Narrow-Linewidth Compound Ring Fiber Laser Using HBF as a Feedback for Sensing and Communication Application

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Abstract. Narrow-linewidth compound ring fiber laser using high birefringence fiber(HBF) as feedback is newly proposed to generate highly stable narrowband fiber laser and enhance the free spectral range. The laser is basically structured on a Compound ring resonator with end reflector by inserting a piece gain mediam EDF in the main cavity, it has two rings: a primary ring that serves as a resonator, and a secondary ring that serves as a filter. When an Er^{3+}-doped fiber is properly pumped, linear polarizer is located at the input port, effective free spectral range (FSR) of the reflected linearly polarized light is dramatically enhanced in compound ring setup due to the vernier effect between the traveling orthogonally polarized lights along the fast and slow axes of the HBF as well as between the primary and secondary rings. What's more, it alleviates the cavity-length problem. To sum up, these special properties Compound ring resonator with high birefringence fiber in one arm is used in our configuration. Theoretical and simulation results are presented. The optimum design relationships are obtained.

Keywords: Compound ring resonator with end reflector (CRRER) · High birefringence fiber (HBF) · Vernier effect · Free spectral range (FSR) · and Linewidth

1 Introduction

Erbium doped fiber lasers at 1550 nm are very attractive for fiber-based coherent lidar, fiber sensors, medical surgery and in communication applications. In general these fiber lasers are designed based on two popular configurations viz linear and ring cavity configuration.Out of these configurations the former one has a problem of spatial hole burning effect due to the counter-propagating waves in the gain medium, while in the later case the introduction of an optical isolator ensures unidirectional operation of the laser system [1–4]. In comparison to the linear configuration fiber laser unidirectional ring lasers have excellent lasing efficiency, and are free from back scattering and special hole burning problems. Consequently these lasers have better potential for achieve in single longitudinal mode oscillations. The main drawbacks reported in these unidirectional ring lasers using optical isolator have been the high cost and intrinsic loss of an optical isolator.

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In past, different configurations based on the combination of fiber couplers and Fiber rings utilizing vernier effect have been reported. Urquhart [2] proposed a vernier fiber ring resonator composed of two single-ring resonators in tandem. While compound double-ring resonators based on three couplers with improved characteristics have also been suggested [3, 4]. In order to achieve verniar operation, Y. H. Ja [5] used S-shape double-ring double-loop resonator based on degenerate two wave mixing. Their a photorefractive fiber has been utilized into common segment of two fiber loops. In order to achieve ultra-narrow linwidth spectrum, Wang et al. [6, 7] have demonstrated a Single-longitudinal-mode (SLM) fiber laser with an ultra-narrow linewidth system using different shapes and ring configurations. In order to increase free spectral range (FSR), Zhang and lit, [8] have studied all fiber compound ring (AFCR) resonator constructed from three single mode coupler by inserting a double-coupler fiber ring filter into the primary resonator ring. Further, Zhang et al. [9] have extended their theory of AFCR to the doped fiber ring laser where theoretical and experimentally also they have obtained the SLM operation with side mode reduction factor of 3 dB.

Also Sun et al. [10] proposed high birefringence fiber (HBF) ring resonator with an inline reflector for the generation of narrow band reflection peaks. These have taken an advantage of intrinsic vernier effect between the travelling orthogonally polarized light of HBF. In order to alleviate the losses of the passive components which degrade the properties of compound ring filters. The main drawback with this setup is dependence of output characteristic of cavity on polarization state of the input signal. Further, in order to eliminate this problem, feedback HBF loop mirror concept has been newly proposed and analysed by Sun et al. [10] for its application in single-frequency fiber lasers.

In this paper, we have exploited the concept of feedback HBF loop mirror suggested by Sun et al. [10] for the design of narrow line-width compound fiber ring EDF laser. The laser cavity is composed of compound ring structure with an end reflector. Which utilises a piece of EDF in the main cavity and HBF to provide feedback in the loop. This configuration will enable the single frequency operation with comparatively large FSR through the vernier effect. Jones matrix formulation has been used to obtained the varies physical parameter of fiber laser viz, loss difference, resonant condition and frequency spectrum property. The proper choice of coupling coefficient for couplers have been worked out by doing optimization of loss difference using Genetic Algorithm and hence obtained the increased value of loss difference 94 dB.

2 Fiber Laser Configuration and Theoretical Modeling

The configuration of fiber laser is a travelling wave fiber ring lasers which incorporates double coupler double ring resonator with a reflector as shown in Fig. 1. The two couplers have intensity coupling coefficients k_1 and k_2, respectively.The two ring cavities viz. primary and secondary are composed of a piece of EDF in length L3 and

SMF of length L1 with a common HBF of length L_2. The primary and secondary rings have the total length $L_p = L_2 + L_3$, and $L_s = L_1 + L_2$, respectively. The FBG is used as end reflector with a reflectivity of 99% and 3 dB bandwidth of 0.1 nm at 1550 nm. The difference between presently investigated resonator and Sun et al. [9] resonator lies in the fact that they utilized EDF instead of SMF in secondary ring and no end reflector in there resonator. Further in the present work the compound ring resonator has been analyzed for the SLM operation of doped laser. The pump light is injected into one end of the gain medium which is the EDF through a 980/1550 nm wave-length division multiplexer (WDM). A polarization controller (PC) is used to manipulate the polarization state of an input light beam and couple the resultant linearly polarized light into input port of PM coupler.

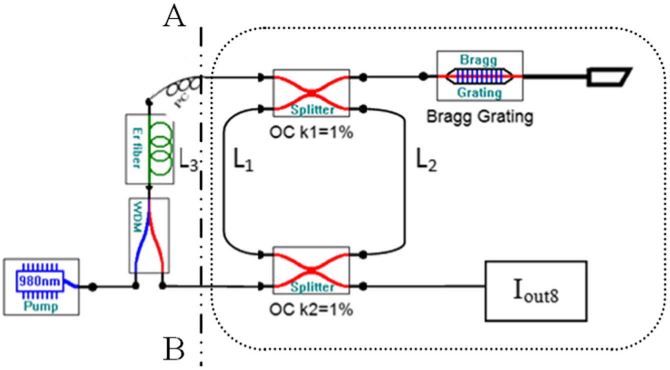


Fig. 1. Schematic diagram of narrow-linewidth compound ring EDF laser with L_3 = 7.75 m L_1 = 0.25 m (SMF) L_2 = 0.25 m (HBF)

Pump power at 980 nm is launched into the Erbium doped fiber through WDM coupler and the output of Er is given into the compound ring laser cavity. For mathematical simplification we will assume that below lasing threshold intensity at points A and B is same due to amplified spontaneous emission. Directionality of the resonator can be seen by analyzing the beams at point A and B. Amplifier spontaneous emission (ASE) beam coming from EDF at point B travels in the counter clockwise (ccw) direction through L_2 and emerges at point A while a part of the beam will travel L_1 and emerges as the output from OC2 where the reflector has no effect. However, the ASE input at point A travelling in clockwise (cw) direction will have an additional contribution due to ccw beam reflected backed by FBG. Therefore the non-reciprocal loss between the two directions is introduced, which will result in unidirectional oscillation in the ccw direction without the use of optical isolator.

2.1 Resonator Loss Difference

The loss difference for the resonator shown in dotted box in Fig. 1 is calculated by considering the input beam at point A and the direction of beam in the resonator to be ccw. The loss difference (LD) is defined as

$$LD = 10\log\left(\frac{RI_A}{RI_B}\right), \tag{1}$$

Where RI_A and RI_B are the returned intensities at points A and B defined as given below.

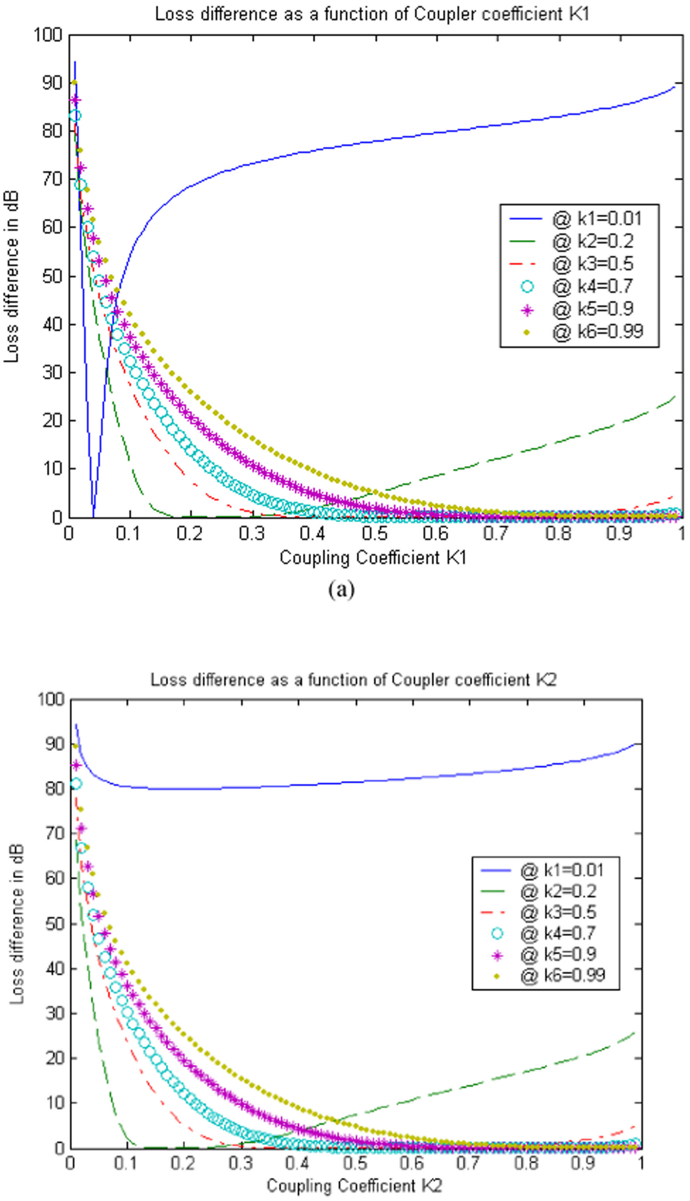
$$RI_A = I_{out1}^{cw} + I_{out1}^{cw}; \quad RI_B = I_{out5}^{cw}. \tag{2}$$

Loss difference in term of the coupling coefficients of OC1 and OC2 is derived as

$$LD = 10\log\left(\frac{R^2[x_1 - x_2(1-\gamma_1)p_1p_2]^4}{(y_1y_2p_2)^2(1 - x_1x_2p_1p_2)^2} + 1\right), \tag{3}$$

Where the effective transmission coefficient and reflection coefficient of the ith coupler are $x_i = \sqrt{(1-k_i)(1-\gamma_i)}$ and $y_i = \sqrt{k_i(1-\gamma_i)}$, respectively with ith coupler intensity loss coefficient γ_i. p_i are defined as transmission factor for length L_i with $i = 1, 2$ and R is the reflectivity of FBG.

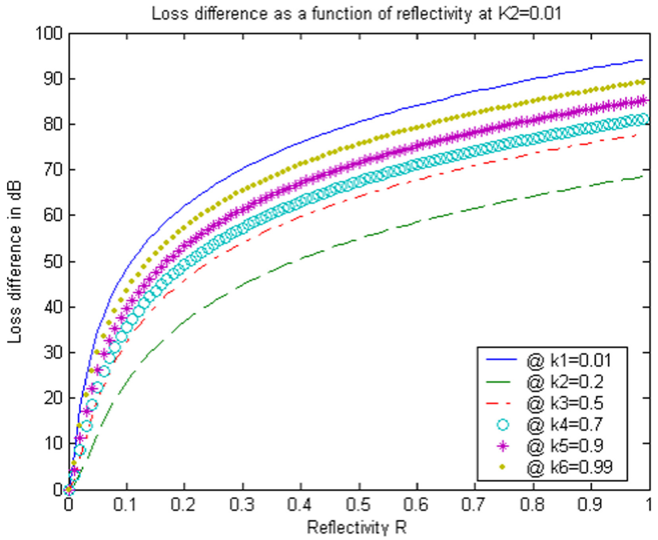
Form Fig. 2(a) and (b), it can be seen that the high loss difference can be obtained if K1 and K2 are chosen to be very small. If the two coupling coefficient is chosen to be very close to the optimum coupling coefficient $K_{opt} = 0.21$, it tell us that at optimum condition, the feedback intensity I_{out2}^{ccw} is going to be zero, and I_{out6}^{cw} becomes maximum which leads to minimum LD of zero. This can be seen from the intersecting point on x-axis in Fig. 2(a) and (b). when k_1 and k_2 are << K_{opt} I_{out2}^{ccw} and I_{out6}^{cw} will become maximum and minimum, which will lead to large values of LD.



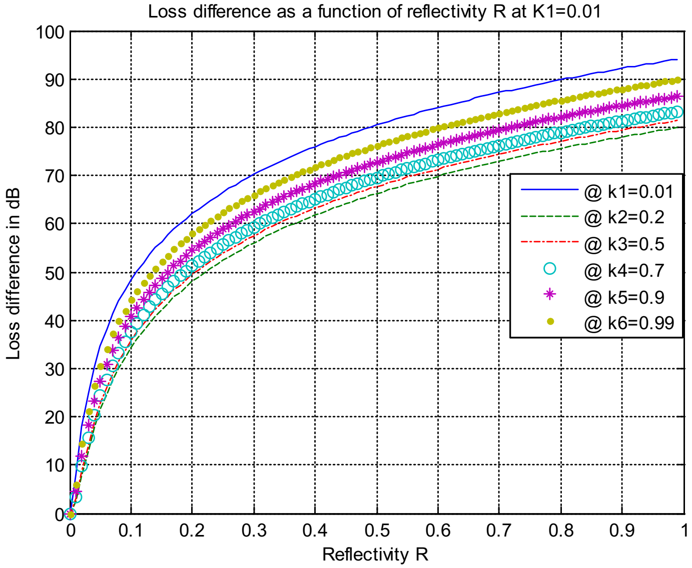
(a)

(b)

Fig. 2. Shows the loss difference: a). as a function of K1 for various values of K2 b). as a function of K2 for various values of K1 c) as a function of R for K2 = 0.1 and various values of K1. D). as a function of R for K1 = 0.1 and various values of K2. Other parameters are $p_1 = p_2 = p_3 = 0.995$, $\gamma_1 = \gamma_2 = 0.005$, and R = 0.99.



(c)



(d)

Fig. 2. (*continued*)

Also in Fig. 2(c) and (d), illustrates loss difference Vs reflectivity(R) at various values of $K_1$for $K_2 = 0.01$ and K_2 for $K_1 = 0.01$, respectively. In both case, It clearly indicates that loss difference increase along with the reflectivity, and also it shows that, if reflectivity tends to zero, the loss difference reduced to zero. It tells as, FBG is the critical component in this configuration.

Moreover, we used the globalization optimization technique called genetic algorithm to determine the appropriate values of the corresponding coupling coefficient that can maximize the loss difference as it is indicated in Fig. 3 below. We have chosen the coupling coefficient $K_1 = K_2 = 1\%$ to maximize the loss difference to about 94 dB.

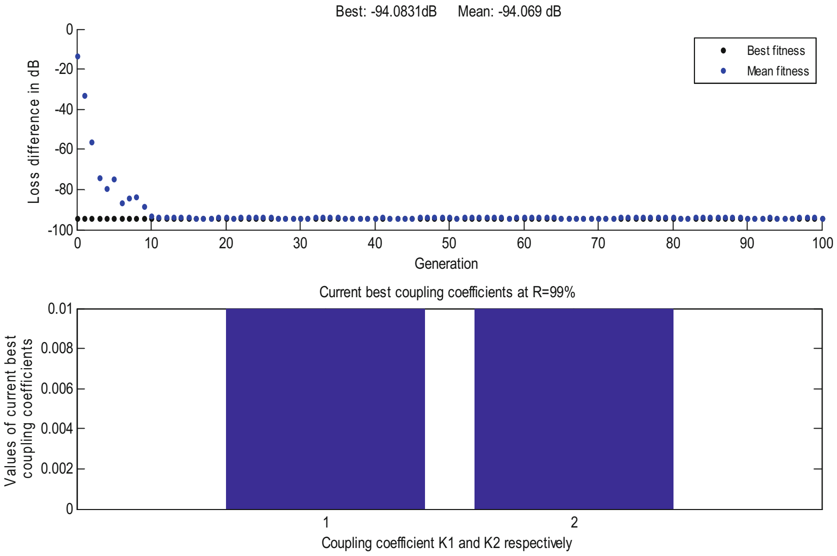


Fig. 3. Shows optimization result using Genetic algorithm

2.2 Fiber Laser Characteristics

Incorporating the double ring double resonator described in above section in the laser cavity, the intensity expression at the output port 8 of the laser has been derived using Jones matrix formulation.

$$I_{out1}{}^{f+}_{s+} = \frac{(x_1 - (1-\gamma_1)x_2p_1p_2)^2 + 4x_1x_2g(1-\gamma_1)p_1p_2\sin^2(\emptyset_{s^{fo}_{so}}/2)}{((1-x_1x_2p_1p_2)^2 + 4x_1x_2p_1p_2\sin^2(\emptyset_{s^{fo}_{so}}/2))} \quad (4)$$

$$I_{out1} = I^{f+}_{out1}\sin^2(\theta) + I^{s+}_{out1}\cos^2(\theta) \quad (5)$$

$$\begin{aligned}\mathrm{I}_{\mathrm{out8}_{\mathrm{s}}^{\mathrm{f}}} = \tfrac{1}{D_s^f}\Bigg[\Bigg\{&(\mathrm{x}_1\mathrm{x}_2\mathrm{p}_3 - \mathrm{y}_1\mathrm{y}_2\mathrm{p}_1 - (1-\gamma_1)(1-\gamma_2)\mathrm{p}_\mathrm{s}\mathrm{p}_3)^2 \\ &\left(4\mathrm{x}_1\mathrm{x}_2\mathrm{y}_1\mathrm{y}_2\mathrm{p}_1\mathrm{p}_3\mathrm{g}\sin^2\left(\left(\emptyset_{\mathrm{p}_{\mathrm{so}}^{\mathrm{fo}}} - \emptyset_{\mathrm{s}_{\mathrm{so}}^{\mathrm{fo}}}\right)\Big/2\right)\right) \\ &+\left(4\mathrm{x}_1\mathrm{x}_2(1-\gamma_1)(1-\gamma_2)\mathrm{p}_1\mathrm{p}_2\mathrm{p}_3^2\mathrm{g}^2\left(\frac{\emptyset_{\mathrm{s}_{\mathrm{so}}^{\mathrm{fo}}}}{2}\right)\right) \\ -(4(1-\gamma_1)(1-\gamma_2)&\mathrm{y}_1\mathrm{y}_2\mathrm{p}_1^2\mathrm{p}_2\mathrm{p}_3\mathrm{g}\sin^2\left(\frac{\emptyset_{\mathrm{p}_{\mathrm{so}}^{\mathrm{fo}}}}{2}\right))\Bigg\}((\mathrm{R}^2\mathrm{I}_{\mathrm{out3}}.\Bigg]\end{aligned} \tag{6}$$

Where,

$$\begin{aligned}D_s^f = {}&(1 - \mathrm{x}_1\mathrm{x}_2\mathrm{p}_1\mathrm{p}_2 + \mathrm{y}_1\mathrm{y}_2\mathrm{p}_2\mathrm{p}_3\mathrm{g})^2 - 4\mathrm{y}_1\mathrm{y}_2\mathrm{p}_2\mathrm{p}_3\mathrm{g}\sin^2\left(\frac{\emptyset_{\mathrm{p}_{\mathrm{so}}^{\mathrm{fo}}}}{2}\right) + 4\mathrm{x}_1\mathrm{x}_2\mathrm{p}_1\mathrm{p}_2\sin^2\left(\frac{\emptyset_{\mathrm{s}_{\mathrm{so}}^{\mathrm{fo}}}}{2}\right) \\ &+ 4\mathrm{x}_1\mathrm{x}_2\mathrm{y}_1\mathrm{y}_2\mathrm{p}_1\mathrm{p}_2^2\mathrm{p}_3\mathrm{g}\sin^2\left(\frac{\emptyset_{\mathrm{p}_{\mathrm{so}}^{\mathrm{fo}}}}{2} - \frac{\emptyset_{\mathrm{s}_{\mathrm{so}}^{\mathrm{fo}}}}{2}\right)\end{aligned} \tag{7}$$

Hence the laser intensity at the output port 8 is given as

$$\mathrm{I}_{\mathrm{out8}} = \mathrm{I}_{\mathrm{out8}}^{\mathrm{f}}\sin^2(\theta) + \mathrm{I}_{\mathrm{out8}}^{\mathrm{s}}\cos^2(\theta) \tag{8}$$

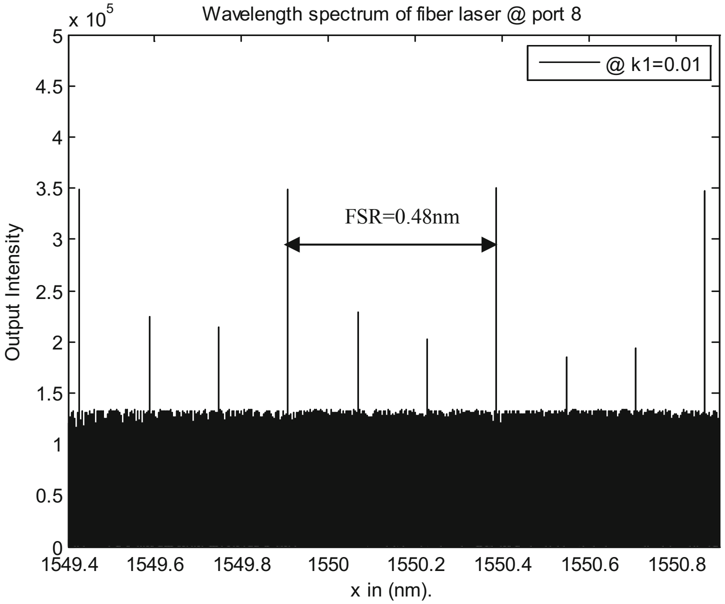
Where: $\emptyset$ is the beam phase on the primary and secondary ring.

$$\varphi_{\mathrm{pf0}} = \frac{2\pi(\mathrm{n}_\mathrm{f}\mathrm{L}_2 + \mathrm{n}_0\mathrm{L}_3)}{\lambda}, \varphi_{\mathrm{ps0}} = \frac{2\pi(\mathrm{n}_\mathrm{f}\mathrm{L}_2 + \mathrm{n}_0\mathrm{L}_3)}{\lambda}$$

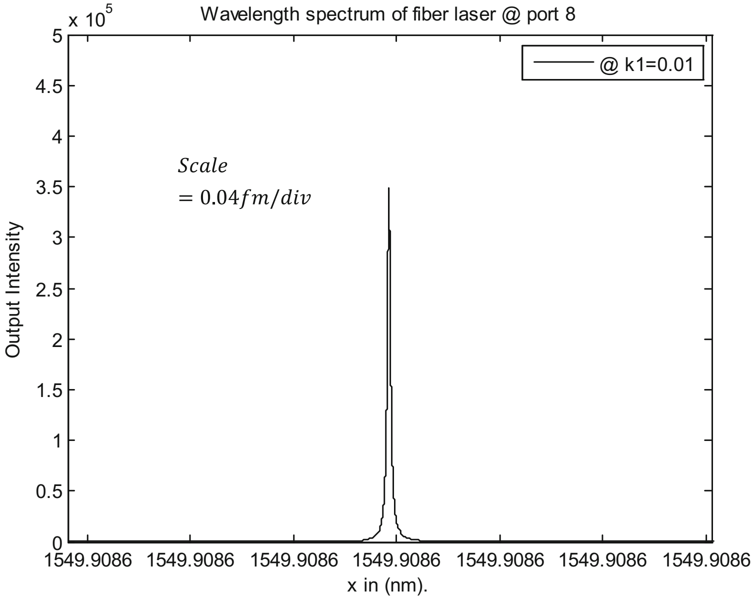
$$\varphi_{\mathrm{sf0}} = \frac{2\pi(\mathrm{n}_\mathrm{f}\mathrm{L}_2 + \mathrm{n}_0\mathrm{L}_1)}{\lambda}, \quad \varphi_{\mathrm{sf0}} = \frac{2\pi(\mathrm{n}_\mathrm{f}\mathrm{L}_2 + \mathrm{n}_0\mathrm{L}_1)}{\lambda}$$

λ is the beam wavelength, $\theta =$ the rotation angle of HBF with the reference of SMF and the subscript numbers indicate the corresponding port in Fig. 1. The superscript letters f and s tell the corresponding intensity in the fast and slow axis of HBF. It follows from Eq. (8) the resultant FSR of $\mathrm{I}_{\mathrm{out8}}$ is dominated by the secondary ring and it can be enhanced if θ is between 0 and 90^0 $(0 < \theta < 90^0)$. For example, considering a scenario when there is no rotation of the birefringence axes $\theta = 0^0$, the second term of the Eq. (8) is null. On the other hand when $\theta = 90^0$, the first term of the function is suppressed. From the above analysis, the transmission spectrum is a combination of the two spectrums which are governed by the function $sin^2(\theta)$ and $cos^2(\theta)$. As a result the enhancement factor relies on the ratio $\emptyset_{so}/\emptyset_{fo}$ which is assumed to be p/q (p and q are relatively prime numbers). The effective FSR is greatly enhanced by q times compared with the FSR along the slow axis.

The output intensities as functions of wave length are shown in Fig. 4. It demonstrates the mode suppression by use of the vernier effect between the traveling orthogonally polarized lights along the fast and slow axes of the HBF in L_2 as well as between the primary and secondary rings. The ratio of the two cavity length is 16:1 and the coupling coefficients are chosen to be K1 = K2 = 1% $\theta = 45°$ from Fig. 4, it can be seen that the effective FSR of the narrow-linewidth compound ring EDF laser is



(a)



(b)

Fig. 4. Output intensity of fiber laser Vs wavelength at $p_1 = 0.995$, $p_2 = 0.995$, $p_3 = 0.995$, R = 99%, and $\gamma_1 = 0.001$

determined by the FSR of the small ring. This can be written $L_p : l_s = m : n$ where m and n are two integers which do not have common factors. For each ring, the FSR is inversely proportional to its length. Therefore, the effective FSR of the compound ring cavity is:

$$FSR = nFSR_l = mFSR_L$$

The main peak occurs when only the primary ring resonates. From the configuration and simulation result, we have got FSR of 59.5 GHz with a full width half maximum (FWHM) of about 3 kHz at the expense of reduction factor (about 0.37) as shown in Fig. 4. The back reflection of the CRRER with HBF as a feedback is as small as ≤ 94 dB. It is also observed that when the ratio of the cavity lengths increases, the reduction factor will increase.

3 Conclusion

According to the directionality analysis, a high loss difference can be obtained by choosing the appropriate value of coupling cofficents k_1 and k_2, we used a Genetic Algorithm optimization technique to select the appropriate value of coupling coefficient and it doubles the loss difference to 94 dB.

Moreover, the effects of the coupling coefficients, losses and resonance numbers on the resonance are investigated. The results show the, reduction factor ($\approx$4.32 dB), and the back-reflection is obtained to be <-94 dB. It is also observed that when the ratio of the cavity lengths increases, the reduction factor will increase.

Based on the CRRER, We have designed a narrow-linewidth compound ring fiber laser. The laser is basically structured on a compound-ring resonator, and uses the vernier principle to effectively increase its free spectral range. The single longitudinal mode(SLM) selection in this laser is achieved by compound ring resonator with end reflector which uses HBF as a feedback. As a result, securely attained with a narrow linewidth of less than 3 kHz with FSR of 59.5 GHz that can be used in sensing and communication applications.

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