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Terahertz band-pass filters based on fishnet metamaterials fabricated on free-standing SiN_x membrane

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A B S T R A C T

Terahertz (THz) band-pass filters constructed by metal–SiN_x–metal hollow fishnet metamaterials were designed and fabricated. Results reveal that the as-fabricated single-layer filter responds at 3.75 THz with a high transmission of 88.1% and broad full width at half maximum of 2.79 THz. For such filters, a free-standing SiN_x membrane is utilized specially as both dielectric and supporting materials, by which the insertion loss widely existed in those filters fabricated on rigid substrates can be efficiently avoided. Moreover, the critical parameters for determining the responses of the filters were systematically investigated. In our approach, multi-layer filters can be easily fabricated just by stacking the metamaterials layer by layer, and thus the spectral transmission, bandwidth, and out-of-band rejection can be rationally adjusted. This work describes a promising approach to design and fabricate THz band-pass filters based on substrate-free fishnet metamaterials.

1. Introduction

Metamaterials (MMs), formed by artificial sub-wavelength components, are highly attractive and widely applied, owing to their peculiar and outstanding electromagnetic properties [1]. A clear superiority of MMs over natural materials is that the former allows researchers to tailor desirable electric or magnetic responses [2,3]. This advantage provides a compelling route to design some exciting devices, such as perfect absorbers [4,5], super lens [6], invisible cloaks [7], acoustic components [8,9], and band-pass filters (BPFs) [10–12]. Among these devices, BPFs are applied widely in imaging, communication, and biological sensing [10–12]. Although BPFs based on plasmonic structure [13], split-ring resonators (SRRs) [14], or complementary metamaterials [15] were previously reported, fabrication of broad-pass and low-loss BPFs still remains challenges.

Recently, some BPFs based on MMs and operated in THz region were reported [16–18]. For example, Zhu and co-workers presented THz BPFs constructed by double-stacked MMs [16]. Unfortunately, rigid glass substrates were used in their work, and thus poor out-of-band rejection and low frequency selectivity were observed [16]. In contrast, bilayer fish-scale THz BPFs with excellent out-of-band rejection and flat pass-band were proposed by Zhang [17], but the negative effects of the rigid Si substrate on the bandwidth and response frequency are similarly unavoidable [17]. Moreover, cascade connection of BPFs will lead to the increment in the substrate thickness, causing negative effects of unwanted resonances, shift of the response frequency, and higher in-band insertion loss [17,18], and thus further degrading the filtering quality.

In order to overcome the negative effects of thick and rigid substrates (e.g. glass, Si, quartz, etc.) on the filtering performance of BPFs, substrate-free THz BPFs based on metal–dielectric–metal MMs were designed and fabricated in this work. Although MMs based on various dielectric materials of Al_2O_3 [19], MgF_2 [20] and benzocyclobutene (BCB) [21] were previously reported, the difficulty in the fabrication of free-standing MMs have not been efficiently solved. Different from Al_2O_3, MgF_2, and BCB, SiN_x exhibits excellent mechanical and optical properties, and thus SiN_x membranes are recently applied in supporting MMs [22,23]. In our work, a free-standing SiN_x membrane servers specially as not only a supporting material, but also the dielectric layer for our BPFs, slightly different from the previous others [22,23]. On the other hand, compared with the planar arrays of split-ring resonators or complementary MMs, fishnet MMs have simpler structures and can

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easily achieve both negative permittivity and negative permeability in the optical range [24], thus allowing rational control of the MM performances. By designing the sizes, the fishnet MMs can be extended to response in the THz range. Moreover, the symmetrical units of the fishnet MMs can be connected with each other, thus guaranteeing the integrity of the whole MM structure. Therefore, our MMs consist of two metal fishnet layers, which are supported and separated by a SiN_x membrane. Since the MM structures were designed to be hollow fishnets (HF), they are denoted by HFMMs. In this work, we will pay attention to the effects of the structural parameters on the filtering characteristics of the HFMMs-based filters. Particularly, multi-layer HFMMs-based filters were also fabricated and investigated. Both simulations and measurements demonstrate that the as-designed and fabricated HFMMs-based filters exhibit excellent THz-filtering performance as band-pass filters.

2. Fabrication and results of single-layer HFMMs-based filters

In our work, the HFMMs-based filters were fabricated by standard photolithography and deposition processes. The fabrication procedures are illustrated in Fig. 1(a). Firstly, two 900 nm-thick SiN_x membranes were deposited by plasma-enhanced chemical vapor deposition (PECVD, STS Multiple) onto both sides of a cleaned 600 μm-thick Si wafer, respectively. Secondly, one SiN_x membrane was patterned as fishnet by stepper lithography machine (Nikon, NSR2005i9c), and then it was etched by reactive ion etching (RIE, FHR 400). Similarly, another SiN_x membrane was patterned as square windows with the sizes of 0.5×0.5 cm^2. Thirdly, the Si substrate was eroded by 60% KOH solution. KOH corrosion was carried out at 60 °C for 6 h until the SiN_x skeleton structure was yielded. Finally, two 100 nm-thick aluminum (Al) films were evaporated by electron beam evaporation on both sides of the SiN_x skeleton, by which free-standing HFMMs-based filter was produced, as displayed in Fig. 1(b). Notably, no any alignment was required in our fabrication. The schematic of a HFMM is illustrated in Fig. 1(b), where a polarized THz wave with certain electromagnetic direction is irradiated. The parameters of *a, b, c*, and *d* are referred to the width of the metal parallel to the magnetic field H, periodic size of cell, width of the metal parallel to the electric field E, and the thickness of the SiN_x membrane, respectively. THz spectra of the as-designed HFMMs-based filters were theoretically simulated by commercial software CST Microwave Studio 2013, and experimentally measured by Fourier transmission infrared spectroscopy (FTIR) and THz time-domain spectroscopy (THz-TDS), respectively.

The actual sizes of the as-fabricated HFMMs-based filters are shown in the top-right inset of Fig. 2(a), where $a = 20.5$ μm and $b = 75.5$ μm. In the simulations, the refractive index (n, and $n = \sqrt{\varepsilon}$) of SiN_x is 1.98, and the conductivity of Al is 3.56×10^7 s m^{-1}. The simulated and measured THz spectra in the range of 0.06–7.5 THz for single-layer filters are displayed in Fig. 2(b). It is worth noting that well agreement between the simulated and FTIR results is observed, both indicating that the resulting single-layer filters can be operated at a center frequency of 3.75 THz with a high transmission of 88.1%, and the full width at half maximum (FWHM) of such single-layer filters reach 2.79 THz. Interestingly, a slight transmission damping exists in the central frequency, which reason will be discussed later. The THz responses in 0.06–2 THz were further characterized by THz time-domain spectroscopy (THz-TDS), which result (red curve in Fig. 2(b)) is also in accordance with those of FTIR and simulation. As comparison, THz spectrum of a pristine SiN_x membrane was also measured and displayed in Fig. 2(b), revealing high transmission of SiN_x in the THz regime. Based on these, one can conclude that the as-fabricated single-layer HFMMs-based filters exhibit a promising functionality as THz band-pass filters.

3. Numerical analysis of single-layer HFMMs-based filters

As shown in Fig. 2(b), single-layer HFMM-based filters exhibit two transmission peaks: P_1 at 3.5 THz and P_2 at 3.95 THz, both of which determine the full width at half maximum (FWHM) for the response peak of the single-layer filters. The characteristics of the as-designed HFMMs were inspected by calculating the effective permittivity $\epsilon_{\mathrm{eff}} = \mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right) + i * \mathrm{Im}\left(\epsilon_{\mathrm{eff}}\right)$ and the effective permeability $\mu_{\mathrm{eff}} = \mathrm{Re}\left(\mu_{\mathrm{eff}}\right) + \mathrm{i} * \mathrm{Im}\left(\mu_{\mathrm{eff}}\right)$. Theoretically, ϵ_{eff} and μ_{eff} can be retrieved from the complex values of transmission coefficient $S'_{21} = S_{21} \cdot e^{i\varphi_{S_{21}}}$ and reflection coefficient $S'_{11} = S_{11} \cdot e^{i\varphi_{S_{11}}}$, where S_{21} and $\varphi_{S_{21}}$ are the amplitude and phase of the transmission coefficient, S_{11} and $\varphi_{S_{11}}$ are the amplitude and phase of the reflection coefficient, respectively. According to Ref. [25], the refractive index n and impedance z can be estimated through the following equations:

$$n = \pm \frac{1}{k \cdot h} \cos^{-1}\left(\frac{1}{2S'_{21}}\left(1 - S'^2_{11} + S'^2_{21}\right)\right), \tag{1}$$

and

$$z = \pm \sqrt{\frac{\left(1 + S'_{11}\right)^2 - S'^2_{21}}{\left(1 - S'_{11}\right)^2 - S'^2_{21}}}, \tag{2}$$

where $h = d + t$, d is the thickness of dielectric layer, t is the total thickness of metal that equals to 0.2 μm. Meanwhile, the wave number is given by $k = \omega / c$, where ω is the frequency and c is the speed of light. Thus, ϵ_{eff} and μ_{eff} can be calculated through the equations of $\epsilon_{\mathrm{eff}} = n/z$ and $\mu_{\mathrm{eff}} = n \cdot z$. In this work, S_{21}, $\varphi_{S_{21}}$, S_{11} and $\varphi_{S_{11}}$ were deduced through CST simulations, by which the ϵ_{eff} and μ_{eff} for the HFMMs-based filters were calculated, as displayed in Figs. 3(a) and (b). The transmission spectrum was given by $T = |S_{21}|^2$, as shown in Fig. 3(c). Meanwhile, the frequency ranges with negative $\mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right)$ or $\mathrm{Re}\left(\mu_{\mathrm{eff}}\right)$ are marked as dashed areas in Fig. 3(c). The results reveal that the real part of permittivity $\mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right)$ becomes negative below 3.5 THz, and $\mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right) \cong -\infty$ at 0.1 THz (the inset of Fig. 3(a)). In contrast, the real part of permeability $\mathrm{Re}\left(\mu_{\mathrm{eff}}\right)$ is negative in the range of 3.6–4.2 THz, and the minimum appears at 3.75 THz (Fig. 3(b)). The fishnet MMs can be regarded as combination of electric structure and magnetic structure, in which the electric structure is formed by the metal wire, while the magnetic structure is formed by the simplified staple, as shown in Fig. 1(b). Drude-like electric resonance of isotropic fishnet is induced by the electric field along metal wires, resulting in negative permittivity [26]. The critical frequency value of electric resonance is defined as plasma frequency f_e, where the $\mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right) = 0$. At $\omega < f_e$, the effective permittivity becomes negative. Meanwhile, the magnetic resonate frequency is defined as f_m, where $\mathrm{Re}\left(\mu_{\mathrm{eff}}\right)$ achieves minimal value. As revealed in Figs. 3(a) and (b), $f_e = 3.5$ THz and $f_m = 3.75$ THz.

In order to investigate the electromagnetic behaviors of the HFMMs-based filters, the distributions of the electric fields along the α plane and magnetic fields along the β plane at the frequencies of 0.1 THz, f_e (3.5 THz), f_m (3.75 THz), and P_2 (3.95 THz) were simulated and shown in Figs. 4(a)–(h), respectively. The α plane is a cross-section plane along the incident E field, and the β plane is a cross-section plane along the incident H field, as illustrated in Fig. 1(b). As revealed in Fig. 4(a), the electric fields are mainly confined in the HFMMs at 0.1 THz. However, such confined electric fields do not appear if the frequency is higher than 3.5 THz, as displayed in Figs. 4(b)–(d), suggesting disappearance of the electric resonance at the frequency range where $\mathrm{Re}\left(\epsilon_{\mathrm{eff}}\right)$ is positive. Simultaneously, the magnetic fields are dispersed if the electric resonance below f_e, as shown in Figs. 4(e) and (f). As illustrated in Figs. 4(g) and (h), the confined magnetic fields, resulted from the magnetic resonances at f_m (3.75 THz) and P_2 (3.95 THz), appear in the SiN_x membrane. At the frequency range of magnetic resonance, the value of $\mathrm{Re}\left(\mu_{\mathrm{eff}}\right)$ is negative. Particularly, the magnetic resonance occurring at the minimal $\mathrm{Re}\left(\mu_{\mathrm{eff}}\right)$ at the frequency of f_m is