Effect of Adding a Long Period Grating in a Double-Pass Backward Er-Doped Superfluorescent Fiber Source

C. D. Su and L. A. Wang

Abstract—We first demonstrate that by inserting an appropriate long period grating in an Er-doped superfluorescent fiber source (SFS) of double-pass backward (DPB) configuration, the output spectrum can be broadened up to 40 nm. The characteristics of a long period grating (LPG) are then shown to have marked effects on the properties of the SFS. Both measured and simulated results agree well in the trend. The spectrum broadening using an LPG is shown effective over a large pump power range, especially for a single-humped DPB SFS. After the analysis of three types of output spectra, the tolerances of LPG's characteristics are found larger for a single-humped DPB SFS having the dominant band in 1558 nm.

Index Terms—Long period gratings (LPG's), spectrum broadening, superfluorescent fiber sources (SFS's).

I. INTRODUCTION

BROAD-BAND light sources have been widely used for several applications such as optical sensing (e.g., fiber optical gyroscope (FOG) [1]–[3]), optical low coherent reflectometry (OLCR) [4]–[5], and spectrum spliced sources for wavelength division multiplexing systems [6], [7]. The interferometric detection method is generally adopted in FOG and OLCR. Although the minimum detectable rotation rate of an FOG is primarily determined by the mean-wavelength stability of its light source [8], a broad linewidth [3] is required to reduce the noises caused from several physical aspects [9]–[11]. For OLCR applications, other than suitable spectral profile [12], a low-temporal coherent light source is also needed since the nominal resolution is approximately proportional to the coherent time [13]. As for spectrum slicing applications, a source with broader linewidth would provide more channels. Several light sources, e.g., light emitting diodes, superluminescent diodes, and rare-earth-doped superfluorescent fiber source (SFS), could be utilized for such applications. Although the semiconductor sources can provide ultrawide spectra, their low output power and poor wavelength stability may limit their usefulness. Conversely, the rare-earth-doped SFS's have more stable spectra with much higher output power. By doping different rare-earth ions, the SFS's can be operated in different wavelength regions [14]–[17], of which the Er-doped SFS has been intensively studied

because its spectrum falls in the third window of optical fiber communication. The characteristics of an Er-doped SFS strongly depends on which configuration is employed [17], and an SFS in DPB configuration has been demonstrated to have a stable broad-band spectrum with high output power [18]–[19]. Note the linewidth of a DPB SFS can vary from 10–30 nm depending on the pump power and the length of erbium doped fiber (EDF). Since the intensity of output spectrum from an Er-doped SFS is not uniform, the useful linewidth is commonly smaller than the original linewidth of an EDF gain spectrum. To furthermore increase the linewidth, several techniques have been used [20]–[25], which share a common principle: the ASE spectrum is reshaped by adding a filter to induce spectral losses in the high-intensity region. The simplest way is to shape the output spectrum through a filter with the inverse spectrum. Blazed gratings [20], [21] and long period gratings (LPG's) [22], [23] have been used for the SFS's in single-pass backward (SPB) configuration. Note when the filter is added at the output end of the ASE source, the output power decreases markedly. The more dominant in certain wavelength range, the more power loss incurs in that range due to the filtering. To reduce such power loss, one could introduce a mechanism to redistribute power from the dominant band to the other spectral ranges. For example, in [22], an LPG was added between two EDF's to redistribute the gain in an SPB configuration and to reduce the excess loss to ~ 0.5 dB. As for the ways of increasing the linewidth of a DPB SFS, an array of screws served as attenuator together with a high reflectance mirror [24] and the use of multiple Bragg reflective gratings as mirror [25] have been demonstrated. Both methods used a wavelength dependent mirror to reshape and to reflect the forward ASE signal to the backward direction. Therefore, the reshaped ASE will cause gain redistribution when it propagates through an EDF, resulting in spectrum broadening.

In this paper, we first demonstrate a new technique by adding a conventional long period grating in a DPB configuration for linewidth increase. Such a technique is simpler than those reported before in the same configuration, and is shown effective to have a broader linewidth with comparable output power than the DPB SFS without any grating. The rest of the paper is arranged as follows. In Section II, experiment results of the linewidth increase are shown for three kinds of typical spectra from a DPB SFS. In Section III, we simulate the effect of an LPG on a DPB Er-doped SFS. Finally, we conclude our study in Section IV.

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Fig. 1. Experiment setup of a DPB SFS configuration with and without an LPG.

II. EXPERIMENT RESULTS

Fig. 1 shows the setup of a DPB SFS with and without an LPG. The output power from a pump laser diode operating at 976 nm is launched into a section of Er-doped fiber through a WDM. The second WDM is used to separate the residual pump power, avoiding its feedback to the pump laser, and to direct the forward ASE to a wavelength-dependent reflector composed of an LPG and a fiber mirror. An optical isolator with ~ 60 dB isolation loss is used to prevent the formation of a resonance cavity due to the optical feedback from the output endface. The LPG is written in a hydrogenated dispersion shifted fiber by using a KrF excimer laser. After exposure, a periodic index variation is formed in the core region. The amount of index variation is a function of the exposure intensity and time. The guided mode is coupled into the forward cladding modes by the imprinted LPG when the phase matching condition is satisfied [26]. The cladding modes disappear after propagating a distance due to weak confinement, resulting in several loss bands whose peak wavelengths, linewidths, and peak losses are controllable. An LPG with appropriate spectral characteristics is chosen to induce an excess loss at one or two dominant bands of the original DPB SFS to redistribute the spectral power for linewidth broadening. In the following, the “DPB SFS” denotes the original DPB SFS without an LPG, and the “filtered DPB SFS” denotes the DPB SFS with an LPG.

The spectrum evolution of a DPB SFS is affected by several parameters such as pump power, EDF length, and so on [18]. For different parameters, the ASE spectrum can be divided into three categories: one-humped at 1530 or 1558 nm, and two-humped at both 1530 and 1558 nm. In the following, three sections of EDF with different length were used to generate such three spectra. The one-humped spectra are obtained by using 10- and 20-m EDF's while the two-humped spectrum by 15-m EDF. Other reasons to choose such three lengths are described as follows. The 10-m EDF SFS could provide larger output power than by using other EDF lengths; the 20-m one could be operated in a pump-power-independent mean wavelength region; the 15-m one could provide two bands with nearly the same peak level. To broaden such ASE spectra, an LPG with corresponding peak wavelength(s) near the peak wavelength(s) of the hump(s) is needed.

Fig. 2 shows the ASE spectra of 10-m DPB SFS's with and without LPG's pumped at 85 mW. For the DPB SFS, the peak wavelength is 1530.4 nm and the linewidth as defined in [16] is 21.5 nm. LPG1 and LPG2 are used, one at a time, to reshape the output ASE spectrum and to analyze the effect due to the variation of LPG's characteristics. The two LPG's have the same peak losses of 6 dB and FWHM of 14.8 nm,

Fig. 2. Measured spectra of the 10-m filtered DPB SFS's.

but different peak wavelengths. LPG1 is 1530.4 nm, while LPG2 is 1532.2 nm. The linewidth is found broadened from 21.5 to 35.0 and 28.6 nm when LPG1 and LPG2 are added, respectively. The effect of using LPG1 is better than LPG2 because of less mismatch in peak wavelength. The forward ASE signal filtered by the LPG is reflected by the fiber mirror. Since the spectral output power increases with the reflected signal, the ASE signal in the LPG's loss band decreases, but increases in the 1558 nm band. Thus the backward ASE signal causes gain redistribution when passing the EDF again, resulting in the output spectrum broadening.

Fig. 3 shows the effect of pump power on the characteristics of the DPB SFS's including mean wavelength, output power, and linewidth. The output power of the filtered DPB SFS is less than that of the DPB SFS because of the LPG loss. The pump efficiency decreases from $\sim 40.4\%$ to $\sim 33.2\%$ for both filtered DPB SFS's. The efficiencies are the same because the two LPG's have the same peak loss and linewidth. In the high-pump power region, the linewidth generally decreases slowly with pump power. Note the linewidth nearly remains the same value, ~ 36 nm, for the filtered DPB SFS with LPG1, but not with LPG2. The major difference comes from the degree of wavelength matching. Due to the matched peak loss wavelength of LPG1, the power in the dominant 1530 nm band is filtered and the total power is redistributed with more transferred from the 1530 to 1558 nm bands when the pump power increases. Therefore, the linewidth remains nearly the same for the filtered DPB SFS with LPG1. Conversely, for the filtered DPB SFS with LPG2, the filtering effect is not enough so that less power is transferred and as pump power increases the residual 1530 nm band becomes more dominant, resulting in linewidth decrease. Fig. 3(b) shows the dependence of mean wavelength on pump power. Note the pump-power independent mean wavelength operation, which is vital to the mean wavelength stability for a gyroscope light source [17], can not be found for the 10-m DPB SFS with or without LPG's. The variation of mean wavelength for the filtered SFS with LPG1 is smaller than that with LPG2 owing to better wavelength matching.

It is indicated that by inserting an appropriate LPG the linewidth of a DPB SFS with single-humped band at 1558 nm

Fig. 3. (a) Measured output power and linewidth and (b) mean wavelength versus pump power for the 10-m filtered DPB SFS's.

Fig. 4. Measured mean wavelength versus pump power for the 20-m filtered DPB SFS's.

could be increased almost as much as two times over a large pump power region with only little power loss [27]. Here we further discuss the mean wavelength stability of such a DPB SFS using the same LPG's. Note the LPG3 and LPG4 designated in this paper are called LPG1 and LPG2 in [27], respectively.

Fig. 4 shows the effect of pump power on the mean wavelength of the 20-m DPB SFS. For pump power larger than

Fig. 5. Measured spectra of the 15-m filtered DPB SFS's.

the threshold value, the mean wavelength firstly increases, then decreases with pump power. Therefore, there exists a pump power region where the slopes are zero or nearly zero. Equivalently, a pump-power independent mean wavelength operation for the 20-m DPB SFS's is feasible. Note that the required pump power range of a filtered DPB SFS for such operation is smaller indicating the addition of LPG's deteriorates the mean wavelength stability.

Fig. 5 shows the two-humped ASE spectra from the 15-m DPB SFS pumped at 85 mW with and without adding an LPG. The LPG has two loss bands corresponding to the two humps. The short wavelength band has a peak loss of 1.2 dB at 1530 nm and an FWHM of 15 nm, while the long wavelength one has a peak loss of 1.5 dB at 1562 nm and the same FWHM. The broadening effect of using an LPG is not significant because the original DPB SFS already has a broad spectrum and the unmatched LPG's linewidth to the original spectrum without LPG. The linewidth increases only from 35.4 to 36.9 nm. Noted that the peak loss of the LPG is only 1.2 and 1.5 dB compared to 6 dB for LPG1 and LPG2 and over 8 dB for LPG3 and LPG4. Due to the gain redistribution the difference of peak intensity between these two bands becomes smaller and a flattened spectrum could be obtained if the matched LPG is used.

Fig. 6(a) and (b) shows the effect of the pump power on the characteristics of the 15-m DPB SFS's. The pump efficiency decreases from 41.7% to 36.1% because of the LPG's loss. A slightly broader linewidth can be obtained in the high-pump power region with the LPG. Although there exists a pump-power independent mean wavelength operation in the low-pump region, the output power is too small to be practically useful. Note the variation of mean wavelength remains nearly the same after adding the LPG, indicating the filtered DPB SFS suffers little degradation on the wavelength stability.

We now discuss how to improve the performance of the filtered DPB SFS with two humps. Note the linewidth of the short wavelength hump of the 15-m DPB SFS is narrower than that of the long wavelength one. The linewidth of the LPG should have been narrower in the short wavelength band for spectrum broadening. Since the linewidth of each loss band of an ordinary binary LPG is approximately proportional to the

(a)

(b)

Fig. 6. (a) Measured output power and linewidth and (b) mean wavelength versus pump power for the 15-m filtered DPB SFS's.

square of its corresponding wavelength [26], an LPG having two loss bands centered at the matched peak wavelengths cannot simultaneously have the required linewidths. To obtain such a desired LPG, one can introduce a phase shift in the ordinary binary LPG to split the loss band into the two bands having different losses and linewidths [28]. Two LPG's with the corresponding loss bands matched to the two humps can also be used to further flatten the spectrum. Since the linewidth of an LPG is about inversely proportional to the LPG's length, more length of an LPG is required to obtain such small linewidth. We are currently limited by the required fabrication facility and leave such improvement for further study.

III. SIMULATION RESULTS

In the simulation, an effective mirror reflectance is used to describe the functions of the fiber mirror and LPG. The mirror reflectance is assumed to have a Gaussian loss profile which fits well to the measured characteristics of LPG's used in the experiment. The mirror reflectance is described as

$$R(\lambda) = R_0 - A \exp \left[-\frac{4 \ln(2) \cdot (\lambda - \lambda_c)^2}{\Delta\lambda^2} \right] \quad (1)$$

where λ_c is the peak loss wavelength, $\Delta\lambda$ the HWHM linewidth, A the amplitude of the loss profile, and R_0 the

Fig. 7. Simulated spectra of the 5-m filtered DPB SFS's.

fixed mirror reflectance without LPG. R_0 is chosen to be 0.5 to include the excess loss of WDM2 used in the experiment. Since the emission and absorption cross sections of the EDF we used are not available, the data reported in [17] are adopted in the following simulation.

The ASE spectrum is divided into 55 regions ranging from 1520–1575 nm. One can solve the power evolution equation [17] to obtain the output ASE spectrum. $R(\lambda)$ is replaced with R_0 for the DPB SFS.

In the following, three lengths are chosen to represent the three kinds of ASE spectra discussed in Section II. Only one band either 1530 or 1558 nm band is dominant for the DPB SFS when the EDF length is set to either 5- or 13.5-m, respectively. A two-humped spectrum is obtained when the EDF is 9-m long. Note for the similar output spectrum the simulated EDF length is smaller than that used in the experiment possibly due to the larger values of simulated cross sections.

Fig. 7 shows the ASE spectra of the DPB SFS's with and without filtering. The output spectra peaked at ~1530 and ~1558 nm with linewidths ~17.1 and ~27.1 nm when the 5- and 13.5-m long EDF's are used, respectively. Since the dominant band of the 13.5-m DPB SFS is broader than that of the 5-m DPB SFS, the required linewidth of the filter should also be wider for better matching. The parameters of the filters are $\Delta\lambda = 25$ nm and $A = 0.4871$ for $\lambda_c = 1530$ nm and $\Delta\lambda = 35$ nm and $A = 0.4540$ for $\lambda_c = 1558$ nm. The amplitude A is chosen to have the maximum linewidth of the filtered DPB SFS for the given filter linewidth. Owing to the gain redistribution caused by the filters, the linewidth is broadened from ~17.1 to ~41 nm for the 5-m DPB SFS and from ~27.1 to ~41 nm for the 13.5-m DPB SFS.

Fig. 8 shows the effect of pump power on the characteristics of the SFS's. Due to the filter's loss, the pump efficiencies decrease from ~19.6% to ~12.1% for the 5-m DPB SFS and from ~36.0% to ~35.3% for the 13.5-m DPB one. Since the forward ASE signal decreases with the EDF length as the EDF length is long enough [17], the filter causes less power loss for a DPB SFS with longer EDF. The small amount of degradation in pump efficiency for the 13.5-m filtered DPB SFS is due to the weak forward ASE signal. A large linewidth could be obtained over a large pump power range for the filtered

(a)

(b)

Fig. 8. (a) Simulated output power and linewidth and (b) mean wavelength versus pump power for the 5-m and 13.5-m filtered DPB SFS's.

DPB SFS's. Fig. 8(b) shows the mean wavelength variation at different pump power. It is clearly seen that the pump-power independent or insensitive mean wavelength operation exists for the 13.5-m DPB SFS's, but not for the 5-m DPB ones either with or without the filter. The pump power range for such operation, where the absolute value of the slope smaller than 10 ppm/mW, is 87–150 mW for the 13.5-m DPB SFS and 72–96 mW for the filtered one. In the high-pump power region the variation of mean wavelength with pump power for the filtered DPB SFS is larger than that for the DPB SFS, indicating the spectrum broadening will deteriorate the light source's wavelength stability. The trends of the simulation results are basically the same as the measured ones as compared to Figs. 3 and 4.

One important thing in utilizing the filtered DPB SFS for practical applications is to have a large tolerance in each parameter of the filter while the broad linewidth can still be obtained. Fig. 9(a) shows the ASE spectra of the filtered SFS for different filter's peak wavelengths. It is seen that the spectrum is strongly dependent on the peak wavelength for the 5-m filtered DPB SFS, but weakly dependent for the 13.5-m filtered DPB one. If the filter's peak wavelength deviates from the optimal value, the ASE spectrum then has a new dominant band resulted from the filtering effect, and its

(a)

(b)

(c)

Fig. 9. Simulated spectra of the 5-m and 13.5-m filtered DPB SFS's for different filter parameters: (a) peak loss wavelength, (b) linewidth, and (c) loss depth.

center wavelength is near the peak wavelength of the DPB SFS but positioned in the opposite side. Therefore, the linewidth decreases when the filter's peak wavelength shifts from the optimal value. Fig. 9(b) shows the output spectra for different filter linewidth. A broad-band ASE spectrum with linewidth larger than 40 nm can be still obtained even if the linewidth of the filter is 8 nm larger or less than the optimal value. It is seen that the variation of spectra to the change of filter's linewidth is small especially for the 13.5-m filtered DPB SFS. As the filter

Fig. 10. Simulated spectra of the 9-m filtered DPB SFS's.

linewidth is smaller than the optimal value, the reshaped ASE signal has more gain in the wavelength regions adjacent to the loss band. The output power in the loss band decreases and the overall power redistributes to the adjacent spectral regions as shown in Fig. 9(b). Conversely, if the filter's linewidth is larger than the optimal one a smaller amount of power in the loss band distributes to the other spectral regions. Note that as the filter's linewidth increases, more forward ASE signal is lost, causing the output power to decrease. Fig. 9(c) shows the ASE spectra of the filtered SFS's with different loss depths. The curves of "3 dB" and "−3 dB" denote the ASE spectra of the filtered SFS's with an LPG having a peak loss larger and smaller than the optimal value, respectively. The output spectrum grows faster in its original dominant band if the loss depth is not large enough, for example 3 dB smaller than the optimal value. As filter's loss depth increases, the original dominant band decreases its strength and the power is transferred from one band to the other bands.

The ASE spectrum of the 9-m DPB SFS shown in Fig. 10 has two dominant bands near 1530 and 1558 nm. To broaden such a spectrum, a filter with two loss bands matched to the two peak wavelengths is needed. The reflectance of such a filter is assumed as

$$R(\lambda) = R_0 - A_1 \exp \left[-\frac{4 \ln(2) \cdot (\lambda - \lambda_{c1})^2}{\Delta\lambda_1^2} \right] - A_2 \exp \left[-\frac{4 \ln(2) \cdot (\lambda - \lambda_{c2})^2}{\Delta\lambda_2^2} \right] \quad (2)$$

where A , λ_c , and $\Delta\lambda$ are defined previously. Subscript letters 1 and 2 represent the short and long wavelength loss bands, respectively. Fig. 10 also shows the spectra of the filtered DPB SFS's. The parameters used here are $A_1 = 0.374$, $\Delta\lambda_1 = 5$ nm, $A_2 = 0.238$, and $\Delta\lambda_2 = 33$ nm. The linewidth increases from 37.2 to 41.2 nm. The effect of the two loss bands is to redistribute the power from the two dominant bands to the dip spectral region. Although the linewidth increment is small, the output ASE spectrum becomes more flattened and the intensity variation is smaller than 2 dB in the spectral range from 1528–1560 nm. Fig. 11 shows the effect of pump power on the characteristics of the SFS's. The pump efficiency decreases little from 33.6% to 33.3%, and the linewidth maintains near constant, ~ 40 nm, when the filter is used. As shown

Fig. 11. (a) Simulated output power and linewidth and (b) mean wavelength versus pump power for the 9-m filtered DPB SFS.

in Fig. 11(b), no pump-power independent mean wavelength operation with high output power can be obtained with or without adding the filter. The trends are also the same as the measured results depicted in Fig. 6.

The tolerances of the filter's parameters are also studied. Fig. 12 shows that the output spectrum is very sensitive to the peak wavelength and to the linewidth of the short-wavelength loss band, but not to the long-wavelength one. As the loss depth of the short wavelength band varies, the intensity of the 1530 nm band changes accordingly and the other spectral ranges remains nearly unchanged. However, a significant change in the spectrum occurs when the loss depth of the long-wavelength band varies. The power is transferred between the two dominant bands, and a flattened spectrum cannot be obtained. Due to the broader 1558 nm band, the tolerances of the peak wavelength and the linewidth of the long-wavelength loss band are much larger than those of the short-wavelength one. Therefore, the short-wavelength loss band and the loss depth of the long-wavelength loss band should be carefully controlled for spectrum broadening when a DPB SFS has a two-humped spectrum.

Note although the simulation results are not exactly identical to the experiment ones, the trend of linewidth broadening by adding an LPG in the DPB SFS is basically the same. One

Fig. 12. Simulated spectra of the 9-m filtered DPB SFS for different parameters of the short-wavelength and long-wavelength loss bands of the filter: (a) peak loss wavelength, (b) linewidth, and (c) loss depth.

may expect that the linewidth broadening effect of adding an LPG would be applied to the DPB SFS's with different EDF's.

IV. CONCLUSION

We have demonstrated that an Er-doped DPB SFS can have a broader spectrum by inserting an appropriate LPG in front of the fiber mirror. The trend of the experiment results is consistent with that of the simulated ones. It is shown that the linewidth of a single-humped DPB SFS could be significantly

increased up to almost two times over a large pump range. As for a double-humped DPB SFS the linewidth increase is not significant; however, a more flattened spectrum could be obtained due to the gain redistribution from the humps to the dips.

Although the spectrum broadening technique by using an LPG can increase the linewidth to nearly cover all the gain spectral range (~ 40 nm) of an EDF, the pump efficiency degrades and the wavelength stability becomes worse. The degradation in pump efficiency becomes smaller due to the weak forward ASE signal for an SFS with longer EDF. Therefore, the spectrum broadening technique causes significant power degradation for a DPB SFS having a single-humped spectrum in 1530 nm, but little degradation for a DPB SFS either having a single-humped spectrum in 1558 nm or a double-humped spectrum.

Simulation results on the LPG's tolerance indicate that the required peak wavelength of the LPG should match the dominant band of a DPB SFS to have the broadest spectrum. In addition, the broader the original dominant band in the DPB SFS, the larger linewidth is needed for the LPG, which results in larger tolerances of the peak wavelength and linewidth. Therefore, the tolerances of using an LPG to broaden the spectrum of a 1558-nm-dominant DPB SFS are found larger than the others, implying a relatively easier implementation for such a case.

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