Photonic crystal waveguide for difference frequency generation in terahertz range

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Abstract. We consider a waveguided semiconductor structure with photonic crystal core for efficient difference frequency generation. The calculation of the dispersion of the eigenmodes shows that this structure pumped by radiation with wavelengths of 1000 and 1003 nm, allows the difference frequency generation at 1 THz with a coherence length of 1 cm.

1. Introduction
Terahertz frequency range of electromagnetic radiation (0.1-10 THz) is one of the ranges that are the most desired but least utilized by the modern industry. This is caused by technological difficulties of creating the compact sources of terahertz radiation. The prospects of the utilization the radiation of this range, both in respect to the applied and fundamental science, look very promising. In particular, THz radiation having longer wavelength (as compared to visible light), e.g. of the order of tenths of millimeters, has higher penetration properties. This allows it to be used in security, biomedicine and telecommunications. In addition, the terahertz sources are much-needed in experimental science, first of all, in spectroscopy of solids.

One of the promising approaches for realization of compact sources of THz radiation is nonlinear optics. Radiation with frequency of few terahertz can be obtained by the difference frequency generation. This effect is used, for example, for dual-frequency VECSEL lasers with a nonlinear crystal inside the resonator [1]. However, the instabilities of such emitters make this approach difficult for realization. Another possible approach is to use semiconductor optical metamaterials [2-4] for efficient difference frequency generation. The theoretical possibility of generating radiation of frequency of 1 THz in semiconductor metamaterial has been shown in [5], where the approach to its description in one-dimensional semiconductor photonic crystal has been considered. This paper describes a photonic crystal designed for the difference frequency generation in a terahertz range and having waveguiding properties at the same time.

The most important conditions for efficient nonlinear conversion of light are, firstly, the presence of a medium with high non-linear susceptibility value and, secondly, the phase matching of waves interacting within the crystal. The fact is that, because of the material dispersion of the refractive index, i.e., its dependence on the frequency, the waves propagating in the medium at different frequencies are not fully coherent and, as a result of their interference, the conversion efficiency is limited. The degree of phase matching is commonly characterized by coherence length $L$ representing the distance at which propagating waves accumulate the phase difference of $\pi$:

$$L = \pi \left| k_2 + k_3 - k_1 \right|^{-1}$$
where \( k_i = \frac{2\pi n(\lambda_i)}{\lambda_i} \) and \( n(\lambda) \) is the refractive index for the wavelength \( \lambda \). Hereafter we will use the following criterion for phase matching: the coherence length should be longer than 1 cm.

In this paper we investigate the waveguide comprising a one-dimensional photonic crystal core with homogeneous semiconductor claddings. The claddings are formed with \( \text{Al}_{0.45}\text{Ga}_{0.55}\text{As} \) solid solution, while the photonic crystal is formed by the alternating layers of GaAs with varying doping levels. The selection of gallium arsenide as the main material for the photonic crystal is dictated by its high value of the second order nonlinear susceptibility, which is very important for the difference frequency generation.

### 2. Schemes of difference frequency generation

We consider two possible schemes for implementing the difference frequency generation in the waveguiding structure. In the first scheme (Figure 1) the pump waves with wavelengths of \( \lambda_1 \) and \( \lambda_2 \), as well as the wave of difference frequency \( \lambda_3 \) propagate along the waveguide in one direction. In this case the phase matching of all three waves must be ensured.

![Figure 1. Collinear radiation propagation scheme of difference frequency generation](image)

In another design (Figure 2) the pump waves propagate almost along the waveguide, while the difference frequency is perpendicular to the growth plane (and propagates along Z axis). In this case the difference frequency wave experiences no modification of the dispersion associated with a waveguide effect and the presence of photonic crystal, while the pumping waves must be coherent. This substantially simplifies the mathematical description of the structure, and therefore this scheme was chosen for our theoretical analysis.

![Figure 2. Propagation of radiation in structure with difference frequency generation through the surface.](image)
3. Calculation of eigenmodes dispersion

To calculate the dispersion of eigenmodes in the described structure, it is necessary to solve jointly the system of equations describing waves in the photonic crystal and the waves in a waveguide. It is convenient to change over from the wave vectors to the effective refractive indexes.

The dispersion equations for waves in metamaterial can be obtained from the Helmholtz equation:

$$\frac{\partial^2 E(z)}{\partial z^2} + \left( \frac{\omega^2}{c^2} \varepsilon(z) - q^2 \right) E(z) = 0$$

with standard boundary conditions. The dispersion equations for a photonic crystal are given in [5].

The equations for waveguide read as follows:

$$\frac{1}{n_z} \left( m\pi + \arctan \left( \frac{n_{z1}^2 - n_{z2}^2}{n_{z1}^2} \right) + \arctan \left( \frac{n_{z2}^2 - n_{z2}^2}{n_{z2}^2} \right) \right) = \frac{\omega}{c} h$$

where $h$ is thickness of the waveguide core, $n_{\text{eff}}$ is the effective refractive index of the waveguide, whereas refractive indices of the claddings $n_{z1}$ and $n_{z2}$ are considered independent of frequency while the refractive index $n_z$ of the waveguide layer has a complicated dependence on frequency, which is caused by the photonic crystal structure.

4. Discussion of results

The calculated results show that, when using a photonic crystal having a thickness of 6 nm with GaAs layers doped to concentration of $10^{18}$ cm$^{-3}$, and when the layers of GaAs itself have thickness of 925 nm, it is possible to achieve an efficient difference frequency generation at 1 THz with pumping wavelengths of 1000 and 1003 nm.

![Figure 3. The dependence of the coherence length L on the thickness a of layers of intrinsic conductivity in a photonic crystal](image-url)
**Figure 4.** The dependence of the coherence length \( L \) on the pump wavelength \( \lambda_1 \).

Figure 3 shows the dependence of coherence length on the thickness \( a \) of a layer of intrinsic conductivity, and Figure 4 shows the dependence of coherence length on the pump wavelength \( \lambda_1 \). The semiconductor technologies allow to grow epitaxial layers with an accuracy much higher than few nanometers. Therefore, the drop of the coherence length observed in Figure 3 for deviation \( a \) of few nanometers from the central value 925 nm may be considered as manifestation of low sensitivity of the structure to technological imperfections. The same can be concluded about the function of the pump wavelength (see Figure 4): modern laser sources in infrared wavelength range easily allow the accuracy of the wavelength better than 1 nm.

5. **Conclusions**

We demonstrate that the use of the photonic crystal as the core of of one-dimensional planar waveguide allows for compensation of the waveguide and material dispersion of the refractive index, thus ensuring a high efficiency of difference frequency generation in terahertz range. Calculation of eigenmode dispersion shows that the coherence length for pumping wavelengths of 1000 and 1003 nm and difference frequency of 1 THz can exceed 1 cm. The proposed structure demonstrates high tolerance to the technological imperfections.

**Acknowledgments**

The research by GMS is supported by the Council for grants of President of Russian Federation (grant No. MK-3671.2019.21). GSS acknowledges support from the Presidium RAS Program No. 5: “Photonic technologies in probing inhomogeneous media and biological objects”.

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