High efficiency single-mode-multimode-single-mode fiber laser with diffraction-limited beam output

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We designed and tested an all-fiber, high efficiency Yb-doped laser operating at 1088 nm with a single-mode-multimode-single-mode (SMS) structure. A larger-mode-area gain fiber of 1.5 m length, with 20/130 μm core/cladding diameters was used to increase the absorption, and a diffraction-limited Gaussian output beam was obtained from the single-mode output fiber. Using a 976 nm laser diode as the pump source, the laser generated an output power up to 38.5 W with a slope efficiency of 70%. The output beam qualities, with and without SMS structure, were compared and showed that the fiber laser with the SMS structure can achieve high gain, short fiber length, and excellent beam quality.

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1. Introduction

In the development of a fiber laser, power scaling is an important topic, due to the increasing demand on high-power laser systems in material processing and other applications [1]. Although more high-power pump diodes have become available, their output typically emits from multimode fibers; the higher the power, the larger the required core diameter. When this fiber-coupled laser diode is used to pump Yb-doped gain fiber, a small core/cladding diameter ratio of the gain fiber leads to low absorption of pump power, which results in a long gain fiber. At high power, a long gain fiber will induce nonlinear effects, such as stimulated Brillouin scattering and Raman scattering that limit the power scale up. Both problems can be solved if the ratio of the core/cladding diameters of the gain fiber can be increased. Recently, some fiber manufacturers started to offer the gain fibers with core/cladding diameters of 15/130 μm, 20/130 μm, and even 30/130 μm. Nevertheless, increasing core size will be detrimental to the beam quality of the fiber laser. As the V-number of the fiber increases beyond 2.405, the high order modes in the fiber laser could also be excited, although single-mode propagation can still be maintained if the numerical aperture (NA) is reduced. However, due to the fabrication limitation, it is difficult for a step-index fiber to reduce its core NA to below 0.06. Some newly developed photonics crystal gain fibers can achieve a large core size and a low NA; however, splicing this fiber with other fibers often introduces a large loss and the cost of this fiber is high [2]. There had been other methods developed to achieve high output power while maintaining diffraction-limited beam output. Some of them involved specialty active fiber design, such as a special refractive-index profile to achieve $M^2 < 2.0$ beam quality [3], ultrashort cavity length with highly doped fiber [4], large-core phosphate fiber with an intracavity spatial-mode filter [5], helical-core fibers with a core

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diameter of 30 μm [6], and leakage channel gain fiber of 3160 μm^2 effective core area [7]. The disadvantages of these methods are the use of specially designed large-mode-area (LMA) fibers that are not commercially available. If a new design can be found that uses a step-indexed large core gain fiber while still maintaining a Gaussian-shaped output beam profile, it would be interesting to many researchers in this field.

In 2006, we demonstrated a single-mode-multimode-single-mode (SMS) bandpass filter that consists of a multimode fiber spliced between two single-mode fibers [8]. Light from the single-mode fiber (SMF) couples into many modes in the multimode fiber and the interference of these modes forms periodic maxima on the fiber axis. If another SMF is spliced to the multimode fiber as an output fiber and the splice point matches one of the interference maxima, efficient transmission of up to 96% can be achieved; an SMS filter functions like a low-loss bandpass filter. However, a typical SMS filter uses a multimode fiber with a core diameter varies from 50 to 125 μm and its length is on the order of centimeters. Whether this structure can be used for high-power fibers is a subject that needs to be studied. Peyghambarian *et al.* reported fiber lasers and amplifiers based on multimode interference [9,10]. An LMA fiber of 25 μm core diameter was used as the gain fiber, which was spliced to an SMF28 fiber for output. Although the laser achieved diffraction-limited output, its slope efficiency is only 8.1% and has an output power of 1.1 W at 1535 nm. We did not find any other reported work that used LMA fiber as the gain media and single-mode output fiber in an SMS structure to achieve high power and diffraction-limited output.

In this paper, we present the design and test results of a Yb-doped fiber laser operating at 1088 nm. Both ends of the LMA fiber were spliced to the single-mode double-cladding fibers to form an SMS structure. The laser is in an all-fiber configuration with two fiber Bragg gratings (FBGs) inscribed onto the two pieces of SMFs, respectively, to form a laser cavity. Using a 976 nm laser diode as the pump source, we generated output power up to 38.5 W with a slope efficiency of 70%. The output beam quality was measured with a laser beam profiler and proved to be in a single-transverse mode.

2. Experiments

In an LMA double-cladding fiber, the cladding absorption of the pump power will increase with the diameter of the core. For example, the cladding absorption can reach ~10 dB/m at 976 nm in a 20/130 μm core/cladding diameter fiber, which is much higher than the cladding absorption in a 6/125 μm fiber (~1.7 dB/m). However, even with such a high absorption, a gain fiber of a few meters is still required for efficient absorption of the pump light. With the length of the multimode fiber extended to about 1–2 m long in an SMS filter with a circular-core LMA, our experiment shows that the periodic high transmission peaks can still be observed. An example of such a spectrum is shown in Fig. 1(a) for an SMS filter with a 25/125 μm LMA fiber of 1.35 meter length spliced between two Hi-1060 single-mode fibers in which transmission peaks are spaced at every 1.9 nm.

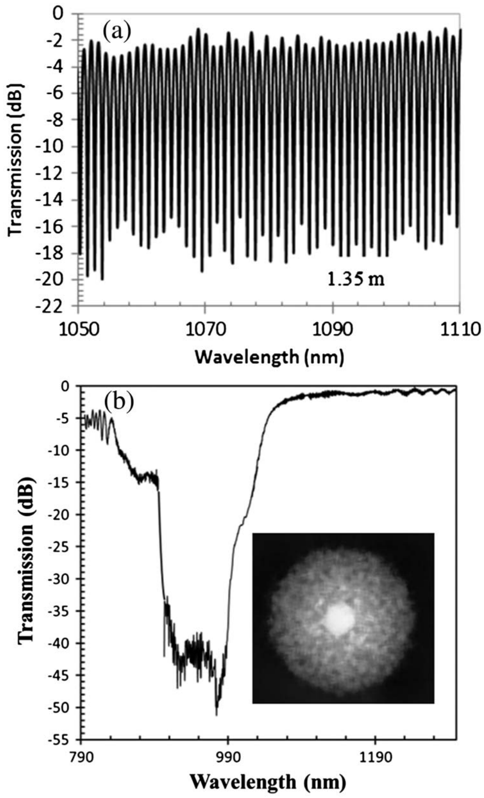

Fig. 1. Transmission spectrum of the SMS filter with (a) a passive multimode fiber with a circular cladding and (b) a gain fiber with an octagonal cladding. The insert shows the photo of the gain fiber core.

Our fiber laser consists of an Yb-doped double-cladding fiber of 1.5 m length spliced between two single-mode fibers (Nufern, SM-GDF-10/125) to form an SMS filter as shown in Fig. 2. The core and cladding diameters of the gain fiber are 20 and 130 μm, respectively. The V-number of the core is 4.36, which allows about 6 modes to propagate in the core. The cladding has an octagonal shape whose cladding absorption was measured to be 3.3 dB/m at 915 nm; therefore, the cladding absorption at 976 nm is estimated to be ~10 dB/m. A highly reflective FBG with a center wavelength at 1088.8 nm and a reflectivity larger than 99% was written in one of the SMFs. A wavelength-matching output coupler (OC) FBG with

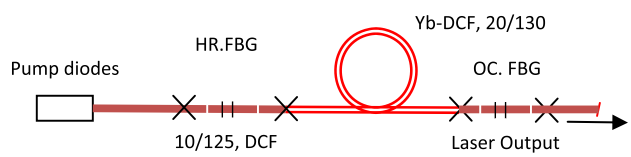

Fig. 2. Schematic diagram of the SMS fiber laser.

a reflectivity of 16% was written in the other SMF to form a laser cavity. A 976 nm diode with a multimode fiber of 105/125 μm core/cladding diameters as an output fiber was used as a pump source that was spliced to the pigtail of the highly reflective (HR) FBG. Thus, the laser was constructed in an all-fiber configuration, with all joints fusion spliced. The output coupler FBG was spliced to an optical cable with an APC connector made with the same 10/125 μm core/cladding diameter fiber. The residual pump power was stripped by coating the splice point with a high index coating.

Transmission spectra were measured with an optical spectrum analyzer (Ando, Model: AQ-6317) at a resolution of 0.1 nm. The output laser beam quality was measured by a beam profiler (Thorlabs, Model BP109-IR).

The transmission spectrum of the SMS laser (without grating) was measured as shown in Fig. 1(b). Instead of interference fringes with a contrast of ~16 dB, shown in Fig. 1(a), a broad absorption spectrum of Yb from 850 to 1050 nm dominates the spectrum. The interference fringes with a contrast of 4 dB were observed on the short wavelength side of the Yb-absorption and the fringes with a low contrast of ~1 dB from 1150 to 1190 nm were also observed. The interference fringes are still present; the lack of high contrast on the longer wavelength side could be attributed to the octagonal cladding shape, which might also modify the shape of the core. The insert in Fig. 1(b) shows a photo of the 20 μm core that exhibits a slightly deformed circular shape, especially on the left side. However, a relatively flat transmission spectral region from 1050 to 1100 nm should benefit the Yb-doped fiber laser's design because any wavelength in this region could be selected as the lasing wavelength. There is no stringent requirement to match the lasing wavelength to a transmission peak. At the lasing wavelength of 1088 nm the insertion loss of the SMS filter is about 1.6 dB.

3. Results and Discussion

We first characterized the power conversion efficiency of the SMS fiber laser. The pump diode was not wavelength stabilized, so its wavelength shifted with temperature at a rate of 0.35 nm/C, which led to a low efficiency when the pump power was below 35 W. However, as the pump power increased from 35 to 70 W, the pump wavelength moved close to 976 nm, and a slope efficiency of 70% was obtained as shown in Fig. 3(a). This efficiency is very close to the efficiency of a cw fiber laser without SMS structure. An output power of 38.5 W was obtained at a pump power of 70 W, which is much higher than the output power reported in [9].

The spectrum of the laser output was measured by coupling the laser beam into an APC connector of an optical jump cable with a lens. The amount of power coupled in can be reduced by defocusing the lens. The APC connector on the other end of the cable is connected to an OSA for spectral measurement. As shown in Fig. 3(b), the laser emission showed an excellent optical signal to noise ratio of over 70 dB at 38.5 W of output power. At that output power, the pump wavelength shifted to the peak absorption of the Yb ion at 976 nm, with its peak at about 40 dB below the laser emission. The laser emission also exhibited a very narrow linewidth of 0.05 nm at −3 dB, shown as the inset in Fig. 3(b). We attributed the narrow linewidth to the large core size and relatively short cavity length that significantly reduced the laser line broadening caused by self phase modulation.

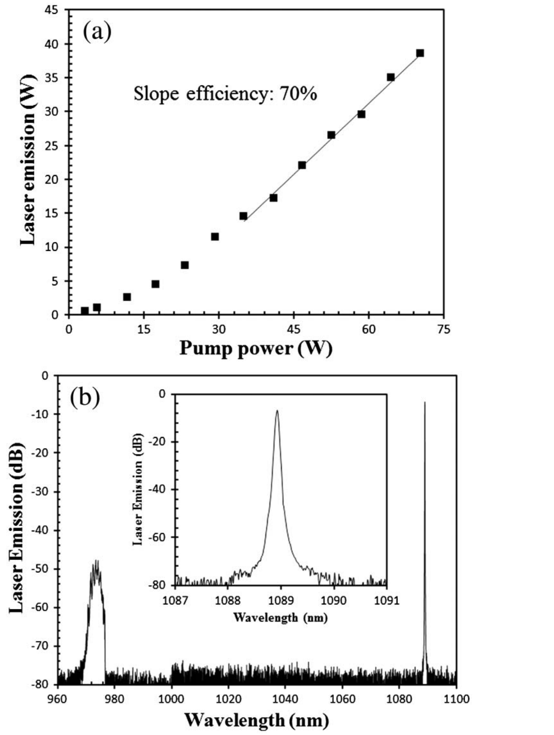

Fig. 3. (a) Laser output power as a function of pump power and (b) laser emission spectrum with output power at 38.5 W.

An important feature of this design is to retain the high beam quality in its output. We characterized the output beam by a laser beam profiler. Fig. 4 shows a 3D output laser beam profile measured at the output power of 38.5 W. The plots on the low part of the figure show the profiles of the cross sections in the x and y direction and associated Gaussian fits, respectively. As can be seen, the beam profiles exhibited near-Gaussian distributions, which proved the high beam quality of the SMS laser output.

In order to prove that the SMS design is essential to the high beam quality, we also measured the beam quality of the laser emission directly from the 20/130 μm gain fiber. The SMF with the output coupler FBG was removed and the end of the 20/130 gain fiber was cleaved at 90° so its flat end face with a 4% reflectivity served as an output coupler. The deterioration of beam quality of this multimode fiber laser is very obvious, as shown in Fig. 5. The center of the beam in the x direction becomes a flat top with interference ripples, indicating the existence of more than one mode and the interference between the modes.

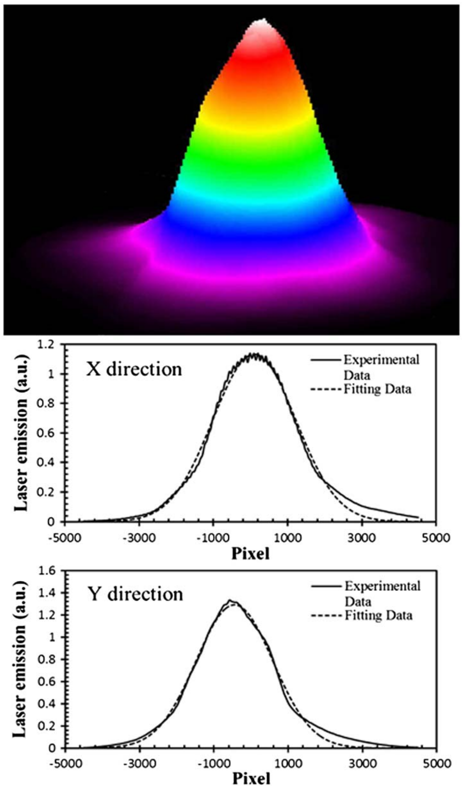

Fig. 4. Output laser beam quality of the SMS laser measured by beam profile at the output power of 38.5 W.

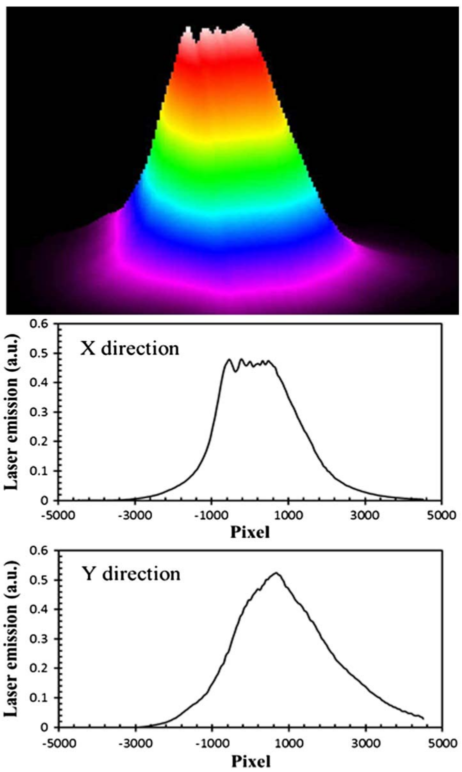

Fig. 5. Output laser beam profile from the multimode fiber at the output power of 34.1 W.

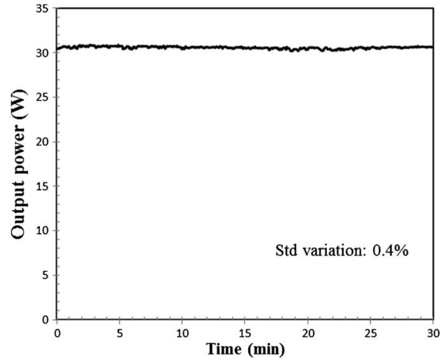

Fig. 6. Output power stability of the laser.

In order to evaluate the effect of the SMS structure on the performance of the laser, the stability of the laser output power was measured over 30 min. The laser exhibited excellent power stability with a power variation of less than 1% in standard deviation, as shown in Fig. 6.

4. Conclusions

We have successfully demonstrated an SMS Yb-doped fiber laser operating at 1088 nm. An LMA gain fiber 1.5 m in length was spliced between two FBGs, inscribed in two SMFs, respectively, to form an SMS filter and a laser cavity. Using a 976 nm laser diode as the pump source, the laser generated an output power up of 38.5 W with a slope efficiency of 70%. The output beam quality was characterized and proved to be in a single-transverse mode. Compared to the laser reported in [3], our laser obtained a much higher output power and excellent slope efficiency. Our work proved that one can use the advantage of high cladding absorption of a large core in the gain fiber while avoiding the beam quality deterioration with the SMS structure.

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