Single-mode fiber laser based on core-cladding mode conversion

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A single-mode fiber laser based on an intracavity core-cladding mode conversion is demonstrated. The fiber laser consists of an Er-doped active fiber and two fiber Bragg gratings. One Bragg grating is a core-cladding mode converter, and the other Bragg grating is a narrowband high reflector that selects the lasing wavelength. Coupling a single core mode and a single cladding mode by the grating mode converter, the laser operates as a hybrid single-mode laser. This approach for designing a laser cavity provides a much larger mode area than conventional large-mode-area step-index fibers. © 2008 Optical Society of America

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Single-mode high-power fiber lasers offer stable diffraction-limited Gaussian output beams, easy thermal management, and alignment-free cavities. Fiber lasers are strong competition for many solid-state lasers for a variety of applications including remote sensing, interferometry, machining, telecommunications, and surgery. The recent success of high-power single-mode fiber lasers has been achieved by the development of double-clad large-mode-area (LMA) fibers and high-power multimode pump diodes [1,2]. Still, the relatively small core remains one limiting factor for achieving even higher output powers with single-mode fiber lasers. Since a large volume of a gain medium is required for high-power operation, a single-mode high-power fiber laser has to be long due to its small core area. Both the small core and long fiber length reduce the threshold of nonlinear effects and limit the maximum laser output power.

In a conventional step-index fiber, a smaller numerical aperture is required to maintain the single-mode operation of an LMA fiber. In practice, this kind of fiber is very bending sensitive and often not well suited for stable fiber laser operation. Therefore, LMA fibers with a few propagation core modes have been used with intracavity mode-filtering techniques to enforce exclusive laser operation of the fundamental mode [3–6]. Utilizing mode filtering, the largest core diameter is $\sim 25\ \mu m$ for a single-mode laser operation [5,6]. An alternative way to achieve an LMA single-mode operation is implemented by photonic crystal fibers, as they allow large-core-size single-mode operation [7]. Such microstructured fibers have been successfully utilized to build LMA fiber lasers [8–10], and rodlike photonic crystal fiber lasers have been recently demonstrated with high-power single-mode emission from a $60\ \mu m$ diameter core [10].

Much larger mode areas than the fundamental core mode can be achieved through the excitations of higher-order modes (HOMs). Such HOM excitations have been applied to manage dispersion and nonlinear effects in optical fibers [11–13]. For example, Ramachandran *et al.* used long-period fiber gratings (LPGs) to convert the fundamental core mode to higher-order core modes or even cladding modes [14] to achieve stable, low-loss, larger area mode propagation in a few mode and double clad fibers, as well as dispersion compensation in femtosecond fiber oscillators. They also pointed out potential applications of HOMs for fiber lasers and amplifiers, and recently demonstrated signal amplification in rare-earth-ion-doped HOM fibers [14,15].

Two different types of gratings can be fabricated in an optical fiber: fiber Bragg gratings (FBGs) and LPGs. Both gratings are periodic modulations of the refractive index along the optical fiber axis. Usually an FBG has a period of the scale of the wavelength of light and couples a core mode to a counterpropagating core mode. In contrast, an LPG typically has a period of hundreds of micrometers and couples a core mode to a copropagating cladding mode. It is well known that an FBG can also couple a core mode to a single cladding mode [16]. However, in the case of an FBG the excited cladding mode is a counterpropagating cladding mode in strict contrast to the case of an LPG.

In this Letter we demonstrate a hybrid single-mode fiber laser that comprises both a core mode and a cladding mode using an FBG as a core-cladding mode converter. Utilizing the proposed and demonstrated intracavity core-cladding mode conversion technique, fiber lasers with extremely LMAs can be fabricated in conventional easy-to-manufacture step-index fibers. Our fiber laser cavity design includes cladding modes with theoretical effective areas up to $\sim 7400\ \mu m^2$ that can be utilized to dramatically increase the output power per active fiber length and simultaneously reduce undesired nonlinear effects.

The fiber laser cavity consists of an active fiber and two gratings, FBG1 and FBG2, as shown in Fig. 1(a). Both FBGs are 25 mm long and written in photosensitive fiber F-SBG-15 (Newport) using a uniform phase mask and a frequency doubled Ar^+ laser. FBG1 has its main Bragg reflection at ~ 1537 nm with an ~ 0.8 nm FWHM as shown in Fig. 1(b). By exposure to UV light for a long period of time, the characteristic wavelengths at which core-cladding coupling occurs appear as dips of ~10 dB or more in the transmission spectrum of FBG1, indicating coupling efficiency to counterpropagating cladding modes of ~90% or more. FBG2 has an ~90% core mode reflectivity at ~1535 nm with an ~0.09 nm FWHM as shown in Fig. 1(c). The active fiber is a 50 cm long Er^{3+}-doped fiber Er80-8/125 (Liekki, Finland). These components were fusion spliced to form a robust fiber laser cavity.

To suppress lasing of a core mode at ~1537 nm, a part of the fiber core, indicated by a black dot labeled DM in Fig. 1(a), was slightly damaged by a focused femtosecond laser at 800 nm. The induced propagation loss is ~5 dB for a single path. The fiber laser cavity is a folded cavity due to the core-cladding mode coupling by FBG1. Figure 1(d) shows a schematic of an equivalent unfolded cavity. During a cavity round trip the light travels as a core mode from FBG2 to FBG1, where it is converted into a counterpropagating cladding mode that travels inside the cladding and is reflected at the cleaved fiber facet; i.e., FBG1 couples the two core and cladding halves of the hybrid single-mode cavity.

Pump light was provided by a single-mode-fiber-coupled semiconductor laser operating at ~980 nm and was coupled into the fiber laser cavity through a WDM fiber coupler. The other end of the fiber laser was cleaved straight to provide feedback via Fresnel reflection (FR). Spectra emitted from the FBG1 side were monitored by an optical spectrum analyzer (OSA) Ando AQ6317B after passing through the WDM fiber coupler. Mode profiles and output power of the fiber laser at the cleaved end were observed by an infrared camera with a microscope objective and a power meter, respectively, through an ~980 nm absorbing filter.

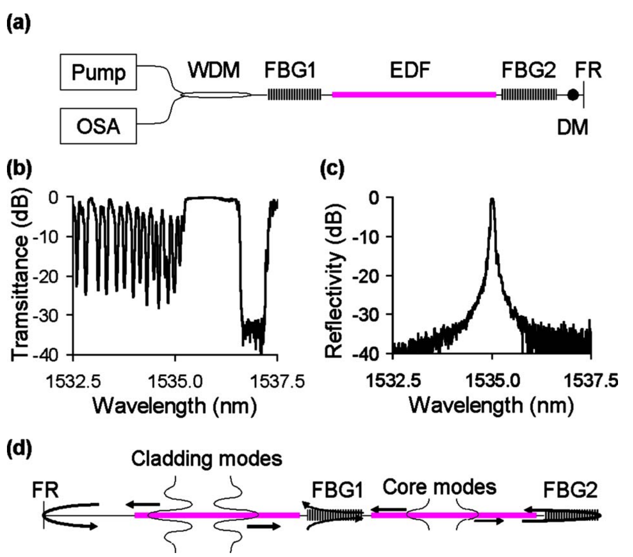

Fig. 1. (Color online) (a) Schematic of the fiber laser setup, (b) transmittance spectrum of FBG1, (c) reflectivity spectrum of FBG2, and (d) schematic of an unfolded cavity that is equivalent to the fabricated folded cavity with core-cladding mode conversion.

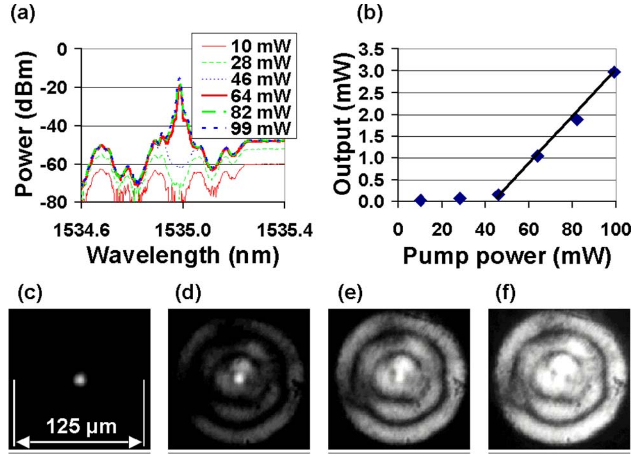

Fig. 2. (Color online) (a) Laser emission spectra at different pump powers, (b) output versus launched pump power, (c) spatial profile of the laser below threshold, and (d)–(f) spatial profiles above threshold. Pump power increases from (d) to (f).

Figure 2(a) shows several room temperature emission spectra measured by the OSA with 0.01 nm resolution for various pump powers. Since the spectra were measured through FBG1, the transmission dips due to core-cladding mode coupling are always present in Fig. 2(a). At increased pump powers, a distinct laser emission peak appears in the spectra of Fig. 2(a) with a measured FWHM of <0.02 nm. In Fig. 2(b) the measured output power at the cleaved end is plotted as a function of the launched pump power. A lasing threshold is observed at ~45 mW of pump power.

Some output mode profiles observed at the cleaved fiber facet are shown in Figs. 2(c)–2(f). Figure 2(c) is a profile below the threshold, while Figs. 2(d)–2(f) are mode profiles at various laser intensities. Below the threshold only the core is bright, and almost no light is seen inside the cladding. Above the threshold, all the mode profiles have significant light intensity in the cladding area. The patterns above the threshold indicate the excitation of a particular cladding mode, HE14 mode, with an intensity that increases with pump power. As seen in Figs. 2(d)–2(f), the profile pattern was quite stable within the measured pump power range.

To confirm that lasing indeed occurred in the hybrid core-cladding cavity, FBG1 was dipped in index-matching fluid (IMF) without turning off the pump at ~64 mW, so that the core-cladding mode coupling at FBG1 could be modified strongly. Due to the IMF most of the core-cladding mode coupling dips were significantly reduced, and lasing of the coupled core-cladding cavity was prohibited. This result emphasizes that the lasing shown in Fig. 2 can be attributed to the coupled core-cladding cavity.

As indicated in Fig. 1(b), an FBG can couple a core mode to different cladding modes in a relatively narrow wavelength range. Thus by changing the resonance wavelength of either FBG1 or FBG2, the cladding mode included in the hybrid laser cavity could be changed. To demonstrate this "tunability" FBG2 was heated or cooled by a Peltier device. Shifting the

Bragg wavelength of FBG2, laser cavities with different modes labeled CM01 and HE12–HE15 in Fig. 3 were successfully achieved. Since there is no core-cladding mode coupling at wavelengths above ~1535.3 nm, the pattern labeled CM01 in Fig. 3 should be generated by exclusive excitation of the core mode, or HE11 mode. This fact is clearly indicated by the observed mode profile. In between the rather clear cases of various single cladding mode excitations shown in Fig. 3, unstable spectra, or spectra with dual peaks and unorderly profiles, can be observed. However, only the CM01 mode was observed for any wavelength beyond ~1535.3 nm. Although the pump power was fixed to ~64 mW for each measurement, Fig. 3 also indicates that the observed lasing peak power was higher when lower cladding modes participate in the laser operation. One of the reasons for this output trend is probably the difference in propagation loss. Since the fiber laser is fabricated in a conventional single-clad fiber and higher-order cladding modes are less confined inside the fiber, they are more likely to have larger loss due to interaction with the fiber surface.

Although the hybrid laser demonstrated in this Letter is far from being optimized, it has shown the potential of LMA fiber laser operation in a conventional step-index fiber. To improve the output power efficiency of the laser, a first step would be to implement a double-clad fiber with much lower propagation losses of cladding modes. In addition, the cladding mode reflection currently provided by the cleaved facet should be optimized using a feedback mirror or a grating. There are many potential applications for the core-cladding conversion. For a high-power short-length fiber laser, a cladding-doped fiber with an extremely large active medium volume can be utilized. Moreover, since the core-cladding mode coupling provides a coaxially folded cavity, ring-laser configurations that are bidirectional or unidirectional can be built in a straight single fiber with FBGs. That is, if one of the FBGs couples a core mode to a cladding mode, another FBG couples the cladding mode to the core mode, and the cavity becomes a traveling-wave cavity.

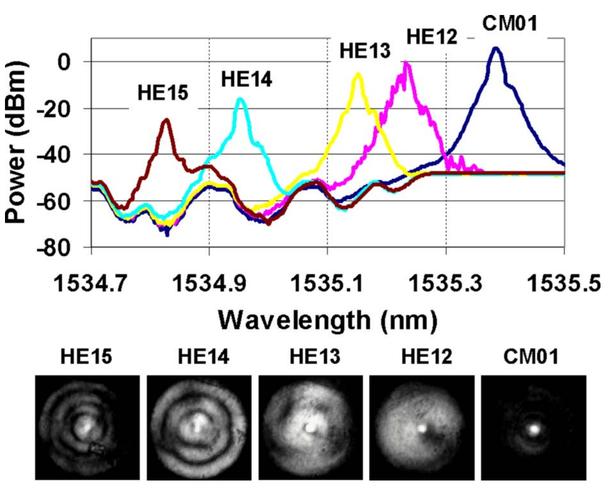

Fig. 3. (Color online) Lasing spectra and spatial profiles of the fiber laser at different temperatures of FBG2.

In conclusion, we have demonstrated an LMA single-mode fiber laser based on intracavity core-cladding mode coupling by FBGs. The fiber laser operates as a single-mode laser with a hybrid cavity that consists of a single-core mode feedback, a single-cladding mode feedback, and an FBG-based mode converter. Shifting the FBGs reflection spectra relative to each other, different cladding modes can be involved in the lasing operation. We believe the intracavity core-cladding mode conversion provides many potential applications in and beyond the field of high-power fiber lasers.

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