CHIN. PHYS. LETT. Vol. 29, No. 8 (2012) 084213

Characteristics Improvement of L-Band Superfluorescent Fiber Source Using Unpumped Erbium-Doped Fiber *

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(Received 9 March 2012)

An effective method for the improvement of the characteristics of an erbium-doped L-band superfluorescent fiber source (SFS) is demonstrated using an unpumped erbium-doped fiber (EDF). With a suitable length of unpumped EDF section in the single-forward pumped configuration, broadening of the L-band spectral linewidth is achieved and the variation of mean wavelength versus pump power is eliminated. A mean wavelength stable L-band SFS with a spectral linewidth of 50.2 nm and an output power of 60.2 mW is obtained experimentally. The method of using unpumped EDF enables one to offer a stable and wideband L-band SFS with high flexibility and to overcome the shortcomings of the synchronous pumping technique.

PACS: 42.72.Ai, 42.81.−i, 42.81.Wg, 42.72.−g DOI: 10.1088/0256-307X/29/8/084213

Superfluorescent fiber source (SFS) based on erbium-doped fiber (EDF) amplified spontaneous emission (ASE) has wide applications in optical device characterization, spectrum-sliced sources in dense wavelength division multiplexing (WDM) systems, optical sensor systems, fiber optic gyroscopes (FOG), and optical coherence tomography[1−3] due to its intrinsic broad and stable emission spectrum and high output power. Especially, the SFS source with a stable mean wavelength and broad linewidth is important for FOG application because the high accuracy of rotation detection and improvement of the signal-to-noise ratio directly result from the mean wavelength stability and linewidth of the light source used. The conventional wavelength band (C-band, 1525–1565 nm) EDF SFSs have been researched in extreme detail in the first few years.[4−6] Recently, researchers have been focusing on the long wavelength band (L-band, 1565–1605 nm) SFS to increase its output power, spectral linewidth, and wavelength stability to cater to the demand of band expansion of the fiber-optic communication window.[7−9] The ultra-broad ASE spectrum covering C-band to L-band was also reported.[10,11] Up to now, the Wall-level L-band SFS can be successfully obtained using two stages configuration with a low power seed and a power amplifier[12] and the mean wavelength stable L-band SFS can be obtained using the synchronous pumping technique.[13] The L-band SFS may be better than the C-band SFS for FOG applications because it can provide a larger linewidth. Therefore, studies are necessary on the wavelength stable and broader linewidth L-band SFS with a new technique and simpler configuration.

In this Letter, we propose an effective method for the improvement of the characteristics of erbium-doped L-band SFS by inserting a segment of unpumped EDF between the reflector and the WDM coupler in a double-pass bi-directional pumping (DP-BD) configuration. The effects of the fiber length ratio of the unpumped EDF section to the total fiber on the output characteristics of the L-band fiber source are analyzed under different pump power arrangements. The output spectral characteristics of this SFS are greatly improved to provide wider spectral linewidth and higher output power. Notably, the widest L-band spectrum is obtained in the case of backward pump power equalling zero, i.e. a single-forward pumped configuration with a segment of unpumped EDF. The variation of the mean wavelength versus pump power with the unpumped EDF length is also studied. It is shown that the pump power independent mean wavelength operation can be obtained in the single-forward pumped L-band SFS configuration by selecting a suitable length of unpumped EDF. The L-band SFS with a stable mean wavelength, such a large linewidth and high output power is the best simple structure reported up to now, to the best of our knowledge.

The configuration that we used to characterize the L-band SFS is shown in Fig. 1. The L-band SFS consists of two sections of EDF, a 980 nm pumping LD, two 980/1590 nm WDM couplers, a power splitter used to divide the pump power into two portions, a fiber loop mirror (FLM), and an optical isolator (ISO) at the output port. In the design, the section of EDF2 is bi-directionally pumped by the LD through two WDM couplers, and the other section (EDF1) is unpumped and arranged between the WDM1 and the FLM. We define the total length of EDF as $L = L_1 + L_2$, where L_1 and L_2 refer to the first stage (EDF1) and the second stage (EDF2) lengths, respectively. The fiber length ratio of the EDF1 length to the total length is defined as $R_L = L_1/L$. Similarly,

*Supported by the National Natural Science Foundation of China under Grant No 61108019, and the Fujian Provincial Natural Science Foundation of China under Grant No 2011J01368.

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the pump ratio is defined as the forward pump power to the total pump power, i.e., $R_{\rm p} = P_1/P_{\rm total}$. Obviously, the configuration becomes a conventional DP-BD configuration with $R_L = 0$. The role and effect of the unpumped EDF1 in this configuration can be explained as follows. The backward ASE generated from EDF2 is imported into EDF1 and is reused as a pump source for EDF1. Then, a longer-wavelength ASE is generated in EDF1 and re-injected into the bi-directional pumped EDF2. That is to say, the unpumped EDF1 used here is equivalent to the generation of an L-band ASE seed source. Therefore, the output ASE of the configuration includes two components: the amplified L-band seed light and the residual ASE of EDF2 in the output port. The wavelength ranges and the proportion of these two components determine the output spectral shape and wavelength range of the SFS. With a suitable fiber length ratio R_L, the L-band SFS of broader linewidth and higher power are expected. In addition, the configuration becomes a double-pass backward configuration if $R_{\rm p} = 0$, which is unable to implement an L-band SFS, as had been demonstrated in Ref. [7]. However, the configuration becomes a single-forward pumped configuration with a segment of unpumped EDF with $R_{\rm p} = 1.0$. It is an improved double-pass forward configuration, which has excellent properties described in the following. The EDF used in both numerical simulations and experiments is a Lucent Technologies heavily doped LRL fiber (type number L12403) with a peak absorption of 27–33 dB/m at 1530 nm, mode field radius of 5.2 μm, cutoff wavelength of 1100–1400 nm, and numerical aperture of 0.25.

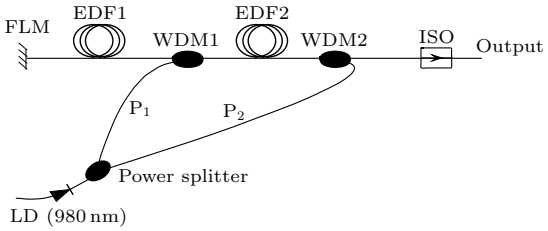

Fig. 1. The proposed configuration of DP-BD L-band SFS.

In the simulation, the commercial amplifier simulation package OASIX[14] is used. It is believed that the simulation software is accurate for presenting the same results as those obtained by experiments.[6,13,15] The mean wavelength and spectral linewidth of the amplified spontaneous emissions (ASE) are computed by

$$\bar{\lambda} = \frac{\sum_{i=1}^{n} p(\lambda_i) \cdot \lambda_i}{\sum_{i=1}^{n} p(\lambda_i)}, \tag{1}$$

$$\Delta\lambda = \frac{\left[\sum_{i=1}^{n} \Delta\lambda_i \cdot P(\lambda_i)\right]^2}{\sum_{i=1}^{n} \Delta\lambda_i \cdot P(\lambda_i)^2}, \tag{2}$$

where λ_i is wavelength of the ith ASE wave; $P(\lambda_i)$ is the power in the ith ASE wave of the emission spectrum; n is the number of discrete ASE wavelengths; $\Delta\lambda_i$ is spectral width represented by the ith ASE wave.

There is no doubt that the output ASE spectrum is largely dependent on the total fiber length used. Previous works have pointed out that an optimal fiber length exists to obtain the flattest L-band spectrum output. Thus, the total EDF length L is first optimized according to spectrum flatness in the case of $R_L = 0$, and $R_{\rm p} = 1$. The effective FLM reflectivity is set to 90% and the total pump power is set to 160 mW. Simulation results show that 19 m is the optimal length to obtain the largest linewidth, i.e. a flattest L-band spectrum. Therefore, the total EDF length is fixed at 19 m for the proposed L-band SFS in the following simulations and experiments.

Then, for different given pump power ratios of a fixed 160 mW total pump power, the effects of the fiber length ratio R_L on the output spectral linewidth of the L-band SFS are simulated, as shown in Fig. 2(a). Figure 2(b) illustrates the available maximum linewidth with the optimized fiber length ratio under different pump power ratios, and its corresponding output power.

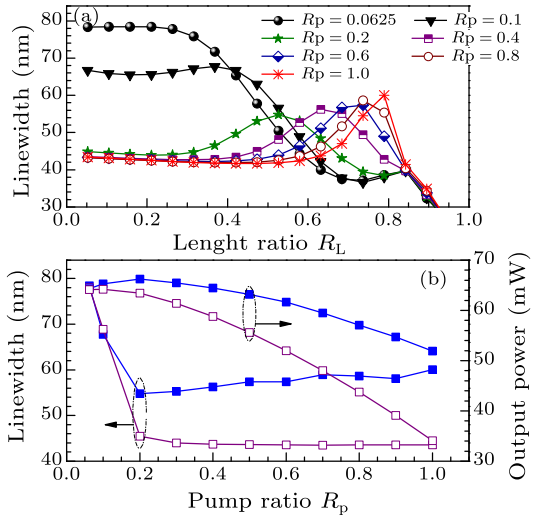

Fig. 2. (a) The spectral linewidth versus R_L in seven given pump power allotments. (b) The available maximum linewidth and its corresponding output power versus pump ratio (the solid squares represent the data for the improved DP-BD SFS, and the hollow squares represent the data for the conventional DP-BD).

From Fig. 2(a) we know that the spectral linewidth is greatly affected by the fiber length ratio R_L in all kinds of pump power ratio cases. However, the effects of R_L on the spectral linewidth and output spectra (not show here) for different $R_{\rm p}$ are different. In cases of a lower value of $R_{\rm p}$, i.e. 0.0625 and 0.1, the spectral linewidth can not be improved by inserting the unpumped EDF. In fact, the output spectra do not fall in L-band but cover both C-band and L-band in both

cases. However, in the case of $R_{\rm p} = 0.2$, 0.4, 0.6, 0.8, 1.0, the output spectra are an L-band SFS, the spectral linewidth will be greatly improved by inserting the unpumped EDF. There respectively exists an optimal R_L to get the widest spectral linewidth for different $R_{\rm p}$ from 0.2 to 1.0. As is apparent from Fig. 2(b), compared with the conventional DP-BD L-band SFS, the improved DP-BD SFS with a section of unpumped EDF can always have a spectral linewidth over 10 nm and higher output power in all pump power arrangements. Further data depicted in Fig. 2(b) show that the value of available maxi-linewidth increases with an increase of R_P. The maximum linewidth reaches almost 60 nm when backward pump power equals zero, i.e. $R_{\rm p} = 1.0$. While from the cover of output power, we find that the corresponding output power decreases with the increase of $R_{\rm p}$.

It is meaningful that the configuration becomes a single-forward pumped configuration without a power splitter when $R_{\rm p} = 1.0$, as shown in Fig. 3. This configuration is similar to the conventional double-pass forward (DPF) L-band SFS but merely separating a section of EDF between the FLM and the WDM coupler. However, the spectral linewidth is broadened up to 60 nm and the conversion efficiency is also greatly enhanced when compared to the conventional DPF L-band SFS.

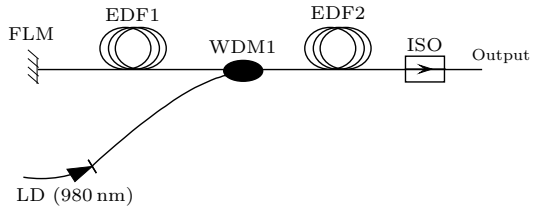

Fig. 3. The single-forward pumped configuration of L-band SFS.

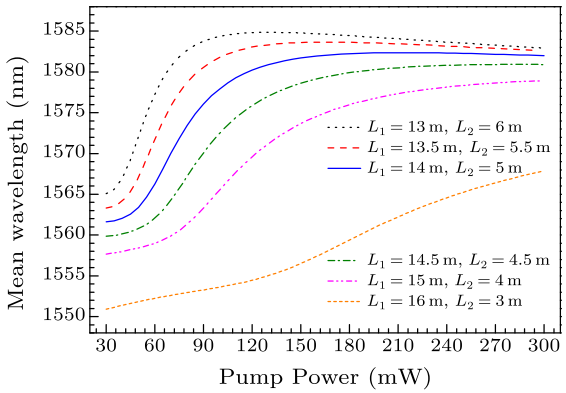

Fig. 4. Mean wavelength versus pump power.

To gain insight into the effect of unpumped EDF on its out characteristics of the single-forward pumped L-band SFS, the variation of the mean wavelength versus pump power has been investigated. Figure 4 compares the mean wavelength profiles against pump power and shows the high tunability of the mean wavelength against the pump power characteristic by adjusting the unpumped EDF length. It is shown clearly in Fig. 4 that by using a section of unpumped EDF with the length $L_1 = 13$ m, the mean wavelength increases with the pump power to the maximum value and then decreases when the pump power further increases to a high level. The similar results are obtained for $L_1 = 13.5$ m, 14 m, and 14.5 m, respectively. While with the unpumped EDF length L_1 increasing to 15 m, the mean wavelength will keep monotonously increasing with an increase of pump power. Then, the stable mean wavelength operation will not be obtained. The results of Fig. 4 demonstrate that the variation of mean wavelength monotonously decreasing with pump power of the conventional DPF L-band SFS can be eliminated by using the unpumped EDF. That is to say, the pump power independent mean wavelength operation with $\partial\bar{\lambda}/\partial P = 0$ can be achieved for the single-forward pumped configuration of L-band SFS source by separating a section of EDF with a suitable length between the FLM and the WDM coupler.

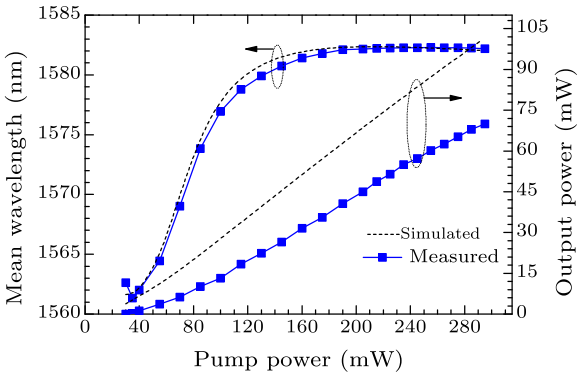

Fig. 5. Measured and simulated mean wavelength and output power versus pump power.

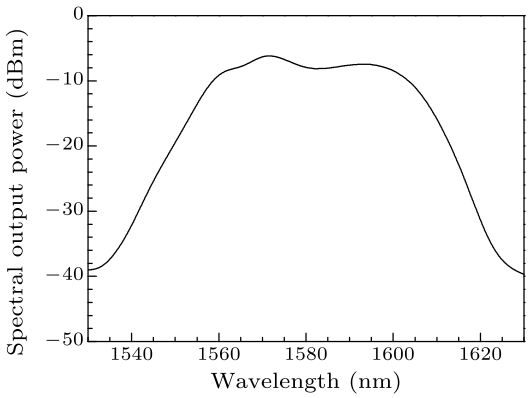

Fig. 6. Measured output spectrum for 255 mW pump power.

Table 1 gives the detailed characteristics of the stable single-forward pumped L-band SFS in terms of the required pump power, pumping efficiency, and linewidth for three cases of fiber length arrangements: (i) $L_1 = 13.5$ m, $L_2 = 5.5$ m; (ii) $L_1 = 14$ m, $L_2 = 5$ m, and (iii) $L_1 = 14.5$ m, $L_2 = 4.5$ m. The stable single-

forward pumped L-band SFS can be achieved for these three cases. However, a higher pump power is required to achieve the stable mean wavelength for the longer unpumped EDF length used. The case for $L_1 = 14\,\mathrm{m}$ and $L_2 = 5\,\mathrm{m}$ is the optimal parameters to obtain a stable L-band SFS of a widest linewidth of 50.4 nm and a moderate conversion efficiency of 33.5%.

Table 1. Characteristics of the stable SFS in terms of required pump power, pumping efficiency, and linewidth.

L_1 (m)	L_2 (m)	Total pump power (mW)	Pump efficiency(%)	Linewidth (nm)
13.5	5.5	160	31.9	50.1
14	5	205	33.5	50.4
14.5	4.5	275	34.6	49.7

Therefore, the output characteristics of the stable single-forward pumped L-band SFS were measured experimentally for the optimal parameters of $L_1 = 14\,\mathrm{m}$, $L_2 = 5\,\mathrm{m}$. Figure 5 shows the measured mean wavelength and output power as a function of the pump power. The simulation results are plotted in the figure for comparison. The output spectrum was measured using an Advantest optical spectrum analyzer (OSA) that divided the spectrum into 1000 discrete points. The mean wavelength and linewidth of the spectrum are computed by Eqs. (1) and (2). In the experiments, the pump power independent mean wavelength operation with $\partial\bar{\lambda}/\partial P = 0$ was observed when the pump power was 255 mW. An output power of 60.2 mW, corresponding to a pumping efficiency of 23.6% was achieved for the stable mean wavelength operation under a pump power of 255 mW. The experimental results show good agreement with the simulations, with quantitative discrepancies attributable primarily to splice loss, insertion loss in the WDM coupler, etc. Figure 6 shows the obtained output L-band spectrum of 255 mW pump power. It can clearly be seen that the linewidth is obviously broadened to the edge of C-band, corresponding to a spectral linewidth of 50.2 nm. Compared with the mean wavelength stability L-band SFS using the synchronous pumping technique,[13] the single-forward pumped configuration to achieve a mean wavelength stable L-band SFS is much simpler by merely separating a suitable length of unpumped EDF between the FLM and the WDM coupler Without using a power splitter; the single-forward pumped L-band SFS overcomes the shortcomings of mean wavelength stability sensitive to the power-splitting ratio. With connecting a section of unpumped EDF at the output port of the single backward pumped configuration, the stable L-band SFS could also be achieved.[15] However, it has the intrinsic danger in resonant lasing effect due to the backward pumped scheme. Therefore, it is expected that the advantages of stable mean wavelength, large linewidth, high output power and simple structure of the single-forward pumped L-band SFS will make it more useful in a high-precision FOG application.

In conclusion, we have demonstrated that an effective method of using a segment of unpumped EDF to improve the characteristics of L-band SFS. In the configuration of DP-BD L-band SFS with a section of unpumped EDF, our simulations show that the output characteristics of spectral linewidth and output power are both greatly enhanced in all pump power arrangements by optimizing the fiber length ratio of the unpumped EDF section to the total fiber. Notably, the widest linewidth of the L-band spectrum reaches almost 60 nm, in the case of the backward pump power it equals zero, i.e. $R_\mathrm{p} = 1$. Then, the configuration becomes a single-forward pumped configuration with a segment of unpumped EDF with $R_\mathrm{p} = 1$. Further studies show that the variation of the mean wavelength versus pump power can be eliminated to achieve a wideband and mean wavelength stable L-band SFS by optimizing the length of unpumped EDF. Finally, a mean wavelength stable L-band SFS having a spectral linewidth of 50.2 nm and an output power of 60.2 mW is experimentally demonstrated using this single-forward pumped configuration. The method of using unpumped EDF enables us to offer a stable and wideband L-band SFS with a simple single-pumped structure and to overcome the shortcomings of the synchronous pumping technique. Therefore, it will be useful in WDM systems, FOGs, and fiber-optic sensor systems.

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