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Theoretical analysis of Sagnac loop mirror with an inline high birefringence fiber ring resonator: Application in single-frequency fiber lasers

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ABSTRACT

We newly propose and theoretically analyze a Sagnac loop mirror with an inline ring resonator containing a piece of high birefringence fiber (HBF) and erbium-doped fiber (EDF). With the EDF properly pumped to offset the passive loss in the inline ring resonator, narrowband transmission peaks with large effective free spectral range can be realized by the intrinsic vernier effect between orthogonally polarized lights traveling along the two primary axes in the HBF. In addition, this property is independent of polarization states of the input signal, which makes the proposed Sagnac loop mirror suitable for a narrowband filter applied to single-frequency fiber lasers.

1. Introduction

Due to its compatibility with fiber based devices, fiber lasers [1–3] have become potential optical source for applications in many fields. Especially, single-frequency fiber lasers are of considerable interest due to their extensive applications in fiber sensors [4], medical surgery [5] and communication systems. Fiber lasers can be grouped into linear and ring structures, and a variety of resonator configurations [6–8] have been employed to accomplish stable single-frequency operation in fiber lasers. Simple linear cavities use a short gain medium to obtain a large free spectral range (FSR) that is required for single-frequency operation. However, this excludes the use of media with a small gain per unit length and limits the attainable output power. For addressing the cavity-length problem, compound ring structures composed of two physical rings with small length difference are usually designed for single frequency selection with comparatively large FSR achieved by the vernier effect [9]. For example, a feedback Mach–Zehnder resonator [10] with an inline reflector was proposed to increase the effective FSR, but it might be as unstable as the common Mach–Zehnder comb filter since the vernier effect involves two different rings. Likewise, most of the complex-ring approaches suffer from the common problem of high sensitivity to environmental fluctuations. Besides this, the passive loss in the complex-ring filter degrades the properties on account that the field at on resonant frequencies circulates more times in the ring resonator and then undergoes more loss than that at off-resonant frequencies.

Recently, a Sagnac loop mirror with several pieces of serially connected high birefringence fibers (HBF), polarization controllers (PC) and 2 × 2 switches [11] attracts much attention due to its simplicity and stability. Most importantly, its transmission spectrum is independent of the polarization state of the input signal. Based on this structure, we propose and theoretically analyze in this work a Sagnac loop mirror with an inline HBF ring resonator for the first time to our knowledge. The ring resonator constitutes an equivalent complex ring cavity due to the small refractive index difference between the slow and fast axes of the HBF. A piece of pumped erbium-doped fiber (EDF) is also inserted in the ring resonator to partly offset the passive loss. By using this method, the Sagnac loop mirror apparently overcomes the disadvantages of the previously reported compound resonators and is more suitable for employment in single-frequency fiber lasers.

2. Schematic setup and operational principle

Fig. 1 illustrates the simple configuration of our proposed Sagnac loop mirror with an inline HBF ring resonator. The Sagnac loop mirror is formed by one 3 dB optical fiber coupler (OC_1) and one polarization controller (PC). The inline HBF ring resonator is composed of another fiber coupler (OC_2), a piece of EDF with length L_1 and HBF with length L_2. Besides these, the EDF is bidirectionally pumped by two 980 nm laser diodes (LD) through 980/1550 nm wavelength division multiplexers (WDM). The two pump powers

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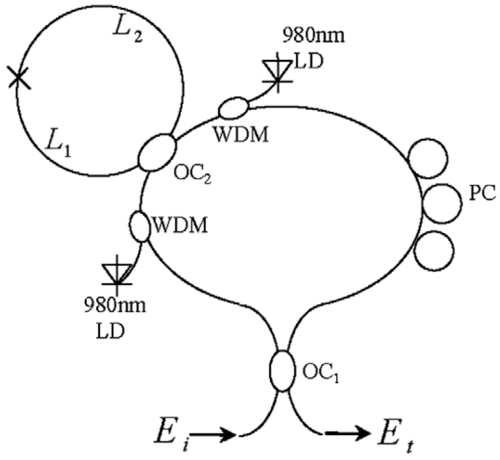

Fig. 1. The schematic setup of our proposed Sagnac loop mirror with an inline HBF ring resonator.

are the same for equally compensating the passive loss suffered by the clockwise and counter-clockwise signals circulating in the HBF ring.

The transmissivity of the Sagnac loop mirror with an inline HBF ring resonator can be given as

$$T = \left|\frac{E_t}{E_i}\right|^2 = \frac{(1-\gamma)^3 \sin^2\theta}{4}\left|\frac{\sqrt{1-k}-\sqrt{g(1-\gamma)}e^{i\varphi_s}}{1-\sqrt{g(1-\gamma)(1-k)}e^{i\varphi_s}} + \frac{\sqrt{1-k}-\sqrt{g(1-\gamma)}e^{i\varphi_f}}{1-\sqrt{g(1-\gamma)(1-k)}e^{i\varphi_f}}\right|^2 \quad (1)$$

where $\varphi_s = 2\pi(n_0L_1 + n_sL_2)v/c$ and $\varphi_f = 2\pi(n_0L_1 + n_fL_2)v/c$ are, respectively, the one-circle phase shift along the slow and fast axes in the HBF ring resonator, whose ratio is assumed to be p/q (p and q are relative prime numbers), E_i and E_t are the input and transmitted signal amplitudes, respectively, θ is the rotation angle of the polarization state when clockwise-propagating light enters the PC, γ is the excess loss of OC_1 and OC_2 and k the cross intensity coupling ratio of OC_2, g is the intensity loss ($g < 1$) experienced by the signal during one revolution around the HBF ring resonator including the connection loss between EDF and HBF, n_0 is the refractive index of the EDF, n_s and n_f are the refractive indexes of the slow and fast axes of the HBF, respectively, c is the speed of light in vacuum, and v the optical frequency.

It is well known that the ring resonator can dramatically enhance the effective phase shift [12] of the transmitted signal. The effective phase shift difference along the two primary axes in the HBF ring resonator may change with the optical frequency in a fast-oscillating manner, which is characterized by inverse of the one-trip traveling time in the HBF ring resonator. At the same time, a slow-varying envelope may appear in the transmission spectrum with period in inverse of one-circle phase shift difference along the two primary axes in the HBF. This property can be shown by noting in Eq. (1) that the transmissivity not only depends on the phase shifts along the two primary axes of the HBF ring resonator but also their difference. Therefore, the transmissivity peaks occur at frequencies where the circulating fields are resonant along both the two primary axes in the HBF. At other frequencies, the transmissivity is reduced. It thus follows that the effective FSR can be dramatically enhanced by the intrinsic vernier effect between the two primary axes in the HBF. Moreover, the property is independent of the polarization state of the input signal.

3. Calculations and discussion

The one-circle passive intensity loss in the HBF ring resonator is $g(1-\gamma)(1-k)$, and thus the gain threshold for lasing is $G_{th} = 1/[(1-\gamma)(1-k)]$. In this work, we are only interested in the case of net loss, i.e. $g < G_{th}$, and the proposed configuration is intended as a filter. For simplicity, we assume the rotation angle θ is equal to $\pi/2$ in our simulation since it has no impact on the transmission spectrum shape.

The transmission property of the Sagnac loop mirror mainly depends on two parameters: k and g. With k equal to 0, the proposed setup degenerates into a Sagnac loop mirror with constant transmissivity. With k equal to 1, it turns into a conventional HBF Sagnac loop mirror with a sine-like transmission spectrum. When the value of k is between 0 and 1, there appear several resonant peaks in the transmission spectrum as shown in Fig. 2. As expected, the peak intervals are characterized by inverse of the single-trip travel time along the inline HBF ring resonator. When the value of g is small, the transmission peaks appear at off-resonance frequencies and dips at resonance frequencies of the ring resonator. It is attributed to the fact that the signals at resonance frequencies circulate more times than those at off-resonance frequencies. Consequently, the former suffers from more loss than the latter. On the contrary, for g large enough, the transmission peaks appear at resonance frequencies whereas dips at off-resonance frequencies as shown in Fig. 3a and b. Moreover, there is one main peak which transmissivity increases more rapidly than other side peaks. The main peak locates at frequency that resonating along both the fast and slow axis in the HBF. And the side peaks appear at frequencies that resonating along either the fast or slow axis in the HBF. It attributes to the fact that increasing g reduces the full width at half maximum (FWHM) of the resonating peaks along the fast axis. The same is to that along the slow axis. Due to the vernier effect between the resonance peaks along the fast and slow axis, the increased side-peak transmissivity by higher g is partly offset by narrower FWHM. Furthermore, it can be seen from Fig. 3b that with g further increasing, single peak are split into dual peaks at side-peak positions.

It is obvious that the side transmission suppression ratio (STSR), FWHM and effective FSR of the main transmission peaks are the three basic parameters for performance evaluation of narrowband comb filters. As shown in Fig. 4, the FWHM in the unit of round-trip phase shift along the slow axis decreases monotonously with g on account that the signal is more amplified at resonance frequencies than at off-resonance frequencies. With increase of g, the FWHM is less sensitive to the value of k. In addition, the FWHM decreases with g, which results in reduction of the increase of the side peaks due to the increase of g. This effect, however, decreases for larger g, and as a result, the STSR first increase to exceed 6 dB, then drops

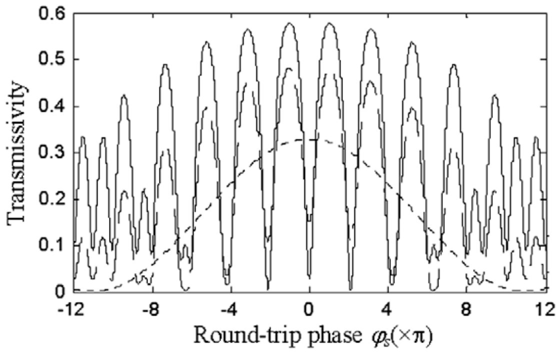

Fig. 2. The transmission spectrum with different k. Solid: $k = 0.7$; dashed: $k = 0.9$; and dotted: $k = 1.0$. Other parameters are: $g = 0.5$, and $r = 0.1$.