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

Guoyong Sun a, Yingwu Zhou b, Yihui Hu a, Youngjoo Chung c,*

a Department of Physics, Shantou University, Shantou, Guangdong 515063, People’s Republic of China
b Department of Physics and Electronic Information Engineering, Minjiang University, Fuzhou, Fujian 350108, People’s Republic of China
c Department of Information and Communications, Gwangju Institute of Science and Technology, 1 Oryong-dong, Buk-gu, Gwangju 500-712, Republic of Korea

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.

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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 (OC1) and one polarization controller (PC). The inline HBF ring resonator is composed of another fiber coupler (OC2), a piece of EDF with length L1 and HBF with length L2. 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...
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

\[
T = \left| \frac{E_t}{E_i} \right|^2 = \frac{(1 - \gamma)^2 \sin^2 \theta}{4} \frac{\sqrt{1 - k - \sqrt{g(1 - \gamma)e^{i\phi_0}}} + \sqrt{1 - k - \sqrt{g(1 - \gamma)e^{i\phi_0}}}}{1 - \sqrt{g(1 - \gamma)e^{i\phi_0}}}
\]

where \(\phi_0 = 2\pi(n_dL_c + n_fL_f)\nu/c\) and \(\phi_f = 2\pi(n_dL_c + n_fL_f)\nu/c\) 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, \(\theta\) is the rotation angle of the polarization state when clockwise-propagating light enters the PC, \(\gamma\) is the excess loss of OC1 and OC2 and \(k\) the cross coupling ratio of OC2, \(g\) 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, \(n_d\) is the refractive index of the EDF, \(n_d\) 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 \(\nu\) 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. 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 \(\theta\) 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. 3b. 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.
A compromise between the FWHM and STSR may be needed when determining $g$.

For compound ring resonators, enhancement of the effective FSR depends on the length ratio $p/q$ of two ring cavities. It is a common practice to set the relative prime number $p$ and $q$ small to minimize the effect of environmental perturbation. For our proposed Sagnac loop mirror, however, the vernier effect originates from the two primary axes of only one physical cavity. As a result, the stability is significantly improved and large $p$ and $q$ values can still be employed by using a piece of HBF with small birefringence.

Fig. 5 illustrates the impact of $p/q$ on the STSR and FWHM of the transmission spectrum. It can be seen that $p/q$ has little impact on the FWHM. However, when the $g$ is not large enough, the STSR is degraded with increase of $p$ and $q$ since the transmissivity increases at side transmission peaks. As $g$ is increased, the decrease of FWHM makes the STSR reaches as large as 6 dB irrespective of the relative prime number ratio $p/q$. The effective FSR can thus be dramatically enhanced with little impact on the STSR in case $g$ is large enough.

From the above analyses, it is concluded that properties of the proposed Sagnac loop mirror with an inline HBF ring resonator can be optimized by choosing large relative prime number ratio and low ring loss. It can be used as a narrowband filter combined with other optical filters such as fiber Bragg gratings in single-frequency fiber ring lasers. As an example, we simulate the lasing properties of the fiber ring laser illustrated in Fig. 6 using the numerical model in Ref. [13]. The gain medium is a piece of EDF with length of 1.4 m pumped by one 980 nm laser diode through a WDM. $F_1$ and $F_2$ are the optical filters. $F_1$ is one fiber Bragg grating with Gaussian transmission spectrum. One fiber coupler (OC) with cross intensity coupling ratio of 0.9 is used as the output coupler. Besides these, two optical fiber isolators (IS) are inserted into the ring cavity to guarantee its unidirectional operation. The whole insertion and connection loss of the ring cavity is assumed to be 20 dB. Typical parameters of the EDF used in the single-frequency fiber laser are: absorption cross sections at 1550 nm and 980 nm are $3.1 \times 10^{-25}$ m$^2$ and $3.7 \times 10^{-25}$ m$^2$, respectively. The emission cross section at 1550 nm is $2.7 \times 10^{-25}$ m$^2$ and erbium doped concentration is $3 \times 10^{25}$ m$^3$. The differential equations governing the EDF are solved by Runge–Kutta method. $F_2$ is the proposed filter with $L_1 = 0.5$ m and $L_2 = 1.0$ m. Other parameters $n_0 = 1.46$, $n_f = 1.45$, $n_s = 1.47$, $k = 0.04$ and $\theta = \pi/2$. When the pump powers bidirectionally launched into the EDF in the HBF ring are both 30 mW, the parameter $g = 0.98 G_{th}$. Therefore, the relative prime
number ratio is 109/110. The results of simulation using these parameters indicate that the FWHM of the main peaks is as narrow as 440 kHz and STSR 7.2 dB, as shown in Fig. 7a. In addition, the effective FSR is enhanced to about 15 GHz. It is wide enough to allow single-frequency operation combined with $F_1$ which 3 dB bandwidth is as broad as 0.12 nm near 1550 nm. Fig. 7b illustrates the output spectrum of the fiber ring laser with the pump power of 100 mW launched into the 1.4 m EDF. The transmission peak of $F_2$ coincides with the main peak of $F_1$. It can be seen that only one main peak selected by $F_2$ is lasing while the side peaks are suppressed. The other main peaks are also suppressed by $F_1$ in the ring cavity. The 3 dB bandwidth of the lasing line is about 1 kHz and output peak power is 17.2 dBm. Further calculation results show when there is a little deviation between the transmission peak of $F_1$ and $F_2$, the fiber ring laser still operates with the single-frequency lasing and just the output power is a little changed.

4. Conclusions

A Sagnac loop mirror with an inline HBF ring resonator is proposed and theoretically investigated. Due to the refractive index difference between the fast and slow axes of the HBF, an equivalent compound ring resonator is realized using only one physical cavity. This configuration dramatically increases the effective FSR by the vernier effect. By properly pumping the EDF to properly offset the passive HBF ring loss, the FWHM and STSR can also be improved. The proposed Sagnac loop mirror with an inline HBF ring resonator is simple, more stable with improved performances compared to the complex rings reported before, which makes it suitable for use as narrowband filters in single-frequency fiber lasers.

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References


