Microstructured polymer fiber laser

Alexander Argyros

Australian Photonics Cooperative Research Centre, Optical Fibre Technology Centre and School of Physics, University of Sydney, Sydney, NSW 2006, Australia

Martijn A. van Eijkelenborg and Stuart D. Jackson

Australian Photonics Cooperative Research Centre, Optical Fibre Technology Centre, University of Sydney, Sydney, NSW 2006, Australia

Richard P. Mildren

Centre for Lasers and Applications, Macquarie University, Sydney, NSW 2109, Australia

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A microstructured polymer optical fiber doped with Rhodamine 6G dye was fabricated and demonstrated as an optical amplifier and a fiber laser. As an amplifier, the fiber achieved a gain in excess of 30 dB. As a pulsed fiber laser, the fiber exhibited a threshold of 20 μJ, a slope efficiency of 18%, and a lifetime as high as 130,000 shots at 10 Hz. The maximum output energy was 16 μJ. The advantages that such fibers offer lie in the simplicity and flexibility of their fabrication and in their potential for use as compact, tunable solid-state sources.

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Solid-state dye lasers, consisting of an organic dye dissolved in a solid matrix, have been the subject of much interest since their demonstration nearly four decades ago.[1,2] The dyes, most commonly dissolved in solgels or polymers, have large absorption and emission cross sections and are tunable from the UV to the near IR. Solid-state dye lasers offer practical advantages such as compactness as well as alleviating some disadvantages associated with the flammable and volatile organic solvents used in liquid dye lasers.

One way to form solid-state dye lasers is to dissolve the dye in a monomer before polymerization, often with additives to increase the solubility of the dye in the monomer or to improve the stability or physical properties of the final product.[3–7] The resultant doped polymer can be used in its bulk form[3,7] or drawn to make a polymer optical fiber.[5,6] As a practical alternative, we present a microstructured polymer optical fiber[8] (mPOF) doped by a much simpler postpolymerization doping method.[9] The method of fabrication is not dye specific, so a wide variety of organic dyes can be used to produce specific properties of the amplifier or laser.

One fabricates microstructured polymer optical fibers by drilling the desired pattern of holes (see Fig. 1) into an 8-cm-diameter preform made from commercially available poly(methyl methacrylate) (PMMA). The preform is drawn to form an intermediate preform that is in turn sleeved and drawn to fiber.[8] To produce doped mPOF, one fills the holes of the intermediate preform with a solution of the dye.[9] The small solvent molecules enter the PMMA and plasticize it, allowing the larger dye molecules to enter the matrix.[10] Solvents with low boiling points are used, as they can easily be removed by heating once the doping is complete. Heating also allows the dye to diffuse evenly throughout the core region and, by removing the solvent, locks the dye in place. The generally large dye molecules are mobile in the polymer only in the presence of a solvent.[9]

For the fiber reported here, the intermediate preform was 6 mm in diameter. We exposed it to a saturated solution of Rhodamine 6G dye (R6G) and acetone for 30 s (by drawing the solution into the holes) and then heated it at 90 °C for 16 h. After this treatment the position of the dye was fixed and was observed to remain unchanged even after two months of further heating, indicating the thermal stability of the dye distribution. The final concentration of the dye in the core was estimated to be 1 mmol/l. The preform was sleeved in a 12-mm tube and drawn to fiber with a 600-μm outer diameter (Fig. 1), a core size of 18 μm, a hole diameter d of 3.5 μm, and a hole spacing Λ of 5.2 μm, thus giving $d/\Lambda = 0.67$. A N.A. of 0.19 and a launch efficiency of 26% were measured at $\lambda = 532$ nm by use of a 16× microscope objective. A large core was chosen to increase the launch efficiency.

We first tested the fiber as a fiber amplifier by using the experimental setup shown in Fig. 2, by pumping the core at 532 nm with a frequency-doubled Q-switched Nd:YAG laser operated at 10 Hz. A small signal (~1 nJ/pulse) was provided by a conventional dye laser with R6G dissolved in methanol that could be tuned from approximately 560 to 585 nm. The pulses from the two lasers arrived simultaneously

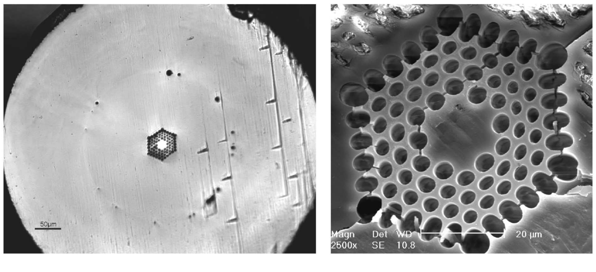

Fig. 1. Left, optical microscope image of a typical mPOF used in this research and right, a scanning-electron microscope image of the 18-μm-diameter core region.

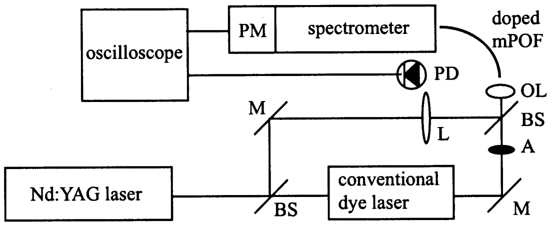

Fig. 2. Setup used in the gain measurements: BSs, beam splitters; M's, mirrors; A, attenuator; L, lens; OL, objective lens; PM, photomultiplier; PD, photodiode. The photodiode was used to trigger the oscilloscope.

at the fiber; the pulses were 10 and 8 ns long for the Nd:YAG and the dye lasers, respectively. The spectral output of the mPOF was measured with a 0.5-m spectrometer with a photomultiplier mounted onto the output slit. For a 2-m length of fiber it was determined that, within the signal's (dye laser's) tuning range, the gain was maximum near 574 nm. Figure 3 shows the gain measured at 574 nm as the pump power was increased. The maximum gain observed was 30.3 dB (a factor of 1072), requiring a launched pump energy of 325 μJ/shot (peak power of 32.5 kW). The gain saturates near that value, and the reason for the low efficiency of 0.3% is that a significant amount of amplified spontaneous emission is produced, caused by the large emission cross section of the dye, the high peak pump power, and, to a lesser extent, the N.A. of the fiber. A higher signal power is expected to increase the efficiency, as it would allow the signal, rather than the spontaneous emission, to dominate the stimulated emission.

Blocking the signal and adjusting the launch conditions caused the output of the fiber to change color, from yellow (fluorescence) to red. A broader spectrum of the output was taken (Fig. 4), and an intense and very narrow peak was observed near $\lambda = 632$ nm, superimposed upon a much weaker background fluorescence. Interference among the various modes of the fiber was observed for the red output, indicating that the red light emitted from the fiber was coherent. The coherence and the sharp, narrow peak are consistent with the fiber lasing. Further fiber samples ranging in length from 2.0 m to 5 cm were also observed to lase. No additional mirrors were required with the cavity being formed between the cleaved ends of the fiber. No special care was taken to polish the ends or to cool the fiber. The laser line appears at $\lambda = 631.9 \pm 0.3$ nm with a full width at half-maximum of 0.5 ± 0.1 nm, which is significantly narrower than the 6-nm linewidths reported for other PMMA–R6G fiber lasers.[5] The errors given here arise from statistical variations from fiber to fiber. The temporal profile of the output is presented in Fig. 5, showing a full width at half-maximum of 8 ns.

The performance of a 1.5-m length of fiber as the pump energy is increased is shown in Fig. 5. A threshold of 20 μJ and a slope efficiency of 18% were observed when the fiber was pumped at 10 Hz. This result is quite satisfactory, given that the intrinsic loss of the fiber is 3 dB/m at both the pump and the lasing wavelengths (with an additional loss of at least 20 dB/m at 532 nm that is due to the dye absorption). The maximum copropagating (with respect to the pump) output observed was 16 μJ/pulse, giving a peak power of 2 kW; this power was limited by the damage threshold of the polymer, which was estimated to be 13 GW/cm^2. The counterpropagating output was found to be small in comparison, i.e., ~1% of the copropagating value. This smaller output is believed to be a result of combining a long cavity with a short, high-power pump pulse and a gain medium with a short fluorescence lifetime [4.8 ns (Ref. 4)]. The high emission cross section of the dye and the high-power pump pulse will result in most of the gain being depleted in the first pass by the laser pulse. Combined with the weak reflections off the fiber ends and the high loss of the fiber, this effect will result in little feedback to which little gain will be available, resulting in the large imbalance between copropagating and counterpropagating outputs.

As in all solid-state dye lasers, the output was observed to diminish with the number of shots because of photodegradation of the dye. An extrapolated half-life of 80,000 shots was measured with a pump energy of 185 μJ/shot, which increased to 130,000 shots when

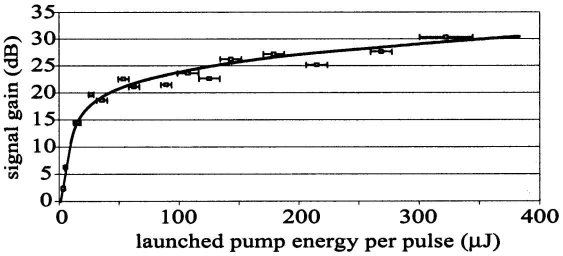

Fig. 3. Gain at $\lambda = 574$ nm as a function of the launched pump energy.

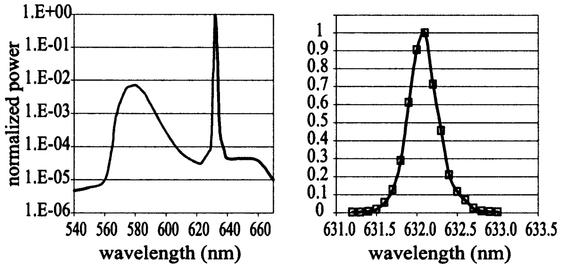

Fig. 4. Left, spectrum of the output of the mPOF laser and right, the spectrum near 632 nm on a linear scale.

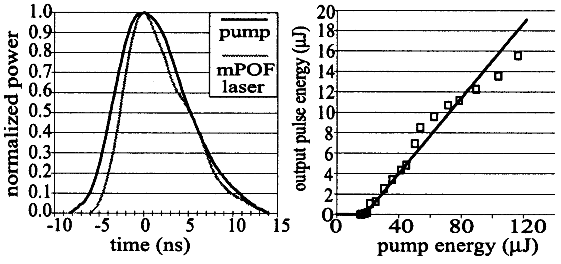

Fig. 5. Left, normalized power temporal profiles for the pump and the mPOF laser. Right, output pulse energy from the dye-doped mPOF laser at 632 nm as a function of the launched pump energy at 532 nm.

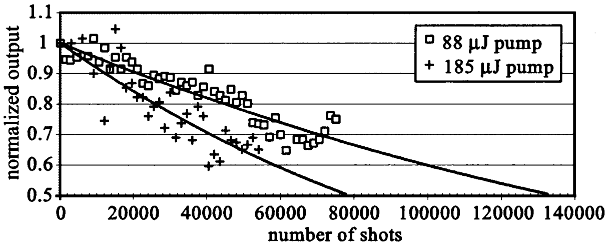

Fig. 6. Pulse energy of the mPOF laser as a function of the number of shots for two launched pump energies.

the pump energy was reduced to 88 μJ/shot, as shown in Fig. 6. This is a slight improvement on values reported earlier.

We also investigated the effects on the properties on the mPOF laser of the dye concentration and the solvent used for the doping. Three more fibers were fabricated, with different concentrations of R6G, and a fourth fiber, which used methanol solvent. Methanol is a better solvent for R6G than acetone and is a nonsolvent for PMMA, allowing for longer exposure and higher concentrations to be obtained. The concentration of dopant for these fibers was estimated to range from 0.6 to 1.3 mmol/l, as determined by examination of the wavelength of maximum fluorescence, which depends on concentration,[11] and by thermogravimetric analysis. Various lengths of these fibers that ranged from 0.9 to 2.0 m were tested, and all were found to lase at the same wavelength as the original fiber and with the same linewidth. This result shows that the lasing wavelength and linewidth are highly reproducible and insensitive to the dye concentration and to the fiber length for the range of values used here. They were also insensitive to the solvent used for doping, as expected, because the solvent is removed at the preform stage. The lasing efficiency was found to decrease for lower dye concentrations.

The fluorescence maximum and lasing wavelengths observed here are shifted to the red by 30 nm compared with those reported elsewhere[3–5,7] for similar systems. It has been observed that one can achieve wavelength shifts to the red by increasing the concentration of R6G in PMMA,[11] mostly by reabsorption of the emitted radiation, which affects the blue end of the emission spectrum. The same effect is produced by the fiber geometry used here, in which the laser light travels through relatively long lengths of doped material, significantly increasing its interaction with the dye. Because no dependence of the lasing wavelength on concentration or length was observed here (within the ranges tested), we have concluded that in all cases the concentration–length products were too large and the reabsorption effects were saturated. The postpolymerization doping method and the absence of additives in the PMMA may also change the local environment of the dye molecules, which will also affect the lasing wavelength.

In conclusion, using a simple doping technique, we have produced what is to our knowledge the first doped microstructured polymer optical fiber amplifier and fiber laser. Its main advantage is the simplicity of fabrication and operation, with a consistent wavelength and a narrow linewidth obtained independently of the various fiber parameters and with no additional mirrors required, despite the high intrinsic loss of the fiber. Our future research will focus on demonstrating this technique at other wavelengths with other dyes and on improving the efficiency. Moreover, we aim to investigate tunable mPOF lasers by taking advantage of the broad tuning range of fiber Bragg gratings in polymer fibers.[12]

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