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Hybrid structures of integrated photonics for directional micro-light sources based on dielectric waveguides and photoluminescent organic microcrystals

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The development of the element base of modern photonics is a relevant and promising area of research. This paper proposes an approach to creating active structures that enable the implementation of directional light microsources by combining a waveguide with an input/output adapter fabricated using two-photon laser printing and an emitting microcrystal made of an organic dye. It is demonstrated that the proposed device enables both the excitation of the crystal's photoluminescence (PL) by radiation coupled through the waveguide structure and, conversely, the extraction of the crystal's PL radiation through the waveguide and adapter. These capabilities also apply to resonant Fabry-Perot modes, the excitation of which is demonstrated for organic dye crystals with a shape similar to a parallelepiped.

Keywords: photonics, two-photon laser printing, organic microcrystals.

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Introduction

The trend toward miniaturization of photonic elements and photonic integrated circuits stimulates the search for new approaches to their manufacture and testing. In this aspect, of great interest is the method of two-photon laser printing (TPL), or direct laser writing, which makes it possible to manufacture both planar and three-dimensional dielectric structures of arbitrary shape and, moreover, not requiring the use of lithographic masks [1, 2]. At the same time, the spatial resolution of TPL can reach down to a few hundred nanometers. As noted in the review [3], the advantages of TPL include the relative simplicity, the operation under ambient conditions (without vacuum requirements), single-cycle manufacturing, and, most importantly, printing arbitrary three-dimensional objects. The latter feature makes it possible, in particular, (a) to print three-dimensional input-

output couplers that allow optical radiation routing normal to a planar photonic structure; and also (b) to produce "suspended" structures located above the substrate [4, 5]. Finally, at the stage of preparing the polymer composition for printing, it is possible to introduce various functional additives into it – such as dye solutions, photoluminescent compounds, nanoparticle suspensions [6, 7], etc., as a result forming qualitatively new properties of materials. Thus, in the work [8], a single-photon light source based on a Fabry-Perot resonator with nanodiamonds was implemented; the structure was manufactured by the TPL method.

Despite the fact that the TPL technology needs further improvement and development, new methods can already be proposed for implementing active photonic devices, one of which is investigated in this work. This method is based on combining a photoluminescence (PL) source – a microcrystal of an organic dye – and a

system for launching and extracting radiation in the form of an adapter with a waveguide, manufactured by the TPL method in a single planar structure. The presented results demonstrate that the positioning a PL microcrystal on a waveguide structure makes it possible to realize a localized efficient source of broadband PL as part of a planar photonic circuit and, conversely, to extract PL radiation from the microcrystal directly into the waveguide while preserving the resonant part of the spectrum. The proposed approach is promising for testing microresonators without the use of precision devices for input and output of radiation required to ensure optical coupling of photonic elements.

Experimental section

For the study, a series of short waveguides with an adapter for vertical input/output of radiation were manufactured; for this, the TPL method described in detail in [9] was used. Printing was carried out using the radiation from a femtosecond laser with a central wavelength of 780 nm and a pulse duration of 380 fs; the voxel diameter during printing was approximately $0.4\text{ }\mu\text{m}$ with a height of less than $0.8\text{ }\mu\text{m}$. The material for TPL was the hybrid negative

photoresist OrmoComp, and crystalline magnesium fluoride plates were used as the substrates.

An image of one of the manufactured structures, obtained with an optical microscope is shown in Fig. 1; the inset shows the three-dimensional model of the structure implemented during printing. The radiation input/output adapter consisted of a lens with a spherical surface with a radius of $9\text{ }\mu\text{m}$, ensuring focusing of radiation in the direction along the normal to the substrate surface into a waveguide with a length of about $42\text{ }\mu\text{m}$, the cross-section of which was $4\times 4\text{ }\mu\text{m}^2$. The flat base of the lens, inclined at an angle of 48° to the plane of the substrate, directed the incident light into the end face of the waveguide due to the effect of total internal reflection. The value of this angle was chosen to optimize the conditions for launching a converging laser beam into the waveguide. Thanks to the presence of a contrast in refractive indices between the substrate (1.38) and the polymer (1.51), such a waveguide supports a multimode regime of the light propagation in the visible spectral range. To give the adapter greater strength, an annular base was used, increasing the area of contact between the structure and the substrate.

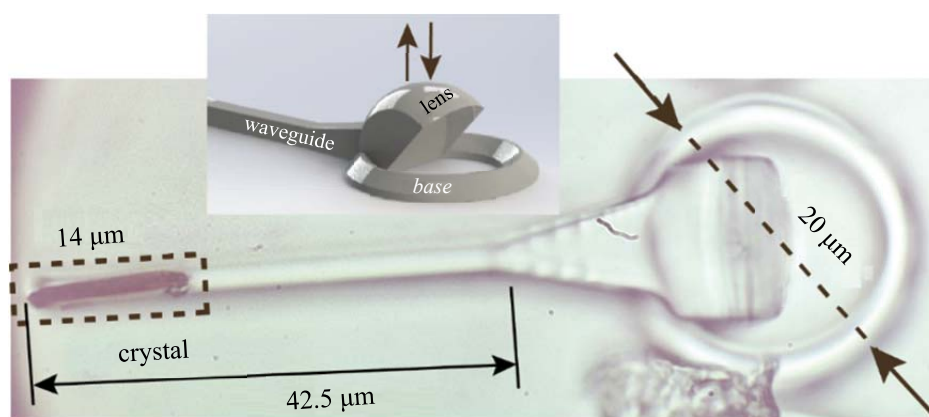


Fig. 1. Image in an optical microscope of the manufactured waveguide structure with a radiation input-output adapter. Inset: the model used during printing by the TPL method; arrows indicate the direction of input/output of radiation

Microcrystals of organic dyes DCM or HDMAC were synthesized on separate glass substrates by the method of sublimation from the gas phase, as described in detail in [10, 11]. The dyes have a band of bright PL in the visible range of the spectrum. Then the selected

microcrystal was mechanically separated from the substrate using a chemically sharpened optical fiber [12] and moved in front of the end face of the waveguide or onto its surface. Fig. 1 shows an image of one of the studied structures, in which a microcrystal of the HDMAC dye in the form of a

strip with dimensions of $1.2 \times 7 \times 14.2 \text{ } \mu\text{m}^3$ is located at the end of the manufactured polymer waveguide; its long side is almost parallel to the waveguide, and its plane is nearly perpendicular to the substrate.

The experiments were carried out using the method of one-photon-excited PL on a confocal microscopy setup (see the inset to Fig. 2); the radiation from a continuous semiconductor laser with an emission wavelength of 405 nm, focused by a Plan Apo 50 $\times$ /0.55NA objective into a spot with a diameter of about 0.9 μm , was used as optical pumping. The PL radiation was collected by a similar objective, passed through a system of filters cutting off the pump radiation, and then the PL signal from the microcrystal was directed into a spectrometer with subnanometer spectral resolution. The experimental setup made it possible to measure PL spectra at different points of the structure, spatially separating the regions of excitation and collection of the PL signal.

First, the PL spectrum of the microcrystal was measured with the regions of irradiation and collection of the PL signal coinciding; the corresponding results are presented in Fig. 2. The black curve shows the measured spectral dependence of PL, modulated by a set of resonant features; the PL spectrum of the microcrystal after extraction of the nonresonant PL signal is shown by the violet line in Fig. 2. The inset to the figure shows a part of the spectrum on an enlarged scale, the wavelengths corresponding to the most intense PL intensity maxima, I , are given. Let us note that in this experimental scheme, the excitation of microresonator modes corresponds to PL maxima arising due to light scattering on inhomogeneities in the near-surface region of the structure. This applies, among other things, to Fabry–Perot modes in the case of their excitation in the microcrystal under consideration; the growth of PL intensity in this case is a consequence of an increase in the density of states of the electromagnetic field under resonant conditions [13].

For the spectrum shown in the inset to Fig. 2, the average intermode distance for the most pronounced maxima is about 9 nm, which corresponds to Fabry–Perot modes excited along the long side of the microcrystal ($L = 14.2 \text{ } \mu\text{m}$) with a refractive index $n = 1.7$. In this case, estimates of the intermode distance for a

wavelength of $\lambda = 670 \text{ nm}$ using the expression $\Delta\lambda \approx \lambda^2/(2nL)$ give a value of about 9.3 nm, which is close to that obtained in the experiment. Considering the spectral width of the PL maxima $\delta\lambda \approx 5 \text{ nm}$, the mode quality factor $Q = \lambda/\delta\lambda$ is about 130. It should be noted that the complex structure of the PL spectrum reflects the presence of Fabry–Perot modes of different orders and different polarization states, as well as other families of resonator modes that can be excited along all three directions in the microcrystal having the shape of a parallelepiped.

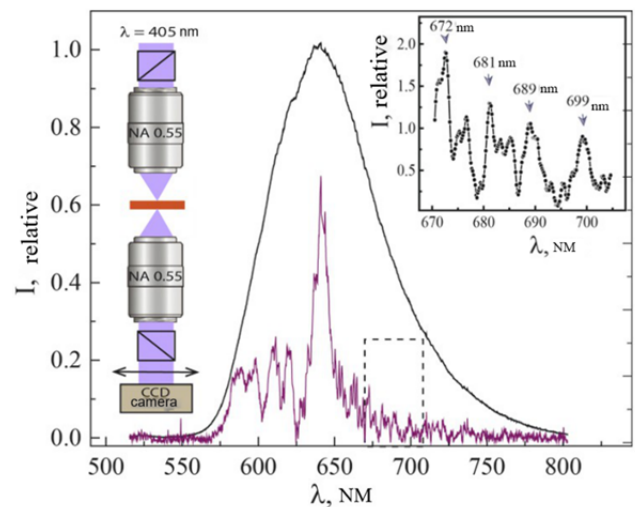


Fig. 2. Spectrum of PL intensity of the HDMAC microcrystal placed on top of the waveguide, measured with coincidence of the regions of PL excitation and its registration (black curve), and the spectrum of microresonator modes isolated from it (violet curve). Inset on the left – schematic diagram of the confocal optical microscopy setup; on the right – the spectrum of the isolated resonant modes (the corresponding region is outlined by a rectangle) on an enlarged scale

Fig. 3 presents the results demonstrating the ability of the structure under consideration to extract PL radiation from a microcrystal located at the end face of the waveguide. In the experiment, a laser beam focused on the microcrystal excites PL in it, and the spectrum of the signal at the output of the adapter is recorded; in this case, the sample was positioned with its substrate toward the pump beam, and the output of the adapter was directed toward the collecting objective. The shape of the PL intensity spectrum obtained in this way is analogous to the initial PL spectrum of the microcrystal; at the same time, the parameters of the isolated resonant modes differ from those presented in Fig. 2, and the

average intermode distance turned out to be significantly larger and amounted to about 18 nm for the most clearly manifested modes (see the inset to Fig. 3). An estimate of the intermode distance for the vertically oriented side of the microcrystal with $L \approx 7 \mu\text{m}$ for $\lambda = 625 \text{ nm}$ gives the value of $\approx 16.4 \text{ nm}$, which is close to the experimental one, while the quality factor $Q \approx 60$. Thus, we assume that in this case scattering of a different type of Fabry–Perot modes is observed compared with those presented in Fig. 2 – namely the modes, oscillating along the side of the microcrystal about $7 \mu\text{m}$ long, located vertically relative to the substrate.

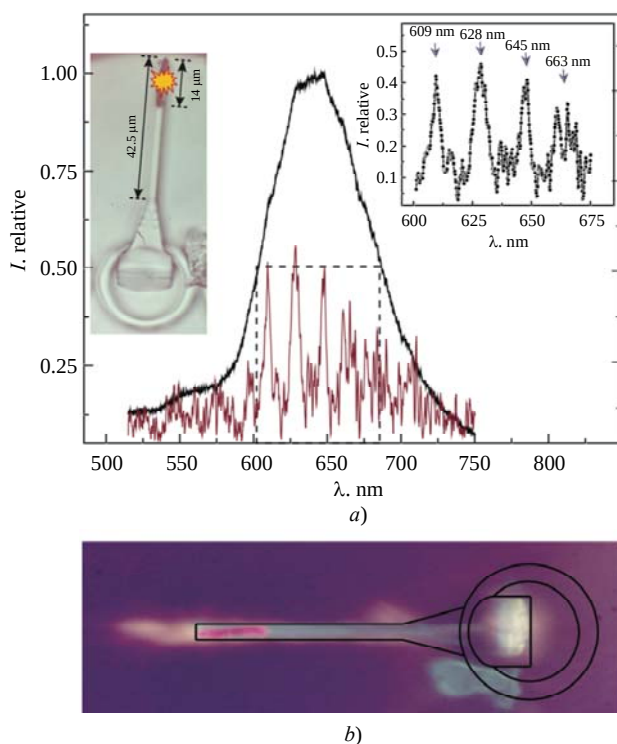


Fig. 3. (a) Radiation spectrum (black curve) at the output of the radiation input-output adapter upon excitation of PL in the microcrystal and the Fabry–Perot mode spectrum isolated from it. Inset on the right – on an enlarged scale, the spectrum of the isolated resonant modes (the corresponding region is outlined by a rectangle). (b) Optical image of the structure upon launching radiation with $\lambda = 405 \text{ nm}$ into the adapter (on the right in the figure)

Fig. 3b shows an optical image of the structure upon pumping the microcrystal with laser radiation with $\lambda = 405 \text{ nm}$, focused into the adapter located on the right in the figure (a pump-cutting light filter is used). Based on the PL signal of the substrate (orange color), a relatively small scattering of the pump light is visible in the regions of the adapter and the junction of the

cone-shaped part of the radiation launching system with the waveguide, which is associated with the non-uniformity of the structure in these regions. The intensity of the scattered radiation is the highest at the output from the waveguide through the adapter. According to the performed calculations [14], the transmittance of the structure is at least 50%, whereas the experimental value of the transmittance for a similar structure with two radiation input/output adapters was about 14%.

The brightest luminescence in the studied structure corresponds to the PL of the dye microcrystal, which indicates its efficient optical excitation by radiation propagating through the waveguide. For such an experimental geometry, the PL spectrum of the microcrystal, recorded directly from the region of its location, is analogous to that presented in Fig. 2. It should be noted that at a pump radiation power of up to $0.5 \mu\text{W}$, no photodegradation of the microcrystal was observed for at least tens of minutes, which corresponds to the results of previous studies [11].

Conclusion

Thus, in the present work, an approach to creating active photonic structures is proposed that combines the potential of the two-photon lithography method for creating polymer waveguides and devices for input and output of optical radiation, with microresonators exhibiting a high PL yield. The possibility of efficient optical excitation of PL of a dye microcrystal (for example, HDMAC) located on the surface of the waveguide has been shown, depending on the method of recording the PL response, different families of resonant modes are observed. Namely, in the PL signal scattered on the microcrystal, Fabry–Perot modes propagating without contact with the waveguide (parallel to the substrate) are predominantly detected, whereas through the waveguide the signal from the Fabry–Perot modes maximally coupled with the polymer structure effectively passes through the waveguide and is recorded.

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