Single-longitudinal-mode fiber laser with a passive multiple-ring cavity and its application for video transmission

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A single-longitudinal-mode erbium-doped fiber laser with a passive multiple-ring cavity (MRC) is proposed for the first time to the authors' knowledge. The laser is fundamentally structured by insertion of three different short ring cavities, which serve as mode filters, into the main cavity. When it is combined with a mode-restricting intracavity fiber Bragg grating, the MRC resonator ensures single-longitundinal-mode laser oscillation. The laser can successfully suppress side-mode frequencies of as much as 1 GHz and provide an output power of 23 mW with a side-mode suppression ratio of 51 dB at 1533 nm. The short-term linewidth of the laser output measured is ~2 kHz. The ability of this fiber laser to act as an AM transmitter source is also demonstrated. © 1998 Optical Society of America

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Single-longitudinal-mode (SLM) erbium-doped fiber lasers (EFL's) have been studied intensively for their potential applications to optical communications, community antenna television (CATV) systems, fiber sensors, and spectroscopy. The unidirectional ring-cavity configuration[1,2] can offer more output power with low relative intensity noise than can a short-linear-cavity laser.[3,4] However, a rather long overall cavity length (always several tens of meters) for the ring-cavity fiber laser is unavoidable because of the required intracavity components and connecting fibers. In a typical ring EFL the long cavity length brings out a huge number (10^5-10^6) of densely spaced longitudinal modes lying beneath the erbium gain curve. To achieve SLM operation, several techniques have been proposed to control single-mode selection.[1,2,5–7] In this Letter we propose and demonstrate, for the first time to our knowledge, an EFL using simply a passive multiple-ring cavity (MRC) for SLM oscillation. When it is combined with a mode-restricting intracavity fiber Bragg grating (FBG), the MRC resonator ensures SLM laser oscillation. High output power with narrow linewidth can be obtained. The feasibility of using this laser as a cw source for CATV has also been investigated.

The proposed configuration and experimental setup of an EFL with a MRC resonator is shown in Fig. 1. The main ring cavity is composed of a 980-nm-pumped EDF amplifier with a saturated output power of 16 dBm, a variable optical coupler, an optical circulator, a reflective FBG, a polarization controller (PC), and a polarization beam splitter. It is important to use the PC and the polarization beam splitter to align the state of polarization with one of the eigenstates of polarization of the ring cavity to guarantee SLM oscillation. The FBG, with a 3-dB bandwidth of 0.25 nm (~31 GHz) and a reflectivity of >90% at 1533 nm, not only determines the lasing wavelength but serves as a mode-restricting element to provide the first restriction on the possible laser modes. Each subring cavity is composed of a PC and a 50:50 coupler. SLM selection in this MRC EFL is achieved with the

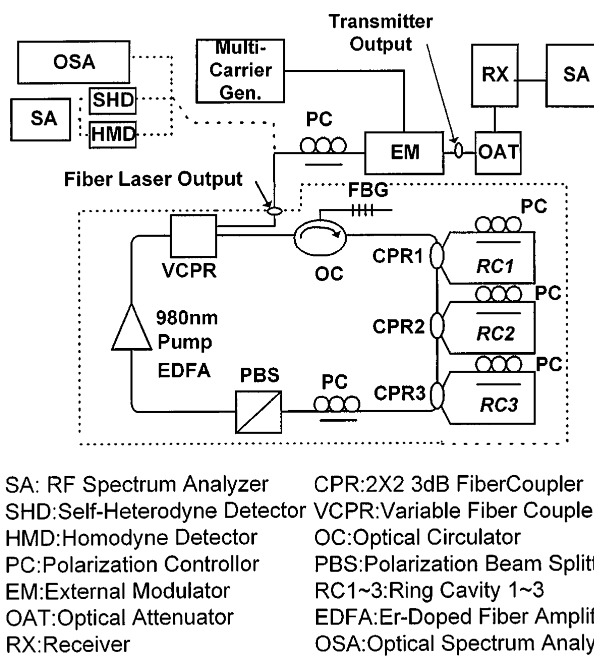

Fig. 1. Single-mode EDF ring laser MRC: proposed configuration and experimental setup.

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combination of the FBG and the MRC. The phase conditions[8,9] of the main and the subring resonant modes can be described by $\beta L_m = 2k\pi$ and $\beta L_i = 2/\pi$ if the main and the subring cavity lengths are L_m and L_i ($i = 1-N$, N is the number of sub-ring cavities), respectively. Here β is the propagation constant in each ring cavity and k and l are positive integers. The laser mode oscillates only at a frequency that satisfies the resonant conditions of the main cavity and all of the subring cavities simultaneously. The PC in each subring cavity must be tuned to the same state of polarization as that of the main cavity; however, the settings of the PC's in all subring cavities are not so critical. The main cavity and the subcavities, which serve as mode filters, have free spectral ranges (FSR's) $\mathrm{FSR}_m = c/nL_m$ and $\mathrm{FSR}_i = c/nL_i$, respectively, where c is the speed of light in vacuum and n is the average refractive index of the fiber of 1.468. The least common multiple number of all FSR's will become the effective FSR, and maximum selectivity will occur at a frequency that simultaneously satisfies resonant conditions of all ring cavities. Thus mode suppression by the vernier effect of MRC's can be realized.

In the experiments the length of the main cavity is 72 m, corresponding to a 2.8-MHz FSR. The lengths of the three subring cavities are 5.8, 5.5, and 3.6 m, corresponding to FSR's of approximately 35.2, 37.2, and 56.8 MHz, respectively. Although each subring cavity has a small FSR with several tens of megahertz, the effective FSR of several tens of gigahertz can be obtained through the vernier effect of the MRC. The operation of the MRC and its influence can be verified by a self-homodyne detection method. Figure 2(a) shows that the detected homodyne frequency spectrum of the EFL without a MRC is noisy and unstable because of the mode hopping, which is enhanced by ambient disturbances of temperature and vibration. This frequency spectrum improves after the first subring cavity with a FSR of 35.2 MHz is added, as shown in Fig. 2(b), and after two subring cavities with FSR's of 35.2 and 37.2 are added, as shown in Fig. 2(c). Stable SLM operation with side-mode suppression to 1 GHz can be achieved only after a third short subring cavity with a FSR of 56.8 MHz is added [Fig. 2(d)]. The output power of this fiber laser is ~23 mW (13.75 dBm), with a side-mode suppression ratio of 51 dB at 1533 nm [Fig. 3(a)], measured by an optical spectrum analyzer with a resolution of 0.2 nm. The 28.75% efficiency of converting the launched 980-nm pump power into the 1533-nm signal output power does not decrease, and there is only an ~0.6-dB decreased output for the MRC-based EFL compared with an EFL without MRC operation. The short-term linewidth of the fiber laser is less than 2 kHz, as shown in Fig. 3(b), measured by a delayed self-heterodyne method. Low relative intensity noise, ≤ -165 dB/Hz for this high-power EFL-based source, can be expected because similar relative intensity noise for a high-power 1319-nm solid-state Nd:YAG laser can be achieved with a high side-mode suppression ratio of >50 dB and a narrow FWHM linewidth of <200 kHz.

When this EFL is used as an AM video transmitter source, the cw output power of the EFL is externally

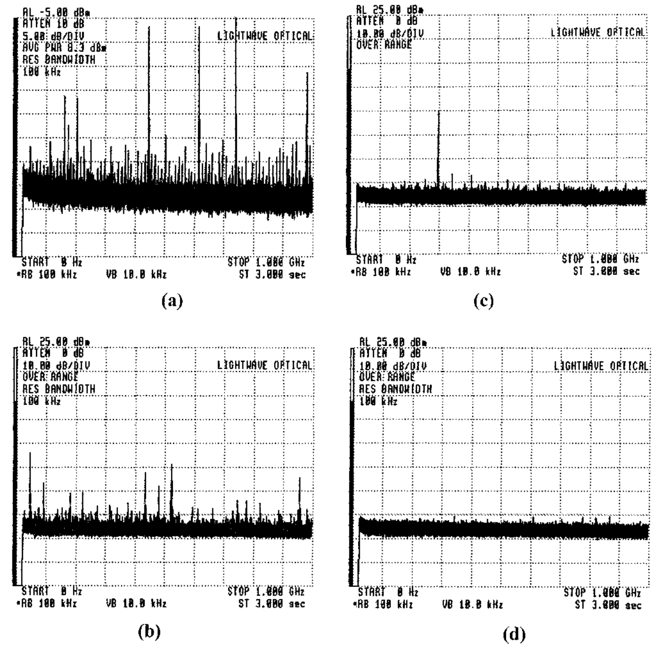

Fig. 2. Detected homodyne frequency spectrum of the fiber laser (a) without MRC operation, (b) with one subring cavity with a FSR of 35.2 MHz added, (c) with two subring cavities with FSR's of 35.2 and 37.2 MHz added, and (d) with all three subring cavities with FSR's of 35.2, 37.2, and 56.8 MHz added.

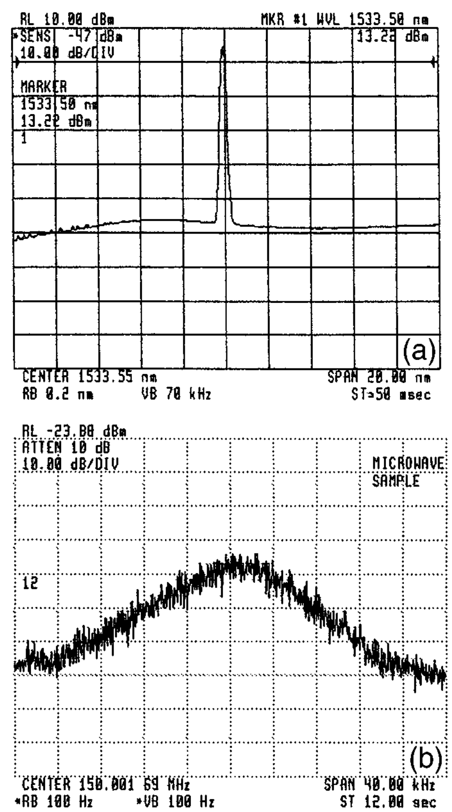

Fig. 3. Characteristics of the MRC-based fiber laser: (a) the laser output spectrum measured by an optical spectrum analyzer with 0.2-nm resolution and (b) the linewidth (single-mode spectrum) measured by a delayed self-heterodyne method.

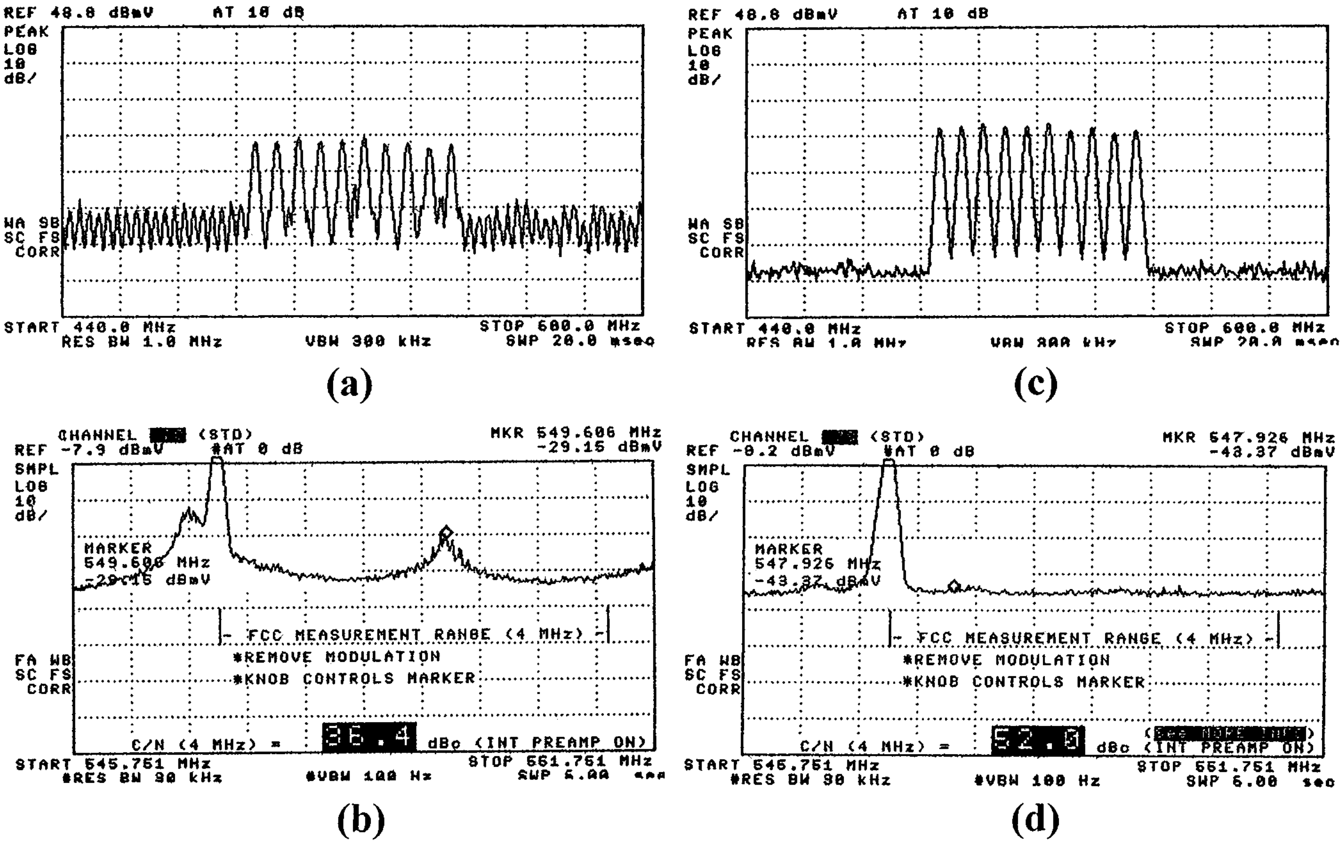

Fig. 4. Performances of the EFL-based AM transmitter without MRC operation of (a) the detected full-channel spectrum and (b) the measured CNR of channel 78 (547.25 MHz) and performance with MRC operation of (c) the detected full-channel spectrum, and (d) the measured CNR of channel 78.

modulated with ~7% optical modulation index per channel, as illustrated in Fig. 1, by 10 NTSC AM-VSB video channel signals (439.25–547.25 MHz from a Matrix carrier generator). The $LiNbO_3$ modulator has an insertion loss of ~10 dB. Keeping the receiving power at 0 dBm, we measure the carrier-to-noise ratio (CNR) performance by using an HP8591C spectrum analyzer. Figure 4(a) shows the detected full-channel spectrum of the EFL-based video transmitter when the MRC is absent; it is very noisy and the CNR is poor, only ~36.4 dB at channel 78, as shown in Fig. 4(b). The CNR should be generally larger than 43 dB at the subscriber end to guarantee good video picture quality. Figure 4(c) shows the pure full-channel spectrum of the transmitter after the MRC has been added to the EFL, and the CNR is at least 52 dB for all channels in a 2-h operation. The measured spectrum of channel 78 is shown in Fig. 4(d). Finally, a video compact-disc player was used to confirm the transmission quality of this transmitter. The received video picture quality is almost the same as the player output.

In conclusion, we have presented a single-longitudinal-mode erbium-doped fiber laser with passive multiple-ring cavities. The laser is structured by insertion of three different short ring cavities, which serve as mode filters, into the main cavity. When it is combined with a mode-restricting intracavity fiber Bragg grating, the MRC resonator ensures SML laser oscillation. The laser can successfully suppress side-mode frequencies up to 1 GHz and provide a high output power of 23 mW with a high signal-to-noise ratio of 51 dB at 1533 nm. The short-term linewidth of the laser output is ~2 kHz. The quality of this fiber laser as an am transmitter source has also been demonstrated and verified in terms of both CNR performance and quality of video transmission.

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