Terahertz wave propagation through metal hole array-dielectric multi-layers : toward fabrication of bulk hyperlens in terahertz region

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Abstract

We propose an approach to fabricate the hyperlens in terahertz (THz) region by using a metal hole array-dielectric multilayer structure. We investigate the effective permittivity of metal hole arrays (MHAs) and find that the frequency dispersion of the MHA can be fitted to Drude response with an effective plasma frequency is located at THz region. By stacking the MHA and dielectric film alternately, we fabricate MHA-dielectric multilayer structure that has the anisotropic effective permittivity required for the hyperlens. We also calculated the THz wave propagation through the MHA-dielectric multilayer by using a finite element method.

1. Introduction

Imaging with terahertz (THz) waves is attracting much attention for last two decades because of potential applications, such as non-destructive security monitors, terahertz tomography, medical diagnostics, etc. However, the spatial resolution is not enough for some applications where the target sample is much smaller than the wavelength of the THz wave. In order to obtain the spatial resolution much smaller than the wavelength, the near-field microscopic technique has been used in THz region. In the conventional near-field techniques, however, a raster scanning method was used to image the sample, and correspondingly a real-time imaging was not possible.

Hyperlens [1] have a potential to realize the real-time imaging with the subwavelength resolution. In 2007, Liu *et al.* [2] demonstrated the subwavelength real-time imaging in ultra-violet region with hyperlens that consisted of metal-dielectric multilayers. In their experiment, the real part of permittivity of metal is about -2.4, which is appropriate value to obtain the effective permittivity of metal-dielectric multilayers as hyperlens. On the other hand, in THz region, the absolute value of the permittivity of metal is several hundreds of thousands. This high absolute value of metal makes it difficult to fabricate the hyperlens in THz region with the same manner to that of ultra-violet region.

In our study, we aim to fabricate the hyperlens in THz region for the real-time subwavelength THz imaging. To do so, we propose that we use metal hole arrays (MHAs) to obtain the effective permittivity that is similar to that of metal in ultra-violet region. We stack the MHA and dielectric film alternately, and finally we fabricate the metamaterial that have anisotropic permittivity required for the implementation of hyperlens.

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2. Experiment

We made metal hole arrays (MHAs) with SUS film by femtosecond laser processing. In our sample, squared metal holes are arranged in a square lattice structure. Inset of Fig. 1(a) shows a picture of one of our MHAs. In order to investigate the effective permittivity of our MHAs in THz region, we measured transmission spectra of MHAs by using THz time domain spectroscopic system (THz-TDS). This system allows us to measure the waveform of the THz wave directly in time domain, and correspondingly we can calculate both the transmission and phase shift spectra from the time-domain waveforms by using Fourier transformation.

3. Results and Discussions

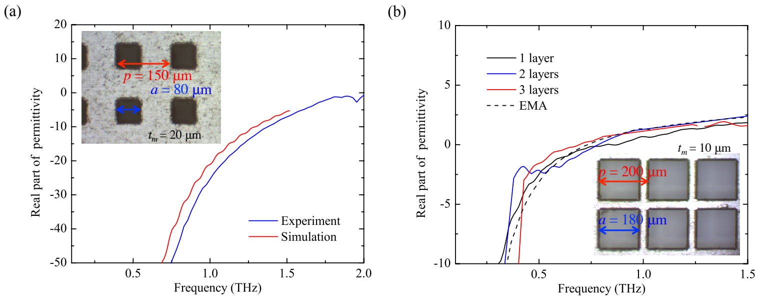

Fig. 1 (a) Measured (blue line) and calculated (red line) real part of permittivity for a MHA single layer. Inset shows the picture of MHA used in this experiment. (b) Measured real part of permittivity for MHA-dielectric multilayer structure for one (black line), two (blue line) and three (red line) sets of layers. Theoretical result calculated from the EMA is also shown (dashed line).

Fig. 1(a) shows the measured real part of effective permittivity (blue line) of the MHA with geometrical parameters of hole size a = 80 μm, lattice constant p = 150 μm and thickness t_m = 20 μm. It is noted that effective permittivity of the MHA shows a Drude response with the plasma frequency at 1.92 THz [3]. The red line indicates the effective permittivity calculated by using finite-difference time-domain (FDTD) method with same geometrical parameters those of experiment. An excellent agreement between experiment and simulation is obtained. These results indicate that we can obtain the effective permittivity with negative and relatively low absolute value, which is required for the hyperlens fabrication.

Next, we fabricate metamaterials of MHA-dielectric multilayers by stacking MHA and dielectric thin film (Zeonor$^{\mathrm{TM}}$ film) alternately. Fig. 1(b) shows the real part of effective permittivity of MHA-dielectric multilayers with one (black line), two (red line) and three (blue line) sets of layers. The geometrical parameters of the MHA are a = 180 μm, p = 200 μm and t_m = 10 μm. The thickness and complex permittivity in the frequency region where we interested are t_d = 40 μm and $\tilde{\varepsilon} = 2.56 + 0.00i$, respectively. We obtained a good agreement between three numbers of the stacked layer, indicating that there is no interaction between neighboring layers. The black dashed line in Fig. 1(b) indicates the calculated effective permittivity by using an effective medium approximation (EMA) with $\varepsilon = (t_m\varepsilon_m + t_d\varepsilon_d)/(t_m + t_d)$, where ε_m is the effective permittivity that is obtained from the experimental measurement of single MHA layer and ε_d is the permittivity of the dielectric film. Again, a good agreement between the EMA and experiment is obtained. This allows us to design a hyperlens structure simply by using EMA.

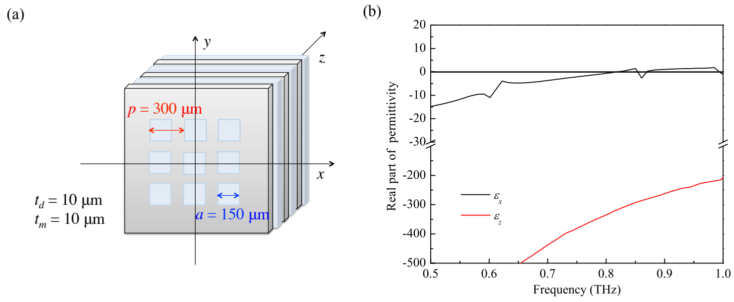

Fig. 2 (a) Structural and optical configuration of the MHA-dielectric multilayer used in our simulation. (b) Calculated real part of effective permittivity of ε_x (black line) and ε_z (red line).

We calculated the effective permittivity ε_z and ε_x of the MHA-dielectric multilayers of three layers, whose geometrical parameters and optical configuration is shown in Fig. 2(a), by using FDTD simulation. Fig. 2 (b) shows the spectra of the real part of ε_z (red line) and ε_x (black line) for this sample. For implementation of hyperlens, the conditions of $\varepsilon_z < 0$ and $\varepsilon_x > 0$ are required. We can obtain the frequency region from 0.8 THz to 1.0 THz where the required conditions of ε_z and ε_x are satisfied.

Finally, we calculate the electric field distribution of the electromagnetic wave that propagates through the MHA-dielectric multilayer structure. We use commercially available simulator (COMSOL$^{\text{TM}}$) based on a finite element method (FEM). Fig. 3(a) shows the spatial distribution of the electric field amplitude. In this calculation, the width and periodicity of metallic wire are 150 μm and 300 μm, respectively. The thicknesses of the metallic wire and dielectric film are same at 10 μm. We assume the permittivity of the dielectric film is 2.56+0.00*i*. The THz wave at 0.9 THz is launched from the 100-μm-wide source, which is located at $x = z = 0$. The THz wave propagates through the MHA-dielectric structure at the end of the material without apparent diffraction. By comparing the electric field distributions with and without the MHA-dielectric structure at the position of $z = 1500$ μm (Fig. 3(b)), we can confirm that the diffraction of the THz wave emitted from the subwavelength source is strongly suppressed by our structure.

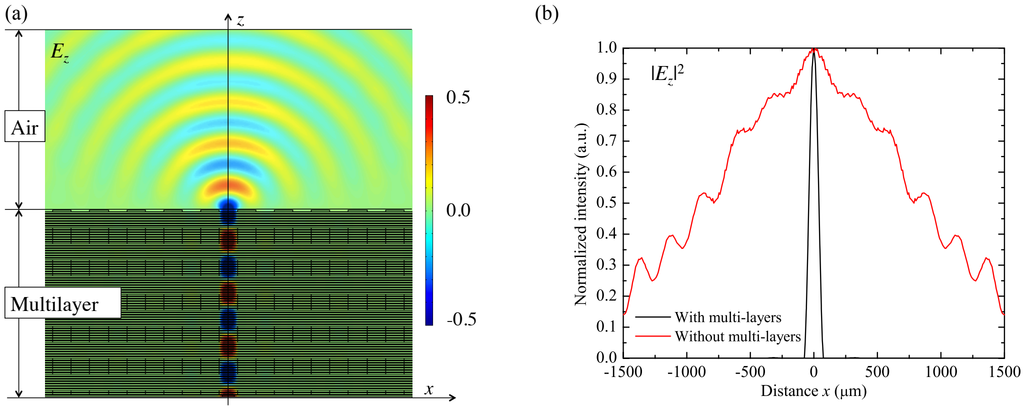

Fig. 3 (a) Calculated electric field distribution for the THz wave propagation through the MHA-dielectric multilayer. (b) Calculated electric field at $z = 1500$ μm in (a) with (black line) without (red line) the MHA-dielectric multilayer.

4. Conclusion

In conclusion we investigated the effective permittivity of MHAs and found that the frequency dispersion of the MHA can be fitted to Drude response with an effective plasma frequency is located at THz region. We fabricate MHA-dielectric multilayer structure, which has the anisotropic effective permittivity required for the hyperlens, by stacking the MHA and dielectric film alternately. An excellent agreement of the effective permittivities between experiment and EMA calculation is obtained. These results allow us to design and fabricate the hyperlens operated in THz region. We also calculated the THz wave propagation through the MHA-dielectric multilayer by using a finite element method, and found that the diffraction of the THz wave emitted from the subwavelength source was suppressed by our metamaterial structure.

References

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