

Stimulated emission at the second order stop-zone edge of the two-dimensional opal–zinc oxide photonic crystal

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Abstract

The fabrication of the 2D periodic structures in ZnO thin films by magnetron sputtering on the opal matrices was developed. The microstructures were characterized by AFM and SEM. The spontaneous and stimulated emissions of the ZnO layers on opal were studied at N₂ laser excitation ($\lambda = 337$ nm). The stimulated emission near 397 nm was observed at room temperature from ZnO–opal structure. The threshold of the electron–hole plasma recombination laser process was $\cong 300$ kW/cm² for this structure. This threshold is two orders of magnitude smaller of that one for the flat ZnO–SiO₂ films owing to DFB resonator effect in 2D structure.
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1. Introduction

Creation of the effective emitters based on photonic crystals (PhC) is based on the PhC ability to extract necessary optical modes and determine their propagation directions. These advantages are important for the design of laser light sources. In works [1–4] the low-threshold PhC lasers, fabricated from the A₃B₅ semiconductors, have been realized in the near infrared spectral range. Recently, two-dimensional (2D) PhC structures with ultra violet (UV) emission based on the wide band gap semiconductors GaN [5,6] and ZnO [7] have been displayed. But their fabrication presents a considerable challenge due to the required small-scale periodicity. Authors [8] have observed UV lasing in three-dimensional PhC:ZnO inverted opal. Amplification of light in a

PhC can be enhanced by localized defect states inside the photonic band gap (PBG) [9] or via modes with reduced group velocity at a photonic band edge [10–13]. Analysis of the feedback mechanisms in 2D PhC laser for in-plane propagation of light had shown [14] that photonic crystal laser can operate with various feedbacks essentially different of those ones well known for conventional 1D distributed feedback (DFB) lasers.

In this paper, two-dimensional UV DFB-lasing of zinc oxide active layer on the surface of opal matrix was realized. In this case the relief of ZnO layer determined by opal structure was working as a distributed Bragg grating. The conditions for basic waveguide mode propagation in ZnO–SiO₂–opal structure allowing Bragg regime were evaluated.

2. Experimental

High purity ZnO films were grown on the opal matrices at a temperature of 350 °C by RF magnetron

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sputtering of the ZnO powder target in a Z-400 Leybold Haereus equipment. The DC potential was 1 kV and the discharge current 0.15 A. The sputtering was performed in Ar plasma at 10^{-2} torr Ar-pressure. The growth rate was about 0.15–0.2 nm/s. The thickness of the ZnO layer was determined by ellipsometry. To remove structural defects induces by sputtering thermal annealing was used. Lasing was achieved in the strongly localized light modes near the edges of the photonic band gap by optical pumping. The position of photonic band gap is determined by the ZnO film thickness and by the opal sphere radius. To overlap the ZnO gain spectrum with the photonic band gap, the thicknesses of films was varied from 120 to 200 nm. The opal structures with diameters of the SiO_2 -spheres $D_{\text{SiO}_2} = 238$ nm and $D_{\text{SiO}_2} = 154$ nm were used. Opal samples with $D_{\text{SiO}_2} = 238$ nm of dimensions $5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$ were cut from bulk piece fabricated by sedimentation of the silica particles suspension [15]. The surface had orientation (1 1 1) of the face-centered cubic lattice of opal. Opal samples with $D_{\text{SiO}_2} = 154$ nm were prepared by deep-coating method [16] in the form of thin films of $0.9 \mu\text{m}$ thickness (seven layers of SiO_2 -spheres) on the silicon substrates. The microstructure of the synthesized films was examined by scanning electron microscopy (SEM) and atomic-force microscopy (AFM).

The optical pumping experiments were performed using a N_2 laser with the 337.1 nm wavelength emission, 9 ns pulse duration and $I = 1.5 \times 10^3 \text{ W}$ output power. The photoluminescence spectra were measured at room temperature at different excitation intensities. The emission signals were collected by a lens (aperture 0.2 radians) at angle $\theta = 45^\circ$ to the sample surface. Photoluminescence was dispersed by a MDR-6 monochromator and detected by a photomultiplier with a spectral resolution better than 0.1 meV.

3. Planar waveguide on a distributed Bragg grating

As an approximation to goffered interface of ZnO–opal structure let us consider planar ZnO– SiO_2 structure where silicon dioxide is a substrate with refractive index $n_s = 1.45$, zinc oxide layer is an active waveguide with refractive index $n_f = 2.35$ for UV spectral range. Air is a cover layer with $n_c = 1$. Total number of the localized modes allowed to propagate in waveguide depends on its thickness and refractive indexes of substrate, waveguide and cover layer for fixed light wavelength [17,18]. Calculations of the zinc oxide layers thickness in planar ZnO– SiO_2 structures performed in [19] showed that the one mode of each polarization (TE_0

and TM_0) only can propagate within waveguiding layers of 120–185 nm thicknesses. Lower we will consider the propagation conditions for the basic (zero) mode of TE_0 -polarization. At zigzag light propagation the total phase shifts occurring at passing and total internal reflection from the waveguide boundaries should be multiple 2π [17]. The self-consistent condition for basic mode is expressed by formular [17]:

$$2kn_f h \cos \theta = 2\phi_s + 2\phi_c \quad (1)$$

where k is the wavevector value, h the thickness of the waveguide layer, n_f the refractive index of active layer, θ the incident angle of wave, and ϕ_s , ϕ_c are the phase shifts caused by total internal reflections at the film–substrate and film–cover layer interfaces, accordingly. The expressions for the phase shifts at the total internal reflections from the waveguide boundaries are in the form of (for the TE_0 -polarization) [17]:

$$\text{tg} \phi_s = \frac{(n_f^2 \sin^2 \theta - n_s^2)^{1/2}}{n_f \cos \theta} \quad (2)$$

$$\text{tg} \phi_c = \frac{(n_f^2 \sin^2 \theta - n_c^2)^{1/2}}{n_f \cos \theta} \quad (3)$$

As it could be seen from the expressions (2) and (3) the phase shifts ϕ_s , ϕ_c are functions of the θ -angle. Eq. (1) is a dispersion of a waveguide, in essence. Fig. 1 displays the graphical solution of the Eq. (1) for basic mode in the ZnO– SiO_2 structure. Under calculation the following parameter values were used: $n_s = 1.45$; $n_f = 2.35$; $n_c = 1$; $\lambda = 397 \text{ nm}$; $h = 40, 70, 100, 120, 140, 170$ and 200 nm .

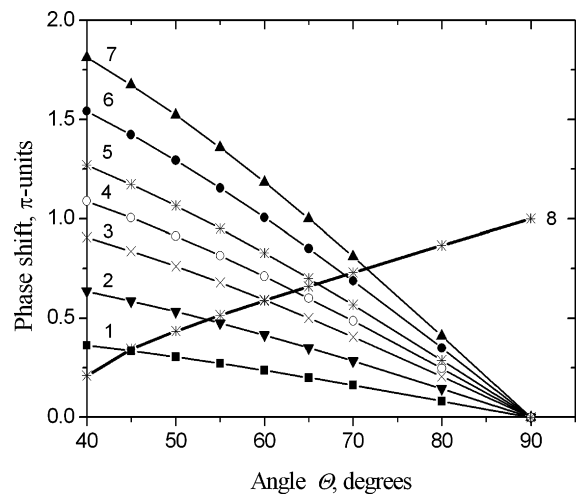


Fig. 1. The graphical solution of the disperse equation for the basic mode TE_0 -polarization of the ZnO– SiO_2 planar waveguide of different thicknesses h : 1, 40 nm; 2, 70 nm; 3, 100 nm; 4, 120 nm; 5, 140 nm; 6, 170 nm; 7, 200 nm; 8, the phase shift sum $\phi_s + \phi_c$.

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