modes, through doped semiconductor. It is thus the TM polarized incident light, as shown in the inset of Fig. 3.9, which is able to couple to the waveguide modes of interest. By varying incidence angle, we can control the wavevector of the incident light in the direction of waveguide propagation. Because dips in reflection correspond to coupling to these waveguide modes, tracking the spectral position of the dips as a function of incidence angle (mode wavevector) allows us to map the dispersion of the photonic wire.
modes. The magnitude of the reflection features will depend on coupling strength to the waveguides: thick n+ InAs layers will better confine the excited modes, but weaken coupling, while thin InAs layers will improve coupling, but to weakly bound modes. The thickness of the n+ InAs was chosen to be 550 nm, thick enough to confine the waveguide modes but thin enough to allow coupling. As incidence angle decreases (towards near-normal incident light), coupling to the true ENZ-like modes is enabled. However, the component of the electric field overlapping the waveguide mode’s field profile decreases, weakening coupling. Thus, our experimental reflection features would be expected to be strongest for larger angles of incidence.

Our waveguide structures are modeled using custom-built rigorous wave coupled analysis (RCWA) software, which is provided by our collaborator Dr. Christopher Roberts and Professor Viktor Podolskiy from UMass Lowell [44]. The RCWA technique originally proposed in [43] can model periodic structures imposing a Bloch-wave-periodicity to the system. This technique allows a rigorous calculation of the reflection of the system. TE- and TM-polarized reflection from our waveguide was simulated for the experimental configuration shown in Fig. 3.6c, for the waveguide geometry shown in Fig. 3.8a (viii), having a waveguide width $w = 6.15 \, \mu m$, sidewall height $h = 6 \, \mu m$, and periodicity $\Lambda = 18 \, \mu m$. We use the permittivity of Au from the literature [74] and the permittivity of the doped InAs extracted from the reflection measurements of epitaxially-grown material, shown in Fig. 3.7. Finally, we assume a spacing layer of 1.5 $\mu m$ between the top of the waveguide sidewalls.

![Figure 3.9: Experimental setup for characterizing the angle- and polarization-dependent reflection from the ENZ waveguide array, with inset showing the sample orientation under test.](image-url)
and the Au-coated carrier wafer, which we discuss further in the subsequent section.

3.10 Results and discussion

The RCWA simulations of TE- and TM-polarized reflection from our fabricated waveguide structures, as a function of incidence angle, are shown in Figs. 3.10a and 3.10b, respectively. Here we see distinct dips in the reflection spectra corresponding to coupling to modes in our fabricated waveguide arrays. In addition, the dashed line in Fig. 3.10b shows the dispersion of the hybrid waveguide mode, shown in Fig. 3.6f, calculated with finite element method, and superimposed on Fig. 3.10b using the momentum matching equation

$$\frac{2\pi}{\lambda_0} \Re(e^{i\tilde{n}}) = k_z = \frac{2\pi}{\lambda_0} \sin(\theta_i)$$  \hspace{1cm} (3.8)

with $k_z$ being the wavevector of the mode in the direction of the mode propagation, $\lambda_0$ being the free-space wavelength, and $\theta_i$ being angle of incidence. As expected, this mode is only present in TM-polarized excitation, and exhibits ENZ behavior at around $\lambda_0 \approx 12 \mu m$. Coupling to the ENZ mode weakens for decreasing angles of incidence, resulting from the aforementioned weaker overlap of the incident TM-polarized E-field with the excited mode. The numerical solutions of Maxwell’s equations reveal the presence of several other modes in the structure at $\lambda_0 \approx 12 \mu m$. Our calculations show that these modes are either (i) volumetric modes that do not have significant overlap with InAs substrate and thus cannot be modulated by doping or (ii) surface-guided modes that are supported by the bottom (unconstrained) InAs-air interface that would not exist in realistic photonic circuits.

Figure 3.11a and 3.11b show the experimental results from the fabricated samples for TE- and TM-polarized incident light. The experimental results largely match the simulated reflection spectra of Fig. 3.10, with coupling to the ENZ-like mode observed across a similar range of wavelengths and incidence angles.

Additional coupling features are seen in the wavelength range $\lambda = 8 - 10 \mu m$ for incidence angles $\theta < 40^\circ$ in both TE and TM polarized data, for
Figure 3.10: RCWA-simulated (a) TE- and (b) TM-polarized reflection as a function of incidence angle. The dashed line in (a) represents coupling to a waveguide volumetric mode, while the dashed line in (b) denotes the calculated coupling angle. Inset in a) shows the mode profile of a representative volumetric mode at $\lambda_0 = 9.18 \, \mu m$.

Figure 3.11: Experimental (a) TE- and (b) TM-polarized reflection as a function of incidence angle. Dashed line in TM-polarized data denotes the calculated coupling angle.

both our experimental and simulation results. Similar to the extra modes at $\lambda_0 \approx 12 \, \mu m$, these modes are identified as volumetric waveguide modes, which also will approach effective indices $n_{\text{eff}} \approx 0$ near cut-off. However,
these modes are not tied to the semiconductor surface (being centered at the waveguide core), and therefore will not strongly interact with any structures fabricated upon the waveguide base. In addition, these modes only appear in the capped waveguide simulations; without the Au cap, the volumetric modes are not bound. Interestingly, the appearance of these modes in the experimental data indicates that the Au-coated surface of the carrier wafer affects the optical properties of the fabricated waveguides, though the ENZ-like modes of interest remain largely unaffected as they are bound to the InAs base of the waveguide, away from the Au cap. The presence of the volumetric modes does allow for an estimate of the average spacer between the top of our waveguide sidewalls and the Au-coated carrier wafer, which we set at 1.5 µm for our simulations.

While our simulations and experimental results show good agreement, the experimental data of Fig. 3.11 can be seen to have a lower baseline reflectivity, as well as slightly broadened coupling features when compared to numerical calculations. The former effect is most likely due to fabrication-related imperfections, including surface roughness and/or oxidation of the exposed, wet-etched n-doped InAs surface upon which our probe beam is incident. We attribute the broadening of the spectral features observed in our experimental results primarily to the variation in the waveguide geometry across length scales commensurate with the probe beam diameter. Small changes in sidewall height, as well as the spacing between the top of the sidewall and the Au-coated carrier wafer can result in slight shifts of the observed spectral features. The wide probe beam diameter (required to maintain minimal angular divergence of the incident beam) ensures that our experiment samples a large number of waveguides, broadening the observed spectral features.

Figure 3.12 shows a comparison of the propagation lengths and cross-sectional mode profiles (in the direction of propagation) for the photonic wires discussed in this work and all- ‘dielectric’ ENZ cladding/air core waveguides proposed in [53], all modeled using realistic losses. It is seen that the all-dielectric guides are highly lossy, and decay over a length scale much shorter than a wavelength. It is also seen that while these guides can be designed to have small cross-sections; the electric field extends over macroscopic distance outside the waveguide core. The all-Au slot waveguides, both open and capped, offer propagation lengths larger than a free-space wavelength. However, these structures support modes which are either weakly bound to the
Figure 3.12: Comparison of propagation lengths for the potential ENZ waveguides discussed, normalized to free-space wavelength. Contour plots show the cross-sectional normalized field profiles ($|E_z|$) for each of the waveguide geometries, along the direction of propagation (normalized to free-space wavelength), with insets showing basic schematics of the waveguide geometry.

Moreover, the all-Au architecture does not allow for direct integration with optoelectronic devices or epitaxially-grown structures on the waveguide base. The hybrid photonic wires, the subject of this work, not only demonstrate potential wire lengths over 2 free space wavelengths ($\delta > 2\lambda_0$), but also local wavelengths an order of magnitude larger than the signal’s free space wavelength ($\lambda > 10\lambda_0$), while at the same time allowing for direct integration of epitaxially-grown materials and devices at the base of the waveguide, where the mode profile is strongest. The lateral confinement of the field in the hybrid and Au-based guides is comparable or better than that in the guides with ENZ cladding.
3.11 Future work on the photonic wires

The next step based on our proposed hybrid waveguide design is to integrate the optical lumped elements into the waveguide, and characterize the resonant behavior of this optical circuit.

Figure 3.13 shows the fabrication process flow of making these photonic wires with lumped elements. Based on previous discussion, another two layers of semiconductor with \( \varepsilon > 0, \varepsilon > 0 \) are added on the waveguide base epitaxially (Fig. 3.13a). Followed by lithographically patterning and dry etching, the lumped elements are defined (Fig. 3.13b). After that, the ENZ waveguide are fabricated as described in Fig. 3.8.

When the optical signal consists of an optical mode with E field polarized parallel to the epi-layer interface, as shown in Fig. 3.14a, the optical displacement current \( \frac{\partial D}{\partial t} \) ‘flows’ along the dielectric \( (\varepsilon > 0) \) and the metal \( (\varepsilon < 0) \) simultaneously; therefore, the structure will function as a parallel combina-

Figure 3.13: Process schematic for fabricating the ‘photonic wire’ with lumped circuit elements embedded into the wire. (a) Monolithically growth our waveguide based with \( \varepsilon > 0 \) and \( \varepsilon < 0 \) layers. (b) Lithographically define the optical lumped components by dry etching. (c) Fabricate the waveguide sidewall as previously discussed.
tion of lumped impedances $Z_{\parallel} = Z_c \times Z_i/(Z_c + Z_i)$, where $Z_c$, $Z_i$ represents the impedance of capacitor and inductor respectively.

When the E field of the optical mode is perpendicular to the epi-layer interface, as shown in Fig. 3.14b, the optical displacement current ‘flows’ transversely across the capacitor and the inductor; in this case, the structure behaves as series combination of lumped impedances of $Z_{\perp} = Z_c + Z_i$. For our waveguide, the dominant ENZ mode was excited by the TM polarized light, which has the E field along the epi-layer interface (as we discussed in the experimental set-up session); therefore, we expect to observe the parallel impedance behavior of our circuit.

Experimentally, the most challenging part is how to launch the ENZ mode into the waveguide. As we shown in Fig. 3.11b, the signature of coupling to the ‘real’ ENZ mode ($n \sim 0$) is diminished when the incident angle approaches zero, which is a result of the weaker overlap between the TM-polarized E field and the mode to be excited. The alternative solution is to integrate an active region into our waveguide along with all of the dielectric and metal components. However, the current design of our photonic wires pushed the ENZ operating frequency up to 12 µm, where a light source is hard to design in the InAs-based material system. Recently, our group has developed a strong mid-infrared source based on In(Ga)Sb/InAs system, which can emit light at $6 \sim 8$ µm. We could shift the plasma wavelength of our doped InAs base towards shorter wavelength ($\sim 5$ µm), then monolithically integrate the source with our proposed optical circuits. Ultimately, our photonic wires are enabled by the designer plasmonic materials (doped semiconductors) which we are able to grow epitaxially, and which serve as the base of our waveguides. By controlling the free carrier concentration in these

![Figure 3.14](image-url)

**Figure 3.14:** (a) Optical signal with E field polarized parallel to the epi-layer interface. (b) Optical signal with E field polarized perpendicular to the interface.
materials, we are able to effectively control the materials' optical properties. While the presence of free carriers thus dramatically alters the optical properties of our semiconductors in the mid-infrared wavelength range, such a change in material properties requires significant free carrier concentrations. Thus moving to even shorter wavelengths of operation is possible, but achieving semiconductor plasma frequencies much below 6 $\mu$m poses a significant challenge.

3.12 Conclusions

In this chapter, we propose and demonstrate a paradigm that takes advantage of the highly controllable optical response of designer ENZ materials made from doped semiconductors and which can thus potentially enable the design and fabrication of an integrated metatronic circuit. Our photonic wires are fabricated using a hybrid doped semiconductor-metal slot architecture, and can be spectrally tuned by controlling the material properties of the doped semiconductor component of the waveguide, as well as the waveguide geometry, increasing the length of the optical wire to multiple free-space wavelengths. The demonstrated ENZ waveguides are of particular interest for the aforementioned nascent field of ‘metatronics’, serving as photonic wires able to carry signals with effective wavelengths much larger than the optical elements with which these modes interact. The use of semiconducting material as a plasmonic component allows for structures fabricated with epitaxial $\varepsilon > 0$ and $\varepsilon < 0$ materials to be grown directly into the waveguides, as well as the potential integration with active optoelectronic structures such as detectors and sources. Our waveguides are designed and modeled using both rigorous wave couple analysis (RCWA) and finite element methods, and characterized using angle- and polarization-dependent Fourier transform infrared (FTIR) spectroscopy. We demonstrate coupling from free space into our waveguiding photonic wire structures, analyze the excited modes in these waveguides, and discuss the challenges as well as the opportunities of the demonstrated photonic wire architecture.
Chapter 4

Multiplexed Infrared Photodetection using Resonant RF Circuits

In this chapter, we demonstrate a room-temperature semiconductor-based photodetector where readout is achieved using a resonant RF circuit consisting of a microstrip split-ring resonator coupled to a microstrip busline, fabricated on a semiconductor substrate. The RF resonant circuits are characterized at RF frequencies as functions of resonator geometries, as well as for their response to incident IR radiation. The detectors are modeled analytically and using commercial simulation software, with good agreement to our experimental results. Though the detector sensitivity is weak, the detector architecture offers the potential for multiplexing arrays of detectors on a single read-out line, in addition to high speed response for either direct coupling of optical signals to RF circuitry, or alternatively, carrier dynamics characterization of semiconductor or other material systems. In Chapter 5, we will discuss approaches for enhancing the sensitivity of the detectors discussed here.

4.1 Background

The rapid growth of wireless communication technology has resulted in many new chip-scale radio frequency (RF) structures and devices, with a corresponding decrease in the device cost. RF components have the potential to bridge the ‘THz gap’ between optoelectronic devices (\(>100\) THz frequencies) and electronic devices, operating now up to hundreds of GHz and even THz frequencies [75, 76, 77, 78, 79, 80, 81]. There is thus increasing interest in technologies and architectures that are able to merge RF and optical capabilities, linking the two foundations of modern communication platforms.

At the same time, greater accessibility of RF components offers new opportunities for materials and device metrology at lower costs, with the po-
ential to efficiently measure high-frequency device performance and material response across a range of optical materials and optoelectronic device architectures. The use of free space microwave radiation for bulk material characterization or IR detection is many decades old [82, 83]; recently, it has been used for measurement of carrier dynamics in semiconductor materials [84]. Also, applying RF circuitry at optical frequencies provides the opportunity to leverage the rapid development of novel RF technologies, producing compact, cost-effective infrastructure for new devices. In particular, the RF frequency range between 1-20 GHz is intriguing, with many low-cost and readily available RF sources and detectors operating at frequencies commensurate with time constants associated with state-of-the-art electronic and optoelectronic devices, and charge carrier dynamics in these devices.

The majority of devices which comprise the field of RF photonics are usually focused on the modulation and de-modulation of optical carrier signals at RF frequencies [85, 86]. A small but growing subfield encompasses the devices where RF signals are modulated by optical signals. Such an approach opens the door to entirely new functionality, where RF signals or circuits can either be modulated/controlled at very high rates (akin to optical circuits), or alternatively, with great sensitivity to incident optical signals. The most recent examples of such devices are the microwave- or lumped element-kinetic inductance detectors (M-KID and LE-KID, respectively). These detectors consist of resonant RF microstrip or coplanar waveguide resonant LC circuits fabricated from superconducting materials, resulting in extremely high Q ($> 10^6$) RF resonances [87, 88, 89]. The high-Q resonators are coupled to a single busline (also of superconducting material) carrying a signal at the resonant frequency of the LC resonator. Light incident on the resonator structure is absorbed by the superconducting material which generates quasiparticles and alters the surface impedance of the metal film. This results in a dramatic change in the resonator Q which can be read out as a change in amplitude or phase of the RF signal on the busline.

As a result of their ultra high-Q, the -KID class of detectors can achieve single-photon sensitivity, coarse energy-resolution, and perhaps most importantly, multiplexing of 1000’s of detectors (with slightly different resonances) along a single busline by careful spectral filtering of the transmitted signal [90, 91, 92]. In addition, this detection mechanism can exhibit sensitivity out to extremely long wavelengths [88, 93]. These features make -KIDs ideal for
low photon flux imaging across a range of wavelengths, attractive for a number of astronomy, astrophysics and particle physics applications. However, these detectors require operating temperatures below the Tc of superconductors, and typically below 1K. The high-Q and long quasi-particle lifetimes, which depend on the superconducting material choice and quality as well as temperature, are typically in the 100’s of microseconds [94, 95], which limits the bandwidth of M- and LE-KIDS to low kHz frequencies. The sharp rise times, however, have been explored for time of arrival resolutions on the order of single µs’s [96].

While some advantages of the superconductor-based KIDs (high sensitivity, high-Q) do not extend to temperatures beyond the superconductor Tc, the broader operation principles of -KIDs can be utilized to design room-temperature, high-speed semiconductor-based detectors capable of similar multiplexing (if not quite as dense as the superconducting -KIDs). Recent work has demonstrated the utility of microwave probes for measuring the carrier dynamics in semiconductor materials [97]. In the work of Ref. [97], electron hole pairs (EHPs) are photon-excited, and the resulting change in the free carrier concentration of the material leads to a corresponding change in the material permittivity, as expected from the Drude formalism. This change is measured in the change of reflectivity for a pump microwave signal, allowing for time-resolved measurement of carrier concentrations in the semiconductor material. A similar effect has been used to demonstrate tunable THz meta-materials, where THz frequency optical transmission through split-ring resonator (SRR) arrays can be modulated by optical excitation of EHPs in the semiconductor-filled gap of the SRR [84, 98, 99, 100, 101, 102, 103].

Combining the results of Refs. [97, 84, 98, 99, 100, 101, 102, 103] with the fundamental approach employed by the -KIDs, we demonstrate high operating temperature detectors where incident light, absorbed by a semiconductor material in the SRR gap, alters the local conductivity (or complex permittivity) of the resonant microwave circuit and is read out as an RF signal.
4.2 Basic structure of the detector

Because our detector architecture is based on microstrip transmission lines (TLs) operating at GHz frequencies, I will first provide a basic background on the RF structures used in our detectors. I will then go on to describe microstrip TLs: including a description of the TL fields, the TL characteristic impedance ($Z_0$), and the general propagation of waves in the TLs. Subsequently, I will describe the SRR, and the capacitive coupling between the SRR and the microstrip TL. Finally I will describe how signals are launched and measured on these TLs.

The microstrip TLs is one of the most popular types of TLs, and has been broadly applied in microelectronics. The basic geometry of a microstrip line is shown in Fig. 4.1a [104]. The bottom of the waveguide is a metallic ground plane, the top consists of a conductor patterned into a stripe line. In between the two conductor layers is a layer of dielectric (thickness $d$) with permittivity $\varepsilon_r$.

When $\varepsilon_r \neq 1$, especially when is the structure is asymmetric (the dielectric material only fills one side of the microstrip line), the behavior of the propagating mode is a little different than a simple stripline embedded in vacuum. Some portion of the modes field lines are in the dielectric region (below the microstrip) and some fraction are in the air above the substrate. Therefore the microstrip line can only support a quasi-TEM wave, a result of the phase matching constraint at the interface. The actual field looks like Fig. 4.1b.

Since the dielectric film is very thin ($d \ll \lambda$), so a good approximation of phase velocity, propagation constant, and characteristic impedance can be obtained from a static solution, where [104]:

![Figure 4.1: A microstrip transmission line. (a) Geometry, (b) electrical and magnetic field lines. [104]](image-url)
\[ v_p = \frac{c}{\sqrt{\varepsilon_e}}, \beta = k_0 \sqrt{\varepsilon_e} \] (4.1)

The effective dielectric constant is [104]:

\[ \varepsilon_e = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2} \frac{1}{\sqrt{1 + 12d/W}} \] (4.2)

Based on the geometry, for \( W/d \leq 1 \) (\( W \) is the strip width) the characteristic impedance is [104]:

\[ \varepsilon_e = \frac{60}{\sqrt{\varepsilon_e}} \ln \left( \frac{8d}{W} + \frac{W}{4d} \right) \] (4.3)

Figure 4.2: A schematic of the equivalent circuit model of the SRR in Advanced Design System.

While the microstrip TL, in its most basic form, is used to transmit an RF signal, control of the geometry of the TL can give the microstrip qualities best described using lumped circuit approximations. Central to our project is the microstrip TL split ring resonator (SRR).

Basically, in its simplest form, the split ring resonator consists of a highly conductive microstrip metallic ring with a broken gap (non-conductive), which is normally filled with air or other dielectric materials. A signal launched on the SRR will result in a current induced in the ring (with an associated magnetic field). As the current propagates, charge will begin to accumulate at the gap, and the energy originally stored in the magnetic field will be transferred to an electric field stored in the vicinity of the gap tips. Therefore, the resonator forms by alternating between energy stored in the electric and magnetic fields of the ring supporting propagating waves. Of
course, this behavior is also associated with a LC resonator, and not surprisingly, we can describe our SRR using a lumped element formalism, where the $L$ is the inductance of the metallic ring, and the $C$ is the capacitance of the gap.

When we put our split ring resonator close to a microstrip line carrying a RF signal, the top arm of the split ring and the busline form a capacitor; therefore the signal transmitted on the busline can capacitively couple into our resonator structure. In the same way, a signal on the SRR can couple back onto the busline. At resonance, the energy carried on the microstrip line will largely stored in the resonator structure. If we measure the S21 parameter of the structure on resonance, we would expected to see a transmission dip at the resonant frequency.

![Figure 4.3: The circuit fitting data compare with an experimental result.](image)

As illustrated in Fig. 4.3, the circuit model can fit the experimental data very well.

### 4.3 Device design

As we mentioned in the previous section, our device consists of a resonant RF circuit as illustrated in Fig. 4.4, a split ring resonator closely placed near a single microstrip line. The circuit can be understood using an equiv-
Figure 4.4: Birdseye schematic (top), cross-sectional schematic (middle) and optical micrograph (bottom) of (a) single and (b) double SRR detector structures showing relevant dimensions. (d) Equivalent circuit model for the SRR RF circuit response and (d) schematic of optically pumped single-SRR detector structure.

alent lumped element model (Fig. 4.4c). In this architecture, the SRR is modeled as an LCR resonator structure that is capacitively coupled (CS) to the busline. Such structures function as a stop-band filter, and have been previously utilized as a platform to study left hand materials in the microwave frequency range [105, 106, 107]. On resonance, the LCR circuit effectively acts as a shunt to ground on the circuits busline, which results in a dip of the transmitted signal at the circuit readout. In such a structure, when light with energy sufficient to excite electron hole pairs (EHPs) in the gap of the SRR, the local conductivity in the capacitive gap is changed near the surface, effectively altering the resistance of the LRC equivalent circuit and thus modulating the circuit’s RF-response (in a similar manner to the tuning of the free-space THz transmission in the metamaterials of [84, 98, 99, 100, 101, 102, 103]).

In this case the detector’s response is directly related to the conductivity of the absorber material under excitation, which is similar to a traditional photoconductive detector. The conductivity of the semiconductor can be written as
\[ \sigma = q(\mu_n n + \mu_p p), \mu_{n,p} = \frac{q m^*_{n,p}}{\tau_{sc}}, n = p = G \tau \]  

(4.4)

where \( \mu_n \) and \( \mu_p \) are the electron and hole mobility, \( n \) and \( p \) are the electron and hole concentration, with unit of \( \text{cm}^{-3} \), \( G \) is the generation rate, and \( \tau \) is the carrier lifetime in the semiconductor.

At resonance, the transmitted RF signal at the output port of the circuit can be used to measure the free carrier concentration and therefore the intensity of the incident light at the capacitive gap (\( C1 \)), or alternatively, could allow for incident light to directly modulate the transmitted RF signal. The RF resonance of the SRR can be easily tuned by modifying the geometry and material properties of the unit cell such that multiple SRRs can be coupled to a single busline, offering the potential for RF-multiplexed detection/modulation using a single input and output port. The time-response of the detector element is determined by a combination of carrier life-times and the inherent time-response of the LCR circuit. The capacitive gap of the SRR can be filled with a range of different materials using direct epitaxial growth on the substrate wafer or some form of pick and place or deposition techniques to achieve significant control of carrier life-time and semiconductor band-gap. This offers a path towards multiple-wavelength and high-speed or high-sensitivity detection of incident radiation. In this chapter, we demonstrate the performance of such detectors using SI GaAs and show control over the RF resonance of the SRR, in addition to the ability to detect light on multiple detectors coupled to a single busline. The optical response and sensitivity of the fabricated detectors are characterized, and potential applications for the demonstrated detectors are discussed. Our results are modeled analytically and simulated with good agreement.

### 4.4 Device fabrication

Our basic device structure is illustrated in Fig. 4.4a,b. The entire circuit is built on semi-insulating (SI) GaAs substrate. We start from surface cleaning, dehydration, then spin-coated a layer of lift-off resist LOR 3A, with 3000 rpm. After soft-baking for \( \sim 4 \) min, another layer of positive photoresist (Shipley 1813) was spin-coated on top of the lift-off resist, with the spin speed.
∼4000 rpm, soft-bake ∼1 min to get rid of the solvent as well as improve the adhesion. A standard photolithography process (i-line 365 nm) was then performed, with optimized dosage ∼60 mJ/cm², and the exposed sample then developed in MF319 for ∼60 seconds. Following the pattern develop, an oxygen plasma descum was performed to strip off the residual resist. The sample was then placed in an e-beam evaporator. We first deposited 10 nm Ti to form an adhesion layer, followed by 500 nm of Au to form the conductor of the microstrip line. The pattern was created using a lift-off process in a PG remover solution. A backside metal deposition with the same metallization recipe (10 nm Ti/500 nm Au) was performed as the final step of the device fabrication.

4.5 Device characterization-RF response

The SRR RF responses were characterized with an Agilent 5230A Performance Network analyzer (PNA) combined with a probe station. The short-load-open-through (SLOT) calibration technique was applied with on-chip standards to shift the measurement reference planes to the tips of the GSG probes. The position of the RF resonance is primarily determined by its geometry. The resonant frequency can be fine-tuned (±0.5 GHz) by controlling the capacitive gap G1 of the SRR. Figure 4.5a,b show the (a) experimental and (b) HFSS simulated RF amplitude transmission \(|S21|\) for a SRR of side lengths 1 mm, and a spacer of \(S = 30 \mu m\), for a range of capacitive gap values \(G1 = 0 \sim 100 \mu m\). Good qualitative agreement is demonstrated between the experimental results and simulations with respect to the depth, linewidth, and spectral shift achieved with changing G1. Figure 4.5c shows the experimental RF amplitude transmission spectra \(|S21|\) for SRRs of side lengths 1 mm, capacitive gap \(G1 = 50 \mu m\), for a range of coupling gap distances \(S = 10 \sim 75 \mu m\). The black line shows the response for a busline without the SRR, which as expected, shows no resonance. For all \(S > 0\), strong resonant features are observed at \(f = 15.5 \text{ GHz}\), with decreasing magnitude and linewidth as a function of increasing coupling gap \(S\). As expected, in the absence of the superconductors used for the -KID devices, we observe significantly diminished Q’s (∼10 − 20) in all of our SRR circuits, which will limit the density of detectors that can be coupled to a single busline.
Finally, a significant shift of the RF resonant frequency (∼3 GHz), and a decrease in linewidth, can be obtained by using a double-SRR structure, as shown in Fig. 4.5c. Here, the inner SRR has side lengths of 0.8 mm, with $G_1 = G_2 = 50 \, \mu m$ and $S = 30 \, \mu m$ for both SRRs.

Figure 4.5: (a) Experimental and (b) Simulated S21 spectral response of single SRR circuits with fixed spacer ($S = 30 \, \mu m$) and varying capacitive gaps ($G_1 = 0, 15, 20, 30, 40, 50, 75, 100 \, \mu m$). (c) Experimental S21 spectra of single SRR circuit with fixed capacitive gap ($G_1 = 50 \, \mu m$) and varying spacers ($S = 10, 20, 30, 40, 50, 75 \, \mu m$), S21 for busline only (no SRR) is shown in black. (d) Spectra for single- and double-SRRs with $S = 30 \, \mu m$, $G_1 = 50 \, \mu m$, and $G_2 = 50 \, \mu m$. Inner SRR on the double-SRR has side length of 0.8 mm.

4.6 Device modeling

We use High Frequency-Structure Simulator to model our structure’s RF response. In the model, the driven model solution method was applied. The substrate is modeled as a dielectric with constant permittivity. All metallic components were assigned as finite conductivity boundaries. Radiation boundary conditions were assigned to all exterior boundaries for the entire simulation domain, except for the ground plane which is a metallic surface. The remaining computational area was characterized as a vacuum domain.
The RF signal was launched through the wave ports, which were placed on the external boundaries of each end of the microstrip line. An Eigenmode solver was applied to solve the waveguide modes in the 2D port, which provides the modal complex propagation constants and characteristic impedances. The calculated mode patterns were used as excitation for the device as well as for generating the S-parameters.

In addition to determining the RRFP’s RF spectra, instead of using the method of moment solver to extract the scattering parameters [108], we use the commercialized HFSS model to extract the electrical field distribution on resonance as a post data processing.

### 4.7 Device characterization-optical response

For optical characterization, a diode laser was focused onto the detectors via a 1” focal length lens after passing through a spatial filter. The laser spot size was measured to be $\sim 50 \, \mu m$ (FWHM), and incident laser powers were measured by replacing the RF detector device with a broadband thermal sensor. The laser light incident upon the surface was controlled by both the laser driving current and neutral density (ND) filters in the laser beam path, and the absorbed laser power determined using calculating transmission at a GaAs/air interface. Because some light is reflected from the Au SRR, the values shown for absorbed laser power are therefore likely slight overestimates. The detector’s RF spectral response was measured using the PNA for varying laser excitation powers. Figure 4.6b shows representative scans of the detector response as a function of absorbed laser power 0 mW to $\sim 45$ mW for a 785 nm laser diode in continuous wave operation. The spectrum for the SRR with no light incident on the gap is shown in black.

It is evident from these results that the generation of EHPs in the capacitive gap of the SRR has a significant effect on the response of the SRR circuit, effectively damping the SRR resonance, and giving a $>5$ dB change in the depth of the SRR resonance at absorbed powers of $\sim 45$ mW. No response was observed when the laser beam was incident anywhere else on the sample surface. Figure 4.6a shows the numerical simulations (using HFSS) for the device in 4.6b. Using the photon flux of our experiments, and assuming a pump laser absorption length of $\sim 700$ nm and a carrier lifetime of $\tau = 0.83$ ns
Figure 4.6: (a) HFSS-modeled S21 spectra of single-SRR circuit with inset showing contour plot of electric field magnitude at resonance, for $\sigma = 0$ S/m. The effect of absorbed light is modeled as a varying conductivity in a $\sim 700$ nm thick layer of GaAs ($\tau = 0.83$ ns) under the split-gap, shown schematically in inset (i). (b) Experimental S21 spectra of single-SRR circuit (shown in inset (ii)) under CW excitation from 785 nm diode laser, and (c) Lumped circuit element modeled S21 spectra of single-SRR circuit with effect of absorbed light modeled as a changing R1 (shown in inset (iii)).

In the SI-GaAs, we are able to calculate a bulk conductivity as a function of incident laser power for the GaAs in the capacitive gap of the SRR. These results show good agreement with the experimental results of Fig. 4.6b. Figure 4.6c shows the results from the equivalent circuit model of the SRR, where the resistor ($R_1$) in the RLC structure represents the combination of the resonator ohmic loss and the conductivity of the SRR gap. By reducing the value of $R_1$, we can qualitatively reproduce our experimental results.

In order to better determine the detector sensitivity, the laser diode was modulated at 50 Hz with a 50% duty cycle pulse, and the transmitted RF signal was measured with a Pasternack 10 MHz-18.5 GHz zero-biased Schottky RF detector. We were able to measure the effect of the incident laser power (down to the $\sim \mu$W range) on the detector response by feeding the detector output into a lock-in amplifier (LIA), and measuring the LIA output in V as...
a function of laser power. The data in Fig. 4.7, linear over a wide range of incident optical powers, gives us some indication of the detector responsivity in V/W, though this value will scale linearly with the RF output from the PNA (set to 3 dBm for this experiment). The results from Fig. 4.7 show that we can measure incident optical powers at the \( \sim \mu \text{W} \) range. While such sensitivity does not exceed state-of-the-art photodetectors, there are yet potential advantages to our detector architecture when compared to standard photodetector devices, which we describe below.

![Graph showing Lock-in Amplifier output signal as a function of absorbed power](image)

**Figure 4.7:** Lock-in Amplifier output signal from the SRR circuit as a function absorbed power, using 785 nm diode laser excitation, modulated at 50 Hz with 50% duty cycle square pulses. Inset shows schematic of SRR excitation.

Since the response of each detector element is relegated to the resonant frequency of the SRR associated with it, multiple detectors can be linked to a single busline. Therefore, only a single input and output are required for measuring the detector response given that each detector occupies a separate range in the RF spectrum. Figure 4.8 shows an example of such a configuration, with three double-SRR detectors coupled to a single busline. The RF transmission of the circuit was measured in dark (no illumination) and with laser illumination on each of the SRR’s inner and outer capacitive gaps (\( G_1 \) and \( G_2 \), respectively). As can be seen from Fig. 4.8, light incident on each
SRR can be resolved in the RF spectrum, with minimal cross talk between detector elements. With the current SRR RF linewidth, approximately 10 SRRs could be read out from a single busline across a 10 GHz span of the RF spectrum.

![Figure 4.8: RF response of circuit with three double-SRR on a single busline. All double-SRRs have an outer ring side length of 1mm, with inner ring side lengths of (a) 0.5mm (magenta), (b) 0.8mm (red), and (c) 0.75 mm (blue). All SRRs have $G_1=G_2=50 \, \mu m$ and $S=30 \, \mu m$. The RF spectra shown for each sample correspond to the detector RF response in dark (black, solid), with the inner capacitive gap ($G_2$) illuminated (dotted) and with the outer capacitive gap ($G_1$) illuminated (solid). Note that in (a) the inner gap illumination spectrum (dotted magenta) largely overlaps with the dark signal (solid black). The schematic inset shows the illumination positions, color coded for each SRR detector structure.](image)

4.8 Conclusions

In conclusion, we demonstrate a room-temperature optical photodetector based on a resonant RF circuit. Our RF circuits utilize SRRs, and can be tuned coarsely by changing the dimensions of the SRR (side length) and finely by controlling the capacitive gap. We show linear detector response
over three orders of magnitude of absorbed laser power for light incident on
the SRR capacitive gap of our RF circuits. The demonstrated devices were
modeled using full-wave electromagnetic simulations in commercial software
(HFSS) as well verified analytically using a lumped circuit element approach.
Results from both sets of models showed good agreement with our experi-
mental results. Finally, we demonstrate multiple detector elements mul-
tiplexed on a single busline and discuss the potential applications of the
demonstrated detectors. In the current design, such detectors would not be
able to compete with the sensitivity or speed of commercial photoconductive
detectors, but the design methodology developed and underlying principles
may benefit numerous applications, including materials characterization, di-
rect integration of optical signals with microwave circuitry, and multiplexed,
high speed read-outs of multiple detector arrays into RF electronic circuitry.
In addition, while we use SRRs fabricated on GaAs in our demonstration,
there are a plethora of other resonant structures and semiconductor sub-
strates/structures that can be used in a similar configuration that have dif-
f erent characteristics (such as higher Q, faster recombination times, different
optical absorption profiles, etc.) that would give the designer a larger design
space for specific applications.
In the previous chapter we introduced the concept of the resonant RF photodetector, and characterized the basic operation of this device fabricated from a GaAs wafer, operating at a microwave frequency of \( \sim 15.5 \) GHz. We demonstrated multiplexing of multiple detectors on a single busline, and characterized the optical response (responsivity) of a representative detector. However, despite the potential applications for such detectors, we were careful to note that the observed responsivity of the photodetectors was well below what would be necessary to compete with state-of-the-art photodetectors. In this chapter, we investigate the responsivity of our resonant RF photodetectors. We demonstrate the ability to control the response of our RRFPs, using two different approaches. Our first approach is rooted in the optical characteristics of the substrate materials employed in the RRFPs. By carefully choosing the semiconductor absorber used, we can significantly tune the device responsivity, as would be expected for a photoconductive device. The second approach focuses on the design of the RF circuit geometry and its impact on device responsivity. Specifically, by engineering the spatial overlap of the RF field hot spot with optical excitation regions, we can significantly boost detector performance. We spatially and spectrally characterize the RRFP detectors (at both RF and optical frequencies) for a range of detector sizes and detector materials. In addition, we perform 2D scans across the entire sample surface, measuring the detector response as a function of the spatial position of the incident light. We demonstrate that such an approach provides us with an approximate experimental readout of the electric field of our RF circuit, potentially offering a new mechanism for mapping RF fields in resonant circuitry.
5.1 Sample preparation and experimental setup

Our first approach to understanding the detector responsivity focuses on the choice of absorber material used. In total, we investigated five types of absorber materials: semi-insulating (SI) GaAs, high-resistive (HR) Si, epi-grown GaAs, epi-grown InAs and epi-grown In\(_{x}\)Ga\(_{1-x}\)As/GaAs quantum wells (QWs) in a GaAs matrix. The SI GaAs wafers and HR Si were obtained from commercial vendors [University Wafer]. The epi-GaAs sample simply consists of 500 nm of undoped GaAs grown on the SI GaAs wafer. The QW sample consists of 13 periods of In\(_{0.15}\)Ga\(_{0.85}\)As/GaAs QWs (10 nm/20 nm) grown on a 300 nm GaAs buffer layer. The InGaAs QW sample is designed to have a ground state transition at a wavelength of 950 nm at room temperature (confirmed by photoluminescence measurements). Because of the unintentional doping of InAs substrates (which will quench the RF signal on the microstrip transmission line), we grow our InAs absorber sample on a SI GaAs wafer, which will have a large lattice mismatch to our InAs epi-layer. The InAs sample consists, from the substrate up, a 200 nm GaAs buffer, followed by a 100 nm GaSb layer, and then 500 nm of InAs (undoped). This follows the approach of [109], which demonstrated that the GaSb layer can be used to minimize lattice mismatch induced defect propagation into the epi-InAs, and is similar to the growth process used for the highly doped InAs used in our photonic wire work.

For the SI-GaAs and the HR-Si samples, our fabrication process is similar to that described in Chapter 4: patterned metal on the detector top side, and a metal ground plane below. For the detectors fabricated from epi-grown samples, we first define a mesa of active absorber by standard photolithography and wet etching. The SRR is then aligned such that the absorber material mesa is placed in the capacitive gap of the split ring. The previously described process steps (bi-layer resist, lithography, develop, deposition, lift-off) are carried out with careful alignment of the RF resonant circuit to the absorber mesa structure. An extra lapping/polishing step is required before the backside metal deposition (required for the microstrip ground plane), in order to remove the indium paste applied on the backside of the wafer during molecular beam epitaxial (MBE) crystal growth.

The (optical) spectral response of detectors was measured using a white light source filtered through a monochromator and chopped before being...
Figure 5.1: (a) Spectral response and (b) spatial response experimental setups. Inserted plot in (b) shows the beam profile for the exciting laser in the spatial response setup. Cross-sectional schematic of detector using (c) wafer absorbing material and (d) epitaxial absorber.

focused on the sample, as shown in Fig. 5.1. The detectors are driven at resonance with an Agilent (HP) 8341B RF sweep generator sourcing 3 dBm. The transmitted RF signal was measured with a Pasternak PE 8013 10 MHz-18.5 GHz zero-biased Schottky RF detector which feeds into the lock-in amplifier, synchronized to the optical chopper. The detector response is measured as a function of the monochromator wavelength and the resulting optical spectrum is normalized to the incident optical power spectrum as measured in the same setup with a Thorlabs PM30 power meter. Figure 5.2 shows the normalized room temperature spectral response of the epi-GaAs and HR-Si detector samples, showing the expected absorption edge at each material's band edge.

The responsivity and spatial response of the detectors was measured using the set-up shown in Fig. 5.1b. Here laser light is collimated and focused on the sample via a 1/2” diameter, 1” focal length BK7 lens, where the long focal length is required in order to avoid having the optical elements interfering with the microwave probes. The inset to Fig. 5.1b shows the beam spot size for the 785 nm laser used in this experiment, which has a full width half maximum (FWHM) of approximately 10 µm. The laser is modulated at 50 Hz with a 50% duty cycle for the responsivity measurements. The RRFPs are driven at resonance and the transmitted RF signal is collected and fed
Figure 5.2: Normalized spectral response of the epi-GaAs (black) and HR-Si (red) detector samples.

into the lock-in amplifier. The DC lock-in output is collected for a range of laser powers. Neutral density filters are used to access low incident powers for the laser while allowing the laser to operate at higher current densities and thus stable output powers. Incident laser power is measured using a broadband power meter and responsivities are characterized using the incident, not absorbed, laser power. The absorbed laser power will be $\sim 30\%$ less than the incident laser power due to reflection from the semiconductor surface. For spatial measurements, the laser is mounted on a linear motorized translational stage (Thorlabs NRT 100) allowing for automated motion normal to the sample surface, so that the laser spot size on the sample surface can be computer controlled. The sample is mounted on a steel plate with a vacuum hole connected to house vacuum and used to fix the sample onto the plate. The plate is then mounted on a combination of two linear motorized translational stages (Thorlabs NRT 100 and LNR 50) that can move horizontally, to allow positioning of the laser spot across the surface of the sample. Both linear and raster scans of the sample response were performed by this system, traveling through the capacitive gap either perpendicular or parallel to the microstrip busline. Later this set-up was used to perform large area scans across the sample surface.
5.2 Detector response-material dependence

The presented RRFP architecture can be integrated with a range of absorber materials. Choice of absorber material not only allows for control of operational wavelengths of the detectors but also responsivity. Though in this work we investigate absorbing substrates with or without epi-layer absorbers, the RRFP architecture also allows for transparent substrates, with absorbing materials placed in the capacitive gap. In all cases the detector response is directly related to the conductivity of the absorber material under illumination, and in this regard is very similar to a traditional photoconductive detector. However, our detector measures changes in the transfer function of a microwave RLC circuit driven on resonance due to a change in RLC resistance vs. simply a change in the quasi-DC voltage across a traditional photoconductive element. As we mentioned in Chapter 4, Eq. 4.4, the local conductivity of the capacitive gap depends on the carrier mobility, $\mu_n$ and $\mu_p$, and carrier density $n$ and $p$ (where the carrier density depends on the generation rate $G$, times the carrier lifetime $\tau$ in the semiconductor).

The mobility of the material depends on the effective mass of the carrier and the carrier scattering time ($\tau_{sc}$). The steady state electron hole pair (EHP) concentrations, for an optically pumped intrinsic semiconductor, are given by the product of the generation rate ($G$ in cm$^{-3}$) and the EHP lifetime (in s). For identical RF resonator and microstrip waveguide designs, the responsivity of the detector depends to first order on the product of mobility and EHP lifetime. However, as for any detector, there are trade-offs associated with improved responsivity. In particular, while RRFPs using materials with long EHP lifetimes will have high responsivity, their frequency response will be limited by the time required for EHPs to recombine. Detectors with high $Q$ RF resonators will also improve responsivity, but again, at the cost of slower response times (as the larger energy storage in the high $Q$ resonators will take longer to dissipate). Detectors with high $Q$ RF resonators will also improve responsivity, but again, at the cost of slower response times (as the larger energy storage in the high $Q$ resonators will take longer to dissipate).

In an ideal detector, both the mobility and the EHP lifetime are independent of carrier concentration, resulting in a linear response. However, at high carrier concentrations, both mobility and EHP lifetime decrease, due to increased effects of additional scattering mechanisms (Auger recombination,
electron-electron scattering, etc.) [110, 111]. Additional nonlinearity at high pumping powers may result from the shift of the quenched RLC resonance compared to the ‘dark’ circuit.

The trade-off between linearity and responsivity can be clearly seen in Fig. 5.3, which shows the change in the transmitted signal through our RF detector circuit as a function of incident optical power for the five different absorber materials. Narrow bandgap InAs shows the most linear response, but also the weakest responsivity. Both effects can be attributed to the rapid EHP recombination in InAs at room temperature [112], which more than negates the somewhat higher mobility of epitaxial InAs compared to our other absorber materials. The short lifetime of the epi-InAs results in low carrier concentrations and consequently a weak, though linear response. Note that the InAs absorber RRFP is pumped with a 980 nm laser, which has a photon energy three times the InAs bandgap, and is therefore a less than efficient optical pump. Thus the results for the InAs absorber RRFP shown in Fig. 5.3 underestimate the InAs responsivity if pumped with a longer wavelength optical source.

Figure 5.3: Transmitted (readout) signal as a function of incident optical power for RRFP with capacitive gaps $G_1=20 \ \mu m$ using different absorber materials: epitaxial InAs (green), InGaAs/GaAs QWs (blue), and epitaxial GaAs (grey), as well as wafers of SI GaAs (black) and HR Si (red).

The InGaAs/GaAs QW sample was pumped below the GaAs bandedge but above the QW ground state transition (with a 904 nm laser diode).
This sample shows a significantly stronger response when compared to the InAs, which can be attributed to both the more efficient pumping and the improvement in carrier lifetime of the epitaxial QWs [113, 114]. However, the QW response is still more than an order of magnitude weaker than the bulk GaAs response, as expected due to the limited volumetric fill factor of the QWs. Finally, the HR Si sample shows the highest sensitivity, with responsivities as high as 1,000 V/W at low optical powers. The HR-Si clearly shows significant nonlinearity in response resulting from the larger carrier concentrations achievable with the long carrier lifetimes (on the order of 100’s of µs) [115] for photon excited EHPs in Si. The combination of the detector nonlinearity and the limitations in response time associated with the resonant RF circuit indicates that the detectors presented here are unlikely to find application in RF photonic applications requiring highly linear detection [116, 117, 118] of optical signals modulated at microwave frequencies [85, 86, 119]. However, for applications requiring either multiplexed detection schemes or direct RF readouts of optical signals (or material properties) at low-GHz frequencies, our detector architecture may have benefits.

Figure 5.2 and 5.3 demonstrate that the choice of optical absorber material in the detector design can not only determine operational wavelength of the detector, but also its responsivity and the linearity of that response. In addition, though it is not the focus of this work, the choice of absorber material also strongly affects the time response of the detector via the EHP lifetime and charge carrier mobilities. The absorber material, however, is not the only parameter available to engineer the responsivity of RRFP devices. Detector responsivity also depends significantly on the geometry of the RF circuit and the location of EHP generation. The latter can be clearly seen in Fig. 5.4, where the response to a fixed incident laser intensity is plotted as a function of the incident laser position on the SI-GaAs detector with the 80 µm gap size.

### 5.3 Detector response-spatial dependence

The data in Fig. 5.4 show a strong variation in detector response with the position of the incident laser. In this respect, the RRFP differs significantly from a traditional photoconductive device. In a standard photoconductor,
a largely uniform DC field between the detector contacts will result in a uniform spatial response across the detector surface.

Figure 5.4: (a) Simulated electric field distribution, on resonance, for the bottom arms of the SRR on a RRFP resonant circuit with 80 µm capacitive gap. (b) Detector response as a function of the position of the incident laser along the bottom arms of the RF resonant detector simulated in (a).

In Fig. 5.4, however, it is observed that the RF detector response varies significantly with spatial location along the surface of a single detector. When comparing the linear scans of detector response to the simulated RF field intensity for the resonant circuit, it becomes clear that the detector response is maximized at the locations where the RF field is enhanced. We also observe local maxima in our detector response at locations where bends in our SRR result in fringing fields extending out from under the microstrip lines, such as at the x=±500 µm positions on the bottom arms of the SRR. Intuitively, this can be understood by thinking of the excited EHPs as generating a localized loss in the RF circuit. The stronger the overlap of this localized loss with the
RF field, the stronger the detector response. Thus, the strongest detector response is observed at locations where the RF field is strongest.

Figure 5.5: (a) Schematic of RF resonant circuit. Detector response as a function of position (b) perpendicular to busline, through capacitive gap and (c) parallel to busline through capacitive gap, for RF resonators with capacitive gaps of 20 µm (green), 40 µm (blue), 80 µm (red), and 120 µm (black). Detector response is collected along the dashed lines in the schematic, dotted lines are guides to the eye. Simulations of RF electric field magnitude on resonance at semiconductor surface for RRFPs with (d) 20 µm, (e) 40 µm, (f) 80 µm, and (g) 120 µm capacitive gaps.

While for a given detector geometry a wide range of responsivities can be achieved dependent on the position of the incident light, the above results also suggest that the detector responsivity can be engineered by careful design of the RF resonator. Figure 5.5 shows the detector response as a function of position along the bottom arms of the SRR, parallel to the microstrip busline [Fig. 5.5c], and across the SRR, perpendicular to the busline and through the center of the capacitive gap [Fig. 5.5b] for four detector structures fabricated on SI GaAs wafers, identical except for the capacitive gap size.

The simulations in Fig. 5.5d - Fig. 5.5g show the on-resonance RF electric
field at the semiconductor surface of the four detector geometries experimentally investigated in Fig. 5.5b and Fig. 5.5c. As can be seen in these simulations, the enhancement of the electric field in the SRR gap increases significantly with decreasing gap size, as the mode is effectively ‘squeezed’ into a smaller volume between the SRR arms. This increases the enhancement of local (RF) electric field strength and should result in a stronger responsivity for the detector structures with smaller gap sizes. This effect is observed in Fig. 5.5b and Fig. 5.5c, where we see two distinct effects with decreasing gap size. First, the linear scan of the detector response shifts from a double peak structure, with strong response at the ends of the SRR arms, to a single peak response, with strong response centered in the SRR gap. Second, we also observe a significant increase in the detector responsivity with decreasing gap size, with an $\sim \times 4$ increase in the transmitted signal for equal incident laser power. Both of these effects are supported by the RF electric field profiles simulated in Fig. 5.5d - Fig. 5.5g.

Figure 5.6: Peak responsivity for RF detector structures as a function of SRR gap size (all other SRR geometries are unchanged). Responsivity is measured, for each resonator, at the spatial location where the response is largest. Thus the large gap size structures have the incident light positioned near the edge of the SRR gap, while the smaller gap sizes are measured with the laser spot centered in the gap.
The responsivity of the RRFP devices, fabricated on a GaAs wafer, as a function of SRR gap size is shown in Fig. 5.6. Here, for each RRFP device, we position the incident light (785 nm laser) at the spatial position on the SRR which produces the largest signal. For the larger gap structures, this is located at the edge of one of the arms. For the smaller gap structures, this is located in the middle of the gap. A clear increase in response is seen as the SRR gap size decreases. As gap sizes decrease below 20 µm, however, the gains in responsivity increase only slightly. This is a result of increased reflection of the incident light from the SRR arms, as the laser spot FWHM is ∼10 µm [Fig. 5.1d]. Therefore, decreasing gap sizes increases shadowing of the semiconductor absorber material from the incident light. Overall, these results show that significant improvement in responsivity can achieved in RRFP devices by engineering RF hotspots. As can be seen in Fig. 4.5b, the change in SRR gap size does not significantly change the RF properties of the SRR (slight change in resonant frequency, little change in resonator $Q$) but has a drastic effect on the device responsivity. This suggests that resonator designs with engineered RF hotspots giving even greater field enhancement could be used to further improve the response of the presented detector devices.

Responsivity, however, is not the ultimate measure of detector performance, especially in our photoconductive devices, where the magnitude of the voltage response can be tuned by control of the amplitude of the drive signal. For this reason, we will focus on the detector detectivity, or $D^*$, which provides a more accurate picture of the device performance. Traditionally, $D^*$ can be defined as: $D^* = \sqrt{A \Delta f / NEP}$, where $A$ is the area of the device, $\Delta f$ is the measurement bandwidth, and NEP is the noise equivalent power (or the lowest optical power measurable from the detector for the $\Delta f$ used in the numerator). For our HR-Si detector with a gap size of 20 µm × 50 µm, we can measure a signal of ∼1 µV on the lock-in amplifier with an integration time of 100 ms ($\Delta f$=10 Hz). At a responsivity of 1,000 V/W, this corresponds to a $D^* \approx 3 \times 10^6$, which is quite low for any commercial detector. However, this result is for an un-optimized structure. We believe that significant gains in responsivity are achievable for our detector architecture with improvements in the resonator $Q$, the drive signal noise, and RF detector noise. Moreover, the expression used above for $D^*$ assumes a traditional photoconductive or voltaic device, which results in the square
root dependence of the $D^*$ on area. It is not clear that our detector devices share this dependence, and our proposed efforts will look to better elucidate the appropriate measure for our detector $D^*$, given our unique architecture. Finally, it should be noted that while our detectors may not achieve the $D^*$ for commercial near-infrared/visible detectors, our unique device architecture may have improved performance in the mid-infrared wavelength range, and may also provide significant benefits for hyperspectral imaging applications.

5.4 Mapping field profiles

The design of RF circuitry has been greatly simplified over the past decades as a result of the dramatic increase in easily available computational power and, and commensurate increase in the amount of commercially available software packages for RF circuits. Understanding the field distribution and loss mechanisms for a RF circuit would be helpful to circuit designers and could potentially provide invaluable feedback in the iterative design process. However, experimental characterization of the circuits remains a costly, time-consuming, and low resolution process. In the past, experimentally mapping fields in RF circuitry was most often achieved using a microwave equivalent of the optical technology referred to as scanning near-field optical microscopy (SNOM). In such a set-up, an open-ended coaxial cable is scanned above the surface of the sample. In passive imaging mode, an RF signal propagates along the cable and is reflected from the sample surface. The measure of reflection depends on the conductivity of the sample when the probe is in close proximity to the surface, allowing for a readout of the surface conductivity. In active mode, the circuit is driven with a microwave signal, and the coax probe picks up scattered evanescent fields, and thus maps out the scattered field across the circuit [120, 121, 122, 123, 124, 125, 126]. More recently, improvements in spatial resolution have been achieved by replacing the open-ended coaxial cable with an ultra-subwavelength parallel strip transmission line [127] or alternatively a scanning tunneling microscopy (STM) tip [128, 129], allowing for nm-scale resolution measurements of material conductivity. Such measurement techniques are non-destructive and contactless, but suffer from the sever length scale mismatch between the RF signal wavelengths and the probe itself, resulting in weak coupling and lim-
Figure 5.7: Experimental (a,c) MMOIL plots and HFSS-simulated (b,d) Electric fields for a square SRR resonator driven (a,b) off and (c,d) on resonance. Experimental data taken at (a) $f_{\text{off}}=13.58$ GHz and (c) $f_{\text{on}}=15.58$ GHz. Simulations performed at (b) $f_{\text{off}}=14$ GHz and (d) $f_{\text{on}}=15.84$ GHz.

limited sensitivity. Thus, measurements of material properties are possible, but measurements of field profiles, which requires coupling of scattered fields into a subwavelength microwave probe, are significantly more difficult.

Here, we utilize our RRFP architecture, combined with our developed 2D scanning stages, to present a new method that allows us to map the electromagnetic field profiles of active RF circuitry. As we discussed in Chapter 4 and Chapter 5, we use a well-focused laser beam scanning on the surface of our RRFPs, and drive the RF circuitry on the resonant frequency. The optically induced loss from the photo-generated carriers will generate a significant change in the output port of the resonator circuit, which will be read
out in the $|S_{21}|$ parameter (which is proportional to the local conductivity change), with this we can map out the field intensity of the entire structure. We dub this approach Microwave Mapping with Optically Induced Losses (MMOIL).

The experimental setup used in our MMOIL approach has been discussed in Fig. 5.1b. For this setup, the laser beam has a full width half maximum (FWHM) of $\sim 10 \, \mu m$, significantly smaller than the wavelength of the RF signal.

Fig. 5.7a and Fig. 5.7 show the experimental MMOIL data for a square resonator with chamfered corners off ($f_{\text{off}}=13.58$ GHz) and on ($f_{\text{on}}=15.58$ GHz) resonance, respectively. As can be seen from the MMOIL data, a significant increase in signal is observed when the SRR is driven at resonance. The MMOIL signal, on resonance, is seen to be localized primarily in the split gap of the SRR, but also along the corners of the lower arm of the SRR. Off resonance, little to no response is seen in the SRR, with the majority of the signal observed in the coupling gap and along the microstrip busline. These results align nicely with the expected behavior of the resonator, which would be expected to store significant energy on resonance, but little to no energy when driven off resonance. Fig. 5.7(b) and Fig. 5.7(d) show the HFSS-simulated field profile at the surface of the semiconductor substrate off and on resonance. The basic field profiles observed in our simulations match nicely with the experimental MMOIL data.

However, the simulations do show differences from the experimental results. First, the model gives unrealistic artifacts (strong fields) at any sharp corners. This effect is well known in finite element methods, and has the effect of artificially skewing the scale of the simulated data (creating an artificially large maximum field near the sharp corners. Secondly, and perhaps more importantly, while the HFSS simulations give the electric field distribution on the microstrip lines, our MMOIL technique cannot measure this field, as MMOIL relies on free carrier generation in the dielectric but cannot induce any significant losses when the laser is incident upon the metal of the microstrip lines. Nonetheless, MMOIL does provide an excellent picture of the field profile in the dielectric, and can be used to characterize the field profiles of RF circuits in the surrounding dielectric. Moreover, the MMOIL technique shows none of the 'spottiness' observed in the HFSS simulations resulting from computation limitations on the allowed finite element mesh.
Our experimental 2D mapping technique, described above, measures the output of the lock-in amplifier signal as a function of the position of the laser beam. We demonstrated above that this signal matches the simulated electric field profiles of our resonant RF circuits. However, there are some experimental imperfections for the 2D field mapping setup related to the configuration of the lock-ion amplifier used in this experiment, which I will explain in the subsequent section. I begin by briefly describing the working principle of the lock-in amplifier.

In our measurement setup, we chose the EG&G Princeton Applied Research 5210 dual phase lock-in amplifier. A lock-in amplifier takes, as its input, a periodic wavefunction (in our case, the optically modulated, and then rectified resonant RF signal on the detector busline). After passing through an input amplifier, the amplified signal is then multiplied it by a reference signal using a phase-sensitive detector (PSD). The reference signal can be internal, or more often, comes externally, from the source of the signal modulation (in our case, the driver of our incident laser). The output of the PSD is simply the product of the two sine waves.

\[ V_{psd} = V_{sig} V_{L} \sin(\omega_r t + \theta_{sig}) \sin(\omega_L t + \theta_{ref}) \]
\[ = \frac{1}{2} V_{sig} V_{L} \cos(\omega_r - \omega_L) t + \theta_{sig} - \theta_{ref} \]
\[ - \frac{1}{2} V_{sig} V_{L} \cos(\omega_r + \omega_L) t + \theta_{sig} + \theta_{ref} \] (5.1)

The PSD outputs are two AC signals, with different angular frequencies \((\omega_r - \omega_L)\) and \((\omega_r + \omega_L)\). When the reference is synchronized with the signal, then it becomes a \(DC + AC\) signal. After passing through a low pass filter, the AC signal are removed. The remaining signal is:

\[ V_{psd} = \frac{1}{2} V_{sig} V_{L} \cos(\theta_{sig} - \theta_{ref}) \sim V_{sig} \cos \theta \] (5.2)

a DC voltage that is proportional to the amplitude of the original input signal. By adding another PSD, the phase dependency \(\theta = (\theta_{sig} - \theta_{ref})\) can be eliminated. The second PSD shifts the phase from the reference by 90°. Following the same derivation in Eq. 5.1, the second PSD output would be:
Now we have two outputs: $X = V_{\text{sig}} \cos \theta$ and $Y = V_{\text{sig}} \sin \theta$, representing the signal as a vector relative to the lock-in reference. We can also get the magnitude and phase of the vector by: 

$$R = \sqrt{X^2 + Y^2}, \quad \theta = \arctan \left( \frac{Y}{X} \right).$$

In our 2D mapping experiment, unfortunately, we choose the $R(\theta)$ mode, and when we did the data acquisition, we skipped the information of $\theta$. So what we actually measured was only the magnitude of the circuit response, but not its phase. Ultimately, this prevented us from observing the sign of the change in our output signal from the detector circuit. As we have shown, when a light source is incident upon the capacitive gap of the SRR, we see an increase in our output signal. However, when our laser is incident upon the busline, away from the SRR, one would expect a decrease in the output signal (as the wave propagation on the microstrip TL is absorbed by photo-generated EHPs). The two conditions described above correspond to portions of our circuit through which energy is transported, or alternatively, where energy is stored. Thus the mapping experiment, if measured in such a way that both amplitude and phase of the signal are collected, may, in addition to giving information about electric field intensity, also offer information as to locations of energy transport and/or storage.

In the future, we intend to re-run the above experiments, this time using the X, Y mode, which would give us both the magnitude and the phase information of our output signal.

5.5 Conclusions

The RRFP device architecture offers a number of potential advantages over traditional photoconductive devices. These include the potential for multiplexing detectors on a single busline, direct integration with RF circuitry, and utility for material metrology. In this work, we demonstrate that significant improvement in device responsivity can be achieved by choice of the photoabsorbing material, which also controls of the absorbing wavelength range similar to traditional photoconductive devices. In addition, however, we demonstrate a marked spatial dependence of the device responsivity and
show that our detector response is maximum for light incident on regions of the detector with the strongest RF field. This is elucidated by measuring the spatial dependence of the response for SRRs with varying capacitive gap sizes, demonstrating that by engineering RF ‘hotspots’, we can significantly enhance detector response. These results demonstrate a substantial improvement in detector response and also offer insight into potential avenues for further improvements by engineering of RF field hotspots in resonant circuit architectures. In the meantime, we utilized our setup for the RRFPs to generate a new technology that map the field of the RF circuitry with a contactless mode, where the resolution is orders of magnitude below the free-space wavelength of the operating RF signals in the circuits.
Chapter 6
Conclusions and Future Works

In this dissertation, we studied three type of devices/structures operating from near-infrared to mid-infrared wavelengths, all of which benefit from either the electrical or the optical properties of free carriers: the buried extraordinary optical transmission (B-EOT) gratings, the epsilon-near-zero (ENZ) photonic wires, and the resonant RF photodetectors.

The MacEtch fabricated B-EOT grating utilizes the electronic property of free carriers (high conductance or electrical access of optoelectronic devices). At the same time, the B-EOT gratings utilize a moth-eye optical structure to effectively avoid the most challenging optical properties associated with free carriers, essentially ‘funneling’ the incident optical signal through the perforated metallic mesh. Such structures were shown to give higher transmission than a bare, unpatterned semiconductor wafer, offering the potential for simultaneous efficient optical and electrical contacts to optoelectronic devices operating in the mid-infrared. Moving forward, we will build on the demonstration of B-EOT structures to demonstrate efficient operation of mid-infrared emitters or detectors, with improvements in both electrical contact and optical access. In this structure, the high conductivity of free carrier is used to provide a uniform electrical contact, where the losses from the metal were avoided by intentionally designing the transmission peak away from the SPP mode that is normally excited by a 2D metallic hole array.

The ENZ photonic wires demonstrated in this thesis are fabricated from a hybrid doped semiconductor-metal slot waveguide architecture, which serves as a photonic wire that groups all the optical lumped elements and carries optical signal with effective wavelength much larger than the elements’ dimension. The use of doped semiconductor as a plasmonic metal allows for monolithic integration of epitaxial materials with different optical properties into the wire. Due to their special characteristics, the photonic wires are of particular interest for the novel optical circuitry formalism described
as ‘metatronics’. In this waveguide architecture, the concentration of the free carriers in the doped semiconductor was carefully controlled to ensure that the material behaves as a mid-infrared plasmonic metal, with the required optical properties (low loss and real permittivity less than zero but still on the order of the surrounding dielectric material). This results in a waveguides mode closely bound to the semiconductor surface (for maximum interaction with subwavelength elements fabricated onto the semiconductor surface), with extended local wavelength and improved propagation length.

Finally, we also demonstrate a room-temperature photodetector where readout is achieved using a resonant RF circuit consisting of a microstrip split-ring resonator coupled to a microstrip busline, fabricated on a semiconductor substrate. The responsivity of the detector is investigated, both materially and geometrically. Significant improvement of detector response can be achieved by choice of proper material system, or positioning the optical excitation region to overlap with the RF field hot spot. The detector architecture offers the potential for multiplexing arrays of detectors on a single read-out line, in addition to high speed response for either direct coupling of optical signals to RF circuitry, or alternatively, carrier dynamics characterization of semiconductor or other material systems. In this device, the optically excited free carriers are utilized as a tuning mechanism to alter the local conductivity of the RF circuit and thus control the amplitude of the transmitted RF signal. Thus, we leverage the free carrier response of our material at RF frequencies to serve as IR-frequency photodetectors.

This thesis presented three very different optical/optoelectronic structures and devices, each leveraging the response of free carriers in unique ways. Traditional metals, with their high (and largely fixed) free carrier concentrations, can provide highly conductive contacts for efficient operation of optoelectronic devices (such as in our B-EOT structures) or alternatively can act as nearly perfect electrical conductors (as the sidewalls in our photonic wires). However, these materials are less than ideal optical structures in many situations. We show that with careful design, we can avoid the difficulties associated with these traditional metals by integrating them into optical structures designed to carry light away from the metallic components (as demonstrated with our moth-eye structures of the B-EOT gratings). However, at times free carrier response can be leveraged for novel optical structures. In the mid-infrared, control of free carrier concentrations in semiconductors offers
an intriguing avenue towards new optical structures. The plasmonic nature of the doped semiconductor base of our photonic wires, used to confine propagating modes to our photonic wires, offers one such example. Of course, losses are unavoidable when free carriers are introduced into optical structures. These losses are avoided in our B-EOT gratings by funneling light through subwavelength apertures. In our photonic wires, they serve as the limiting factor in the modes’ propagation length. However, in our RF detector structures, we demonstrate that the presence of these losses can actually be leveraged to demonstrate new functionality, and a new type of infrared detector.

The work presented here thus demonstrates three novel optical/optoelectronic structures with potential applications for the infrared wavelength range, all of which leverage the response of free carriers to provide new functionality at optical frequencies.
References


