Side-pumped short rectangular Nd-doped phosphate glass fiber lasers

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Watt-level short fiber lasers side-pumped through fiber-to-waveguide couplers are demonstrated. The fiber lasers are fabricated from Nd-doped phosphate glass with large numerical aperture of 0.2 and rectangular cross section of 1.5 × 0.5 (mm). Single transverse mode output is achieved by the gain-guiding effect. Average power of 1 W is generated from a 4.0-cm-long fiber laser with a slope efficiency of 10%.

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Fiber lasers have been successful in generation of high power laser output in past few years. Continuous-wave (CW) laser outputs around $1-2$ kW have been reported from several groups[1,2], and the average output powers of ultrafast lasers have also exceeded hundred watt level[3]. These high power fiber lasers are usually several to tens of meters in length. More compact fiber lasers are of great interest in applications of photonic circuits and bio-optical chips. In addition, short fiber lasers are beneficial to the generation of narrow linewidth coherent radiations[4]. Many efforts have been put on short fiber lasers based on the traditional single-mode fibers[5,6]. Because of difficulties in launching high pump power into the single-mode core, the laser power is usually less than 1 W. Recently, watt-level output has been demonstrated from cladding-pumped short fiber lasers[7,8], and side-pumping techniques have also been proposed[9,10]. Because the effective absorption coefficient of double-clad fiber is proportional to the ratio of cladding-to-core area[11], the pump absorption efficiency of double-clad fiber is low. Complete absorption of pump power cannot be obtained in a short fiber laser. Pumping direct to the doped core is an alternative way to improve the absorption efficiency. In this situation, the doped core should have a large area to allow high pump power to be coupled into. However, if the doped core is large, the fibers would be multi-mode fibers, and it is a challenge to obtain single transverse mode oscillation in multi-mode fibers.

Due to its high solubility for rare-earth oxides, phosphate glass can be highly doped, leading to high gain in a short fiber length. Therefore, the maximum achievable output power of a phosphate fiber source will be much higher than that in a silica fiber source with a comparable length. In addition, the study of phosphate fiber lasers offers an opportunity to evaluate the possible higher photodarkening threshold for phosphate glass than silica glass.

In this letter, we demonstrate a watt-level short rectangular Nd-doped fiber laser, which is side pumped through a fiber-to-waveguide coupler. The advantage of high gain for Nd-doped phosphate glass fibers guarantees the fiber laser a special compact laser source. Besides, the rectangular shape of the fiber and the compactness feature of the laser system make it easy to be imbedded into photonic chips.

The rectangular fibers with the cross section of 1.5×0.5 (mm) were fabricated from a Nd-doped phosphate glass preform. The polymer coating was overlaid on the fiber surface automatically in the drawing process, giving a numerical aperature (NA) of 0.2. The fiber end surfaces were polished carefully, and no anti-reflection coating was applied. In comparison with silica glass, phosphate glass has lower clustering effects and allows higher doping concentration of rare-earth ions. In addition, the emission cross section of Nd^{3+} ion in phosphate glass is larger than that in silica glass. The Nd^{3+} ion doping concentration in proposed fibers is about 2 wt.-%, and the absorption coefficient at 808 nm is 2 cm^{-1}.

A fiber-coupled laser diode emitting at 808 nm was used as the pump source. The power delivery fiber was a multi-mode fiber with a 200-μm core in diameter and a NA of 0.22. The delivery fiber end was polished in an angle of 10° to the propagation axis, and adhered to the Nd-doped phosphate fiber (see Fig. 1). The pump light was then launched into the Nd-doped fiber through this angled fiber-to-waveguide coupler. More than 95% pump power can be coupled into the Nd-doped fiber[12]. In the thickness direction of the Nd-doped fiber, the pump light was reflected back and forth by the fiber surfaces, and propagated in the zig-zag path. Meanwhile, because the

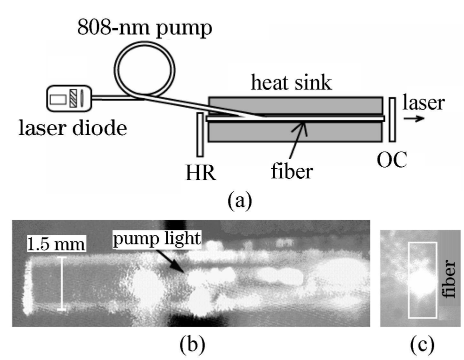

Fig. 1. (a) Schematic of experimental setup. HR: high reflective mirror, OC: output coupler; (b) top view and (c) side view of pump light trace inside the fiber. The white rectangle indicates the region of the fiber core.

Nd-doped fiber was much wider than the diameter of pump beam, the pump light propagated undisturbedly in the width direction. As shown in Fig. 1(c), the pump beam inside the Nd-doped fiber was about 200 μm in diameter. The pump light formed a narrow gain waveguide inside the Nd-doped fiber for the laser beam.

The Nd-doped fiber was clamped tightly by two aluminum heat sinks, which were cooled by convectional air. The laser cavity was composed of two planar mirrors. One of them attached to one end of the fiber had a high reflectivity ($R > 99.8\%$) at 1054 nm, and another one used as the output coupler was separated 4 mm away from the fiber outlet. The reflectivity of output coupler was 98% at 1054 nm and $> 99.7\%$ at 808 nm.

A 4-cm-long Nd-doped fiber was used in the experiments, and more than 94% pump light can be absorbed by this fiber. The thermal focal length was estimated longer than 1.0 m, and the fundamental laser mode was deduced to be about 250 μm in diameter in our plane-plane resonator with the $ABCD$ matrices method.

The laser output power versus the delivered pump power for the 4-cm-long fiber laser is shown in Fig. 2. The threshold pump power is around 0.4 W. Near the threshold, the laser exhibits a large fluctuation. Above 1.2-W pump power, the laser becomes very stable. Up to 1.05-W CW laser output was obtained under 12-W pump power with the average slope efficiency of about 10%. Due to high absorption of the pump power, the efficiency is higher than that of the cladding-pumped short fiber lasers[13]. A roll-over of the slope efficiency was observed for the pump power larger than 6.0 W. The stability of the short fiber laser was detected during 10-min operation with 12-W pump power. The output power stability was 3.41% root-mean-square (RMS) with the maximum and minimum values of 1.05 and 0.98 W, respectively. Considering the output power fluctuation of the pump diode laser, the fiber laser is high stable. Due to the skillful drawing technique, the slab fiber has a high uniform structure. The influence of microstructural nonuniformity of the fiber on the performance of the laser system is negligible.

The output laser beam was monitored by a charge-coupled device (CCD) camera. Near-field beam profiles at different pump powers are shown in Fig. 3. The solid curves are the Gaussian fits to the measured data. Although the fiber cross section is rectangular, the output beam is nearly axial symmetry. The laser beam diameter was measured about 180 μm, which is much less than that calculated from the thermal lens effect. The narrowing of the laser beam was determined by gain guiding of the pump beam[14,15]. The pump beam has a diameter of about 200 μm and is nearly Gaussian profile inside the Nd-doped fiber. The net laser gain is $g \propto (\eta P - \alpha)$, where P is the pump power, η is the pump conversion coefficient, and α is the loss. Supposed $\eta = 0.5$, and $\alpha = 0.01$ cm^{-1}, the gain profile is calculated to be Gaussian with a diameter less than 170 μm. The laser beam size was narrowed by this slender gain waveguide. In addition, because the gain waveguide was narrower than the fundamental mode, single mode oscillation was generated in the laser.

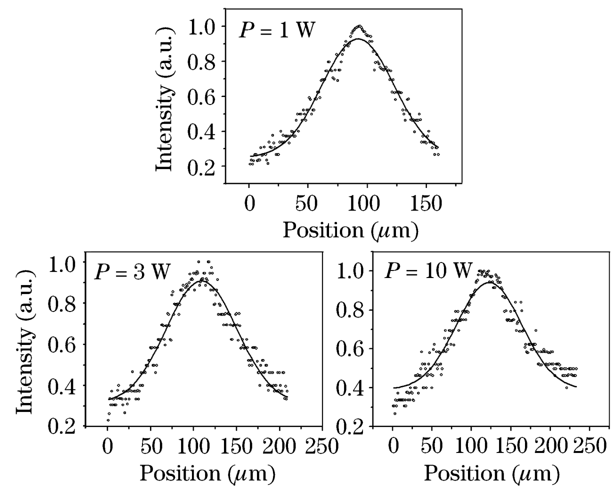

Fig. 3. Near-field laser beam profiles for various pump powers. Solid curves are Gaussian fits to the measured data.

In the stable zone of a conventional plane-plane resonator, the laser beam size will be reduced with increasing thermal lens effect. However, as shown in Fig. 3, the laser beam size is enlarged as the pump power is increased. Near the laser threshold, the laser beam was about 120 μm wide. With 10-W pump power, the beam size increased to 180 μm. This can be explained by the gain guiding effect. Under low pump power, the gain in the wings of the pump beam was not high enough to overcome the loss, and the gain waveguide was thin. Increasing the pump power, the gain waveguide became wider, and consequently the laser beam size was enlarged.

We measured the laser beam size by a double convex lens. The beam size as a function of the propagation distance is shown in Fig. 4. The beam propagation factor

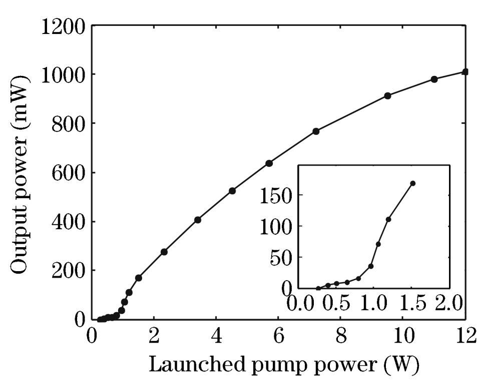

Fig. 2. Output power versus launched pump power. Inset: output power near threshold.

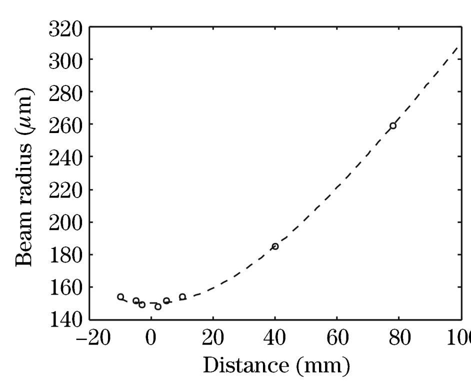

Fig. 4. Beam width as a function of propagation distance. Dashed line is calculated with $M^2 = 1.2$.

was calculated to be $M^2 = 1.2$, which was independent of the pump power. Single transverse mode oscillation in the proposed short fiber laser was confirmed by the measurement. The uncoated fiber end facets distorted the laser beam, and impaired the beam quality. The beam quality can be improved by applying anti-reflection coating on the fiber end facets.

In conclusion, we have demonstrated a short rectangular Nd-doped phosphate fiber laser with watt-level laser output and a slope efficiency of 10%. Single transverse mode has been obtained by the gain guiding of the narrow pump beam. In the experiment, the pump light is delivered into the Nd-doped fiber through an angled fiber-to-waveguide coupler. This method can be extended to slab lasers, for example, several power delivery fibers are arranged side by side to create a series of parallel gain channels inside the slab. Phase-locking between each gain channel is achieved by evanescent wave coupling. The output laser power can be scaled up with wider slabs. Because the pump power from each fiber can be adjusted independently, a preferable advantage of the laser is the controllable gain distribution inside the slab, which provides an opportunity for the development of compact, multi-functional slab lasers.

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