Single-frequency fiber ring laser with 1 W output power at 1.5 μm

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Abstract: We report a single-frequency fiber laser with 1 W output power at 1.5 μm which is to our knowledge, five times the highest power from a single-frequency fiber laser reported to-date. The short unidirectional ring cavity approach is used to eliminate the spatial gain hole-burning associated with the standing-wave laser designs. A heavily-doped phosphate fiber inside the ring resonator serves as the active medium of the laser. Up to 700 mW of output power, the longitudinal mode hops have been completely eliminated by using the adjustable coupled-cavity approach. At higher power levels, the laser still oscillates at a single longitudinal mode, but with infrequent mode hops that occur at a rate of few hops per minute. Compared to the Watt-level single-frequency amplified sources, our approach is simpler and offers better noise performance.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber; (140.3560) Lasers, ring; (140.3570) Lasers, single-mode

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1. Introduction

High power single-frequency fiber lasers can find applications in such areas as communications, nonlinear optics, interferometry and as the master oscillators in high-power Master-Oscillator-Power-Amplifier designs (MOPA) [1]. Traditionally, two approaches have been exploited to produce high-power single-frequency output directly from a fiber laser. The first is the so-called DFB fiber laser design, with the fiber Bragg grating written directly on the active fiber [2]. To our knowledge, the output power from the DFB fiber lasers presently approaches 100 mW. The second approach employs active fibers based on low melting temperature glasses that allow an extremely high concentration of the active ions in the fiber core. Such fibers allow for the high-gain linear laser cavity to be sufficiently short so that a single longitudinal cavity mode can be isolated with a narrow-band fiber Bragg grating. The latter approach has produced close to 200 mW output power at 1.5 μm, which is, again to our knowledge, the highest single-frequency output power achieved directly from a fiber laser to-date [3]. The output power in both of the above approaches is limited as they suffer from the spatial gain hole-burning associated with the standing-wave laser cavities [4].

An alternative way to achieve high-power single-frequency output from a fiber source is by using the MOPA system with the DFB-fiber laser as a master oscillator [1]. Although this approach is power efficient, such systems are quite complex and typically require two amplifier stages to reach the Watt level. In addition, a stand-alone laser offers better ASE-noise performance compared to a low-power laser, amplified to a comparable output power level. For example, in the single-frequency MOPA source recently reported in [1], when the system is operating at the Watt-level, $\sim$2% of the source output power is carried by the broadband spectral background of the narrow-band, primary emission wavelength. In comparison, the fraction of the ASE-noise in the direct output power from a single-frequency fiber laser in general and from the fiber laser reported in this paper, is smaller by at least two orders of magnitude. Furthermore, to avoid instabilities in the amplifying stages of a MOPA system, the output of the master oscillator typically has to be polarization-scrambled causing rapid variations of the polarization state at the output of the device, which may be undesirable in some applications.

It is known that the spatial hole-burning in the gain medium can be eliminated by using the unidirectional ring laser cavity. Until recently, using this approach with fiber lasers had a limited success, mostly because of the large active fiber length required to absorb a substantial amount of the pump power in the fiber. Consequently the cavity length in the reported ring fiber lasers was at least several meters, causing the longitudinal modes of the laser to be very close to one another in frequency [5]–[9].

In this paper, we report a single-frequency fiber laser with 1 W of direct output power, which is to our knowledge, five times the highest single-frequency output power from a stand-alone fiber laser reported to-date. By using the heavily-doped phosphate active fiber in the unidirectional ring-cavity fiber laser, we were able to reduce the total cavity length to ~ 0.5 m, while maintaining a high pump absorption in the active fiber. Using such active fibers to achieve Watts-level multimode output from short linear-cavity fiber lasers have been recently reported in [10],[11].

Received 14 March 2005; revised 12 April 2005; accepted 12 April 2005

2. Experimental results

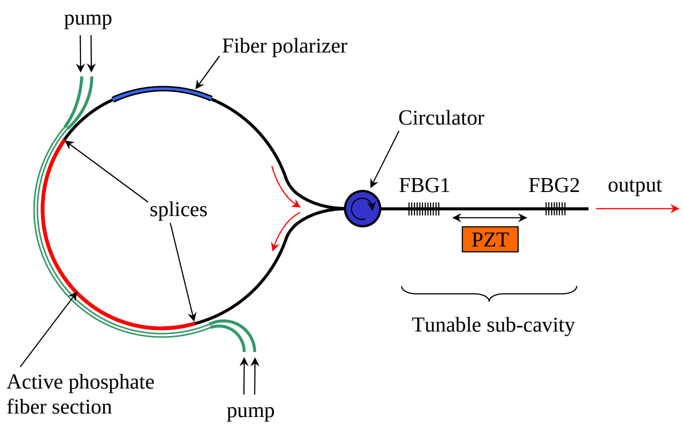

Fig. 1. Diagram of the short-cavity fiber ring laser.

The fiber laser reported here is schematically shown in Fig. 1. An 11 cm - long piece of a heavily doped phosphate-glass fiber serves as the gain medium of the laser. The active fiber has a circular core with a diameter of 14 μm, which is co-doped with 1% of Er^{+3} and 8% of Yb^{+3}. These concentrations are at least an order of magnitude higher than those possible in conventional active fibers based on fused silica. The Er^{+3}–Yb^{+3} combination in a glass host is known to absorb a pump light at around 980 nm and to emit light at around 1.5 μm. The fiber NA is low enough for the fiber to be single-mode at the laser wavelength. The active fiber is cladding-pumped using the contact side-pumping scheme [12] which has been modified in order to promote the rapid pump absorption over the short length of the active fiber. The detailed description of the pumping scheme can be found elsewhere [10]. Briefly, the active fiber is surrounded by four core-less silica fibers that can deliver the pump light from up to eight independent low-brightness diode lasers. The pump light penetrates from the silica fibers into the active phosphate fiber via evanescent field coupling between the fibers. In the experiments reported here we have pumped four out of eight inputs of the fiber bundle, leaving four remaining inputs un-used.

Except for the active phosphate-fiber section of the laser, the rest of the optical circuit is based on fused silica, single-mode fiber components (SMF-28 fiber by Corning Inc.). In particular, a commercial polarization-independent, fiber-pigtailed optical circulator is used to ensure the unidirectional operation of the laser. A 4 cm - long piece of a *polarizing* fiber (PZ-fiber by 3M Corp.) included in the laser cavity, serves to isolate a single polarization mode. The PZ-fiber is designed to attenuate one propagating linear polarization mode and to transmit the other mode with low loss. Typically, a few meters of PZ-fiber is required to polarize light to better than 30 dB. A short PZ-fiber section is used in our laser as a weak linear fiber polarizer that provides $\sim$15% of polarization extinction. The polarization extinction provided by the short PZ-fiber section has been chosen to be high enough to ensure the stable single-polarization operation of the laser, but at the same time low enough to prevent strong fluctuations of the output power caused by polarization coupling in the polarization non-preserving laser cavity [14]. The entire optical circuit is fusion-spliced together, including the interfaces between the active phosphate fiber and the SMF-28. These two splices have to be performed on the fibers cleaved at an angle, to minimize the Fresnel reflection of the laser light from the splice points. This is particularly important for the upper splice in Fig. 1. The total splice loss in the laser cavity was measured

#6856 - $15.00 US
Received 14 March 2005; revised 12 April 2005; accepted 12 April 2005

at 2.1 dB and resulted from the mismatch in the mode-field diameters between different fibers used. In addition, the circulator contributed ∼1 dB of extra loss.

Since the optical circuit is not polarization-maintaining, there was a chance that two polarization eigenmodes of the laser cavity which are of course, not necessarily linear, would experience identical loss in the weakly-polarizing PZ-fiber section. In that case the laser would operate at two frequencies corresponding to two simultaneously oscillating polarization components of the same longitudinal mode. Consequently, in the set-up we allowed for a physical rotation of the polarizing fiber section around its axis. This feature however turned out to be not necessary, as the 15% polarization extinction in the PZ-fiber was large enough to ensure a single polarization mode operation of the laser at nearly any orientation of the PZ-fiber section. In fact, by rotating the fiber polarizer we were not able to achieve a stable dual-polarization operation of the laser.

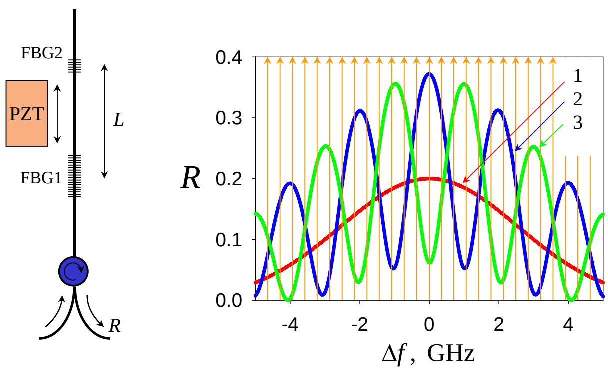

Fig. 2. Operation of the sub-cavity filter. The graph shows a calculated reflection coefficient from the filter as a function of optical frequency, for three different cases: Reflection from the FBG1 alone **(1)**; Reflection from the two gratings with total sub-cavity length $L_1 \simeq 5$ cm **(2)**; Reflection from the two gratings with the sub-cavity length $L_2 = L_1 + 0.27\,\mu$m **(3)**. (The increment equals to one quarter of the wavelength of the laser light in the fiber.) Vertical arrows mark the locations of the main cavity modes.

The primary optical feedback in the laser comes from the fiber Bragg grating spliced to the output of the circulator (FBG1 in Fig. 1). The reflection band of the grating is centered at around 1,535 nm, and the peak reflection and 3dB-bandwidth of the grating are 20% and 0.06 nm (7.5 GHz), respectively. The overall fiber-cavity length of the laser has been measured at 60 cm which corresponds to the cavity free-spectral range (FSR) of 340 MHz. This cavity length is about an order of magnitude shorter than the ones used in the previously reported ring fiber lasers. It is however still too long to yield a stable, mode-hop-free operation, even with a narrow-band fiber grating. In fact, we have confirmed that with the feedback provided by the FBG1 alone, the ring laser oscillated at a single longitudinal mode, but with frequent mode hops at a rate ∼ one hop per second.

To suppress the longitudinal mode hops we used the coupled-cavity approach [13]. The principle of operation of this method is shown in Fig. 2. A second weak grating reflector (FBG2) is spliced behind the primary reflector FBG1. The peak reflection and the 3 dB-bandwidth of the second grating in our setup are ∼5% and 0.2 nm, respectively, and the two gratings have about the same peak reflection wavelength. The additional grating modulates the amount of feedback in the laser cavity, in the frequency domain, introducing an additional discrimination between the longitudinal cavity modes. By varying the fiber length between the gratings, the period of this modulation can be changed. We have found experimentally that the total length

#6856 - $15.00 US
Received 14 March 2005; revised 12 April 2005; accepted 12 April 2005

of the sub-cavity filter that works best in suppressing the mode hops is ∼5 cm. By calculating the amount of optical feedback provided by the system of the two gratings, we have found that in order to achieve a robust isolation of a single longitudinal laser mode (the situation illustrated with the curve **2** in Fig. 2), the sub-cavity has to be made with a lengthwise precision of a fraction of the laser wavelength in the fiber, which is virtually impossible in practice. If the sub-cavity length was chosen incorrectly, the laser could hop between two longitudinal modes, corresponding to the two symmetric peaks of the curve **3** in Fig. 2. To address this problem, we mounted the single-mode fiber separating the two fiber gratings on a PZT stretcher, and adjusted the sub-cavity length by applying a DC-voltage to the PZT, while monitoring the output laser spectrum in real time. Using this method, the longitudinal mode hops have been virtually eliminated, as described below. Note that a simple straight fiber cleave instead of the secondary grating FBG2 worked just as well, but in that case the ring laser did not have the advantage of having a pigtailed output.

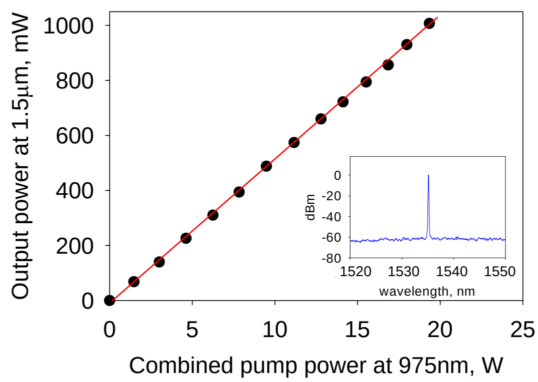

Fig. 3. Output power at 1.5 μm vs. total pump power at 975 nm. The inset shows the laser emission spectrum measured with an OSA. The suppression of the ASE-noise background is better than 60 dB.

The output laser power at 1.535 μm vs. the combined applied pump power at 975 nm is shown in Fig. 3. The output power exceeds 1 W at 19 W of pump, corresponding to slightly over 5% slope efficiency which can be increased both by improving the efficiency of the side-pumping scheme and by reducing the splice loss in the optical circuit, e.g. by using an active fiber with a propagating mode that closely matches that of SMF-28. Note that due to the low extinction ratio of the polarizing-fiber section, the output power remains linear within ∼2% in spite of the unavoidable variations of the polarization coupling in the laser cavity.

The inset in the Fig. 3 shows the spectrum of the laser light measured with an optical spectrum analyzer (OSA). It shows better than 60 dB suppression of the ASE noise background. From the data, we estimate that the fraction of the ASE noise in the output power is below 10^{-4}. The resolution of the OSA was not high enough to resolve possible multi-frequency operation of the laser. To resolve the fine spectral details we have used the optical heterodyne technique. The ring laser output was attenuated by ∼30 dB and mixed with the output of a stable single-frequency, tunable laboratory laser source (Agilent 81682A), using a fiber coupler. The mixed signal was sent to a GHz-fast photodetector whose voltage output was monitored in real time with an RF-spectrum analyzer. The wavelength of the tunable laser was initially varied to catch the beat frequency between the lasers in the 3 GHz-wide frequency span of the RF-analyzer. By scanning the wavelength of the tunable laser we have confirmed that the ring laser operated at a single longitudinal mode throughout the entire range of the output power. The RF-spectrum of the beat signal between the lasers is shown in Fig. 4(a).

#6856 - $15.00 US Received 14 March 2005; revised 12 April 2005; accepted 12 April 2005

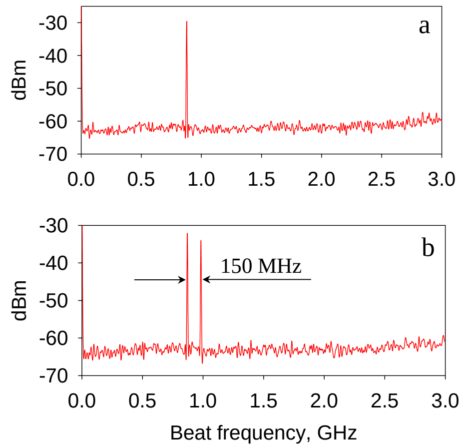

Fig. 4. RF-spectrum of the beat signal between the ring laser and a single-frequency tunable diode laser (a). A separate ring laser made without the polarizing fiber in the laser cavity shows a dual-frequency operation corresponding to simultaneous oscillation of the two polarization components of the same longitudinal mode (b).

When the pump power was incremented, the laser showed frequent mode hopping between adjacent longitudinal modes, due to thermal transients in the active fiber. This hopping stopped once the pump power was fixed. We have measured the frequency difference between the adjacent longitudinal modes in the transient regime and found it equal to 340 MHz, which is consistent with the measured length of the laser cavity.

In Fig. 4(b) we show the RF spectrum of the beat signal measured with a separate ring laser that was identical to the one shown in Fig. 1, with the exception of having no polarizing fiber section in the laser cavity. The latter spectrum shows the laser oscillation at two frequencies separated by $\sim$150 MHz which correspond to two independent orthogonal polarization components of the same longitudinal mode of the ring laser. In this case the beat signal between the two polarization modes is absent because these modes are polarized orthogonally to one another and therefore they do not coherently interfere.

No temperature stabilization was applied to the elements of the optical circuit. Therefore at a fixed pump power level, the single longitudinal mode of the ring laser with the polarizing-fiber section in the cavity was thermally drifting back and forth at a rate $\sim$10 MHz/sec. However, up to approximately 700 mW of output power the laser robustly remained mode hop-free. At higher power, the span and the rate of the thermally-induced drift of the oscillation frequency became large enough to cause occasional mode-hops at a rate of a few hops per minute. We believe that this residual mode-hopping can be straightforwardly eliminated by a proper temperature stabilization of the laser cavity.

Note that, although the laser operated in a single polarization mode, the output polarization state of the laser was in general not linear. Furthermore, the output polarization state was different at different levels of the pump power. We speculate that a stable linearly-polarized output from the laser can be straightforwardly achieved by replacing the elements of the optical circuit by their polarization-maintaining counterparts.

Acknowledgments

The authors would like to acknowledge support from the AFOSR under contract F49620-03-1-0194 and from the State of Arizona Technology and Research Initiative Fund program.