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SINGLE CRYSTAL SBN:Yb/OPAL MATRIX (SiO_2):Er COMPOSITE AS A NANOPHOTONIC STRUCTURE

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Abstract. Thin layer of opal matrix on SBN:Yb crystal substrate of <001> orientation was prepared via sedimentation method and post-growth annealing treatment. The film thickness was 25 cubic package monolayers of SiO_2 nanospheres (240 nm in diameter). Erbium oxide (Er_2O_3) was introduced into the interspherical space of opal matrix (about 35–40% relative to the pore volume), using the sol-gel method. The specific features of photoluminescence in the nanocomposites are discussed.

1. INTRODUCTION

Erbium lasers and amplifiers attract the essential interest due to the radiation is in the range of 1.55 mm wavelength (third communications window) [1]. At the same time, erbium has small absorption cross-section and, as a result, considerable part of pump energy remains not absorbed in the case of realization of compact systems. Laser transitions Er^{3+} form 3-level system and, hence, it is necessary to realize at least 50% population inversion to receive the amplification. Carefully selection of pumping laser is required to match it with narrow pump band at 800 nm, 980 nm or 1480 nm bands in the Er^{3+} media. Reabsorption from $^4I_{13/2}$ level can lead to upconversion (especially for high dopant concentrations) and worsen the device quality.

Laser crystals doped with Yb^{3+} ions have some advantages in comparison with other widespread laser media [2]. In particular, for Yb^{3+} (electronic configuration $4f^{13}$) only two electronic states are possible – ground $^2F_{7/2}$ and excited $^2F_{5/2}$. Hence, there is no parasitic absorption from the ground or excited levels in IR or visible spectral regions, that considerably reduces the crystal heating during the generation process. It prevents the thermal instability of the output radiation. The quantum efficiency is practically close to unity.

The fluorescence lifetime is 0.2-0.4 ms, that provides an effective accumulation of laser energy. Besides, small ionic radius of Yb^{3+} (in comparison with other rare-earth ions) gives essential advantages being introduced into the crystal matrix, that allows to get highly concentrated active media. Note, that Yb^{3+} ions have broad absorption band, that provides the possibility of tuning in IR spectral region (and also ultrafast pulses generation). As a drawback: 3-level generation scheme leads to losses due to reabsorption and the temperature-dependent parasitic effects.

The energy of $^2F_{5/2}$ level of Yb^{3+}, is almost coincides with energy of $^4I_{11/2}$ level of Er^{3+} in Er-Yb system. The energy exchange between closely spaced ions of Er and Yb is possible in cooperative cross-

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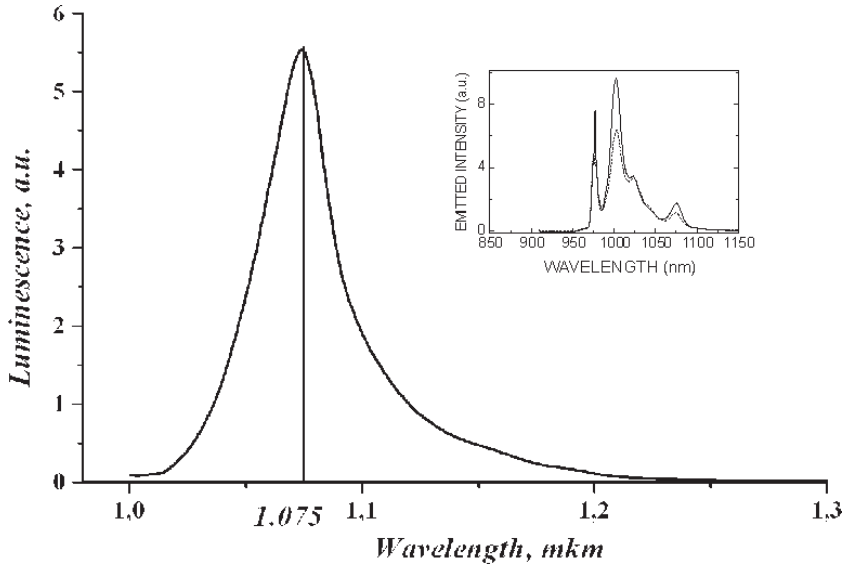

Fig. 1. The luminescence spectrum of SBN:Yb^{3+} crystal in the wavelengths of 1-1.3 mm. In the inset: the spectra of low-temperature luminescence for different polarizations in the same area [2].

relaxation process [3]. In particular, electrons from excited $^2F_{5/2}$ state of Yb^{3+} can pass to the ground state, providing the Er ions transition from the ground state to the $^4I_{11/2}$ excited state. In the case of effective cross-relaxation process, considerable part of adsorbed pump energy is transferred to the erbium system. Thus, Er-Yb co-doping can considerably increase the absorption of pump energy at 980 nm and provide the effective laser generation at wavelength of 1.55 μm (even in devices of centimeter length).

2. NANOCOMPOSITE PREPARATION

The development of optical systems for communication and information processing to some extent repeats a way of radiofrequency electronics from discrete elements and devices to integral optoelectronics. Last assumes that the similar systems should work with optical signals in tiny devices located on a uniform substrate. There can be sources of optical energy, optical waveguides, connectors, detectors of optical signals and devices for the appropriate transformations of optical signals. The present paper is concerned to research the opportunities of 'hybridization' of optical crystals (with piezoelectric, electrooptical and acoustooptical properties) and photonic crystals (materials with photonic bandgap). Ferroelectric crystal of strontium barium niobate $Sr_{0.61}Ba_{0.39}Nb_2O_6$ (SBN:61) was used as optical medium [2]; opal matrix (cubic package of SiO_2 nanospheres) was chosen as photonic crystal [4]. The nanophotonic structure was created based on single crystal plate of SBN:61 doped with Yb, covered by thin layer of opal matrix. Erbium oxide was introduced (Er_2O_3) into interspherical space of opal matrix.

Single crystal SBN:Yb^{3+} was grown from the melt by Czochralski method [2]. Yb_2O_3 dopant was introduced into the melt in concentration of 2.6 wt.%. The growth parameters were as following: pulling rate-4 mm/h, rotation rate-15 rpm, the vertical thermal gradient at the crystallization front-85 degree/cm. According to x-ray luminescence data, the Yb^{3+} concentration in a crystal was $1.1 \cdot 10^{20}$ ions/cm^3. In our experiments the crystal plates of sizes 5x3x1 μm^3 and thin plates by thickness less than 500 mm were used. The plane of a plate was perpendicular to the crystal optical axis. Similar samples were also prepared from nominally pure SBN:61. The preparation of SBN plates included short-time etching in HF acid, washing in flowing water, processing by spirit and drying in thermostat at 100 °C during 30-40 minutes.

Self-ordering packing of spherical colloidal particles (SiO_2 nanospheres) is one of attractive technologies for manufacturing 3D- and 2D-photonic crystals with photonic bandgap (PBG) in an optical wavelengths, which can be used for development of optoelectronic devices. Colloidal crystals available now have not complete PBG because small differences in refractive indices of periodic structure. Neverthe-

Table 1. Laser transitions in ionic system Er^{3+} - Yb^{3+}.

Yb		Er	
Transition	*Wavelength*	*Transition*	*Wavelength*
Absorption			
		$^4I_{15/2}$ - $^4I_{9/2}$	800 nm
$^2F_{7/2}$ - $^2F_{5/2}$	980 nm	$^4I_{15/2}$ - $^4I_{11/2}$	980 nm
Radiation			
$^2F_{5/2}$ - $^2F_{7/2}$	1075 nm	$^4I_{13/2}$ - $^4I_{15/2}$	1530 nm
Cross-relaxation			
$^2F_{5/2}$ (Yb) - $^4I_{11/2}$ (Er)			

less, such materials provide an ideal basis for creation of structures with complete PBG by introduction substances with high refractive indices into the opal matrix and subsequent removal of initial SiO_2 nanospheres. There are various methods to obtain the colloidal crystals [5]. The gravitational sedimentation of SiO_2 colloids from various suspensions is the most frequently used method for creation of colloidal crystals.

The realization of perfect photonic crystals remains a significant technological problem [5]. The large concentration of various internal defects, such as dislocations, vacancies, packing defects, etc, is one of the fundamental limiting factors of a self-ordering method. Thermodynamically stable phases are characteristic for face centered cubic packing, but free Gibbs energies for phases with hexagonal dense packing and face centered cubic packing differ not so great, that leads, as a rule, in generation of a plenty of packing defects. As a result, the colloidal crystal is a polycrystalline mixture of misoriented domains. In a case of slowly growing samples the face centered phase prevails above a hexagonal phase. There are some technological factors improving quality of self-ordering colloidal crystals. We modified the methods of sedimentation from tetraethoxysilane (TEOS) suspensions and obtained the planar structures of homogeneous multilayers. The high quality of planar structures was provided by using suspensions with high monodispersity (deviation in diameters of nanospheres did not exceed 5%) and special regimes of evaporation, drying and annealing. The special temperatures of evaporation provided small speeds of the growth of colloidal films. The obtained samples had small concentration of dislocations and vacancies, that was controlled by optical and electron microscopy methods. The SBN-opal matrix and SBN:Yb^{3+}-opal matrix nanocomposites were obtained. The Er^{3+} ions (erbium nitrate) were introduced into interspherical voids using standard sol-gel technique. Series of samples of various film thickness and Er^{3+} concentration were fabricated. So we used the films to 20-80 layers with polycrystalline domains to 0.01 mm^3. Increase in Er^{3+} ions concentration leads to the shift of PBG to red wavelengths, it was controlled visually on the reflection.

3. EXPERIMENT.

The features of behavior of Er^{3+} and Yb^{3+} ions in different matrices were investigated earlier, for example in glasses [3,6], where cross-relaxation effects were observed (see Table 1).

In this work the photoluminescence spectra were investigated at room temperature. The semiconductor lasers (with emission wavelengths of 800 nm and 980 nm) were used for luminescence excitation under identical irradiation geometry [7]. The laser beam was focused to the sample at the angle of 60 degree. The luminescence radiation passed through the monochromator MDR-23 and the spectra were registered by non-cooled germanium detector DPD 2000 (DILAS Co.). The silicon filter cut off the pump radiation. The measurements were carried out in a lock-in technique with modulation frequency 30 Hz. The experimental data were registered and processing by personal computer.

The luminescence spectrum of the SBN:Yb^{3+} crystal obtained with excitation radiation at wavelength 980 nm is presented in Fig. 1. The superluminescence is observed in the material at wave-

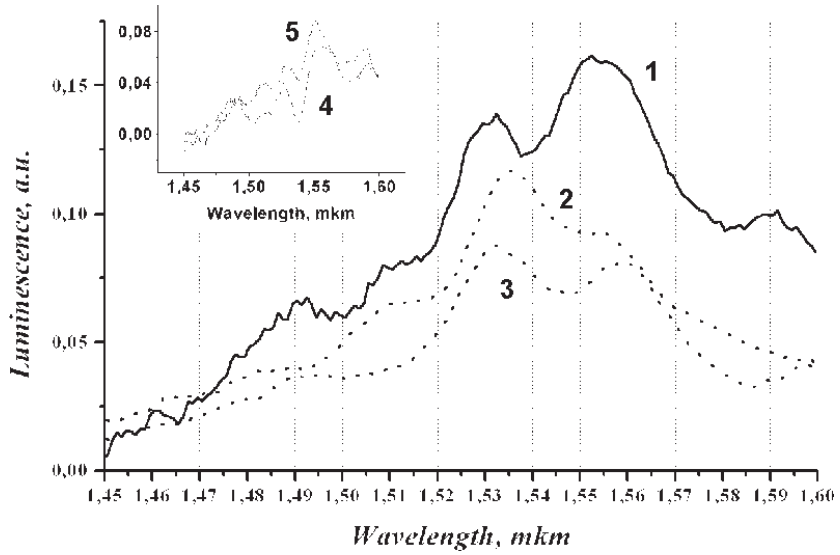

Fig. 2. The luminescence spectrum of SBN:Yb^{3+}-opal:Er^{3+} nanocomposite (1) in comparison with the spectra of SBN-opal:Er^{3+} nanocomposite (curve 2 and 3 - 'red' and 'green' reflection). In the inset: difference spectra between curves 1 and 2 and between curves 1 and 3. Pump at wavelength of 980 nm.

length 1075 nm that coincide with estimation in [2]. For comparison the low temperature luminescence spectra of the SBN:Yb^{3+} are shown in the inset [2].

The luminescence spectra of the SBN:Yb^{3+}-opal:Er^{3+} nanocomposite (curve 1) and the nominally pure SBN-opal:Er^{3+} nanocomposite (curves 2 and 3) with 980 nm pump wavelength are presented in Fig. 2. Curves 2 and 3 correspond to samples with 'red' and 'green' reflection, respectively. The difference spectra at around 1.5 mm for nanocomposites of nominally pure SBN:61 (curve 4) and SBN:Yb^{3+} (curve 5) are shown in the inset. The experimental results show the presence of exchange processes between electronic subsystems of Yb^{3+} ions in SBN crystal medium and Er^{3+} ions in opal matrix.

The luminescence spectra of the SBN:Yb^{3+}-opal:Er^{3+} nanocomposite at pump wavelengths of 800 nm and 980 nm were studied (Fig. 3). The strong redistribution of luminescence intensity between Stark components of 1.53 mm and 1.55 mm was observed.

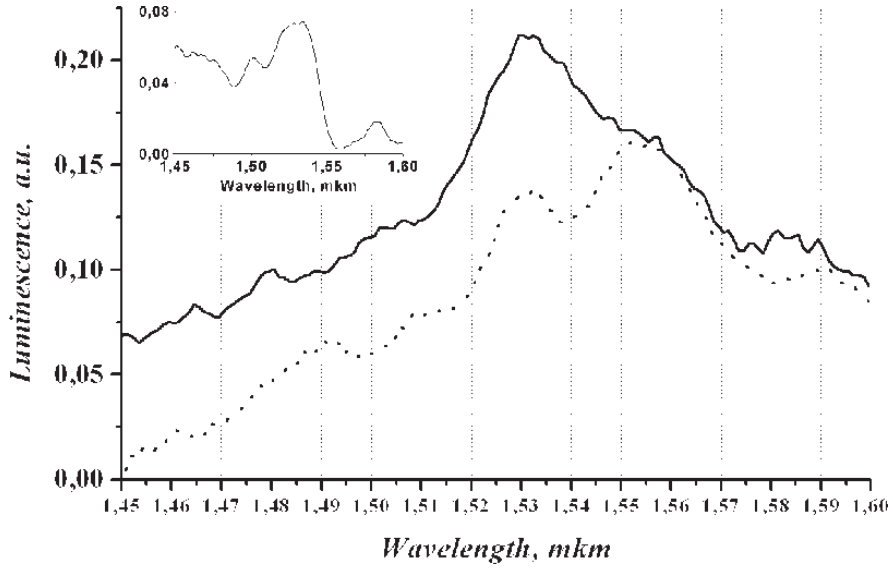

Fig. 3. The luminescence spectrum of SBN:Yb^{3+}-opal:Er^{3+} nanocomposite under pump at wavelength of 800 nm (solid line) and 980 nm (dashed line). In the inset: difference spectrum.

4. CONCLUSIONS.

Until now various optoelectronic devices are mostly realized on optically active media, especially on the crystals having piezoelectric, electrooptical and acoustooptical properties. A new type of optical media – 'photonic crystals' gives opportunity for development of new optoelectronic devices. The first experiments on hybridization of traditional optical crystals with photonic crystals are presented in this work. The luminescence data obtained for SBN:Yb^{3+}-opal:Er^{3+} nanocomposite show one of the ways to create new optical elements.

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