Individually Switchable and Widely Tunable Multiwavelength Erbium-Doped Fiber Laser Based on Cascaded Mismatching Long-Period Fiber Gratings

Xuesong Liu, Li Zhan, Shouyu Luo, Yuxing Wang, and Qishun Shen

Abstract—A novel concept of individually switchable and widely tunable erbium-doped multiwavelength fiber laser (MWFL) is proposed and experimentally demonstrated. The key component of the laser is a channel transmissivity individually variable comb filter composed of two cascaded different-length long-period fiber gratings (LPFGs), named cascaded mismatching LPFGs. When inserted into the laser cavity, this polarization-dependent comb filter functions as the wavelength selector and switching filter simultaneously. By properly adjusting the polarization controllers (PCs) in the laser cavity and in the high birefringence Sagnac loop mirror (HiBi-SLM), eleven individually switchable wavelengths with different flexible lasing states, including successively tunable adjacent single-, dual- and triple-wavelength outputs, nonadjacent dual- and triple-wavelength outputs, as well as quadruple- and quintuple-wavelength outputs, have been achieved. This MWFL may be useful in optical fiber sensing or other fields desiring very flexible optical source.

Index Terms—Erbium-doped fiber laser (EDFL), long-period fiber grating (LPFG), multiwavelength fiber laser, polarization-dependent loss, switchable fiber laser, tunable fiber laser.

I. INTRODUCTION

IN THE PAST decade, multiwavelength fiber lasers (MWFL), as attractive optical sources, have been significantly advanced due to their potential applications in precise spectroscopy, optical wavelength-division-multiplexing (WDM) systems, optical instrument testing, etc. Switchable fiber laser is an important type of MWFLs for its enhanced functionality and flexibility to meet different requirements in practice, and relevant investigations have been extensively reported up to date [1]–[16]. Switchable MWFLs can fall into two categories, in terms of whether the lasing wavelengths can be switched individually. The first type is based on comb filters, such as Lyot-Sagnac filter [1], Mach–Zehnder interferometer (MZI) [2], [3], superimposed chirped fiber Bragg grating (CFBG) [4], [5]. These MWFLs output many channels, but they can be only switched regularly not individually, e.g., interleaving operation or wavelength spacing changed equally. Because the spectral behavior of most tunable comb filters tends to change as a whole, or all channel transmissivities uniformly increase or decrease in the tuning process, so it’s difficult to switch an individual wavelength without impacting other channels. In contrast, the other type of switchable MWFLs, with comparatively less lasing wavelengths, can be individually switched among multiple lasing channels, which is notably suitable for fiber sensors or wavelength routers of WDM network. Most switchable MWFLs of this type are based on versatile fiber Bragg grating (FBG) techniques, such as cascaded FBGs [6], [7], FBGs connected to an array waveguide grating [8], [9], FBGs inserted into a fiber Sagnac loop interferometer [10] and FBGs written in birefringence fibers [11], [12]. Because FBGs are discrete wavelength selectors, unlike a periodic comb filter, it is convenient to switch the lasing wavelengths individually. Nevertheless, there are some intrinsic defects about the second type of switchable lasers. Since the amount of switchable wavelengths equals to that of FBGs if ordinary FBGs are in use, more lasing wavelengths lead to larger insertion loss as well as higher complexity of the laser. More importantly, it’s still hard to find an effective mechanism to individually switch dozens of lasing channels. In practice, switchable-wavelength amount rarely exceeds four in one laser based on FBGs [8], [11], [13]. Recently, there is a trend that employing modified high-birefringence Sagnac loop mirror (HiBi-SLM) as the comb filter to obtain individually switchable MWFLs [14]–[16], but the results didn’t present major breakthrough on the flexibility or switchable-wavelength amount in comparison with FBG-based MWFLs. On the other hand, erbium-doped fiber (EDF), a frequently used gain medium, is a homogeneous broadening medium at room temperature, which results in severe mode competition and unstable lasing in an erbium-doped fiber laser (EDFL). This disadvantage further limits the amount of switchable wavelengths if they are separated nearby from each other (several nanometers or smaller), so sometimes it requires extra techniques to suppress the mode competition for stable
lasing, e.g., four-wave mixing effect in high-nonlinear fiber or photonic-crystal fiber, which consequently increases the cost and complexity of the laser [7], [8].

In 2007, a triple-wavelength switchable MWFL based on the comb filter composed of cascaded long-period fiber gratings (LPFGs) induced by side exposure of CO₂ laser was reported by M. Yan et al. [17]. Thanks to its polarization-dependent loss (PDL) property, this special comb filter is endowed with a unique advantage that its channel transmissivities exhibit unequal variations with the incident states of polarization (SOP), so it is possible to switch the lasing wavelengths individually. Though cascaded LPFGs had been researched earlier as the comb filter in a MWFL [18], it's essentially different from that in [17]. The former is based on Raman amplifier, which requires high pump power. Moreover, its wavelengths are not switchable without PDL. However, there was not any derivative since [17], in which the origin and specific principle behind the cascaded LPFGs responsible for the switching operation was not clear, but merely explained and demonstrated briefly. In addition, the amount of switchable wavelengths in that laser is only three.

In this study, we advance the work of [17] in theory and experiment significantly, present a new concept of individually switchable and widely tunable erbium-doped MWFL. A pair of cascaded LPFGs with different grating lengths, or named “cascaded mismatching LPFGs”, is comprehensively analyzed with LPFG relevant theory, for the first time to our knowledge. Theory and experiment both indicate that not only PDL but also the difference between the two LPFGs is necessary to obtain the comb filter with individually variable channel transmissivities. The PDL property of cascaded mismatching LPFGs originates from the birefringence induced in their fabrications. In the laser cavity, this special comb filter acts as the wavelength selector and switching filter simultaneously, since the cavity losses at the lasing wavelength candidates can be altered unequally through adjusting the SOP. With the cooperation between the cascaded mismatching LPFGs and a broadband HiBi-SLM which tunes the oscillating band, lasing wavelengths can be not only individually switched but widely tuned among eleven channels from 1544 nm to 1568 nm with 2.4 nm spacing. Adjacent single-, dual- and triple-wavelength outputs are successively tuned out among the eleven channels. Nonadjacent switchable dual- and triple-wavelength outputs are also observed, as well as some quadruple- and quintuple-wavelength output schemes. Besides, it needs no extra stabilizing technique to overcome the mode competition in this EDFL. There are as many as eleven channels involved in the individually switchable operation, prevailing over most of the previously reported individually switchable MWFLs in terms of the flexibility and amount of switchable wavelengths. Moreover, the usage of two LPFGs, instead of multiple FBGs, necessarily lowers the insertion loss and complexity of the laser. The favorable features of this individually switchable and widely tunable MWFL are difficult to achieve in other methods so far.

II. PRINCIPLES OF OPERATION

Fig. 1 shows the configuration of this individually switchable and widely tunable MWFL. The left part is a sub-ring cavity that serves as the reflector, which consists of a PC (PC1) and the cascaded mismatching LPFGs, connected by an optical circulator that assures unidirectional operation. A 10 dB coupler outputs 10% laser power from the cavity to the analyzer (OSA). In the middle of the configuration is the gain medium of a 12 m EDF with 400 ppm erbium-ion concentration pumped by a 980 nm laser diode with the max power of 300 mW. The right part is the broadband HiBi-SLM filter, made up of a 50:50 coupler, a section of 18 cm polarization maintaining fiber (PMF) with the birefringence of 4.5 × 10⁻⁴, and two PCs (PC2 and PC3). The linear-cavity design of the laser has advantages including low threshold power, high conversion efficiency, and easily resulted spatial hole-burning (SHB) effect, which alleviates the mode competition in the EDFL. The key component of the switchable MWFL, placed inside a foam box, is the cascaded LPFGs separated by about 28 cm, with identical grating period of 625 μm but different grating lengths that one is 3.75 mm and the other is 11.25 mm. Such LPFGs are fabricated through side irradiating single-mode fiber (SMF) with long-pulse CO₂ laser [19]. Cascaded LPFGs form a comb filter, and if it is inserted into the laser cavity, lasing oscillations tend to occur at the spectral interference peaks, because of the minimum cavity losses at these wavelengths. Distinct from most of other comb filters, the channel transmissivities of the cascaded mismatching LPFGs exhibit variations in different degrees with the incident SOPs, controlled by PC1, which changes the cavity losses at the wavelengths unequally so that the lasing oscillations can be switched individually. With the cooperation of the HiBi-SLM to shift the laser gain region about 1550 nm, via setting PC2 and PC3 properly, individually switchable and widely tunable operations in the laser can be realized.

Although cascaded LPFGs have been broadly researched, most investigations were developed on the premise of identical LPFGs in cascading [18], [20]–[22]. The concept of cascaded mismatching LPFGs, manifested as different grating lengths in this paper, is the first time to be put forward to our knowledge. The theoretical analysis, numerical simulation and validation in experiment on this special comb filter are presented as follows.

A. Cascaded Mismatching LPFGs

LPFG is a mode coupler that couples the core mode to a certain co-propagating cladding mode in fiber, resulted from the longitudinally periodic refractive-index (RI) perturbation, with typical order of hundreds of micrometers. As shown in Fig. 2, after passing the first LPFG of length d₁, the coupled cladding mode and the residual core mode propagate simultaneously in the grating-free region of length L, with different velocities due
to the index difference between the cladding mode and core mode. If they encounter a second LPFG of length \(d_2\), part of the cladding mode is recoupled to the fiber core, interacts with the residual core mode and generates interference fringes.

From the coupled-mode theory, the amplitudes of the core mode \(a_{\text{co}}\) and the cladding mode \(a_{\text{cl}}\) are expressed in a matrix form [21], [22], after passing through the cascaded LPFGs:

\[
\begin{pmatrix}
  a_{\text{co}}(D) \\
  a_{\text{cl}}(D)
\end{pmatrix} = T_2 \begin{pmatrix}
  \exp(i\beta_{\text{co}}L) & 0 \\
  0 & \exp(i\beta_{\text{cl}}L)
\end{pmatrix} T_1 \begin{pmatrix}
  a_{\text{co}}(0) \\
  a_{\text{cl}}(0)
\end{pmatrix}
\]

(1)

where, \(\beta_{\text{co}}\) and \(\beta_{\text{cl}}\) are the respective propagation constants of the core mode and cladding mode in the grating-free region, with \(D = d_1 + L + d_2\). \(T_i\) (\(i = 1, 2\)) is the transfer matrix of the first or the second LPFG, defined as

\[
T_i = \exp\left(\frac{i\beta_{\text{co,in}} + \beta_{\text{cl,in}}}{2}d_i\right) \times \begin{pmatrix}
  \exp\left(i\frac{\delta_n}{2}s_i\right) & 0 \\
  0 & \exp\left(-i\frac{\delta_n}{2}s_i\right)
\end{pmatrix} \cdot \begin{pmatrix}
  \cos s_i d_i + i\frac{\delta_n}{2s_i}\sin s_i \\
  i\frac{\delta_n}{2s_i}\sin s_i
\end{pmatrix} \begin{pmatrix}
  \cos s_i d_i - i\frac{\delta_n}{2s_i}\sin s_i \\
  i\frac{\delta_n}{2s_i}\sin s_i
\end{pmatrix}
\]

(2)

\[
\beta_{\text{co,in}} = 2\pi(n_{\text{co,eff}} + d\overline{n}_{\text{co,eff}})/\lambda
\]

(3.1)

\[
\beta_{\text{cl,in}} = 2\pi(n_{\text{cl,eff}} + \overline{n}_{\text{cl,eff}})/\lambda
\]

(3.2)

\[
s = \sqrt{k_n^2 + (\delta_n/2)^2}
\]

(4)

where, \(\lambda\) is the wavelength, \(\Lambda\) is the grating period; \(k_n\) is the “ac” cross-coupling coefficient, \(k = \pi(\overline{n}_{\text{co,eff}} - \overline{n}_{\text{cl,eff}})/\lambda; \overline{n}_{\text{co,eff}}\) and \(\overline{n}_{\text{cl,eff}}\) are the average index modulations of the core mode and cladding mode, respectively, but usually \(|\overline{n}_{\text{co,eff}}|\) is far bigger than \(|\overline{n}_{\text{cl,eff}}|\). The propagation constants of the core mode and cladding mode in the grating region are modified as \(\beta_{\text{co,in}}\) and \(\beta_{\text{cl,in}}\), defined in (3.1)–(3.2), because of the RI perturbation. \(n_{\text{co,eff}}\) and \(n_{\text{cl,eff}}\) are the unperturbed effective indexes of the core mode and cladding mode. And \(\delta_n\) is the detuning, given by \(\delta_n = \beta_{\text{co,in}} - \beta_{\text{cl,in}} - 2\pi/\lambda\). Substitute (2)–(4) into (1), the core mode transmission of the cascaded LPFGs can be written in a compact expression in polar form:

\[
T(\lambda) = |a_{\text{co}}(D)|^2 = |\sqrt{t_1(\lambda)t_2(\lambda)}\exp(i\Phi) - \sqrt{1 - t_1(\lambda)}|\cdot\sqrt{1 - t_2(\lambda)}|^2
\]

(5)

\[
\Phi = \tan^{-1}\left[\delta_n/\tan(s_d)/2s\right] + \tan^{-1}\left[k_n/\tan(s_d)/2s\right] + (\beta_{\text{co}} - \beta_{\text{cl}})L
\]

(6)

Here, \(t_1(\lambda) = \cos^2 s_d + (\delta_n/2s)^2\sin^2 s_d \leq 1\)

(7)

The equal sign holds only for \(t_1(\lambda) = t_2(\lambda)\), so the upper envelop curve of the cascaded mismatching LPFGs spectrum is always curved, for \(d_1 \neq d_2\).

Based on the above theoretical model, the transmission spectrum of cascaded mismatching LPFGs can be calculated. Since only the core mode is incident into the first LPFG, \(a_{\text{co}}(0) = 1\) and \(a_{\text{cl}}(0) = 0\). Here, \(L = 28\) cm, other parameters are listed in Table 1. Because the LPFGs were induced by CO_2 laser, \(\overline{n}_{\text{co,eff}}\) is negative and its value is in the order of \(10^{-5}\) [23], [24]. Fig. 3 plots the transmission spectra of the cascaded mismatching LPFGs and the component LPFGs, respectively. From Fig. 3, if short LPFG1 and long LPFG2 are cascaded, all the spectral peaks deviate from unity and the deviations of them are different from each other, as predicted by (8).

PDG effect that a LPFG spectral performance is influenced by incident SOP, originates from its birefringence structure, i.e., the azimuthal asymmetric distribution of the RI perturbation resulted from the side exposure of CO_2 laser during the fabrication [25], [26]. In fact, the average effective index modulations should be modified as \(\overline{n}_{\text{cl,eff}}(x, y)\), not uniform in the fiber cross section, so incident core modes under different SOPs tend

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LPFG1</th>
<th>LPFG2</th>
</tr>
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<tbody>
<tr>
<td>(d (\text{cm}))</td>
<td>3.75</td>
<td>11.25</td>
</tr>
<tr>
<td>(\delta n_{\text{co,eff}})</td>
<td>-5 \times 10^{-5}</td>
<td></td>
</tr>
<tr>
<td>(\Lambda (\mu\text{m}))</td>
<td>625</td>
<td></td>
</tr>
<tr>
<td>(n_{\text{co,eff}})</td>
<td>1.465125</td>
<td></td>
</tr>
<tr>
<td>(n_{\text{cl,eff}})</td>
<td>1.462567</td>
<td></td>
</tr>
</tbody>
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Fig. 3. Simulated transmission spectra of the cascaded mismatching LPFGs and the component LPFGs.
to experience effective index perturbations at varying levels. To lower the difficulty in discussion, we define that one SOP corresponds to one $\Delta n_{\text{eff}}$ value. Then the influence of PDL on cascaded mismatching LPFGs can be simulated by comparing the transmission spectra with different values of $\Delta n_{\text{eff}}$, whereas other parameters remain unchanged. As shown in Fig. 4, the upper envelope of the comb spectrum is always curved at each SOP, but the curvature changes with input SOP. In other words, all transmissivities vary with the incident SOP, but the variations are different. For example, during $\Delta n_{\text{eff}}$ varies from $-5.0 \times 10^{-5}$ to $-6.3 \times 10^{-5}$, the spectral peak at 1552.5 nm falls whereas the peak at 1588.6 nm rises.

In experiment, we fabricated a pair of mismatching LPFGs on a section of SMF with the same grating period and lengths as in the simulation. The exposure direction is strictly consistent to make sure the distributions of the RI perturbation are the same for the two LPFGs. In addition, the whole LPFG pair is coating layer removed, kept straight with no torsion or twisting to minimize the cladding mode loss. Moreover, the grating pair is adhered to a rigid plastic plate and packaged in a foam box to avoid external mechanical or temperature disturbances. Two measured transmission spectra (normalized) of the cascaded mismatching LPFGs with considerable deviation under SOP1 and SOP2 are given in Fig. 5, exhibiting considerable distinctions. The result basically coincides with the calculation in Fig. 4 that the upper envelope of the comb spectrum changes with SOP. e.g., the peak transmissivity at 1563.0 nm at SOP1 is smaller than that at SOP2 by 2.22 dB, whereas is larger by 2.22 dB at 1542.6 nm. The peak spacing is fixed as 2.4 nm, which is determined by the LPFGs’ separation and the effective index difference between the core mode and cladding mode [27]. Moreover, most of the wavelengths of the transmission peaks are almost unchanged, so the potential lasing lines are generated rigidly among these wavelengths.

Note that the $\Delta n_{\text{eff}}$ values used in the calculation do not represent the measured SOP1 and SOP2, since the value of $\Delta n_{\text{eff}}$ is difficult to acquire to date. Nevertheless, it does not affect the experimental verification on the theoretical model.

The comb filter of cascaded mismatching LPFGs possesses the unique advantage that the transmissivities exhibit unequal variations with incident SOPs. There are two essentials for this advantage: one is the LPFGs must be different, or else each peak transmissivity is always unity, according to (8); the other is the birefringence of LPFGs, which is the origin of the PDL.

B. Switching and Tuning Operation Principle

Generally, the homogeneous broadening property of EDF is a disadvantage that should be suppressed. However, it is in favorable of individually switchable MWFL largely, because mode competition means a small change on cavity loss can break the balance between gain and loss to realize wavelength switching, which hardly exists in Raman- or semiconductor optical amplifier (SOA)-based fiber laser. In this EDFL, the comb filter with unequal peak transmissivities brings about unequal cavity losses at the lasing wavelength candidates, so their lasing thresholds are different from each other. Then proper adjustment on input SOP to equally change the peak transmissivities by several dBs, is possible to break the original balances between loss and gain at different channels, and then switching operation is obtained at last.

However, if merely the cascaded mismatching LPFGs are inserted into the laser, lasing would only occur at a few wavelengths within the maximum net gain region. In order to extend the switchable capacity of the MWFL, the simple way we have followed is utilizing a broadband HiBi-SLM filter as the wavelength-dependent mirror. Its principle is well known: the reflective spectrum is a periodic sinusoidal curve, and the reflective bandwidth is given by $\Delta \lambda = \lambda^2 / (\Delta n \cdot l)$ ($\Delta n$ is the modal birefringence, $l$ is the length of the PMF). Different from those with HiBi-SLM as a comb filter, the PMF in our scheme is comparatively short. Therefore, the reflective bandwidth is so large $\sim 30$ nm that one period of the reflective profile covers many channels of the comb spectrum, provided by
the cascaded mismatching LPFGs. But only at the wavelengths near the center of the reflective profile can gain reach cavity loss to generate lasing. Moreover, the effective gain region can be tuned along with the reflective bandwidth, a little smaller. In our experiment, it’s observed the eleven peaks from 1544.6 nm to 1568.6 nm are lasing wavelength candidates, because other peaks are beyond the effective gain range, on account of the EDF length and laser structure. However, the possible lasing band is believed to be modified by changing the EDF and optimizing the PMF length simultaneously.

In this MWFL, the lasing oscillations are tuned or switched in two ways. Now assume SOP2 in Fig. 5 is input into the cascaded mismatching LPFGs; take \(1 - T(\lambda) + \alpha\) as the total cavity loss, and \(\alpha\) is the constant loss item resulted from other wavelength-independent devices; for simplicity, define lasing is created once cavity loss is smaller than the initial gain, the profile of which is shaped and tuned by the HiBi-SLM; then the tuning principle is illustrated in Fig. 6(a). If Gain Profile (0) occurs, lasing at \(\lambda_1, \lambda_2\) are generated; if Gain Profile (1) is tuned out, lasing at \(\lambda_3\) also happens; and if PC2 and PC3 are adjusted in a large scale, Gain Profile (2) is given, so that lasings at \(\lambda_4, \lambda_5, \lambda_6\) occur instead. On the other hand, with a certain proper gain profile, wavelength switching is achieved through adjusting the SOP into the cascaded mismatching LPFGs. As shown in Fig. 6(b), if SOP2 is incident at first, initial gains at \(\lambda_1, \lambda_2, \lambda_3\) are large enough to induce lasings; however, if SOP1 occurs, the losses at \(\lambda_2, \lambda_3\) become larger than gain, and only lasing at \(\lambda_1\) still remains.

In general, coarsely tune the HiBi-SLP to require lasing band at first; then adjust PC1 to switch the lasing wavelengths, and sometimes returning to finely tune PC2 or PC3 is necessary. Thanks to the polarization-independent property of the HiBi-SLM, the two filters won’t conflict with each other.

### III. EXPERIMENTAL RESULTS AND DISCUSSION

With the close cooperation between the HiBi-SLP and cascaded mismatching LPFGs, versatile lasing states are observed. The individually switchable operations are divided into two types, the fully switchable and the partially switchable. Fully switchable operation is quite feasible for adjacent three wavelengths, meaning that any combination of the three wavelengths \((C_3, C_2, C_1)\) can be obtained. More than that, the three fully switchable wavelengths are not fix, but can be widely selected among eleven channels from 1540s nm to 1560s nm. It generates some novel switchable effects that adjacent single-, dual- and triple-wavelength outputs are successively tuned out in the spectrum with high uniform quality, as shown in Figs. 7(a), (b), and (c). The wavelength interval is 2.4 nm, in agreement with the peak spacing of the cascaded mismatching LPFGs. So, from another perspective, this switchable MWFL is also a widely tunable laser.

A series of other output spectra, representing the partially switchable operations, are shown in Fig. 8. Tunable dual-wavelength outputs with double intervals (4.8 nm), also as complements of the triple-wavelength fully switchable lasings are observed, two of which are presented in Figs. 8(a) and (b); and Figs. 8(c) and (d) give examples of dual-wavelength outputs with triple- even quadruple-intervals. Two typical results of nonadjacent triple-wavelength lasing schemes, that one is unequally spaced and the other is equally spaced, are shown in Figs. 8(e) and (f). In addition, partially switchable quadruple- and quintuple-wavelength outputs are also obtained, as shown in Figs. 8(g) and (h). Such flexibly switchable operations are difficult to achieve in other methods so far.

In our experiment, the 980 nm pump power varies with the lasing channel amount, so that the power of each lasing wavelength can be uniformly maintained as about 0 dBm, but the maximum power does not exceed 260 mW. The signal-to-noise ratio (SNR) of each channel does not degrade, kept as 40 dB, which is mainly attributed to the high contrast of the comb spectrum of the cascaded mismatching LPFGs (See Fig. 5). Moreover, the measured 3 dB linewidth of each channel reads 0.077 nm, limited by the precision of the OSA (0.065 nm). This linewidth is much narrower than that in Raman- or SOA-based tunable or switchable MWFL, in which the wavelength spacing increases with linewidth deteriorated (see [1, Fig. 3(d)] and [3, Fig. 3]). If our proposed laser works in the state of single-wavelength lasing, it won’t be difficult to realize single-longitudinal-
mode oscillation by virtue of a saturable absorber [28] or the multi-ring cavity structure [29].

The stability of our MWFL is investigated in two ways. At first, the output spectrum of an adjacent triple-wavelength operation is repeatedly scanned every minute. Fig. 9 is a screenshot from the OSA, showing the lasing is highly stable in ten minutes. Considering that more lasing channels exhibit severer mode competition, a more challenging stability test on the quintuple-wavelength output is carried out, by recording its spectrum every five minutes. As the statistical results shown in Fig. 10, even in the state of quintuple-wavelength operation, the respective power fluctuations and wavelength drifts do not exceed 2.1 dB and 0.19 nm in an hour. The channel uniformity and stability of this MWFL both present better performance than when only one single comb filter is used [16], because the
balance in multiwavelength lasing can be more easily controlled with two independent tunable filters, the cascaded LPFGs and the HiBi-SLP. Here, the used PCs are mechanical devices. If they are replaced by programmable PCs with monitoring mechanism, we believe not only the stability but the rapid switchability will be further improved.

Compared with the first type of switchable MWFL, as mentioned in the “INTRODUCTION”, the simultaneous lasing wavelengths of this MWFL are comparatively less, but are individually switchable, which is hardly accomplished by the first type. It’s known that in some applications, such as optical sensing or optical instrument testing system, switchable dual- or triple-wavelength output is enough and light source with too many channels turns to be a disadvantage instead, because extra-cavity wavelength selection and amplification technologies will increase the cost and complexity. Our laser also exhibits evident advantages over other individually switchable MWFLs. Firstly, there are tens of flexible outputs among eleven channels in a laser, covering versatile single-, dual-, triple-, quadruple- and quintuple-wavelength lasings; secondly, the achievements are realized in a compact and simple configuration, composed of two LPFGs and a HiBi-SLP, not eleven FBGs along with complex switching mechanisms. In fact, the output property, e.g., the possible lasing band and wavelength spacing is not difficult to be modified through optimizing the parameters of the cascaded mismatching LPFGs, HiBi-SLP and the gain medium.

IV. CONCLUSION

We have proposed and experimentally demonstrated a new concept of individually switchable and widely tunable erbium-doped MWFL based on cascaded mismatching LPFGs. Theory and experiment have proved that, the birefringence and different lengths of the two LPFGs endow this special comb filter with a unique advantage: the channel transmissivities can unequally vary with input SOP. This comb filter serves as the wavelength selector and switching filter in the cavity. With the fine cooperation of the cascaded mismatching LPFGs and a broadband HiBi-SLM, lasing wavelengths can be individually switched and widely tuned among the channels from 1544.6 nm to 1568.6 nm, including successively tunable adjacent single-, dual- and triple-wavelength outputs, nonadjacent dual- and triple-wavelength outputs, and some quadruple- and quintuple-wavelength outputs. Compared with individually switchable MWFL based on FBGs, our laser is compact, simple and needs no extra stabilizing techniques. This individually switchable and widely tunable MWFL may be useful in various fields, such as optical sensing, wavelength routers of WDM network, which desire not a large amount of lasing channels but very flexible output schemes.

REFERENCES


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