COMPACT INTEGRATED-OPTICAL AMPLIFIERS FOR THE TELECOMMUNICATION C - BAND ON THE BASIS OF POLYMER WAVEGUIDES WITH EMBEDDED NALUF$_4$/YB^{3+}/ER^{3+}/CE^{3+} NANOCRYSTALS

**I.M. Asharchuk^(a)^, A.S. Akhmanov^(b)^, I.O. Goriachuk^(c)^, M.M. Nazarov^(d)^, A.V. Nechaev^(e)^,
K.V. Khaydukov^(f)^, V.I. Sokolov^(g)^**

(a), (b), (c), (f), (g) Institute on Photonic Technologies, Federal Research Center «Crystallography and Photonics»,
Russian Academy of Sciences, Moscow, Russia
(d) National Research Center «Kurchatov Institute», Moscow, Russia
(e) Moscow State University of Fine Chemical Technologies, Moscow, Russia
(b), (g) Federal Research Center «Scientific Research Institute of System Developments», Russian Academy of Sciences,
Moscow, Russia
(a) Ilya-asharchuk@ya.ru, (b) Asakhmanov@mail.ru, (c) Io.gorjachuk@physics.msu.ru, (d) Nazarovmax@mail.ru,
(e) Chemorg@mail.ru, (f)Khaydukov@mail.ru, (g)Visokol@rambler.ru

ABSTRACT

Nano-sized β-NaLuF$_4$/Yb^{3+}/Er^{3+}/Ce^{3+} core-shell crystals possessing intense photoluminescence in the 1530 – 1565 nm telecommunication C - band under 980 nm laser excitation were prepared by thermal decomposition approach. The synthesized nanoparticles (NPs) were dispersed in SU-8 photo-resist and single-mode polymer channel waveguides with embedded NPs were fabricated on the thermally oxidized silicon wafer using UV photolithography and wet etching techniques.

The relative optical gain of 2.5 dB was demonstrated at λ = 1549.2 nm wavelength in the 12 mm long waveguide, which means 2.1 dB/cm per unit gain. These results reveal that composite polymer material on the basis of SU-8 photo-resist and β-NaLuF$_4$/Yb^{3+}/Er^{3+}/Ce^{3+} NPs is promising for fabricating compact integrated-optical amplifiers for the C – band.

Keywords: rare-earth doped nanocrystals, photo-luminescence, UV photolithography, polymer waveguides, optical amplifiers, telecommunication C – band.

1. INTRODUCTION

Erbium doped polymer waveguide amplifiers are attracting considerable attention due to their intense $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions of Er^{3+} ions, which match well to the low-loss telecommunication window of optical fibers in the 1530 – 1560 C - band (Wang 2015; Zhai, Li, Liu, Wang, Zhang, Qin, Qin 2013; Zhai, Liu, Liu, Wang, Zhang, Qin, Qin 2013; Zhao 2014). For real applications in the field of integrated optics the Er^{3+} doped NPs should possess small crystalline size, good dispersibility in the polymer matrix as well as highly efficient photoluminescence (PL) in the C - band.

In this work Er^{3+}, Yb^{3+}, Ce^{3+} co-doped β-NaLuF$_4$ NPs with the core/shell structure were synthesized and used for fabricating single-mode waveguide optical amplifiers with SU-8 polymer material.

2. SYNTHESIS OF β-NALUF$_4$/YB^{3+}/ER^{3+}/CE^{3+} NANOCRYSTALS

Nano-sized hexagonal β-NaLuF$_4$/Yb^{3+}/Er^{3+}/Ce^{3+} crystals with the core-shell structure (active β-NaLuF$_4$ core doped with Yb, Er, Ce and inert undoped β-NaLuF$_4$ shell) were prepared by thermal decomposition approach, which was developed in our research group earlier (Grebenik 2013). In Figures 1, 2 one can see TEM and high-resolution TEM photographs of synthesized NPs with the diameter in the range from 20 to 40 nm. Nanoparticles are covered with oleic acid thin film, which results in good dispersibility of NPs in the polymer matrixes.

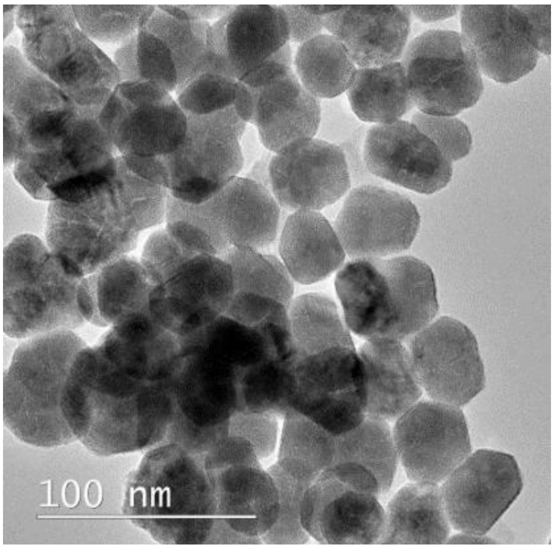


Figure 1. TEM microphotograph of the synthesized β-NaLuF$_4$:Yb^{3+}:Er^{3+}:Ce^{3+} core/shell nanocrystals.

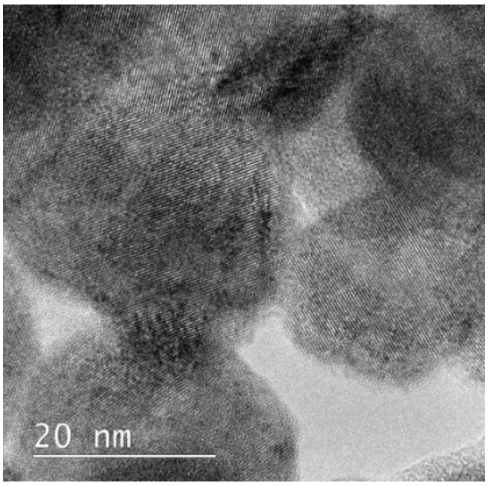


Figure 2. High-resolution TEM microphotographs of the hexagonal β-$NaLuF_4$:Yb^{3+}:Er^{3+}:Ce^{3+} core/shell nanocrystals.

The synthesized β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ nanocrystals possess intense PL in the 1530 – 1565 nm telecommunication C – band. In Figure 3 the simplified scheme of Yb^{3+}, Er^{3+} and Ce^{3+} energy levels is presented whereas Figure 4 shows PL spectrum of β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ NPs under 980 nm laser excitation. One can see from Figure 4 that FWHM of the PL spectrum equals 75 nm, which potentially permits to provide optical gain at any wavelength in the C – band.

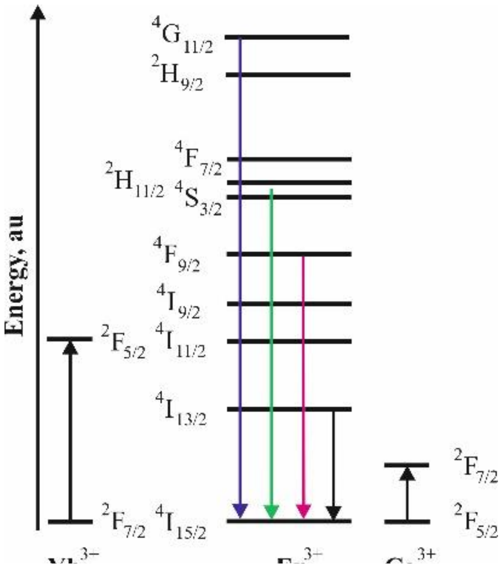


Figure 3. Simplified scheme of Yb^{3+}, Er^{3+} and Ce^{3+} energy levels. The energy transfer between ytterbium and erbium ions is stipulated by transitions $^2F_{5/2}$ (Yb^{3+}) + $^4I_{15/2}$ (Er^{3+}) → $^2F_{7/2}$ (Yb^{3+}) + $^4I_{11/2}$ (Er^{3+}), whereas that between erbium and cerium ions is due to $^4I_{11/2}$ (Er^{3+}) + $^2F_{5/2}$ (Ce^{3+}) → $^4I_{13/2}$ (Er^{3+}) + $^2F_{7/2}$ (Ce^{3+}) transitions.

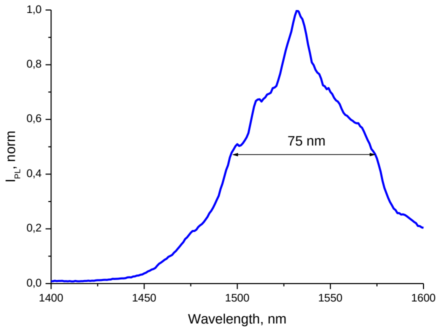


Figure 4. PL spectrum of β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ nanoparticles under 980 nm laser excitation. The intense photoluminescence band around 1532 nm is stipulated by $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions in Er^{3+} ions.

3. NUMERICAL SIMULATION OF SINGLE-MODE POLYMER WAVEGUIDES

Single-mode propagation of light in the polymer waveguide is controlled by the geometrical parameters of the light-guiding core (width *w* and height *h*) as well as by its numerical aperture

$$NA = \sqrt{n_{core}^2 - n_{clad}^2} \tag{1}$$

where n_{core} is refractive index of the core and n_{clad} – that of the cladding. One can see from Equation (1) that *NA* depends upon the refractive indices of polymer materials used for the core and cladding respectively. The typical numerical aperture, which provides single – mode operation of the waveguide is in the range *NA* = 0.1 – 0.16.

The design of the polymer channel waveguide we have chosen is shown in Figure 5.

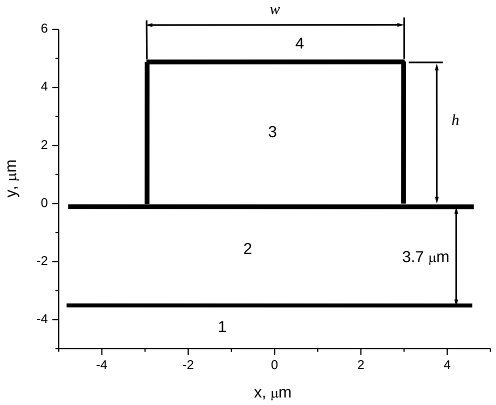


Figure 5. Cross-section of the polymer channel waveguide. 1 - silicon wafer, 2 - thermally grown 3.7 μm SiO_2 buffer layer, 3 - SU-8 rectangular core with embedded β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ NPs, 4 – amorphous polystyrene cap layer. *w* and *h* are the width and height of the light-guiding core respectively.

Using n_{core} = 1.575 (SU-8 photoresist), n_{SiO2} = 1.444 and n_{clad} = 1.564 (amorphous polystyrene) at 1550 nm we employed the beam propagation method in BeamProp software to calculate the mode field distribution in the rectangular channel waveguide, shown in Figure 5. The numerical simulation has revealed the range of geometrical parameters of the core, which provides single-mode operation of the waveguide in the telecommunication C - band. By taking into consideration the results of the simulation we have chosen the width and the height as w = 8 µm and h = 4 µm to have both single-mode light transmission and reasonably small losses when launching light from the optical fiber into the waveguide and vice versa. The computed transverse fundamental mode profile in the SU-8 polymer waveguide at 1550 nm is presented in Figure 6.

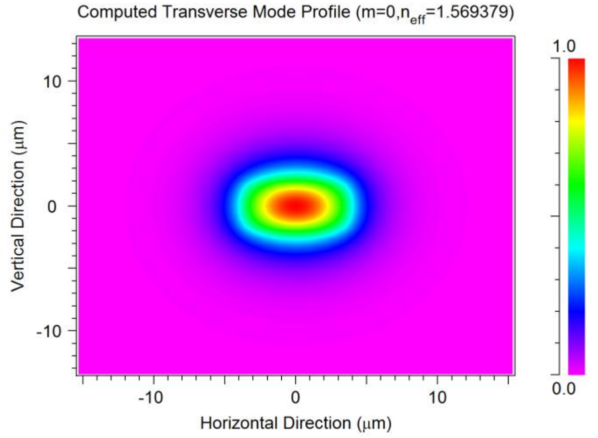
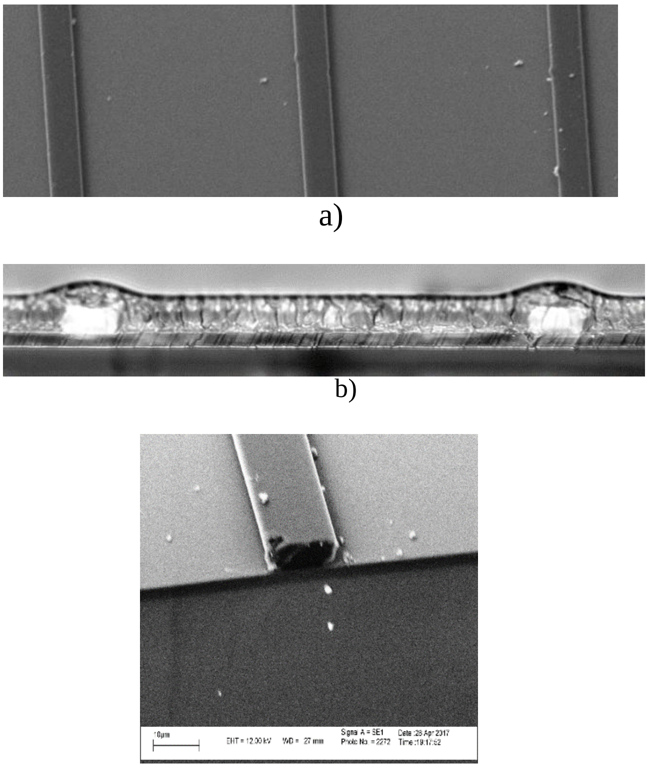


Figure 6. Computed transverse fundamental mode profile in the rectangular channel waveguide (see Figure 5) at 1550 nm. The width and the height of the light-guiding core are w = 8 µm and h = 4 µm respectively. The refractive indices of the core and cladding materials at 1550 nm are given in the text.

4. FABRICATION OF SINGLE-MODE POLYMER WAVEGUIDES WITH EMBEDDED β-NALUF$_4$/YB^{3+}/ER^{3+}/CE^{3+} NANOCRYSTALS

First, the synthesized β-NaLuF$_4$/Yb^{3+}/Er^{3+}/Ce^{3+} NPs were dispersed in SU-8 photo-resist at concentration 0.2%. Then, by using this nano-composite material the films with the thickness 3 – 5 µm were spin coated on Si wafers with the thermally grown 3.7 µm silicon dioxide layer. The thickness of the films was measured by m - lines technique using Metricon2010/M Prism coupler and original computer program, realized in FORTRAN (Asharchuk 2016). This program permits to calculate refractive index, extinction coefficient and thickness of multilayer thin film structures from the measures reflection coefficients for TE and TM polarized Gaussian light beams.

Single-mode polymer waveguides with embedded NPs were fabricated by using standard UV photolithography (365 nm mercury lamp) and wet etching techniques. Finally the waveguides were covered with amorphous polystyrene cap layer. In Figure 7 one can see the photographs of the fabricated array of polymer waveguides, made with the optical (a, b) and scanning electron (c) microscopes. The width of the waveguide cores is 8 µm, the height equals 4 µm. The length of the waveguides in the array equals 12 mm.



a)

b)

c)

Figure 7. Photographs of single-mode polymer waveguides with embedded β-NaLuF$_4$:Yb^{3+}:Er^{3+}:Ce^{3+} nanocrystals before (a, c) and after covering with polystyrene cap layer (b).

5. CHARACTERIZATION OF POLYMER WAVEGUIDE AMPLIFIES

The scheme of experimental setup for measuring optical amplification in the polymer waveguides in the telecom C - band is presented in Figure 8. We used Santec TSL-550 tunable semiconductor laser as signal source and MS9710B optical spectrum analyser as photoreceiver.

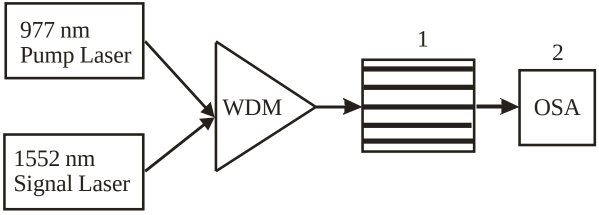


Figure 8. Scheme of experimental setup for measuring optical gain in the polymer waveguide amplifier. 1) Array of single-mode polymer waveguides with embedded β-NaLuF$_4$/Yb^{3+}/Er^{3+}/Ce^{3+} nanoparticles, 2) OSA - Optical Spectrum Analyser. WDM is 1550/980 nm fiber wavelength division multiplexer.

Figure 9 represents the measured optical gain in the polymer waveguide amplifier as a function of 980 nm pump power P_{pump}. The gain was measured by normalizing the output signal power with pump «on» and «off». One can see that the gain increases with P_{pump} and equals 1.6 dB (see the inset to Figure 9) for P_{pump} = 80 mW. Since the length of the waveguide is 12 mm, the per-unit gain of the device equals 1.3 dB/cm.

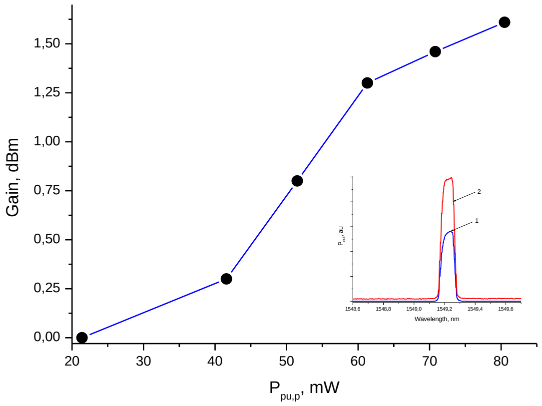


Figure 9. Optical gain in SU-8 polymer waveguide amplifier with embedded β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ NPs at λ = 1549.2 nm as a function of 980 nm pump power P_{pump}. The signal power is 0.1 mW. Inset: output signal with pump «off» (1) and «on» (2).

By increasing the concentration of NPs in the polymer matrix up to 0.5% we have got the optical gain 2.5 dB (2.1 dB/cm) at λ = 1549.2 nm.

6. CONCLUSIONS

By using β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ NPs and SU-8 photo-resist, single-mode waveguide amplifiers for the telecommunication C - band were fabricated. The relative optical gain of 1.6 - 2.5 dB was demonstrated at 1549.2 nm in the 12 mm long waveguide. These results reveal that composite polymer material on the basis of SU-8 and β-$NaLuF_4/Yb^{3+}/Er^{3+}/Ce^{3+}$ NPs is promising for fabricating compact integrated-optical amplifiers for the C – band.

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AUTHORS BIOGRAPHY

Ilya M. Asharchuk graduated from Volgograd state university in 2014. He is research scientist at Institute on Photon Technologies, Federal Research Center «Crystallography and Photonics», Russian Academy of Sciences, Moscow, Russia. The fields of scientific interests: upconversion nanoparticles, polymer composite materials, optical waveguides, waveguide lasers. The author of 8 paper.

Alexander S. Akhmanov was born in Moscow in 1955. He graduated from Physical Department of Moscow State University. He received the Ph.D. degree in Physics and Mathematics and is senior research scientist at Institute on Photon Technologies, Federal Research Center «Crystallography and Photonics», Russian Academy of Sciences, Moscow, Russia. The fields of scientific interests: high-speed telecommunications, polymer integrated optics. The author of 60 scientific paper.

Ivan O. Goryachuk was born in Moscow in 1993. He graduated from Physical Department of Moscow State University in 2017. He is research scientist at Institute on Photon Technologies, Federal Research Center «Crystallography and Photonics», Russian Academy of Sciences, Moscow, Russia. The fields of scientific interests: polymer waveguides, polymer integrated optics, numerical simulation of light transmission in thin film structures. The author of 3 paper.

Maxim M. Nazarov received the Ph.D. degree in Physics and Mathematics from Physical Department of

Moscow State University in 2002 on the topic of surface plasmon enhanced optical harmonics on metal grating. He was scientific researcher at MSU till 2012 on the topics of femtosecond lasers and THz spectroscopy. In 2012 he is a scientific researcher at Institute on Laser and Information Technologies of the Russian Academy of Sciences on the topic of polymer waveguides for THz and visible ranges, nanoparticles and integrated optics. In 2016 he is the head of laboratory of ultraintense laser pulses in National Research Center «Kurchatov Institute», Moscow, Russia. He is the author of more then 60 publications in peer-reviewed scientific journals.

Andrey V. Nechaev graduated from Moscow State University of Fine Chemical Technologies. He received the Ph.D. degree in Chemistry. Now he is Docent at this university. Specialization: synthesis of rare-earth doped nanoparticles. The author of 37 scientific paper.

Kirill V. Khaydukov graduated from Volgograd state university in 2014. He is research scientist at Institute on Photon Technologies, Federal Research Center «Crystallography and Photonics», Russian Academy of Sciences, Moscow, Russia. The fields of scientific interests: rare-earth doped nanoparticles, polymer waveguides, waveguide amplifiers, integrated optics. The author of 10 paper.

Victor I. Sokolov was born in Moscow in 1956. He received Ph.D. degree in Physics and Mathematics in 1991 at Moscow State University. In 1991 - 2016 he was Scientist, Senior Research Scientist, Head of the lab at Institute on Laser and Information Technologies of the Russian Academy of Sciences. Since 2016 he is the Head of the Institute on Photon Technologies, Federal Scientific Research Centre «Crystallography and Photonics». He is the author of more than 100 publications in the field of interaction of laser radiation with matter, photonics, integrated optics, polymeric materials and design of scientific instruments.