Fabrication and characterization of dye mixture doped polymer optical fiber as a broad wavelength optical amplifier

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Rhodamine 6G and Rhodamine B dye mixture doped polymer optical fiber amplifier (POFA), which can operate in a broad wavelength region (60 nm), has been successfully fabricated and tested. Tunable operation of the amplifier over a broad wavelength region is achieved by mixing different ratios of the dyes. The dye doped POFA is pumped axially using 532 nm, 10 ns laser pulses from a frequency doubled Q-switched Nd: YAG laser and the signals are taken from an optical parametric oscillator. A maximum gain of 22.3 dB at 617 nm wavelength has been obtained for a 7 cm long dye mixture doped POFA. The effects of pump energy and length of the fiber on the performance of the fiber amplifier are also studied. There exists an optimum length for which the amplifier gain is at a maximum value. © 2008 Optical Society of America

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1. Introduction

Polymer optical fibers (POFs) have attracted much attention during the past two decades for short distance communication because of their unique characteristics, such as flexibility, ease of handling, and relative low cost in coupling [1–3]. Although higher loss factor is a major handicap for POF, recently developed techniques for decreasing losses in polymethyl methacrylate (PMMA) based POF have raised much interest in this field [4,5]. The implementation of optical communication in the visible region demands the development of suitable optical amplifiers working in this region. POFs doped with dyes or rare earth elements are potential candidates for this purpose [6–16]. Laser dyes, which act as highly efficient media for lasing and amplification, have a wide range of tunability in the visible region. Dye molecules that have large absorption and induced emission cross sections due to allowed π–π transitions are ideal active dopants for the generation and amplification of intense light pulses. The advantage of incorporating laser dyes in solid matrices such as POF is that it is easier and safer to handle them than when they are in liquid form. The first optical amplification in dye doped polymer optical fiber was demonstrated by researchers in Japan [8,9]. In their experiment using a dye-doped gradient index (GI) POF, maximum gain of 27 dB was achieved at 591 nm wavelength with a pump power of 11 kW. Also, Peng *et. al.* have achieved high gain and high efficiency optical amplification in a rhodamine (Rh) B doped POF with a low pump power of 1 kW, [7], and Karimi *et al.* have reported a high gain of 30 dB in Rh B doped POF [13]. A microstructured POF fiber based amplifier with a high gain of 30 dB has been reported by Argyros *et al.* [17]. Reilly *et al.* have achieved a gain of 14 dB in a polymer waveguide with dye doped cladding [18]. A rare earth doped POF

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is also a potential candidate for the development of optical amplifiers [19].

Perhaps the most unique advantage of a dye doped polymer is the fact that it can be impregnated with several different dyes simultaneously to make a broadband amplifier [20–22]. Implementation of wavelength-division-multiplexed optical communication systems demand the development of optical fiber amplifiers that can be operated in a broad wavelength region. In this paper we report the development of a dye mixture doped polymer optical fiber amplifier (POFA) that can be used for amplifying signals in a broad wavelength region of the visible spectrum.

2. Experiment

The dye doped POFs used for the present studies are based on PMMA. PMMA is chosen as the host, as it has good optical quality and is compatible with most of the organic dyes used as dopants. It has to be noted here that the vibrations of carbon—hydrogenC—H bonds and its harmonic waves are a main cause for the absorptive losses encountered in PMMA polymer fibers, along with the Rayleigh scattering losses. In particular, the harmonic waves at 627 nm (sixth harmonic wave) and 736 nm (fifth harmonic wave) essentially determine the level of attenuation within the application range of PMMA-POF [23]. The dyes used as dopants are Rh 6G and Rh B, which have high quantum yield, low intersystem crossing rate, low excited state absorption at both pump and lasing wavelengths, and reasonably good photostability. The dye doped POF for the present study is fabricated as described in our previous paper [16,24].

A schematic of the experimental setup for the amplification studies is shown in Fig. 1. The pump source is a frequency doubled Q-switched Nd:YAG laser at 532 nm wavelength, and the signal source is a tunable output from an optical parametric oscillator (OPO), which is pumped by the third harmonic at 355 nm from the same Nd:YAG laser. The full width at half-maximum of both the signal and the pump pulses is about 10 ns, and the repetition rate of the pulses is 10 Hz. The pump beam is combined with the signal beam both temporally as well as spatially by using an appropriate optical delay system and beam splitter and they are coaxially launched into the dye doped POF. A convex lens of 7 cm focal length is used to focus the pump and signal beams to the fiber. A photodetector of 1 ns response time (Newfocus 1621) along with a 1 GHz digital storage oscilloscope (Tektronix TDS 540) are used to monitor the amplified output. A monochromator CCD–PC assembly (Acton Spectrapro) is used to study the spectral response of the output signal. For investigating the effect of pump pulse energy and length of the dye doped POF on the gain of the amplifier, pump energy is varied 0.01–0.07 mJ/pulse and the length is varied 3–11 cm. The signal pulse energy is kept at 0.1 μJ/pulse.

For investigating the increase in gain bandwidth of a dye mixture doped POFA compared to a single dye doped POFA, four fiber samples with a diameter of 510 μm are used having the following dye concentrations: (a) Rh 6G (0.25 mM), (b) Rh 6G (0.25 mM) and Rh B (0.11 mM), (c) Rh 6G (0.25 mM) and Rh B (0.25 mM), and (d) Rh B (0.25 mM).

3. Results and Discussion

Figure 2 shows a comparison of fluorescence emission from POF doped with a Rh 6G and Rh 6G–Rh B dye mixture and Rh B at a pump energy of 0.06 mJ/pulse. Energy transfer of Rh 6G:Rh B dye mixtures in a PMMA matrix has been well studied by several researchers [25]. The main mechanisms that have been proposed for such an energy transfer are (1) radiative transfer, i.e., absorption of donor emission by an acceptor, (2) diffusion controlled collisional transfer, and (3) resonance transfer via dipole–dipole interaction [26,27]. The origin of resonance transfer is the long-range dipole–dipole Coulomb in-

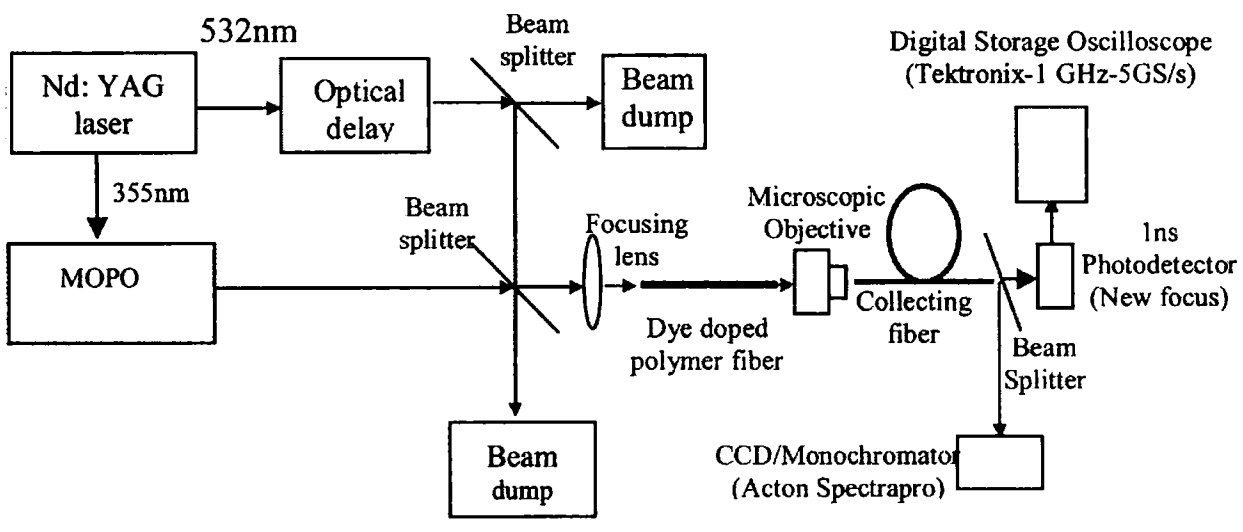

Fig. 1. Experimental setup for the amplification studies in dye doped POF.

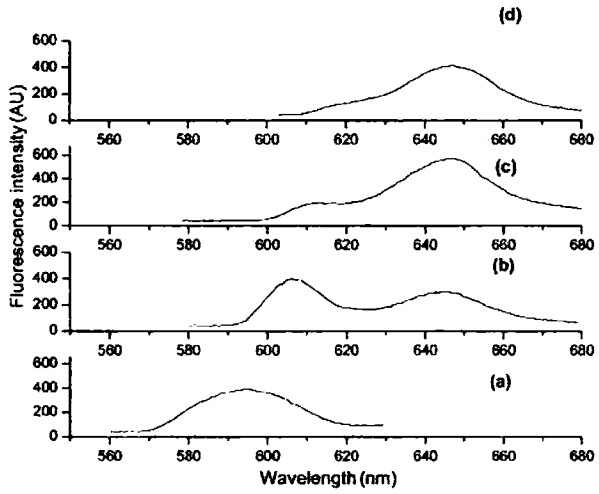

Fig. 2. Shift of fluorescence emission peak due to nonradiative energy transfer process in dye mixture doped POF (a) Rh 6G (0.25 mM), (b) dye mixture Rh 6G (0.25 mM) and Rh B (0.11 mM), (c) dye mixture Rh 6G (0.25 mM) and Rh B (0.25 mM), and (d) Rh B (0.25 mM). Pump energy is 0.06 mJ/pulse.

teraction [28]. The probability of such an energy transfer is large if the emission spectrum of the donor strongly overlaps with the absorption spectrum of the acceptor. Such a strong overlap of the emission spectrum of Rh 6G (donor) with the absorption spectrum of Rh B (acceptor) has been reported [29]. Radiationless energy transfer in the laser dye mixture consisting of Rh 6G (donor) and Rh B (acceptor) has also been studied using fluorescence lifetime measurements [30].

In Fig. 2(b), the fluorescence spectrum from the POF doped with Rh 6G (0.25 mM) and Rh B (0.11 mM) shows a red shift in comparison with that of Rh 6G (0.25 mM) doped POF (Fig. 2(a)), confirming that energy transfer occurs from Rh 6G(donor) to Rh B(acceptor) [25–30]. Fig. 2(b) also shows an enhancement of spectral width up to 60 nm compared to the 40 nm spectral width of Rh 6G doped POF (Fig. 2(a)). This indicates the potentiality of the dye mixture doped POF as a medium for broad wavelength light amplification. Also, the tunable operation of the amplifier in different wavelength regions can be achieved by mixing specific ratios of the dyes. When both Rh 6G and Rh B are present in equal concentration (0.25 mM), the spectrum shifts more toward the emission region of Rh B (Fig. 2(c)). This is because maximum energy transfer occurs when both dyes are taken in equal concentration [31]. Fig. 2(d) represents the fluorescence spectrum corresponding to Rh B (0.25 mM).

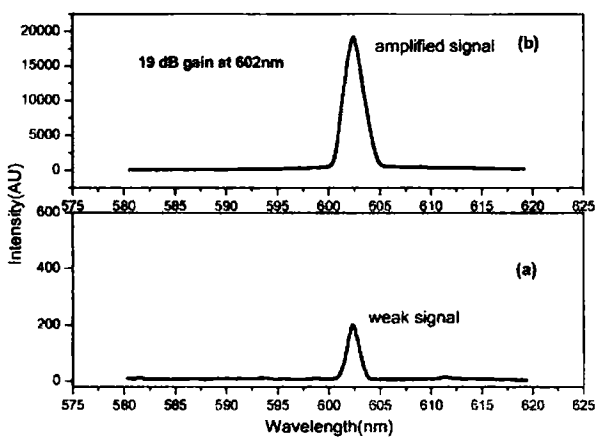

Fig. 3. Amplification of a weak signal at 602 nm in a 7 cm long dye mixture doped POF amplifier [Rh 6G(0.25 × mM) and × Rh B (0.11 × mM)]. Pump energy is 0.06 mJ/pulse.

To check the efficiency of the dye doped POF as an optical amplifier, experiments are carried out to measure the amplification factor by injecting a weak signal (at 602 nm) and measuring the output intensity with and without the pump beam. Pump pulse energy is 0.06 mJ, and the length of the POFA is always selected as 7 cm. As can be seen from Fig. 3, there is a clear signal amplification in the presence of the pump source, which proves beyond doubt that dye doped optical fiber can be used effectively as an amplifier in a communication link in the visible spectral region.

Figure 4 depicts the gain for different signal wavelengths in the case of the above mentioned four dye doped POF samples under study. A maximum gain of 18.6 dB at 592 nmand a gain bandwidth of 40 nm (574–610 nm) are achieved in the case of a Rh 6G (0.25 mM) doped POFA (Fig. 4(a)). In the case of Rh 6G (0.25 mM) and Rh B (0.11 mM) doped POFAs, a maximum gain of 20.5 dB is achieved at a redshifted wavelength of 608 nm (Fig. 4(b)). A redshift of the maximum gain wavelength is due to the shift in the fluorescence emission peak resulting from the energy transfer process in a Rh 6G–Rh B dye mixture system. The enhancement in the gain factor (20.5 dB) is the result of the increase in total dye concentration. Also, an increased gain bandwidth of about 60 nm (596–

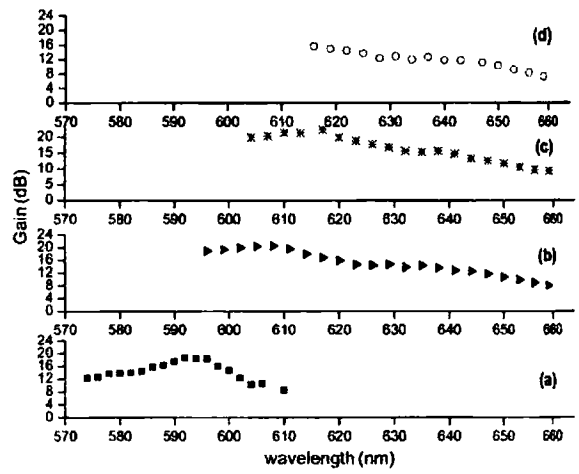

Fig. 4. Gain for different signal wavelengths in a 7 cm long dye doped POFA at a pump energy of 0.06 mJ/pulse: (a) Rh 6G (0.25 mM), (b) dye mixture Rh 6G (0.25 mM) and Rh B (0.11 mM), (c) dye mixture Rh 6G (0.25 mM) and Rh B (0.25 mM), and (d) Rh B (0.25 mM).

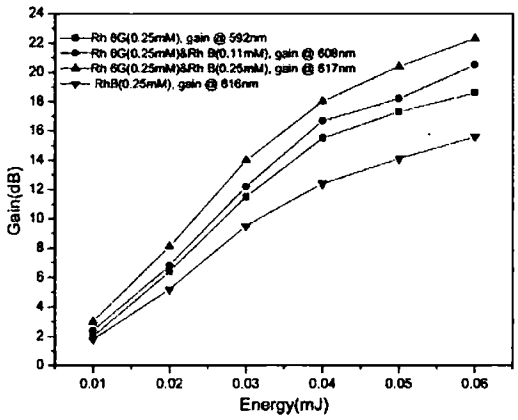

Fig. 5. Gain dependence on the input pump energy of the dye doped POFA. Here the fiber length is 7 cm.

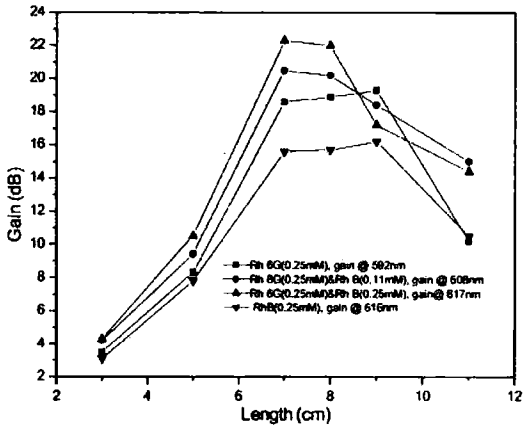

Fig. 6. Gain dependence on the length of the POFA. Here the pump energy is 0.06 mJ/pulse.

660) is obtained in dye mixture doped POFA. In the case of Rh 6G (0.25 mm) and Rh B (0.25 mM) doped POFA a maximum gain of 22.3 dB is observed at 617 nm, which is higher than in the previous two cases because of the presence of more dye molecules (Fig. 4(c)). Here also the gain bandwidth is about 60 nm. In a Rh B (0.25 mM) doped POFA a maximum gain of 15.6 dB is observed at 616 nm (Fig. 4(d)).

Figure 5 shows the variation of gain with the input pump energy for the four fiber samples under study. Amplified spontaneous emission or resonant lasing is not observed from the fiber when the pump energy is varied from 0.01 to 0.07 mJ/pulse. A linear relation between the gain and the launching pump energy is observed up to 0.03 mJ/pulse. Above 0.03 mJ, the relationship deviates from linearity, showing a tendency of gain saturation. The saturation behavior is essentially because, as the pump energy is increased, more and more dye molecules become inverted, and for large pump energies almost all of the dye molecules are inverted. Hence there would be no more increase in inversion and hence gain. [7–11].

Figure 6 shows the variation in gain with length of the dye doped POFA at a pump energy of 0.06 mJ/pulse. It is clear from the plot that the gain increases with length up to an optimum length (L_z) for which the amplifier gain is maximum, and after this length the gain reduces [7–11]. Signal gain increases up to this optimum length due to the stimulated emission in the inverted medium that dominates the signal absorption. Intensity of the pump beam gets reduced along the POFA as length increases due to absorption by the dye molecules. This results in a decrease of the population inversion of the medium as length increases. Thus the signal absorption along the fiber medium dominates the stimulated emission beyond a certain length and the signal gain reduces. In the case of Rh 6G (0.25 mM) doped POFA and Rh B (0.25 mM) doped POFA, the optimum length for maximum gain is 9 cm at signal wavelengths 592 nm and 616 nm, respectively, and further increase in the length reduces the gain of the amplifier. In the case of the two dye mixture doped POFA, optimum length occurs at a shorter distance of 7 cm. This is because, with an increase in dye density, the optimum length of the amplifier becomes shorter. This optimum length actually depends on the input pump energy because a longer length of inverted medium can be achieved by a higher pump energy [32]. The fact that we can have a high gain of, say, 22 dB for a length of 7 cm is an advantage of dye doped POFA in comparison with erbium doped fiber amplifier (EDFA), which needs a length of several meters to attain optimum gain [33,34].

One of the main concerns in developing solid-state dye doped gain media is their photostability. In order to investigate the photostability of the dye doped POF, a typical sample, Rh 6G (0.25 mM) and Rh B (0.11 mM) doped POF, is continuously pumped by the laser pulses of energy 0.06 mJ at which the amplification experiment is carried out and the fluorescence spectrum is recorded as a function of time for 300 minutes at intervals of 5 minutes. The fluorescence emission intensity at a typical wavelength (at 605 nm) is plotted against the time of exposure of the pump and is shown in Fig. 7. The figure shows that the fluorescence intensity is unaltered up to 180,000 shots of pump pulse which indicates the stability of POFA within the duration of the optical amplification experiment.

4. Conclusion

A broad wavelength light amplifier has been successfully fabricated from a Rh 6G:Rh B dye mixture doped POF. An increased gain bandwidth of about 60 nm is obtained in a Rh 6G:Rh B dye mixture doped POF amplifier compared to the 40 nm gain bandwidth of a Rh 6G doped POFA. Tunable operation of an amplifier in a different wavelength region is achieved by mixing different ratio of dyes. A high gain of 22 dB is achieved at 617 nm from a 7 cm long dye mixture doped POFA. There exists an optimum length for the amplifier at which the gain is maximum, and this length in the case of a dye doped POFA is much shorter than the conventional EDFA, which needs several meters to have optimum gain. It is observed that the gain increases with pump energy and a tendency of gain

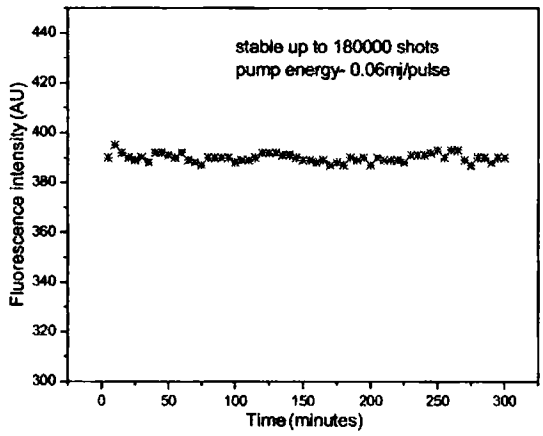

Fig. 7. Fluorescence intensity (for a typical sample Rh 6G (0.25 mM) and Rh B (0.11 mM) doped POF (at 605 nm) versus the time of exposure of the dye doped POF to the pump pulse of energy 0.06 mJ at 532 nm.

saturation occurs at higher pump energies. The dye doped POFA is found to be stable up to 180,000 shots of pump pulse.

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