Distributed feedback fiber laser pumped by multimode laser diodes

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A distributed feedback fiber laser made of highly Er-Yb codoped phosphate glass fiber has been demonstrated experimentally. Efficient pump absorption allows for multimode pumping into the cladding of the active fiber. Output powers up to 160 mW have been achieved. The 35 mm long fiber laser device emits with >50 dB side mode suppression ratio. © 2008 Optical Society of America

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Since their first introduction [1,2], there has been growing interest during the past 15 years in high-performance, single-frequency, grating-based fiber lasers. A relatively simple fabrication involving only the writing of a grating structure with ultraviolet (UV) light into an appropriate fiber together with their stable performance, compared to single-frequency semiconductor lasers, make these devices attractive. In addition, single-mode pump light can be sent into the fiber core that contains the active ions inside the laser cavity, leading to an alignment-free resonator with optimum overlap of pump and signal light.

To ensure robust single-frequency operation without mode hopping, the fiber laser cavity needs to be short, a few centimeters in length at most. Both distributed feedback (DFB) fiber lasers as well as short fiber lasers with distributed Bragg reflectors (DBRs) as cavity-forming elements have been demonstrated. Historically, the laser efficiencies and output powers have been rather low, typically a few percent and in the milliwatt regime, respectively. This is a direct consequence of the low pump absorption in the short fiber cavity and the limited power of available single-mode pumping sources. To achieve higher pump absorption, the doping level in the active core can be increased. However, germanosilicate glasses, while having the merit of being photosensitive, are particularly prone to rare-earth-ion clustering, which leads to a degradation in laser efficiency and instabilities in performance. To boost the output powers to useful levels for applications such as lidar, community antenna television, or fiber optic sensing, most single-frequency fiber lasers need to be amplified, which prevents them from reaching best performances as low-noise sources.

There has been an ongoing effort to increase the operating power of short cavity fiber lasers. One of the main avenues is the utilization of active fibers with high Er and Yb concentrations that rely on the high absorption of Yb and efficient energy transfer from Yb to Er. Excited Er ions then provide sufficient gain to achieve lasing of short cavities at wavelengths of ~1550 nm. Using this approach, the 980 nm pump absorption could be increased by more than an order of magnitude, resulting in sizable increases in laser output power.

Unfortunately, most glasses with high solubility to Er and Yb ions, such as phosphate and phosphosilicate glass, also show a lack of photosensitivity that is necessary for fabrication of efficient fiber gratings [3]. Two main approaches have been developed to circumvent this problem. One is the introduction of a photosensitive annular region surrounding the phosphosilicate core where strong gratings can be written with relative ease in spite of the nonphotosensitive core [4], enabling efficient lasers with up to ~60 mW output power [5]. The other route is the fabrication of hybrid phosphate–silicate fiber devices [6–9]. Here, the active fibers are made from highly doped phosphate glass while the fiber gratings are written into photosensitive silicate fiber sections that are fusion spliced to the phosphate fibers. In these devices both optical losses and mechanical instabilities at the splicing joints present inherent challenges owing to large differences in thermal properties, such as melting temperature and thermal expansion coefficient, between the different glasses. In addition, this method is only suitable to make short cavities with Bragg reflectors, while more robust and better tunable DFB fiber laser schemes cannot be implemented. An enabling breakthrough for our novel DFB fiber laser pumping scheme is the recently demonstrated possibility of direct UV writing of gratings into undoped and doped phosphate glass fibers [10,11].

In this Letter we present and demonstrate what we believe to be the first DFB fiber laser that is pumped by multimode diode lasers. The laser resonator is formed by an asymmetric grating structure that provides distributed feedback for 1535 nm signal light propagating in the single-mode core of an active Er–Yb codoped phosphate fiber. Going beyond the limitation of all previous DFB fiber lasers that are pumped by single-mode lasers, the ability to utilize high-power, multimode pump lasers has the potential to fabricate stable, high-power, and wavelength-tunable, single-frequency laser oscillators. In addition, schemes of multiple cascaded DFB fiber lasers that are pumped by a single, high-power source become feasible.

The geometry of our linear-cavity DFB fiber laser is shown in Fig. 1. The multimode pump delivery fiber with 105 μm core diameter, 125 μm cladding diameter, and a numerical aperture of 0.22 was fusion spliced to the active fiber to launch 976 nm pump light from multimode semiconductor laser diodes. The active fiber is fabricated from phosphate glasses that allow for high levels of rare-earth-ion doping in the active core with 1.1×10^{26} Er^{3+} ions/m^3 and 8.6×10^{26} Yb^{3+} ions/m^3. The gain fiber is ~5 cm long and has a core diameter of 9 μm, 125 μm outer diameter, and a numerical aperture of 0.12.

The DFB grating structure is written directly into the doped single-mode fiber by exposure to 193 nm UV light through a phase mask. The grating consists of a 2 cm long section close to the pump side and a 1.5 cm long section at the single-mode DFB emission side that are separated by a 50 μm wide gap that creates the defect state inside the grating's reflection band. The overall ~3.5 cm long grating structure is located approximately at the center of the active fiber piece, and the asymmetric DFB grating design results in unidirectional DFB laser emission. This laser device contains no adjustable parts and can only be controlled externally by the amount of pump power that is injected and by the temperature adjustment of the grating.

The signal versus pump power performance of the cladding-pumped DFB fiber laser is shown in Fig. 2. Lasing starts at a threshold of ~1 W of multimode pump power. A maximum output power of 160 mW was achieved. After an initial pump-to-signal conversion efficiency of ~3% the laser showed saturation behavior. The relatively low slope efficiency is a consequence of pumping into active fiber sections that are on both sides of the 3.5 cm long DFB grating structure but do not contribute to the DFB cavity and also of limited pump absorption within the DFB section. The efficiency can be further improved by reducing or eliminating doped fiber segments that are not part of the DFB. We verified experimentally that about 30% of the pump light is transmitted unabsorbed through the active fiber section. This number will be even higher by reducing the unused active fiber sections, and the remaining pump light can be utilized in cascaded cladding-pumped DFB fiber laser schemes that are currently under investigation but beyond the scope of this Letter.

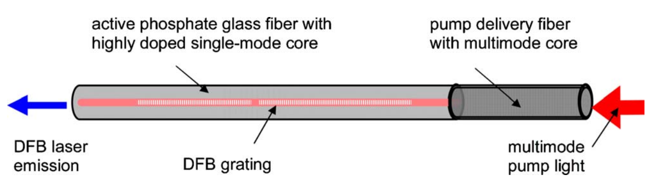

Fig. 1. (Color online) Illustration of the fiber chain including the 3.5 cm long DFB grating section inside the rare-earth-doped, single-mode core, and the multimode delivery fiber used to launch 976 nm pump light into the cladding of the active fiber.

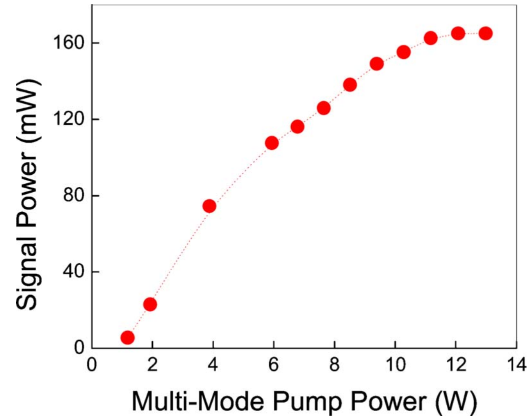

Fig. 2. (Color online) Signal power (1535 nm) of the cladding-pumped DFB fiber laser as a function of multimode pump power (976 nm) launched into the cladding of the active fiber.

The emission spectrum of the cladding-pumped DFB fiber laser measured by an optical spectrum analyzer is shown in Fig. 3. Typical for any DFB laser, our cladding-pumped DFB fiber laser emits only a narrow laser line located at the grating structure design wavelength of ~1535 nm. The width of the measured line in Fig. 3 is limited by the resolution of the spectrum analyzer (0.01 nm), and the true emission linewidth is much narrower: self-delayed homodyne measurements [12] have been performed with 20 km of fiber for the delay. At low-to-moderate power levels the emission linewidth is below 30 kHz, while it increases to ~50 kHz at pump levels of ~10 W. Up to the highest output power the side-mode suppression ratio is better than 50 dB, indicating stable single longitudinal mode operation of the DFB laser. We observed a tendency to spontaneous pulsation at high pump levels that might be related to the extremely high doping levels in the active core [13].

One of the inherent advantages of DFB lasers over single-frequency lasers formed by two DBRs is the possibility of relatively wide emission wavelength tuning without the occurrence of mode hopping between different longitudinal modes. Figure 4 demon-

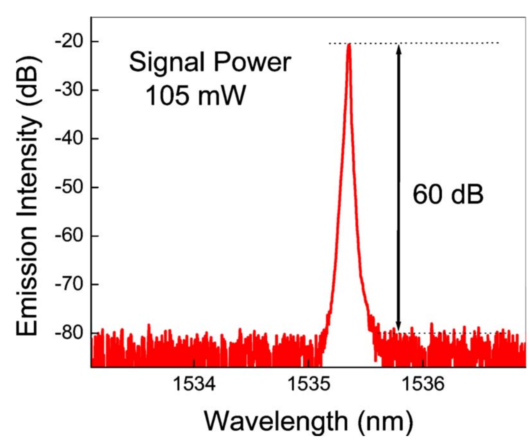

Fig. 3. (Color online) Emission spectrum of the cladding-pumped DFB fiber laser measured by an optical spectrum analyzer with 0.01 nm resolution. The real emission linewidth of the order of tens of kilohertz has been obtained by self-delayed homodyne measurements.

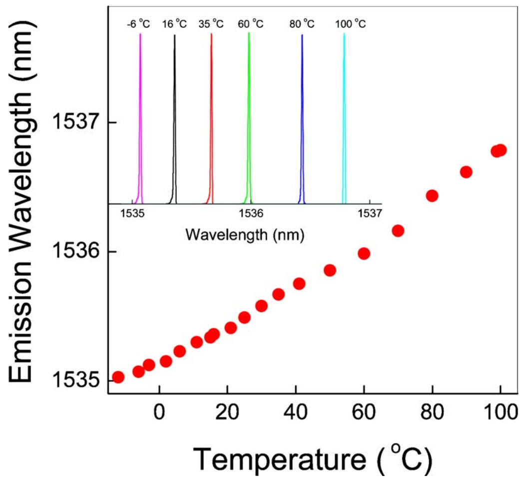

Fig. 4. (Color online) Wide-range temperature tuning of the DFB fiber laser emission wavelength. Normalized emission spectra at selected temperatures are shown in the inset. To pump the temperature controlled DFB fiber laser 4 W of multimode light has been launched.

strates that we were able to tune the emission wavelength by almost 2 nm by changing the temperature, resulting in changes of the grating period and the refractive indices and a tuning of 0.016 nm/°C.

The precise knowledge of the emission wavelength versus operating temperature also allows us to obtain a good estimate of the laser heating during high-power operation. From the measured peak wavelength at different pump and output levels shown in Fig. 2, we can conclude that despite the large amount of "wasted" pump light and our relatively crude level of thermal management efforts, the maximum temperature up to 165 mW of output power is ~40°C, indicating that heating can be tolerated at even higher levels of pump power in future devices.

To demonstrate the stability of our DFB fiber laser we have observed its continuous performance over a 10 h period at an output power level of 150 mW. The variations in output power and emission wavelength were below 2% and 0.05 nm, respectively. The achieved power level is already amongst the highest reported output powers for any DFB fiber laser, indicating the potential of our novel laser scheme for the development of high-power DFB fiber lasers.

In conclusion, we have demonstrated a novel DFB fiber laser scheme based on multimode cladding pumping. Such a cladding-pumping scheme has been known to be effective for high-power fiber lasers with a long section of active fiber but, to the best of our knowledge, has never been proposed or demonstrated for any DFB fiber laser. The achieved device performance makes our DFB laser a promising candidate for the fabrication of single-frequency fiber lasers that can be optimized for high-power, long-range wavelength tuning, and low noise. It has a very simple and robust structure and, in the applied forward pumping geometry, it does not require wavelength multiplexing structures or optical isolators. Another important feature of this novel scheme is the easy implementation of a fiber laser cascading scheme. A single, high-power multimode pump light source can be utilized to pump a string of DFB resonators that can be imprinted into the same active fiber and can be designed to emit at several wavelengths.

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