Design, simulation and fabrication of a new terahertz cross-shaped metamaterial bandpass filter to obtain a narrow frequency bandwidth

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Abstract
In this study, a new terahertz cross-shaped metamaterial bandpass filter is designed, simulated and fabricated. Among the properties of the proposed filter, compared to built-in filters (especially cross-shaped filters), one may refer to higher output transfer intensity (of almost 100%) and less noise effects (unwanted frequencies) in the whole range of 0.1 to 3 THz. The simulation is conducted by the CST STUDIO software and the FDTD method. Experimental results with THz-TDS system and simulation results with CST STUDIO software that are well matched.

Keywords Terahertz metamaterial cross-shaped bandpass filter · Frequency width at half maximum (FWHM) · Unwanted frequency · Transmission coefficient · THz-time domain spectroscopy

1 Introduction

So far, many designs and methods have been presented to construct terahertz metamaterial bandpass filters with different aperture geometries. How these aperture geometries affect transmission properties has also been discussed. Terahertz cross-sectional metamaterials are intended for the selective transmission of terahertz waves along a desired wavelength or frequency range. The structures of these materials range from a simple periodic array of holes on a thin metal film to complex multilayer structures made through nano-fabrication techniques. In general, it is very important to have a pattern for the designing and
development of terahertz bandpass metamaterials because it determines the transmission property of the peaks in terahertz spectra. A comprehensive overview of the designs for terahertz metamaterial bandpass filters is provided here (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015).

Light transmission in the visible spectrum can be achieved through apertures smaller than the wavelength created in thin metal layers. It has been well established that light transmission through such structures constructed on metal films can be increased for several times. The physics of this phenomenon is elucidated, and it is believed that the Surface of Plasmon Polaritons (SPPs) produced by sub-wavelength structures serves for electromagnetic radiation. In recent years, researchers have successfully demonstrated that surface structures of appropriate characteristic wavelengths can have extraordinary transmissions in the terahertz field. Those structures have also found applications in such areas as terahertz measurement and imaging (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015; Paul et al. 2009; Gao et al. 2020).

2 Design basics

Several factors must be carefully considered when designing an effective transient material in the terahertz domain. First, the resonant frequency of the terahertz transmission spectrum must be determined. To calculate that frequency for a typical aperture array diaphragm, researchers have developed an analytical method. In addition to the transmission resonance for a typical aperture array diaphragm, the central terahertz transmission wavelength must be calculated for the other apertures. An experimental equation has been proposed to calculate terahertz bandpass cross-shaped apertures (Wang et al. 2019). Müller et al. also proposed the following experimental equation to determine approximate central wavelengths (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015; Paul et al. 2009; Gao et al. 2020) (Fig. 1):

$$\lambda_{\text{peak}} = 1.8L - 1.35W + 0.2P$$

(1)

where $P$ is the period, $L$ is the width, and $W$ is the length of the cross-shaped aperture. Those researchers also summarized several experimental equations with different coefficients for $L$, $W$ and $P$, as compared to Eq. (1). However, Eq. (1) has been used more in recent works in which terahertz cross-shaped metamaterials are constructed (Paul et al. 2009; Gao et al. 2020; Ao et al. 2017).

![Fig. 1 Schematic diagram of a THz bandpass filter with a cross-shaped aperture: the parameters $L$, $W$, $P$ and $T$ represent the arm length, arm width, period and thickness of the cross structure respectively (Gao et al. 2020)](image-url)
3 Geometric pattern design

The position of the transmission peak is a key feature for the best terahertz transmission and is considered the most important factor when designing terahertz SSPs. Using Eq. (1), the geometric parameters can be changed to effectively determine the location of the transmission peaks. Therefore, the basic design principles for terahertz bandpass metamaterials can be summarized as follows:

1. Select the appropriate aperture geometry according to the design needs.
2. Determine the appropriate dimensional parameters to achieve the desired transmission property (e.g., location of the resonant frequency).

Based on these principles, researchers have proposed different geometric designs, such as different hole diaphragm geometries. These geometries include alternating circular or square perforated diaphragms, cross-shaped diaphragms, or slit rings, as shown in Fig. 2. The following section provides a comprehensive review of diaphragm structures for terahertz bandpass metamaterials (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015; Paul et al. 2009).

Circular diaphragms have been widely used for terahertz bandpass metamaterials. The research shows that the effect of a terahertz bandpass filter can be effectively achieved through a circular hole array. The effects of design factors on terahertz transmission have also been well studied. This includes the period, direction and diameter of holes. Experimental results show that, when these geometric parameters are changed, it is possible to obtain such terahertz transmission properties as the location of the resonant frequency, intensity of the resonance transfer and frequency width at half maximum (FWHM). The effect of square apertures on terahertz bandpass filters has also been investigated. Cao and Nahata mounted circular and square diaphragm arrays on 75-um stainless steel sheets and showed the importance of aperture shape in terahertz transmission with increasing resistance (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015). Geometry and aperture are important factors to consider when designing terahertz non-conducting materials. Appropriate geometric parameters must be selected to achieve the desired terahertz transmission property.

In addition to ordinary aperture arrays, innovative surface patterns have been designed and tested to achieve extraordinary terahertz transmission effects. In this

![Fig. 2 Different diaphragm geometries of terahertz bandpass metamaterials: a circular, b square, c cross-shaped, and d folding slit (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015; Paul et al. 2009)](image)
regard, cross-diaphragm has been proposed and studied by many researchers in recent years (Wang et al. 2019; Chiang 2011; Sedykh et al. 2015; Paul et al. 2009; Gao et al. 2020).

A cross-shaped diaphragm is easily constructed, and it provides another important geometric pattern for the realization of terahertz resonance. Using various structural parameters, the resonance frequency of terahertz bandpass metamaterials can be modified (Lin et al. 2017). Very narrow FWHM have been obtained using cross-shaped bandpass ultrastructures built into sources [ibid]. Table 1 shows the performance of three cross-shaped bandpass monolayer filters, as in Fig. 1, achieved through simulation with the FDTD method.

Another new type of structure is designed for the terahertz bandpass metamaterials in Jesus cross structure (Xiong and Li 2020). It has a transfer coefficient of 57% to 89%, which is lower than that of a cross-shaped structure (Table 1). These types of structures have been simulated using the CST STUDIO software and compared with experimental results; they have proved to provide very similar results (Xiong and Li 2020).

Another type of terahertz bandpass filters are produced through the design and fabrication of frequency selective surfaces (FSSs) that operate within a range of more than 300 GHz. These structures serve as open-space electromagnetic filters and, thus, provide multispectral remote sensing tools by dividing radiation into separate frequency channels (Dickie et al. 2011). This new design for quasi-optical filters has a drop of 0.3 dB at 700 GHz and can be designed to be independent of the polarization of collision signals (Dickie et al. 2011).

Of all the different geometries ever designed and fabricated for terahertz bandpass filters, cross-shaped bandpass filters are advantageous in terms of spectral transmission and frequency bandwidth (Melo 2012; Ri-Hui and Jiu-Sheng 2018; Mittholiya et al.; Shahounvand and Fard 2020).

Table 1 Performance of three cross-shaped bandpass monolayer filters (Fig. 1) obtained through FDTD simulation and THz-TDS system measurement (Lin et al. 2017)

| Filter | T   | T*  | f_c (GHz) | f*_c (GHz) | FWHM (GHz) | FWHM* (GHz) |
|--------|-----|-----|-----------|------------|------------|-------------|
| A      | 0.9 | 1   | 557       | 550        | 154        | 177         |
| B      | 0.89| 0.98| 372       | 367        | 70         | 74          |
| C      | 0.75| 0.91| 325       | 325        | 53         | 56          |

Fig. 3 The output frequency of a cross-shaped filter at the central frequency of 2.2 terahertz with dimensions L = 81, W = 29 and P = 154 um. A comparison of the simulation results (dotted line) with the reference (Yan et al. 2021; Liu, et al. 2007; Komarov and Meschanov 2019) (solid line).
4 Filter structure and the results

A cross-shaped bandpass filter is designed on a copper substrate using the CST STUDIO simulator software. The coordinates (p), (w) and (l) of every filter structure (Fig. 1) are different at different frequencies. In the simulation process, to produce a filter with the output of a frequency spectrum near 2.2 terahertz (Fig. 3), p, w and l have the values of 29, 100 and 154 µm respectively (Fig. 1 and Eq. 1). To confirm the accuracy of the simulation with the CST STUDIO software, these coordinates are evaluated against those reported in the studies conducted on cross-shaped filters (Yan et al. 2021; Liu, et al. 2007; Komarov and Meschanov 2019). A comparison of the simulation results with the reference (Yan et al. 2021; Liu, et al. 2007; Komarov and Meschanov 2019) is shown in Fig. 3.

In the next step, to reduce the frequency bandwidth of the output beam, two examples of this structure are placed at different distances (i.e., distance d as in Fig. 4). This causes the frequency bandwidth to differ from the initial state (single filter). The value of d changes at the distances λ, λ / 2 and λ / 4 from the central wavelength (resonance wavelength). As observed, the maximum reduction in the frequency bandwidth is obtained in the λ / 2 mode, which is about half the frequency bandwidth of the initial state (single filter) (Fig. 5) (Gao et al. 2020; Soboleva et al. 2017; Lu et al. 2018; Huang, et al. 2020).

According to the results obtained on the basis of Fabry-Pert principles, placing two filters in a row at the distance of half the wavelength reduces the frequency bandwidth. The results of this simulation are consistent with the computational results reported in some other sources (Shahounvand and Fard 2020; Asgari and Fabritius 2020).
Proposing a new cross-shaped metamaterial bandpass filter

In this section, a new cross-shaped bandpass filter is designed and simulated (Fig. 6). The A, B, C and D dimensions of the proposed cross-shaped bandpass filter are 154, 81, 29 and 9.6 µm respectively. These dimensions are used in accordance with the wavelength dimensions (Fig. 1) in cross-shaped filters \( A \equiv P, B \equiv L, C \equiv W, D \equiv 1/3W \), which helps

![Diagram of the proposed new cross-shaped bandpass filter](image)

**Fig. 6** The proposed new cross-shaped bandpass filter (coordinates A, B, C and D are selected according to dimensions L, W and P in Fig. 1)

![Graph showing the effects of noise and output spectrum](image)

**Fig. 7** The effects of noise (unwanted frequencies) and the intensity of the output spectrum: a the proposed filter (dotted-line diagram) and b cross-shaped filter (solid-line diagram)
to compare the output of the proposal filter with that of cross-shaped ones. Through the simulation of cross-shaped filters and the proposed filter, the outputs have been compared in terms of the percentage of transmission of the output spectrum, noise (unwanted frequency) (Fig. 7) and FWHM (Fig. 8).

Among the properties of the proposed filter, compared to built-in filters (especially cross-shaped filters), one may refer to higher output transfer intensity (of almost 100%) and less noise effects (unwanted frequencies) in the whole range of 0.1 to 3 terahertz.

According to Figs. 1 and 6, dimensions A and B have an effect on the central wavelength or resonant wavelength (Eq. 1), but dimensions C and D like the results shown in Figs. 4 and 5, are effective in reducing the frequency bandwidth (FWHM) and unwanted frequency (Fabry-Pert principles). This special design, by combining A, B, C, D as a special set with high output efficiency conditions, low unwanted frequency and FWHM, plays the best effect in the structure of bandpass filters.

6 Comparison of the fabricated experimental device and the simulated sample

The transmission spectrum is measured by terahertz time domain spectroscopy (THz TDS) (Fig. 9). The system uses a femtosecond laser with a wavelength of 780 nm, a time width of less than 100 femtoseconds and an output power of 50 mW. The laser is made

**Fig. 8** The frequency bandwidths (FWHM) of a the proposed filter (dotted-line diagram) and b cross-shaped filter (solid-line diagram)

**Fig. 9** Schematic display of a terahertz time domain spectroscopy (THz TDS) system
In this type of spectroscopy system, both antenna generators and detectors are made by Batop Company with the abbreviated code of PCA-90-01-10-800-h.

The built-in filter is shown in Fig. 10. A substrate with a copper layer is used as a cathode in the electroplating process. The SU-8 photoresist is also deposited using a spin coater. Photolithography is the main process practiced with a UV exposure machine to make the graph of the mask projected onto the photoresist (Lu et al. 2018).

Figure 11 shows two spectra of experimental results with THz-TDS system and simulation results with CST STUDIO software that are well matched.

7 Conclusion

A new bandpass filter is designed, simulated and fabricated based on the samples already made for terahertz cross-shaped bandpass filters. The output spectrum of the filter proves to be of a high percentage (approximately 100%) and of an output noise (unwanted frequencies) less than the frequency range of 0.1 to 3 terahertz.

![Image of the THz cross-shaped bandpass filters fabricated based on a photoresist](Yan et al. 2021)

![Comparison of the experimental results (dotted-line graph) with the simulation results (solid-line diagram)](Lu et al. 2018)
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