Band-gap structure of photonic crystal with metasurface-teflon layers

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Abstract: In present work the band-gap spectrum structure of photonic crystal made of metasurface/sitall/teflon layers is discussed.

Introduction

Recently a lot of attention has been dedicated towards metamaterials, especially photonic crystals [1,2,3]. Photonic crystals are composites made of alternating unit cells composed of multiple layers with various (usually dielectric) materials and can be of different configurations: 1D, 2D, 3D. Photonic crystals are useful instrument to implement such devices as frequency selective mirrors and filters. Today these devices are of high value for terahertz applications, as terahertz frequency range became extensively researched not long ago - terahertz technologies are at their infancy and effective components are to be developed. A lot of effort has recently been made towards designing filters, which can be extensively used in THz spectroscopy and tomography.

Considered structure

Present work investigates the band gap structure of photonic crystal made of alternating layers of metasurface (SRRs + sitall CT-50-1 (a counterpart of Schott Zerodur glass-ceramic) substrate) and teflon (Fig. 1). The photonic crystal consists of 10 bilayers: one having permittivity ($\varepsilon_{\text{teflon}}=2.25$) and thickness ($h_{\text{teflon}}=300$ um) of teflon and another – that of metasurface/sitall layer (experimentally obtained $\varepsilon_{\text{sitall}}(\omega)$ and $h_{\text{sitall}}=550$ um). SRR geometric parameters can be found in [4].

Figure 1: Considered photonic crystal structure composed of metasurface/sitall/teflon layers.
Metasurface dispersion characteristics extraction from experimental data.

Prior to numerical simulation of above mentioned photonic crystal, metasurface/sitall layer (Fig. 2) dispersion characteristics were obtained.

![Figure 2: Metasurface unit cell dimensions (a) and photos of fabricated metasurfaces with various resonator side and relative period (b).](image)

Time-domain spectroscopy setup (Fig. 3) was used to record transmission and reflection spectra of metasurface/sitall layers with different lengths and relative periods (different p/l ratios). This setup utilizes generation of THz radiation in semiconductor InAs crystal placed into strong magnetic field under femtosecond pulse excitation. Pump laser radiation is absorbed by the filter F, so only THz radiation reaches the sample, passes through it and then alters the orientation of CdTe crystal polarization plane depending on the amount of THz radiation transmitted. Thus CdTe crystal changes the state of polarization of probe pulse from linear to elliptical polarization. Quarter-wave plate is used to set the phase shift between its components. Wollaston prism is used to spatially separate orthogonal components of the probe pulse. The difference of the amplitudes of those components is registered by balanced detector. To increase signal-to-noise ratio lock-in detection (lock-in amplifier and modulator) is utilized. Delay line allows to perform time-base sweep by varying the phase lag between pump and probe pulses.

Fourier transform and Happ-Genzel apodization function were applied to those spectra. Resulting amplitude and phase spectra were normalized on the spectrum of free space. Real and imaginary parts
of refractive index $n(\omega)$ and $k(\omega)$ are obtained from amplitude and phase spectra by using the following relations:

$$n_{\text{smpl}}(\nu) = 1 + \frac{c}{2 \pi \nu d} (\Phi_{\text{smpl}}(\nu) - \Phi_{\text{air}}(\nu))$$

$$k_{\text{smpl}}(\nu) = 1 + \frac{c}{2 \pi \nu d} \frac{E_{\text{smpl}}(\nu)}{E_{\text{air}(\nu)}}$$

(1)

It can be seen that metasurface/sitall $n$ and $k$ indeces spectra feature several regions where they change abruptly. This regions correspond to the eigenfrequencies of SRRs for lower frequencies and to plasmonic resonance for higher frequencies. Those can be most clearly seen on Fig. 4 for metasurface with $l=150$ um and $p=188$ um.

Figure 4: Refraction $n$ and absorption $k$ indeces of the metasurfaces.

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Simulation and results

MATLAB program implementing transmission matrix method [5] for photonic crystal spectra acquisition was used to obtain transmission spectra (Fig. 5) of the proposed structure.

Figure 5: Transmission spectra of metasurface/sitall/teflon photonic crystals with various length and period of metasurface SRRs.
It can be seen that resonant peaks corresponding to plasmon resonances (higher frequencies) occur near frequencies where $k_{SRR} > n_{SRR}$. Peaks corresponding to LC-resonance (lower frequencies) occur near SRR eigenfrequency. The shift of transmission peaks as compared to resonance frequencies of the metasurface is probably due to the presence of sitall and teflon layers. Compared to the transmission spectra of the photonic crystal band-gap structure of the PC with metasurfaces becomes negligible. It is also notable that such structures have Q-factor $Q = \frac{\Delta f}{f} = 60$ (for metasurfaces with l=150 um) that is about 12 times greater (for both LC and plasmon resonance peaks) as that of the metasurfaces studied in [4] (see [6] for comparison).

**Conclusion**

Primary result of this work are numerically simulated spectra of photonic crystals with different metasurface lattice constant. This work will be used as a groundwork for development of tunable THz narrowband filters. Tunability can be realized in the variety of ways: the most trivial way is to create photonic crystal composed of areas with different relative period: photonic crystal made of such metasurfaces and layers of dielectric material can be mechanically tuned by shifting the structure along layer surface. Yet a more practical and flexible approach to realize tunable metamaterials is to use semiconductors [7] as a substrate for SRRs. It can be used to generate free carriers by the means of optical pumping or applied voltage in order to vary substrate permittivity. Tunable filters can find extensive use in THz biomedical applications – for example such filters can be use to cut THz frequencies that give negative impact on biological cells under study.

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References

[1] M. Alessandro “Photonic Crystals - Introduction, Applications and Theory” – 2012 - p 344
[2] Tarapov S.I., Khodzitsky M., Chernovtsev S.V " Frequency control of the microwave Tamm state " - 2010 - Physics of the Solid State - 52 (7) - pp. 1427-1431.
[3] Girich A., Khodzitsky M., Nedukh S. " Experimental analysis of metamaterials' spectra to design tunable THz-GHz passive devices " - 2011 - NATO Science for Peace and Security Series B: Physics and Biophysics - pp. 159-164
[4] Y.Terekhov, M. Khodzitsky, Y. Grachev, E.Sedykh “The influence of period between U-shaped resonators on metasurface response at terahertz frequency range” – Proc. of SPIE – 2013 – Vol. 8806 – 88062Q
[5] A. Denisultanov, M. Khodzitsky “Band-gap structure for N-fold layers inside bilayer cell of photonic crystal for THz frequencies” – Proc. of SPIE – 2013 – Vol. 8806 – 88062I
[6] “Metafilms characteristics for the terahertz frequency range at the geometric parameters scaling” - Scientific and technical journal of information technologies, mechanics and optics - 2013 - issue 1 (83)
[7] R. D. Averitt, W. J. Padilla “Terahertz Metamaterial Devices” – Proc. of SPIE – 2007 – Vol. 6772 – 677209