Diode-pumped 1 018-nm ytterbium-doped double-clad fiber laser

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We report a 1 018-nm ytterbium-doped double-clad fiber laser pumped by 970-nm diode. A pair of fiber Bragg gratings with reflectivities of 99.9% and 9% at a center wavelength of 1 018.9 nm are employed as cavity mirrors. The ytterbium-doped double-clad fiber is a 2.6-m-long Liekki fiber. Laser output power of 7.5 W at 1 018 nm is obtained under the pump power of 59.2 W. The overall slope efficiency of the fiber laser is about 16%. This low slope efficiency is mainly due to the incomplete absorption of the pump power.

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Fiber lasers attract great attention due to their excellent beam quality, high efficiency, and power scalability. The output power of fiber lasers has been increased rapidly in the past few years[1−5]. Jeong *et al.* demonstrated in 2004 a cladding-pumped ytterbium-doped fiber laser generating 1.36 kW of continuous-wave (CW) output power[1]. The CW ytterbium fiber laser of 2 kW was reported by IPG Photonics Corporation in 2005[2]. In China, 1.75-kW fiber laser using China-made ytterbium-doped double-clad fiber as the gain medium was reported by He *et al.*[3]. Although combining the coherent beams of fiber lasers can increase the output power[6,7], the most fundamental way to improve their performance is through a single fiber. Recent research shows that the upper limit of output power is 36 kW for single-mode laser from a single ytterbium-doped fiber[8]. Single-mode fiber lasers have reached 10 kW as reported by IPG in 2009[5]. Such high power was obtained from an oscillator-amplifier configuration with a two-stage pumping process. The output 1 070-nm laser was pumped with fiber lasers emitting at 1 018 nm, which was in turn pumped with 975-nm diodes. Although the absorption of ytterbium-doped fiber at 1 018 nm is much weaker than that at 975 nm, the 1 018-nm fiber lasers are much brighter than diode pumps at this wavelength and can be coupled into a rather small fiber inner cladding. Therefore, the pump absorption is quite good due to the small cladding-to-core area ratio[9]. The quantum defect of laser ions is defined as $\eta=1-h\nu_1/h\nu_2$, where h is the Planck's constant, and ν_1 and ν_2 are lasing and pumping frequency, respectively[10]. The quantum defect is about 9% when pumping a 1 070-nm ytterbium-doped fiber laser with a 975-nm laser diode (LD). However, for 1 018-nm pumped 1 070-nm ytterbium-doped fiber laser, the quantum defect is less than 5%. As most of the thermal power comes from the quantum defect[10], the small quantum defect of 1 018-nm pumping mitigates the thermal problems. In addition, some research shows that lasers whose wavelength is near 1 018 nm have potential use for athermal amplification[11], which is realized by laser cooling. Although the ytterbium-doped fiber acts as a quasi-four-level system for emission in the spectral range of 1 010–1 170 nm[12], laser operation below 1 030 nm is difficult due to the relatively large absorption cross sections[13].

In this letter, we report a 1 018-nm fiber laser pumped by 970-nm diodes. The fiber laser employs a pair of fiber Bragg gratings (FBGs) whose reflectivities are 99.9% and 9% separately at a center wavelength of 1 018.9 nm as cavity mirrors. A 2.6-m-long Liekki ytterbium-doped double-clad fiber is employed as the gain medium. The fiber laser generates 7.5 W of output power at 1 018 nm under the pump power of 59.2 W. The slope efficiency of the fiber laser is about 16%.

The fiber laser is pumped with a laser diode emitting at 970 nm. The laser oscillation cavity consists of a pair of FBGs and a length of ytterbium-doped double-clad fiber. The experimental setup is shown in Fig. 1.

The FBGs are inscribed in passive fibers with a core/cladding diameter of 20/400 μm with phase mask technique. The high-reflectivity FBG1 has a reflectivity of 99.9% or higher with a center wavelength of 1 018.9 nm and a bandwidth of 0.52 nm. The low-reflectivity (9%) FBG2 is centered at 1 018.9 nm with a bandwidth of 0.35 nm. The reflection spectra of the FBGs are shown in Fig. 2. The noise on the spectra is due to the weak light source; the real spectral profile should be very smooth. The collimated pump light after the collimating lens

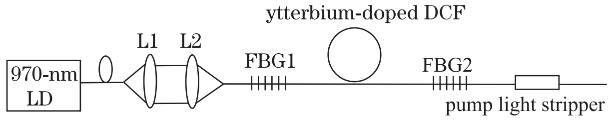

Fig. 1. Experimental setup of the fiber laser.

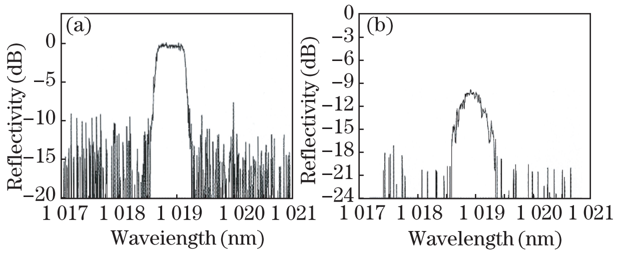

Fig. 2. Reflection spectra of the fiber Bragg gratings. (a) FBG1 and (b) FBG2.

L1 is coupled into one end of the FBG1 with focusing lens L2. The other end of the FBG1 is spliced with the ytterbium-doped double-clad fiber. The FBG2, which is employed as the output coupler, is spliced with the other end of the gain fiber. The ytterbium-doped double-clad fiber is a 2.6-m-long Liekki fiber. This Liekki fiber, which is made by direct nanoparticle deposition (DND) fiber production technology, has a 20-μm core and 400-μm cladding; its peak cladding absorption at 976 nm is 3.0 dB/m. Its core numerical aperture (NA) is about 0.07, and the cladding NA is larger than 0.46. A length of 20/400-μm passive fiber is spliced after the FBG2. About 4-cm-long outer cladding of the passive fiber is removed and then coated with liquid of high refractive index in order to strip residual pump light. Both fiber facets are angle cleaved for the purpose of suppressing the amplified spontanuous emission (ASE) and self-oscillation.

With increasing pump power from zero, the fiber laser reaches the threshold at a pump power of 13.5 W. When the pump power is 59.2 W, a 1 018-nm output laser of 7.5 W is obtained. Figure 3 shows the output laser spectrum of the fiber laser at an output power of 7.5 W. The laser spectrum is centered at 1 018.5 nm, which is close to the center wavelength of the FBGs. The full-width at half-maximum (FWHM –3-dB bandwidth) of the output laser is about 0.04 nm. Although there is a large amount of residual pump light that has not been absorbed by the ytterbium-doped double-clad fiber, most of it is stripped by the pump light stripper. The peak of 1 018-nm laser is about 22 dB higher than that of the residual pump light. The pump wavelength deviation from the absorption peak contributes to the low pump absorption efficiency. Another reason for the low pump absorption is the short length of the gain fiber. Limited by experimental conditions, the ytterbium-doped fiber is only 2.6-m long, which cannot completely absorb the pump power. A relatively longer ytterbium-doped fiber can absorb more pump power, but the 1 018-nm laser may also be absorbed by the fiber core. There is an optimal length for the ytterbium-doped fiber, which can be calculated with a numerical model based on rate equations.

The change in 1 018-nm laser output power versus pump power is shown in Fig. 4. The slope efficiency of the fiber laser is about 16%. Compared with fiber lasers emitting at about 1 070 nm, the efficiency of this 1 018-nm fiber laser is relatively low. The inefficiency of pump light absorption contributes to the low slope efficiency. In the experiment, the reflectivity of the FBG2 is not optimized; with an optimized reflectivity of the FBG2, the efficiency of the fiber laser can be

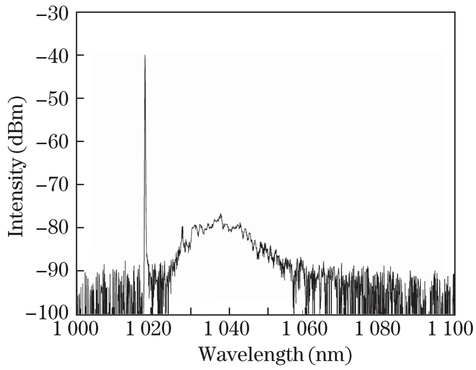

Fig. 3. Output spectrum of the fiber laser at output power of 7.5 W.

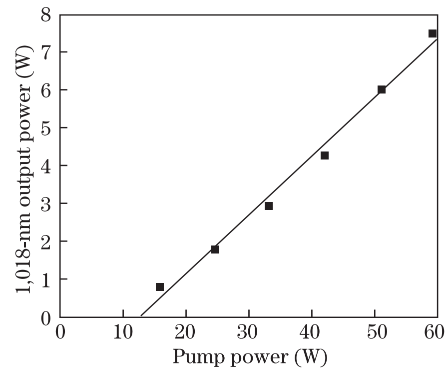

Fig. 4. 1 018-nm output power versus pump power.

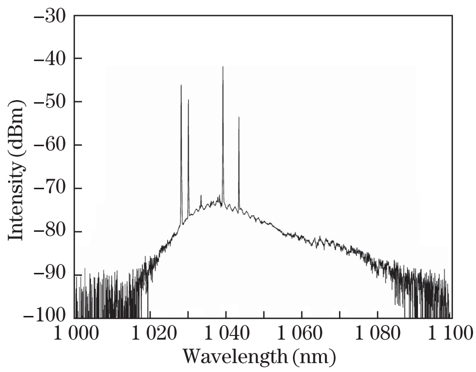

Fig. 5. Laser output spectrum with 4% Fresnel reflection as the output coupler.

improved. To obtain a high output power of 1 018-nm laser, the doping composition of the ytterbium-doped fiber should also be optimized, which may be different from the common commercial ytterbium-doped double-clad fibers. The beam quality of the fiber laser has not been measured. As the double-clad fiber used has a core diameter of 20 μm and NA of 0.07, the output laser is promising to have a good beam quality. In addition, the beam quality of the fiber laser can be improved with coiling technique[14]. In the experiment, the gain fiber is coiled to a cylinder with a diameter of 14 cm.

Some other fiber lasers take the 4% Fresnel reflection as the output coupler[15,16], in which the FBG2 is replaced by a perpendicular cleaved fiber end. We performed an experiment with 4% Fresnel reflection as the output coupler of the fiber laser. The FBG2 is removed, and the end of the ytterbium-doped double-clad fiber is cleaved with an angle of 0°. Figure 5 shows the laser output spectrum at a pump power of 16.0 W. The 1 018-nm laser has not been generated. The fiber laser emits at wavelengths of about 1 030 and 1 040 nm. The FBG1 with a center wavelength at 1 018.9 nm does not cause the 1 018-nm laser to oscillate in the cavity formed with 4% Fresnel reflection. The Fresnel reflection from the cleaved end of the fiber is considered independent of the wavelength[17]. As the reflection of the end of the FBG1, in which the pump light is launched into, cannot be completely eliminated even if it is angle cleaved, 1 030- and 1 040-nm lasers oscillate in the cavity due to their larger emission cross sections and smaller absorption cross sections compared to that at 1 018 nm[13]. For this type of Liekki fiber, it is necessary to employ a pair of fiber Bragg gratings to build the oscillating cavity.

In conclusion, we demonstrate a diode-pumped 1 018-nm ytterbium-doped double-clad fiber laser. The fiber laser generates 7.5 W of output power at 1 018 nm under 59.2 W of pumping at 970 nm. The slope efficiency is about 16%, which is limited by the incomplete absorption of the pump power. The fiber laser employs double-clad fibers, and the output power can be improved by optimizing the length of the ytterbium-doped fiber and the reflectivity of the FBG.

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