Theoretical calculation of optical transfer functions in SiC superlens imaging system

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***Abstract*—Optical transfer function(OTF) is conventional equation to calculated electromagnetic wave propagation in medium. OTF have a two variables, one is optical property of medium, the other is wave vectors. Imaging system have different case whether this variables are integer or complex. So we adapted this theoretical calculation at SiC superlens.**

***Index Terms*—Optical propagation, Optical surface wave, Propagation losses, Infrared imaging**

I. Introduction

Every optical imaging system have a limit of imaging object size. That is fundamental problem in optics and photonics. So, There have been many studies that can overcome the limit. In 2000, JB Pendry published paper[1] about 'perfact lens'(superlens) that can be enhance evanescent waves which have sub-wavelength imaging information by Negative index materials(NIM). In 2005, X Zhang group succeeded in sub-wavelength imaging in the ultraviolet region, using the Silver slab[2]. Some thin metal slab have a NIM property in ultraviolet region. And T Taubner researched mid-IR superlens using SiC slab.[3] After that, many studies have been conducted.[4]-[6] Typically superlens is consist of NIM sandwiched between two layer of dielectric. How to design a superlens, can be divided into two cases, depending on the optical properties of the materials. Integer material property is lossless case, complex material property is lossy case.

In this paper calculation of conventional optical transfer functions of SiC superlens each case. SiC superlens consist of SiO_2 dielectric two layer and SiC NIM layer. So compare to each case and predict the experiment.

II. Optical transfer function

The optical transfer function (OTF) of symmetric slab superlens system for TM mode can be represented as a function of k_x and ε, as following.

$$k_z{}^i = \pm\sqrt{\varepsilon_i \mu_i \left(\frac{\omega}{c}\right)^2 - k_x{}^2} = k_z{}^i(\varepsilon_i, k_x) \tag{1}$$

$$r_{1M} = \frac{\dfrac{k_z{}^{(1)}}{\varepsilon_1} - \dfrac{k_z{}^{(M)}}{\varepsilon_M}}{\dfrac{k_z{}^{(1)}}{\varepsilon_1} + \dfrac{k_z{}^{(M)}}{\varepsilon_M}} = -r_{M2} = r_{1M}(\varepsilon_i, k_x) \tag{2}$$

$$OTF = \frac{H_{img}}{H_{obj}} = \frac{t_{1M} t_{M2} e^{ik_z{}^{(1)} d1} e^{ik_z{}^{(2)} d2}}{e^{-ik_z{}^{(M)} d_m} + r_{1M} r_{M2} e^{ik_z{}^{(M)} d_m}} = OTF(\varepsilon_i, k_x) \tag{3}$$

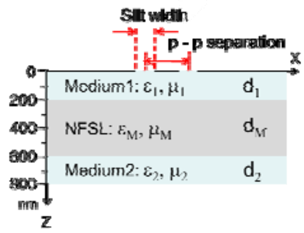

Fig. 1. Schematic of superlens system

The dielectric permittivity of SiO_2 was interpolated from experimental measurements, and that of SiC was derived from the dispersion relation as following. (d_M=440nm, d_1=d_2=220nm)

$$\varepsilon_M = \varepsilon_M{}' + i\varepsilon_M{}'' = \varepsilon_\infty \frac{\omega^2 - \omega_{LO}^2 + i\omega\Gamma_{LO}^2}{\omega^2 - \omega_{TO}^2 + i\omega\Gamma_{TO}^2} \tag{4}$$

The two variables of k_x and ε can be considered as real or complex numbers. There are two cases of possible k_x and ε. From the surface plasmon resonance (SPR) condition, there are two solutions.

$$\frac{k_z{}^{(M)}}{\varepsilon_M}\tanh\!\left(-i\frac{k_z{}^{(M)} d}{2}\right) + \frac{k_z{}^{(1)}}{\varepsilon_1} = 0 \ : \text{Upper mode} \tag{5}$$

$$\frac{k_z{}^{(1)}}{\varepsilon_1} + \frac{k_z{}^{(M)}}{\varepsilon_M}\coth\!\left(-i\frac{k_z{}^{(M)} d}{2}\right) = 0 \ : \text{Lower mode} \tag{6}$$

On the other hand, the same two SPR solutions can be derived from the condition of denominator of OTF should be zero,

$$1 + r_{1M} r_{M2} e^{2ik_z{}^{(M)} d_m} = 0 \tag{7}$$

Therefore, the dispersion relation derived from SPR solution is supposed to be exactly overlapped with the maximum peaks of OTF plot in k_x domain

III. Case 1 : Lossless case

ε is real and k_x is real. Both effects of loss in the metal (polar crystal) and the damping in the surface plasmon (phonon) polariton propagation are ignored.

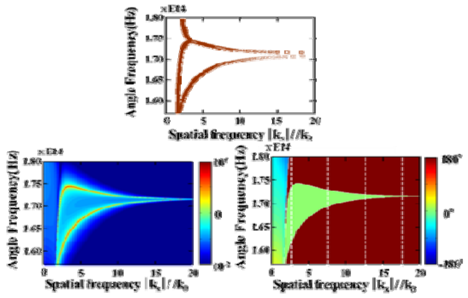

Fig. 2. MTF and PTF(White dot line (a)~(d))

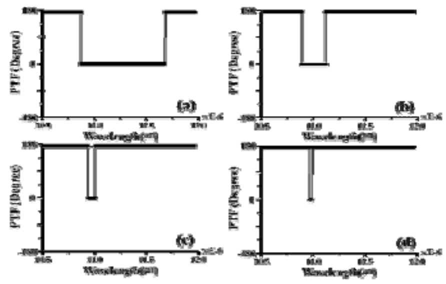

Fig. 3. PTF curve at each point.

In case I, when ε and kx are assumed to be real values, the dispersion curve (see Fig. 2(a)) derived from Eqs. (5), (6) and the MTF (see Fig. 2(b)) versus kx and ω, PTF (see Fig. 2(c)) versus kx and ω from Eqs. (1)-(3) are shown in Fig. 2, respectively. If we overlap two graphs, the dispersion curves exactly match the peaks of MTF plot. On the resonance frequency, the MTF has highly sharp peak even when kx diverges to infinity. Because the OTF is real value, the phase can be only 0° or 180°. The sign of OTF changes across the resonant kx, hence, the PTF discontinuously changes from 0° to 180° on the dispersion curves. Figure 3 shows the PTF (phase change from object to image) versus incident light's wavelength depending on kx.

IV. CASE 2 : LOSSY CASE

ε is complex and kx is real. The effect of loss in the metal (polar crystal) is included. However, the damping in the surface plasmon (phonon) propagation is ignored.

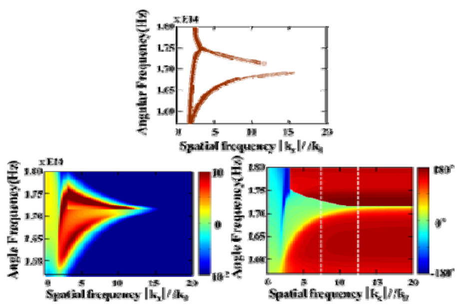

Fig. 4. MTF and PTF(White dot line (a)~(b))

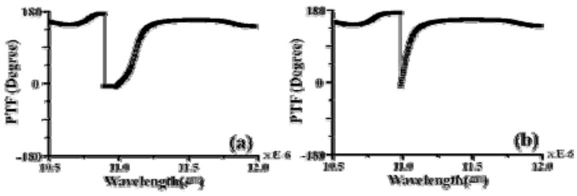

Fig. 5. curve at each point.

In case II, if ε= ε' + i ε'' is complex while the imaginary part of kx is ignored, the MTF (see Fig. 5(a)) versus kx and ω, PTF (see Fig. 5(b)) versus kx and ω from Eqs. (1)-(3) are shown in Fig. 5, respectively. If we overlap dispersion curve on Fig. 5, the dispersion curves exactly match the peaks of MTF plot. Because the lossy effect of metal (ε= ε' + i ε'') is included, the peaks of lower mode (bound mode) are well softened. However, the peaks of upper mode (QB mode) are still sharply resonant because the significant damping effect of propagation (k''x) is unrealistically ignored in QB mode region. Figure 6 shows the PTF (phase change from object to image) versus incident light's wavelength depending on kx. The zero PTF always appears at the resonance frequency, ~11μm. The PTF continuously changes from 180° to 0° in the bound mode due to the softening from the lossy effect. However, the softening due to the significant damping effect in QB mode is not included and the PTF discontinuously changes from 0° to 180° across the dispersion curve of upper mode.

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