Research on Multiparameters relation of Hyperlens

Junxian Ma

College of Information Engineering,
Shenzhen University,
Shenzhen, People's Republic of China
e-mail: majx@szu.edu.com

Qiulin Xiong

College of Information Engineering,
Shenzhen University,
Shenzhen, People's Republic of China

Xiaopeng Li

College of Information Engineering,
Shenzhen University,
Shenzhen, People's Republic of China

Wenjing Guo

College of Information Engineering,
Shenzhen University,
Shenzhen, People's Republic of China

Abstract—Optimization of hyperlens structure and composition of materials is a key problem for its application in biological imaging and nanometer lithography. This paper systematically optimizes and analyzes overall structure of the curved multilayer hyperlens. The influences of structure parameters, such as layer number, layer thickness, filling ratio, permittivities, curvature radius, thickness of photoresist (PR) and reflector layer (PRL) are numerically emulated. It shows that the full width at half maximum (FWHM), the contrast and the electric field intensity of the output beam can be comprehensively influenced by these parameters. As a result, Ag and Al2O3 is the best metal and dielectric，less layer number and thinner layer thickness will be better, the optimal size of the curvature radius may fluctuate for practical fabrication of hyperlens, Ag is the best selection for PRL and Cu can sometimes be the substitute for decreasing the cost, The optimal PRL thickness varies from 40 to 80nm and the optimal range of PR thickness is between 30 nm and 50nm.

Keywords-metarmaterial;hyperlens;parameters optimazation ;surface plasmon;FDTD solution

I. INTRODUCTION

Hyperlens, also called curved multilayer superlens, which can break through the diffraction limit, has received much extensive attentions in theoretical research and experimental production[1-3]. It is necessary to optimize the hyperlens, PRL, PR, and even mask's parameters for improving image features including resolution, contrast, and image intensity[4]. The existing simulation parameters includes layer number, layer thickness, filling ratio, wavelength, permittivity of metal and dielectric，curvature radius, PR thickness, PRL material and its thickness. Wei-ping Wang simulated and analyzed the impact of structure parameters of hyperlens on sub-diffraction imaging. He found the FWHM reach the minimum when the output interface radius value is 365nm (λ), while the output intensity decreases and the beam divergence increases when the structure curvature radius increases from λ/2 to 3 λ /2 [5]. Dong-dong Li optimized the performance of the hyperlens by adjusting geometric parameters. It showed that the performance of the hyperlens improves as the number of periods increases, but the improvement starts to saturate as the number of periods reaches a critical level[6]. Ji-Gang Hu found that the intensity and the FWHM of the output beam can be controlled by the structure parameters and operating wavelength. He adopted 365 nm as the optimized working wavelength to balance beam transmitted intensity and divergence of the beam, he also found that two factors work together to affect the output beam intensity and FWHM[7]. Heng-yi Li suggested the thickness of PR can't be too thin or too thick for the surface plasma excitation of PRL[8].

So imaging performance of the hyperlens cannot to be partially considered. In fact, the influence of structure parameters should be thought as a whole. Similarly, indexes that measure whether the parameters contribute to the resolution also mutually restrict each other. Based on the existing simulation researches, this paper aims to find the optimized parameters by coordinating the relation between parameters and materials in a systemic environment.

II. SIMULATION AND RESULTS ANALYSIS

The FDTD solution model of the curved multilayer hyperlens lithography system[9] is shown in Fig .1 and we are in the effective medium regime when d $\leqslant \lambda \leqslant r_{inner}$[10].
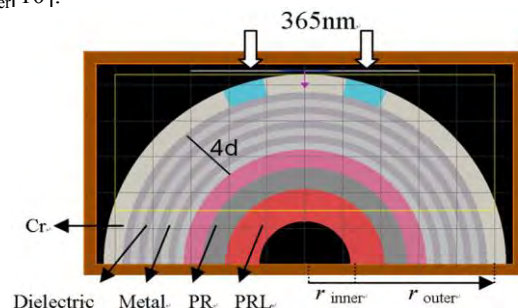

Figure 1. Simulation model of curved multilayer hyperlens lithography system.Wavelength of the incident TM polarization light is 365nm, Chromium mask is fixed at 50nm thick, the slit width in the mask is 50nm with 200nm center-to-center space, Each unit of the periodic curved multilayer structure consists of one metal layer and one dielectric layer.

The principle of curved multilayer hyperlens imaging can be expressed by dispersion equation of electromagnetic waves in cylindrical coordinates[11].

$$k_r^2 / \varepsilon_\theta - k_\theta^2 / |\varepsilon_r| = \omega^2 / c^2 \qquad (1)$$

Where ε_θ and ε_r are medium permittivities in transversal and radial direction respectively, k_θ and k_r are corresponding wave vectors. Given proper matching permittivities of metal and dielectric, the transversal wave vectors k_θ gradually compressed along radial direction. It can be captured by conventional lens to form an image with sub-diffraction resolution.

Table I. （A, B） lists the initial parameters of our experiments, each column containing nine parameters presents an experiment. We change only one of them to obtain optimal parameters.

TABLE I.   PARAMETERS OF THE EXPERIMENTS(A)

No. \ Items	1	2	3	4	5	6
Layer number	4,6,10,14,18,22	8	8	8	8	8
Layer thickness(nm)	20	8,10,15,20,25,30,35,40	10	10	10	8,10,12
Curvature radius(nm)	Inner: 320	Inner :200	Inner:220-820	Inner :200	Inner :200	Inner :200
ε_m	-2.40+0.25i	-2.40+0.25i	-2.40+0.25i	-2.08+7.03i -2.19+4.95i,-2.40+0.25i,	-2.40+0.25i	-2.40+0.25i
ε_d	3.217	3.217	3.217	3.217	3.217,2.29,2.17,	3.217
Filling ratio	0.5	0.5	0.5	0.5	0.5	0.4,0.5,0.6
PRL	0	0	0	0	0	0
PRL thickness(nm)	0	0	0	0	0	0
PR thickness (nm)	40	40	50	50	50	40

TABLE II.   PARAMETERS OF THE EXPERIMENTS (B)

7	8	9
8	8	8
10	10	10
Inner :320	Inner :320	Inner :320
-2.40+0.25i	-2.40+0.25i	-2.40+0.25i
3.217	3.217	3.217
0.5	0.5	0.5
Ag,Cu,Ni,Fe,Al	Ag	Ag
50	20,40,60,80,100,120	50
50	50	20, 40,60,80,100

A. The impact of medium material

Given same thickness of the medium (p=0.5), permittivities in transversal and radial direction are calculated by:

$$\varepsilon_r = \frac{2\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d} \qquad \varepsilon_\theta = \frac{\varepsilon_m + \varepsilon_d}{2} \qquad (2)$$

Here we assume Al_2O_3 as the ideal dielectric material and select Ag, Al, Ni as the candidates for optimal metals, Fig .2(a) shows three dispersion relation curves of the three metals. Obviously, Ag has the flattest curve among the three exciting metals, which means more transversal wave vectors are compressed along radial direction and the ray divergence is the minimal. So we fixed Ag to experiment the dielectric materials among Al_2O_3, SiO_2 and PMMA. According to Fig .2(b), we believe PMMA is the optimal dielectric. In order to prove this idea we simulated electric field intensity distribution of the three parameters in Fig .3. Unexpectedly, the FWHM of electric field intensity of Ag-SiO_2 and Ag-PMMA is 66nm, which is wider than that of the Ag-Al_2O_3 56nm. We can also find the difference from Fig .3 that the ray divergence of Ag-Al_2O_3 is the smallest. Here the theory curves cannot match with the simulation result very well, which caused by light-admitting quality of the material SiO_2 and PMMA.
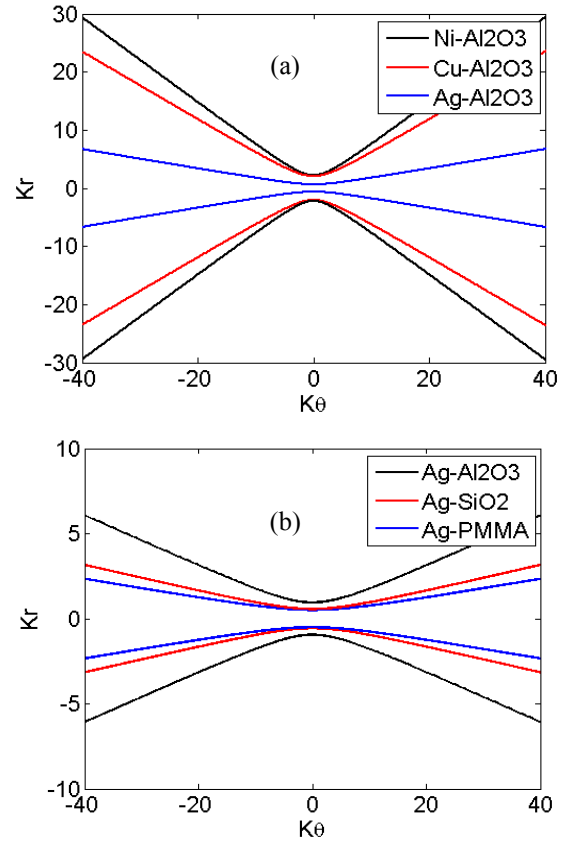

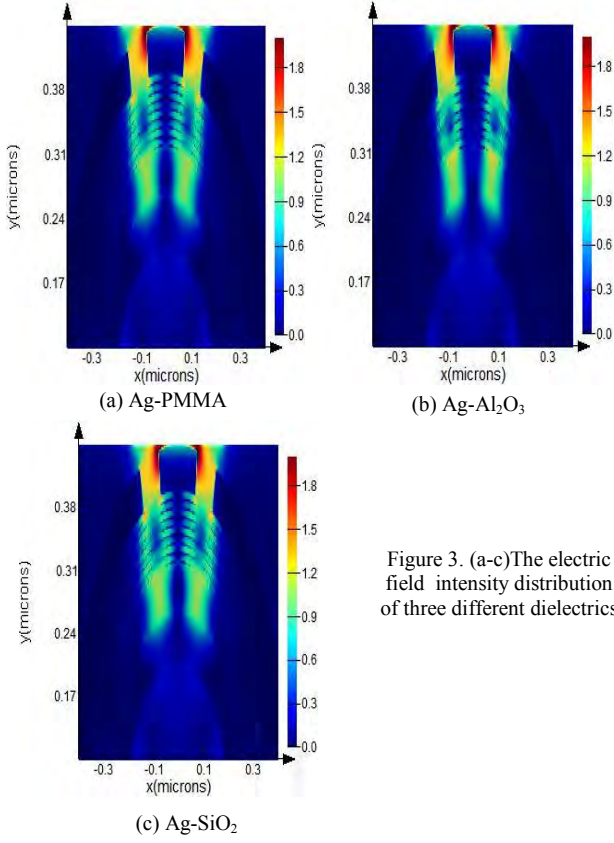Figure 2.   Dispersion relation curves of three metals(a) and three dielectrics (b).

(a) Ag-PMMA

(b) Ag-Al$_2$O$_3$

(c) Ag-SiO$_2$

Figure 3. (a-c)The electric field intensity distribution of three different dielectrics

B. The impact of geometric parameters

The filling ratio is expressed by the equation $p = d_m / (d_m + d_d)$, where d_m and d_d are thickness of metal and dielectric respectively. We can expand the permittivities of the medium in transversal and radial direction by:

$$\varepsilon_\theta = p\varepsilon_m + (1-p)\varepsilon_d \quad \varepsilon_r = \frac{\varepsilon_m \varepsilon_d}{p\varepsilon_d + (1-p)\varepsilon_m} \quad (3)$$

We simulate filling ratio from 0 to 1 with a step size of 0.1 and select 0.4-0.6 to show the respective dispersion relation of the hyperlens, as shown in Fig .4. Obviously, the curve p=0.5 is the flattest, so we adopt p=0.5 as the optimal filling ratio based on the Ag-Al$_2$O$_3$ structure. Of course, different structure may lead to different p.
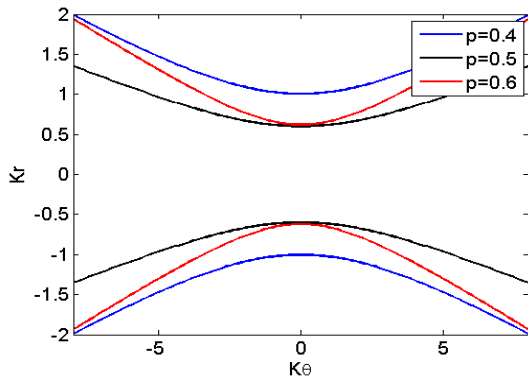

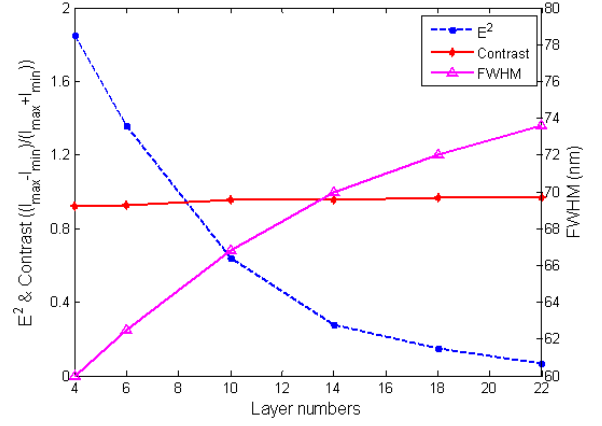Figure 4. Dispersion relation curves of different filling ratio.

Figure 5. Relation curves between imaging indexes and layer numbers.
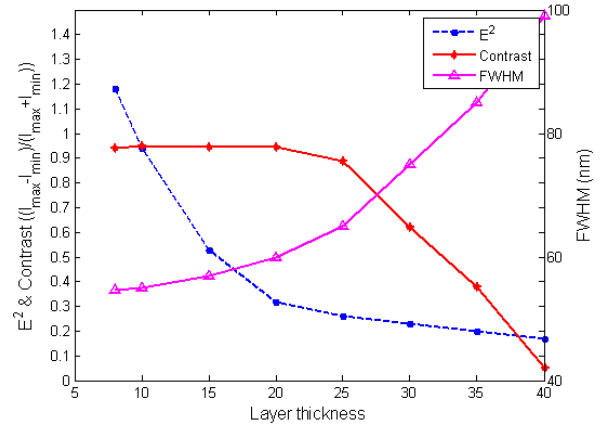

Figure 6. Relation curves between imaging indexes and layer thickness.

Layer number and layer thickness are two main parameters that affect the repeated excitation of surface plasma, as mentioned in Ref.[5,7]. Their research shows that the increase of divergence of the output beam follows the increase of layer number or layer thickness. Our simulation (Fig .5 and Fig .6) agrees with them very well. Judging from the figures, the fewer layer number or layer thickness the better imaging performance.

But layer number or layer thickness changing will unavoidably affect the curvature radius, which plays an important role in imaging performance and scaling. As shown in Fig .7(a).
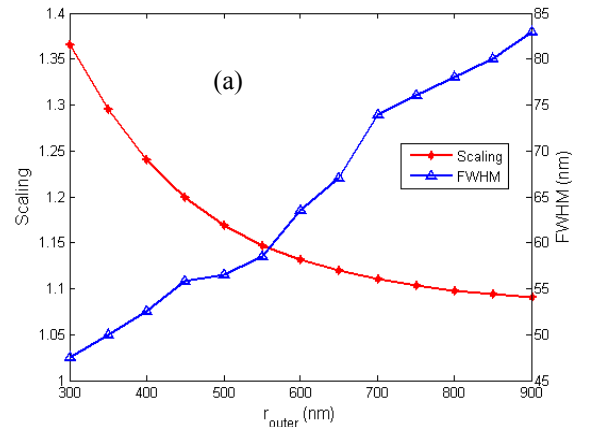

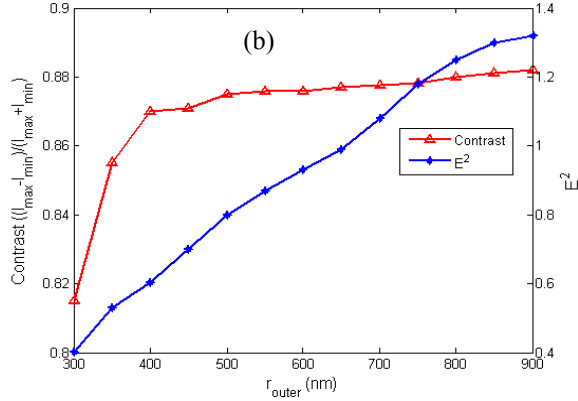Figure 7. (a) Relation curves between imaging indexes (Scaling, FWHM) and radius

Figure 7. (b) Relation curves between imaging indexes (contrast, Electric field intensity) and radius

From Fig .7(a,b), for one thing, the decrease of radius brings small resolution also leads to the decrease of electric field intensity, which goes against the photoreception of PR. For another, the increase of radius enhances the electric field intensity, but r_{inner}/r_{outer} decreases, thus, the scaling that is proportional to r_{inner}/r_{outer} decreases too, so the optimal size of the curvature radius depends on the actual demand.

C. The impact of PRL and PR

PRL helps to improve imaging performance by enhancing both resolution and images intensity[8,12]. The feature reflecting evanescent wave shared by common metals, but their reflecting abilities are different due to different metals. We simulate the imaging performance with different materials Al, Au, Ag, Cu, Fe and Ni, then find that Cu, Ag, Ni are relatively well. Fig .8(a-c) shows the electric field intensity distribution of the three metals and Ag is the best. Considering the cost, Cu can be the substitute sometimes.
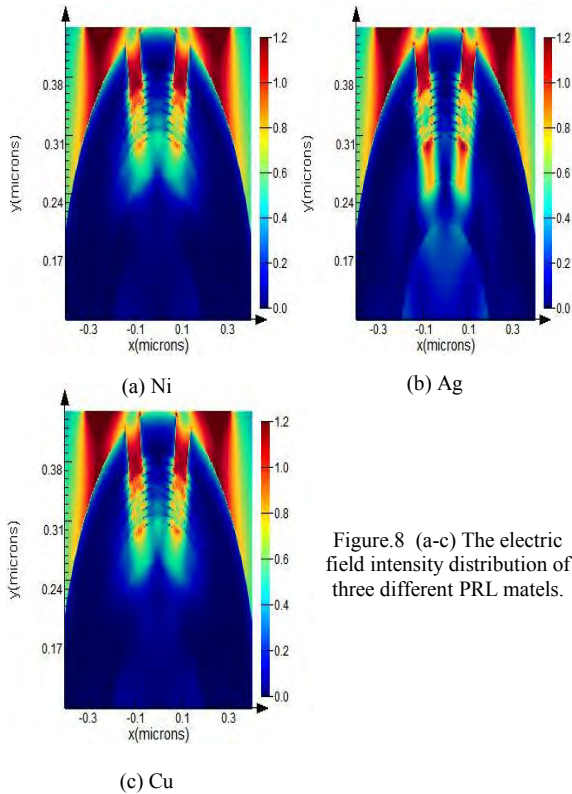

(a) Ni

(b) Ag

(c) Cu

Figure.8 (a-c) The electric field intensity distribution of three different PRL matels.

Given the PRL Ag，the influence of its thickness should also be optimized. Considering from FWHM shown in Fig .9, the thickness should be greater than 40nm or less than 18nm.
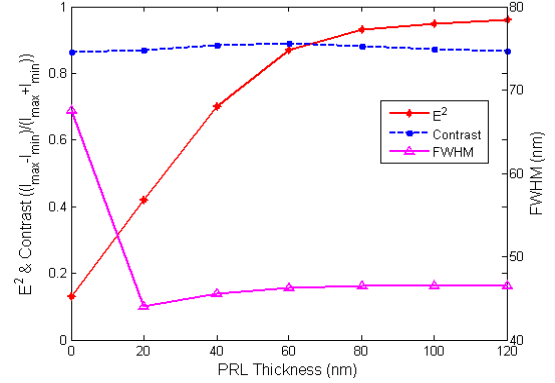

Figure 9. relation curves between imaging indexes and PRL thickness.

But the Contrast begins to fall when PRL thickness is greater than 60nm. Meanwhile, the electric field intensity is 0.68 when PRL thickness is fixed at 40nm and continues to increase afterwards. Directly, the range of PRL thickness should be located at 40nm to 80nm, we choose 60nm. Of course, the result will be different if the PRL material is Cu or other metals.

PR is direct imaging part of the hyperlens, naturally, changing of its thickness will affect the indexes of imaging performance. The FWHM presented in Fig .10 is proportional to PR thickness, so the thinner thickness the better imaging performance.
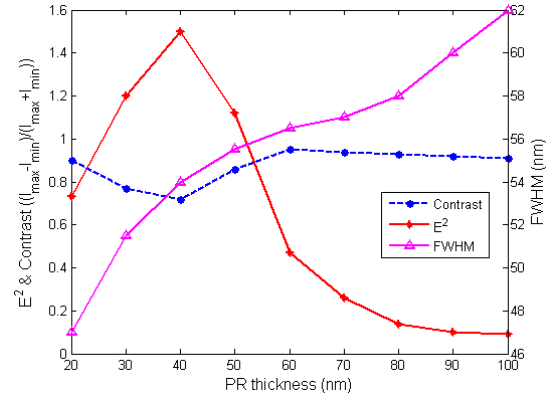

Figure 10. Relation curves between imaging indexes and PR thickness.

But thinner thickness of PR corresponds to weaker electric field intensity. The Contrast keeps above 0.6, while the electric field intensity will experience a period of weak electric field intensity before 20nm, and decreases rapidly to 0.4 beyond 40nm, which is harmful to photoreception of PR. The decrease of PR thickness widens the distance between multilayer structure and PRL, which will weaken the transformation from high frequency spatial information to Surface plasma mode. From above discussions, it is proper to choose the thickness of PR from 30nm to 50nm.

III. CONCLUSION

We simulate and analyze the multiparameters including medium material, geometric parameters, PRL

and PR. Ag and Al_2O_3 is the best metal and dielectric based on the same thickness of the medium and the wavelength 365nm. To gain smaller resolution，less layer number and thinner layer thickness will be better，but that results in changing of radius，which also affects the imaging performance and scaling. So the optimal size of the curvature radius may fluctuate for different fabrication of hyperlens. According to our work, Ag is the best selection for PRL and Cu can sometimes be the substitute for decreasing the cost. The optimal PRL thickness varies from 40 to 80nm and the optimal range of PR thickness is between 30 nm and 50nm.

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