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Multiwavelength fiber lasers based on multimode fiber Bragg gratings using offset launch technique

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Abstract

The reflective characteristics of a multimode fiber Bragg grating (MM-FBG) and the changes of reflective spectra with mode excitation conditions in the multi-mode fiber were investigated. Two multiwavelength fiber laser configurations using offset launch technique to MM-FBG with hybrid gain mediums are proposed and demonstrated. Different multiwavelength outputs were obtained by variation of the spatial launching position of the single-mode fiber against the MM-FBG to achieve different mode group excitation. The first laser employs one MM-FBG in the ring cavity, achieving seven output wavelengths with a wavelength spacing of 0.76 nm. The second laser comprises two MM-FBGs connected in parallel, yielded 10 output wavelengths.

Keywords: Fiber laser; Multi-mode fiber Bragg grating (MM-FBG); Multiwavelength lasers; Offset launch technique

1. Introduction

Multiwavelength fiber lasers are useful light sources for wavelength-division-multiplexed (WDM) fiber communication systems, fiber sensors, and optical instrument testing. Various techniques have been proposed to realize multiwavelength oscillations in fiber lasers by utilizing cascaded fiber Bragg grating (FBG) cavities [1,2], tree, inline topology FBG [3], polarization-dependent loss element [4], FBGs written in birefringence fibers [5,6], sampled chirp FBG [7], mechanically formed long-period fiber gratings [8], and polarization dependent multiple-quantum-well waveguide [9]. Multiwavelength fiber laser was also demonstrated by incorporating a spatial mode beating filter in the laser cavity [10], and with FBG and photonic crystal fiber [11]. Some of the systems mentioned above allow control of the wavelengths, but they require a different FBG for each wavelength [1–4].

Singlemode FBGs are ideal wavelength selection components for fiber lasers due to the unique advantages of fiber compatibility, ease of use and low cost. Different types of FBGs have been used to perform simple or more elaborated filtering functions [1–8]. In contrast, the use of FBG written in multimode fibers did not attract much attention. The early use of multimode fiber Bragg gratings (MM-FBGs) was reported by Wanser et al. [12], followed by the report of theoretical and experimental studies on the characteristics and applications of MM-FBGs for strain, temperature and bending sensors in [13–15]. In 2004, we reported the first use of MM-FBGs in dual-wavelength fiber lasers for wavelength selections [16,17].

Recently, Zhao et al. reported a switchable five-wavelength SOA-fiber laser which uses a slanted MM-FBG for wavelength selection and a mode scrambler for wavelength switching [18]. In this letter, we investigate the detailed reflective spectral characteristics of MM-FBGs, and the changes of the reflective spectra due to transverse

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displacement when the spatial-launching position of a singlemode fiber against a MM-FBG is varied. On the basis of these studies, two multiwavelength fiber lasers with hybrid gain mediums are proposed and demonstrated experimentally, both employed MM-FBGs to perform the selection of the operation wavelengths using the offset launch technique. Seven-wavelength lasing operation with a wavelength spacing of 0.76 nm at room temperature was achieved for the first laser source. It has the advantages of simple configuration and precisely controlled stable lasing wavelength. The second laser design comprises two MM-FBGs connected in a parallel configuration, which emits 10 wavelength output signals. The advantage of the second configuration is its scalability, and more lasing wavelengths can be generated simply by adding more MM-FBGs to the systems.

2. Multi-mode fiber Bragg gratings

A major difference between singlemode FBGs and multimode FBGs is that multiple reflection peaks are observed in the latter. A multimode fiber supports many modes that propagate with different velocities and exhibit different mode field profiles. If a Bragg grating is written in a multimode fiber, those modes that satisfy the phase-matching condition of the grating will be reflected by the grating, and because these modes have different propagation constants, a corresponding number of reflection wavelengths will be observed in the reflection spectrum. The phase-matching condition, or Bragg reflection condition, of a grating with the period Λ is given by $\beta_1 - \beta_2 = 2\pi/\Lambda$, where β_1 and β_2 are the propagation constants of the forward and back ward propagating modes, respectively. For reflection to the same mode, $\beta_1 = -\beta_2 = \beta$. Then the phase-matching condition can be simplified as:

$$\beta = \pi/\Lambda. \tag{1}$$

In the case of graded-index MMF, the propagation constant for the Nth principal mode is approximated by the equation [13]:

$$\beta = \frac{2\pi}{\lambda} n_1 \sqrt{1 - 4\Delta \frac{N+1}{V}}, \tag{2}$$

where $V = 2\pi a NA/\lambda$, is the normalized frequency. NA is the maximum numerical aperture, a is the core radius, n_1 is the refractive index of the core and Δ is the maximum relative index difference of the graded-index MMF.

The Bragg wavelengths of the MM-FBG can be calculated from Eqs. (1) and (2). However, the coupling of forward $N(N+1)$ modes to backward $N+1$ (N) modes is not considered in these equations. The reflection spectrum of a multimode FBG depends on the mode group excitation. For example, if several lower-modes are excited in the MMF and incident on the MM-FBG, then only a few wavelengths reflection occurred. If more higher-order modes are launched to the MMF, the number of reflected peaks will increase. Consequently, the number of reflected wavelengths is determined by the spatial distribution of the MMF modes that are excited. Fig. 1 shows the experimental setup where different spatial distributions of the MMF modes are excited by changing the lateral displacement between a SMF and MMF. Amplified spontaneous emission (ASE) from an erbium-doped fiber amplifier (EDFA) was used as a broadband light source. The ASE was launched through a singlemode 3-dB fiber coupler into the MM-FBGs. The SMF and the MMF are aligned using a fusion splicer, and the lateral displacement between them can be adjusted under manual mode operation of the splicer. The reflected light was measured with an optical spectrum analyzer (OSA) to observe the reflection spectra of the MM-FBG when the lateral displacement between the SMF and the MMF is varied.

A fiber Bragg grating was written in a standard graded-index multimode fiber which has a numerical aperture of 0.275, a core diameter of 62.5 μm, and a refractive index of 1.472. The grating period of the FBG is about 1064.2 nm. Using Eqs. (1) and (2), the reflection wavelengths were calculated to be about 1565.2 nm, 1563.6 nm, 1562.0 nm,... for $N = 0, 1, 2, \ldots$, respectively. Reflected wavelengths (i.e. 1564.4 nm, 1562.8 nm,...) located between these calculated wavelengths due to the forward $N(N+1)$ modes coupled to backward $N+1$ (N) modes are not considered in Eq. (1) [13] and will appear mid-way between the calculated wavelengths. That is, the modes reflected are equally spaced in β space, leading to a wavelength separation of about 0.8 nm.

Fig. 2 shows the normalized reflection spectra of the MM-FBG for different lateral displacements of the SMF and the MMF. The lateral displacements for Figs. 2(a)–(c) are, respectively, about 1.8, 4.2, and 7.6 μm. The measured reflected wavelengths of the MM-FBG are 1565.18 nm, 1564.42 nm, 1563.66 nm, 1562.88 nm,..., which agrees fairly well with the predicted results.

It can be seen from Fig. 2 that the coupling between the MM-FBG and SMF is more selective for smaller offset due to the better overlap integral between the two fibers. For example, there are only 3 lower modes (shown in Fig. 2(a)) when the lateral displacement is ~0 μm. When the lateral displacement is increased more reflection peaks occur (as shown in Fig. 2(c), where 10 higher-order modes reflected from the MM-FBG to the SMF were observed). The latter effect is due to the better coupling of the high-order modes from the MM-FBG to the SMF when the offset is larger. The experimental results agrees well with the

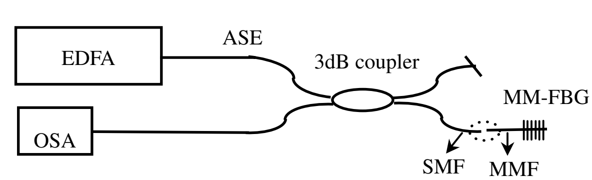

Fig. 1. Experimental setup to excite different spatial distribution to a MM-FBG.

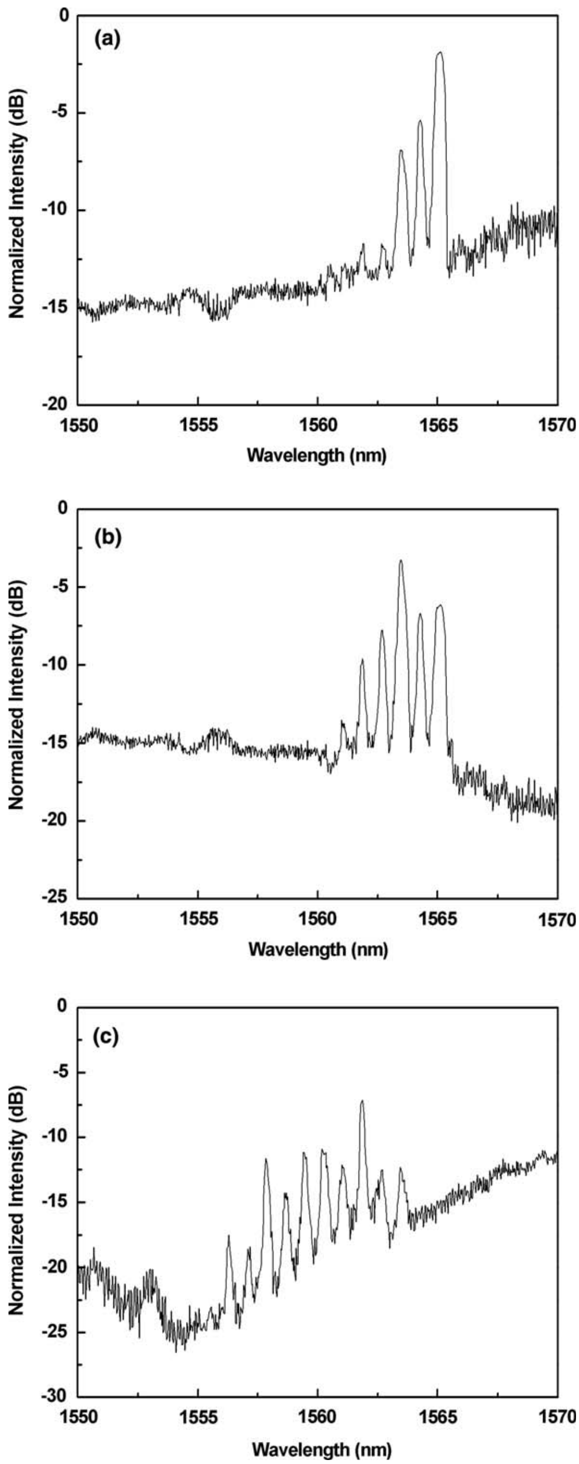

Fig. 2. Reflection spectra of the MM-FBG under offset of: (a) 1.8 μm; (b) 4.2 μm; and (c) 7.6 μm between the SMF and the MMF.

work of Denis Donlagic et al. in their investigation of modal filtering properties of MMF microbends [19].

Therefore, the measured reflective spectra of the MM-FBG depend on the condition of excitation of modes, and the offset between the SMF and the MMF is the critical factor that influences the reflective characteristic of the MM-FBG. The offset launch technique allows the excitation of a well defined subset of predominately higher-order mode groups to be generated. It is of great interest to control the number of reflection wavelengths of the MM-FBG and their reflectivities. As mentioned above, this can be accomplished by adjusting the lateral offset of the single-mode fiber with respect to the multimode fiber to fully suppress some reflections, while maintaining strong other order modes conversions [12]. Based on this principle, two multiwavelength fiber lasers are proposed and successfully demonstrated with MM-FBGs (identical to that used in Fig. 2) using the offset launch technique.

3. Experiment and results

The configuration of the first proposed laser is shown schematically in Fig. 3. The principle of the proposed scheme is based on the hybrid gain medium and the MM-FBG. The MM-FBG is introduced into the cavity by an optical circulator (OC) for multiwavelength selection. The PC is used to rotate the polarization state and allowed continuous adjustment of the birefringence within the cavity. The hybrid gain medium is composed of the SOA and EDFA. The SOA was driven by a 110 mA current source and can offer an output saturation power of about 10 dBm. The EDFA was pumped by a laser diode with pumping power of 100 mW at 980 nm, and can offer an output saturation power of about 13 dBm. Intrinsic properties of EDFA such as homogeneous line broadening and gain competition can be suppressed by the integration with the SOA, which results in a stable multiwavelength operation [20]. In addition, it is possible to achieve a higher SNR in the hybrid gain medium than that only using SOA due to the low noise figure of EDFA. The fibers in the cavities are all SMFs except a section of about 1 m MMF containing the MM-FBG. The laser output was taken via a 90:10 fused fiber coupler. The spectral characteristic was measured using an optical spectrum analyzer with 0.1 nm resolution.

As mentioned in Section 2, through adjusting the lateral offset of the SMF with respect to the MMF, the reflection characteristic of the MM-FBG can be changed, the output of the proposed laser will also change. The PC is used to adjust the polarization states of different modes, and balance the gain and loss between the peak reflections of the MM-FBG. Fig. 4 shows the output spectra of the multiwavelength fiber laser for two different spatial-launching

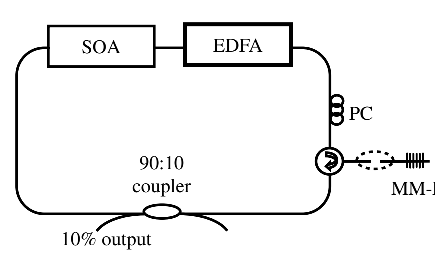

Fig. 3. Schematic diagram of the first proposed laser.

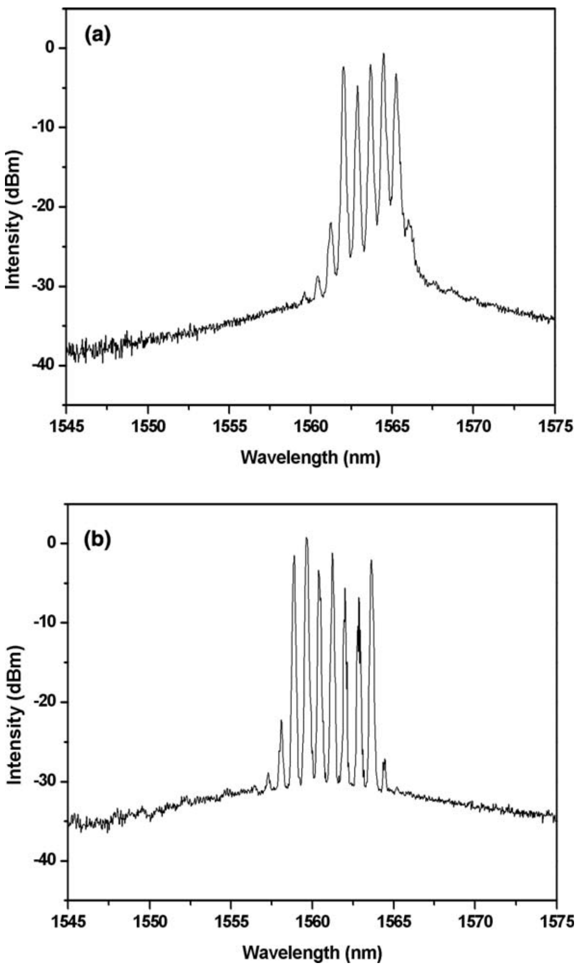

Fig. 4. Output spectra of the multiwavelength fiber laser for two different SMF–MMF displacements.

position of the SMF against the MM-FBG. When the offset is small, we obtained five wavelength output corresponding to lower-order mode excitation, as shown in Fig. 4(a). When the offset becomes larger, seven wavelength output corresponding to higher-order mode excitation was obtained, and the wavelengths position shift to short wavelength, as shown in Fig. 4(b).

The configuration of the second proposed laser is shown schematically in Fig. 5. It also used the SOA and EDFA to provide the gain. A 3-dB fiber coupler is used to incorporate two identical MM-FBGs into the laser cavity. Optical power inside the ring is thus divided into two branches of approximately equal power. Each of the branches is composed of the MM-FBG and a PC, used to finely adjust the gain of the corresponding wavelength in order to balance the powers of oscillations. Ninety percent of the power was coupled into the cavity to compensate for the high loss when the lateral offset is large.

In the experiment, through carefully adjusting the polarization states of the two PCs and the offsets of the two MM-FBGs against the SMFs, up to 13 wavelength output can be obtained, but with relatively larger amplitude differences. Fig. 6 shows an example of the output of the multiwavelength laser with good uniform power across 10 wavelengths. The amplitude variations in each wavelength were measured to be less than 0.5 dB, and the power differences between them are within 2 dB. It is worth mentioning that splicing of lateral offset joints is possible using commercial fusion splicers with reduced fusion time and fusion current, to attain better coupling loss.

The SOA employed in the fiber ring configuration is polarization dependent. The polarization state may change when the environmental conditions are changed, which leads to a change in the SOA gain. Further more, the back reflection from the MM-FBG also exhibits polarization dependence to some extent [10]. In the experiments, the PCs have to be tuned to maintain a stable multiwavelength lasing with almost equal amplitudes. The proposed scheme therefore needs active polarization control in practical application.

It is not possible to obtain multiwavelength oscillations at unrestricted shorter wavelength using only one MM-FBG just by increasing the offset because of the increased loss. It is important to note that the MM-FBG structure is sensitive to external perturbations such as temperature or stress, which can cause model interference effects. This sensitivity could be reduced by shorten the fiber length between the joint and the MM-FBG.

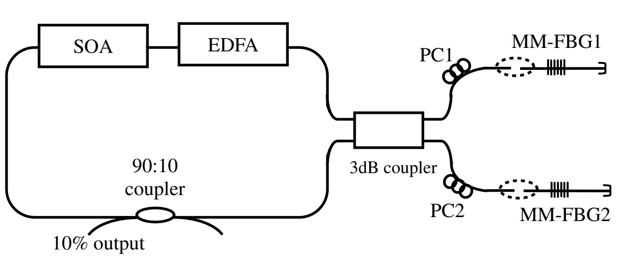

Fig. 5. Schematic diagram of the second proposed laser.

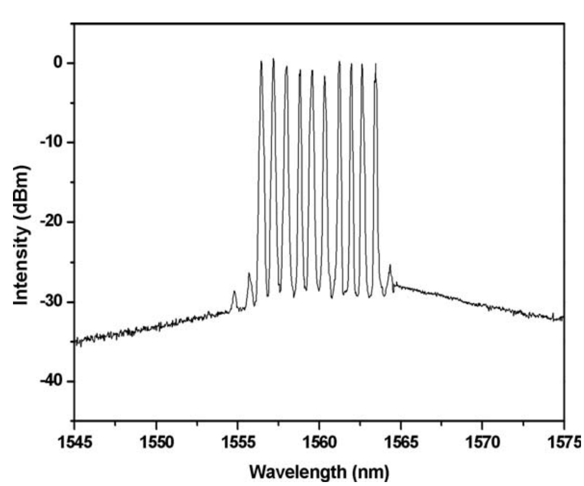

Fig. 6. Ten-wavelength laser oscillation output.

The second proposed laser configuration has the advantage of scalability. The number of lasing wavelength could be increased by adding more branches of SMF–MM-FBG or cascading more MM-FBG with different Bragg wavelengths. For example, an additional two identical MM-FBGs different from that we used above can be cascaded after MM-FBG1 and MM-FBG2 in Fig. 5. Then, more than 20 wavelengths output could be obtained in a wide switching range, using the offset launch technique. Three 3-dB fiber couplers could also be used to incorporate four branches into the laser cavity, creating a tree topology. Each branch can include some numbers of MM-FBGs. Then, using the proposed configuration and the offset launch technique, many lasing wavelengths could be generated provided that the spectral gain bandwidth of the cavity is wide enough.

4. Conclusion

In conclusion, the detailed reflective spectra characteristics of the MM-FBG are investigated. The changes of the reflective spectra are studied when the mode excitation condition in the multi-mode fiber is altered. On the basis of these studies, two multiwavelength fiber lasers using offset launch technique with hybrid gain mediums are proposed and demonstrated, both by variation of the spatial-launching position of the single-mode fiber against the MM-FBG to achieve different mode group excitation. It has a simple configuration and the MM-FBG was used as equal spaced multiwavelength selection element to construct a precisely controlled stable multiwavelength laser. The second laser comprises two MM-FBGs in a parallel configuration, which emits 10 wavelength output signals. The advantage of the second configuration is its scalability, and more lasing wavelengths could be generated by easily adding more MM-FBGs to the systems.

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References

[1] Qinghe Mao, J.W.Y. Lit, IEEE Photon. Technol. Lett. 14 (2002) 612.
[2] Y.Z. Xu, H.Y. Tam, W.C. Du, M.S. Demokan, IEEE Photon. Technol. Lett. 10 (1998) 334.
[3] L. Talaverano, S. Abad, S. Jarabo, M. Lopez-Amo, J. Lightwave Technol. 19 (2001) 553.
[4] Yong Wook Lee, Byoungho Lee, IEEE Photon. Technol. Lett. 15 (2003) 795.
[5] Bong Ahn Yu, Jaejoong Kwon, Seunghwan Chuang, Electron. Lett. 39 (2003) 649.
[6] Xinhuan Feng, Yange Liu, Lei Sun, Shuzhong Yuan, Guiyun Kai, Xiaoyi Dong, Chinese Phys. Lett. 21 (2004) 659.
[7] Jianliang Yang, Swee Chuan Tjin, Nam Quoc Ngo, IEEE Photon. Technol. Lett. 16 (2004) 1026.
[8] Kyung-Rak Sohn, Kwang Taek, IEEE Photon. Technol. Lett. 17 (2005) 309.
[9] J. Sun, J. Qiu, D. Huang, Opt. Commun. 182 (2000) 193.
[10] S. Jarabo, Fiber Integrated Opt. 20 (2001) 325.
[11] Xueming Liu, Xiaoqun Zhou, Xiufeng Tang, Junhong Ng, Jianzhong Hao, Teck Yoong Chai, E. Leong, Chao Lu, IEEE Photon. Technol. Lett. 17 (2005) 1626.
[12] K.H. Wanser, K.F. Voss, A.D. Dersey, Proc. SPIE 2360 (1994) 265.
[13] Toru Mizunami, Tzvetanka V. Djambova, Tsutomu Niiho, S. Gupta, J. Lightwave Technol. 18 (2000) 230.
[14] Jirapong Lim, Qingping Yang, B.E. Jones, Phillop R. Jackson, IEEE Trans. Instrum. Measur. 51 (2002) 622.
[15] T. Mizunami, T. Niiho, T.V. Djambova, Proc. SPIE 3746 (1999) 216.
[16] X.H. Feng, Y.G. Liu, S.G. Fu, S.Z. Yuan, X.Y. Dong, IEEE Photon. Technol. Lett. 16 (2004) 762.
[17] X.H. Feng, Y.G. Liu, S.Z. Yuan, G.Y. Kai, W.G. Zhang, X.Y. Dong, Opt. Express 12 (2004) 3834.
[18] Chun-Liu Zhao, Zhaohui Li, M.S. Demokan, Xiufeng Yang, Wei Jin, Opt. Commun. 252 (2005) 52.
[19] Denis Donlagic, Brian Culshaw, J. Lightwave Technol. 18 (2000) 334.
[20] D.N. Wang, F.W. Tong, Xiaohui Fang, W. Jin, P.K.A. Wai, J.M. Gong, Opt. Commun. 228 (2003) 295.