An Ultralow Noise and Narrow Linewidth $\lambda/4$-Shifted DFB Er-Doped Fiber Laser With a Ring Cavity Configuration

Akihito Suzuki, Youhei Takahashi, Masato Yoshida, and Masataka Nakazawa, *Fellow, IEEE*

***Abstract*—We report a polarization-maintaining $\lambda/4$-shifted distributed feedback (DFB) Er-doped fiber laser with a ring cavity configuration. The ring cavity suppressed the self-pulsation of the stand-alone Er-doped DFB fiber laser. The laser with a 57-m-long ring cavity achieved single-longitudinal-mode operation, a linewidth as narrow as 6 kHz, and relaxation-oscillation-free noise characteristics.**

***Index Terms*—Distributed feedback (DFB) lasers, erbium-doped fiber (EDF), optical fiber lasers.**

I. Introduction

A $\lambda/4$-shifted distributed-feedback (DFB) fiber laser is an attractive device for dense wavelength-division-multiplexing (WDM) systems and sensing applications due to its robust single-mode operation, narrow linewidth, fiber compatibility, and ease of fabrication [1]–[4]. The first $\lambda/4$-shifted DFB fiber laser was realized by using an Er–Yb-doped phosphosilicate fiber and a thermally induced $\lambda/4$-shift grating [1]. Permanent $\lambda/4$-shifts based on fiber Bragg grating (FBG) techniques have also been achieved [5], [6] and DFB germanosilicate erbium-doped fiber lasers (EDFLs) have been reported [2], [3]. An FBG can be effectively fabricated in an EDFL because of the high photosensitivity that results from the germanium doping in the core. A high-power and low-noise Er–Yb-doped phosphosilicate fiber laser has been demonstrated [4] but the fiber structure is somewhat complicated for FBG fabrication because germanium could not be included in its core [7].

With heavy erbium doping, the EDFL experiences the serious problem of self-pulsation, which is caused by an ion pair interaction. This ion pair interaction functions as a saturable absorber [8]. Various attempts have been made to suppress the pulsations [9]–[11]. Although a resonant pumping scheme [10] and a coaxial pumping scheme [11] are available, they are not cost-effective methods because they require another pump source. An effective and simple technique for suppressing self-pulsation is the codoping of aluminum ions in the core [9].

A reduction in the threshold and an improvement in the linewidth by using a ring configuration of $\lambda/4$-shifted DFB fiber lasers were demonstrated in 1996 [12]. However, this ring-type EDFL suffered from self-pulsation. Furthermore, only 1% of the total output power was available even with the continuous-wave (CW) ring-type Er–Yb-doped fiber laser.

In this letter, we report the complete suppression of EDFL self-pulsation by adopting a ring configuration and codoping aluminum ions in a polarization-maintaining (PM) $\lambda/4$-shifted DFB EDFL. We also realize a linewidth of 6 kHz and relaxation-oscillation-free noise characteristics with a ring cavity length of 57 m.

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The authors are with the Research Institute of Electrical Communication (RIEC), Tohoku University, Sendai-shi 980-8577, Japan (e-mail: sakihito@riec.tohoku.ac.jp).

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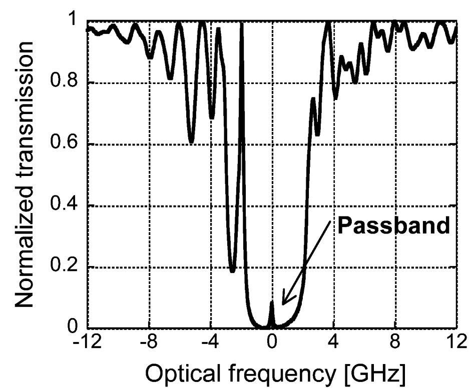

Fig. 1. Measured transmission spectrum of the $\lambda/4$-shifted FBG. (40-MHz resolution.)

II. Measurement Results and Discussion

A. PM $\lambda/4$-Shifted DFB EDFL

We fabricated a PM $\lambda/4$-shifted DFB EDFL with a PANDA-type Er-doped germanosilicate fiber. The erbium concentration and peak absorption of the fiber were 0.4 wt% and 29 dB/m at 1.53 μm, respectively. The fiber was codoped with 12-wt% aluminum ions to reduce the number of ion pairs. The $\lambda/4$-shifted FBG was fabricated in the PM EDF by the phase mask method [13]. A permanent $\lambda/4$-shift was produced by using a phase mask with a π phase shift in the center. A 14-cm-long FBG was fabricated by scanning a mirror along the phase mask in a similar way to that described in [14] and [15]. The scanning velocity was appropriately adjusted to obtain a single-longitudinal mode laser oscillation.

We measured the reflection spectrum of the $\lambda/4$-shifted FBG by using a PM circulator and an optical network analyzer with a 40-MHz resolution. Fig. 1 shows the normalized transmission spectrum. The passband resulting from the $\lambda/4$-shift was observed in the center of the stopband. The 3-dB bandwidth of the stopband was 4 GHz. This corresponds to a grating strength of $\kappa L = 8$ from a numerical result obtained using the transfer matrix method [16]. Here, κ is the coupling coefficient and L is

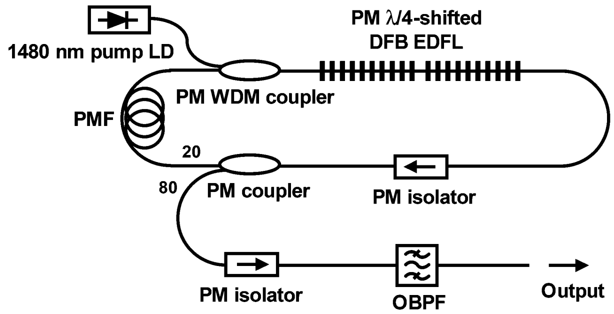

Fig. 2. Configuration of a ring-type PM $\lambda/4$-shifted DFB EDFL.

the FBG length. The calculated passband was 2 MHz and the measured passband was insufficiently resolved with a 40-MHz resolution.

We constructed a PM $\lambda/4$-shifted DFB EDFL consisting of a 14-cm-long PM EDF with a $\lambda/4$-shifted FBG, a 1480-nm laser diode, and a PM WDM coupler. The oscillation wavelength and the output power were 1542.2 nm and 0.5 mW for a pump power of 100 mW, respectively. The linewidth was 82 kHz measured by the delayed self-heterodyne technique with an 80-km fiber delay line, and the relative intensity noise (RIN) at the relaxation oscillation frequency was -79 dB/Hz for 100-mW pumping.

The laser exhibited single-longitudinal mode oscillation, but it produced self-pulsation above a pumping threshold of 10 mW. CW operation was achieved by increasing the pump power to 100 mW. These results indicate that it is difficult to suppress the self-pulsing behavior with a simple pumping scheme in the $\lambda/4$-shifted DFB EDFL even if the fiber is codoped with a large quantity of aluminum ions.

B. Ring-Type PM $\lambda/4$-Shifted DFB EDFL

The performance of the DFB EDFL was greatly improved by employing a ring cavity configuration. Fig. 2 shows the configuration of a ring-type PM $\lambda/4$-shifted DFB EDFL. The ring cavity was constructed by connecting both ends of the DFB laser described in Section II-A. The entire ring cavity was composed of PM fibers and devices connected with the same polarization axis. A PM isolator was installed in the ring cavity. A linearly polarized light with a slow axis propagated unidirectionally in the ring cavity. A PM coupler was used to obtain the laser output from the ring cavity. Twenty percent of the power was fed back to the laser and 80% was used as the output power. At the output of the laser, a PM isolator was used to prevent backward reflection and a bandpass filter was used to eliminate the pump light.

In Fig. 3, we compare the output signals of the conventional and the ring-type PM $\lambda/4$-shifted DFB EDFLs with 60-mW pumping. The ring-type laser successfully achieved CW operation at this pump power, whereas it was difficult to realize CW oscillation with the conventional-type DFB laser. With the ring-type configuration, CW operation was immediately obtained with a 10-mW pumping threshold and continued at any pump power. A ring-type configuration realizes a large cavity Q-value and constructs a very narrow passband within the passband of $\lambda/4$-shifted FBG. This plays an important role in limiting the number of oscillation modes and therefore suppressing the self-pulsation.

We confirmed the single-longitudinal mode operation of the ring-type PM $\lambda/4$-shifted DFB EDFL by using a

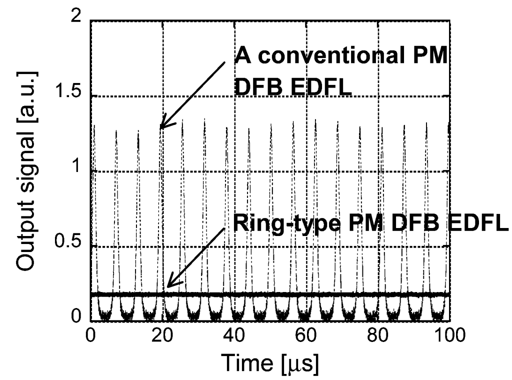

Fig. 3. Changes in the output signals of conventional and ring-type PM $\lambda/4$-shifted DFB EDFL.

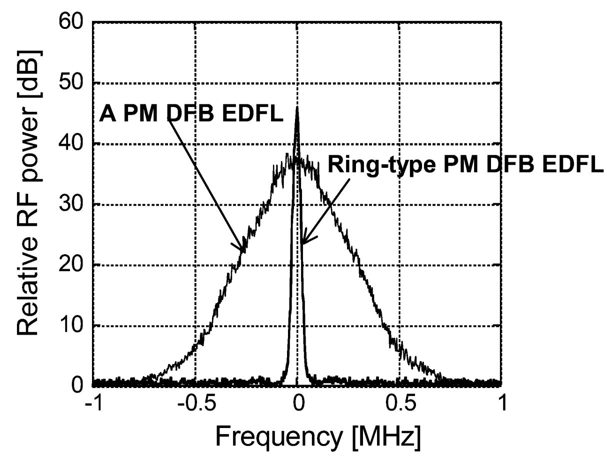

Fig. 4. Delayed self-heterodyne RF beat spectrum of conventional and 57-m ring-type PM $\lambda/4$-shifted DFB EDFL.

heterodyne radio-frequency (RF) beat signal with a stable single-mode semiconductor laser. Stable single-longitudinal oscillation was confirmed even in a 57-m-long ring cavity. The single-polarization-mode operation was verified from the zero ellipticity by using an optical polarization analyzer. The output power of the ring-type laser was 0.4 mW for 100-mW pumping. The output power is limited by the length of PM EDF on which FBG can be fabricated and by the erbium concentration that can be doped to the silica fiber. We expect that the output power can be slightly increased by using a different PM coupler such as 90 : 10 while the self-pulsation is still suppressed. The oscillation wavelength was the same as that of the conventional laser and a high optical SNR of about 65 dB was obtained.

Fig. 4 shows the delayed self-heterodyne RF beat spectrum of the ring-type PM $\lambda/4$-shifted DFB laser with a 57-m ring cavity compared with that of a conventional laser with 100-mW pumping. The linewidth with the ring-type laser was significantly reduced from 82 to 6 kHz. Fig. 5 shows the RIN spectrum of a conventional laser and a 57-m-long ring-type laser with 100-mW pumping. Surprisingly, the RIN peak disappeared with the ring-type configuration. This result indicates that the relaxation oscillation was sufficiently suppressed by the ring configuration.

Fig. 6 shows the changes in the linewidth and RIN at the relaxation oscillation frequency as a function of ring cavity length. The linewidth was reduced in inverse proportion to the

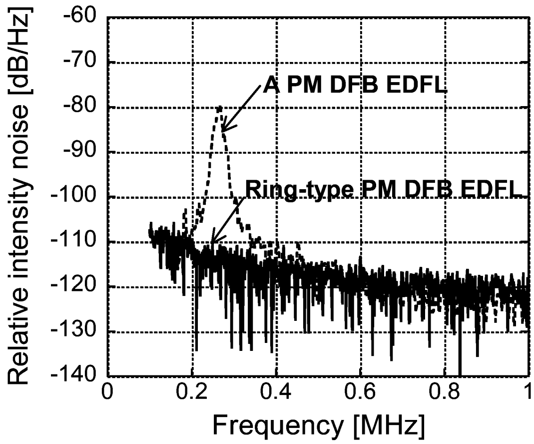

Fig. 5. RIN spectrum of conventional and 57-m ring-type PM $\lambda/4$-shifted DFB EDFL.

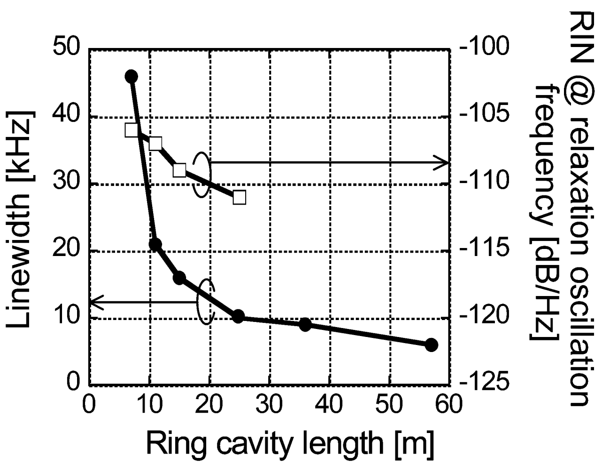

Fig. 6. Changes in the linewidth and RIN at relaxation oscillation frequency of ring-type PM $\lambda/4$-shifted DFB EDFL as a function of ring cavity length.

cavity length. The RIN peak also decreases when the cavity length is extended and the RIN peak disappeared when the ring cavity length was over 25 m. These improvements were obtained due to the enhanced Q-value of the laser cavity. The ring configuration makes the lasing signal pass repeatedly through the ultra-narrowband filter due to the $\lambda/4$-shift transmission characteristics. Therefore, single longitudinal-mode operation was realized even when the ring cavity was as long as 57 m.

III. Conclusion

We have successfully suppressed self-pulsation in a PM $\lambda/4$-shifted DFB EDFL by using a ring configuration. Furthermore, a linewidth as narrow as 6 kHz and relaxation-oscillation-free noise characteristics were simultaneously achieved with this ring-type PM $\lambda/4$-shifted DFB EDFL with a 57-m-long cavity.

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