Single-frequency laser oscillator with watts-level output power at 1.5 μm by use of a twisted-mode technique

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We report an all-fiber laser oscillator producing as much as 1.9 W of single-frequency direct output at 1.5 μm. Spatial gain hole burning in the active fiber has been eliminated by use of a twisted-mode cavity approach. The two short pieces of a polarization-maintaining fiber that were spliced to the ends of the active fiber served as ultracompact quarter-wave plates. To our knowledge, the use of such a wave plate to manipulate the polarization state of light inside a fiber laser cavity is reported here for the first time. The laser output is linearly polarized and delivered through a polarization-maintaining fiber pigtail. We believe that the output power of our laser is the highest among all single-frequency fiber laser oscillators reported to date. © 2005 Optical Society of America

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The development of high-power fiber lasers has been advancing rapidly, with reports of kilowatt-class multimode fiber lasers.[1–3] This progress, however, has not been so rapid for single-frequency fiber laser oscillators. The highest output power achieved directly from a standing-wave, single-frequency fiber oscillator until recently has been 100–200 mW.[4,5] Because of spatial gain hole burning, the length of the active fiber in a standing-wave single-frequency fiber laser has to be kept as short as several centimeters, which limits the output power substantially.[6]

A single-frequency fiber laser with direct output in the watts range can find numerous applications in nonlinear optics, remote sensing, and free-space communications. In addition, if it is used as a master oscillator in a high-power master-oscillator–power-amplifier system,[7] such a source can be a practical alternative to the distributed-feedback fiber laser[4] by eliminating the need for several low-power amplification stages. Compared with an amplified single-frequency laser system, a standalone laser oscillator offers a superior amplified spontaneous emission noise performance that can be critical in some applications.

We recently achieved a single-frequency fiber laser oscillator with 1 W of output power at 1.5 μm by using a unidirectional ring laser cavity approach that eliminated spatial gain hole burning in the active fiber.[8] Although the laser reported in Ref. 8 had higher output power than that of previously reported fiber oscillators, the ring approach with a nonreciprocal element in the laser cavity was somewhat complex: further, the slope efficiency with respect to the launched pump power at 975 nm was only $\sim 5\%$, and the output light was elliptically polarized.

In this Letter we report an all-fiber single-frequency linearly polarized Er^{3+}–Yb^{3+} laser oscillator that overcomes these limitations. In our approach, the spatial gain hole burning in the active fiber has been eliminated by use of a twisted-mode cavity technique.[9] Although it has been extensively explored with bulk solid state lasers (see, for example, Ref. 10), this approach to our knowledge has never been used in the all-fiber format. We believe that the reason is that the standard polarization controllers that are used in fiber systems to emulate the quarter-wave plates needed for constructing the twisted-mode cavity laser add tens of centimeters to the laser cavity length, thus substantially reducing the frequency spacing between the longitudinal modes of the laser cavity. Furthermore, with standard doped fibers based on fused silica, the doping concentration is limited to less than 1%; therefore, to achieve a reasonable pump absorption in the gain medium, the active fiber itself has to be at least several tens of centimeters long, which also makes isolating a single longitudinal mode of the laser cavity virtually impossible.

In our approach, two short pieces of a polarization-maintaining (PM) fiber, cut to a precise length and spliced to the ends of the active fiber, serve as ultracompact and stable quarter-wave plates. Such all-fiber wave plates were used previously in optical fiber current sensors[11] but not inside the cavity of a fiber laser. In addition, a heavily doped, phosphate-glass fiber used in our approach is only ~ 10 cm long. The single-mode (not PM) active fiber is short enough to produce negligible polarization mode coupling inside the laser cavity, which is essential for the operation of the twisted-mode cavity laser. Owing to the high doping concentration, however, such length is sufficient to achieve watts-level output power from the laser.[12] As a result, 1.9 W output power has been achieved directly from an all-fiber single-frequency laser oscillator. We believe that this output power is the highest among the single-frequency fiber oscilla-

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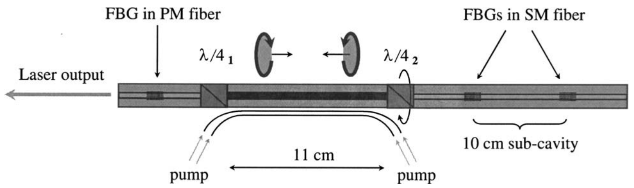

Fig. 1. Schematic diagram of the twisted-mode fiber laser: FBGs; fiber Bragg gratings.

tors reported to date. The output light from the laser is naturally linearly polarized and delivered though a PM-fiber pigtail.

The short fiber laser reported here is shown schematically in Fig. 1. The core of the single-mode (SM) active fiber is doped with 1% Er^{3+} and 8% Yb^{3+}. The active fiber is optically pumped by a scalable side-pumping method,[13] which has been modified to promote the rapid pump absorption over the short length of active fiber. A detailed description of the pumping scheme can be found in Ref. 14.

The optical feedback in the laser is provided by Bragg gratings spliced into the cavity. One of the gratings is written into a PM fiber; it has a bandwidth of 0.05 nm and a peak reflection of 20%. Owing to the refractive-index difference for the two linearly polarized eigenmodes of the PM fiber, the reflection peaks for the two polarizations are separated by ~0.4 nm in the wavelength domain. An 80% reflective, SM Bragg reflector at the other end of the cavity is fabricated such that its reflection band overlaps that of the PM grating for only one polarization. Thus the laser cavity naturally acts as a linear polarizer,[5] provided that the coupling between the polarization modes in the laser cavity is negligible. Because the PM grating has much lower peak reflection than the SM grating, the linearly polarized output light from the laser is emitted predominantly from the PM side of the cavity and is naturally keyed to one of the two birefringent axes of the PM fiber.

The total cavity length of the laser is 20 cm, which corresponds to a longitudinal mode spacing of ~500 MHz; i.e., 12 times smaller than the 3 dB bandwidth of the PM fiber grating. To improve the longitudinal mode discrimination in the laser cavity, we spliced a second 40% reflective Bragg grating behind the primary SM reflector. The two SM gratings form a low-finesse Fabry–Perot etalon, which modulates the amount of optical feedback in the laser, in the frequency domain, thus improving the longitudinal mode discrimination.[15]

Two short segments of a standard PM fiber are spliced to the ends of the active fiber. The polarization-mode beat length in the PM fiber has been measured as (4900 ± 10) μm. The length of the PM fiber segments was chosen equal to one quarter of the beat length; thus these segments act as ultracompact and robust quarter-wave plates. At the splice point between the PM fiber grating and the adjacent wave plate the birefringent axes of the two fibers have been aligned at 45° to each other. If the retardation in both wave plates is exactly one quarter of a wave, and the polarization mode coupling inside the laser cavity is negligible, the two counterpropagating waves inside the cavity have circular polarizations that are orthogonal to each other. Thus no standing-wave intensity pattern is formed in the active fiber, and spatial gain hole burning is eliminated. However, owing to the finite tolerances in the wave-plate fabrication process there is a weak spurious standing-wave pattern inside the active fiber. We performed a Jones matrix analysis of the polarization evolution in the laser cavity. The imperfections of the polarization retardation in the wave plates, a deviation from perfect 45° alignment at the splice point between the wave plate and the PM fiber grating, as well as the twist-induced birefringence introduced by the rotation have been included in the model. We found that, by rotating one of the wave plates about the fiber axis within approximately one half of a full turn, we could reduce this spurious standing-wave intensity pattern substantially. Consequently, in the setup the active fiber section is clamped to an aluminum heat sink, while the adjacent passive section including the fiber wave plate and the pair of SM fiber gratings is mounted upon a rotation stage, which is adjusted in the operation of the laser as described below. Note that the extra birefringence introduced inside the laser cavity by such rotation is circular; thus it does not introduce coupling between the orthogonal, circular polarization modes.

The total single-pass loss though the fully spliced fiber laser cavity has been measured at 1.5 dB. The main contributions to the loss are the mode mismatch at the splice points between the active phosphate fiber and the passive silica fibers, and scattering in the active fiber.

We verified experimentally that use of both the twisted-mode technique and modulation of the gain profile introduced by the two SM fiber gratings were essential for stable single-frequency operation of the laser. In particular, without the second SM fiber grating the laser operated in single longitudinal mode but with frequent mode hops, which occurred at a rate of ~1 hop/s. Conversely, a laser identical to the one shown in Fig. 1 but without the fiber wave plates was not single frequency at all and operated at two to five longitudinal modes.

The power performance of the laser is shown in Fig. 2. For as much as ~1 W of output power, the laser operates at a single frequency and remains mode-

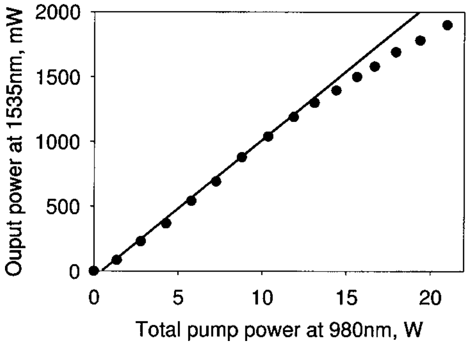

Fig. 2. Output power at 1.5 μm versus total launched pump power at 975 nm. Filled circles, data points; line, linear fit. The threshold pump power is ~500 mW, and the initial optical-to-optical slope efficiency is 11%.

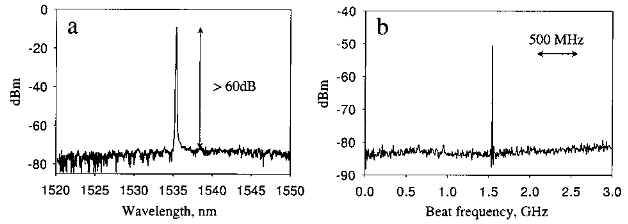

Fig. 3. a, Optical spectrum of the laser emission measured by an optical spectrum analyzer with a resolution bandwidth of 0.07 nm at the highest power level. b, rf spectrum of the beat signal between the twisted-mode fiber laser and a stable, single-frequency laboratory laser. The frequency spacing between adjacent longitudinal modes of the twisted-mode laser is 500 MHz.

hop free at a *fixed* orientation of the wave plates with respect to each other. If a wave plate is deliberately rotated from its optimum position, the laser starts simultaneously oscillating at two to three longitudinal modes. The heat generated in the operation of the laser is dissipated both by placement of the laser on an aluminum heat sink and by natural convection. Owing to the somewhat inadequate heat management, at the power levels higher than 1 W a single adjustment of the rotation stage with a mounted wave plate becomes necessary when the pump power is changed, to maintain single-frequency operation. In addition, at a fixed pump power level the single oscillating longitudinal mode thermally drifts back and forth at a rate of ~2 MHz/s. We believe that improving the heat dissipation from the device can help to reduce the drift rate of the oscillating laser mode and eliminate the need for wave-plate adjustments at different pump power levels. The maximum output power from the laser reaches 1.9 W and is limited by the available pump power. The optical-to-optical slope efficiency in the linear part of the power curve in Fig. 2 is 11%. Note that at the highest power level the laser operates ~40 times above threshold, still not having reached the multimode threshold as defined in Ref. 6.

In Fig. 3a we show the optical spectrum of the twisted-mode fiber laser at the highest level of the output power. From the data we estimate that the fraction of the amplified spontaneous emission-noise background in the output laser light is well below 10^{-4}.

To resolve the possible multifrequency operation of the laser, and to monitor the fine details of the optical spectrum in real time, we used the optical heterodyne technique. The output light from the laser was attenuated and optically mixed with the light from a tunable, single-frequency laboratory laser source. The rf spectrum of the resultant beat signal is shown in Fig. 3(b). The single peak in the curve corresponds to the single oscillating longitudinal mode.

Finally, the polarization of the laser light emitted from the PM side was measured to be better than 20 dB linear. The slight residual ellipticity of the polarization state was due to both imperfections in the wave-plate fabrication and the weak polarization-mode coupling in polarization-nonpreserving active fiber.

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