

# Active polymer fibres doped with organic dyes: Generation and amplification of coherent radiation

G.V. Maier, T.N. Kopylova, V.A. Svetlichnyi, V.M. Podgaetskii, S.M. Dolotov, O.V. Ponomareva, A.E. Monich, E.A. Monich

**Abstract.** The technology is developed for manufacturing active polymer optical fibres doped with organic dyes. Stimulated emission and amplification in the long-wavelength part of the visible spectrum is studied for rhodamine 11B, phenalemine 512 and substituted DCM pyran in polymer optical fibres. Lasing was observed upon longitudinal and transverse pumping by the second harmonic of a Nd:YAG laser. The gain in polymer fibres was estimated by measuring the intensity ratio of radiation of a master oscillator (dye laser) propagated through the excited (pumped) and unexcited (not pumped) fibre pieces doped with organic dyes. It is shown that the lasing efficiency of rhodamine 11B in a transversely pumped polymer fibre can achieve 36%. The maximum gain ( $25 \text{ dB m}^{-1}$ ) is obtained in fibres doped with phenalemine 512.

**Keywords:** laser, optical fibre, dye, spectra, lasing, amplification.

## 1. Introduction

An important landmark in the development of tunable lasers was the observation of stimulated emission of organic molecules in solutions in 1966. The first solid-state dye lasers were demonstrated in 1967 [1] and 1968 [2]. These lasers had obvious advantages over liquid lasers because they were more compact and convenient in operation and did not use inflammable and toxic solvents. However, the energy parameters and photostability of solid active media were second to those achieved in solutions, and considerable efforts were made by chemists and physicists to create solid-state active media for tunable lasers with parameters not inferior to those of solutions. At present this problem is solved for the visible spectral range, and

dyes lasing efficiently in various materials [polymethyl methacrylate (PMMA), sol–gel matrices, hybrid organic matrices)] [3–9] were synthesised.

The attention of researchers was mainly focused for a long time on the development of polymer blocks. Much less attention was devoted to the creation of active polymer fibres doped with organic dyes, although tunable fibre lasers and amplifiers proved to be quite promising for applications in optical networks [10, 11]. However, interest in the development of polymer active fibres doped with organic dyes (PAFDs) and devices based on them has quickened in the last years.

This is explained by the fact that PAFDs have a number of advantages over silica fibres. Thus, lasing in erbium-doped  $\text{Er}^{3+}:\text{SiO}_2/\text{GeO}_2$  glass fibres has been obtained only in the near-IR spectral range. At the same time, amplification and lasing in PAFDs can be tuned in a broad visible spectral range, and the absorption and luminescence cross sections for organic compounds considerably exceed (by 4–5 orders of magnitude) these cross sections for  $\text{Er}^{3+}$  ions.

In addition, a high mechanical strength of polymer materials provides a high stability of polymer fibres to multiple twistings. Their critical bending diameter is considerably smaller than that for silica fibres and can be only a few millimetres. The manufacturing technology of polymer fibres is simpler than that of glass fibres and the cost of polymers is lower.

The main problem in the PAFD manufacturing is the necessity to develop optical fibres of special types, which can be fabricated without subjecting organic compounds to large thermal loads producing their decomposition [12–20].

In 1996, the authors of paper [21] reported the fabrication of a sol–gel glass fibre doped with rhodamine 6G. The fibre laser was pumped by the 532-nm second harmonic of a Nd:YAG laser with a pulse repetition rate of 1 Hz. The lasing efficiency  $\xi \sim 3\%$  was achieved. In a laser based on a step-index rhodamine 6G-doped PMMA fibre pumped by a nitrogen laser with a pulse repetition rate of 1 Hz, the efficiency  $\xi \sim 10\%$  was obtained.

American and Japan researchers [22, 23] developed the technology for manufacturing PAFDs from graded-index polymer (PMMA) optical fibres. The main advantage of such fibres (without luminophore dopants) is the low attenuation of radiation ( $\sim 0.13 \text{ dB m}^{-1}$  at 650 nm) [24].

In such PAFDs based on PMMA doped with rhodamine 6G (R6G), rhodamine B (RB), oxazine 4 perchlorate (OX4PC), and 4-dicyanomethylene-2-methyl-6-(4-diethylaminostyryl)-4H-pyran (DCM), rather high power gains were achieved upon pumping by 10-ns second harmonic pulses

G.V. Maier, T.N. Kopylova, V.A. Svetlichnyi V.D. Kuznetsov Siberian Physical-Technical Institute, Tomsk State University,

pl. Novo-Sobornaya 1, 634050 Tomsk, Russia;

e-mail: kopylova@phys.tsu.ru;

V.M. Podgaetskii Moscow State Institute of Electronic Engineering (Technical University), pr. 4806, 124498 Moscow region, Zelenograd, Russia; e-mail: bms@miee.ru;

S.M. Dolotov, O.V. Ponomareva Deltacor Limited Liability Company, ul. Pervomaiskaya 44, Moscow region, 141700 Dolgoprudnyi, Russia;

A.E. Monich, E.A. Monich Impulse Scientific and Technical Center, ul. Profsoyuznaya 156, Krasnodarskii krai, 352690 Apsheronsk, Russia

Received 20 April 2006; revision received 19 July 2006

Kvantovaya Elektronika 37(1) 53–59 (2007)

Translated by M.N. Sapozhnikov

from a Nd:YAG laser:  $\sim 33 \text{ dB m}^{-1}$  for R6G at 572 nm,  $\sim 27 \text{ dB m}^{-1}$  for RB at 580 nm,  $\sim 20 \text{ dB m}^{-1}$  for OX4PC at 649 nm, and  $\sim 3 \text{ dB m}^{-1}$  for DCM at 560 nm [14, 17, 25].

The authors of [26] performed a comparative study of the lasing parameters of graded-index PAFDs based on PMMA doped with R6G and of block laser elements fabricated by drawing from acryl copolymer doped with R6G. The diameter and length of block elements were 0.6 mm and 5 cm, respectively (these dimensions are close to those of graded-index PAFDs). The ends of the laser elements were polished and the resonator was formed by a dielectric mirror, which was deposited on one of the polished planes, and the element end. The fibres and block elements were transversely pumped by the second harmonic of a Nd:YAG laser.

The efficiency and threshold pump energy of the R6G-doped fibre laser were  $\xi \approx 43\%$  and  $E_{\text{th}} \approx 100 \mu\text{J}$ , whereas these parameters for the 'block' laser were  $\sim 8\%$  and  $375 \mu\text{J}$ , respectively. It was shown that the 'block' laser pulse duration was shorter than the pump pulse duration, which is most likely caused by high scattering losses at the material–air interface. The operation life of this laser was considerably shorter than that of the fibre laser.

It follows from the above discussion that lasing and amplifying PAFDs can find wide applications and studies devoted to the refinement of such fibres and tunable fibre lasers and amplifiers are quite promising. This paper is devoted to the development of a new method and the improvement of the manufacturing technology of PAFDs containing various lasing dyes. The main goal of the paper was to determine the optimal parameters of PAFDs based on the study of their lasing and amplifying properties for the development of tunable fibre lasers and amplifiers.

## 2. Samples and fabrication methods

### 2.1 Justification of the method and general information

A typical polymer optical fibre (POF) is a long thread of diameter  $\sim 1 \text{ mm}$  consisting of a cylindrical core surrounded by a light-reflecting cladding with slightly lower refractive index  $n$ . Polymer optical fibres are almost always multimode fibres with the large numerical aperture and large core diameter. They have usually the step or gradient distribution of the refractive index along the fibre diameter (step-index or graded-index fibres, respectively). Polymer fibres can also have a multilayer cladding consisting of step-index layers. To reflect light, a cladding should have the thickness no less than  $(3 \div 5)\lambda$  because upon total internal reflection, light exponentially decays in a material with a lower refraction index. In practice, the cladding thickness (or thickness of each of the layers of a multilayer cladding) should be a few micrometres. In this study, we developed the technology for fabricating polymer optical fibres of all these types.

Well-known polymers with high transmission such as PMMA and polystyrene (PS) have wide applications. They are thermoplastic and can be used to fabricate POFs. At the first stage of our investigations, we used the following polymers that were available and most convenient as fibre core–cladding pairs: PS–PMMA, PS–butyl methyl methacrylate (BMA) copolymer, PS–fluoro-substituted derivatives of methacrylic acid, PMMA–BMA copolymer,

and some other polymer pairs. Almost all these polymers have comparatively large differences of the refractive indices of the core and cladding  $\Delta n$  ( $\sim 0.1 - 0.2$ ), which provides the high numerical aperture of POFs.

Based on technological and constructive considerations, we selected the PMMA (core)–BMA copolymer (light-reflecting cladding) pair to fabricate the first samples of polymer active fibres. Although  $\Delta n \approx 0.05 - 0.06$  for this pair, it is promising for practical applications. In addition, step-index fibres of the simplest structure with a single-layer cladding can be used because low-divergence beams involved in lasing and amplification of light do not require large numerical apertures. The quality of an optical fibre in the case of such light beams is manifested in fibres of length of the order of metre and more. Therefore, we plan in the future to use more complicated fibre structures and other promising materials.

At present the synthesis of PMMA and its analogues is studied in detail; however, the synthesis of high-quality PMMA for POFs still remains a complicated problem. To fabricate highly transparent PMMA, it is necessary to use a MMA monomer that should have a specified refractive index and high transparency in the UV and visible regions.

Polymerisation was performed in a mass (the monomer was preliminary carefully cleaned from mechanical impurities, washed off from the polymerisation inhibitor, and was finally purified by vacuum distillation in a glass apparatus) by using chemical initiators and regulators of the molecular mass. Inhibitors and similar impurities were removed from monomers by filtering through an aluminium oxide layer and then by twice distillation at the atmospheric pressure. The polymerisation initiator was isobutyric acid dinitrile (IAD), and n-dodecylmercaptan (DMC) was used as the molecular mass regulator. At the preliminary stage, we fabricated samples containing different amounts of the DMC regulator and performed control technological drawings of fibres from these samples to determine the optimal regulator concentration providing the required rheologic properties of a polymer matrix. To ensure these properties, the molecular mass of the obtained PMMA should be  $\sim (6 - 8) \times 10^4 \text{ au}$ . We determined the optimal DMC concentration in preliminary studies and fabricated samples with the specified properties.

The light-reflecting cladding of POFs was made of a copolymer developed by us, which had the refractive index  $n = 1.45$  and consisted of 20% of PMMA and 80% polybutyl methacrylate (PBMA). The copolymer has good adhesion with respect to PMMA and PS and its rheologic properties are matched with the properties of these polymers. The methods of copolymer polymerisation are similar to the methods of PMMA polymerisation considered above.

### 2.2 Fabrication of preforms for active polymer fibres

First we fabricated a fibre preform consisting of a core and a cladding deposited on the core. The fibre core was prepared by monomer polymerisation in sealed ampoules. The polymer core of a PAFD should be doped with an organic dye. The latter should have a high quantum yield of fluorescence in the given polymer matrix and a high solvability in the corresponding monomer and also possess good thermo- and photostability. An organic luminophore selected for this purpose was dissolved by stirring in MMA at temperature  $30 - 40^\circ\text{C}$ . Then, the DMC molecular mass

regulator at the volume concentration 0.25 % and the IAD polymerisation initiator at the mass concentration 0.1 % were added to the solution. The obtained solution was poured in cylindrical glass ampoules from which oxygen was pumped out by the freezing–freezing out method, and then the ampoules were sealed off. To reduce adhesion, the surface of glass ampoules was treated with the 5 % solution of dimethyl-dichlorosylane (DDCS) in hexane. Polystyrene samples were polymerised at an elevated temperature. After the end of the process, ampoules were opened and the obtained rods were used in the subsequent technological operations. The rods had a diameter of 15 mm and a length of 150 mm.

We fabricated an experimental batch of 15 PMMA rods doped with rhodamine 11B (R11B), phenalemine 512 (P512), and pyran-substituted DCM at different concentrations. A cladding was applied on rods by the deposition of a polymer from the solution. We used the solution of the BMA copolymer in ethyl acetate. The polymer layer was deposited until the required thickness ( $\sim 0.3$  mm) was obtained. The preforms obtained in this way were dried at an elevated temperature. Despite precautions that have been taken, the side surface of some polymer rods had defects, which were later manifested as fibre defects. These defects consisted mainly in the deviation of the fibre cross section from a circular shape.

### 2.3 Fabrication of fibres

Optical fibres were fabricated by drawing in a controllable way from a preform whose structure completely corresponded to that of the future fibre. We used this method due to its technological flexibility allowing the fabrication of fibres of any structure by varying the geometrical parameters of fibres in broad range and preserving the purity of initial materials during the entire technological process of polymer reprocessing. This method also permits the fabrication of POFs doped with organic dyes.

The drawing method is based on the ‘similarity decrease’ principle. A preform was heated in a narrow zone (drawing zone) up to the softening temperature and was drawn in the form of a filament from the heated zone at a velocity exceeding the velocity of preform introduction to this zone by a factor of  $(D/d)^2$ , where  $D$  and  $d$  are the preform and fibre diameters, respectively.

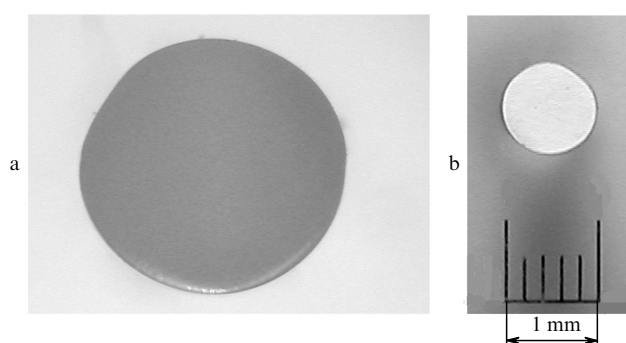
In the development of the setup and technological equipment for fabricating POFs by the drawing method we paid special attention to the kinematic units specifying the velocity of preform movement to the technological drawing zone and the velocity of fibre reception behind this zone. The velocity should be specified and maintained constant during the entire technological process at least within  $\pm 0.05$  %. The temperature in the drawing zone should be should be stabilised at least within  $\pm 0.05^\circ\text{C}$ . The setup was equipped with a system for diagnostic and control of technological parameters. In particular, temperature was continuously controlled at least in three sites of the drawing zone, the preform temperature in the ‘bulb’ zone was controlled within  $\pm 1^\circ\text{C}$  (by the contactless method with the help of an IR temperature sensor), and the preform feed velocity and velocity of fibre removal from the drawing zone, as well as the fibre diameter were continuously controlled.

We fabricated 15 fibres from 15 preforms of the experimental batch, which were doped with different dyes

at different concentrations. Because we have only theoretical estimates of the optimal concentration of dyes, we fabricated samples with different dye concentrations varying within almost two orders of magnitude and then determined the optimal concentration experimentally. For the same reason, the diameter of each of the fibres was varied in the range from 0.5 to 1.2 mm.

### 2.4 Fabrication of active elements

Active elements used in the study were fabricated from PAFDs manufactured by the method described above. The diameter of active elements cut from different regions of an optical fibre was from 0.5 to 1.2 mm and their length was 50 mm. The ends of fibre laser elements were polished by hand. Figure 1 shows the photograph of the end of a typical fibre element.



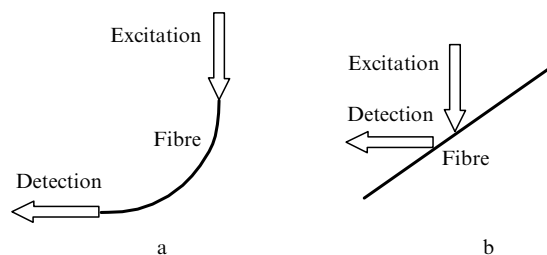
**Figure 1.** Photography of the cross section of a fibre element doped with R11B at concentrations  $0.2\text{ mmol L}^{-1}$  ( $100\times$  magnification) (a) and  $1\text{ mmol L}^{-1}$  ( $10\times$  magnification).

## 3. Results and discussion

We performed the following spectroscopic studies of fibreoptic laser elements.

(i) The fluorescence spectra of samples upon longitudinal or transverse excitation were recorded with a CM2203 spectrofluorimeter (Fig. 2). The results of measurements are presented in Fig. 3 and Table 1, where the wavelengths and half-widths of fluorescence bands observed upon longitudinal and transverse pumping are given.

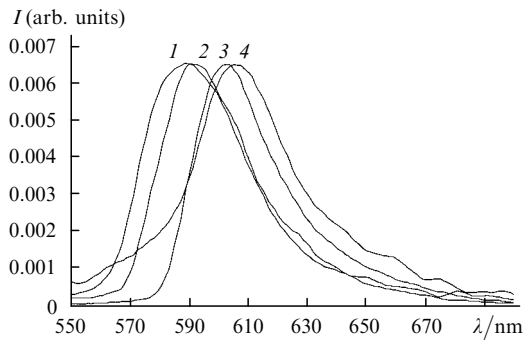
One can see that the spectra recorded upon longitudinal excitation are shifted to the red by 15–40 nm compared to the spectra of the same sample recorded upon transverse excitation. This is observed both for fibres doped with R11B and P512 dyes having strong reabsorption and for fibres



**Figure 2.** Schemes of longitudinal (a) and transverse (b) excitation of fluorescence of active polymer fibres.

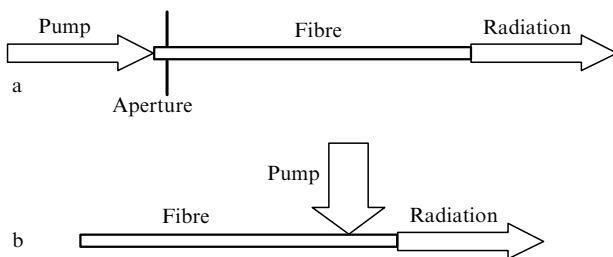
**Table 1.** Spectral parameters of active polymer fibres at different concentrations of dyes.

Dye	Fibre diameter/mm	$C_d/\text{mmol L}^{-1}$	$\lambda_{\text{long}}^{\text{max}}/\text{nm}$	$\Delta\lambda/\text{nm}$	$\lambda_{\text{cross}}^{\text{max}}/\text{nm}$	$\Delta\lambda/\text{nm}$	$\lambda_{\text{long}}^{\text{max}} - \lambda_{\text{cross}}^{\text{max}}/\text{nm}$
R11B	0.85	0.05	585	42	561	55	24
	0.95	0.1	589	40	560	55	29
	0.87	0.2	591	39	566	55	27
	0.80	1.0	602	35	579	45	23
	1.00	1.0	602	35	579	45	23
	0.82	2.0	605	35	589	42	16
P512	0.80	0.1	599	55	581	65	18
	0.80	1.0	621	43	589	55	32
	1.05	3.6	641	38	601	55	40
DCM	0.85	0.1	585	56	565	84	20
	0.95	0.5	594	49	579	70	15
	0.85	1.0	597	43	581	63	16
	0.64	5.0	609	48	588	55	21

**Figure 3.** Fluorescence spectra of R11B upon longitudinal excitation at dye concentrations 0.1 (1), 0.2 (2), 1 (3) and 2  $\text{mmol L}^{-1}$  (4).

doped with the DCM dye whose absorption and fluorescence spectra almost do not overlap. The broad fluorescence bands of dyes shift to the red by 20–40 nm with increasing the dye concentration  $C_d$ , which is also illustrated by the fluorescence spectra of fibres doped with R11B.

(ii) Lasing in PAFDs was studied upon longitudinal or transverse pumping by 15-ns second harmonic pulses from a Nd:YAG laser (the pulse energy was varied from 1 to 100 mJ) (Fig. 4). Upon longitudinal pumping, the radiation power density incident on the fibre end face was  $40 \text{ MW cm}^{-2}$  and the end face surface was excited uniformly. Upon transverse pumping, the pump radiation was focused by a cylindrical lens to a rectangle of size  $4 \text{ mm} \times 0.4 \text{ mm}$ . The focused radiation power density was  $50 \text{ MW cm}^{-2}$ . The fibre was excited at a distance of

**Figure 4.** Scheme of longitudinal (a) and transverse (b) pumping of active polymer fibres.

3 mm from its end, and radiation was detected from this end.

The results of the study of lasing parameters are presented in Table 2, where the wavelength and half-width  $\Delta\lambda$  of stimulated emission bands observed upon longitudinal and transverse pumping and the lasing efficiency  $\xi$  of POFs are given. One can see from Table 2 that upon longitudinal pumping of the DCM-doped fibre, the increase in the dye concentration leads to the increase in the lasing efficiency up to 2.5% and narrowing of the emission band down to 18 nm. This is caused by weak reabsorption and the increase in the fibre excitation efficiency because the absorption spectrum of DCM in the PMMA fibre lies in the region between 460 and 470 nm and the second harmonic of a Nd:YAG laser excites this dye in the long-wavelength tail of the absorption band.

The increase in the concentration of R11B and P512 dyes in fibres also results in the narrowing of stimulated emission bands observed upon longitudinal pumping, however, the pump efficiency decreases due to reabsorption of

**Table 2.** Lasing parameters of active polymer fibres at different concentrations of dyes.

Dye	$C_d/\text{mmol L}^{-1}$	$\lambda_{\text{long}}^{\text{max}}/\text{nm}$	$\Delta\lambda/\text{nm}$	$\xi$ (%)	$\lambda_{\text{cross}}^{\text{max}}/\text{nm}$	$\Delta\lambda/\text{nm}$	$\xi$ (%)
R11B	0.05	570	11	0.8	561	25	–
	0.1	568	11	0.4	562	17	0.4
	0.2	579	20	0.5	559	20	0.5
	1.0	581	2	–	566	3	12
	596	30	–	579	3	12	
	1.0	590	21	–	571	3	18
	590	3	18				
	2.0	593	2	–	576	42	14
	602	30	–	580	42	14	
	594	42	14				
P512	0.1	587	27	2.0	575	55	–
	1.0	612	27	0.2	598	5	1.5
	580	35	1.5				
	3.6	610	2	–	615	7	9
641	38	–	593	16	9		
DCM	0.1	590	60	0.6	570	85	–
	0.5	597	42	0.4	582	65	0.2
	1.0	600	32	0.4	592	65	0.2
	5.0	604	18	2.5	606	15	3.0

radiation in the fibre and a decrease in the penetration depth of pump radiation into the fibre. The maximum values of  $\xi$  for fibres doped with P512 and R11B dyes were 2% and 0.8%, respectively. In the case of transverse pumping, the increase in  $C_d$  was accompanied by the increase in the pump radiation conversion efficiency and narrowing of the stimulated emission band, which demonstrates efficient excitation and considerable amplification in the excited fibre. The maximum values of  $\xi$  were higher than in the case of less efficient longitudinal pumping and were  $\sim 3\%$  for DCM,  $\sim 9\%$  for P512, and  $\sim 18\%$  for R11B.

It should be taken into account that radiation was detected only from one end of the fibre, whereas upon single-pass lasing the radiation propagates in the fibre symmetrically to both sides. Therefore, the total value of  $\xi$  upon transverse pumping can be twice the value presented in Table 2. The lower values of  $\xi$  for DCM-doped fibres are explained, as pointed out above, by weak absorption of the pump radiation. In R11B-doped fibres, a few lasing bands were observed with increasing  $C_d$ , the long-wavelength band being related to the double-pass amplification upon reflection from the opposite end of the fibre. The lasing spectra of polymer fibre laser elements are presented in Figs 5 and 6.

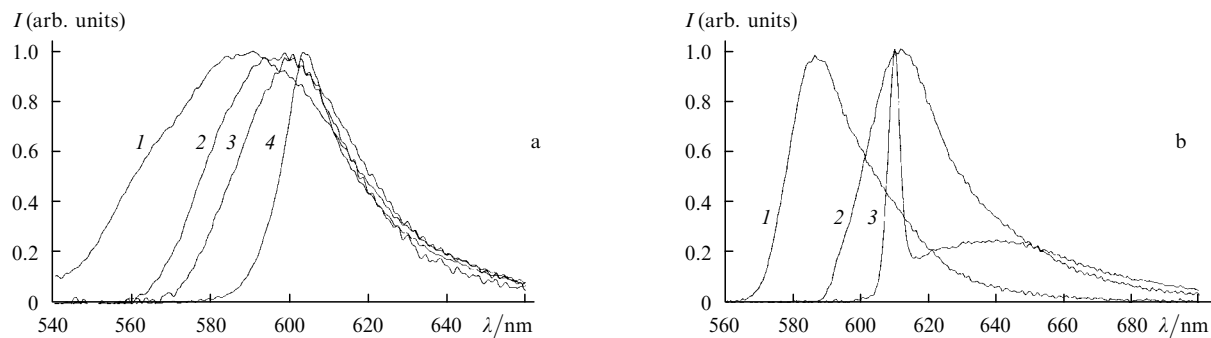
Thus, the pump conversion efficiency in transversely pumped dye-doped polymer fibres with the optimal set of parameters (dye concentration, the absence of defects, the resonator  $Q$  factor) developed in our paper can be comparable with that in more complicated graded-index polymer fibres ( $\xi = 18\%$  for R11B and this value should increase up to 36% after the deposition of a highly reflecting mirror on one of the ends of the element).

The obtained result shows that the main factor providing the high pump radiation conversion efficiency is the degree

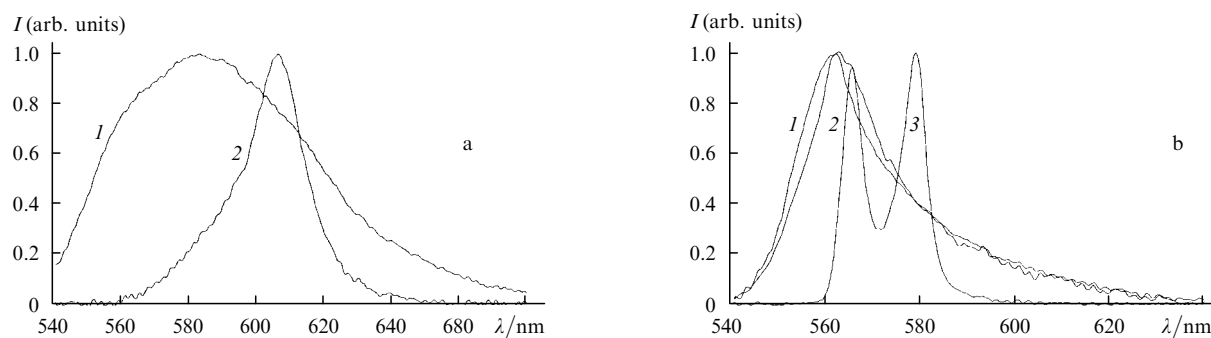
of polymer matrix ordering rather than the fibre structure. Otherwise the efficiency for samples of the simplest structure studied in this paper would be considerably lower than that obtained here. The method of fibre drawing from a preform that we used in our study is similar to the final stage of the manufacturing technology of graded-index polymer fibres, and it is this technological procedure that provides the high degree of orientation of produced polymers. This circumstance suggests that there is reason to hope that PAFDs fabricated by us will have a considerable operating life.

Unlike mechanical properties affecting the operating life, the high conversion efficiency in oriented polymer samples is determined by the degree of orientation of a polymer matrix only indirectly. When macromolecules of a polymer matrix are oriented during fibre drawing, asymmetric elongated molecules of organic dyes doped into this matrix are also oriented along the fibre axis. It seems that oriented dye molecules in the polymer matrix provide the higher pump conversion efficiency compared to weakly oriented samples obtained from block polymer matrices. Probably, the transverse pumping is more efficient than the longitudinal one for the same reason. Absorption and emission of radiation by organic dyes has, as a rule, the dipole nature, and the presence of directions in which almost completely polarised laser radiation is absorbed more efficiently in oriented fibres is quite real. This problem requires a special study, which we plan to perform in the future. We also plan to investigate the photostability of dye-doped polymer fibre laser elements.

(iii) Dye-doped polymer fibre amplifiers were studied using the setup shown schematically in Fig. 7. Radiation from a dye laser (the P512 dye in ethanol) ( $\lambda = 617$  nm,  $\tau = 15$  ns,  $W = 70$   $\mu$ J) was focused on the fibre end face. The fibre was excited transversely by the second harmonic of a



**Figure 5.** Emission spectra observed upon longitudinal pumping of active polymer fibres doped with DCM at concentrations 0.1 (1), 0.5 (2), 1 (3), and 5 mmol L<sup>-1</sup> (4) (a) and with P512 at concentrations 0.1 (1), 1 (2), and 3.6 mmol L<sup>-1</sup> (b).



**Figure 6.** Emission spectra observed upon transverse pumping of active polymer fibres doped with DCM at concentrations 0.1 (1) and 5 mmol L<sup>-1</sup> (2) (a) and with R11B at concentrations 0.05 (1), 0.1 (2), and 1 mmol L<sup>-1</sup> (3) (b).

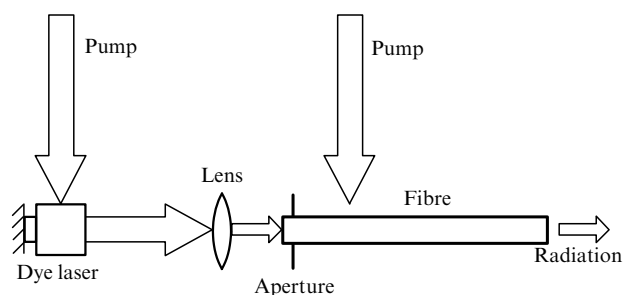


Figure 7. Excitation scheme of a fibre amplifier.

Nd:YAG laser. The radiation was focused by a cylindrical lens to a rectangle of size  $5 \text{ mm} \times 0.4 \text{ mm}$  at a distance of 17 mm from the fibre end face through which radiation from the master oscillator (the dye laser) was coupled.

The results of the study of radiation amplification in polymer fibres are presented in Table 3. The gain  $\theta$  was determined as the ratio of intensities of dye laser radiation transmitted through the excited (pumped) and unexcited (in the absence of pumping) fibre pieces.

Table 3. Parameters of fibre amplifiers.

Dye	$C_d/\text{mmol L}^{-1}$	Gain/ $\text{dB m}^{-1}$
R11B	0.05	5
	0.1	6
P512	0.1	8
	1.0	21
	3.6	25
DCM	0.1	3
	0.5	6
	1.0	12
	5.0	19

One can see from Table 3 that the gain in a polymer fibre doped with R11B is weak ( $\theta = 5 - 6 \text{ dB m}^{-1}$ ), which is caused by a small overlap between the emission line of the master oscillator and the absorption band of the dye. As the R11B concentration was increased, stimulated emission appeared at  $\sim 570 \text{ nm}$  (Fig. 8c), resulting in the disappearance of inversion in the volume. For this reason, it is reasonable to use R11B-doped fibres for amplification of shorter-wavelength radiation (580–600 nm).

The best results were obtained for P512-doped fibres. The maximum value of  $\theta$  was  $\sim 25 \text{ dB m}^{-1}$ . For DCM-doped fibres, this value was somewhat lower ( $\sim 20 \text{ dB m}^{-1}$ ) due to insufficient absorption of the pump radiation, as pointed out above.

Figure 8 presents typical emission spectra of the fibre amplifier in the presence and absence of the signal from the maser oscillator. One can see from these spectra that all the dyes amplify probe radiation at 617 nm. In the case of P512 and DCM dyes, the radiation energy is completely transferred to the region near 617 nm (broadband emission observed in the fibre amplifier excited without the driving pulse is absent). In the R11B-doped fibre, which has the shortest-wavelength emission spectrum compared to other dyes under study, no complete energy transfer to the emission band of the master oscillator occurs. For this reason, both the amplified emission of the probe signal at 617 nm and stimulated emission at 580 nm in the fibre

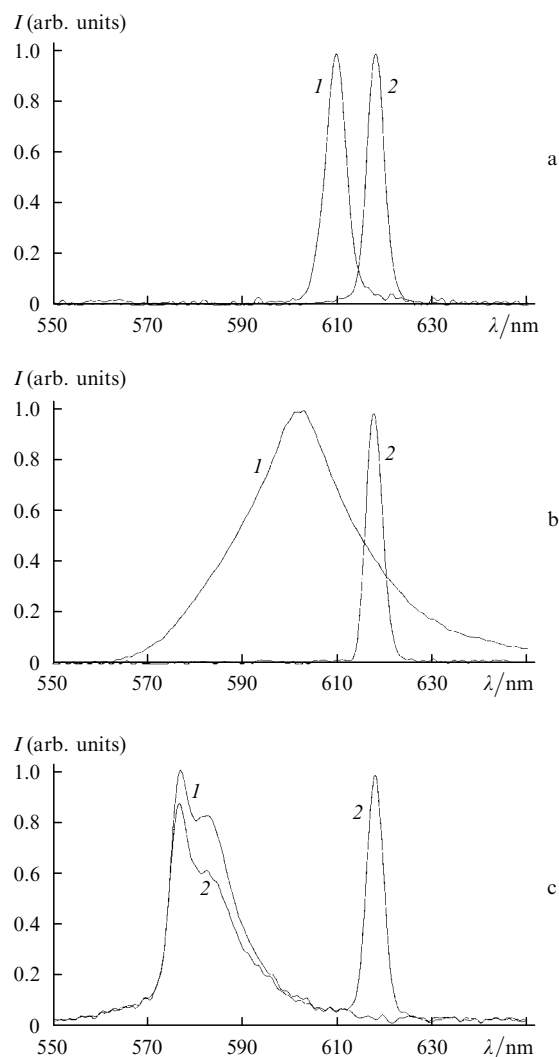


Figure 8. Emission spectra of the amplifier in the absence ( $I_1$ ) and presence ( $I_2$ ) of a signal from the master oscillator for P512 ( $3.6 \text{ mmol L}^{-1}$ ) (a), DCM ( $1 \text{ mmol L}^{-1}$ ) (b), and R11B ( $0.2 \text{ mmol L}^{-1}$ ) (c).

amplifier are observed. Fibres doped with R11B will amplify more efficiently radiation in the region 580–600 nm.

Thus, the amplification parameters of dye-doped polymer fibres studied in this paper show that these fibres are promising for practical applications.

## 4. Conclusions

Let us formulate the main results of the study.

(i) The technology has been developed for fabricating active polymer optical fibres doped with organic dyes.

(ii) Stimulated emission of organic dyes R11B, P512, and DCM in polymer optical fibres pumped by the second harmonic of a Nd:YAG laser has been studied in the long-wavelength visible region. It has been shown that the lasing efficiency for a transversely pumped R11B-doped fibre achieves 36%.

(iii) The maximum gain ( $25 \text{ dB m}^{-1}$ ) has been achieved for the P512 dye at a wavelength of 617 nm.

(iv) The optimal concentration of R11B found from the study of lasing parameters of transversely pumped samples is close to  $1 \text{ mmol L}^{-1}$ . The optimal concentrations of phenalemine and DCM probably have not been achieved.

Therefore, it is necessary to fabricate and study new samples containing dyes at higher concentrations. The optimal diameter of fibres is 0.8–1.0 mm.

(v) The obtained results show that active polymer optical fibres fabricated in the study are promising for practical applications in tunable fibre lasers and amplifiers.

**Acknowledgements.** This work was partially supported by the Russian Foundation for Basic Research (Grant Nos 05-02-98005-r-ob', 06-02-96907-r-ofi, and 06-08-00624) and the Foundation for Assistance in the Development of Small Scientific and Technical Enterprises (State Contract No. 2900r/3642).

## References

1. McFarland B.B. *Appl. Phys. Lett.*, **10**, 208 (1967).
2. Peterson O.G., Snavely B.B. *Appl. Phys. Lett.*, **12**, 238 (1968).
3. Costela A., Garcia-Moreno I., Gomez C., Garcia O., Sastre R. *Appl. Phys. B*, **75**, 827 (2002).
4. Costela A., Garcia-Moreno I., Gomez C., Garcia O., Sastre R. *Appl. Phys. B*, **78**, 629 (2004).
5. Costela A., Garcia-Moreno I., Gomez C., Garcia O., Sastre R., Roig A., Molins E. *J. Phys. Chem. B*, **109**, 4475 (2005).
6. Garcia-Moreno I., Costela A., Cuesta A., Garcia O., Agua D., Sastre R. *J. Phys. Chem. B*, **109**, 21618 (2005).
7. Duarte F.J., James R.O. *Opt. Lett.*, **28**, 2088 (2003).
8. Duarte F.J., James R.O. United States Patent 6,888,862 (2005).
9. Duarte F.J., James R.O. *Appl. Opt.*, **43**, 4088 (2004).
10. Koike Y., Ishigure T., Nihei E. *J. Lightwave Technol.*, **13**, 1475 (1995).
11. Van den Boom H.P.A., Li W., Van Bennekom P.K., Monroy I.T., Khoe G.-D. *IEEE J. Sel. Top. Quantum Electron.*, **7**, 461 (2001).
12. Stone J. *J. Quantum Electron.*, **8**, 386 (1972).
13. Tagaya A., Teramoto S., Yamamoto T., Fujii K., Nihei E., Koike Y., Sasaki K. *J. Quantum Electron.*, **31**, 2215 (1995).
14. Tagaya A., Koike Y., Nihei E., Teramoto S., Fujii K., Yamamoto T., Sasaki K. *Appl. Opt.*, **34**, 988 (1995).
15. He G.S., Bhawalkar J.D., Zhao C.F., Park C.-K., Prasad P.N. *Opt. Lett.*, **20**, 2393 (1995).
16. Peng G.D., Chu P.L., Xiong Z., Whitebread T.W., Chapin R.P. *J. Lightwave Technol.*, **14**, 2215 (1996).
17. Tagaya A., Teramoto S., Nihei E., Sasaki K., Koike Y. *Appl. Opt.*, **36**, 572 (1997).
18. Vigil S.R., Zhou Z., Canfield B.K., Tostenrude J., Kuzyk M.G. *J. Opt. Soc. Am. B*, **15**, 895 (1998).
19. Kobayashi T., Blau W.J. *Electron. Lett.*, **38**, 67 (2002).
20. Saito M., Honda A., Uchida K. *J. Lightwave Technol.*, **21**, 2255 (2003).
21. Gvishi R., Ruland G., Prasad P.N. *Opt. Commun.*, **126**, 66 (1996).
22. Ohtsuka Y., Nihei E., Koike Y. *Appl. Phys. Lett.*, **57**, 120 (1990).
23. Koike Y., Nihei E., Tamio N., Ohtsuka Y. *Appl. Opt.*, **29**, 2686 (1990).
24. Ishigure T., Nihei E., Koike Y. *Appl. Opt.*, **33**, 4261 (1994).
25. Kuriki K., Kobayashi T., Imai N., Tamura T., Nishihara S., Nishisawa Y., Tagaya A., Koike Y. *Appl. Phys. Lett.*, **77**, 331 (2000).
26. Jiang C., Kuzuk M.G., Ding J.-L., Johns W.E., Welker D.J. *J. Appl. Phys.*, **92**, 4 (2002).