Switchable emissions of an Erbium-doped fiber laser using cascaded MZIs based on CHCF

Emisiones conmutables de un láser de fibra dopada con Erbio utilizando MZIs en cascada basados en CHCF

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Abstract

In this work, a single and dual-wavelength erbium-doped fiber laser (EDFL) based on two Mach-Zehnder interferometers (MZIs) in cascade structure was experimentally validated. MZIs were assembled by joining a capillary hollow-core fiber (CHCF) piece between two multimode fibers (MMFs) sections. The switchable operation is reached by moving the spectrum of one MZI when the temperature is increased. The maximum measured signal noise to ratio (SNR) was more than 50 dB for the single and dual-wavelength laser lines. Besides, stable output is shown since no power and wavelength variations were noticed. It is important to mention that emissions are obtained at precise wavelength positions and not arbitrarily as described by other investigations. This EDFL can be used in applications of optical fiber communications systems and fiber sensing.

Erbium-doped fiber laser, Mach-Zehnder interferometer, Multiwavelength laser emission

Resumen

En este trabajo, se validó experimentalmente un láser de fibra dopada con erbio (EDFL) con emisión simple y dual, basado en dos interferómetros Mach-Zehnder (MZI) en cascada. Los MZI se ensamblaron uniendo una pieza de fibra de núcleo hueco capilar (CHCF) entre dos secciones de fibras multimodo (MMF). La operación conmutable se logra desplazando el espectro de un MZI cuando se aumenta la temperatura. El valor máximo medido de relación señal a ruido (SNR) fue de más de 50 dB. Además, se muestra una salida estable ya que no se observaron variaciones de potencia ni de longitud de onda. Es importante mencionar que las emisiones se obtienen en posiciones de longitud de onda precisas y no de manera arbitraria como lo describen otras investigaciones. Este EDFL se puede utilizar en aplicaciones de sistemas de comunicaciones de fibra óptica y sensores.

Láser de fibra dopada con erbio, Interferómetro Mach-Zehnder, Emisión múltiple

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Introduction

Multiwavelength erbium-doped fiber lasers (EDFLs) are used for different applications like wavelength division multiplexing [1], [2], optical fiber sensing [3], [4], and microwave photonics [5], [6]. In this kind of lasers, unstable emissions is commonly appreciated [7–9]. Several optical fiber structures have been implemented to fabricate interferometers for this lasers. Y. Lv *et al*. [10] recommended a Mach-Zehnder interferometer (MZI) with a triple-core pho-tonic crystal fiber to obtain single, dual and triple-wavelength EDFL.

The side-mode suppression ratio (SMSR) was 50, 45, and 37 dB for single, dual, and triple-wavelength emission, respectively, and the 3 dB linewidth was 0.026 nm. The power fluctuations for single, dual, and triple-wavelength emissions were 0.44, 0.77, and 0.96 dB, respectively. Y. Qi *et al*. [11] proposed a switchable single, dual, and triple-wavelength EDFL, depending on a MZI using the core-offset technique with 57 cm of few-mode fiber between two single-mode fibers (). A signal-noise ratio (SNR) of 54, 43, and 49 dB for single, dual, and triple-wavelength emission respectively, was presented, and the 3 dB linewidth was 0.02 nm. The power variations for single, dual, and triple-wavelength emissions were 1.14, 2, and 4.33 dB, respectively. For the mentioned works, the multiwavelength lasing operation was accomplished by changing the polarization controller (PC) positions. This method requires a lot of time and shows lack of control of emissions.

Alternatively, other investigations use two filters in cascade to achieve multiwavelength laser emissions [12–16]. Z. Tang *et al*. [12] proposed two MZIs to obatain a single and dual-wavelength laser. One of the MZI was fabricated by splicing a piece of a photonic crystal fiber between two SMF, the second one uses two conventional fiber couplers. The reported SMSR was of 45 and 42 dB for single and dual-wavelength emissions, respectively, and the measured 3 dB linewidths of the single and dual-wavelength emissions were 0.026 and 0.03 nm, respectively. One disadvantage of these works is the assemblage of MZI with couplers, making the setup huger.

In this work, a stable single and dual-wavelength EDFL based on two cascaded MZIs was offered and experimentally validated. The MZIs were fabricated by splicing a piece of capillary hollow core fiber (CHCF) between two sections of multimode fibers (MMF). The maximum length of these MZIs was 5 mm, making these devices attractive because of their simple fabrication, small size and low cost. The MZI with larger FSR was used as wavelength chooser, and the other MZI controls the separation of the switchable emissions.

The innovation of this single and dual-wavelength EDFL is that the switchable operation is accomplished by thermally moving the interference pattern of one MZI and not by changing the polarization state like the examples cited before. This setup offers an easy method to switch emissions over predicted wavelength positions, removing the unpredictability through polarization tuning. The maximum value of SNR was 58.9 dB for the single and dual-wavelength laser emissions, and the linewidth was 30 pm. Furthermore, no power and wavelength variations were identified during the single and dual-wavelength operation.

1. Content

As presented in Figure 1, a fiber ring laser was assembled, where a laser diode launched light to a 980/1550 wavelength division multiplexer (WDM) fiber coupler. A section of 4 m of EDF was utilized as the gain medium, a PC and an isolator were added to the cavity to achieve an enhanced SNR and to operate in a unidirectional way, respectively. An optical fiber coupler (90/10) allowed to observe the output, where the 10% port was linked to optical spectrum analyzer (OSA), and the 90% port was used to close the cavity for continuous laser generation. Additionally, the two MZIs were positioned into the cavity.

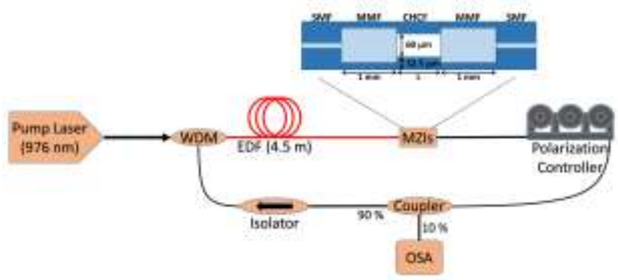

Figure 1 Experimental setup of the fiber ring laser

1.1 Fabrication and working principle

These MZIs consist of splicing a section of CHCF (inner and outer diameters of 62.5 and 125 µm, respectively) between two pieces of 1 mm of MMF (105/125 µm), and this structure was inserted between two standard SMF, see Figure 1. MMF sections work as mode couplers, distributing light to the hollow core and the ring cladding of the CHCF.

Three MZIs where fabricated with different free spectral range (FSR). The execution of this laser involves two MZIs in a cascade structure. One of these devices (MZI1) has an FSR of more than 10 nm, and the other (MZI2) has an FSR of less than 2 nm. For the MZI1, two MZIs were fabricated, and their FSRs are 17.82 and 13.29 nm equivalent to a predictable dimension of 0.3 (MZI1a) and 0.4 mm (MZI1c), respectively (see Figure 2). On the other hand, MZI2 was built with a FSR of 1.8 nm (see Figure 2), corresponding to an estimated length of 3 mm.

It is vital to mention that we reported [18] a tunable erbium-doped fiber ring laser using a MZI based on CHCF, where we prove that the spectral response of the MZI experiences a movement to higher wavelength when the temperature rises with a slope of 33 pm/ ºC. This thermal tunability allows us to combine two MZIs in a fiber ring laser cavity using the MZI1 as a wavelength picker (bigger FSR), and MZI2 is in a stable state. Then, the interference pattern of the MZI1 is moving over the spectrum of the MZI2 to select a peak/s for laser emission. The MZI2 controls the switchable period (FSR =1.8 nm), and the laser linewidth of 0.03 nm for all emissions when the two MZIs are connected in a cascade arrangement.

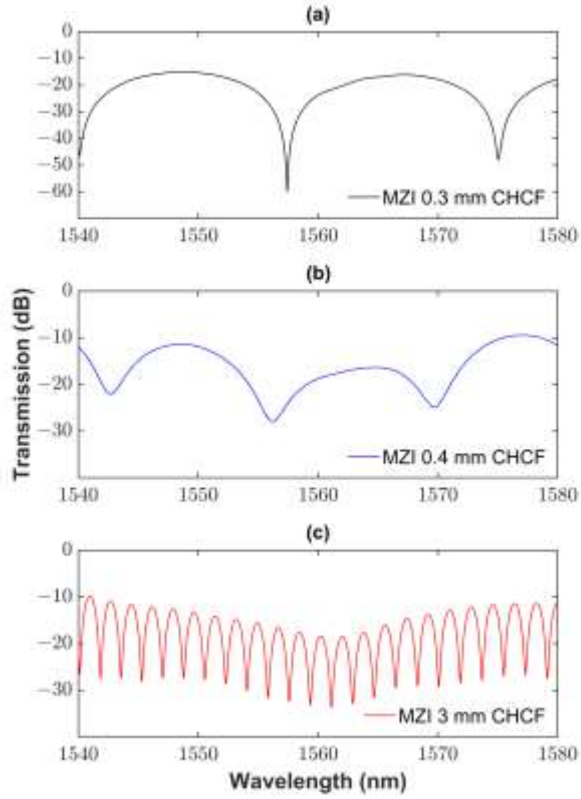

Figure 2 Transmission spectra of (a) MZI1a, (b) MZI1b, (c) MZI2

The spectral responses of the cascade combination of the MZI1a and MZI1b with the MZI2 are shown in Figure 3. For an improved understanding, the peaks with maximum transmission in the interference pattern produced by two cascaded MZIs are marked to specify the high probability to become a laser emission.

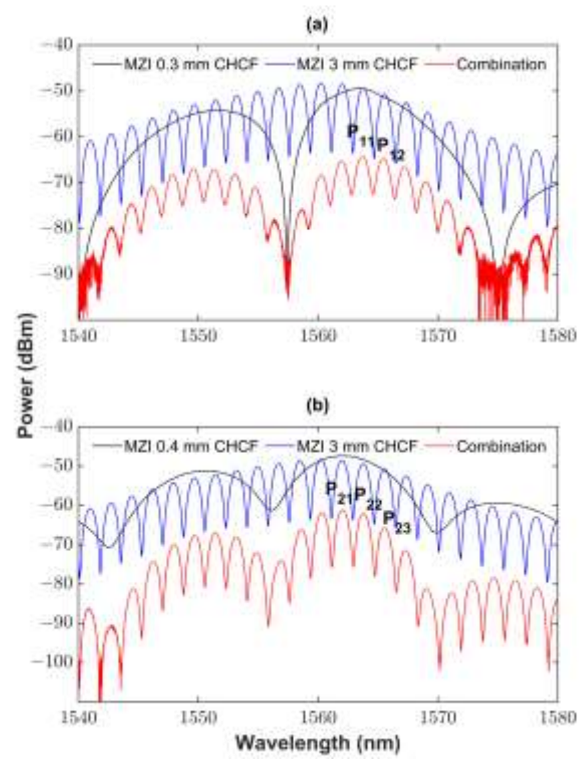

Figure 3 Transmission spectra of the MZI2 linked in sequence with the (a) MZI1a, (b) MZI1b (Cascade configuration)

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1.2 Results and Discussion

An experimental study was carried out to examine the switchable operation of the EDFL. The MZI2 was placed on a hot plate (Echotherm, Model IC20) at a constant temperature of 20 °C, meanwhile the MZI1 was on another hot plate (Thermo Scientific™, model HP88854100), where the temperature was increased.

The transmission spectrum of the cascaded MZI2 and MZI1a is shown in Figure. 3 (a). Consequently, laser emission will possibly emerge at P11 since this peak shows the maximum transmission. At the beginning, the pump laser current was static at 400 mA, and both interferometers were at 20 ºC, with these conditions, a laser emission at 1563.7 nm is observed (P11) with a SNR of 58.9 dB (see Figure. 4). Then, MZI1a was heated in steps of 1 ºC until to 29 ºC, where laser emission remains immobile. When the MZI1a temperature reached 30 ºC, another laser emission shows up at 1565.5 nm (P12) with a SNR of 58.6 dB. This dual emission is present until the MZI1a reaches a temperature of 40 ºC, where the EDFL changes to one laser emission at P12, remaining fixed from 40 to 160 ºC (see Figure 4). Moreover, the wavelength stability of laser emissions was measured and variations were not detected.

For the second case, the peak P21 shows the highest transmission (see Figure. 3), therefore a laser emission was detected at 1562.7 nm (P21) with a SNR of 50.3 dB (see Figure. 5). An analogous study was carried out, now achieving another two wavelength positions with laser emission, P22 and P23 at 1564.5 and 1566.3 nm with a SNR of 50.9 and 50.8 dB respectively.

The greatest noteworthy characteristic of our EDFL is that it can be switched from single-wavelength laser emission to a dual-wavelength by increasing the temperature of the MZI1, proposing a huge benefit compared with others switchable lasers based on polarization mentioned before. Another advantage is the constant wavelength spacing of 1.8 nm between the emissions, provided by the FSR of the MZI2, showing the controlled way of the achievement of our EDFL emissions.

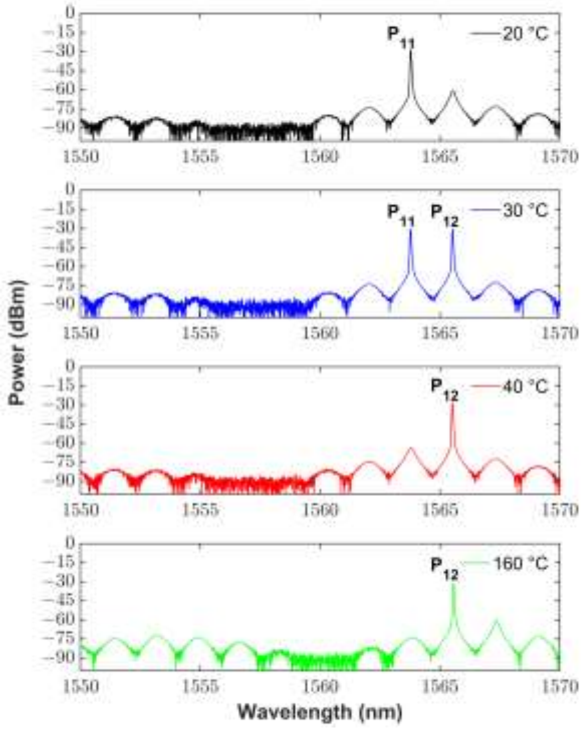

Figure 4 Switchable operation of the EDFL using MZI2 and MZI1a

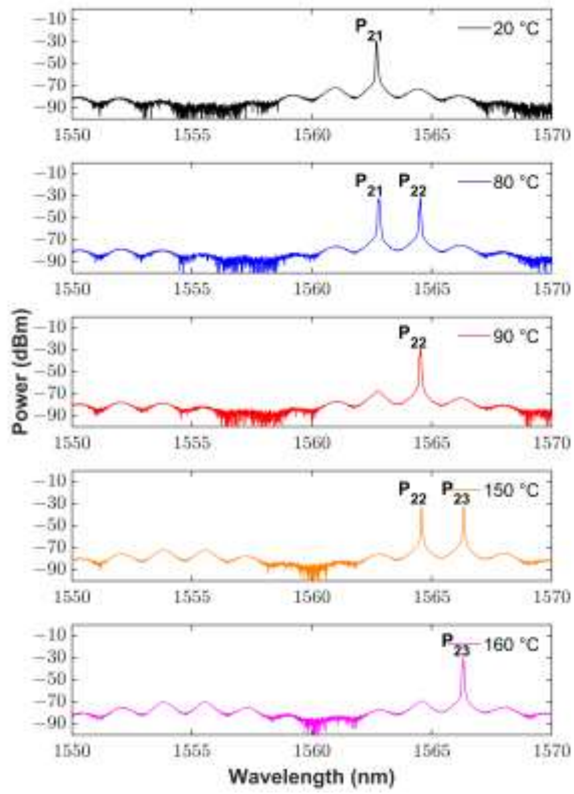

Figure 5 Switchable operation of the EDFL using MZI2 and MZI1b

Conclusions

In this work, a single and dual-wavelength EDFL has been proposed and experimentally verified. The all-fiber MZIs were fabricated by splicing a small piece of capillary hollow core fiber (CHCF) between two segments of MMF.

These MZIs show good features like easy fabrication, small size, low cost, and robustness. Furthermore, their interference patterns have high fringe contrasts and do not suffer alterations when the input polarization state of light is changed. The MZI with bigger FSR was used as wavelength selector, meanwhile, a MZI with smaller FSR determine the spacing of the switchable step. The innovation of this EDFL is that the switchable operation is accomplished by thermally tuning the interference pattern of the MZI and not by changing the polarization state into the cavity. The maximum SNR was 58.9 dB and no power and wavelength fluctuations were detected. For a future work, the nice performance of this switchable EDFL can be tested in optical fiber communications systems and fiber sensing applications.

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Referencias

[1] Sang-Mook Lee, Ki-Man Choi, Sil-Gu Mun, Jung-Hyung Moon, Chang-Hee Lee, "Dense WDM-PON based on wave-length-locked Fabry-Perot laser diodes", IEEE Photonics Technol. Lett., 17, pp. 1579–1581, 2005. *https://doi.org/10.1109/LPT.2005.848558*

[2] M.K.S. Al-Mashhadani, T.F. Al-Mashhadani, H.H. Goktas, Broadly tunable 40 GHz Brillouin frequency spacing multiwave-length Brillouin–Erbium fiber laser for DWDM, Opt. Commun., 451, pp. 116–123, 2019. *https://doi.org/10.1016/j.optcom.2019.06.040*

[3] S. Diaz, M. Lopez-Amo, Dual-wavelength single-longitudinal-mode erbium fiber laser for temperature measurements, Opt. Eng., 53, 036106, 2014. *https://doi.org/10.1117/1.OE.53.3.036106*

[4] Y. Li, C. Zhou, J. Tian, S. Ji, Y. Yao, An all-fiber multi-channel ultrasonic sensor using a switchable fiber Bragg gratings filter in erbium-doped fiber laser, J. Light. Technol., 37, pp. 4330–4339, 2019. *https://doi.org/10.1109/JLT.2019.2923645*

[5] N. A. B. Ahmad, S.H. Dahlan, M. H. Jamaluddin, R. Sanchez-Lara, N. A. Cholan, A microwave signal generation technique based on Brillouin-erbium fiber laser, Int. J. Integr. Eng., 11, 2019. *https://doi.org/10.1109/JLT.2019.2923645*

[6] A. Kumar, A. Gautam, V. Priye, Microwave photonic mixer using DP-DDMZM for next generation 5G cellular systems, Fiber Integr. Opt., 39, pp. 149–168, 2020. *https://doi.org/10.1080/01468030.2020.1826068*

[7] D.S. Moon, U.-C. Paek, Y. Chung, Multi-wavelength lasing oscillations in an erbium-doped fiber laser using few-mode fiber Bragg grating, Opt. Express., 12, 6147. 2004. *https://doi.org/10.1364/OPEX.12.006147*

[8] Y. Liu, X. Dong, P. Shum, S. Yuan, G. Kai, X. Dong, Stable room-temperature multi-wavelength lasing realization in ordinary erbium-doped fiber loop lasers, Opt. Express., 14, 9293, 2006. *https://doi.org/10.1364/OE.14.009293*

[9] W.G. Chen, S.Q. Lou, S.C. Feng, L.W. Wang, H.L. Li, T.Y. Guo, S.S. Jian, Switchable multi-wavelength fiber ring laser based on a compact in-fiber Mach-Zehnder interferometer with photonic crystal fiber, Laser Phys., 19, pp. 2115–2119, 2009. *https://doi.org/10.1134/S1054660X09210026*

[10] Y. Lv, S. Lou, Z. Tang, X. Liu, X. Wang, Tunable C-band and L-band multi-wavelength erbium-doped fiber ring laser based on a triple-core photonic crystal fiber with polarization-dependent loss, Opt. Laser Technol., 128, 106269, 2020. *https://doi.org/10.1016/j.optlastec.2020.106269*

[11] Y. Qi, Z. Kang, J. Sun, L. Ma, W. Jin, Y. Lian, S. Jian, Wavelength-switchable fiber laser based on few-mode fiber filter with core-offset structure, Opt. Laser Technol., 81, pp. 26–32, 2016. *https://doi.org/10.1016/j.optlastec.2016.01.022*

[12] Z. Tang, S. Lou, X. Wang, Stable and widely tunable single-/dual-wavelength erbium-doped fiber laser by cascading a twin-core photonic crystal fiber based filter with Mach-Zehnder interferometer, Opt. Laser Technol., 109, pp. 249–255, 2019. *https://doi.org/10.1016/j.optlastec.2018.07.060*

[13] W. He, H. Yuan, X. Lou, L. Zhu, M. Dong, Multi-wavelength switchable erbium-doped fiber laser based on a hybrid filter incorporating a bi-tapered Mach–Zehnder interferometer and Sagnac loop, Phys. Scr., 94, 125502, 2019. *https://doi.org/10.1088/1402-4896/ab3375*

[14] Y. Chang, L. Pei, T. Ning, J. Zheng, J. Li, C. Xie, Switchable and tunable multi-wavelength fiber ring laser employing a cascaded fiber filter, Opt. Fiber Technol., 58, 102240, 2020. *https://doi.org/10.1016/j.yofte.2020.102240*

[15] L. Zhang, Z. Tian, N.-K. Chen, H. Han, C.-N. Liu, K.T.V. Grattan, B.M.A. Rahman, H. Zhou, S.-K. Liaw, C. Bai, Room-temperature power-stabilized narrow-linewidth tunable erbium-doped fiber ring laser based on cascaded Mach-Zehnder interferometers with different free spectral range for strain sensing, J. Light. Technol., 38, pp. 1966–1974, 2020. *https://doi.org/10.1109/JLT.2020.2971666*

[16] L. Xin, X. Zhou, J. Chen, Low threshold multi-wavelength erbium-doped fiber ring laser with NOLM and Lyot filter, Opt. Fiber Technol., 68, 102800, 2022. *https://doi.org/10.1016/j.yofte.2021.102800*

[17] S. Marrujo-García, I. Hernández-Romano, D.A. May-Arrioja, V.P. Minkovich, M. Torres-Cisneros, In-line Mach–Zehnder interferometers based on a capillary hollow-core fiber using vernier effect for a highly sensitive temperature sensor, Sensors., 21, 5471, 2021. *https://doi.org/10.3390/s21165471*

[18] S. Marrujo-García, L.A. Herrera-Piad, I. Hernández-Romano, D.A. May-Arrioja, V.P. Minkovich, M. Torres-Cisneros, Narrow spectral linewidth and tunable erbium-doped fiber ring laser using a MZI based on CHCF, Opt. Fiber Technol., 67, 102739, 2021. *https://doi.org/10.1016/j.yofte.2021.102739*