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Low-index-metamaterial for gain enhancement of planar terahertz antenna

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We theoretically present a high gain planar antenna at terahertz (THz) frequencies by combing a conventional log-periodic antenna (LPA) with a low-index-metamaterial (LIM, $|n| < 1$). The LIM is realized by properly designing a fishnet metamaterial using full-wave finite-element simulation. Owing to the impedance matching, the LIM can be placed seamlessly on the substrate of the LPA without noticeable reflection. The effectiveness of using LIM for antenna gain enhancement is confirmed by comparing the antenna performance with and without LIM, where significantly improved half-power beam-width (3-dB beam-width) and more than 4 dB gain enhancement are seen within a certain frequency range. The presented LIM-enhanced planar THz antenna is compact, flat, low profile, and high gain, which has extensive applications in THz systems, including communications, radar, and spectroscopy. © *2014 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.* [http://dx.doi.org/10.1063/1.4868384]

I. INTRODUCTION

Over the past decade, terahertz (THz) science and technology has emerged into an active research area with extensive applications in biology, space exploration, radio-astronomy, communications, radars, imaging, sensing, and so on.[1–6] With the rapid development of THz technology, high performance THz antennas are increasingly in demand.[7–9] Planar antennas with compact size and low profile are much preferable for their easy integration in most practical THz systems. Unlike those in radio frequency or microwave range, the performances of antennas at THz frequencies (0.1–10 THz) are significantly degraded due to surface wave excitations occurs in substrates[10] and the lack of intrinsic responses from naturally occurring materials.[11,12] For instance, planar THz antennas, such as dipole, slot, bow-tie, log-spiral and log-periodic antennas, trend to radiate most of their energy into substrates, which are very much different from ordinary radio frequency and microwave antennas.[10] The performance of planar THz antennas can be improved by incorporating an extended hemispherical dielectric lens.[7–9] However, this increases the weight and volume of the antenna and makes it “non-planar”.

Artificially engineered composite materials, termed metamaterials,[13] have recently attracted significant attention in both scientific and engineering communities owing to their unconventional properties. The refractive index of a metamaterial can be tailored to be negative,[13] close to zero,[14–19] or even extremely high,[20] which does not normally exist in natural materials. The design of

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metamaterials offers a unique approach for efficiently manipulating THz waves.[12,21,22] Among various metamaterials, zero-index-metamaterial (ZIM, $n = 0$), was first presented by Enoch *et al.*[23] in 2002, and has received consistent attention in the microwave,[24,25] THz,[26,27] optics,[14,28] and even acoustics.[29] According to Snell's Law of refraction between two media ($n_1 \sin\theta_1 = n_2 \sin\theta_2$), if one medium is a ZIM with $n_1 = 0$ and the other one has $n_2 \neq 0$, then whatever the incident angle θ_1 is, the refraction angle θ_2 will trend to zero. This implies that the radiation wave from a source embedded inside a ZIM should be perpendicular to the ZIM's surface, which can be employed for enhancing the directionality and gain of an antenna.[23,30–36] In principle, a ZIM created by either epsilon-near-zero (ENZ, $\varepsilon \approx 0$) or mu-near-zero (MNZ, $\mu \approx 0$) metamaterial can improve the antenna gain.[23,30–36] However, the impedance ($Z = \sqrt{\mu/\varepsilon}$) of a ZIM is very sensitive to the variation of both ε and μ when these values approaching zero. The impedance may vary from zero to extremely large value, which may introduce serious mismatch between the antenna and metamateirals and reduce the radiation efficiency of the antenna. Even when the ZIM is created by a medium with both permittivity and permeability near zero, a certain space between the antenna and ZIM is necessary because the effective impedance of ZIM is just matched to the free space.[34–36]

In this paper, we theoretically demonstrate that metamaterials with low refractive index ($|n| < 1$) can also function like ZIMs for improving the performance of planar antenna. Besides the similar improvement of antenna directivity and gain, the impedance of a low-index-metamaterial (LIM) can be easily adjusted to match to that of the planar antenna, resulting a better radiation efficiency. As an example, we theoretically present a compact LIM-enhanced planar antenna at THz frequencies by properly applying an LIM with impedance matching to the substrate of the antenna. Owing to this impedance matching, the LIM and the substrate of antenna can be connected seamlessly, which makes our LIM-enhanced planar antenna ultra-compact. By optimizing the geometry of a fishnet structure, we achieve a metamaterial with low index and its impedance is well matched with the antenna substrate at the working frequencies. We confirm these features by retrieving the effective constitutive parameters using scattering parameters from finite-element based full-wave simulations. The antenna performances with and without an LIM are compared, which confirms the effectiveness of using LIM for antenna gain enhancement.

II. LOW-INDEX-METAMATEIRAL (LIM)

Figure 1(a) schematically shows a unit cell of the axially symmetric fishnet metamaterial at THz frequencies, which consists of metal-dielectric-metal sandwich layers. We assume both metal layers are made of gold and are separated by a benzocyclobutene (BCB) substrate. Same fishnet patterns are designed on both metal layers with geometrical parameters listed in the caption of Fig. 1. Only single layer fishnet metamaterial is considered in our work in order to maximize the transmission while minimize the absorbtion loss. Worth noting that the proposed structure is planar isotropic, such that it is polarization insensitive to the normal incident waves.

The scattering parameters of the metamaterial are calculated using commercial finite-element package Ansys HFSS. In our simulation, gold is considered as a conductor with a conductivity of 4×10^7 S/m and BCB is characterized by its relative permittivity with a real component of 2.6 and loss tangent of 0.005. In Figs. 1(b) and 1(c), we plot the magnitude and phase of the scattering parameters, *i.e.*, reflection (S_{11}) and transmission (S_{21}), of the proposed fishnet metamaterial. It is seen that the transmission magnitude is larger than 80% from 0.317 to 0.380 THz and nearly uniform (>90%) at 0.320 and 0.360 THz. Such a good passband feature is very useful when applying this metamaterial for designing high gain antennas. In addition, as shown in Fig. 1(c), the jump in the phase of the transmission (S_{21}) is an indicator that the fishnet metamaterial possesses a negative refractive index for frequencies around 0.320 THz.[37]

The effective impedance (Z), refractive index (n), permeability (μ), and permittivity (ε) of the metamaterial are extracted from the scattering parameters with effective medium theory.[38,39] Figure 2 shows the retrieved effective material parameters of the fishnet metamaterial. It is seen that the most interesting feature we expected is within the frequency range between 0.338 and 0.342 THz, where the refractive index of the metamaterial is less than unity. In this frequency, the proposed metamaterial can be considered as an LIM. A close comparison between Figs. 2(c)

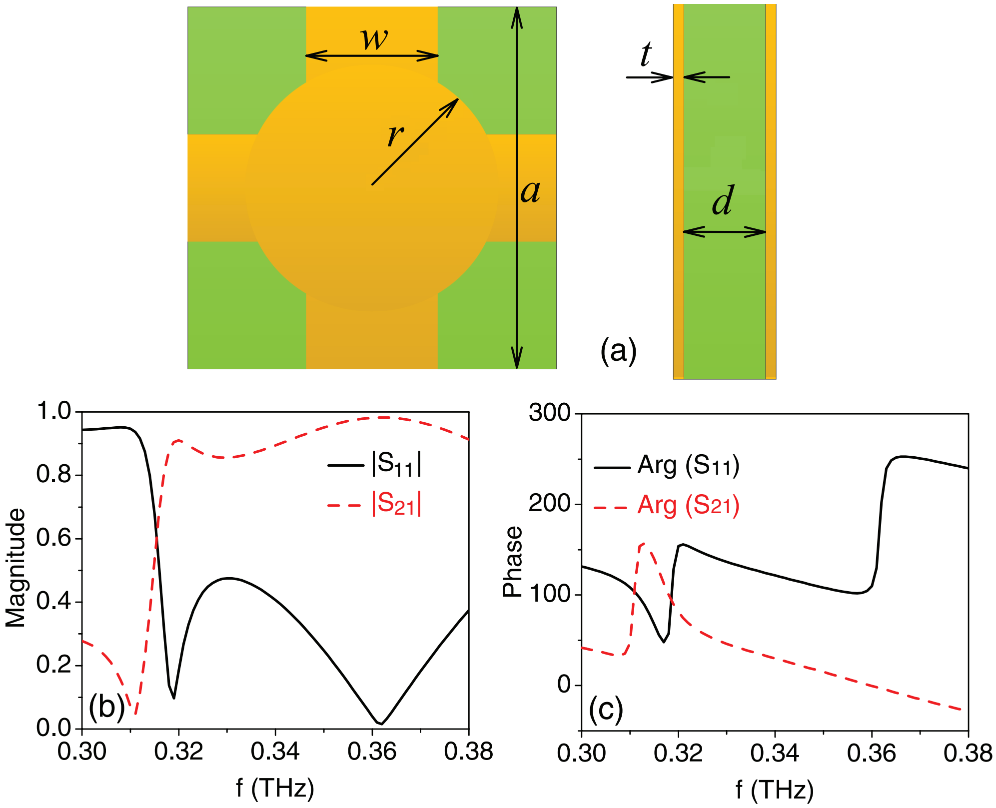

FIG. 1. (a) Top view (left) and side view (right) of the unit cell of the THz low-index-metamaterial (LIM). Geometrical dimensions are: $a = 550$ μm, $w = 161$ μm, $r = 236$ μm, $d = 87$ μm, and $t = 200$ nm. (b) Magnitude and (c) phase of scattering parameters of the THz LIM

and 2(d) also shows that the effective permittivity of the metamaterial is around 8 times larger than the effective permeability, resulting a relatively low impedance (near 0.3) which matches well to that of the antenna's substrate. This implies that the proposed metamaterial can be a good candidate for designing planar high gain THz antennas.

III. LIM-ENHANCED HIGH GAIN PLANAR THZ ANTENNA

The LIM discussed above can be employed as a flat lens adding to a planar antenna operating at 0.340 THz for the purpose of enhancing the antenna gain. Figures 3(a) and 3(b) show the side view of the LIM-based planar THz antenna and the geometry of the log-periodic antenna (LPA), respectively. The LIM-enhanced antenna is realized by covering one unit cell of the LIM on a LPA, with total dimensions of $a \times a \times (H + d + t)$. The LPA is a linearly polarized antenna with wide bandwidth and has been widely used in THz applications.[10] The substrate of the LPA is gallium arsenide (GaAs) with a thickness $H = 250$ μm and a dielectric constant $\varepsilon_{\mathrm{GaAs}} = 12.8$. The LPA is specified with expansion parameters τ, tooth-width parameter σ, inner angle β, and outer angle δ, where $\tau = r_2/r_1 = 0.65$, $\sigma = a_n/r_n = 0.81$ ($n = 1, 2$), and $r_1 = 151$ μm is the outer radius of the LPA in this design. The antenna substrate has a impedance $Z_{\mathrm{AS}} \approx 0.3$ which approximates to the microstrip substrate impedance, *i.e.*, $Z_{\mathrm{AS}} \approx \sqrt{1/\varepsilon_{\mathrm{AS}}}$, where $\varepsilon_{\mathrm{AS}} = (\varepsilon_{\mathrm{GaAs}} + 1)/2 + (\varepsilon_{\mathrm{GaAs}} - 1)[1 + 12H/(r_1 - a_1)]^2/2$.[40]

In Fig 3(c) we show the reflections of the antenna with and without the LIM. It is seen that the 10 dB bandwidths for the LIM-enhanced antenna and the conventional LPA are 6 GHz (0.337–0.343 THz) and 10 GHz (0.335–0.345 THz), respectively. Although the antenna operating bandwidth narrows down after integrating the LIM, the center frequency of the antenna remains the same. This

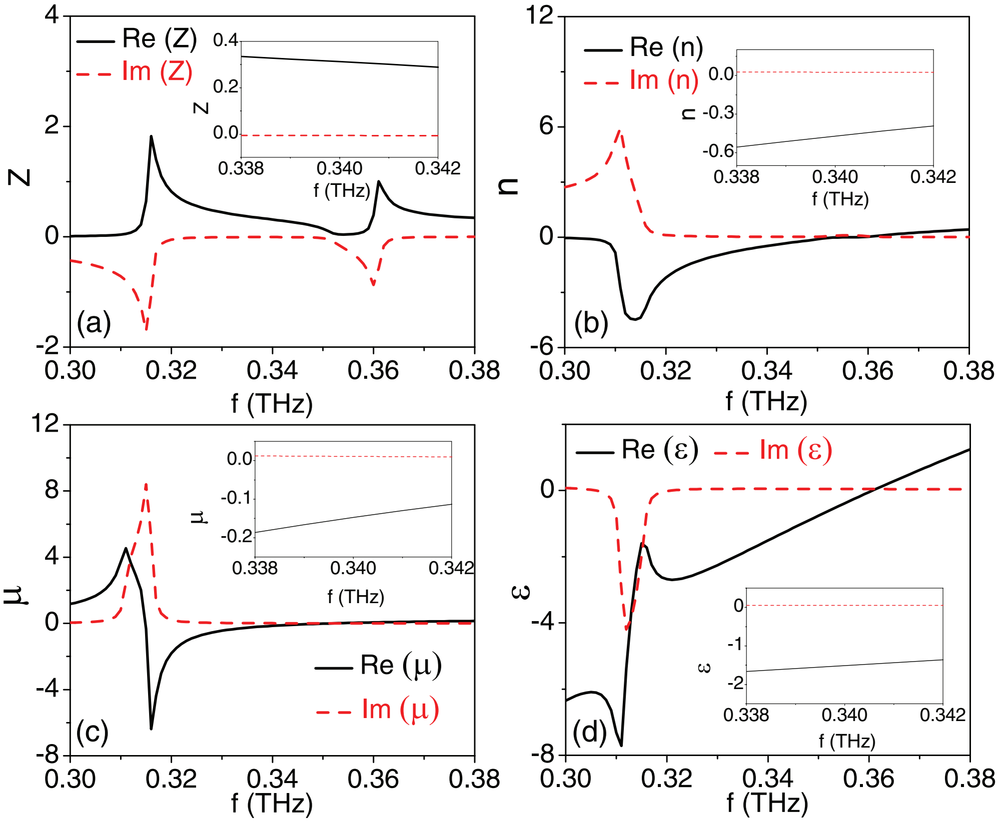

FIG. 2. (a) Retrieved effective impedance, (b) refractive index, (c) permeability, and (d) permittivity of the THz fishnet metamaterial. The real and imaginary parts of these parameters are plotted by solid and dashed curves, respectively. Insert in each panel shows the zoomed view between 0.338–0.342 THz.

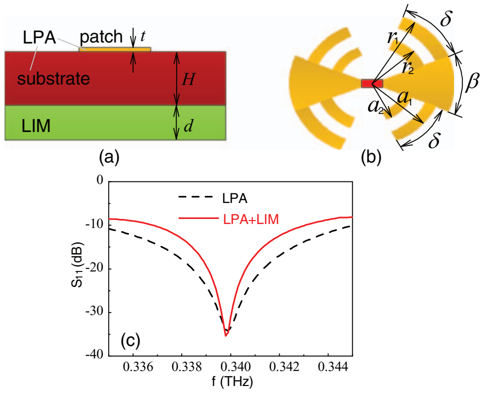

FIG. 3. Schematic illustration of (a) side view of the matched LIM-based planar THz antenna and (b) the geometry of the log-period antenna (LPA). (c) Reflections of the antennas with and without LIM.

implies that the coupling between the LIM and the LPA will not significantly affect the antenna's working band. Moreover, the frequency band of low index of the metamaterial falls in the antenna's operating band. The direct connection between the LIM and the LPA is provided because the impedance of LIM equals to that of the antenna substrate in the band of 0.339-0.441 THz.

To illustrate the gain enhancement of the antenna using matched LIM, we show in Figs. 4(a)–4(c) the radiation patterns of the LIM-based planar THz antenna and the conventional LPA at 0.339,

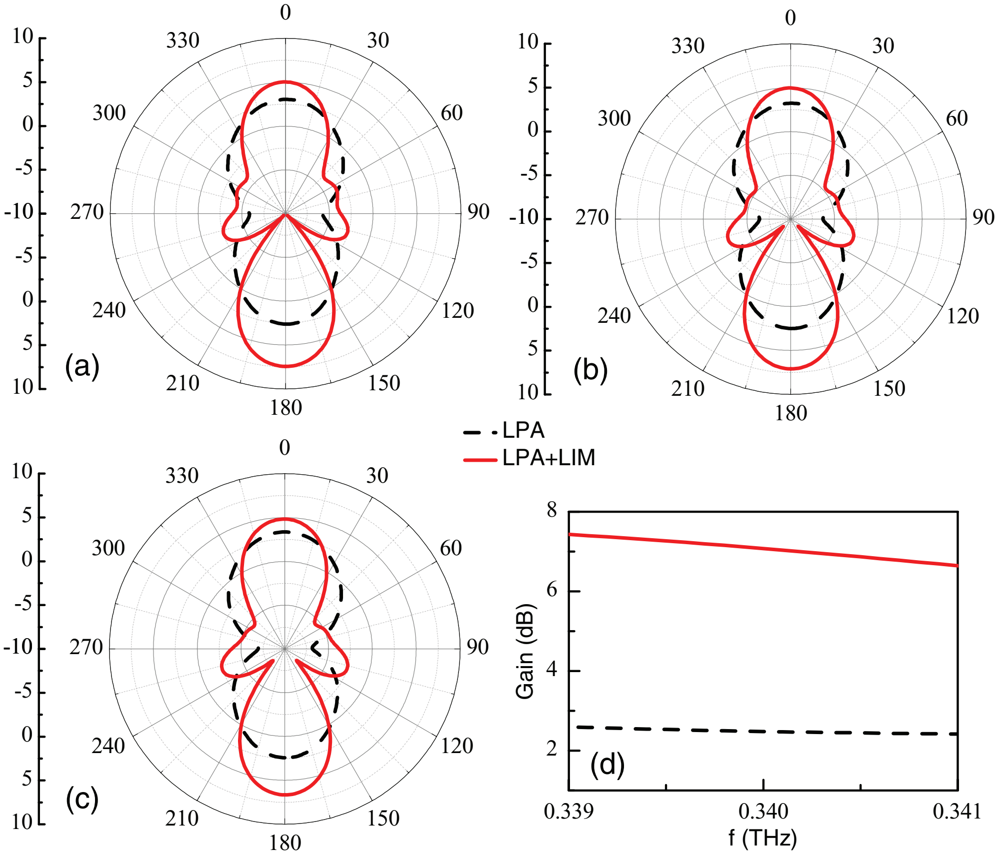

FIG. 4. Radiation patterns at (a) 0.339 THz, (b) 0.340 THz, and (c) 0.341 THz, and (d) antenna gains with and without LIM.

TABLE I. Performance comparison between the LPA and LPA+LIM

	3-dB beam-width (°)		Gain (dB)	
f (THz)	LPA	LPA+LIM	LPA	LPA+LIM
0.339	70	40	2.6	7.4
0.340	70	40	2.5	7.1
0.341	72	40	2.4	6.6

0.340, and 0.341 THz. The half-power beam-widthes (3-dB beam-widthes) of the LIM-based planar antenna is reduced by 30° compared to the conventional LPA. In Fig. 4(d) we see that the antenna gain of the conventional LPA is around 2.5 dB at the frequencies of interest. When the LIM is introduced, the antenna gain is enhanced by more than 4 dB within the operating band. This is because the matched LIM can concentrate the radiant energy while at the same time minimize the reflection by improving the impedance matching. The electric field distributions in the cross-sections, as shown in Fig. 3(a), for the LPA with and without the LIM are compared in Fig. 5. At 0.340 THz, one can see that the bare LPA generates a spherical-like wave, while the radiation of the LIM-enhanced LPA shows a clear concentration to the perpendicular direction. The detailed comparison of 3-dB beam-widthes and gains is given in Table I. By using the matched LIM, it is seen that significant improvements of both 3-dB beam-widthes and gains are achieved at the entire frequency range.

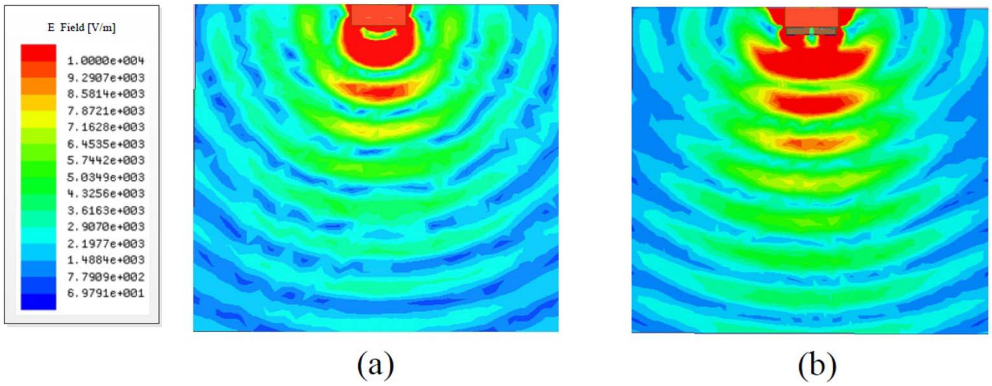

FIG. 5. The electric field distributions of the LPA (a) without and (b) with LIM at 0.340 THz.

IV. CONCLUSION

In this paper, we have theoretically presented a high gain THz planar antenna by seamlessly combing a conventional LPA with an LIM. A fishnet metamaterial was designed for achieving low reflective index by full-wave finite-element simulation. The effective constitutive parameters of the metamaterial were further retrieved according to effective medium theory, which shows clearly a low reflective index in a wide frequency band. The LIM can be placed seamlessly on the substrate of the LPA owing to the impedance matching between these two components. By comparing the antenna performance with and without LIM, it is demonstrated that the antenna gain can be enhanced by 4 dB within the frequency range of interest. We believe that similar idea can also be applied to other types of planar THz antennas and arrays, which is very helpful for improving practical THz systems.

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