Multi-wavelength fiber source based on double-pass superfluorescent fiber source and a reflection Mach-Zehnder filter

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A spectrum-sliced multi-wavelength fiber source (SS-MWFS) based on double-pass superfluorescent fiber source (SFS) with a reflection Mach-Zehnder filter (RMZF) as the reflected comb filter is demonstrated. With backward pumped configuration, MWFS with 50 wavelength channels of extinction ratio (ER) of 16.7 dB is obtained over the almost total C-band gain region. Total output power of the MWFS is 16.2 mW which shows that a power of about 0.3 mW of per channel is achieved. The SS-MWFS with forward pumped configuration is also discussed for comparing. The backward pumped configuration can provide a larger output power while only a little smaller ER than that of the forward pumped configuration.

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Wavelength division multiplexing (WDM) is an important technique for fiber optical communication since it can increase transmission capability by orders of magnitude. Among the multi-wavelength sources required for a WDM system, the spectrum-sliced multi-wavelength fiber sources (SS-MWFSs) have attracted much attention because only one broadband light source and a comb filter are needed, thus the cost and complexity may be relieved as compared with currently distributed feedback (DFB) lasers array and multi-wavelength fiber lasers that are still under research stage[1−3]. Erbium-doped superfluorescent fiber source (SFS) has been widely used as the broadband light source for spectrum-sliced source in the past years for its potential low spectral ripples and high spectral intensity. Fabry-Perot filters, arrayed-waveguide gratings and cascaded long period fiber gratings (LPFGs) have been used as the filter in the SS-MWFS[4−6]. However, since the filter is placed at the output end of a broadband light source for SS-MWFS, it inevitably incurs a considerable power loss. Recently, Su *et al.*[7] introduced a new technique to cause power redistribution from the unwanted wavelength range to the wanted wavelength range. Therefore, the output power of the SS-MWFS is greatly enhanced. We can call it active spectrum-sliced technique. Namely, the comb like filter is arranged just before the reflective mirror, the sliced spectrum is reflected back to the gain medium and causes power redistribution of the amplified spontaneous emission (ASE). However, the long period gratings (LPGs) have many disadvantages, such as complicated fabrication process of two LPGs with same transmittance spectra, the LPGs and the fiber between them cannot be coiled to avoid large loss of the cladding modes mentioned in Ref. [7]. Moreover, the peak transmittance of the cascaded LPFGs is unequal and its extinction ratio (ER) is low. The fiber between the LPFGs and the fiber mirror must be coiled to avoid other interference, which is believed to be the reason for the total power small reduced.

In this letter, a reflection Mach-Zehnder filter (RMZF) simply composed by two 3-dB fiber couplers is used as the reflected comb filter to build the SS-MWFS. The RMZF has many advantages such as easy fabrication process, equal peak transmittance, and no cladding mode influencing etc.. Thus the RMZF is better than the LPGs as a filter to build a SS-MWFS. The SS-MWFS based on RMZF and double-pass SFS of backward and forward pumped configurations are investigated and their characteristics of ER and output power are compared.

Figures 1(a) and (b) show the schematic diagram of the designed SS-MWFS of double-pass backward (DPB) and double-pass forward (DPF) pumped configurations with active spectrum slicing technique, respectively. The pump power is launched through a WDM into a section of erbium-doped fiber (EDF) from a diode laser operating at 977 nm. Another WDM is used to separate the residual pump signal and the forward signal and avoid the feedback of pump power to the pump laser. The RMZF provide the filtering effect and the double-pass function simultaneously. Thus, the filtered ASE is reflected back into the EDF, which causes power redistribution of the ASE from the undesired wavelength range to the desired wavelength. As a result, output power of the MWFS is greatly enhanced. An isolator with ∼ 60-dB isolation is used to prevent the formation

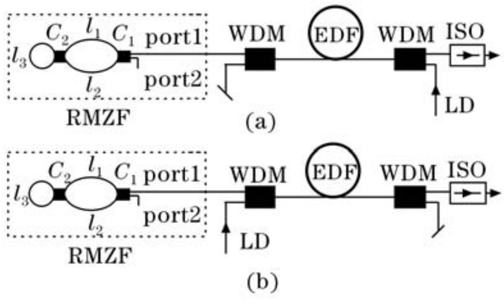

Fig. 1. Schematic diagram of backward and forward pumped SS-MWFS with a RMZF.

of oscillation due to the optical feedback from the output end face. An ANDO6317B optical spectrum analyzer is used for spectra measurement.

The RMZF is formed by concatenating together the two output ports of a conventional single-pass Mach-Zehnder filter composed by two 3-dB fiber couplers, as shown in Fig. 1. For power launch into port1, assume the electric field intensity of port1 is E_1, then the reflected back electric field intensity from port1 and port2 (E_1', E_2') can be calculated by

$$\begin{bmatrix} E_1' \\ E_2' \end{bmatrix} = \begin{bmatrix} \sqrt{1-C_1} & -j\sqrt{C_1} \\ -j\sqrt{C_1} & \sqrt{1-C_1} \end{bmatrix} \begin{bmatrix} \exp(-jk_0nl_1) & 0 \\ 0 & \exp(-jk_0nl_2) \end{bmatrix} \begin{bmatrix} \sqrt{1-C_2} & -j\sqrt{C_2} \\ -j\sqrt{C_2} & \sqrt{1-C_2} \end{bmatrix} \begin{bmatrix} 0 & \exp(-jk_0nl_3) \\ \exp(-jk_0nl_3) & 0 \end{bmatrix} \begin{bmatrix} \sqrt{1-C_2} & -j\sqrt{C_2} \\ -j\sqrt{C_2} & \sqrt{1-C_2} \end{bmatrix} \begin{bmatrix} \exp(-jk_0nl_1) & 0 \\ 0 & \exp(-jk_0nl_2) \end{bmatrix} \begin{bmatrix} \sqrt{1-C_1} & -j\sqrt{C_1} \\ -j\sqrt{C_1} & \sqrt{1-C_1} \end{bmatrix} \begin{bmatrix} E_1 \\ 0 \end{bmatrix}, \quad (1)$$

where C_1 and C_2 are the couple coefficients of the two couples, n is the core refractive index of the fiber, l_1, l_2, l_3 are the lengths of the three fiber sections, as shown in Fig. 1. We assume that $C_1 = C_2 = 0.5$, then Eq. (1) is simplified as

$$E_1' = 0.5j\exp(-jk_0nl_3)\,[\exp(-jk_0n2l_2) - \exp(-jk_0n2l_1)]\,E_1, \quad (2a)$$

$$E_2' = -0.5\exp(-jk_0nl_3)\,[\exp(-jk_0n2l_2) + \exp(-jk_0n2l_1)]\,E_1. \quad (2b)$$

According to the relations of $P_1 = E_1E_1^*$, $P_1' = E_1'E_1'^*$, and $P_2' = E_2'E_2'^*$, the intensity reflectivity is

$$R_{11} = \sin^2\frac{2\pi n\Delta l}{\lambda}, \quad (3)$$

where we define $R_{11} = P_1'/P_1$, Δl ($\Delta l = |l_1 - l_2|$) is the length difference between the two arms. It can be seen from Eq. (3) that the reflection spectrum of a RMZF is characterized by a series of equally spaced reflection peaks. The wavelength spacing between the reflection peaks is given by

$$\Delta\lambda = \frac{\lambda^2}{2n\Delta l}. \quad (4)$$

Therefore, using a RMZF as the reflector of a double-pass SFS, it can not only provide spectrum filtering but also feedback the filtering signal to the EDF again to cause ASE power redistribution. Equation (4) also indicates that a MWFS with various wavelength spacing can be obtained through control arm length difference of the RMZF.

Figure 2 records the MWFS obtained by backward pumped configuration with different pump powers of 27, 40, and 71 mW. Changes of the MWFS with pump power are clearly revealed. It notes that MWFS of the longer wavelength channels generates first and reaches a large ER quickly with increasing the pump power. The reason is that the absorption coefficient of the EDF is larger at shorter wavelength. In fact, in the small pump power case, the forward ASE signal is small and its mean wavelength is longer, therefore, the feeding back filtering signal causes the power redistribution at the longer wavelength range earlier. With the increase of the pump power, the MWFS will cover the total C-band and reach an almost same ER of the shorter and longer wavelengths gradually. As the pump power increasing further, the main changes of the MWFS is output power increasing, and the ER will saturate and keep constant, as shown in Fig. 2(c). Figure 3 depicts the ER and output power of the MWFS against pump power. Two channels centered at 1530 and 1561 nm are selected for representing the shorter and longer wavelength channels. It notes that the ERs of these two channels both increase with pump power. The ER of the longer wavelength channels increase and saturate earlier with increasing the pump power than that of the shorter wavelength channels. The required pump power to obtain saturated ER for 1530 and 1561 nm wavelength channels is round 70 and 50 mW, respectively. However, saturated ERs of the two channels are almost equal. In our experiment, the saturated ERs of the two channels are both 16.7 dB.

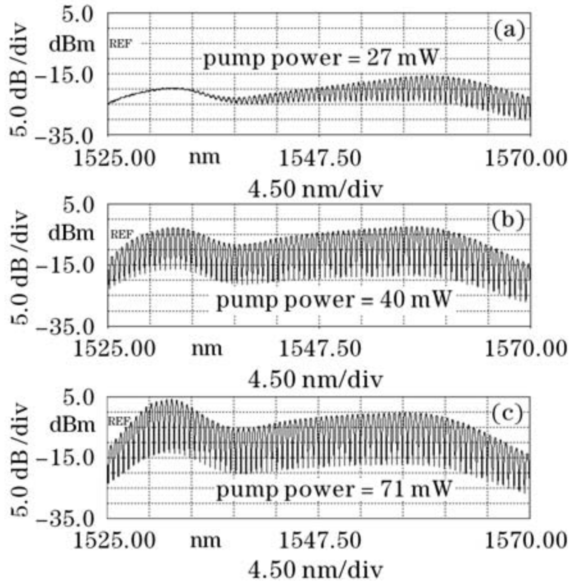

Fig. 2. Output spectra of the backward pumped MWFS under different pump power levels.

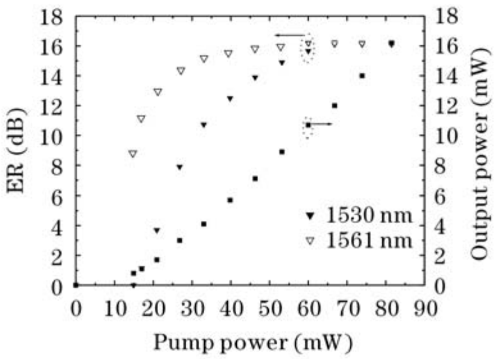

Fig. 3. Extinction ratio and output power versus pump power for backward pumped MWFS.

Figure 4 show the output spectra of the MWFS and the DPB SFS (replaced the RMZF by a fiber loop mirror) with 71-mW pump power. The inserted figure is the forward ASE signal measured before the RMZF in this pump power case. The output power of the forward ASE is 1.4 mW and its spectrum covers the total C-band which ensures the RMZF feeding back a total C-band filtering signal into the EDF again, and with the equal peak reflection of the RMZF, therefore, MWFS with almost the same ER is obtained over the total C-band gain region. The output powers of the MWFS and the DPB SFS are 16.2 and 15.9 mW, respectively, which shows that a power of about 0.3 mW of per channel is achieved by simply estimating. The experiment shows that using actively spectrum slicing technique, the MWFS with no power loss compared with the EDF SFS is obtained. The power with the DPB SFS is slightly smaller than that of the MWFS because the reflectivity of fiber mirror may be slightly less than the RMZF possibly. While in Ref. [7], the MWFS using cascaded LPFGs has a power loss ~ 0.55 dB. They consider it is due to the weak forward ASE signal. However, the true reason is that the fiber between the LPFGs and the fiber mirror is coiled, therefore, the reflected signal is reduced. So the power loss is inevitable because the fiber must be coiled to avoid other interference. The channel wavelength spacing of Fig. 4 is measured to be 0.57 nm, which notes that the arm difference of the RMZF is about 1.44 mm. Therefore, between the 1530 and 1561 nm, there are more than 50 wavelength channels with ER of 16.7 dB. As the peak position of MWFS corresponds to the peak wavelength of the RMZF reflection spectrum, and its channel spacing is the same as the wavelength spacing of the RMZF, the channel spacing of the SS-MWFS could be adjusted to be exactly at 0.8 nm, if needed, by fine adjustment of the arm length difference of the RMZF using a PZT.

In order to discern the characteristics of SS-MWFS on the SFS configuration, the SS-MWFS using forward pumped configuration is also investigated. As well known, the forward pumped configuration will provide a smaller output power than that of the backward pumped configuration[8]. Figure 5 shows ER and output power against pump power with forward pumped configuration. With forward pumped configuration, the ERs of the longer and shorter wavelength channels increase and saturate with pump power almost at the same

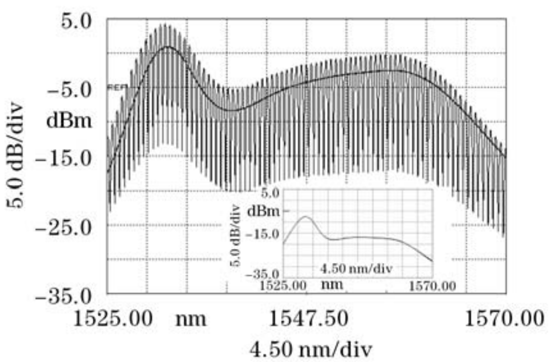

Fig. 4. Output spectra of the backward pumped MWFS and DPB SFS (the inset shows the forward ASE spectrum before the RMZF).

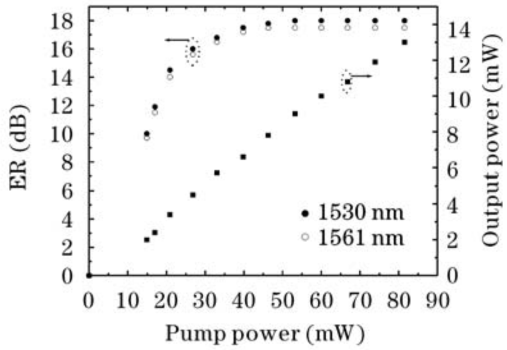

Fig. 5. Extinction ratio and output power versus pump power for forward pumped MWFS.

time. In our experiment, the required pump powers to obtain saturated ERs of the two channels are both about 45 mW. The saturated ER of 1561-nm wavelength channel is 17.5 dB that has 0.5 dB smaller than the 18 dB of 1530-nm wavelength channel. Compared with the backward pumped configuration, the saturated ER of the forward pumped configuration is a little larger than that of backward pumped configuration. Their different characteristics of the ER because of the filtering signal are provided by the backward ASE for the forward pumped SS-MWFS configuration, while for the backward pumped SS-MWFS, the filtering signal is provided by the forward ASE. In the output power aspect, the backward pumped configuration is superior to the forward pumped configuration. Output power of the MWFS by the forward pumped configuration is only 13 mW that has 3.2 mW less than 16.2 mW of the backward pumped case with the same pump power. Namely, the SS-MWFS generated by the backward pumped configuration has higher output power while the ER is a little smaller than that by forward pumped configuration. Therefore, backward pumped configuration is more suitable to build a SS-MWFS.

It should be noted that this SS-MWFS is temperature sensitive since the RMZF is made by fiber couplers. A waveguide RMZF is perfect for high stability MWFS. On the other hand, the contour line of the SS-MWFS channel power level follows the original SFS spectrum. Therefore, a more flat MWFS with small channel's power variation could be obtained by inserting a proper wavelength-dependent loss filter in the device.

In conclusion, we have experimentally presented a SS-MWFS that has high output power and large ER using double-pass SFS configuration with a RMZF as the reflected comb filter. The RMZF provides not only spectrum filtering but also the double-pass function. A MWFS with 50 wavelength channels of ER of 16.7 dB is obtained over the almost total C-band gain region by backward pumped configuration. Though the characteristics of SS-MWFS depend on the SFS configuration, the backward pumped configuration can provide a larger output power while only a little smaller ER than that by forward pumped configuration. Such a SS-MWFS is superiors to the forepassed ones for its more simple fabrication process, higher output power, broader wavelength channels range with almost the same ER.

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