Switchable dual-wavelength fiber ring laser featuring twin-core photonic crystal fiber-based filter

Khurram Karim Qureshi

Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Corresponding author: kqureshi@kfupm.edu.sa

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A simple configuration for the generation of a switchable dual-wavelength fiber ring laser is presented. The proposed configuration employs a short twin-core photonic crystal fiber acting as a Mach–Zehnder interferometer at room temperature. A polarization controller is further utilized to enable switchable dual-wavelength operation.

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Multiwavelength fiber lasers have been well studied in recent years because of their potential applications in fiber sensors, wavelength division multiplexed communication systems, photonic component testing, and spectroscopy. Of particular interest are switchable light sources for wavelength routing networks, optical fiber sensing, and generation of terahertz waves. Several methods for generating switchable multiwavelength lasers based on unique cavity designs have been reported in Refs. [1−13]. For example, a tunable dual-wavelength fiber laser incorporating an AWG and an optical channel selector was reported by Ahmed *et al.*[1]. The output power of both laser beams was equalized by controlling cavity loss using two programmable optical attenuators. Another scheme based on the use of a chirped Moiré filter along with a saturable absorber was reported in Ref. [2]. Zhao *et al.*[3] developed a configuration for dual-wavelength generation based on a linear cavity design. This laser incorporated an AWG with two fiber-optic switches. A switchable dual-wavelength linear cavity laser realized by introducing two Sagnac loops at two ends has also been proposed[4]. In this laser, dual wavelength operation was accomplished by placing a tunable narrow band thin film filter and a fiber Bragg grating (FBG) inside a loop mirror serving as the output port for the laser. Mao *et al.*[5] implemented a switchable linear multiwavelength fiber laser with the use of cascaded fiber-grating cavities. In Ref. [6], a switchable multi wavelength erbium-doped fiber amplifier (EDFA) ring laser with a multi section high-birefringence fiber loop mirror (HiBi-FLM) was demonstrated; this fiber loop mirror helped in the selection of the lasing wavelength.

Wavelength switching is achieved by modifying the reflection spectrum of the HiBi-FLM. A scheme to realize switchable multiwavelength lasers based on broadband cascaded quadratic nonlinear interactions in an aperiodically poled MgO-doped lithium-niobate waveguide was reported in Ref. [7]. Here, the output lasing light beams were selected by launching two seeded lights with different wavelengths and wavelength spacing. In Ref. [8], a scheme based on cascaded mismatched long period FBGs (LP-FBGs) for the generation of switchable multiwavelength fiber laser was presented. The key components of this scheme included two cascaded LP-FBGs of different lengths that act as channel selectors.

Photonic crystal fibers (PCFs) offer numerous flexible properties and are therefore widely studied for the development of novel sensors and interferometers[9,11]. A switchable multiwavelength PCF laser based on nonlinear polarization rotation was proposed by Zheng *et al.*[9]. This laser configuration consisted of a polarization-dependent isolator with a PCF to form an equivalent fiber filter. In Ref. [10], a linear switchable dual-wavelength fiber laser based on a PCF Sagnac loop and a broadband FBG was demonstrated.

In this letter, a technique to achieve a switchable dual-wavelength fiber ring laser based on an in-line fiber Mach–Zehnder interferometer in a twin-core PCF (TC-PCF) is presented. The proposed laser incorporates a high-power EDFA as a gain medium and a TC-PCF as a Mach–Zehnder interferometer comb filter. By carefully adjusting the polarization controller (PC) in the laser cavity, the proposed device can perform single and switchable dual-wavelength operations. In the proposed scheme, the TC-PCF acts simultaneously as a wavelength selector and as a polarization-dependent element.

Our TC-PCF is based on the stack-and-draw technique. The complete procedure for the fabrication of this fiber is described in detail in Refs. [14,15]. Scanning electron micrographs of the whole fiber and its hole area are respectively shown in Figs. 1(a) and (b). The TC-PCF had an outer diameter (d) of 125 μm, and the d of each core was approximately 2.5 μm. The pitch (Λ) of the

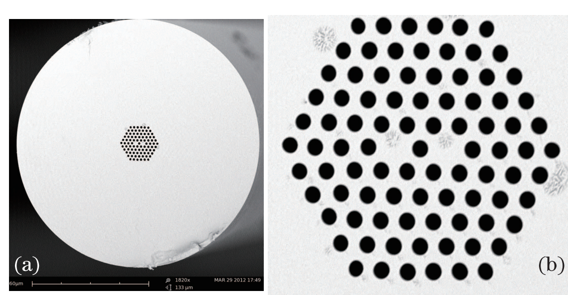

Fig. 1. Scanning electron micrograph of the TC-PCF: (a) whole fiber and (b) hole section.

structure was approximately 1.85 μm, and the d of the air holes was approximately 1.1 μm. The loss of the drawn TC-PCF was measured to be approximately 4.4 dB/m. The in-line Mach–Zehnder interferometer was configured by splicing a 30-cm-long piece of the TC-PCF between standard single-mode fibers (SMF-28, Corning, USA) using a commercially available Furukawa (FITEL-177) fusion splicer. Some of the parameters of the fusion splicer (i.e., arc power, 2 steps; arc duration, 120 ms) were modified to facilitate this splicing[16]. To maximize the contrast of the interference fringes, a broadband light source and an optical spectrum analyzer (OSA) were used to monitor the transmission spectrum. By introducing an offset between the alignments of SMF-28 and the TC-PCF, the contrast was improved. By fine tuning the $x - y$ positions of the fibers prior to splicing, an optimized contrast was obtained. At this position, the core of SMF-28 was aligned to one of the cores of the TC-PCF, and the two fibers were fused together by repeated discharges. For optimal splice points 6 to 7, arc discharges were used. This procedure ensured strong splice points at the two ends of the fiber. The total splice loss at the two ends was observed to be close to 3 dB.

The light beam from the core mode of the lead-in SMF was coupled into the two cores of the 30-cm-long TC-PCF at the first splice point. After propagation through the TC-PCF, the beam was finally re-coupled at the core of the lead-out SMF to produce intermodal interference at the second splicing point. The two cores of the TC-PCF behaved as independent wave guides with mode coupling. Four super modes exist for the two polarizations: the even and odd modes for x-polarization and the even and odd modes for y-polarization. The x- and y-polarizations were orthogonal to each other, such that the total intensity at the output could be expressed as[14]

$$I(\lambda) = 1 - \cos\left[\frac{\pi}{\lambda}(\Delta n_{x,\mathrm{group}} + \Delta n_{y,\mathrm{group}})L\right] \cos\left[\frac{\pi}{\lambda}(\Delta n_{x,\mathrm{group}} - \Delta n_{y,\mathrm{group}})L\right], \qquad (1)$$

where L is the length of the TC-PCF and λ is the operating wavelength; $\Delta n_{x,\mathrm{group}}$ represents the difference between the effective group indices of the even and odd modes for x-polarization; $\Delta n_{y,\mathrm{group}}$ represents the difference between the effective group indices of the even and odd modes for y-polarization.

The transmission spectrum of the TC-PCF was characterized with a broadband light source and an OSA with a resolution of 0.1 nm, as shown in Fig. 2. The measured wavelength spacing of the TC-PCF-based Mach-Zehnder comb filter is approximately 1.6 nm, and the total transmission loss at the gain peak is approximately 12 dB.

Figure 3 shows the experimental setup of our proposed switchable dual-wavelength fiber laser employing the TC-PCF. The laser consists of a high-power EDFA (Amonics Corporation, China) operating in the C-band. The laser exhibits an output saturation power of approximately 27 dB m, a gain of 30 dB, and a typical noise figure (NF) of 5.5 dB for an input power of 0 dBm. The polarization-dependent gain is less than 0.3 dB, whereas the input/output isolation is greater than 30 dB. A 30-cm-long TC-PCF was inserted in the cavity to serve as a selective wavelength comb filter. A PC was also

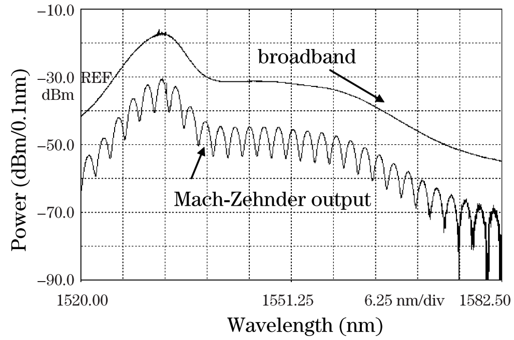

Fig. 2. Transmission spectra of the broadband light source and TC-PCF interferometer.

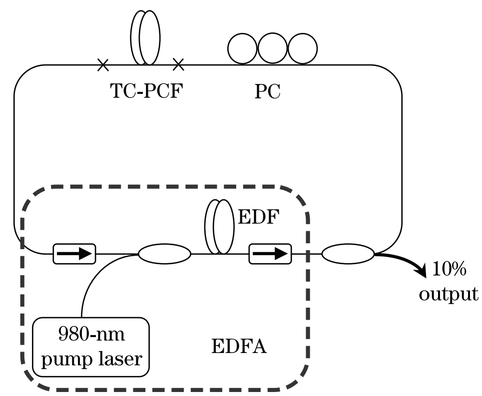

Fig. 3. Experimental configuration of a switchable dual-wavelength laser with a TC-PCF.

incorporated in the laser cavity to control the state of polarization (SOP). Finally, the laser output was extracted by inserting a 10% optical fiber coupler into the cavity.

When a broadband light beam travels through the TC-PCF, a comb-like transmission spectrum is observed. The TC-PCF serves as both a filter and a polarization-dependent element. The PC in the experimental setup adjusts the SOP of each wavelength, and wavelengths with certain SOPs become the transmission peaks. The birefringence of the TC-PCF induces polarization hole burning, which facilitates the stable dual-wavelength operation of the laser. Figure 4 shows the output spectrum of the single-wavelength laser at 1532.4 nm. The signal-to-noise ratio (SNR) of the laser is over 42 dB with a peak power of approximately −11 dBm. The laser has a 3-dB bandwidth of approximately 0.02 nm limited by the resolution of the OSA. A total power fluctuation of less than 0.2 dB is observed for a duration of 1 h. When the PC is slightly adjusted, the single laser line splits into two wavelengths to realize dual-wavelength operation. Figure 5 shows the switchable dual-wavelength operation of the PC at two different settings. In Fig. 5(a), dual-wavelength operation is realized simultaneously at 1530.8 and 1532.4 nm. These simultaneous laser lines have a SNR of over 38 dB. The peak powers of the two lasing lines are −12.5 and −17 dB m. The lasing wavelength spacing is nearly 1.6 nm, which is in accordance with the transmission maximum of the TC-PCF based comb filter. By slightly adjusting the PC to change the SOP in the cavity, the dual-wavelength operation maybe switched to 1532.4 and 1534 nm simultaneously, as shown in Fig. 5(b). The peak power of the two lasing lines is approximately −21.5 dBm. The wavelength spacing of 1.6 nm remains fixed during the switching operation. These dual laser lines have a SNR of over 32 dB. The peak power fluctuation in the case of simultaneous dual-wavelength operation does not exceed 0.3 dB for a fixed setting of the PC at room temperature. Gain competition between the two competing lasing lines and the presence of multiple longitudinal modes in the cavity explain the somewhat higher peak power fluctuation in the case of dual-wavelength operation than that in the case of single-wavelength operation. The laser has a total output power of approximately −1 dBm. In both cases, the lasing line at 1532.4 nm is always notably present because it is located at the gain peak of the EDFA. Moreover, the dual wavelengths may be simultaneously tuned over the C-band by stretching of the TC-PCF.

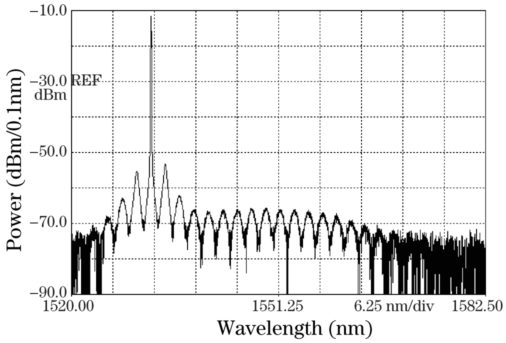

Fig. 4. Output spectrum of the single-wavelength operation of the fiber laser.

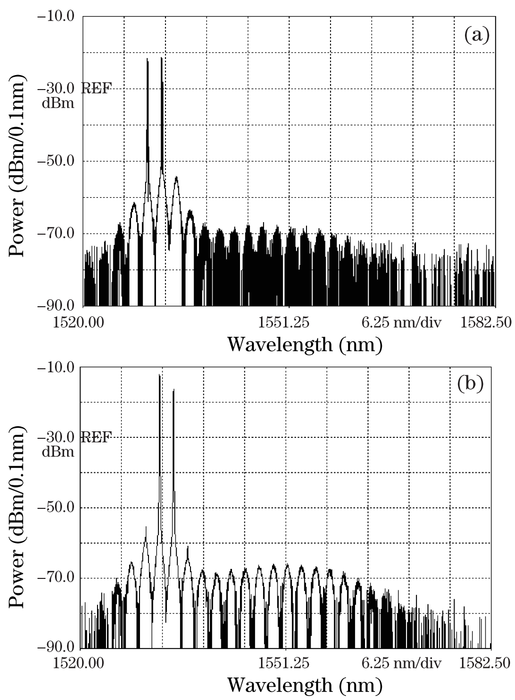

Fig. 5. Output spectra of the switchable dual-wavelength operation of the fiber laser.

In conclusion, an EDFA-based switchable dual-wavelength fiber ring laser employing a TC-PCF is proposed and experimentally demonstrated. The proposed configuration incorporates an EDFA as a gain medium. A short TC-PCF simultaneously serves as a wavelength selective comb filter and as a polarization-dependent element. Switching between two wavelengths is achieved by controlling the SOP inside the laser cavity while maintaining the wavelength spacing. The laser exhibits stable operation at room temperature. Further improvement in stability is possible through packaging of the laser cavity.

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References

1. H. Ahmad, M. Z. Zulkifli, A. A. Latif, and S. W. Harun, Opt. Commun. **282,** 4771 (2009).
2. S. Feng, S. Lu, W. Peng, Q. Li, C. Qi, T. Feng, and S. Jian, Opt. Laser Technol. **45,** 32 (2013).
3. J. Zhao, T. Liao, C. Zhang, R. Zhang, C. Miao, H. Li, and Z. Tong, Optik **124,** 1092 (2013).
4. M. A. Ummay, N. Madamopoulos, M. Razani, A. Hossain, and R. Dorsinville, Opt. Express **20,** 23367 (2012).
5. Q. Mao and J. W. Y. Lit, IEEE Photon. Technol. Lett. **14,** 612 (2002).
6. S. Hu, L. Zhan, Y. L. Song, W. Li, S. Y. Luo, and Y. X. Xia, IEEE Photon. Technol. Lett. **17,** 1387 (2005).
7. G. Qu, Y. Chen, M. Gong, and X. Chen, IEEE J. Quantum Electron. **46,** 945 (2010).
8. X. Liu, L. Zhan, S. Luo, Y. Wang, and Q. Shen, J. Lightwave Technol. **29,** 3319 (2011).
9. W. Zheng, S. Ruan, M. Zhang, W. Liu, Y. Zhang, and X. Yang, Opt. Laser Technol. **50,** 145 (2013).
10. W. Chen, S. Lou, S. Feng, L. Wang, H. Li, T. Guo, and S. Jian, Proc. SPIE **7630,** 76302J (2009).
11. S. Feng,O. Xu,S. Lu, and S. Jian, Chin. Phys. Lett. **26,** 064208 (2009).
12. H. Ahmad, A. A. Latif, M. Z. Zulkifli, N. A. Awang, and S. W. Harun, Chin. Opt. Lett. **10,** 010603 (2012).
13. Y. Bai, W. Xiang, P. Zu, and G. Zhang, Chin. Opt. Lett. **10,** 111405 (2012).
14. Z. Liu, M. L. V. Tse, C. Wu, D. Chen, C. Lu, and H. Y. Tam, Opt. Express **20,** 21749 (2012).
15. K. K. Qureshi, Z. Liu, H. Y. Tam, and M. F. Zia, Opt. Commun. **309,** 68 (2013).
16. M. L. V. Tse, H. Y. Tam, L. B. Fu, B. K. Thomas, L. Dong, C. Lu, and P. K. A. Wai, IEEE Photon. Technol. Lett. **21,** 164 (2009).