All-fiber traveling-wave laser with nonreciprocal ring configuration

O. G. Okhotnikov,[a] A. B. Lobo Ribeiro, and J. R. Salcedo[b]
Centro de Optoelectrónica, INESC, R. José Falcão 110, 4000 Porto, Portugal

(Received 1 July 1993; accepted for publication 7 September 1993)

An all-fiber ring laser geometry in the form of a nonreciprocal *S*-ring is presented and demonstrated. Its operation is demonstrated to allow unidirectional laser oscillation. The intensity ratio for laser oscillation in each of the two directions were measured, and found to be larger than 150. This value is the largest such ratio obtained for a ring laser without Faraday isolators.

Unidirectional laser oscillation, as made possible by a ring configuration, allows the elimination of spatial hole-burning effects which in turn makes it possible to raise the pumping level above threshold while maintaining single-frequency operation.[1–4] In particular, a unidirectional ring geometry also allows a significant reduction of etalon and backscatter effects; in addition, for this geometry passive mode locking may self-start from noise, contrary to standing wave geometries where passive mode-locking operation must be initiated by some appropriate trigger, as provided by mode lockers, moving mirrors, or equivalent systems.[5] Several different techniques for obtaining traveling-wave operation in ring resonators have been demonstrated using specific cavity designs.[1,2,6–8] One of these specifically introduces some degree of directional nonreciprocity by utilizing an appropriate external mirror which reflects part of the beam circulating in one direction back into the opposite direction. This back reflected signal serves as an injected seed to the field circulating in the opposite direction, and leads to a much stronger laser oscillation in this direction.[1,2] This method seems to be attractive especially for a high gain laser medium like an erbium-doped fiber, and recently[9] it was successfully applied to a semiconductor ring laser diode. In this letter we report an all-fiber unidirectional ring laser which utilizes this concept to provide the source of directional nonreciprocity. We demonstrate that efficient unidirectional laser oscillation can be achieved by an elegant all-fiber cavity design.

The experimental configuration of the *S*-ring all-fiber, erbium-doped laser is shown schematically in Fig. 1(a). For the amplifier section of the ring cavity, we used 30 m of standard erbium-doped fiber, with an Al_2O_3-GeO_2-SiO_2 core (dopant level of 200–300 ppm) and a cutoff wavelength of 1 μm. This amplifier section was pumped at 980 nm by a cw Ti:sapphire laser via a WDM (980/1550 nm) fiber coupler. The two 3 dB fiber couplers of the ring cavity shown in Fig. 1(a) are standard telecommunication couplers (SIFAM Corp.) and are characterized by a relatively flat transmission across the 1.55 μm wavelength region. A 10 dB fiber coupler fitted to the ring opposite the amplifier section, allows light from either propagation direction to be coupled out. This allows us to verify the traveling-wave operation of the laser, as well as measure the intensity ratio between the two counterpropagating waves. All components were spliced using a fiber fusion splicer and the overall ring cavity length was about 35 m. The passive intraring S-shaped fiber was built, by connecting the base and apex of the 35 m ring cavity, using the other output ports of the standard 3 dB fiber couplers. A set of polarization disks to control the polarization states within the all-fiber laser cavity were incorporated. In addition, great care was taken to ensure that reflections from the fiber ends did not contribute to the laser operation.

The performance of the erbium *S*-ring laser was measured for pumping levels consistent with diode pumping. Figure 2 shows the laser output power through each port of the optional 1:10 coupler as a function of pump power for (a) bidirectional and (b) traveling-wave regimes. All plots in this figure were obtained under identical experimental conditions including the state of the polarization disks. The laser was first operated with the intraring S-shaped fiber included [Fig. 2(b)]. Laser threshold was measured to be 7.9 mW of launched pump power at 980 nm, and the total slope efficiency was measured to be 15.2%, with the total output power being about 2 mW for a pumping power of 21 mW (calculated for the laser out-

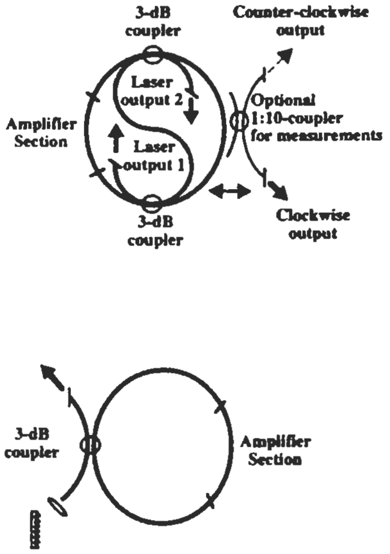

FIG. 1. Schematic diagram of the laser configurations with intraring crossover *S*-fiber (a) and with diffraction grating as external retroreflector (b).

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[a] On leave from the General Physics Institute, Russian Academy of Sciences, Russia.

[b] Also with Dept. Fisica, Universidade do Porto, Praca Gomes Teixeira, 4000 Porto, Portugal.

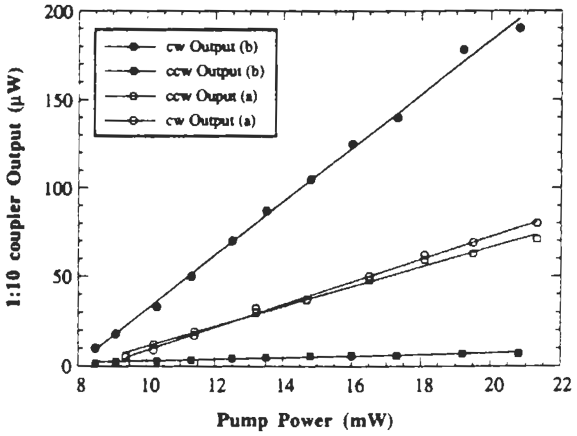

FIG. 2. Laser output powers against pump power through each port of 1:10 optional coupler (a) without *S* connection and (b) with *S* connection.

puts 1 and 2 in addition to the 1:10 coupler output). The crucial role of the S-shaped fiber in the ring was demonstrated by breaking this fiber. Bidirectional laser oscillation with approximately the same power as the oppositely propagating beams was observed without this fiber connection included [Fig. 2(a)]. Figure 3 shows the laser spectra as measured at the output ports of the optional coupler, for the traveling-wave mode of operation at launched pump power of about 21 mW. The intensity ratio for the clockwise (cw) to the counterclockwise (ccw) beam was measured to be 50 at the 21 mW pump power available at 980 nm. This ratio was increased from about 50 up to 150 by proper adjustment of the intracavity polarization controllers. This demonstrates that nonreciprocity of the cavity (or, equivalently, the difference in laser thresholds for the two propagation directions) is very high. The physical reason for this behavior is quite evident from the laser configuration itself. The S-shaped fiber couples out a portion of the wave propagating in the counterclockwise direction, reinjecting it into the ring as a cw wave. The source of directional nonreciprocity is precisely this S-shaped fiber, which provides the feedback signal. To provide the wavelength tunability, we have used the modified version of this laser with one of the 3-dB couplers removed and with the diffraction grating as back reflector for achieving both unidirectional lasing and wavelength selection [Fig. 1(b)]. The grating with 600 ℓ/mm was blazed at 1.5 μm. To collimate the beam from the fiber onto the grating, a 0.1 NA microscope objective was used. With the introduction of the grating, the difference in the cw and ccw outputs was comparable to that obtained with previous *S*-ring design, while continuous tuning was achieved over 7 nm (Fig. 4) and susceptibility to mode hopping was drastically reduced, giving stable laser output. The wavelength tuning range was limited by appearance of bidirectional oscillation, although tunable operation could be obtained around both 1.53 and 1.55 μm, depending on the settings of the polarization controllers. We are presently working toward the replacement of the bulk diffraction grating in Fig. 1(b), by a fiber grating with the reflection Bragg wavelength tuned externally. This should provide a wavelength tunability range larger than the one shown in Fig. 4. Additionally this is the way to implement a tunable unidirectional all-fiber laser.

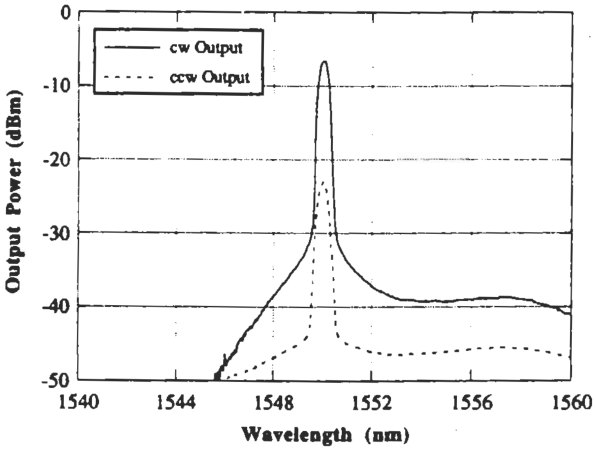

FIG. 3. Optical spectrum for the clockwise (cw) and counterclockwise (ccw) propagating lasers beams, from each port of 1:10 coupler (pump power$\approx$21 mW).

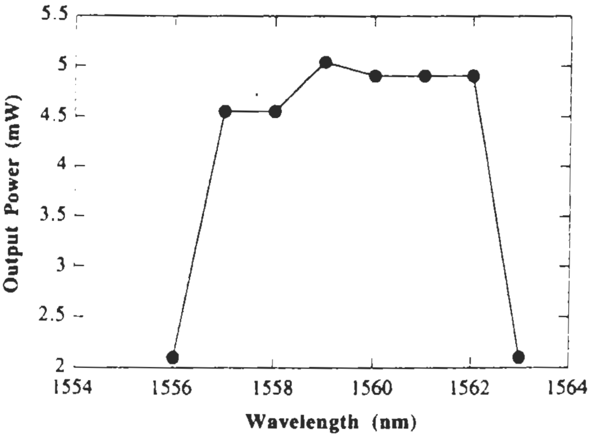

FIG. 4. Fiber laser tuning curve.

In conclusion, we have demonstrated a novel Er^{3+}-doped all-fiber ring laser that shows unidirectional behavior over a wide range of pumping power. The intensity ratio between the two waves propagating along opposite directions was larger than a factor of 150; to our knowledge, this is the largest value obtained for ring lasers which do not include bulk Faraday isolators.[2] A lasing threshold of 7.9 mW and a slope efficiency of 15.2% have been measured. The novel all-fiber laser configuration that we demonstrate in this letter does not require bulk Faraday isolators to ensure unidirectional lasing operation and seems to be an attractive concept to design and build diode-pumped tunable single frequency as well as mode-locked all-fiber lasers.

[1] A. Ananèv, *Résonateurs Optiques et Probléme de Divergence du Rayonnement Laser* (Mir Editions, Moscow, 1982).

[2] A. E. Siegman, *Lasers* (University Science Books, Mill Valley, CA, 1986), p. 534.

[3] J. B. Schlager, S. Kawanishi, and M. Saruwatari, Electron. Lett. 27, 2072 (1991).

[4] N. Park, J. W. Dawson, K. J. Vahala, and C. Miller, Appl. Phys. Lett. **59**, 2369 (1991).

[5] K. Tamura, H. A. Haus, and E. P. Ippen, Electron. Lett. **28**, 2226 (1992)

[6] O. G. Okhotnikov, D.Sc. thesis, General Physics Institute, Russian Academy of Sciences, Moscow, 1992.

[7] E. M. Dianov, T. R. Martirosian, O. G. Okhotnikov, and V. M. Paramonov, Sov. J. Lightwave Commun. **2**, 153 (1992).

[8] E. M. Dianov, T. R. Martirosian, O. G. Okhotnikov, and V. M. Paramonov, *Conference on Optical Fiber Communications* (OSA, San Jose, CA, 1993), p. 103.

[9] J. P. Hohimer, G. A. Vawter, and D. C. Craft, Appl. Phys. Lett. **62**, 1185 (1993).