REFERENCES

1. Q.G. Zhao and C. K. Chan, A wavelength-division-multiplexed passive optical network with flexible optical network unit internetworking capability, IEEE J Lightw Technol 22 (2004), 1970–1977.
2. Sunish Mathews, Gerald Farrell, and Yuliya Semenova, Experimental demonstration of an all-fiber variable optical attenuator based on liquid crystal infiltrated photonic crystal fiber, Microwave Opt Technol Lett 53 (2011), 539–543.
3. Shien-Kuei Liaw, Ying-Tse Lai, Ming-Hung Chang, and Yi-Gun Lai, High-dynamic-range C+L band variable optical attenuator using a titled angle shutter, Microwave Opt Technol Lett 48 (2006), 1000–1002.
4. Pablo A. Costanzo-Caso, Michael Gehl, Sergio Granieri, and Azad Siahmakoun, Optical bistable switching with symmetrically configured SOAs in reverse bias, Microwave Opt Technol Lett 52 (2010), 2753–2759.
5. J.M. Walker, The future of MEMS in telecommunications networks, J Micromech Microeng 10 (2000), R1–R7.
6. J. Li, Q. X. Zhang, and A.Q. Liu, Advanced fiber optical switches using deep RIE (DRIE) fabrication, Sens Actuators A 102 (2003), 286–295.
7. Wei Dong, Shengping Ruan, Xindong Zhang, Caixia Liu, Dongming Sun, Cuiping Jia, Jianxuan Pan, Ping Ji, and Weiyou Chen, Design and fabrication of slantcounter electrodes for optical switches, Microwave Opt Technol Lett 41 (2004), 273–275.
8. Yao-Joe Yang, Wen-Cheng Kuo, Kuang-Chao Fan, and Wu-Lang Lin, A 1 × 2 optical fiber switch using a dual-thickness SOI process, J Micromech Microeng 17 (2007), 1034–1041.
9. H. Toshiyoshi, K. Isamoto, A. Morosawa, M. Tei, and H. Fujita, A 5-volt operated MEMS variable optical attenuator, In: Digest Tech. Papers Transducers ′03 Conference, Boston, MA, 8–12 June, 2003, pp. 1768–1771.
10. D. Khalil, H. Maaty, A. Bashir, and B. Saadany, The effect of shutter thickness on opto-mechanical variable optical attenuators, Microwave Opt Technol Lett 36 (2003).
11. Cornel Marxer, Vertical mirrors fabricated by deep reactive ion etching for fiber-optic switching applications, J Microelectromech Syst 6 (1997), 277–285.
12. H. Cai, X.M. Zhang, C. Lu, A.Q. Liu, and E.H. Khoo, Linear MEMS variable optical attenuator using reflective elliptical mirror, IEEE Photon Technol Lett 17 (2005), 402–404.
13. C.R. Giles, V. Aksyuk, B. Barber, R. Ruel, L. Stulz, and D. Bishop, A silicon MEMS optical switch attenuator and its use in lightwave subsystems, IEEE J Sel Top Quant 5 (1999), 18–25.
14. K.C. Heung, P. Namkyoo, and K.Y. Kweon, MEMS reflective type variable optical attenuator using off-axis misalignment, In: Conf. Dig. IEEE/LEOS Int. Conf. Optical MEMS, 2002, pp. 55–56.
15. Roman V. Kruzelecky, Brian Wong, Jing Zou, Emile Haddad, and Wes Jamroz, Advanced MEMS and integrated-optic components for multifunctional integrated optical micromachines, In: Proc. Int. Conf. MEMS, NANO and Smart Systems (ICMENS ′04), Banff, Alberta, Canada, 2004, pp. 315–321.
16. G. Wu, et al. Design and use of compact lensed fibers for low cost packaging of optical MEMS components, IEEE J Micromech Microeng 14 (2004), 1367–1375.
17. M.W. Pruessner, N. Siwak, K. Amarnath, S. Kanakaraju, W.-H. Chuang, and R.Ghodssi, End-coupled optical waveguide MEMS devices in the indium phosphide material system, IEEE J Micromech Microeng 16 (2006), 832–842.
18. T.J. Brosnihan, W.A. Webster, and J. Villarreal, Wafer-level packaging of MEMS accelerometers with through-wafer interconnects, In: Conf. Dig. IEEE/ECTC Int. Conf. Electronic Components and Technology, 2005, pp. 320–323.
19. C.A. Edwards, H.M. Presby, and C. Dragone, Ideal microlenses for laser to fiber coupling, J Lightw Technol 11 (1993), pp.252–257.
20. Yan Jian-Hua, Ou Wen, Ou Yi, Caixia Liu, and Zhao Li-Jun, Design and fabrication of novel microlens–micromirrors array for infrared focal plane array, Microwave Opt Technol Lett 54 (2012), 879–884.

EFFECT OF LOOP DIAMETER ON THE PERFORMANCE OF MKR-BASED DUAL-WAVELENGTH ERBIUM-DOPED FIBER LASER

Azlan Sulaiman,[1,2] Sulaiman Wadi Harun,[1,3] S. F. Norizan,[3] K. Dimyati,[4] and H. Ahmad[3]

[1] Department of Electrical Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia; Corresponding author: swharun@um.edu.my
[2] Advance Communication Network, TM Research and Development, 63000, Cyberjaya, Selangor, Malaysia
[3] Photonics Research Center, Department of Physics, University of Malaya, 50603, Kuala Lumpur, Malaysia
[4] Department Electrical and Electronic Engineering, Faculty of Engineering, National Defense University of Malaysia, Kem Sungai Besi, 57000 Kuala Lumpur, Malaysia

Received 11 May 2012

ABSTRACT: *A dual-wavelength Erbium-doped fiber laser (EDFL) is demonstrated using a 1.5-m long EDF with a microfiber knot resonator (MKR) structure at the output end. The MKR is fabricated by heating and stretching a 3-cm long piece of EDF to form a microfiber, which is then manipulated to create a knot. The performance of the EDFL is investigated for two different MKR loop diameters. At a loop diameter of 4 mm, dual-wavelength laser is obtained at 1532.4 and 1556.0 nm with peak powers of −7.5 and −7.1 dBm and the corresponding optical signal-to-noise ratios of 22 and 32 dB, respectively. As the MKR diameter is reduced to 2 mm, the operating wavelength of laser shifts to a shorter wavelength, especially for the second lasing with a significant drop in output power due to the bending loss, which is more pronounced at smaller loop diameter. The slope efficiency of the EDFL drops from 0.55 to 0.09% as the MKR diameter decreases from 4 to 2 mm.* © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 55:236–238, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.27292

Key words: *microfiber knot resonator; flame brushing technique; dual-wavelength laser*

1. INTRODUCTION

Erbium-doped fiber (EDF) has been widely used for commercial fiber amplifiers and lasers owing to its high optical gain and low noise figure in 1550 nm region. Dual-wavelength and multiwavelength erbium-doped fiber lasers (EDFLs) are useful sources in fiber-optic communication systems, fiber sensors, and many other applications [1–3]. Due to the effect of homogeneous gain broadening of EDF at room temperature, multiwavelength EDF lasers experience cross-saturation between different wavelengths that causes unstable lasing [4, 5]. To date, various techniques have been developed to stabilize the dual-wavelength or multiwavelength operation of EDFLs such as using an elliptical core EDF, a multimode fiber Bragg grating and linear overlapping grating cavities [4–8]. For instance, Zhang et al. [9] reported an EDFL with 24-wavelength lasing operation within the 3 dB spectral range of 1573–1594 nm with the assistance of a highly nonlinear photonic crystal fiber.

Recently, microfiber-based resonators have attracted considerable interest for emerging applications such as biomedical sensors [10], microlasers [11], nonlinear optics [12], and optical signal processing [13], due to their small size and high quality factor. For instance, many research efforts have focused on the development of microfiber knot resonators (MKRs) that can serve as optical filters, which have many potential applications in optical communication and sensors [14, 15]. In this article, a

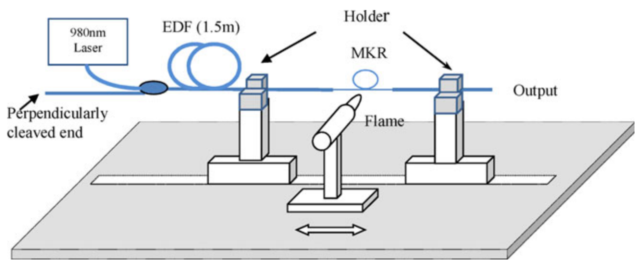

Figure 1 Schematic diagram of the experimental setup for the proposed MKR-based dual-wavelength EDFL. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

compact dual-wavelength EDFL is demonstrated using a MKR, which was fabricated at the output end of the EDF to act as both filter and reflector. The effect of MKR loop diameter on the performance of the EDFL is also investigated. The MKR is fabricated by micromanipulating the microfiber, which was obtained by heating and stretching a short portion of the EDF.

2. EXPERIMENT

Figure 1 shows the proposed MKR-based dual-wavelength EDFL, which consists of a piece of highly concentrated EDF with an MKR at one end of the fiber and WDM coupler at the other end. A 980 nm laser diode was used as a pump, which the light is injected into the EDF via a 980 nm/1550 nm coupler. The gain medium is a 1.5 m long EDF with an Erbium ion concentration of about 2000 ppm, which a small section of the fiber about 3 cm long near one of its ends was stripped for assembling the MKR. The stripped portion of the EDF was horizontally held by two fiber holders where one of them was attached to a motorized translation stage that can be moved. A microfiber was made by heating and stretching the uncoated EDF using flame-brushing technique. In the process, the position of an oxy-butane burner was controlled automatically, so that it can be moved according to a specific algorithm to distribute the heat from the burner evenly. This step is important to avoid producing rough surface on the microfiber so that the transmission loss of the microfiber can be minimized.

The MKR was assembled by micromanipulating the fabricated microfiber. First, the microfiber was cut into two unequal parts, where the longer part of the microfiber was twisted to form a large loop and the end of the microfiber was inserted inside the loop to form a knot. The required loop diameter is obtained by gradually pulling one of the fiber ends. The shorter part of the microfiber was coupled to the knot by van der Walls force to collect the light transmitted out from the knot by means of evanescent coupling. Figure 2 shows the microscope image of the fabricated MKR. The knot configuration was sustained by elastic-bend-induced tensile force and friction at the intertwisted area and thus ensuring the structural stability of the device. The resonator cavity was formed by this MKR and a perpendicularly cleaved fiber end at the other hand of the laser. Owing to the refractive index difference between silica glass and air, approximately 4% of light was reflected back into the cavity for laser oscillation. The output of the EDFL was tapped from another side of the laser and characterized by an optical spectrum analyzer (OSA) with a resolution of 0.015 nm.

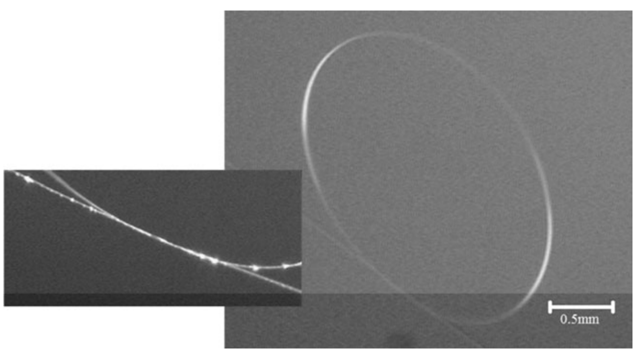

Figure 2 Microscope image of the fabricated MKR

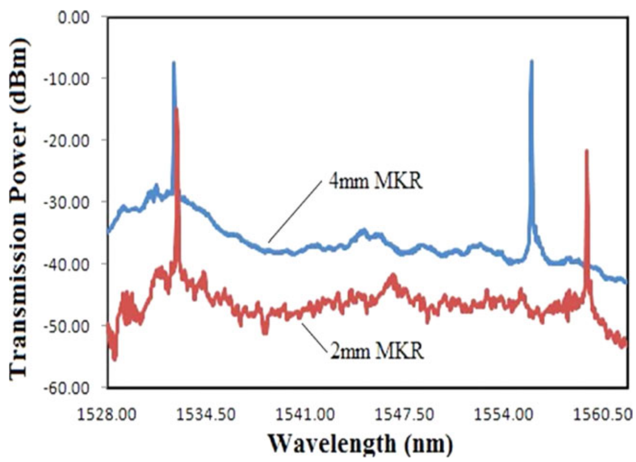

Figure 3 Output spectra of the EDFL at two MKR diameters of 4 and 2 mm. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

3. RESULT AND DISCUSSION

Figure 3 shows the output spectrum of the MKR-based laser, which operates at C-band region for two different MKR loop diameters when 980 nm pump is fixed at 78 mW. As the MKR is formed at the end of the EDF, the ASE oscillates in the loop to allow some fraction of the light to be reflected back and oscillates in the laser cavity. The operating wavelength is mainly determined by the EDF gain and cavity loss in the cavity whereby the comb-like peaks in the MKR compete to lase. As the MKR diameter is fixed at 2 mm, two lasing are obtained at 1532.6 and 1559.4 nm with peak powers of −14.6 and −21.1 dBm, respectively. Obviously, the measured corresponding optical signal-to-noise ratios (OSNRs) were 29.6 and 25.0 dB. The

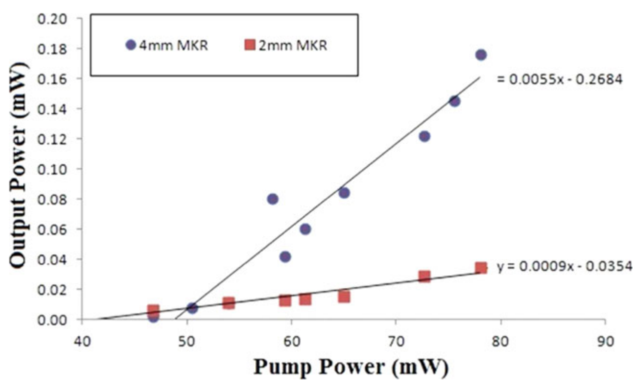

Figure 4 The peak power of the EDFL against the 980 nm pump power. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

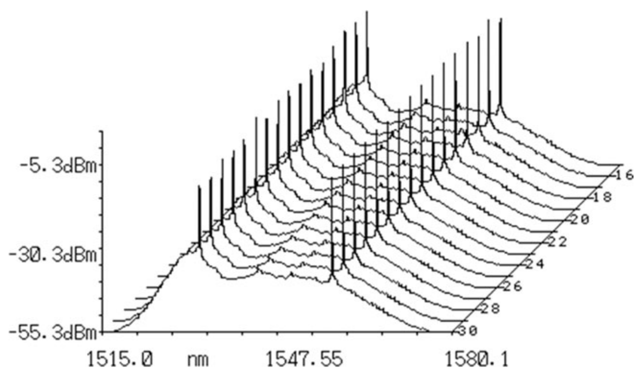

Figure 5 Spectral evolution of proposed EDFL with 4 mm MKR's diameter at 78 mW pump power. The spectrum was recorded for scanning in every 10 min

dual-wavelength operation is achieved due to the filtering characteristic of MKR, which reduces the mode competition in the linear cavity. It is observed that wavelength spacing is smaller as the MKR diameter is changed to 4 mm. The output power is at least 10 dB higher with the larger MKR diameter due to the insertion loss, which is reduced as the diameter increases. This allows both lasers to be generated at a higher output power and shifts the second lasing at a shorter wavelength. The insertion loss of MKR is mainly contributed by the bending loss. At MKR loop diameter of 4 mm, the EDFL operates at 1532.4 and 1556.0 nm with peak powers of −7.5 and −7.1 dBm, and OSNRs of 22 and 32 dB, respectively. The operating wavelength slightly shifts to a shorter wavelength due to the changes in the bending loss and phase shift inside the knot loop.

Figure 4 shows the peak output power of the shorter wavelength peak of the lasers against the 980 nm pump power. It is observed that laser starts to lase at a threshold power of about 47 mW for both MKR diameters. The output laser power increases with the pump power with a slope efficiency of 0.55 and 0.09% with MKR diameters of 4 and 2 mm, respectively. The slope efficiency is reasonably decreased with the reduction of MKR diameter, which contributes to the increment of the bending loss. The low efficiency is due to the use of a short length of EDF, which significantly produces residual pump. Lower threshold can be acquired by improving the evanescent field which propagates outside of the taper area. This can be achieved by improving the *Q* factor of the microfiber knot structure as well as resonating both of the pumping and input signal light in the same knot [11]. Figure 5 shows the spectral evolution of the output spectrum of the EDFL with MKR diameter of 4 mm recorded in every 10 min, which indicates the stability of the laser. The wavelength shifts of the highest peak are observed to be less than 0.01 nm while the output power fluctuation measured by OSA is less than 0.1 dB. This small variation of wavelength and output power is due to the fluctuation of the 980 nm pump power and the temperature variant.

4. CONCLUSION

A dual-wavelength EDFL operating in room temperature is demonstrated using a MKR at the output end of the EDF, which was obtained by fabricating and manipulating the microfiber. The two-wavelength lasing is obtained when the loop diameters of MKR are fixed at 2 and 4 mm. The laser operates at 1532.4 and 1556.0 nm with peak powers of −7.5 and −7.1 dBm, respectively. Both laser output is stable with an OSNR of more than 22 dB at room temperature. Due to the bending loss, the EDFL operates at lower peak powers and smaller wavelength spacing as the loop diameter is changed to 2 mm.

REFERENCES

1. J. Tian, Y. Yao, J.J. Xiao, X. Yu, and D. Chen, Tunable multiwavelength erbium-doped fiber laser based on intensity-dependent loss and intra-cavity loss modulation, Opt Commun 285 (2012), 2426–2429.
2. H. Ahmad, M.Z. Zulkifli, A.A. Latif, and S.W. Harun, Tunable dual wavelength fiber laser incorporating AWG and optical channel selector by controlling the cavity loss, Opt Commun 282 (2009), 4771–4775.
3. S. Shahi, S.W. Harun, and H. Ahmad, Multi-wavelength Brillouin fiber laser using Brillouin-Rayleigh scatterings in distributed Raman amplifier, Laser Phys Lett 6 (2009), 737–739.
4. D.S. Moon, U. Paek, and Y. Chung, Polarization controlled multi-wavelength Er-doped fiber laser using fiber Bragg grating written in few-mode side-hole fiber with an elliptical core, Opt Express 13 (2005), 5574–5579.
5. S. Yamashita and K. Hotate, Multiwavelength erbium-doped fibre laser using intracavity etalon and cooled by liquid nitrogen, Electron Lett 32 (2005), 1298–1299.
6. X. Feng, Y. Liu, S. Yuan, G. Kai, W. Zhang, and X. Dong, L-band switchable dual-wavelength erbium-doped fiber laser based on a multimode fiber Bragg grating, Opt Express 12 (2004), 3834–3839.
7. G. Das and J. Lit, L-band multiwavelength fiber laser using an elliptical fiber, IEEE Photon Technol Lett 14 (2002), 606–608.
8. C. Yeh and S. Chi, A broadband fiber ring laser technique with stable and tunable signal-frequency operation, Opt Express 13 (2005), 5240–5244.
9. A. Zhang, H. Liu, M. Demokan, and H. Tam, Stable and broad-band width multiwavelength fiber ring laser incorporating a highly nonlinear photonic crystal fiber, IEEE Photon Technol Lett 17 (2005), 2535–2537.
10. F. Xu, P. Horak, and G. Brambilla, Optical microfiber coil resonator refractometric sensor, Opt Express 15 (2007), 7888–7893.
11. X. Jiang, Q. Song, L. Xu, J. Fu, and L. Tong, Microfiber knot dye laser based on the evanescent-wave-coupled gain, Appl Phys Lett 90 (2007), 233501.
12. G. Vienne, Li Yuhang, L. Tong, and P. Grelu, Observation of a nonlinear microfiber resonator, Opt Lett 33 (2008), 1500–1502.
13. Y. Chen, Z. Ma, Q. Yang, and L.-M. Tong, Compact optical short-pass filters based on microfibers, Opt Lett 33 (2008), 2565–2567.
14. A. Sulaiman, S.W. Harun, F. Ahmad, and H. Ahmad, Electrically tunable microfiber knot resonator based erbium-doped fiber laser, IEEE J Quantum Electron 48 (2012), 443–446.
15. K.S. Lim, S.W. Harun, S.S.A. Damanhuri, and H. Ahmad, Low-cost spectral tunable microfibre knot resonator, IET Optoelectron 5 (2011), 281–284.

MEASUREMENT ACCURACY ENHANCEMENT USING AN OPTICAL PROBE SYSTEM FOR ELECTRICALLY SMALL MIMO ANTENNAS

Jae-Young Chung and Wonbin Hong
Department of Electrical and Information Engineering, Seoul National University of Science & Technology, 232 Gongneung-ro, Nowon-gu, Seoul, 139-743, South Korea; Corresponding author: jychung@seoultech.ac.kr

Received 16 May 2012

ABSTRACT: *Well-known measurement inaccuracy issues for electrically small multiple-input–multiple-output (MIMO) antennas incurred by conventional metallic cable and feed effects are mitigated*