L-band Erbium-doped Optimization of double-pass two-directional broadband superfluorescent fiber source

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A simple method for characteristics improvement of double-pass bidirectional L-band erbium-doped superfluorescent fiber source (SFS) is demonstrated. The output spectral characteristic of this SFS is greatly improved by inserting a segment of unpumped fiber between the reflector and the wavelength division multiplexing (WDM) coupler. The effects of the fiber length and pump power arrangement on the output characteristics of the L-band fiber source are simulated and analyzed in detail. For a given pump power arrangement, there is an optimal fiber length ratio of the unpumped fiber section to the total fiber for obtaining widest L-band spectrum. Notably, the optimal fiber length ratio is drastically depended on the pump power arrangement. Wide flat spectrum with a 3-dB bandwidth of 63 nm (1540 nm-1603 nm) is achieved.

Keywords: Erbium-doped fiber (EDF), Superfluorescent fiber source (SFS), L-band.

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1. Introduction

Incoherent broadband superfluorescent fiber sources (SFS) at 1550 nm have been applied in various areas such as optical sensor systems, fiber optic gyroscopes, spectrum-sliced sources in wavelength division multiplexing (WDM) systems and optical devices characterizations [1-4]. The sources based on the amplified spontaneous emission (ASE) from an erbium-doped fiber (EDF) are considered to be good candidates for the intrinsic broad emission spectrum and the ease with which high output power can be generated using semiconductor pumps. The conventional wavelength band (C-band) EDF SFSs have been researched with extreme details in the first few years [2,3,5-7]. Recent demand for immediate expansion of the fiber-optic communication window has led to the development of long-wavelength-band (L-band, 1565 nm – 1625 nm) sources. Various experimental configurations have been presented that increase the output power, spectral bandwidth and wavelength stability of the L-band source, such as dual forward-pumping scheme [8], double-pass bi-directional pumping configuration [9], long-period fiber grating-based scheme [10], two stages configuration with a low power seed and a power amplifier [11] and so on. However, these L-band SFS configurations are all based on complicated pumping schemes, which increase the fabrication difficulty and economy cost. It has been reported that for a single-laser pumped L-band erbium-doped fiber source, the double-pass forward (DPF) configuration is the best [12]. Bandwidth broadening and efficiency enhancement of a DPF L-band source has been obtained by using a section of unpumped fiber between the reflector and the wavelength division multiplexing (WDM) coupler [13]. It is also found that the double-pass bi-directional (DP-BD) L-band source can achieve higher conversion efficiency than that of the DPF configuration [14]. Therefore, further studies are necessary on characteristics improvement of DP-BD L-band fiber sources.

In this paper, an improved DP-BD broadband L-band erbium-doped SFS with a section of unpumped EDF between the reflector and the first wavelength division multiplexing (WDM) coupler is proposed. The effects of the fiber length arrangement and the pump power arrangement on the output characteristics of the L-band SFS are simulated and analyzed in detail. Compared with the conventional DP-BD L-band SFS, the novel DP-BD SFS has wider spectral bandwidth. For a given pump power arrangement, there is an optimal fiber length arrangement to achieve broadband L-band erbium-doped SFS with widest flat output spectrum. The variation of the optimal fiber length arrangement with the pump power ratio of forward to total pump power is also studied. The proposed method to obtain broadband erbium-doped fiber source is much simpler than those reported before [8-10].

2. Configuration of L-band SFS

Figure 1 illustrates the configuration of the novel DP-BD L-band erbium-doped SFS. The L-band SFS consists of erbium-doped fiber (EDF), a 980 nm laser diode (LD), two 980/1550 nm WDM couplers, a power splitter used to divide the pump power into two portions, a high reflectivity fiber loop mirror (FLM) constructed by a 3-dB coupler, and an optical isolator (ISO) at the output port. The EDF is divided into two segments, one of which (EDF2) is bidirectional pumped by a 980nm laser diode through the two WDM couplers, and the other one (EDF1) is arranged between the FLM and the first WDM coupler. EDF1 is unpumped. The total length of the EDF is defined as $L=L_1+L_2$, where L_1 and L_2 refer to EDF1 and EDF2 lengths, respectively. The fiber length ratio of the EDF1 length to the total length is defined as $R_L=L_1/(L_1+L_2)$. The pump power ratio of forward to total pump power of EDF2 is defined as $K=P_{forward}/P_{total}$, which is the splitting ratio of the power splitter. When the effects of R_L and K on the output characteristics of the L-band SFS are analyzed, the total length of the EDF is fixed, which is optimized to obtain widest flat L-band spectrum when R_L=0. The EDF used in our search is Lucent Technologies Erbium-doped fiber with type number of EDF-MP980/MOB1201. All connections are fusion spliced and the total loss of the fiber source is assumed as 0.5 dB.

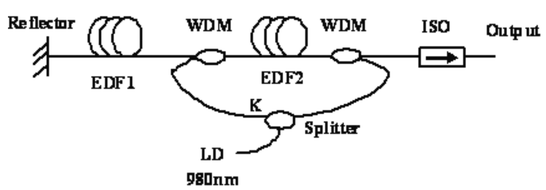

Figure 1 Configuration of the DP-BD Erbium-doped SFS.

3. Simulation results and discussion

The following simulation results are based on the amplifier simulation package OASIX [15]. The simulation software is accurate for presenting the same results as those obtained by experiments [6,13-14]. The mean wavelength of the amplified spontaneous emissions (ASE) is computed by:

$$\bar{\lambda}_{ASE} = \frac{\sum_{i=1}^{n} \lambda_i P_{ASE,i}}{P_{ASE,tot}} \tag{1}$$

and the spectral bandwidth is defined as:

$$\Delta\lambda_{ASE,tot} = \frac{\left[\sum_{i=1}^{n} P_{ASE,i} \times \Delta\lambda_i\right]^2}{\sum_{i=1}^{n} P_{ASE,i}^2 \times \Delta\lambda_i} \tag{2}$$

Where, λ_i: wavelength of the *i*th ASE wave; $P_{ASE,i}$: power in the *i*th ASE wave; $P_{ASE,tot} = \sum_{i=1}^{n} P_{ASE,i}$; *n*: number of discrete ASE wavelengths; $\Delta\lambda_i$: spectral width represented by the *i*th ASE wave. The width represented by the *i*th wave encompasses half the wavelength range from the *(i-1)*th wave to the *(i+1)*th wave.

For the conventional DP-BD L-band erbium-doped SFS, an optimal fiber length exists to obtain widest flat L-band spectrum output [12]. So, the total EDF length is firstly optimized when R_L=0, for different given *K*'s. From figure 1 we can see that when R_L=0, the L-band SFS becomes a conventional DP-BD configuration. The effective FLM reflectivity is selected to be 100% and the total pump power is set to 150 mW. For different given *K*'s, the output spectra of the L-band SFS with R_L=0 at various EDF lengths are simulated by the simulation software, and the result indicates that when the total pump power is 150 mW, for different *K*'s, the optimal EDF length to obtain widest L-band spectrum is different, such as, the optimal EDF length is 118 m for *K*=0.8, 116 m for *K*=0.3, and 106 m for *K*=0.1. Hence, the total EDF length is fixed at the corresponding optimal length values for different *K*'s in the following simulations.

Then, for different given *K*'s, the effects of the fiber length ratio R_L on the output characteristics of the L-band SFS are simulated. The pump power is set to 150 mW. The spectra of the L-band SFS with different R_L are given in figure 2. Figure 2 (a) to (c) correspond to *K*=0.8, 0.3 and 0.1, respectively. The variations of the mean wavelength and bandwidth versus R_L are illustrated in figure 3, with figure 3 (a) to (c) corresponding to *K*=0.8, 0.3 and 0.1, respectively. As is apparent from figure 2 and figure 3, the fiber length ratio R_L has great effects on the spectral characteristics of the L-band SFS and the effects of R_L on the spectral characteristics are different for different given *K*'s. When *K*=0.8, the lower R_L has almost no influence on the spectral shape, when R_L increases to be larger than 0.7, the spectral intensity increases in the short wavelength range and decreases in the long wavelength range gradually, which results in the mean wavelength shifting toward shorter wavelengths and the bandwidth increasing to a maximum value followed by decreasing with the increment of R_L. When R_L is adjusted to around 0.80, flat spectrum with maximal bandwidth is obtained and the bandwidth is 14 nm broader than that with R_L=0 (the conventional DP-BD configuration). R_L=0.80 is the optimal fiber length ratio to achieve flat L-band spectrum with maximal bandwidth for K=0.8, under the pump power of 150 mW. Simulation results also indicate that the evolution of the spectral characteristics with R_L of the L-band SFS remain almost similar for different K's from 0.4 to 1.0. When K=0.3, there is also an optimal fiber length ratio R_L to obtain flat L-band spectrum with maximal bandwidth. The optimal R_L is 0.54. As can be seen from figure 3(b), the maximal spectral bandwidth remains almost unchanged with R_L for R_L from 0.54 to 0.80, which means that to obtain widest flat spectrum, the tolerance of R_L variations is larger for K=0.3. This virtue is significant because the fiber length ratio may not be set exactly in experiments. When K=0.1, the spectral evolution with the fiber length ratio R_L is different from those for K=0.3 and 0.8. The optimal R_L is 0 and flat spectrum with 3-dB bandwidth of 63 nm (1540nm-1603 nm) is obtained. When R_L is larger than 0.3, the bandwidth decreases rapidly with the increment of R_L. This is mainly due to the rapid shift to the C-band of the spectrum with R_L increasing larger than 0.3, as shown in figure 2(c).

The spectral evolution phenomena with R_L shown in figure 2 and figure 3 can be explained as follows. The proposed DP-BD SFS with EDF1 between the reflector and the first WDM coupler can be considered as an L-band ASE seed source with a bidirectional pumped erbium-doped fiber amplifier. Thus, the total output of the SFS includes two components: the amplified L-band seed light and the residual ASE of EDF2. The wavelength ranges and the proportion of the two components decide the spectral shape and wavelength range of the SFS.

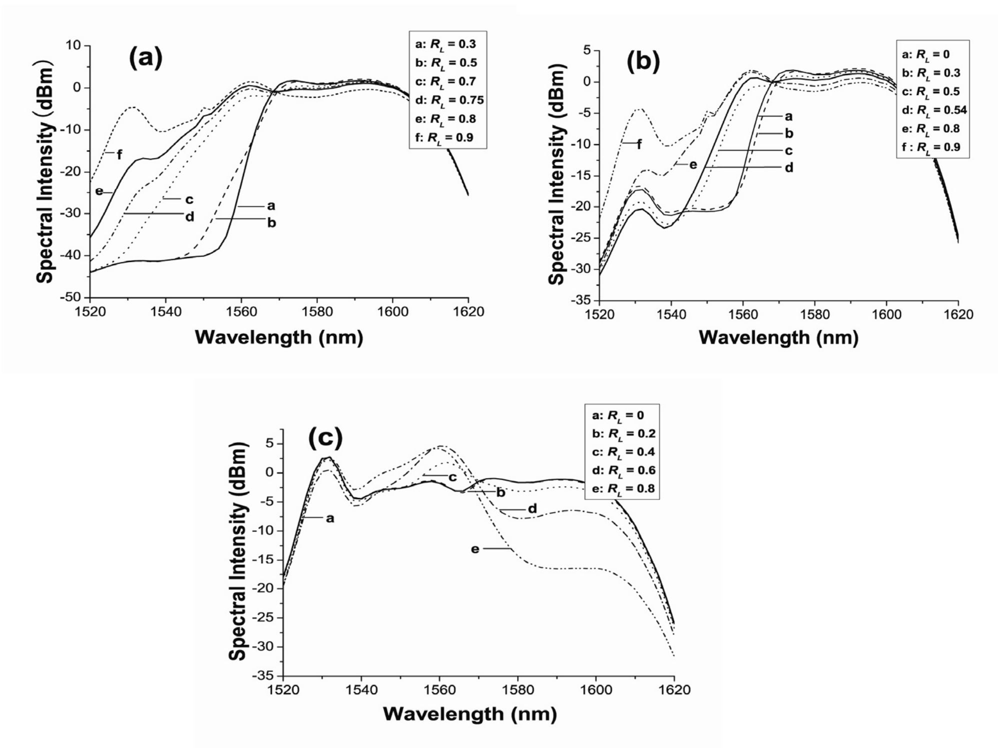

Figure 2 Output spectra of the SFS with R_L under 150 mW total pump power for different K's.

(a): K=0.8, (b): K=0.3, (c): K=0.1.

When R_L is very low, the effect of the unpumped fiber is weak. The spectral characteristics of the proposed SFS have little changes as compared to the conventional DP-BD SFS. With the increment of R_L, the amplified L-band seed light has gradually considerable power to compete with the ASE of EDF2. At the same time, the wavelength range of the ASE of EDF2 shifts to the long-wavelength edge of C-band due to the shorter EDF2.

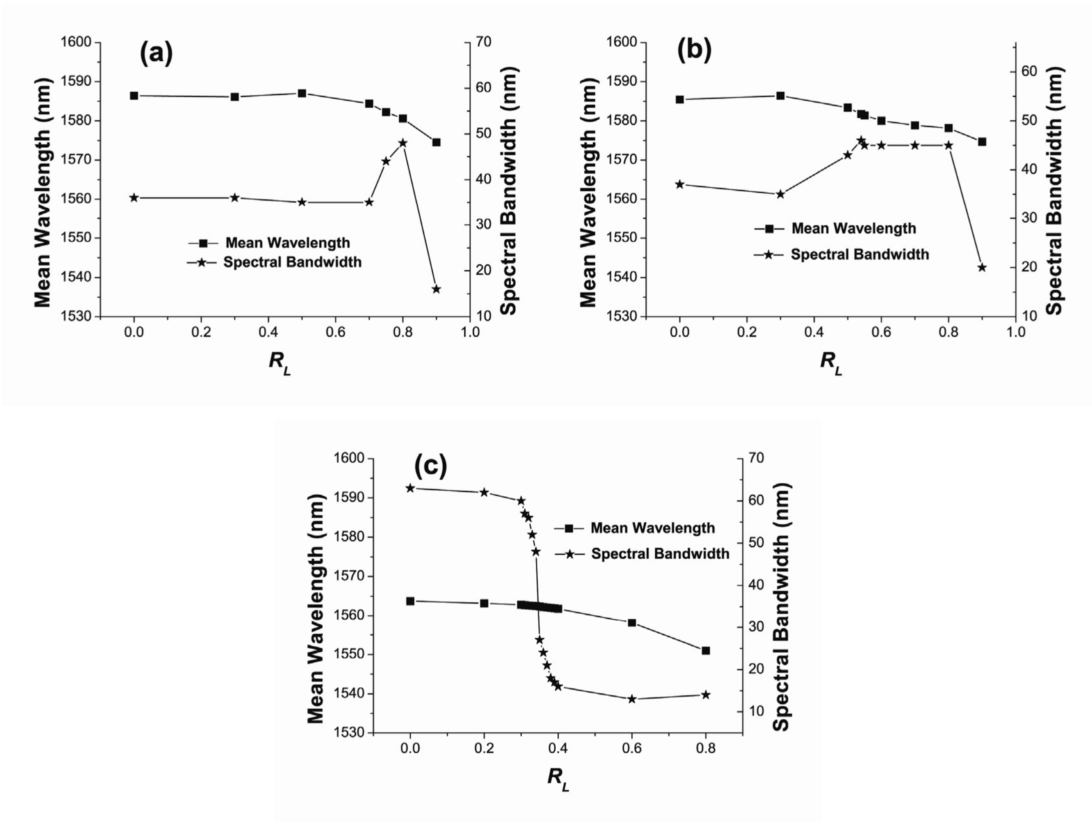

Figure 3 Mean wavelength and spectral bandwidth versus R_L for different *K*'s.

(a): *K*=0.8 (b): *K*=0.3, (c): *K*=0.1.

When R_L is at its optimal value, the power density at the L-band is nearly equal to that at the long-wavelength edge of the C-band, as indicated by curve *e* in figure 2(a) and by curve *d* in figure 2(b), so a flattened spectrum with a broadest bandwidth can be obtained. For the case of K=0.1, the spectral evolution with R_L has some differences. The optimal R_L is 0 to obtain the widest flat spectrum and the spectrum covers C-band and L-band, as shown by curve *a* in figure 2(c). This is mainly because that when *K*=0.1, the L-band ASE light produced by the forward pump power has enough power to be amplified and at the same time the backward pump power can produce C-band ASE with considerable power. Thus, there is no need to move a segment of EDF before the first WDM coupler to produce additional L-band seed light to broaden the spectrum. The widest spectrum can be achieved from the conventional DP-BD configuration when *K*=0.1, under the total pump power of 150 mW.

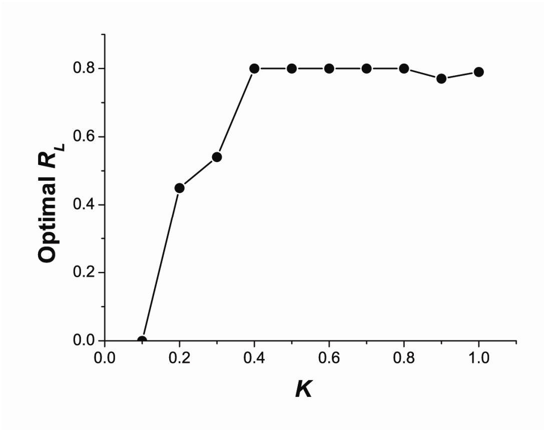

Figure 4 Variation of the optimal fiber length ratio R_L versus K.

As can be seen from the above simulation results, the optimal fiber length ratio R_L is different for different pump power ratio K's. Figure 4 depicts the variation of the optimal fiber length ratio R_L versus the pump power ratio K with the total pump power fixed at 150 mW. The optimal fiber length ratio R_L initially increases rapidly with the increment of K and becomes saturated soon. This is mainly because of the operation principle of the improved DP-BD SFS as described above. Based on this result, in order to obtain widest flat spectrum from the novel DP-BD SFS, the fiber length ratio R_L should be optimized for corresponding pump power arrangements. This is quite useful for constructing broadband SFS in simple configurations in experiments.

4. Conclusions

In conclusion, we have presented an improved DP-BD L-band erbium-doped SFS. With an unpumped segment of fiber in front of the first WDM to take full use of the backward ASE, obvious enhancement in spectral bandwidth is obtained. Simulation results show that flat L-band spectrum with maximal bandwidth can be obtained by means of optimizing the fiber length ratio of the unpumped fiber to the total fiber and the pump power ratio of forward to total pump power. Additionally, the optimal fiber length ratio R_L is depended on the pump power ratio K. When K>0.4, the optimal R_L tends to be changeless with the increment of K. When K=0.1, the optimal R_L is 0 and widest flat spectrum is achieved with a 3-dB bandwidth of 63 nm (1540 nm-1603 nm). This result is important for constructing broadband SFS in simple configurations. It is believable that broader and flatter spectrum may be obtained by further optimizing the lengths of EDF1 and EDF2 and adding flattening spectrum instruments.

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