Flexible Film with Paired Cut Wires for a Uniquely High FOM above 300

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***Abstract*—Wireless communication in the terahertz waveband is progressing by synthesizing unique compounds including man-made metamaterials. However, it has still not been fully shown how metamaterials can be the basis for structures with a high refractive index and no reflection or how they could lead to potential metadevices. Here we achieve a uniquely high potential of figure of merit (FOM=Re(*n*)/Im(*n*)) above 300 at 0.29 THz by a flexible film structure consisting simply of cut wires. The results here offer a way ahead for many applications with on-demand electromagnetic properties.**

I. INTRODUCTION

Wireless communication urgently requires the ability to utilize higher frequencies like 0.3 THz and practical terahertz communication abilities is only a question of time. It is essential to miniaturize terahertz devices and manipulate terahertz waves to accelerate the progress of terahertz technology. Optical lenses on transmitters and receivers in the terahertz waveband do not have high refractive indices and are commonly bulky because they are made of naturally available materials. Applications such as the resonant tunneling diode will require materials with high refractive indices or flat lenses with high directivity. However, it is still not certain whether metamaterials will be able to provide path-breaking sophisticated structures with high refractive indices [1] for ultrathin flat lenses. Here, we demonstrate a flexible film structure consisting simply of cut wires with an unprecedented high FOM, above 300, at 0.29 THz.

II. MECHANISM AND DESIGN

Fig. 1 shows the unit cell model of the paired cut wires on a cyclo-olefin polymer film. The one-unit cell model can be extracted from the full model by assuming periodic boundary walls as the full model is periodic along both the *x* and *y*-directions and large when compared to the wavelength. Both the dielectric and magnetic properties can generate high refractive indices. Fig. 2 shows contour maps of the effective refractive indices and transmission power at 0.31 THz optimized with the cut-wire gap *g* and length *l*. The other parameters are set to $w = 46$ µm, $p_x = 208$ µm, $d = 50$ µm, and $t = 0.5$ µm. The design is developed with ANSYS HFSS Ver.13.0.2, and a refractive index of $1.53 + j0.0012$ is used for the cyclo-olefin polymer film. The effective refractive index can be derived from the scattering matrix of the unit cell model [2]. The "X"es are at the fabricated parameters of $g = 85$ µm and $l = 313$ µm which achieve the high effective refractive index of $7.0 + j0.32$ and the high transmission power of 82% at 0.31 THz. The contour maps also indicate that the effective refractive indices can be controlled by the parameters of the paired cut wires and suggest the possibility of an ultrathin ($\lambda/20$), flexible, and flat lens with the gradient indices.

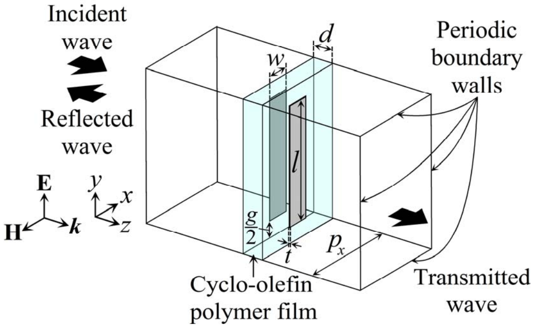
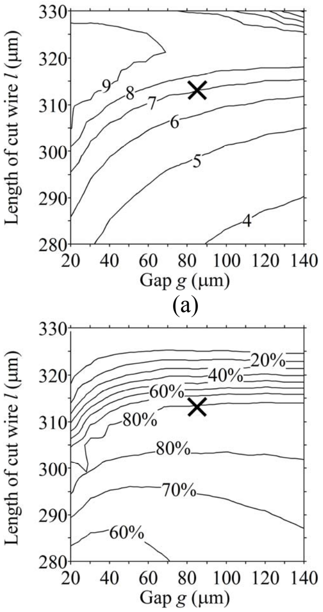


Fig. 1 Model for the analysis of paired cut wires.



(a)

(b)

Fig. 2 Contour maps at 0.31 THz for (a) the refractive index, and (b) the transmission power.

III. FABRICATION AND MEASUREMENT

Fig. 3 shows the fabricated paired cut wires. The copper paired cut wires composed of 19,200 units are fabricated by etching both sides of a low loss 4 cm × 4 cm cyclo-olefin polymer film. Fig. 4 shows the FOMs and measured effective refractive indices by terahertz time-domain spectroscopy. The measurements coincide well with the simulation. The measurements show a high effective refractive index of $n_{\mathrm{eff}} = 6.6 + j0.11$ and a high transmission power of 92% at 0.31 THz and $n_{\mathrm{eff}} = 4.9 + j0.016$ and 69% at 0.29 THz. The measured FOMs are 60.1 at 0.31 THz and 314 at 0.29 THz. Fig. 5 shows the measured relative permittivity and relative permeability, and Fig. 6 shows the measured relative wave impedance. The measurements show that the real part of a relative permittivity is constant at approximate 10 below 0.3 THz, and the real part of the relative permeability is lower than 4 below 0.3 THz. The magnetic resonance in the paired cut wires increases the real part of a relative permeability to become higher than 10 at 0.31

THz, and the real part of the relative wave impedance is approximately 1 because of an impedance matching between the flexible film with the paired cut wires and free space. The high refractive index and high transmission power are produced by the simultaneously high values of the permittivity and permeability.

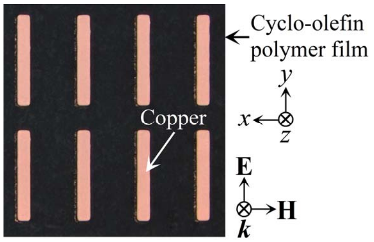


Fig. 3 Fabricated paired cut wires.

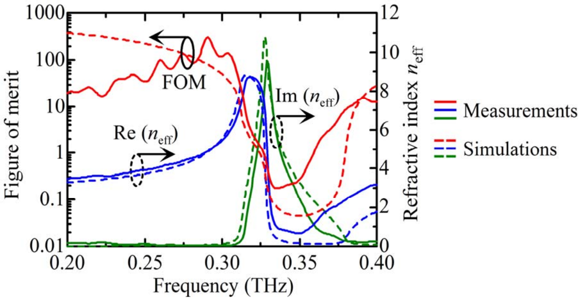


Fig. 4 Measurements and simulations of the FOMs and refractive indices.

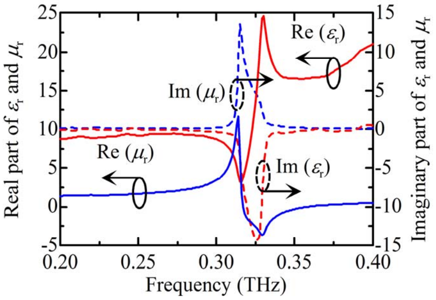


Fig. 5 Measurements of the relative permittivity and relative permeability.

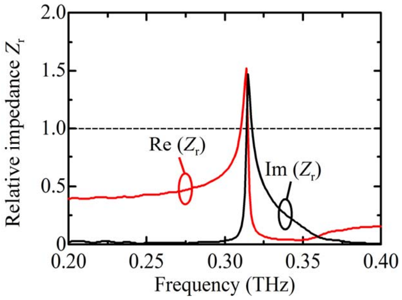
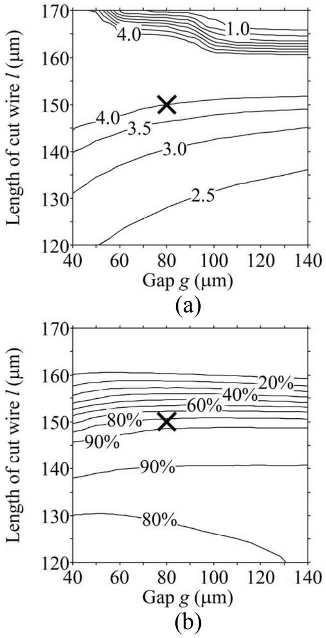


Fig. 6 Measurements of the relative impedance.

IV. DESIGN FOR HIGHER FREQUENCIES

The paired cut wires can provide a high refractive index at high frequencies by controlling the cut-wire length l and gap g. Fig. 7 shows contour maps of the effective refractive indices and transmission power at 0.6 THz. Other parameters are set to w = 46 μm, p_x = 208 μm, d = 50 μm, and t = 0.5 μm. The parameter of g = 80 μm and l = 150 μm achieves the high effective refractive index $n_{\rm eff}$ = 4.0 + j0.078 and high transmission power of 88% at the "X"es of Fig. 7. The effective refractive index is lower than that at 0.3 THz in Fig. 2. However, the potential of paired cut wires achieving a high effective refractive index and a high transmission power at higher frequencies by controlling only the cut-wire length l and gap g is confirmed.



(a)

(b)

Fig. 7 Contour maps at 0.6 THz for (a) the refractive index, and (b) the transmission power.

V. SUMMARY

Here we present a terahertz metamaterial formed by paired cut wires, with the high FOM of 314 at 0.29 THz representing a high effective refractive index and a very low loss. The potential for paired cut wires to achieve a high effective refractive index and a high transmission power at higher frequencies is confirmed. The results can be directly applied to ultrathin (λ/20) lenses and would also provide potential solutions to metadevice applications [3] for devices with on-demand electromagnetic performance.

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