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A low-threshold multiwavelength Brillouin fiber laser with double-frequency spacing based on a small-core fiber*

Lu-Lu Xu(徐路路)[1,3,4], Ying-Ying Wang(王莹莹)[1,3,4], Li Jiang(江丽)[1,3,4], Pei-Long Yang(杨佩龙)[1,3,4], Lei Zhang(张磊)[2], and Shi-Xun Dai(戴世勋)[1,3,4,†]

[1] *Laboratory of Infrared Materials and Devices, The Research Institute of Advanced Technologies, Ningbo University, Ningbo* 315211, *China*
[2] *Research and Development Center, Yangtze Optical Fiber and Cable Company Ltd, Wuhan* 430073, *China*
[3] *Key Laboratory of Photoelectric Materials and Devices of Zhejiang Province, Ningbo* 315211, *China*
[4] *Engineering Research Center for Advanced Infrared Photoelectric Materials and Devices of Zhejiang Province, Ningbo* 315211, *China*

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We demonstrate multiwavelength Brillouin fiber lasers (MWBFLs) with double-frequency spacing based on a small-core fiber (SCF) and a standard single-mode fiber (SMF), which have core diameters of 5 and 8.8 μm, respectively. Experimental results show that the SCF-based MWBFL exhibits a higher laser output power and a lower pump threshold. The output powers of the SCF-based MWBFL are >1.4 times those of the SMF-based MWBFL. Moreover, the threshold power required to generate each channel of the SCF-based MWBFL is 59% that of the SMF-based MWBFL. When the same pump power of 180 mW is injected, the number of laser channels generated for the SCF-based MWBFL is 13, which is twice that generated for the SMF-based MWBFL. In addition, the SCF-based MWBFL exhibits good wavelength tunability from 1535 to 1565 nm and temporal stability over an hour.

Keywords: nonlinear optics, fiber laser, small-core fiber, stimulated Brillouin scattering

PACS: 42.55.Wd, 42.81.−i, 42.65.ES, 42.81.Cn **DOI:** 10.1088/1674-1056/abff47

1. Introduction

Stimulated Brillouin scattering (SBS) in optical fibers has been widely investigated over the past few decades. This phenomenon arises from the interaction of light and the acoustic modes of nonlinear media.[1] When the injected pump power exceeds a certain value, the backward scattered Stokes wave is generated downshifted from the pump in terms of frequency. The frequency difference between the pump and Stokes light is numerically equal to the value of the acoustic wave frequency.[2] The SBS effect can be easily generated in silica fibers because of the low threshold, which causes most of the input signal power to be transferred to the backward Stokes, resulting in the unnecessary loss of incident light energy and the reduction in the optical signal-to-noise ratio (OSNR).[3] Therefore, numerous efforts have been made to suppress this adverse effect.[4–6] However, the SBS in optical fibers has been utilized advantageously in diverse applications, such as Brillouin amplification,[7,8] microwave signal generation,[9] multiwavelength Brillouin fiber lasers (MWBFLs),[10,11] and distributed strain/temperature sensing.[12] Among these applications, MWBFLs have been of great interest for utilization in dense wavelength division multiplexing communication systems because of their narrow linewidth,[13] wide tunable range,[14] and stable operation at room temperature.[15]

For silica-based fibers at 1550 nm, the frequency downshift of the Stokes light from the pump light is approximately 10 GHz or 0.08 nm. Such a fixed and narrow frequency spacing complicates demultiplexing and limits the practicability of MWBFLs. Therefore, various methods have been proposed to realize MWBFLs with double wavelength spacing. Shee *et al.* realized a multiwavelength Brillouin erbium fiber laser with double-frequency spacing by circulating odd-order Stokes signals in a 6.7 km-long standard single-mode fiber (SMF) using a four-port circulator.[16] Tang *et al.* utilized the four-wave mixing of Stokes lights to generate high odd-order Stokes lights in a 2.5-km SMF and then accomplished the output with double frequency spacing.[17] Qian *et al.* proposed a novel tunable MWBFL with switchable frequency spacing by exploiting Brillouin gain and absorption in two SMFs of different lengths.[18] MWBFLs with double-frequency spacing have achieved a high OSNR, wide tunability, and multiple channels in SMFs. Meanwhile, as we have previously reported, small-core fibers (SCFs) exhibit a lower threshold power because of their smaller effective mode field area (A_{eff}) and slightly larger Brillouin gain coefficients than SMFs.[19] Therefore, a MWBFL with a low threshold and high output power can be achieved using an SCF as the Brillouin gain fiber.

In this work, we experimentally demonstrated a low-threshold MWBFL with double-wavelength spacing using an SCF with a core diameter of 5 μm as the Brillouin gain

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†Corresponding author. E-mail: daishixun@nbu.edu.cn

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medium. The output spectra and laser powers of the MWBFLs based on an SCF and an SMF were measured for comparison. The threshold powers required to generate the first five laser channels of the two MWBFLs were also recorded. Furthermore, the tuning wavelength range and optical power fluctuations of the SCF-based MWBFL were investigated to evaluate its wavelength tunability and temporal stability.

2. Experimental setup

The experimental configuration of the MWBFL with double-frequency spacing is shown in Fig. 1. The Brillouin pump (BP) with a frequency ω_p is provided by a tunable laser source (TLS) with a 3 dB linewidth of < 100 kHz and an output power of 10 dBm. The BP is firstly amplified by an erbium-doped fiber amplifier (EDFA), and then injected into the main cavity by a 70/30 optical coupler 1 (OC1). Next, 99% of the BP power is launched into the sub fiber cavity, which consists of two circulators (CIRs) and the fiber under test (FUT), by the 99/1 OC2. The FUTs used in this experiment are an SCF and an SMF, respectively. Two mode field adaptors (MFAs) with the total insertion loss of 0.5 dB are employed to reduce the power loss originating from the mode-field mismatch between the SCF and the pigtails of CIRs.[20] When the counter-clockwise BP power after CIR1 exceeds the SBS threshold of the FUT in the sub fiber cavity, the first-order Stokes (S1) with a frequency ω_{s1}, which is downshifted by ν_B from the BP optical frequency ω_p, is generated clockwise and directed into the FUT again due to the unidirectionality of the CIRs, while the residual BP power is split out by CIR2. Once the power of S1 exceeds the threshold for the next order Stokes, S2 ($\omega_{s2} = \omega_{s1} - \nu_B = \omega_p - 2\nu_B$) is generated and travels in the opposite direction to S1, i.e., in the same direction as the BP's traveling path. The laser output is connected by the 1% port of OC2 to a power meter or an optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The remaining 99% optical power of S2 is directed into the sub cavity by CIR2 as a new pump for the generation of the next order Stokes S3 ($\omega_{s3} = \omega_p - 3\nu_B$). Hence, S1 and S3 firstly take place as a degenerate four-wave mixing (FWM) process, which will produce S5 ($\omega_{s5} = 2\omega_3 - \omega_1 = \omega_p - 5\nu_B$) and the first anti-Stokes AS1 ($\omega_{As1} = 2\omega_1 - \omega_3 = \omega_p + \nu_B$). These generated Stokes and anti-Stokes (AS) then interact and create the higher Stokes and AS through SBS and multiple FWM processes. These processes continue until the Stokes power of a certain order is insufficient to excite the SBS effect. Under this condition, the odd orders of S1, S3, S5, and so on are eventually limited in the sub cavity, while the 1% port of OC2 in the main cavity only outputs BP and the even orders of S2, S4, S6, and so on, thus forming an MWBFL with double wavelength spacing. The polarization controller inserted inside the cavity needs to be adjusted constantly to keep the polarization parallel between the BP and Brillouin gain throughout the experiment.[21]

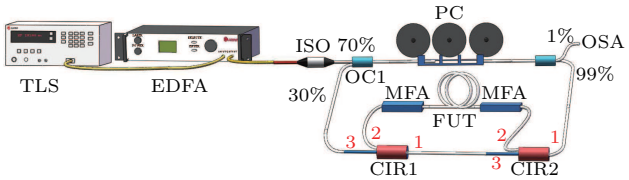


Fig. 1. The experimental setup of the MWBFL with double-frequency spacing.

3. Experimental results and analysis

The Brillouin gain spectra of the two FUTs are detected using the pump and probe technique,[22] and the results are illustrated in Fig. 2. The measured Brillouin frequency shift ν_B and the Brillouin linewidth ($\Delta\nu_B$) of the SMF are 10.72 GHz and approximately 29 MHz, respectively, while those of the SCF are 10.498 GHz and 43 MHz, respectively. These results are basically consistent with our previous work.[19] As can be clearly seen, the measured ν_B of the SMF is slightly higher than that of the SCF. This result may be related to the core size and the dopant content, such as GeO_2 or F.[23] For the SCF, the refractive index increases with the GeO_2 concentration in the

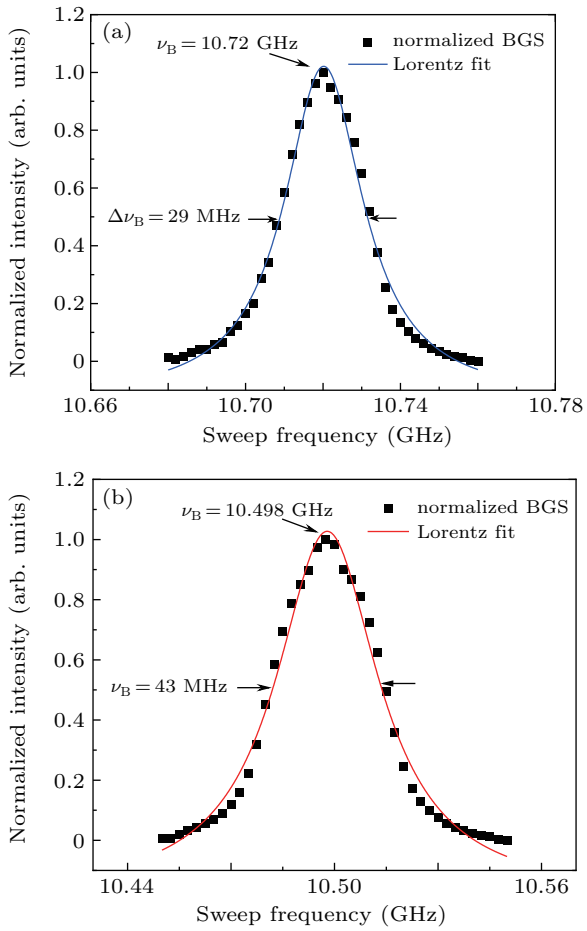


Fig. 2. Measured Brillouin gain spectra of the two fibers. (a) SMF and (b) SCF. The blue/red line shows a Lorentzian fitting.

core; thus, the longitudinal velocity decreases, accounting for the lower ν_B of the SCF than that of the SMF.[24] Meanwhile, these factors can also increase the $\Delta\nu_B$ of fibers. Additionally, the shear acoustic waves cannot be completely neglected in a fiber with such a small core size, making the $\Delta\nu_B$ of the SCF slightly larger than that of the SMF.[25]

Figure 3 shows the output spectra of the MWBFLs based on the two FUTs obtained at different pump powers. In this experiment, the center wavelength of the BP is set at 1560 nm because it coincides with the peak gain position of the EDFA. For MWBFLs, the number of the generated even-order Stokes increases gradually as the BP power is changed from 20 mW to 150 mW. Multiple orders of anti-Stokes (AS) are observed on the left side of the BP, especially in the SCF.[26] This observation is attributed to the role of the FWM in the FUTs given that AS with new frequencies on the short wavelength side from the BP cannot be induced by SBS.[27] In addition, the number of Stokes generated in the SCF is obviously generally more than that in the SMF when injecting the same pump power.

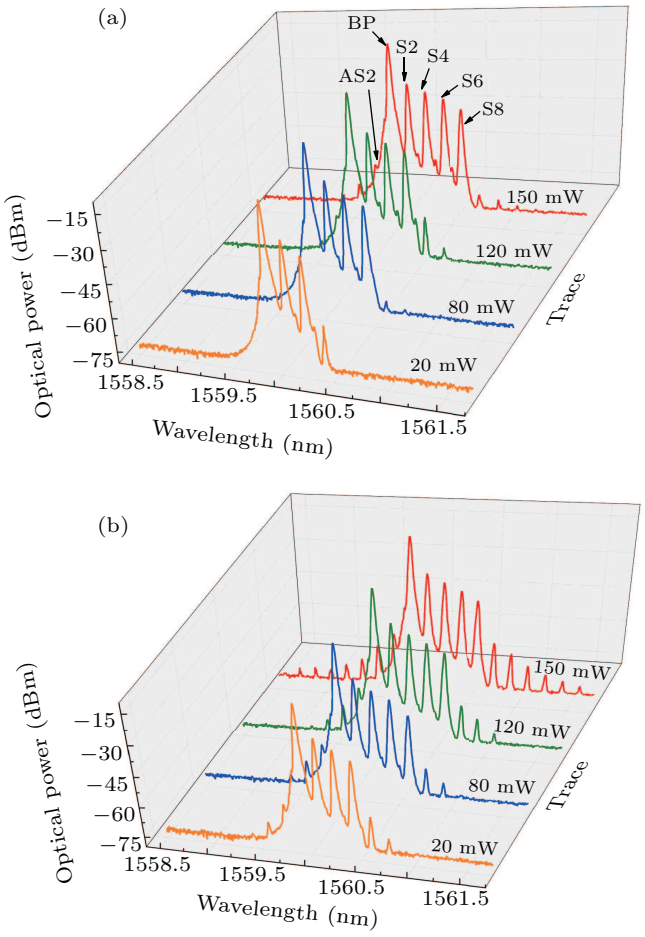


Fig. 3. Output spectra of the MWBFLs based on (a) SMF and (b) SCF with different pump powers.

Figure 4(a) depicts the output spectra of the MWBFLs based on the two FUTs at the maximum pump power of 180 mW. It is shown that only six channels with a wavelength interval of 0.17 nm between every two adjacent laser channels are generated when the SMF is used as the Brillouin gain medium. In contrast, the laser channel interval in the SCF is 0.166 nm and the total number of channels is 13, which is twice the total number of channels in the SMF. The laser output power versus the pump power of the MWBFL is plotted in Fig. 4(b). The output powers increase linearly with the BP powers regardless of whether the SMF or SCF are used as the Brillouin gain fiber. When the BP power is 180 mW, the laser output power of the MWBFL based on the SCF is 1.4 mW, which is larger than that of the MWBFL based on the SMF (1 mW). All of the output powers for the SCF are >1.4 times more than those for the SMF when the same BP power is injected. In addition, the laser output power of the MWBFL is improved further if the insertion loss of the MFAs can be reduced.

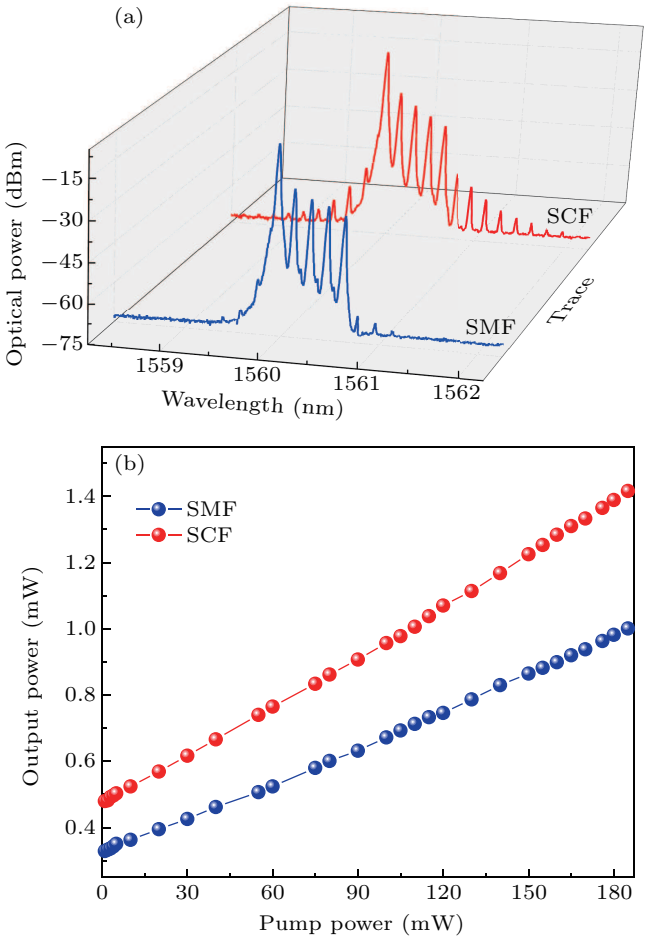


Fig. 4. (a) Output spectra of the MWBFLs based on the SCF and the SMF at 180 mW pump power. (b) Output power versus the pump power for the two kinds of fibers above.

The pump powers required for the first five laser channels of the MWBFLs based on the two FUTs are given in Fig. 5. Here, we define the threshold power as the value of the BP power when the intensity of the next channel is equal to 1% of the former channel, which means 20 dBm lower than the former. The threshold powers for S2, S4, S6, S8, and S10 are 5.96, 17.64, 52.43, 89.95, and 118.62 mW, respectively, in the

SMF and are 3.62, 9.75, 31.91, 53.08, and 70.36 mW, respectively, in the SCF. On average, the threshold power required to generate the same order Stokes for the SCF is almost 59% that for the SMF, showing that the SCF has a lower threshold than the SMF and making it potentially appropriate for use in some applications that demand low power consumption.

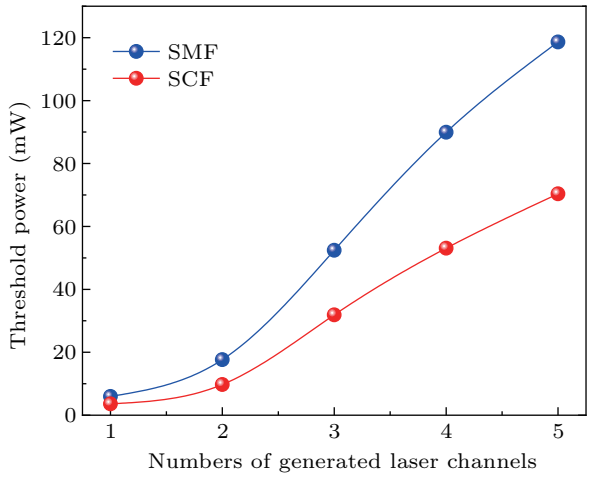


Fig. 5. The pump power required for each channel of the MWBFLs based on the SMF and SCF.

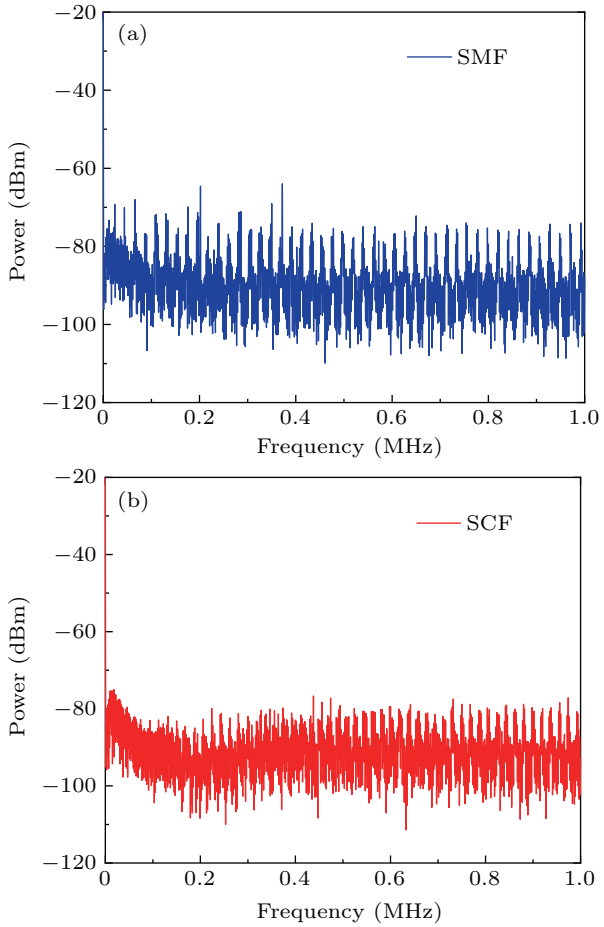


Fig. 6. Electrical spectra of the MWBFLs based on the (a) SMF and (b) the SCF.

Figure 6 shows the RF spectra of the SMF- and SCF-based MWBFLs recorded within a frequency span of 1 MHz by directing the laser output into a photodetector followed by an RF spectrum analyzer.[28] The results show that the RF spectra for the SMF and SCF cases exhibit multiple longitudinal mode operations[29] with spacing of approximately 20 and 19 kHz, respectively, corresponding to the free spectral range of the ring cavity.[30] This phenomenon is caused by the gain competition and the mode hopping of multiple longitudinal modes due to the relatively long cavity length. This situation needs to be carefully treated when such an MWBFL is used as the light source to generate pulse signals.[31] Currently, as the fiber was not polarization maintaining, the unstable oscillation is caused by the polarization state changing with the surrounding environment, which required occasional readjustment of the polarization of the input light. Furthermore, by enclosing the gain fiber in a temperature-controlled system, it should be possible to eliminate the variation in ambient temperature which leads to the laser oscillation instability.[32] However, it can be considered that the sub-second instability of multiple longitudinal modes does not have a significant effect on the multiwavelength light source. Moreover, a single longitudinal mode can finally be achieved by shortening the length of Brillouin gain fiber, that is, the length of the whole cavity.

The wavelength tunability of the SCF-based MWBFL is measured at the same pump current as the EDFA and is shown in Fig. 7. The BP can be freely changed over 30 nm from 1535 to 1565 nm. Hence, a wide wavelength tuning range is obtained.

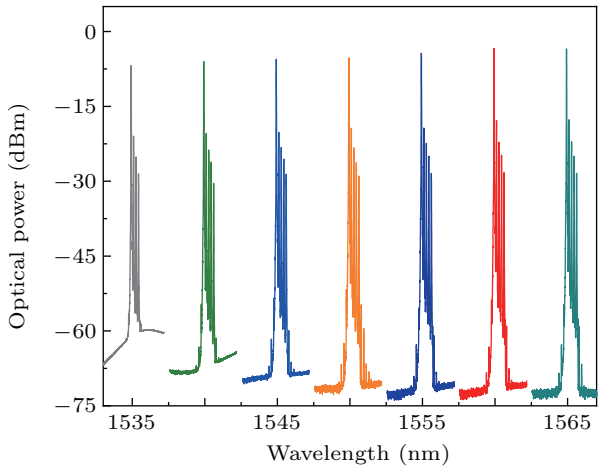


Fig. 7. Output spectra of the SCF-based MWBFL from 1535 to 1565 nm.

Temporal stability is one of the most important properties in multiwavelength lasers. The power fluctuations of the BP and the first eight channels of the SCF-based MWBFL are measured at a BP power of 180 mW over an hour at 5 min intervals at room temperature. As shown in Fig. 8, the maximum power fluctuation for the BP and the first four channels with double spacing is less than 0.5 dB, whereas that for the higher-order Stokes is 3.3 dB and is unstable relative to those of lower-order Stokes.[33] This is because the unsaturated higher-order Stokes is relatively sensitive to instability accumulation from the BP and the lower-order Stokes.

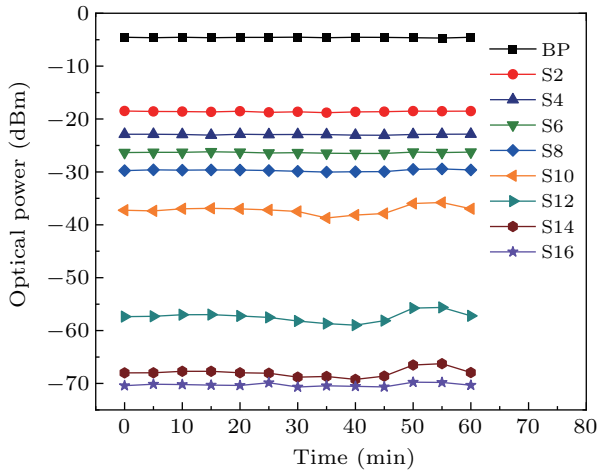


Fig. 8. Temporal stability measurement of the laser channels generated in the SCF-based MWBFL with the BP power of 180 mW over an hour.

4. Conclusion

In summary, MWBFLs with double Brillouin frequency spacing are demonstrated based on the SCF and SMF, which have two different core diameters of 5 and 8.8 μm, respectively. The threshold power required to generate each laser channel in the SCF-based MWBFL is approximately 59% of that in the SMF-based MWBFL. Meanwhile, under the same BP power, the output powers of the SCF-based MWBFL are $>$ 1.4 times those of the SMF-based MWBFL. When injecting a BP power of 180 mW, the number of channels generated in the SCF-based MWBFL is 13, which is more than twice that generated in the SMF-based MWBFL. Moreover, the SCF-based MWBFL shows good properties in terms of wavelength tunability from 1535 nm to 1565 nm and temporal stability over an hour. The proposed SCF-based MWBFL with wider wavelength spacing shows potential for use in applications that require low power consumption and opens up the potential for MWBFL to be used as the wavelength division multiplexing (WDM) light sources that are beneficial for wavelength demultiplexing. In addition, it has great potential to be an alternative laser source for applications in sensing.

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References

[1] Garmire E 2018 *Int. J. Opt.* **2018** 1
[2] Kobyakov A, Sauer M and Chowdhury D 2010 *Adv. Opt. Photonics* **2** 1
[3] Chraplyvy A R 1990 *J. Light. Technol.* **8** 1548
[4] Tian X, Zhao X, Wang M and Wang Z 2020 *Opt. Lett.* **45** 4802
[5] Tei K and Yamaguchi S 2020 *Opt. Express* **28** 17793
[6] Hu X Y, Chen W, Tu X B and Zhou M 2014 *Chin. Phys. B* **23** 124208
[7] Yang F, Gyger F and Thévenaz L 2020 *Nat. Photon.* **14** 700
[8] Li W S, Ba D X and Lv Z W 2019 *Chin. Phys. B* **28** 024212
[9] Wu Z, Shen Q, Zhan L, Liu J, Yuan W and Wang Y 2010 *IEEE Photon. Technol. Lett.* **22** 568
[10] Al-Alimi A W, Cholan N A, Yaacob M H, Abas A F, Alresheedi M T and Mahdi M A 2017 *Opt. Express* **25** 19382
[11] Zhang Z X, Wu J, Xu K, Hong X B and Lin J T 2010 *Chin. Phys. B* **19** 064209
[12] Bao X, Wan Y, Zou L and Chen L 2005 *Opt. Lett.* **30** 827
[13] Xiang D, Lu P, Xu Y, Chen L and Bao X 2016 *Opt. Lett.* **41** 4839
[14] Yuan Y, Yao Y, Yi M, Guo B and Tian J 2014 *Opt. Express* **22** 15352
[15] Shahi S, Harun S W, Shahabuddin N S, Shirazi M R and Ahmad H 2009 *Opt. Laser Technol.* **41** 198
[16] Shee Y, Al-Mansoori M, Ismail A, Hitam S and Mahdi M 2011 *Opt. Express* **19** 1699
[17] Tang J, Sun J, Chen T and Zhou Y 2011 *Opt. Fiber Technol.* **17** 608
[18] Qian L, Fen D, Xie H and Sun J 2015 *Opt. Commun.* **340** 74
[19] Jiang L, Wang Y, Yang P, Zhang L, Yang L, Dai S and Lou C 2020 *Opt. Commun.* **459** 125040
[20] Wang Y, Xu L, Jiang L, Dai S, Yang P and Yi L 2021 *Opt. Commun.* **484** 126678
[21] Randoux S and Zemmouri J 1999 *Phys. Rev. A* **59** 1644
[22] Nikles M, Thevenaz L and Robert P A 1997 *J. Light. Technol.* **15** 1842
[23] Koyamada Y, Sato S, Nakamura S, Sotobayashi H and Chujo W 2004 *J. Light. Technol.* **22** 631
[24] Dragic P D 2009 *Electron. Lett.* **45** 256
[25] Beugnot J C and Laude V 2012 *Phys. Rev. B* **86** 224304
[26] Hu K, Kabakova I V, Lefrancois S, Hudson D D, He S and Eggleton B J 2014 *Opt. Express* **22** 31884
[27] Tang J, Sun J, Zhao L, Chen T, Huang T and Zhou Y 2011 *Opt. Express* **19** 14682
[28] Ahmad H, Samion M Z, Kamely A A, Wang S, Wang Y and Sahu J K 2020 *J. Light. Technol.* **38** 6886
[29] Iezzi V L, Büttner T F S, Tehranchi A, Loranger S, Kabakova I V, Eggleton B J and Kashyap R 2016 *New J. Phys.* **18** 055003
[30] Cowle G J, Stepanov D Y and Chieng Y T 1997 *J. Light. Technol.* **15** 1198
[31] Tehranchi A, Iezzi V L, Loranger S and Kashyap R 2016 *IEEE J. Quantum Electron.* **52** 1
[32] Abedin K S 2006 *Opt. Express* **14** 4037
[33] Wang X, Yang Y, Liu M, Yuan Y, Sun Y, Gu Y and Yao Y 2016 *Appl. Opt.* **55** 6475