Optical Engineering 45(4), 044201 (April 2006)

Temperature stability improvement of a multiwavelength Sagnac loop fiber laser using a high-birefringent photonic crystal fiber as a birefringent component

X. Yu
Nanyang Technological University
Network Technology Research Center
Research TechnoPlaza
Slab Block, Fourth Storey, 50 Nanyang Drive
Singapore 637553

D. Liu
Nanyang Technological University
Photonics Research Center
School of Electrical and Electronic Engineering
50 Nanyang Drive
Singapore 637553

H. Dong
S. Fu
X. Dong
M. Tang
P. Shum
Nanyang Technological University
Network Technology Research Center
Research TechnoPlaza
Slab Block, Fourth Storey, 50 Nanyang Drive
Singapore 637553

N. Q. Ngo
Nanyang Technological University
Photonics Research Center
School of Electrical and Electronic Engineering
50 Nanyang Drive
Singapore 637553

Abstract. We experimentally demonstrate a temperature-stable multiwavelength erbium-doped fiber laser source using a high-birefringent photonic crystal fiber (HiBi-PCF) as the birefringent component of the Sagnac loop filter within the laser cavity. Three different high-birefringence (Hi-Bi) fibers are used in the loop filter to compare the temperature stability of the fiber laser systems: polarization-maintaining erbium-doped fiber (PM-EDF), panda Hi-Bi fiber, and HiBi-PCF. Because of the high birefringence and low temperature sensitivity of the HiBi-PCF, fiber length in the loop is greatly reduced and the temperature stability of the system is dramatically enhanced. [DOI: 10.1117/1.2192513]

Subject terms: wavelength division multiplexing; fiber laser; Sagnac loop filter; highly birefringent; photonic crystal fiber.

Paper 050339R received Apr. 28, 2005; revised manuscript received Aug. 24, 2005; accepted for publication Sep. 5, 2005;

1 Introduction

Wavelength division multiplexing (WDM) is an attractive technology that enables the transmission of multiple wavelength channels in the same large bandwidth of a single optical fiber. With the massive expansion of WDM technology, erbium-doped fiber lasers (EDFLs) simultaneously emitting in multiple wavelengths over the 1550-nm wavelength range have been extensively studied in recent years.[1–6] The basic requirements for this multiwavelength optical source include a large number of lasing lines over a large wavelength span, good optical signal-to-noise ratio (OSNR), and moderate output power. Several techniques have been proposed to achieve multiwavelength fiber lasers with fixed wavelength spacing using cascaded linear cavities,[1] polarization hole-burning effects,[2] and a fiber-grating-based Sagnac loop filter with liquid nitrogen for room temperature operation,[3] a Mach-Zehnder comb filter,[4] an in-fiber comb filter,[5] and a fiber Fabry-Perot filter[6] in a single-fiber cavity. However, the use of a fiber Fabry-Perot filter increases the insertion loss of the cavity, and a Mach-Zehnder filter is sensitive to environmental changes, as its two optical paths are different. Also, in our recent work,[7] we have proposed a multiwavelength source by using a polarization-maintaining erbium-doped fiber (PM-EDF) as a gain medium. Good performance and stability at room temperature have been achieved. However, there are two main problems for using the PM-EDF in this fiber laser system. First, employing both high birefringence and high erbium-doped concentration will suppress the effects of one another. Thus the concentration of erbium ions of the PM-EDF is relatively low, which results in a small output optical power of the fiber laser. Moreover, because of the large thermal coefficient of the stress apply part (SAP) in the PM-EDF, this laser source is expected to be very sensitive to environmental temperature variation. The second prob-

0091-3286/2006/$22.00 © 2006 SPIE

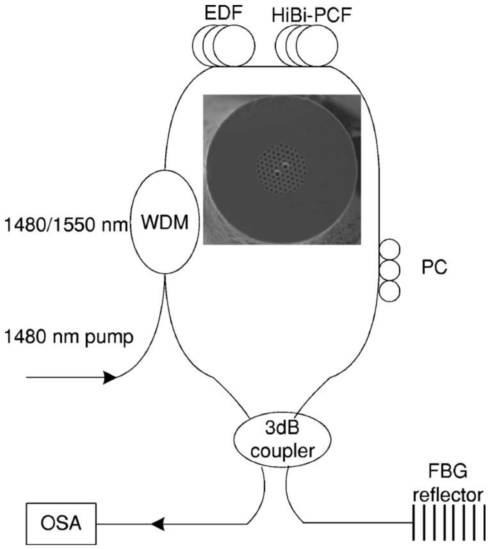

Fig. 1 Schematic diagram of the proposed multiwavelength fiber laser source based on the fiber Sagnac loop filter.

lem commonly existing in most of the previous techniques is that, for an EDFL that can work in a harsh environment, the temperature-induced instability must be overcome.

Photonic crystal fiber (PCF) is a new class of optical fiber that has emerged in recent years.[8] It is formed by an array of air holes running along the fiber length and guides light by total internal reflection between the solid core and the holey cladding region. Designing the air-holes arrangement in such a microstructured fiber rather than using doped materials such as SAP to induce stress birefringence can induce very large form birefringence. So the high-birefringence (HiBi) PCFs are typically made of only a single material (fused silica in this case), thus lower and more uniform thermal expansion coefficients can be expected from this novel fiber. So far, temperature insensitivity has been observed in many PCF-based devices, such as long period gratings (LPGs),[9] interferometers,[10] and fiber Bragg grating sensors.[11]

In this work, an improved temperature-stable multiwavelength erbium-doped fiber laser source using a HiBi-PCF-based Sagnac loop filter is presented. A relatively short length of HiBi-PCF as a birefringent component is spliced together with a section of erbium-doped fiber (EDF) and a 3-dB coupler to form the Sagnac loop filter. Taking advantage of the high birefringence and the low temperature sensitivity of the HiBi-PCF, a multiwavelength fiber laser with a relatively short cavity length and good temperature stability is demonstrated. To our knowledge, this is the first time that a HiBi-PCF is incorporated into a Sagnac loop filter in an EDFL scheme to improve the temperature stability effectively.

2 Experimental Setup and Operating Principle

The experimental setup of the proposed fiber laser is shown in Fig. 1. The structure of the EDFL is formed by a Sagnac loop filter and a reflector, and consists of a 1480/1550-nm WDM coupler, a section of EDF and Hi-Bi fiber, a polarization controller (PC), a 3-dB fiber coupler, and a linearly chirped fiber Bragg grating (LCFBG) as a fiber mirror with a 17.5-nm stop band of over 25 dB centered at 1545 nm. The multiwavelength fiber laser in our previous work[7] consists of a single gain medium using 15-m elliptical-core PM-EDF with a numerical aperture of 0.26, a birefringence of 2.40×10^{-4} at 1550 nm, and an erbium ion concentration of $3 \times 10^{24}\ \mathrm{m}^{-3}$. The pump laser is a stable laser diode with a power of 180 mW at 1480 nm. The high birefringence of any polarization maintaining fiber (PMF) produces a wavelength-dependent phase difference δ between the components of the fast and slow axes of the beams propagating in the loop, that is,

$$\delta = (2\pi BL)/\lambda, \tag{1}$$

where B is the modal birefringence, L is the length of the Hi-Bi fiber, and λ is the operation wavelength. As the phase difference of these two counterpropagating lightwaves existing the loop filter at the 3-dB coupler is wavelength dependent, the intensity transfer function of the fiber loop is periodic, and is given as

$$T(\lambda) = \sin^2(\delta/2). \tag{2}$$

The resonance wavelengths of the loop filter depend on the modal birefringence and length of the HiBi fiber, and is given by

$$\lambda = 2BL/(2k+1), \tag{3}$$

where k is an integer determined by the ratio of total gain and loss of the laser cavity. The wavelength separation between two transmission peaks of the Sagnac loop filter's output is given by

$$\Delta\lambda = \lambda^2/BL. \tag{4}$$

Thus, the channel spacing of the EDFL is determined by the birefringent component only, which is the Hi-Bi fiber within the Sagnac loop filter.

3 Results and Discussion

To investigate the temperature stability of the EDFL as presented in Ref. 7, we control the temperature of the PM-EDF with a thermal heater from room temperature to 100 °C. The average resonance variation is obtained from a repetition test for more than 10 h and the spectral data are recorded every 10 min. Thus the results given in this work can concisely indicate the temperature stability improvement. The thermal dependency of the lasing wavelength is 46 pm/°C, whereas the thermal coefficient of the channel spacing is 0.5 pm/°C. In the EDFL system, the instability is mainly caused by the homogeneous gain broadening of EDF and the thermal instability of the birefringent component. However, in the case of the single gain medium, it is difficult to distinguish the influences of the homogeneous gain broadening of EDF and SAP thermal effects on the laser instability.

Our effort is to improve the laser system's thermal stability, so we replaced the PM-EDF (as presented in Ref. 7) with 10-m EDF spliced with a section of 4.8-m panda PMF and applied the thermal heat to the section of PMF only. The EDF has a numerical aperture of 0.24 and an erbium ion concentration of 1500 ppm, and the panda PMF has a birefringence of 3.875×10^{-4} at 1550 nm. We increased the

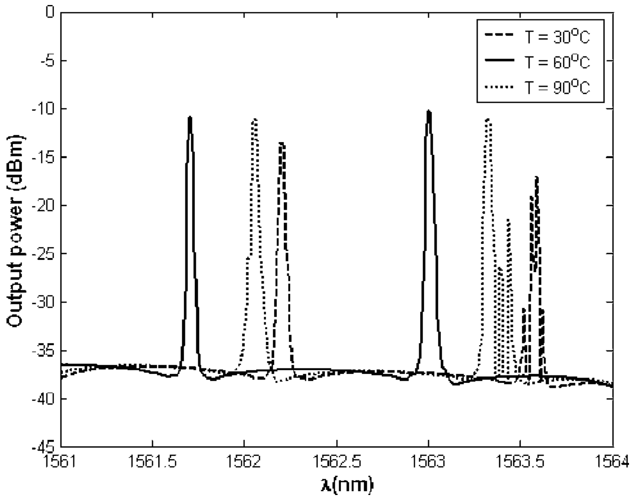

Fig. 2 Transmission spectra as a function of temperature for the panda PMF-based fiber laser.

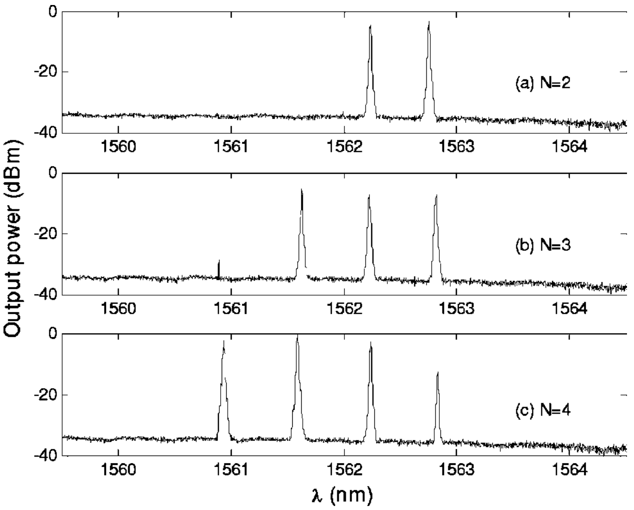

Fig. 3 Output optical spectrum of the fiber laser at different settings of the polarization controller: (a) two, (b) three, and (c) four lasing lines.

temperature from 30 to 90 °C, and the corresponding spectra for this fiber loop are shown in Fig. 2. The influence of the erbium-doped fiber is not taken into account, since only the PMF is heated. The birefringence of the PMF reduces as the environment temperature increases. With the increase of temperature from 30 to 60 °C, the birefringence reduction dominates the fiber elongation, thus the resonance peaks are first blue-shifted as the resonant wavelength is determined by the product of birefringence B and fiber length L. When we increase the temperature further to 90 °C, the fiber elongation effect will be dominant, so the transmission peaks experience a red shift. We obtained 16 and 12 pm/°C temperature coefficients for lasing wavelengths from 30 to 60 °C and 60 to 90 °C, respectively. The temperature coefficient of the fiber laser reduced to about one third of the previous structure, because the PMF used here is much shorter than the 15-m PM-EDF. However, we also obtained a channel spacing variation with temperature up to 2.3 pm/°C. The degrade of the stability is due to the increased channel spacing from 0.67 nm in PM-EDF to 1.3 nm.

Such large temperature coefficients for the previous two setups will limit the practical applications of the fiber laser as a reliable light source. Taking advantage of the high birefringence and low temperature sensitivity of the HiBi-PCF, a new EDFL, as shown in Fig. 1, is demonstrated here. The 4.8-m Panda PMF in the setup before is now replaced with a section of HiBi-PCF with the same length. The scanning electron micrograph of the HiBi-PCF is shown as an inset of Fig. 1. The modal birefringence B of the HiBi-PCF was measured to be 8.65×10^{-4} at 1550 nm. Two ends of the HiBi-PCF were spliced to the EDF and a conventional single-mode fiber (SMF). Mode field diameters at the two orthogonal polarization axes of the PCF are 3.6 and 3.1 μm, and the mode field difference will cause a large coupling loss. The PCF to SMF splicing loss is about 3 dB, which increases the cavity loss of the multiwavelength fiber laser up to around 18 dB. Two counterpropagating lightwaves travel along different axes of the HiBi-PCF by setting the PC in the loop; the PC was set to generate a 90-deg rotation to the polarization state of the light going through it in both directions. From Fig. 3, we observe that multiple lasing lines are generated between 1560 and 1564 nm, with equal wavelength spacing. The wavelength separation between two lasing lines is about 0.6 nm, which agrees well with the theoretical value of the channel spacing 0.59 nm calculated from Eq. (4). The optical power of all lasing lines is about 0.3 mW, and relatively flat output powers of all the lasing wavelengths are observed. By changing the setting of the PC within the laser cavity, the losses in two polarization states also change, so loss and gain balancing can be achieved with more lasing wavelengths. The 3-dB linewidth of each lasing line is less than 50 pm, which is limited by the resolution of the optical spectrum analyzer (OSA). Figure 3(b) shows simultaneously three lasing lines at 1561.6, 1562.2, and 1562.8 nm. Figure 3(c) shows that four lasing lines can be simultaneously obtained by carefully adjusting the PC. The signal-to-noise ratio (SNR) of all of these lasing lines is very large (more than 30 dB). All these lasing lines have an optical power greater than 100 μW.

When the temperature of the HiBi-PCF is increased, the fiber will elongate and the modal birefringence will vary due to thermal expansion. We have found that the channel spacing increased with a 0.05-pm/°C temperature coefficient for the HiBi-PCF-based Sagnac loop, which matches well with the results presented in Ref. 10. Transmission spectra at different temperatures are shown in Fig. 4. The transmission peaks as well as the channel spacing change with temperature variation. The channel spacing is reduced because of the slight elongation of the PCF. Most distributed feedback (DFB) lasers show a wavelength sensitivity with respect to temperature of about 2 pm/°C.[12] In the case of the HiBi-PCF-based Sagnac loop, the shift of the center wavelength with temperature can reach approximately 2 pm/°C.

The results of all temperature coefficients are shown in Table 1. The stability of the lasing wavelength is determined by the polarization coupling ratio at a fixed PC set-

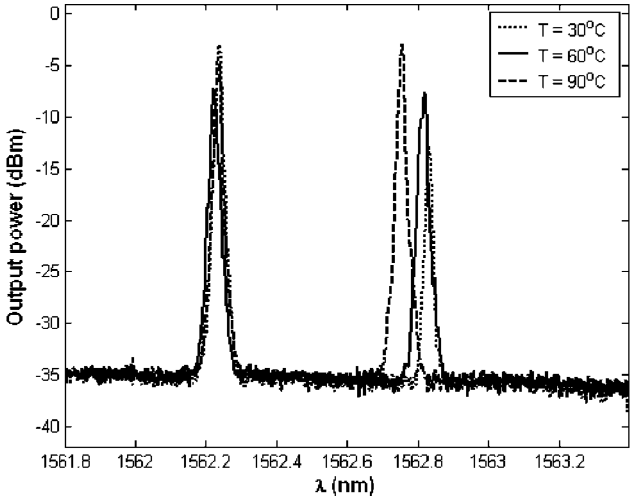

Fig. 4 Transmission spectra as a function of temperature for the HiBi-PCF-based fiber laser.

ting, which makes the Hi-Bi fiber in the Sagnac loop a key component for temperature sensitivity. The resonance wavelength λ and the channel spacing Δλ are both related to the product of birefringence B and fiber length L, where L increases with the operating temperature. The fiber core of a panda PMF is GeO_2 doped, while the PCF is made of silica only. For the HiBi-PCF, the fiber elongation (ΔL) with an increase in temperature will be smaller compared with that of the normal PM fiber. The birefringence is stress induced in PMF, which has a strong temperature dependence because of its higher thermal coefficient ($6.1 \times 10^{-6}/{}^{\circ}\mathrm{C}$) compared with pure silica ($0.55 \times 10^{-6}/{}^{\circ}\mathrm{C}$). The thermal expansion coefficient is more uniform in the two orthogonal directions of PCF, so its birefringence is relatively stable with temperature. Furthermore, due to the large birefringence of HiBi-PCF, the length of the birefringent component is much shorter than using normal PM fiber. Thus, the temperature sensitivity of the EDFL system influenced by the variation of BL product is much smaller for a PCF-based Sagnac loop.

Table 1 Comparison of temperature stability of the fibers used in three Sagnac loop filters.

	PM−EDF	EDF+PMF	EDF+HiBi−PCF
$\delta(\Delta\lambda)/\delta T$	0.5 pm/°C	2.3 pm/°C	0.05 pm/°C
$\delta\lambda/\delta T$	46 pm/°C	16 pm/°C	2 pm/°C

4 Conclusion

We demonstrate a temperature-stability improved multiwavelength erbium-doped fiber laser based on the HiBi-PCF Sagnac loop filter. Due to the uniform material of the PCF, the modal birefringence has good temperature stability. We achieved 0.05-pm/°C thermal coefficient for the channel spacing of the EDFL by using PCF, which is a ten-fold improvement compared to using PM-EDF. The lasing wavelength variation with temperature can be reduced to 2 pm/°C, which is comparable to the DFB laser.

References

1. Q. Mao and J. W. Lit, "Switchable multiwavelength erbium-doped fiber laser with cascaded fiber grating cavities," *IEEE Photonics Technol. Lett.* **14**(5), 612–614 (2002).
2. J. Sun, J. Qiu, and D. Huang, "Multiwavelength erbium-doped fiber lasers exploiting polarization hole burning," *Opt. Commun.* **182**, 193–197 (2000).
3. X. Shu, S. Jiang, and D. Huang, "Fiber grating Sagnac loop and its multiwavelength-laser application," *IEEE Photonics Technol. Lett.* **12**(8), 980–982 (2000).
4. H. L. An, X. Z. Lin, E. Y. B. Pun, and H. D. Liu, "Multi-wavelength operation of an erbium-doped fiber ring laser using a dual-pass Mach-Zehnder comb filter," *Opt. Commun.* **169**, 159–165 (1999).
5. J. Chow, G. Town, B. Eggleton, M. Ibsen, K. Sugden, and I. Bennion, "Multiwavelength generation in an erbium-doped fiber laser using in-fiber comb filters," *IEEE Photonics Technol. Lett.* **8**(1), 60–62 (1996).
6. S. Yamashita and K. Hotate, "Multiwavelength erbium-doped fiber laser using intracavity etalon and cooled by liquid nitrogen," *Electron. Lett.* **32**(14), 1298–1299 (1996).
7. N. Q. Ngo, D. Liu, X. Y. Dong, L. N. Binh, S. Y. Li, and S. C. Tjin, "A spacing tunable multiwavelength fiber laser source using a Sagnac loop filter," *Opt. Eng.* **44**(1), 014202 (Jan. 2005).
8. T. A. Birks, P. J. Roberts, P. S. J. Russell, D. M. Atkin, and T. J. Shepherd, "Full 2-D photonic bandgaps in silica/air structures," *Electron. Lett.* **31**, 1941–1942 (1995).
9. Y. Zhu, P. Shum, H. Bay, M. Yan, X. Yu, J. Hu, J. Hao, and C. Lu, "Strain-insensitive and high-temperature long-period gratings inscribed in photonic crystal fiber," *Opt. Lett.* **30**, 367–369 (2005).
10. C. L. Zhao, X. F. Yang, C. Lu, W. Jin, and M. S. Demokan, "Temperature-insensitive interferometer using a highly birefringent photonic crystal fiber loop mirror," *IEEE Photonics Technol. Lett.* **16**(11), 2535–2537 (2004).
11. X. F. Yang, C. L. Zhao, Q. Z. Peng, X. Q. Zhou, and C. Lu, "FBG sensor interrogation with high temperature insensitivity by using a HiBi-PCF Sagnac loop filter," *Opt. Commun.* **250**, 63–68 (2005).
12. N. Frigo, IEEE 802.3ah Ethernet in the First Mile Task Force (2001).

Biographies and photographs of authors not available.