Tunable narrowband filters with cross-shaped resonators for THz frequency band

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Abstract. This work presents simulation of transmission spectra of tunable narrowband and broadband filters for terahertz frequency range comprised of cross-shaped metallic resonators both free standing and deposited on semiconductor substrate.

1. Introduction
Terahertz radiation is an intensely researched field which strives to find applications in our everyday life: from medicine and security to nondestructive evaluation [1]. Special interest is paid to terahertz spectroscopy and communication at terahertz frequencies. It is also important to develop elementary base for terahertz frequency communication devices. Such elements as low-pass, high-pass, bandstop [2, 3] and bandpass filters are required to control the frequency of generated THz radiation, providing the opportunity to implement frequency modulation in THz frequency range. Another important field is terahertz spectroscopy, which can be used to study and identify organic molecules which have energy transition with energies that of photon of terahertz frequency associated with rotation and vibration degrees of freedom. The goal of this work was to estimate different designs of X-shaped bandpass filters which can be used for THz frequency domain. A lot of papers devoted to the topic have been continuously published since the first papers of Ulrich[4, 5] considering square shaped resonators and complementary slot structures for far infrared frequency domain and the following papers considering arrays with different slot geometries [6]-[11].

2. Simulated structures
Present work shows the results of numerical simulation of transmission spectra of the following structures: the first being arrays of X-shaped slots of different shapes (with straight and mitred edges) cut out in the layer of metal, the second being X-shaped slot placed on tunable substrate (simulated for values of $\varepsilon = 10.24, 10.89, 11.56$), the third being X-shaped slot with varying slope of slot sides and the forth being the X-shaped slot with width varying alongside the length of a bar. Transmittance spectra of all structures were simulated for sets of parameters listed in Tables 1-3. All the slot arrays were simulated using unit cell model with periodic boundary conditions backed by 30 $\mu m$ layers of air followed by PML layers on both sides of the plane. Ports were set at boundaries between a layer of air and PML.

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**Figure 1.** Unit cell of the grid composed of X-shaped slots.

**Figure 2.** Unit cell of the grid composed of X-shaped slots with length varying across the width of the slot.

**Figure 3.** Unit cell of the grid composed of X-shaped slots width varying across the length of the slot.

**Table 1.** Simulation parameters for grid of X-shaped slots with straight edges with respective resonant frequencies

| Resonant frequency, THz | W, um | L, um | P, um |
|-------------------------|-------|-------|-------|
| 0.27                    | 163   | 574   | 901   |
| 0.49                    | 89    | 313   | 492   |
| 0.76                    | 57    | 203   | 318   |

**Table 2.** Simulation parameters for grid of X-shaped slots with edges mitred at 45 deg with respective resonant frequencies

| Resonant frequency, THz | W, um | L min, um | L max, um | P, um |
|-------------------------|-------|-----------|-----------|-------|
| 0.27                    | 163   | 492       | 656       | 901   |
| 0.49                    | 89    | 268       | 358       | 492   |
| 0.76                    | 57    | 174       | 231       | 318   |

**Table 3.** Simulation parameters for grid of X-shaped slots with bar width varying along its length

| Resonant frequency, THz | W min, um | W max, um | L, um | P, um |
|-------------------------|-----------|-----------|-------|-------|
| 0.27                    | 82        | 232       | 574   | 901   |
| 0.49                    | 44        | 127       | 313   | 492   |
| 0.76                    | 29        | 82        | 203   | 318   |
2.1. X-shaped slots with straight and mitred sides

The structure composed of X-shaped slots (Fig.1) exhibits narrow transmission band with central frequency determined by its dimensions. The central wavelength of the transmission peak for X-shaped slot depends on its surface area to bar width relation [6, 7] which gives:

$$\lambda_r = 2L - W,$$

where L is the length of cross bar and W is its width, see Fig.1. As mentioned in [6] this estimation can be made more accurate using results of numerical simulation of several grid structures which gives the following empiric equation:

$$\lambda = 1.8L - 1.35W + 0.2P,$$

where P is the period of the structure, see Fig.1.

It was demonstrated by numerical simulation of transmission spectra that metasurface composed of the X-shaped slots with sides mitred at 45° (length of the slot varies over its width, see Fig.2) and having the same surface area for the each parameter set listed in Fig.1 exhibits transmission peaks with higher quality (Fig.5) (e.g. 126 GHz (straight sides) versus 107 GHz (mitred sides) using FWHM criteria for the 1st set of parameters) which increases with for higher frequencies. The choice of particular combination of L, W and P parameters satisfying this criteria is determined by the desired quality Q of the grid [9].

2.2. X-shaped slots with variable slope of its sides

The central frequencies of the resonant transmission peaks can be varied by altering the width of the cross bar alongside its length or vice versa, assuming that the surface of the slot remains unchanged. Simulated transmission spectra for the case where width of the slot varies along the length are shown in Fig.6, and Fig.7 shows the case where the width of the slot varies across the length of a bar. Transmission spectra of the structure show in Fig.6 was simulated for the same sets of parameters and surface area values as X-shaped slots with straight sides in order to make a meaningful comparison. It is shown that transmission peak can be shifted by varying arm width of a slot alongside the length of the bar of the cross. The spectra of the structure shown in Fig.7 appears to have low frequency transmission peak with high Q-factor and high frequency transmission peak with low Q-factor.

Figure 4. Simulated transmission spectra of arrays of X-shaped slots for parameter sets (peak transmission frequencies equal to 0.27, 0.49, 0.76 THz for blue, green and red curves respectively) listed in Table 1.
Figure 5. Simulated transmission spectra of arrays of X-shaped slots with sides mitred at 45° for the parameter sets listed in Table 2 (peak transmission frequencies equal to 0.27, 0.49, 0.76 THz for blue, green and red curves respectively).

Figure 6. Simulated transmission spectra of arrays of X-shaped slots with sides mitred at 30° (blue), 45° (green), 60° (red) for the 2nd parameter set listed in Table 1.

2.3. Influence of substrate on the transmission properties of the filter
By changing substrate permittivity (e.g. by applying electric field to the silica film) the transmission peak of the structure is shifted alongside the spectrum (increasing the $\epsilon$ redshifts the transmission peaks, see Fig.8). The presence of the substrate also gives a set of resonant peaks in the transmission spectra attributed to Fabri-Perot resonances, which are not desirable for passband filters.

3. Conclusion
In the present work the transmission spectra of X-shaped slots with straight bars, with bar width varying over length, with bar length varying over width and with substrate of variable were numerically simulated. It is shown that X-shaped slots with mitred sides have narrower passbands than straight ones but significantly less transmission. Variation of slope angle of
Figure 7. Simulated transmission spectra of the grid composed of X-shaped slots with width varying alongside the bar length of the cross. Blue, green and red curves correspond to the same parameter sets listed in Table 3 (peak transmission frequencies of 0.27, 0.49, 0.76 THz respectively).

Figure 8. Simulated transmission spectra of the grid composed of X-shaped slots placed on 500µm thick Si substrate which permittivity $\epsilon$ takes the values of 10.24, 10.89, 11.56. The parameters of the slot are that for resonant frequency 0.49 THz listed in Table1

the sides of the cross while preserving its surface area redshifts the resonant transmission peak. Spectra of the X-shaped slots with width varying along the length of a bar show two passbands in their spectra: one low frequency transmission peak of high quality and wide, low quality, transmission peak at higher frequencies. Finally the position of the transmission peak of the slot grid can be altered by varying the substrate permittivity: increasing its value redshifts the center frequency of the passband. These features can be used to develop narrowband filters with high Q-factor.

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