Highly efficient tunable tapered-polymer-fiber lasers

Qinjun Peng, a) Guiling Wang, Yong Bo, Xinjun Guo, Aicong Geng, and Zuyan Xu
Optics Physics Lab, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
Liyong Ren, Yani Zhang, Yishan Wang, Wei Zhao, and Lili Wang
Xi’an Institute of Optics and Precision Mechanics of CAS, Xi’an 710068, China

(Received 6 June 2005; accepted 25 October 2005; published online 13 December 2005)

A highly efficient tunable tapered-polymer-fiber (TPF) laser was demonstrated by use of a compound parabolic TPF doped with Rhodamine-6G (R6G) dye. The tuning ranges over 40 nm at the visible region for laser output with the maximum output energy of 600 μJ at 570 nm and the optical-optical conversion efficiency of 23% were achieved by a prism as a spectrally selective element. Moreover, the coupling efficiency for the taper exceeded 90%. Compared to traditional polymer fibers with a micrometer-size core diameter, the taper allows for a higher pump to be launched without damaging the fiber endfaces, and it can efficiently couple the light into the fiber and alleviate the alignment difficulty. So, the TPF laser not only possesses all of the advantages of traditional polymer-fiber lasers, and it can also obtain higher output energy and higher efficiency. Additionally, it is insensitive to geometrical displacements. © 2005 American Institute of Physics. [DOI: 10.1063/1.2149155]

The wide tuning ranges of dye lasers, covering from the ultraviolet to the infrared, have resulted in their popularity for many applications, such as optical spectroscopy, medicine, basic scientific research, and so on. The earlier studies mainly focused on the liquid dye lasers. Subsequently, the tapered-fiber liquid dye lasers which rely on the interaction between the evanescent field of a tapered fiber and a surrounding laser dye solution, were also developed. Though it has a lower lasing threshold, it does not overcome the disadvantages of the conventional liquid dye lasers. The bulk solid-state dye lasers which have been demonstrated have many advantages over liquid dye lasers by being nonvolatile, nonflammable, nontoxic, compact, and mechanically stable. However, the thermal effect in the bulk solid dye will influence the further development of bulk solid dye lasers because it will reduce lifetime of the dye. The polymer-fiber laser can combine the advantages of the fiber laser with low thermal effects and the solid dye laser with wide spectral tuning ranges provided by laser dyes, so it has become a subject of much interest in recent years. However, it is difficult to scale to higher output energy and higher efficiency for the traditional polymer fiber laser owing to the relatively small core diameter at micrometer-size which will give rise to damaging the fiber endfaces at a higher pump power and alignment difficulty.

In this letter, we report a highly efficient tunable tapered-polymer-fiber (TPF) laser by use of an R6G-doped TPF which is fabricated by typical fabrication procedures and control techniques. The TPF laser not only possesses all of the advantages of traditional polymer fiber lasers, including low thermal effect, long life, compactness, nontoxicity, nonflammability, nonvolatileness, and so on, it can also scale to the higher output energy and higher efficiency and be insensitive to geometrical displacement. Polymer fibers typically have much larger bulk strength than endface strength, due to the presence of small scratches, pits, and voids introduced during the fabrication and polishing process. The TPF has larger input cross-sectional area than traditional polymer fiber, so it allows for the higher pump to be launched without damaging the fiber endfaces for one to scale to a higher output energy. It can also efficiently couple the light into the fiber for high efficient laser operation and alleviate the alignment difficulty. So, it may become a good tunable laser source to implement in practical use.

Our design for TPFs is similar to that of the compound parabolic concentrator which has been used in solar energy systems to collect solar radiation efficiently to achieve maximum concentration. The profile of the designed compound TPF shown in Fig. 1(a) can be expressed as

\[
y = \frac{2r(1 + \sin \alpha)\sin \varphi}{1 - \cos(\alpha + \varphi)} - r \quad \text{and} \quad z = \frac{2r(1 + \sin \alpha)\cos \varphi}{\cos(\alpha + \varphi) - 1},
\]

where \(r\) is the radius of the exit aperture, \(\alpha\) is one-half of the acceptance angle of edge rays, and \(\varphi\) is a variable parameter from \(\alpha\) to \(90^\circ\). The radius of input aperture \(R\) and the length \(\ell\) can be given as \(R = r/\sin \alpha\) and \(\ell = (R + r)/\tan \alpha\), respectively. To have total internal reflection (TIR) within the compound parabolic TPF, the maximum refracted angle (\(\beta\)) of

\*

a)Electronic mail: pengqinjun@163.com
the incident ray at \( B' \) or \( B \) and \( \alpha \) must satisfy \( \cos(\alpha + \beta) \geq 2(n_2/n_1)^2 - 1 \), where \( n_1 \) and \( n_2 \) are the refractive indices of the core and the cladding, respectively. Once these extreme edge rays with \( \beta \) satisfy the TIR condition, rays within \( \beta \) at any distance from \( B \) or \( B' \) will also satisfy the TIR condition. So, the parameters of TPF can be appropriately selected to make \( \beta \) greater such that the incident divergent light is completely collected. In our design, \( R=0.8 \) mm, \( r=0.2 \) mm, \( \ell =4 \) mm, \( n_1=1.495 \), \( n_2=1.34 \), we can obtain \( \beta \) of \( \sim 38^\circ \). Thus, the divergent angle of the pump wave must be smaller than \( \arcsin(n_1\sin\beta)=67^\circ \) in the design process of laser generation for efficient coupling. The typical fabrication procedure of a TPF is as follows. First, a mixed solution of methyl methacrylate (MMA) and Rhodamine-6G (R6G) (100 ppm wt \%) containing a specific amount of \( \text{-butyl peroxy isopropylcarbonate} \) as the polymerization initiator, \( \text{-butyl mercaptan} \) as a chain transfer reagent was prepared. Then the mixed solution was poured into a glass tube of 1.7 cm inner diameter. The polymerization was carried out at 90 \( ^\circ \)C for 24 h. The preformed rod obtained was placed into an oven at 110 \( ^\circ \)C for 20 h for the complete polymerization. The preformed rod was heatdrawn to directly shape the sample of the TPF. The preformed rod was heated to directly shape the TPF with a slow extending control method at 190 \( ^\circ \)C. The obtained TPF, with a refractive index of 1.493, had a small diameter of 1.56 mm for the taper.

FIG. 2. Schematic of the experimental setup for the tunable TPF laser experiment.

When we rotated the mirror (M), we achieved the tuning range over 40 nm (550–590 nm), as shown in Fig. 5. In addition, the previous reports on the polymer-fiber laser mainly focus on the laser free running with no tuning ele-

FIG. 3. Measured fluorescence spectrum with 532 nm excitation and measured lasing spectrum at 570 nm.

cavity as a wavelength selective element. In addition, the divergent angle of the pump wave was estimated to be smaller than 30\(^\circ\) when L3 was used in the cavity, so all rays of the pump can be of TIR in the tapered fiber. Lastly, the output laser beam was collimated by the aspheric lens (L4) with a focal length of 6 mm.

Figure 3 shows the measured fluorescence spectrum with 532 nm excitation and the measured lasing spectrum at 570 nm. The laser output spectrum peaked at 570 nm with a linewidth of \( \sim 1.8 \) nm. The input-output power curve at 570 nm is shown in Fig. 4. The maximum energy of 600 \( \mu \)J with a pump energy of 2.6 mJ was obtained. The lasing threshold is 310 \( \mu \)J, and the calculated optical-optical conversion efficiency is 23\%. If the prism, L3, and fiber endface were antireflection coated, or fiber Bragg gratings\(^\text{13}\) were used in our experiment, the efficiency would be improved and the threshold would be lower. We found that slightly dithering the taper did not affect the output energy. This demonstrates its insensitivity to geometrical displacements.
ments. For a pump energy of 2.6 mJ with a repetition rate of 10 Hz, a half-life of ~110 000 shots for the TPF laser has already been evaluated, which is close to the half-life among solid-state polymer-fiber lasers reported. At last, we cut the TPF along BB′ in (Fig. 1) and polish the cut endface after the TPF laser was exhausted. A coupling efficiency of 91% for the taper was obtained by the cut-back method under the same experimental setup.

Under the same experimental setup, the TPF was replaced by a traditional polymer fiber whose R6G-doped concentration and length were the same as the TPF, and its diameter was 400 μm. The input-output power curve at 570 nm and the tuning curve were also shown in Figs. 4 and 5. The optical-optical conversion efficiency of 13.6% and a coupling efficiency of 54% were obtained. It can be seen that the TPF laser can obtain the higher efficiency and higher output energy than a traditional polymer laser with the same pump energy.

In conclusion, we have produced the first tunable TPF laser by use of a compound parabolic TPF doped with R6G dye. Because the new type of TPF laser combines the advantages of a conventional polymer fiber laser with the merits of more efficient coupling and higher power pumping, it has the potential for scaling to higher output energy and higher efficiency. Our next work will focus on improving the efficiency, lifetime, and output energy by optimizing the design of the TPF and resonator, and by developing the precise control technique of the profile in the fabricated process of TPF. We also will further investigate the tuning techniques by a broad tuning range of the fiber Bragg technique applied to TPF and various dyes.

The authors are grateful for the support of the CAS PP-KIP and the 863 Program and the National Natural Science Foundation of China (Grant Nos. KGCX2-SWJG, 2002AA311120, and 60437020, respectively). They also thank Professor D. F. Cui, X. Yang, and Dr. Z. Sun for their helpful discussions.