STUDY OF FORCE DISCRIMINATION ON CHIRAL MOLECULES AND PARTICLES BY CIRCULAR POLARIZED LIGHT AND METASURFACE ENHANCED FIELD

BY

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THESIS

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ABSTRACT

This thesis aims to explore force discrimination on chiral particles and molecules, when experiencing an electromagnetic field. This thesis focuses especially on incident fields with handedness. These fields come from incident circular polarized light or from enhanced fields generated by a plasmonic metasurface. This topic was first motivated by the need of separating enantiomers mechanically. Now many works have been done by different groups. Inspired by these works, a general expression of force under an incident time-varying electromagnetic field is derived in this thesis. Some of the recent works is reviewed and discussed. This thesis also talks about the development of an open source near field simulation tool. Many simulations were done and summarized here, along with a discussion of the results.
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CHAPTER 1: INTRODUCTION

1.1. Motivation

Chiral molecules are molecules that have same composition but are mirror images to each other. This property is called chirality or handedness and often happens when a carbon atom is attached to four different substituents. This is due to the 3D structure of carbon atom and its four covalent bonds. Chiral molecules widely exist in nature. For example, 19 of the 20 common amino acids that form proteins are chiral. These enantiomers can have different effects on living body, so studying them is important to chemistry, biology and pharmacy.

For example, many drugs have chirality, but when being synthesized both enantiomers are produced in the ratio of one to one. Only the molecules with certain chirality have effect on human body and the other halves are usually useless or even toxic to human body. Therefore, pharmaceutical industry is really interested in how to synthesize the half they want or how to separate them after synthesis.

Our motivation is to find a method to separate large chiral molecules using plasmonic metasurface enhanced nearfield. This method can be extremely useful and may have great potential in chemical and pharmaceutical industry.
1.2. Circular dichroism and circular birefringence

The fundamental assumption of this thesis is that chiral particles and chiral molecules will interact with circular polarized light. The proof of this interaction lies in two phenomena called circular dichroism and circular birefringence. The macro level change of circular polarized light indicates the micro interaction between them.

A linear polarized light is an electromagnetic wave whose electric field or magnetic field oscillate in a confine plane alone propagation. Circular polarized light (CPL) can be seen as a superposition of two linear polarized light with same wavelength propagating in the same direction with perpendicular polarization, these two linear polarized light also have a $\pi/2$ phase difference so the maximum of the electric field is always the same but circulating in a clockwise of counter-clockwise mode.

As a CPL can be seen as two linear polarized light, a linear polarized light can also be seen as a superposition of one right CPL and another left CPL with no phase difference. When a linear polarized light propagate through a birefringence material, one of the CPL will travel slower than the other one. This will cause a phase difference between the two, thus the superposition of the two, the linear polarized light, will change its direction of polarization. This difference in propagation speed of CPL is called circular birefringence and the change of polarize direction when a linear polarized light going through the material is called an optical rotation.
Unlike circular birefringence, circular dichroism (CD) only happens when chiral molecules absorb CPL at a different rate. As a result, an incoming linear polarized light will become an elliptically polarized light since one of the CPL in the linear polarized light will have lower intensity than the other one. A detailed demonstration of circular dichroism is shown in Fig 1.1 [1]. Circular dichroism spectroscopy is widely used in biology and chemical studies to determine the concentration of chiral enantiomers in the solution.

1.3. Conventional ways to separate chiral molecules

There are several conventional ways to separate enantiomers, here four of them will be introduced [2]. Because of the nature of the chiral molecules, they usually have two forms of crystal structures, one left handed and one right handed. In a supersaturated solution of racemic mixture, two seeds of left and right handed crystal were planted and with certain condition, enantiomers will grow on the corresponding crystal. In few cases this process will even occur without any seeds. This method of crystallization is widely used because of its easiness and cost efficiency.

Another common way is reaction resolution. It often involves the use of enzymes to selectively reacts with one enantiomers and preserve the other one. This will be followed by several other reactions and resolution techniques to realize the separation. This method is fast and straight forward but can be expensive. For example, most enzymes can only survive in some rather expensive organic solvents.
The other two methods are liquid chromatography and membrane separation. These two methods are based on a similar principle. When the mixture solution goes through a membrane or a chromatography stationary phase, two enantiomers will experience different forces. In the membrane case, one enantiomer will be left behind, and in chromatography one enantiomer will pass through slower than the other one.

A common mechanism is a three points interaction model. As shown in Fig 1.2 [5], if the molecule A’B’C’R represent the stationary phase or the membrane. The left enantiomer ABCD molecule will have one more bond to A’B’C’R than the molecule with opposite handedness. This will cause the molecule on the left side to travel slower than the one on the right. Thus separation of enantiomers can be realized. These bonds can be hydrogen bonds, ionic interactions or other chemical bonds.

Other than chemical interactions, physical interaction can also be applied here. For example, a left handed spiral cannot go through a right handed spiral shaped hole. These two methods are becoming popular these days because of their cost efficiency, but they still need improvement since membranes used here are usually fragile. [3]

### 1.4. Optical force and Optical tweezer

Photons carry energy and momentum, when photons interact with other objects, whether reflected or transmitted, there will be force added by this photon on the object. The force
could be very small in a sense, but if the object itself has very low mass, this force can have
dramatic impact on it, and thus optical manipulation can be achieved.

A photon in vacuum with wavelength $\lambda_0$ carries energy $E_0 = hc/\lambda_0$, and momentum
$p = h/\lambda_0 \mathbf{\hat{u}}$, where $\mathbf{\hat{u}}$ is the unit vector of propagation. According to Phil et al. [6],
consider a light ray with power $P$ is reflected by a perfect mirror back to the direction of
incident. The number of photons that impinge on the mirror per unit time is $N = P/E_0$
and the change in momentum of each photon equals to $-2p$, so the total change in
momentum per unit time is $-2Np = -2(P/c)\mathbf{\hat{u}}$ thus the maximum optical force can be
generated by a light ray of power $P$ is
\[
F = \frac{2P}{c} \mathbf{\hat{u}}. 
\] (1.1)

In a more general situation, the incident light will not be perpendicular with the plane, the
plane could also have some radius of curvature, part of the light will be reflected and part
of the light will be transmitted. In this case, the optical force can be separated into two
parts. Scattering force, the force pushes the particle in the direction of propagation, and the
gradient force, the force pulls the particle perpendicular to the direction of propagation.

The optical force of the first incident can be calculated using
\[
F_{ray} = \frac{n_i P_i}{c} \mathbf{\hat{f}}_i - \frac{n_i P_r}{c} \mathbf{\hat{f}}_r - \frac{n_i P_t}{c} \mathbf{\hat{f}}_t. 
\] (1.2)

The total force on the object can be calculated using ray tracing, in the situation of a
homogeneous sphere all the lights will be confined in the place of incident.
Notice that the ray trace can be carried on and on to infinite times of reflection as shown in Fig 1.3 [6]. According to Fig 1.4 by Philip et al. [6] the approximation of two reflections is already accurate enough.

This force can be used in two beam particle manipulating. Two counter propagating beam can form an optical trap. As shown in Fig 1.5 [6], the scattering force will push the particle in the direction of propagation. When two counter-propagating beams incident on the same particle, the scattering forces are balanced and only gradient forces pulling the particle will work so the particle is trapped. The gradient force will only pull the particle when the surrounding medium has higher refraction index than the particle, otherwise it will push the particle away.

In practice, the counter-propagating beams are usually replaced by one Gaussian beam, highly focused by a large numerical aperture lens system. As Fig 1.6 [6] shown below, as long as the NA is large enough, the scattering force will trap the particle.

The calculation discussed in this chapter are based on the assumption that the particle is much larger than the wavelength of the light used for trapping. If the particle is around same size of wavelength or smaller than wavelength, many conditions will change and the optical force will be different.

1.5. Plasmonic metasurface optical trapping

Surface plasmon opens a whole new dimension of optical trapping. Unlike conventional
optical trapping, the optical force comes from evanescent electromagnetic field, usually
generated by a Kretschmann geometry, see Fig 1.7 [7], when total reflection happens at a
metal-dielectric interface. The advantages of this method are mainly two fold. First, the
field intensity is higher which means a low power laser can be used for trapping purpose.
Second, it can trap objects smaller than traditional optical tweezer.

Due to the nature of metal, there are many free electron gas in the lattice of positive ions.
When an external electric field is applied, the electrons will move according to the external
field, this is how the metal gets polarized. When the external field is off, all the electrons
will move to the other side, and oscillate until the kinetic energy of electrons finally turns
into thermal energy. This is a rough model for plasmon.

Surface plasmon can be considered as a special condition of volume plasmon, it happens
at metal-dielectric interface, the motion of the electrons will be confined to the surface. A
surface plasmon polaritons or SPPs arise from the excitation of free electrons oscillating in
a thin metal film, this will create a density wave propagating through the surface, and an
associate evanescent electromagnetic field will also be generated. A localized surface
plasmons or LSPs correspond to the same phenomenon on a nanoparticle. A demonstration
of SPP and LSP is shown in Fig 1.8 [6].

SPPs are usually applied in optical manipulation. As one can imagine, the oscillation of the
free electron is due to the EM wave shined on the interface. When the SPPs resonant with
the external field, a dramatic portion of the energy in the EM wave will be transferred into
these electrons. Thus the evanescent field generated will be large. This is how the enhanced field is generated.

Recent research shows that by designing the shape of metal surface on the dielectric substrate, even higher field intensity can be achieved and particle manipulation throughout the surface can be done. [8-12] These designed surface that achieves extraordinary local properties without changing the bulk properties of the material are called metasurface.
1.6. Figures

Fig 1.1 [1]:

A demonstration of circular dichroism.

Fig 1.2 [5]

Difference in number of bonds for enantiomers.
Infinite of reflection and transmission inside a particle.

Fig 1.3 [6]

Trapping efficiencies of glass spherical \( n_p=1.5 \) particle in water \( n_p=1.33 \) (a) taking into account all scattering events (b) considering only first two scattering events.
Force on an article under (a) one incident light, (b) one incident light when surrounded by lower refraction index media, (c) two coaxial counter propagating lights, (d) two counter propagating light in different axis.

Fig 1.5 [6]
Fig 1.6 [6]

Force difference of optical tweezer with a NA of (a) 1.20, (b) 1.00, (c) 0.50.

Fig 1.7 [7]:

Excitation diagram for a Kretschmann geometry.
Fig 1.8 [6]:

Demonstration of (a) surface plasmon polariton (b) local surface plasmons.
CHAPTER 2: THEORY AND FORCE EXPRESSION

2.1. General model of chiral molecules

In this paper, a chiral molecule is treated as a particle who has both electric and magnetic polarizabilities. Under the influence of an external field, in this case a time variating electromagnetic field, the particle will be polarized into a combination of an electric dipole and a magnetic dipole. According to the mirror symmetry, two enantiomers, under the same external field, should be mirror image to each other in polarization wise. Thus the force acting on them by the external field should also have direction difference in some terms. This difference will vary from molecules to molecules, a certain structure might have very obvious difference in force, and others may not.

Here we start by studying the polarizability of a dielectric sphere under a time varying electric field, this particle will become a dipole whose dipole moment is determined by its polarizability. Next, a correction originated from chirality will be introduced. Finally, we find out the force of an electromagnetic field induced on this dipole. Since this particle can also be considered as a magnetic dipole, the force associated with it will also be calculated.

In this chapter, a detailed derivation of the force on a chiral particle under a time-variant electromagnetic field will be shown. This derivation was inspired by many source [6, 13-19].
2.2. Electric polarizability and Clausius-Mossotti relation

In the presence of an external electric field, a change in charge distribution will occur in an isolated atom or molecule. This will lead to an induced dipole moment. There is a linear relationship between the electric polarization $\mathbf{p}_e$ of the particle and the external electric field $\mathbf{E}_0$.

$$\mathbf{p}_e = \alpha \mathbf{E}_0. \quad (2.1)$$

This linear relationship will hold as long as the external field is not too strong. Here $\alpha$ is the polarizability of the particle. The value of $\alpha$ is briefly derived here, inspired by Aspnes et al. [14]. Assume an isotropic dielectric sphere with permittivity $\varepsilon$ surrounded by vacuum with permittivity $\varepsilon_0$, the relationship between the internal field $\mathbf{E}_i$ and the external field $\mathbf{E}_0$ is

$$\mathbf{E}_i = \frac{3\varepsilon_0}{\varepsilon + 2\varepsilon_0} \mathbf{E}_0. \quad (2.2)$$

The polarization density in the sphere is

$$\mathbf{P}_e = (\varepsilon - \varepsilon_0)\mathbf{E}_i. \quad (2.3)$$

Considering the dipole moment is the volume integral of $\mathbf{P}_e$ i.e. $\mathbf{p}_e = V \mathbf{P}_e$ and bring equation (2.1) and (2.2) together we can get that the polarizability of the small sphere is

$$\alpha = 3V\varepsilon_0 \frac{\varepsilon - \varepsilon_0}{\varepsilon + 2\varepsilon_0} \quad (2.4)$$

where $V = 4/3\pi a^3$ is the volume of the sphere. This is obtained in a static external field and is known as the Clausius-Mossotti relation. The similar relation under a time varying
electromagnetic field can be found under quasi-static limit, when \( a \ll \lambda_0 \), where \( \lambda_0 \) is the wavelength of the EM wave.

\[
\alpha(\lambda_0) = 3V\varepsilon_0 \frac{\varepsilon(\lambda_0) - \varepsilon_0}{\varepsilon(\lambda_0) + 2\varepsilon_0},
\]

This is called Lorentz-Lorenz relation. Under the influence of a harmonic homogeneous time varying electric field, the polarization of the particle will also oscillate with the same angular frequency. This oscillating dipole will radiate an electric field. This field will interact with dipole itself so the original Clausius-Mossotti relation will needs correction. This correction was first proposed by Draine and Flatau in 1993 [17]. We will not go through the detailed derivation here but only give the result.

\[
\alpha_{DG} = \frac{\alpha_{CM}}{1 - \frac{\varepsilon - \varepsilon_0}{\varepsilon + 2\varepsilon_0} \left[ (k_0a)^2 + \frac{2I}{3}(k_0a)^3 \right]},
\]

where \( \alpha_{CM} \) refers to the polarizability in Clausius-Mossotti relation, and \( \alpha_{DG} \) refers to the polarizability derived by by Draine and Goodman, and \( k_0 \) here is the wave number. Notice there is an imaginary part in the expression which comes from the interaction between the dipole and the field scattered by itself.

2.3. The correction of Clausius-Mossotti relation due to chirality

For a chiral particle, there will be another correction when the concept of reciprocity \( \chi \) and chirality \( \kappa \) are introduced. Follow by a similar process leads to the Clausius-Mossotti relation. The external electric and magnetic fields \( E_0 \) and \( H_0 \), respectively, can cause internal fields
\[
\begin{align*}
(\frac{E_i}{H_i}) &= \left(\frac{E_0}{H_0}\right) - \frac{1}{3} \left(\frac{P_e}{\varepsilon_0 \mu_0} \frac{P_m}{\mu_0}\right) \quad (2.7)
\end{align*}
\]

where \(P_e\) and \(P_m\) are internal electric and magnetic polarization densities, they are related to the internal fields by

\[
\begin{pmatrix}
P_e \\
P_m
\end{pmatrix} = \begin{pmatrix}
\varepsilon - \varepsilon_0 \\
\chi - i\kappa \sqrt{\mu_0 \varepsilon_0} \\
\mu - \mu_0
\end{pmatrix} \begin{pmatrix}
E_i \\
H_i
\end{pmatrix} \quad (2.8)
\]

Combining equations (2.7) and (2.8), the relationship between internal and external fields can be found as

\[
\begin{pmatrix}
E_i \\
H_i
\end{pmatrix} = \frac{3}{\Delta} \begin{pmatrix}
\varepsilon_0 (\mu + 2\mu_0) & -\mu_0 (\chi - i\kappa) \sqrt{\mu_0 \varepsilon_0} \\
-\varepsilon_0 (\chi + i\kappa) \sqrt{\mu_0 \varepsilon_0} & \mu_0 (\varepsilon + 2\varepsilon_0)
\end{pmatrix} \begin{pmatrix}
E_0 \\
H_0
\end{pmatrix} \quad (2.9)
\]

where

\[
\Delta = (\mu + 2\mu_0)(\varepsilon + 2\varepsilon_0) - (\chi^2 + \kappa^2)\mu_0\varepsilon_0 \quad (2.10)
\]

Similar to the Clausius-Mossotti relation, the electric and magnetic dipole moment are related to the external field by corresponding polarizabilities. Define \(\alpha_{ee}\), \(\alpha_{me}\), \(\alpha_{em}\) and \(\alpha_{mm}\) as polarization coefficients:

\[
\begin{pmatrix}
P_e \\
P_m
\end{pmatrix} = \begin{pmatrix}
\alpha_{ee} & i\alpha_{em} \\
-i\alpha_{me} & \alpha_{mm}
\end{pmatrix} \begin{pmatrix}
E_0 \\
H_0
\end{pmatrix} \quad (2.11)
\]

where the first index in \(\alpha\) denotes the polarization type and the second index refers to the origin field of the polarization. Since the dipole moments are the integrals of the polarization densities over the volume \(V\)

\[
\begin{pmatrix}
P_e \\
P_m
\end{pmatrix} = \int dV \begin{pmatrix}
P_e \\
P_m
\end{pmatrix} = V \begin{pmatrix}
P_e \\
P_m
\end{pmatrix} \quad (2.12)
\]

By solving the above equations, the polarizabilities can be found as
\[ \alpha_{ee} = 3\varepsilon_0 V \frac{(\mu+2\mu_0)(\varepsilon-\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}, \]
\[ \alpha_{em} = 3\mu_0\varepsilon_0 V \frac{3(\chi-\kappa)\sqrt{\mu_0\varepsilon_0}}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}, \]
\[ \alpha_{me} = 3\mu_0\varepsilon_0 V \frac{3(\chi+\kappa)\sqrt{\mu_0\varepsilon_0}}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}, \]
\[ \alpha_{mm} = 3\varepsilon_0 V \frac{(\mu-\mu_0)(\varepsilon+2\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-(\chi^2+\kappa^2)\mu_0\varepsilon_0}, \] (2.13)

Notice that if the material is normal where \( \chi \to 0 \) and \( \kappa \to 0 \), the polarization coefficients reduce to

\[ \alpha_{ee} = 3\varepsilon_0 V \frac{(\varepsilon-\varepsilon_0)}{\varepsilon+2\varepsilon_0}, \]
\[ \alpha_{mm} = 3\mu_0 V \frac{\mu-\mu_0}{\mu+2\mu_0}, \]
\[ \alpha_{me} = \alpha_{em} = 0. \] (2.14)

Notice that \( \alpha_{ee} \) holds a same value as in Clausius-Mossotti relation. In this paper we will focus on particles only with chirality so here reciprocity \( \chi \to 0 \), and the polarizabilities will reduce to

\[ \alpha_{ee} = 3\varepsilon_0 V \frac{(\mu+2\mu_0)(\varepsilon-\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}, \]
\[ \alpha_{em} = 3\mu_0\varepsilon_0 V \frac{3\kappa\sqrt{\mu_0\varepsilon_0}}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}, \]
\[ \alpha_{me} = 3\mu_0\varepsilon_0 V \frac{3\kappa\sqrt{\mu_0\varepsilon_0}}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}, \]
\[ \alpha_{mm} = 3\varepsilon_0 V \frac{(\mu-\mu_0)(\varepsilon+2\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}{(\mu+2\mu_0)(\varepsilon+2\varepsilon_0)-\kappa^2\mu_0\varepsilon_0}, \] (2.15)

2.4. Optical force on dipoles

Considering a dipolar particle with relative dielectric permittivity \( \varepsilon \) and magnetic permeability \( \mu \) immersed in an isotropic medium, experiencing an incident electromagnetic field \( \mathbf{E}_0(\mathbf{r}, \omega) \) and \( \mathbf{H}_0(\mathbf{r}, \omega) \). The time-averaged electromagnetic force acting on the
particle is [14]:

\[
\langle \mathbf{F} \rangle = \frac{1}{8\pi} \text{Re} \left[ \int_S \left( (\mathbf{E} \cdot \mathbf{n}) \mathbf{E}^* + (\mathbf{H} \cdot \mathbf{n}) \mathbf{H}^* - \frac{1}{2} (|\mathbf{E}|^2 + |\mathbf{H}|^2) \right) \, dS \right].
\]  

(2.16)

This equation is derived using Maxwell Stress Tensor, here Re represent the real part of a complex number, \( dS \) is the integral element for the surface enclosed the particle, \( \mathbf{n} \) is the local normal unit vector of the surface \( S \). The electric and magnetic fields here represented by \( \mathbf{E} \) and \( \mathbf{H} \) are total fields which means they are consist of the external field or the incident field and the radiated field originated from the oscillating dipole. \( \mathbf{E} = \mathbf{E}_0 + \mathbf{E}_r \), \( \mathbf{H} = \mathbf{H}_0 + \mathbf{H}_r \).

According to Jackson [13] the scattered fields \( \mathbf{E}_r \) and \( \mathbf{H}_r \) are

\[
\mathbf{E}_r = e^{ikr} \left\{ [3\hat{r}(\hat{r} \cdot \mathbf{p}) - \mathbf{p}] \left( \frac{1}{r^3} - \frac{ik}{r^2} \right) + \frac{k^2}{r} (\hat{r} \times \mathbf{p}) \times \hat{r} - k^2 (\hat{r} \times \mathbf{m}) \left( \frac{1}{r} + \frac{i}{kr^2} \right) \right\},
\]

\[
\mathbf{H}_r = e^{ikr} \left\{ [3\hat{r}(\hat{r} \cdot \mathbf{m}) - \mathbf{m}] \left( \frac{1}{r^3} - \frac{ik}{r^2} \right) + \frac{k^2}{r} (\hat{r} \times \mathbf{m}) \times \hat{r} - k^2 (\hat{r} \times \mathbf{p}) \left( \frac{1}{r} + \frac{i}{kr^2} \right) \right\},
\]

(2.17)

where \( \mathbf{p} \) and \( \mathbf{m} \) are the electric and magnetic dipole moment which we discussed above, \( k \) is the wave vector \( \hat{r} \) here is the unit vector in the \( \mathbf{r} \) direction. The surface can be any surface as long as it enclosed the particle being considered. Here we chose a sphere with radius \( a \ll \lambda_0 \), \( \lambda_0 \) is the wavelength for the incident wave. The molecules are usually 1 to 10 nm in size which is two magnitudes smaller than the wavelength we usually use.

Equation (2.16) leads to the expression

\[
\langle \mathbf{F} \rangle = \frac{1}{2} \text{Re} \left[ (\nabla \mathbf{E}^*) \cdot \mathbf{p} + (\nabla \mathbf{H}^*) \cdot \mathbf{m} - \frac{ck^4}{6\pi} (\mathbf{p} \times \mathbf{m}^*) \right].
\]  

(2.18)
Substitute the \( \mathbf{p} \) and \( \mathbf{m} \) in (2.11), the equation of force will expand to [13]

\[
\langle \mathbf{F} \rangle = \frac{1}{2} \text{Re} \left[ \alpha_{ee} (\nabla \mathbf{E}^*) \cdot \mathbf{E} + \alpha_{mm} (\nabla \mathbf{H}^*) \cdot \mathbf{H} + i \alpha_{em} (\nabla \mathbf{E}^*) \cdot \mathbf{H} - i \alpha_{em} (\nabla \mathbf{H}^*) \cdot \mathbf{E}
\right]
\]

\[
- \frac{ck_0^4}{6\pi} (\alpha_{ee} \mathbf{E} + i \alpha_{em} \mathbf{H}) \times (\alpha_{mm}^* \mathbf{H}^* + i \alpha_{em}^* \mathbf{E}^*) .
\] (2.19)

2.5. The expansion of the force expression

Now on the right hand side of equation (2.19) there are several terms and we will expand them one by one.

\[
\text{Re}[\alpha_{ee} (\nabla \mathbf{E}^*) \cdot \mathbf{E}]
\]

\[
= \text{Re}[\alpha_{ee} [((\mathbf{E} \cdot \nabla) \mathbf{E}^* + \mathbf{E} \times (\nabla \times \mathbf{E}^*))]]
\]

\[
= \text{Re}[\alpha_{ee}] \left\{ \frac{1}{2} [(\mathbf{E} \cdot \nabla) \mathbf{E}^* + (\mathbf{E}^* \cdot \nabla) \mathbf{E}] + \text{Re}[\mathbf{E} \times (\nabla \times \mathbf{E}^*)] \right\}
\]

\[
- \frac{1}{2i} \text{Im}[\alpha_{ee}] [((\mathbf{E} \cdot \nabla) \mathbf{E}^* - (\mathbf{E}^* \cdot \nabla) \mathbf{E}] + \omega \mu_0 \text{Im}[\alpha_{ee}] \text{Re}[\mathbf{E} \times \mathbf{H}^*]
\]

\[
= \frac{1}{2} \text{Re}[\alpha_{ee}] |\mathbf{E}|^2 + 2\omega \mu_0 \text{Im}[\alpha_{ee}] \langle \mathbf{S} \rangle + \frac{2\omega}{\varepsilon_0} \text{Im}[\alpha_{ee}] \nabla \times \langle \mathbf{L}_e \rangle .
\] (2.20)

Similarly,

\[
\text{Re}[\alpha_{mm} (\nabla \mathbf{H}^*) \cdot \mathbf{H}]
\]

\[
= \frac{1}{2} \text{Re}[\alpha_{mm}] |\mathbf{H}|^2 + 2\omega \varepsilon_0 \text{Im}[\alpha_{mm}] \langle \mathbf{S} \rangle + \frac{2\omega}{\mu_0} \text{Im}[\alpha_{mm}] \nabla \times \langle \mathbf{L}_m \rangle .
\] (2.21)

The next two terms coming from the expanded dipole moment, notice that \( \alpha_{em} = \alpha_{me} \) so in the equation we only used \( \alpha_{em} \).

\[
\text{Re}[i \alpha_{em} (\nabla \mathbf{E}^*) \cdot \mathbf{H} - i \alpha_{em} (\nabla \mathbf{H}^*) \cdot \mathbf{E}]
\]

\[
= \text{Re}[i \alpha_{em} [(\mathbf{H} \cdot \nabla) \mathbf{E}^* + \mathbf{H} \times (\nabla \times \mathbf{E}^*) - (\mathbf{E} \cdot \nabla) \mathbf{H}^* - \mathbf{E} \times (\nabla \times \mathbf{H}^*)]]
\]
\[-\operatorname{Re}[\alpha_{em}] \Im[(\mathbf{H} \cdot \nabla)\mathbf{E}^* - (\mathbf{E} \cdot \nabla)\mathbf{H}^*] - \Im(\alpha_{em}) \Im[\omega \mu_0 \mathbf{H} \times \mathbf{E}^* + \omega \varepsilon_0 \mathbf{E} \times \mathbf{E}^*]
\]
\[-\operatorname{Im}[\alpha_{em}] \Re[(\mathbf{H} \cdot \nabla)\mathbf{E}^* - (\mathbf{E} \cdot \nabla)\mathbf{H}^*]
\]
\[= -\operatorname{Re}[\alpha_{em}] \Im[\nabla (\mathbf{H} \cdot \mathbf{E}^*)] - 4 \omega^2 \operatorname{Im}[\alpha_{em}](\langle \mathbf{L}_m \rangle + \langle \mathbf{L}_e \rangle) - 2 \operatorname{Im}[\alpha_{em}] \nabla \times \langle \mathbf{S} \rangle. \tag{2.22} \]

The last two parts can be expressed as
\[-\frac{ck^4}{6\pi} \Re[(\alpha_{ee} \mathbf{E} + i\alpha_{em} \mathbf{H}) \times (\alpha_{mm}^* \mathbf{H}^* + i\alpha_{em}^* \mathbf{E}^*)]
\]
\[= -\frac{ck^4}{6\pi} \left\{ \Re[\alpha_{ee} \alpha_{mm}^*] \Re[\mathbf{E} \times \mathbf{H}^*] - \Im[\alpha_{ee} \alpha_{mm}^*] \operatorname{Im}[\mathbf{E} \times \mathbf{H}^*] + \Re[\alpha_{ee} \alpha_{em}^*](i\mathbf{E} \times \mathbf{E}^*)
\]
\[-\Re[\alpha_{em} \alpha_{em}^*](i\mathbf{H} \times \mathbf{H}^*) - \alpha_{em} \alpha_{em}^* \Re[\mathbf{H} \times \mathbf{E}^*] \right\}
\[= -\frac{ck^4}{6\pi} \left\{ 2(\Re[\alpha_{ee} \alpha_{mm}^*] + \alpha_{em} \alpha_{em}^*) \langle \mathbf{S} \rangle - \frac{4\omega}{\varepsilon_0} \Re[\alpha_{ee} \alpha_{em}^*] \langle \mathbf{L}_e \rangle - \frac{4\omega}{\mu_0} \Re[\alpha_{em} \alpha_{mm}^*] \langle \mathbf{L}_m \rangle
\]
\[-\operatorname{Im}[\alpha_{ee} \alpha_{mm}^*] \operatorname{Im}[\mathbf{E} \times \mathbf{H}^*] \right\} \tag{2.23} \]

Combine equations (2.20) to (2.23) above and final expression of the force is
\[\langle \mathbf{F} \rangle = \nabla U + \sigma \mathbf{E} \frac{\langle \mathbf{S} \rangle}{c} - \operatorname{Im}[\alpha_{em}] \nabla \times \langle \mathbf{S} \rangle + c \sigma_e \nabla \times \langle \mathbf{L}_e \rangle + c \sigma_m \nabla \times \langle \mathbf{L}_m \rangle + \omega \gamma_e \langle \mathbf{L}_e \rangle
\]
\[+ \omega \gamma_m \langle \mathbf{L}_m \rangle + \frac{ck^4}{12\pi} \operatorname{Im}[\alpha_{ee} \alpha_{mm}^*] \operatorname{Im}[\mathbf{E} \times \mathbf{H}^*]. \tag{2.24} \]

Here
\[U = \frac{1}{4} \Re[\alpha_{ee}] \nabla |\mathbf{E}|^2 + \frac{1}{4} \Re[\alpha_{mm}] \nabla |\mathbf{H}|^2 - \frac{1}{2} \Re[\alpha_{em}] \operatorname{Im}[\mathbf{H} \cdot \mathbf{E}^*],
\]
\[\langle \mathbf{S} \rangle = \frac{1}{2} \Re[\mathbf{E} \times \mathbf{H}^*],
\]
\[\langle \mathbf{L}_e \rangle = \frac{\varepsilon_0}{4\omega l} \mathbf{E} \times \mathbf{E}^*,
\]
\[\langle \mathbf{L}_m \rangle = \frac{\mu_0}{4\omega l} \mathbf{H} \times \mathbf{H}^*,
\]
\[\sigma_e = \frac{k_0 \operatorname{Im}[\alpha_{ee}]}{\varepsilon_0}, \]
\[ \sigma_m = \frac{k_0 \text{Im}[\alpha_{mm}]}{\mu_0}, \]

\[ \sigma = \delta_e + \delta_m - \frac{c^2 k_0^4}{6\pi} (\text{Re}[\alpha_{ee}\alpha_{mm}^*] + \alpha_{em}\alpha_{em}^*), \]

\[ \gamma_e = -2\omega \text{Im}[\alpha_{em}] + \frac{ck_0^4}{3\pi \varepsilon_0} \text{Re}[\alpha_{ee}\alpha_{em}^*], \]

\[ \gamma_e = -2\omega \text{Im}[\alpha_{em}] + \frac{ck_0^4}{3\pi \mu_0} \text{Re}[\alpha_{mm}\alpha_{em}^*]. \]

\( \langle S \rangle \) is the time-averaged Poynting vector, \( \langle L_e \rangle \) and \( \langle L_m \rangle \) are the time-averaged spin densities. Equation (2.24) is the final expression of time-averaged force on a chiral particle under an incident EM field with the scattered field originated by the particle itself considered.
CHAPTER 3: LITERATURE REVIEW

3.1. Chiral near fields

In Chapter 2 we derived the force expression of a chiral particle under an electromagnetic field, now an asymmetrical or chiral near-field is what we need to realized different force on enantiomers.

Genet et al. [20] show an effective way to generate chiral optical field. They use two coherent surface plasmons (SP) propagating perpendicularly with each other on a smooth metal film to generate a chiral field. This chiral field distribution will induce chiral force onto chiral particles or molecules. The discussion starts by introducing the density of chirality and the flow of chirality of an electromagnetic field [21-23]:

\[ K(\mathbf{r}, t) = \frac{\varepsilon}{2} \mathbf{E} \cdot (\nabla \times \mathbf{E}) + \frac{\mu}{2} \mathbf{H} \cdot (\nabla \times \mathbf{H}), \]

\[ \Phi(\mathbf{r}, t) = \frac{1}{2} \mathbf{E} \times (\nabla \times \mathbf{H}) - \frac{1}{2} \mathbf{H} \times (\nabla \times \mathbf{E}). \]  

(3.1)

Next, by analyzing one SP mode propagating on a metal-dielectric interface, the paper gives the electromagnetic field distribution of this evanescent field. By proving the field generated by SPs can superpose with each other, they give a simulated result of the field distribution by two normal propagating SPs. As shown in Fig 3.1(a). Then, use (24) to evaluate the density and flow of chirality on the same interface. Fig 3.1(b) shows \( K(\mathbf{r}) \) as a function of position across the surface, normalized by \( \omega \mathbf{I}_{1,2}/c^2 \). The dashed line and the solid line represent the minimum and the maximum of the chirality density.
In reality it is not easy to reproduce the exact situation illustrated in this paper since the field by SPs are evanescent. However, the field maximum of CPL are constantly changing in direction either clockwise or counterclockwise, so the fields generated by CPL should also have chirality.

3.2. Discriminative force and optical trapping

Many methods have been developed to realize asymmetrical or chiral field distribution, and using these field many proved that discriminative force exist on enantiomers. Chan and Wang [15] here brings up a very intriguing result that chiral discriminative force can happen even with linear polarized light on opposite handedness enantiomers, given the right condition.

The setup of the experiment is a chiral particle, represented by spring here, on a substrate experiencing longitudinal incident linearly polarized light. The spring is made of gold and has an inner radius of 50nm and outer radius of 150nm and pitch P=300nm. As shown in Fig 3.3 [15], a lateral force in y direction will appear and, according to the handedness of the spring this force will have opposite direction. The blue arrow shows the handedness of the spring in the diagram. Notice that the springs in Fig 3.3 (a) and (c) without any substrate will have only scattering force acting on them.

The different behavior lies in the field scatted by spring onto the substrate and back to the spring itself. As shown in Fig 3.4 [15] (a) and (b), the magnetic field distribution on the
substrate has an asymmetrical pattern alone the propagation direction. In Fig 3.4 (c), the relationship between chirality and the magnitude of the force was also discussed. The number of pitches in a spring represent the chirality and as it grows the force will become larger.

The result here is intriguing but the asymmetrical field here related closely to the substrate. The substrate is made of gold so there are many free electrons response to the scattered field from the spring, if the substrate were dielectric material this field distribution would disappear. The particles used here are relatively large while our target particles are too small thus the scattered field would be negligible.

Although this setup is not suitable for small particles, it inspired us about how to generate fields with chirality. Up to this time, we always use chiral light interacts with chiral structure, the field generated by this setup is definitely chiral but hard to predict. However, if we simplify the condition using linear light interact with chiral structure or using chiral light interact with achiral structure, we could still get a chiral field but much easier to predict.

Yang et al. [24] demonstrate a setup of plasmonic optical tweezer powered by CPL which can selectively trap different handedness nanoparticles. This set up is based on the interaction between CPL and an achiral structure to generate chiral field distribution. They start with force calculation with a similar approach as this thesis, then they simplified the force by several methods. First, they picked out the transverse optical forces (the force
acting in the x-y plane). Second, the curl-spin and the vortex force are both small enough to neglect within the wavelength range they defined. The force is finally reduced to [24] \[
F_{tr} = \frac{\text{Re}(\alpha_{ee})}{4} \nabla |E|^2 + \text{Im}(\alpha_{em})^{\frac{1}{2}} \nabla \text{Im}(E \cdot H^*).
\] (3.2)

The nano-aperture has a silver core of radius 60nm and is surrounded by a silicon dioxide ring of radius 85nm, illuminated by a polarized light with \( \lambda = 711 \text{nm} \). The particles have a diameter of 10 nm and a chirality \( \kappa = \pm 2.5 \).

As shown in Fig 3.2 [24], the S and R enantiomers will experience a similar potential throughout the cross section of the optical trap if illuminated by linear polarized light. Whereas the optical trap illuminated by CPL will generate a very different potential curve upon S and R enantiomers. One of them will experience a flat potential curve so it is unstable around the trap and the other one will experience a potential well which is perfect for optical tarping. Since the structure is symmetrical, this difference in trapping force can only arise from the force discrimination by external fields.

There are several concerns with regards to the result. First, the force calculated in the paper is relatively small, so we still don’t know whether a stable trapping can be realized under the influence of Brownian movement. Second, the paper evaluated particles with diameter of 10nm, the size of a typical organic molecule. This paper assumes they are homogeneous particles while in reality they are anisotropic. Thus the orientation of the molecule can change the optical force upon it.
3.3. Related experiments

Till now some of the simulations done in related area was introduced, the results from these works is promising but in reality there are still many difficulties to overcome. The latest experiment by Hernandez et al. [27] demonstrate discriminative optical trapping using optical tweezer on chiral particles. The experiment is preformed on isotropic cholesteric liquid crystal (CLC) particles. The CLC has a unique helix like molecule structure and, by certain techniques it is made into isotropic small particles. By making them fluorescent, the behavior of those particles under optical tweezers can be observed. The setup of this experiment still use a conventional optical tweezer only here a CPL is used. As shown in Fig 3.7 [27] the particles are attracted under right CPL and repelled under left CPL. Keep in mind the particles used in this particular experiment is relatively large at around 5μm in diameter. This size is much larger than molecules but it still shows great potentials.

In above content, we discussed about how linear polarized light interacts with chiral materials could generate chiral fields. An experiment done by Shimoyama’s group shows a similar experiment setup and interesting results. In experiment they build a polarization modulator consists of an array of gold spirals attached on silicon substrate. The spirals are attached to the substrate at the end and lift off in the middle. By applying air pressure onto the device, the spirals will be pushed to the side with lower pressure and thus the handedness of the spirals will change. This can be fine-tuned by adjusting the air pressure applied. Details of this setup can be found in Fig 3.5 [26].
When a linear polarized light (in this paper, with frequency between 0.4-1.8 THz) shine on the device, it will be modulated as if it went through a wave plate. The maximum azimuth rotation angle is $\theta_{\text{max}} = 28.7^\circ$ at 1.0 THz. When the chirality of the spring is different the rotation angle is also different. Thus by tuning the chirality and the height of the spring array the rotation angle can be controlled. The paper also talks about the time-averaged current distribution in the spirals when CPL shine on them. As Fig 3.6 shows, the behaviors of current distribution are very differently regard to the handedness of the incident light. These behaviors show the possibility of spiral shaped micro structure manipulate the incident light field.

In the next chapter we made a similar simulation on spiral structure and incident CPL. The results show similarity in field distribution. The experiment here does not correspond with the assumption we made in this thesis. One possible alternative setup of it may be able to realize chiral field distribution. If a Kretschmann geometry like Fig 1.7 was used and the evanescent field interact with chiral structure on the interface, a chiral field could be realized.
3.4. Figures

Demonstration of (a) field distribution by of two normal propagating SPs, (b) density of chirality across the surface.
Potential diagram for (a) S enantiomers under linear polarized light, (b) R enantiomers under linear polarized light, (c) S enantiomers under circular polarized light, (d) R enantiomers under circular polarized light.

Force by linear polarized light onto (a) S spiral without substrate, (b) S spiral with substrate, (c) R spiral without substrate, (d) R spiral with substrate.
Magnetic field distribution on substrate of (a) S spiral and (b) R spiral. (c) the relationship between chirality and magnitude of lateral force.

Air pressure controlled chirality MEMS spring.
Current density distribution on spiral shined by left and right CPL at (a) 0.45 THz, (b) 0.67 THz, (c) 1.08 THz.

Isotropic small particle made of CLC is attracted by right CPL and repelled by left CPL.
CHAPTER 4: EXPERIMENTS AND SIMULATIONS

In addition to the main project, an attempt of making an open source near-field simulation tool was made. It is called nanoDDSCAT+ and we have done many works. Although the software is far from perfect, and there are many bugs, but it can now perform calculation on the electric field, in both vector field and scalar field. An option of magnetic field output is also available, but as discussed below, its accuracy is still in doubt. Further from these field, with the use of Paraview, the force associate with the particle can be calculated. The substrate can be single or repeat structure in 1D or 2D. A wavelength swept can also be done. In this chapter, the basic idea of DDA will be discussed, then the result from nanoDDSCAT+ will be compared to other software we are using. Followed with a discussion on data processing and a discussion on chiral optical field generated by spring structure.

4.1. DDA introduction

DDA, or discrete dipoles approximation, was first developed by DeVoe in 1964 [25] to calculate the scattering and absorption properties of electromagnetic waves interacting with arbitrary shapes. The exact solution of Maxwell equations only exists for certain geometrical shapes like sphere and cylinder, therefore many methods of approaching the solution was developed. Given enough calculation power, DDA method can approach the
exact answer accurately.

The method begins with separate the arbitrary shape large object into discrete dipoles. Generally speaking, the more dipoles used, the more accurate is the result hence the heavier the calculation load. Each dipole \((i = 1, 2, \ldots, N)\) is assigned with its own polarizability \(\alpha_i\) and position vector \(r_i\). The polarization of a certain dipole is \(p_i = \alpha_i E_i\) where \(E_i\) is the superposition of the incident wave and the field contributes by all the other dipoles. The incident wave \(E_{\text{inc},i} = E_0 \exp(i k \cdot r_i - i \omega t)\), and \(E_i\) can be expressed as

\[
E_i = E_{\text{inc},i} - \sum_{k \neq i} A_{ik} p_k, \tag{4.1}
\]

where \(-A_{ik} p_k\) is the electric field generated by dipole \(p_k\) at \(r_i\) including retardation effect.

\[
A_{ik} = \frac{\exp(ikr_{ik})}{r_{ik}} \times \left[ k^2 (\hat{r}_{ik} \hat{r}_{ik} - I_3) + \frac{ikr_{ik} - 1}{r_{ik}^2} (\hat{r}_{ik} \hat{r}_{ik} - I_3) \right], k \neq i, \tag{4.2}
\]

where \(k \equiv \frac{\omega}{c}, r_{ik} \equiv |r_i - r_k|, \hat{r}_{ik} \equiv \frac{(r_i - r_k)}{r_{ik}},\) and \(I_3\) is a \(3\times3\) identity matrix. Combine all the equations from \(i = 1\) to \(N\), the electric field at each point can be found.

4.2. nanoDDSCAT+

The nanoDDSCAT+ is based on the free software developed by Draine et al. [17], who also improved the original DDA method. They applied fast Fourier transformation and conjugate gradient method to solve convolution problem in large target DDA calculation. They also published an open source code called DDSCAT which is the core of our software. Before I joined the group a user interface was developed and by than it can only preform
calculation on electric field distribution. The accuracy was satisfying compare to the other software.

According to equation 3.1 the result of the scattering field is already with their direction information. Which means adding the vector field to the software is straight forward. Notice that the result given here are discrete values because of the nature of DDA. So the first improvement we made to nanoDDSCAT+ was to add a vector field output option. In the calculation process, all the magnetic permeability of the materials is considered as \( \mu_0 \), same as the permeability of vacuum. Therefore, the magnetic field calculated under this condition is definitely wrong. However, if the discrete dipoles are also treated as magnetic dipoles with its corresponding magnetic permeability, and with a similar method derived above, a magnetic field distribution can also be obtained.

Unfortunately, we didn’t come up with the right code for this part. The attempts to calculate magnetic field all failed because the results don’t make physical sense. Many our results break symmetry where is apparently shouldn’t. We still added the option of vector magnetic field output. Thus, as long as the right code is developed in the future, we can use this function immediately. Based on the magnetic field data we got, we did some other calculations to further evaluate the accuracy of the magnetic field. Now with an incident electromagnetic field on a plasmonic structure, we can get the time averaged electric and magnetic field (not accurate), both in vector form.
4.3. comparison of nanoDDSCAT+ and other software

We now compare the results of simulation on certain structures in two software. The setup in as following. On a large silicon dioxide substrate, two triangle shape pillar are place tip to tip like a bowtie. The detailed dimensions are illustrated in Fig 4.1 drew by one of our team member Qing Ding. The bowtie is made of gold and have a thickness of 50nm. The simulation used only one bowtie to study its individual behavior. The dimension of the substrate isn’t too important here as long as it is significant larger than the bowtie. Here we used $400\text{nm} \times 400\text{nm} \times 100\text{nm}$ silicon dioxide substrate.

The results can be found in Fig 4.2 and 4.3. Fig 4.2 shows the resonant peak of absorption cross section found by two software, and they both are around 700nm. Fig 4.3 (a) and (b) show the electric field distribution of same setup in Lumerical and nanoDDSCAT+ respectively. The distribution diagrams show great resembling, while the maximum intensity are different from each other.

4.4. data processing for force calculation

The force on a particle can be calculated using Maxwell stress tensor, by integral the Maxwell stress tensor around a surface enclose the target particle. The software we use here is developed by one of our team member Jinlong Zhu. However, the electric and magnetic field we obtained from nanoDDSCAT+ is the field across the whole space. Therefore, further data processing is needed. Theoretically, any surface encloses the
particle we are trying to analyze can be used, but since in DDA method all the discrete
dipoles are considered as a radiate source, so the choice of the surface must exclude any
other materials in the system.

In this process we used an open source software named Paraview. Since the coordinates of
the points are hard to find, the process to find desired data was a little complicated. First,
cut out a cubic box encloses the particle and extract all the data points inside the box.
Second, inside the box cut another slightly smaller box concentric with the big one and
extract the data points outside it. The remaining data is a 2D cube with electric and
magnetic field information on all sides. According to method of Maxwell stress tensor, the
surface could be chosen arbitrarily, here we chose a small cube close to the particle because
this will dramatically reduce the amount of data we need to process. If we take the whole
space above the substrate, the date points we need to process is around 160000, compare
at 4059 points we got from the small box.

4.5. Spiral structure simulation

Besides the attempt to calculate force associate with small particles, we also did several
interesting simulations on spiral shaped nano-antenna with incident circular polarized light.
This experiment features the same substrate with the bowtie structure, a 4 round spiral with
thickness of 50nm, width between 3nm to 8nm, and gap of 5nm was used here. Two
simulation was performed with same experiment setup and different incident light, one
with left CPL and one with right CPL. The results for left and right CPL are shown in Fig 4.4 respectively. We can clearly see the distribution of spots for high electric field density are different for left and right CPL. This result indicated that the handedness of light does effect the field distribution when interact with certain structure also with chirality.
4.6. Figures

![Symmetric Bowtie Nanoantennas](image)

Fig 4.1

Dimension of nano bowtie antenna array.
Fig 4.2

The comparison of absorption cross section results between Lumerical and nanoDDSCAT+.
Simulation result on single nano bowtie antenna in (a) nanoDDSCAT+, (b) Lumerical at $\lambda = 780\text{nm}$.
Field distribution of (a) left CPL, (b) right CPL onto spiral structure at $\lambda = 780$ nm.
CHAPTER 5: DISCUSSION AND CONCLUSION

In summary, this thesis starts with a calculation of the force on a chiral particle under a time variant electromagnetic field. It then reviewed some of the latest works followed by discussion of the results, especially on how to generate chiral fields. This is followed by a brief introduction of our near-field simulation tool nanoDDSCAT+. Using nanoDDSCAT+ we have done several simulations and the results correspond to what we discussed in Chapter 3.

There are still some remaining challenges we are facing now. First, the molecules have irregular shape which means the orientation of molecules will change the optical force they will experience. One potential solution is to add a strong static external electric field. This field will apply a torque on all the dipoles so that they will align in the same direction.

Second, the molecules we are trying to manipulate are small and are effected by Brownian motion, so the optical force must be large enough to overcome this random movement.

Third, the method we discussed in this thesis will be used mostly on organic molecules, these molecules are usually sensitive to short wavelength light. The photon in the ultraviolet art of the spectrum has the energy to break down the molecular structure. Therefore, either we need to isolate molecules from the incident light or we can only use visible or infrared light. This restriction may bring new challenges. For example, plasmonic structures usually have at least a single resonant peak wavelength. Therefore, a restriction on wavelength leads to a restriction on structure dimension.
REFERENCES


