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A new fold-cross metal mesh filter for suppressing side lobe leakage in terahertz region

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ABSTRACT

In this paper we propose a new type of fold-cross metal mesh band pass filter, which keeps diffraction side lobe far away from the main transmission peak and shows much better side lobe suppression. Both experimental and theoretical studies are made to analyze the mechanism of side lobe. Compared to the traditional cross filter, the fold-cross filter has a much lower side lobe with almost the same central frequency, bandwidth and highest transmission about 98%. Using the photolithography and electroplating techniques, we experimentally extend the distance between the main peak and diffraction side lobe to larger than 1 THz for the fold-cross filter, which is two times larger than the cross filter while maintaining the main peak transmissions of 89% at 1.25 THz for the two structures. This type of single layer substrate-free fold-cross metal structure shows better design flexibility and structure reliability with the introduction of fold arms for metal mesh band pass filters.

1. Introduction

With the rapid development of the terahertz (THz) technology, various THz instruments are applied more and more widely in various regions like biological imaging, space exploration and military radar [1–3]. In all these THz instruments, the bandpass filter is always an indispensable element. Except for the ordinary properties such as frequency selective, noise filtering, and gain equaling [4,5], the metal mesh filter, also called frequency selective surfaces (FSS), can be introduced to the THz system with various geometric structures. An extraordinary optical transmission can be excited from these structures for the resonance between the free electrons in the metal and the optical photons from the incident light [6,7]. These filters are compact and easily fabricated, which could act as high pass, low pass, band-pass, or reject band filters [8–11]. In 1967, Ulrich first proposed two structures to investigate the metal mesh filter, a metallic grid mesh and its complementary structure, which shows that the grid mesh structure exhibiting high pass with transmission line theory while its complementary structure revealing low pass property [12]. Owing to metal mesh filters exhibiting high transmission and easier fabrication process, many authors study on different geometry structures to present different spectral response. The cross shape is one of the best known band pass geometry. Chase and Joseph [13] present the relationship between the filter bandwidth, peak position and structure parameters systematically. The study shows that the main transmission wavelength is determined by the length of cross arm and coupling between the crosses decide the bandwidth. Furthermore, structures with substrate-free cross shape structure with methods like photolithograph and electroplating techniques are studied extensively, which possess the transmission higher than 97%. However, the transmission of pass band will decrease with the increase of center frequency [14].

In recent years, different substrate and fabrication techniques [15,16] have been applied to realize frequency selective. Various resonant units like metamaterials with broadband band pass filter for the surface resonance between layers [17–19] have been used as metal mesh filter. Meanwhile, materials with special properties like graphene are adapted to the metal mesh structure, which can make an adjustable filter [20]. Companies like Thorlabs and Lakeshore have designed a series of substrate-free bandpass THz filters with cross-absent pattern, which can tune the bandpass frequency from 510 GHz to 30 THz [21]. However, a common problem that the mesh filter has a side lobe leakage in wavelength shorter than peak wavelength exists in all these studies. Various studies have been made to solve this problem. Methods like defected ground planes with coupled line [22] and dielectric materials beneath substrate [23] have been proposed to suppress side lobe in short wavelength region. Unfortunately, these techniques cannot be applied to THz frequency range. Traditional methods to suppress the undesirable high frequencies in the THz range are stacking several identical mesh

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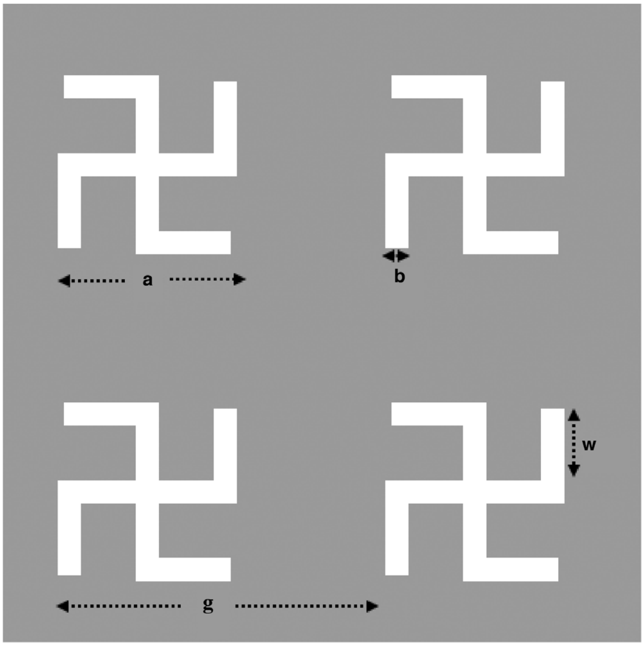

Fig. 1. Schematic of fold-cross shape mesh FSS.

filters [24] and using a lossy glass substrate [25]. However, stacking several identical mesh filters will result in a low main transmission. Besides, a glass substrate can only suppress the leakage in specific narrow range frequencies for the property that glass substrate exhibit high absorption at frequencies higher than 1 THz [26,27].

Comparison all the methods above, we propose a new method to solve the side lobe leakage in THz range with high main frequency transmission maintaining. We design a fold-cross structure to make the main transmission peak far away from the side lobe region achieving suppression in a wider range with the highest transmission about 98% theoretically. With simulating the influences between geometric parameter and bandwidth, transmission and side lobe position, we try to explain the generating mechanism of the side lobe and remove it away from the main transmission frequency as far as possible. Finally, we successfully prepare the substrate-free metal mesh filter with photolithography and electroplating techniques. Compared to the traditional cross filter, the fold-cross filter exhibits a much lower side lobe with almost the same central frequency and bandwidth. With maintaining the main transmission around 89%, we successfully extend the distance between the main peak position and diffraction side lobe position to more than 1 THz, which is one times larger than the cross shape ones. Besides, compared with products of Companies like Thorlabs, our fold-cross shape filter exhibits not only a lower and farther side lobe but also more solid and easily prepared structure compared with the cross-absent shape.

2. Sample simulation and preparation

Many outstanding journal articles and books have provided a solid foundation about frequency selective surfaces (FSS). Various geometries suited for different filters to achieve distinct purposes are designed. The fold-cross mesh we designed is shown in Fig. 1 to realize the main transmission peak far from the side lobe region, high transmission pass band and low transmission of out of band frequencies. Its performance is mainly determined by periodicity g, length a, width b, fold arm length w, and thickness d.

Photolithography, electroplating and etching techniques are the main process to manufacture the substrate-free metal mesh structure. The fabrication process steps are shown in Fig. 2. Fig. 2(a) shows the prepared substrate with copper layer as a cathode in the electroplating process. Deposited SU-8 photoresist using a spin coater is shown in Fig. 2(b). Photolithograph is the main process with UV exposure machine to make the graph of mask projected onto the photoresist in Fig. 2(c). Fig. 2(d) shows the electroplating process using 24 V DC power supply to achieve 8um thickness nickel film. The next step is the etching conductive copper layer process in Fig. 2(e). Removing the photoresist is shown in Fig. 2(f) to obtain the substrate-free fold-cross structure.

Following with the processes above, we first deposited a 100 nm thickness copper layer upon a silicon substrate, which possesses good conductivity for nickel electroplating. Then we spun a layer of 12 μm thickness SU-8 photoresist above the substrate (spin rate: 1400 rpm, time: 30 s). The sample was then soft baked at 65 °C for 10 min and cooled down for 5 min. A UV radiation exposure (Power: 8 mW, time: 30 s) was followed after 4.5 min post bake. Then we immersed the sample in developing solution about 2.1 min and rinsed clearly with deionized water. A copper-coated silicon substrate covered with an array of 12 μm thickness fold-cross photoresist was prepared after these steps. Then we used a water solution of nickel sulfate, nickel chlorine and boric acid with a current density of 4.5 A/dm^2 to electroplate nickel above the structure. After the electroplating process, we removed the photoresist and cooper layer by immersing the sample in ammonia, hydrogen peroxide and ultrasonic cleaning equipment. Finally, we measured the transmission spectrum with the terahertz time-domain spectroscopy (THz TDS).

3. Results and discussions

The band pass properties of substrate-free metal mesh are simulated based on the finite element method. Fig. 3(a) shows the transmission spectrums corresponding to different periods. With the increase of period, it can be found that both the center frequency and side lobe exhibit red shift, and the bandwidth becomes narrower due to reducing the interaction between the units. From the contrast curve, we can see that period is the main factor in affecting the position of appearing diffraction side lobe. The reason is that the side lobe position, which is also called Wood anomaly [28], appears mainly while wavelength of the side lobe (λ) equaling to the period (g) numerically ($\lambda = g$). For example, as shown in Fig. 3(a), the side lobe frequencies are 2.02 THz, 2.32 THz, 2.7 THz corresponding to different period (g) 150 μm, 130 μm, and 112 μm, respectively. Fig. 3(b) shows the dependence of transmission on different width of arms. It is obviously that positions of side lobe remain almost the same because of the same period, which is consistent with the Wood anomaly. We can also see that the bandwidths become wider and center frequencies exhibit blue shift. Besides, the transmission of side lobe region becomes lower with the decrease of width of arms which means we can suppress the transmission of side lobe by reducing the width of arms. Moreover, with the increase of the width of the arms, the transmission of both main frequency and diffraction side lobe improves for the increasing of duty ratio.

Successively, the influence of length of fold-cross shape is investigated and shown in Fig. 4(a). We can see that the main resonance peak exhibits red shift and the bandwidth becomes wider with the increase of main arm. Owing to the same period, the positions of side lobe maintain almost the same. The red shift of main peak reveals that the shape of the hole affected the resonance obviously, as discussed in Ref. [10]. Besides, the enhanced coupling between adjacent holes is main reason for bandwidth becoming wider. Fig. 4(b) shows that a high second peak emerges with increase of fold arm length. It can be seen that the second peak is probably the high-order resonance. When the sum of main arm length and fold arm length is larger than the period numerically, high-order resonance transmission can reach to about 100% as the strongly coupling of high-order resonance between the adjacent period units. We also can see that the main peak exhibits