Two-dimensional waveguide for efficient second-harmonic generation in visible range

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Abstract. A semiconductor structure is proposed that generates the second harmonic with an output wavelength of 550 nm. The structure consists of a two-dimensional waveguide with a semiconductor photonic crystal located in its core. Calculation of dispersion of eigenmodes in this structure shows that the coherence length of nonlinear conversion can exceed 1 cm.

1. Introduction

At present, the technology of semiconductor lasers operating in the near infrared range is very well developed. However it is still not possible to cover the entire visible range by fully semiconductor devices. For this purpose, nonlinear optical effects such as generation of second and third harmonic are used. The devices that convert infrared into visible light can solve the problem of creating inexpensive and compact semiconductor laser sources with a tunable operating wavelength [1-2]. However, the efficiency of these devices is not high enough [3]. The low efficiency of modern nonlinear converters is first of all due to the problem of phase matching of the fundamental and converted waves. The methods developed to date for increasing the conversion efficiency significantly complicate the technology of fabrication of such devices, make them expensive, and thus complicate their production.

We propose a semiconductor structure that converts near-infrared electromagnetic radiation (wavelength 1100 nm) into visible radiation with a wavelength of 550 nm. The conversion is carried out through the use of semiconductor optical metamaterials that consist of alternating semiconductor layers with different doping. Similar waveguide structures were studied in [4-5], however, in these publications a one-dimensional waveguide was considered. In this paper, we study a two-dimensional waveguide with both transverse and lateral confinement.

2. Coherence length as a limiting factor for efficiency of nonlinear light conversion

The efficiency of nonlinear light conversion is mainly affected by two factors. First, there are the nonlinear properties of the medium itself, characterized by the quadratic nonlinear susceptibility. Second, it is the phase matching between the fundamental and the second harmonic waves. The phase mismatch occurs due to the material dispersion of the refractive index of all known natural materials. A measure of phase mismatch is the coherence length, which is the distance at which the phase difference between the generated waves does not exceed 180 degrees. When light fluxes propagate at a distance exceeding the coherence length, their destructive interference occurs, as a result of which they may “extinguish” themselves. Thus, the domain of efficient conversion is limited by the coherence length. Therefore, no matter how high the nonlinear susceptibility of the medium is, only the region the dimension of which is smaller than the coherence length participate in real conversion. Hence, there are
two ways to increase the efficiency of nonlinear light conversion: to select the materials having the highest possible quadratic nonlinear susceptibility or to increase the effective conversion region, i.e., the coherence length. In this study, we consider the increase in the coherence length as the simplest way to increase the efficiency of nonlinear light conversion. Here, we study the structures that provide a coherence length of 1 cm.

3. Structure description

The structures under study are planar waveguides. The cores of them consist of an optical metamaterial comprising a set of alternating layers of intrinsic and heavily doped semiconductor. The thicknesses of the layers are determined by theoretical calculations of the structure in which the dispersion of the refractive index and the waveguide dispersion of light at given frequencies are compensated. This allows the in-phase propagation of waves along such waveguides. The general view of the structure is shown in Figure 1.

![Figure 1. General view of waveguide structure.](image)

The alternation of layers in the metamaterial occurs along the Z axis. The waveguide layer of AlN is surrounded by the layer of Si$_3$N$_4$. Figure 2 shows the structure in the YZ plane, where 1 is the intrinsic conductivity AlN layers, and 2 is doped AlN layers.

The coherence length in the waveguide structure is determined by the effective refractive indices characterizing the wave propagation along the waveguide (along the Y axis):

$$L = \frac{\pi c}{\omega_1 \left| n_y (\omega_2) - n_y (\omega_1) \right|},$$

where $\omega = 2\pi c \lambda^{-1}$, and $\omega_1$ corresponds to a wavelength of 1100 nm, $\omega_2 = 2\omega_1$ corresponds to a wavelength of 550 nm, $n_y$ is the refractive index for waves propagating in y direction.

The dispersion equations for such structures are

$$\frac{\varepsilon_1 (\omega) + \varepsilon_2 (\omega) + 2n_y (\omega)}{2\sqrt{n_y^2 (\omega) - \varepsilon_1 (\omega) \sqrt{n_y^2 (\omega) - \varepsilon_2 (\omega)}}} (S (\omega) + C (\omega)) = \cos \left( \frac{\omega}{c} \sqrt{n_x^2 + n_z^2} (a + b) \right),$$

where $S (\omega)$ and $C (\omega)$ are the refractive indices and $n_x, n_z$ are the refractive indices for waves propagating in the horizontal plane.
The constraints along the X and Z axes lead to simple dispersion relations for the waves propagating in plane waveguides:

\[
\frac{1}{n_j} \left( m \pi + \arctan \left( \frac{n_{j1}^2 - n_{j2}^2}{n_{j1}^2} \right) + \arctan \left( \frac{n_{j1}^2 - n_{j2}^2}{n_{j2}^2} \right) \right) = \frac{\omega}{c} h_j. \tag{3}
\]

Here \( m \) is an integer characterizing the mode number, \( j = x, z \), \( n_{j1} \) and \( n_{j2} \) are the refractive indices of the plates, and \( h_j \) are the thicknesses of the active region in the direction \( j \).

Thus, we have four equations for the frequencies \( \omega_1 \) and \( \omega_2 \) along the z and x directions.

4. Results and discussion
The solution of the system of equations (2-3) shows that when AlN layers with a thickness of \( a = 1.399 \, \mu m \) and layers doped to a level of \( 10^{18} \, cm^{-3} \) AlN with a thickness of \( b = 10 \, nm \) are used, a waveguide with dimensions \( h_z = 5.6 \, \mu m \) (4 periods of the photonic crystal), \( h_x = 4 \) microns provides effective suppression of the refractive index dispersion. Figure 3 shows the result of calculation of the coherence length (1) that depends on the thickness \( a \) of the undoped layers. The maximum occurs at 1.399 \( \mu m \), while a noticeable decrease in the coherence length occurs when \( a \) deviates by a few nanometers from this value. This agrees with the technological limitations on the thicknesses of epitaxial layers. Thus, the proposed waveguide structure can be used to efficiently generate the second harmonic in the visible wavelength range.
5. Conclusions

Two-dimensional semiconductor waveguide with spatial confinement in X and Z directions is described. Self-consisted solution of a system of equations describing light propagation through the waveguide is found. The calculation shows that utilization of metamaterial based on alternating layers of intrinsic and heavily doped AlN as the waveguide core provides the effective suppression of the refractive index dispersion and allows to enhance the efficiency of the second harmonic generation. The coherence length is shown to be more than 1 cm for nonlinear light onversion from wavelength of 1100 nm to 550 nm.

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