Tunable fiber ring laser employing a Sagnac interferometric filter

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A tunable erbium-doped fiber ring laser employing an all-polarization-maintaining fiber loop filter is proposed and demonstrated. The lasing frequencies can be selected by properly adjusting the polarization controller in the cavity.

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Erbium-doped fiber lasers operating in the 1550-nm communication window have important applications in wavelength division multiplexing (WDM) communications, true-time-delay (TTD) control of microwave phase-array antenna (PAA) systems, and fiber sensors[1−3]. Among different types of fiber lasers, unidirectional traveling-wave ring laser has the advantages of eliminating back scattering and spatial hole-burning effects, and therefore has been intensively investigated recently. Optical filters, such as fiber Bragg grating (FBG)[4], Fabry-Perot filter[5], multi-mode filter[6], and high birefringence fiber[7,8], have been used for the construction of fiber lasers as the wavelength selector. A single fiber laser capable of generating several discrete frequencies is desirable, which requires a comb filter with equal frequency spacing. It will be proved that all stress-induced polarization-maintaining fiber (PMF) loop with a single coupling point exactly meets this requirement.

Sagnac loop with a certain birefringence has been proposed by Miller[9] and Fang *et al.*[10]. However, since a standard single-mode fiber coupler is used to construct the loop filter, unstable birefringent effects of single mode fiber can cause the filter to change randomly with time. In this letter, we propose and demonstrate a novel configuration of fiber ring laser using an all-PMF loop as the comb filter.

We consider the simplest case as shown in the Sagnac filter part of Fig. 1, in which only one polarization mode-coupling point exists, i.e., the filter is constructed by splicing two output PMF pigtails of the PMF coupler with lengths l_1 and l_2 respectively, with a certain angle difference of the principal axes in the splice point. The

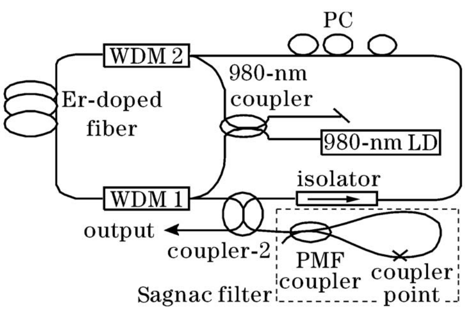

Fig. 1. Fiber ring laser using a PMF Sagnac loop as the frequency selector.

intensity transfer function F_{re} for the reciprocal port can be derived as

$$F_{\mathrm{re}} = 1 - \sin^2\theta \cdot \sin^2(\Delta\beta \cdot \Delta l/2), \quad (1)$$

where $\Delta l = l_2 - l_1$ is the length difference between two PMF segments in the loop, θ is the angle difference of principal axes of two PMFs and $\Delta\beta(\omega) = \beta_x(\omega) - \beta_y(\omega)$ is the two propagation constant difference of the high-birefringence fiber that supports two linearly orthogonal fundamental modes HE_{11}^x and HE_{11}^y. From Eq. (1), it shows that when $\theta \neq 0$ or π the intensity of the reflection spectra is maximum according to the following equation

$$\Delta\beta(\omega_m) \cdot \Delta l/2 = m\pi, \quad (m = 1, 2, \cdots). \quad (2)$$

Light with frequency ω_m will disappear at the non-reciprocal port for the case $\theta = \pi/2$ since the transfer function of the non-reciprocal port is $F_{\mathrm{non-re}} = 1 - F_{\mathrm{re}}$, where F_{re} is the transfer function of the reciprocal port. There are two kinds of high-birefringence fibers, namely, stress-induced birefringence fiber and geometry-induced fiber, where the former has greater effect. Here we only consider the stress-induced birefringence fiber because of the simple relationship between modal birefringence and wavelength. Its modal birefringence B is independent of wavelength since the effective index of each polarization mode is influenced by stress alone, that is

$$\Delta\beta = \frac{2\pi}{\lambda}B. \quad (3)$$

Thus, the reflection spectrum of the Sagnac PMF loop will have a maximum intensity at the reflective frequencies ν_m according to the following equation

$$\nu_m = mc/B\Delta l, \quad (m = 1, 2\cdots) \quad (4)$$

and the interval of the contiguous frequencies is

$$\nu_{m+1} - \nu_m = c/B\Delta l, \quad (5)$$

where c is the speed of light in the vacuum. Equation (5) means that the loop with one coupling point is a comb filter with equal frequency interval. It is noted that although the frequency-dependent intensity transfer function is independent of the input polarization, the polarization state of the output generally depends on the polarization state and frequency of the input. If the coupling point occurs at the coupling area of PMF coupler, the splice point of the loop can be cancelled. One can also cascade several uniform loop filters to obtain the filter with sharp peaks in the non-reciprocal port output.

To verify the proposed filter theory, in our experiment, a 1×2 PMF coupler from E-tek and 13.98-m PMF from Newport were used to form the loop filter with single coupling point. As shown in Fig. 2, we got the interferometric intensity of polarizations coupling of the loop filter and estimated the wavelength interval about 0.33 nm in the 1550-nm window, this was matched with the parameters we used as $B = 5.2 \times 10^{-4}$ and $\Delta l = l_2 - l_1 = 13.98$ m, according to Eq. (5).

The schematic of the unidirectional tunable fiber ring laser used in our experiment is shown in Fig. 1. It is constructed using 15-m-long silica optical fiber doped with approximately 200 ppm of erbium. The numerical aperture (NA) of the erbium-doped fiber is 0.21 and the cutoff wavelength is 920 nm. The erbium-doped fiber has an absorption coefficient of 12 dB/m at 980 nm. To increase the optical pump efficiency, the erbium-doped fiber is pumped at 980 nm in dual directions by a diode laser through two 980/1550-nm wavelength division multiplexers (WDMs). A polarization independent fiber isolator is used to achieve the unidirectional ring oscillation so as to avoid spatial hole burning in the gain medium. A polarization controller (PC) is used in the cavity to adjust the polarization state. The coupler acts as the output coupler of the fiber laser and also the port to direct the lightwave to the Sagnac filter. The lasing wavelengths or frequencies are determined by the reflective peak of the filter and can be tuned by compressing or stretching the loop. It was observed experimentally that, as the polarization controller in the ring cavity is adjusted, different lasing wavelengths were observed at the output under low pump power of about 400 mW, as shown in Fig. 3(a) — (c). With higher pump power, several wavelengths appear simultaneously. Figure 4 is the output of fiber ring laser under higher pump power around 900 mW, four dominant lasing wavelengths are observed.

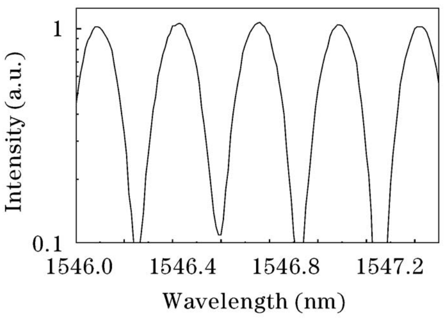

Fig. 2. Measured reflective intensity from the loop filter.

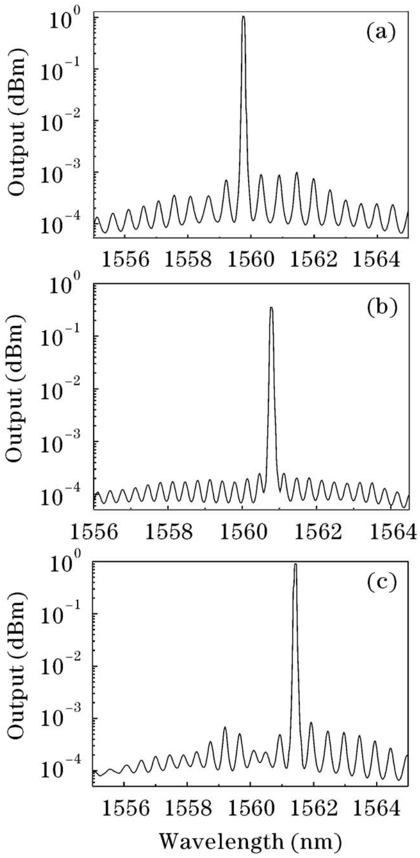

Fig. 3. Measured output spectra of the fiber ring laser under low pump power of about 400 mW, as PC in the ring cavity is adjusted (a) — (c) .

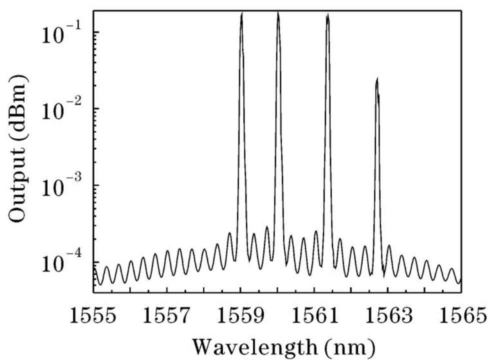

Fig. 4. Output of fiber ring laser under higher pump power around 900 mW.

In conclusion, we have designed and implemented an erbium-doped fiber ring laser employing an all-PMF Sagnac loop. In this configuration, the possible lasing frequencies are determined by the stable loop filter, which is formed by all-PMF segments and a PMF directional coupler. We can select the lasing frequencies by properly adjusting the polarization controller in the ring cavity. Fiber ring laser employing the all-PMF loop filter presents several advantages. Using the design equations as presented here, one can design the filter to generate the desired lasing frequency spacing. The all-PMF frequency selector is easy to construct without using expensive equipment. Multiwavelength operation using the all-PMF loop has also been realized when a 10-kHz frequency shifter is induced in the laser cavity.

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