Polarized erbium-doped superfluorescent fiber source utilizing double-pass backward configuration

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An erbium-doped superfluorescent fiber source utilizing a double-pass backward configuration is analyzed when a polarizer is inserted into an erbium-doped fiber to obtain polarized output light. Such a polarized configuration is simulated and experimentally confirmed to have the following characteristics: high polarization power conversion efficiency, pump-power-independent mean-wavelength operation, and low sensitivity to polarizer insertion loss. © 2005 Optical Society of America

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1. Introduction

The accuracy of detecting rotation speed utilizing a fiber-optic gyroscope (FOG) is determined by the stability of its scale factor, which can be expressed as $2\pi LD/\lambda c$, where L is the fiber length, D is the diameter of fiber coil, λ is the mean wavelength of a light source, and c is the speed of light. The more stable the mean wavelength is, the higher the accuracy of the detection of rotation speed that can be obtained. For example, a mean-wavelength variation of ~ 1 ppm (part per million) is needed for an inertial-navigation grade FOG to be used in the most demanding applications.¹ In addition, high output power and broad bandwidth are also required to improve signal-to-noise ratio and eliminate coherent errors, respectively. Many efforts have been made to improve the mean-wavelength stability of various light sources over more than the past 20 yr. Though semiconductor light sources such as superluminescent diodes are attractive because of their compactness and integration capability with other functional optoelectronic devices, the mean-wavelength stability of these sources is generally not sufficient because their thermal spectral variations are too high (~ 400 ppm/ $^{\circ}\text{C}$). Recently, rare-earth doped superfluorescent fiber sources (SFSs) have been chosen as the light sources for the navigation-grade FOG because

they could provide high output power, broadband, and stable mean-wavelength operation. However, it has been found that the characteristics of SFSs are strongly related to the employed configuration and have attracted much attention to find the optimal performance for each configuration.^{2–8} SFSs can be generally classified into four basic configurations, namely, single-pass forward or backward (SPF, SPB) and double-pass forward or backward (DPF, DPB), as schematically shown in Fig. 1. In the paper published by Wysocki *et al.* in 1994, SPB, SPF, and DPF configurations were studied extensively.³ Hall *et al.* then analyzed the SPB SFSs in great detail in 1995.² These works did not explore the DPB configuration except for a curve in Fig. 11,² in which a straight cleaved fiber might implicitly represent a weak DPB SFS. Afterwards, a DPB SFS was shown potentially useful for FOG applications owing to its good properties⁶ as compared with other configurations.^{7,8} Note that, among these configurations, only SPB² and DPB^{6–8} have been experimentally demonstrated to have pump-power-independent mean-wavelength operation, an important characteristic to be described later. One disadvantage of the DPB configuration may be the need of an isolator to prevent lasing, but an isolation value of less than -60 dB is shown well sufficient⁷ and commercially available.

Typically, the SFS output is coupled to a rotation-sensing fiber coil through a polarizer. When an unpolarized SFS is used, half of its power is lost at the input of the coil. If a SFS is capable of generating a linearly polarized output, this loss can be eliminated. Adding a polarizer in a common erbium-doped fiber (EDF) as shown in this work can produce linearly polarized output. To characterize the polarization power conversion, a figure of merit k value is defined

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Fig. 1. Schematic diagram of four SFS basic configurations: (a) SPF, (b) SPB, (c) DPF, and (d) DPB.

as $k = P_{\parallel}/P_u$, where $P_{\parallel}$ is the output power in the desired polarization for an SFS using a polarizer, and P_u is the output power in the same polarization without a polarizer. Thus a k value of 2 denotes a complete polarization power conversion.

A polarized SPB SFS has been demonstrated to have a high k value of 1.76 by the insertion of a polarizing fiber with 0.55-dB loss.⁹ However, the degradation of k value is very sensitive to the polarizing fiber's insertion loss. A 3-dB polarizer loss will lower the k value to unity, which has no polarization power conversion at all.

In this paper, we demonstrate a polarized DPB SFS with higher polarization power conversion ($k = 1.88$) and less sensitivity to the insertion loss of a polarizer. Moreover, it provides higher output power than the SPB SFS owing to its double-pass configuration. Like an unpolarized SFS, the polarized SFS is also shown capable of conserving pump-

power-independent mean-wavelength operation and broad bandwidth. The rest of the paper is arranged as follows. In Section 2, the simulation procedures are highlighted and then followed by the simulated results regarding the characteristics of a polarized DPB SFS. In Section 3, the experimental results are presented and compared with the simulated ones. Finally, we conclude our study in Section 4.

2. Simulation

To simulate the behavior of a polarized SFS with various parameters, we utilize a set of power-evolution equations to describe both amplified-spontaneous-emission (ASE) and pump signals. The full ASE spectrum ranging from 1525 nm to 1565 nm is divided into ten spectral divisions, which are proven sufficient for predicting a polarized SFS's characteristics. A total of 41 propagating optical signals are considered: two forward $P^+(z, \lambda_i)$ and two backward $P^-(z, \lambda_i)$ polarized signals for each spectral division plus a unidirectional pump signal. The boundary conditions for a polarized DPB SFS are

$$\begin{aligned} P_{\text{ASE}(\parallel)}^+(\lambda_i) &= 0, P_{\text{ASE}(\perp)}^+(\lambda_i) = 0, z = 0; \\ P_{\text{ASE}(\parallel)}^-(\lambda_i) &= RP_{\text{ASE}(\parallel)}^+(\lambda_i), P_{\text{ASE}(\perp)}^-(\lambda_i) \\ &= RP_{\text{ASE}(\perp)}^+(\lambda_i), z = L. \end{aligned}$$

where $P_{\text{ASE}(\parallel)}^{\pm}$ and $P_{\text{ASE}(\perp)}^{\pm}$ are forward (+) and backward (−) ASE signals in parallel and perpendicular polarizations of a polarizer; i represents the i th spectral division; L is the total length of EDF; R is the reflectance of the fiber mirror. When a polarizer is inserted along the EDF, the power is changed according to its polarization state. Equivalently, there exists a polarization-dependent loss at $z = L_P$, where L_P is the length from the pumped input end of an EDF to the polarizer's position. The power before, $P(\lambda_i)$, and after, $P'(\lambda_i)$, the polarizer can be expressed as

$$\begin{aligned} P_{\text{ASE}(\parallel)}^+(\lambda_i) &= \alpha_{\parallel} P_{\text{ASE}(\parallel)}^+(\lambda_i), P_{\text{ASE}(\perp)}^+(\lambda_i) \\ &= \alpha_{\perp} P_{\text{ASE}(\perp)}^+(\lambda_i), \\ P_{\text{ASE}(\parallel)}^-(\lambda_i) &= \alpha_{\parallel} P_{\text{ASE}(\parallel)}^-(\lambda_i), P_{\text{ASE}(\perp)}^-(\lambda_i) \\ &= \alpha_{\perp} P_{\text{ASE}(\perp)}^-(\lambda_i), \text{ at } z = L_P, \end{aligned}$$

where $\alpha_{\parallel}$ and $\alpha_{\perp}$ are the equivalent losses in parallel and perpendicular polarizations. Since we do not have the cross sections of the EDF used in our experiment, the cross-section parameters³ are utilized in our simulation plus the inclusion of extinction ratio (ER) and insertion loss of a polarizer. The birefringence effect of an EDF is not considered for simplicity. Simulation results may have some differences from the experiment ones; however, they will be shown to agree well in trend. In the following, the

output signal's extinction (ER) is defined as follows: $ER = 10 \log(P_{\parallel}/P_{\perp})$, and the linewidth is defined as

$$\Delta\nu = \frac{\left[\int P(\nu) d\nu \right]^2}{\int P^2(\nu) d\nu}.$$

Since the mean-wavelength stability determines the accuracy of rotation detection, it is regarded as one of the most important parameters for a FOG. The variation of mean wavelength with temperature has three contributing sources: intrinsic thermal effect and pump-wavelength- and pump-power-related effects, and it can be expressed as follows:

$$\begin{aligned} \frac{d\bar{\lambda}_{\text{source}}}{dT} = & \frac{\partial \bar{\lambda}_{\text{source}}}{\partial T} + \left(\frac{\partial \bar{\lambda}_{\text{source}}}{\partial \bar{\lambda}_{\text{pump}}} \right) \left(\frac{\partial \bar{\lambda}_{\text{pump}}}{\partial T} \right) \\ & + \left(\frac{\partial \bar{\lambda}_{\text{source}}}{\partial P_{\text{pump}}} \right) \left(\frac{\partial P_{\text{pump}}}{\partial T} \right). \end{aligned}$$

The first term, intrinsic thermal coefficient, is purely related to the EDF materials and is typically small (<5 ppm/ $^{\circ}\text{C}$) for the EDF lengths and the pump-power range used in our experiment. The second term, pump-wavelength-induced variation, can be eliminated by choosing the pump wavelength at the absorption peak of an EDF.^{3,10} We will therefore focus on minimizing the third term, namely, pump-power dependence, which is strongly affected by the configuration being chosen. Though an unpolarized DPB SFS has been demonstrated to be capable of operating with stable pump-power-independent mean wavelength (i.e., $\partial \bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$),⁶ it remains to be seen that a polarized DPB SFS can still conserve such a characteristic. Meanwhile, could it be like a SPB SFS in that the k value is sensitive to the insertion loss of a polarizing element?

To explore these, we assume that pump power is 90 mW and mirror reflectance is 90%. Figure 2 shows the dependence of k value on the polarizer position (L_p) with various EDF lengths. The polarizer is assumed lossless with an ER of 20 dB. It is shown that if the EDF length is too short, the polarizer has no improvement on k value because the ASE is too weak to deplete the fiber gain. As the EDF exceeds 3 m, the forward ASE is strong enough and becomes dominant in the desirable polarization. Being reflected from the mirror, the polarized backward ASE is amplified but limited by the gain saturation so that k goes asymptotically to a plateau region. For longer EDF lengths (≥ 6 m), the DPB configuration supports a wide range of polarizer position that would maintain a high k value. When the polarizer is inserted near the far end of a long EDF where the pump power is small, the forward ASE reduces and causes k value to decrease. However, when the polarizer is placed even closer to the mirror end, the forward ASE pumping effect seems less affected by the polarizer position, and k value increases again.

Fig. 2. Simulated dependence of k values on polarizer positions for the DPB SFS.

Shown in Fig. 3 is the effect of insertion loss on k value. The EDF length is chosen to be 13 m since, at this length, an unpolarized DPB SFS can have $\partial \bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$ operation. Note that when the polarizer position shifts toward the mirror end, the effect of polarizer's insertion loss on k value becomes weak. From the results of Fig. 2 and Fig. 3, the optimal polarizer position should be at the mirror end.

Next we compare some characteristics of polarized SFSs in different configurations but with the same working parameters such as pump power and mirror reflectance. It is always desired for the polarized source to have stable mean-wavelength operation, high k value, and high output power. Since not all configurations can have $\partial \bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$, a proper comparison is made according to the following opti-

Fig. 3. Simulated dependence of k values on polarizer positions for the DPB SFS having a 13-m-long EDF but different insertion losses.

Table 1. Optimal Conditions for Four Basic Superfluorescent Fiber Sources

Configuration	EDF Length (m)	Polarizer Position L_p (m)
SPF	8.5	4
SPB	13	4
DPF	6.5	0
DPB	13	13

mal conditions. For SPF and DPF SFSs, the aim is for obtaining *both* high output power *and* maximum k , while for SPB and DPB SFS, an additional aim is to obtain $\partial \lambda_{\text{source}} / \partial P_{\text{pump}} = 0$ operation. It will be shown later that the comparison demonstrates some unique properties of a polarized DPB SFS. Table 1 lists each optimal EDF length and polarizer position L_p . Note that a trade-off between high output power and maximum k value is required when selecting the proper EDF length and the position of the polarizer. For example, in the SPB configuration, an EDF shorter than the listed value can result in a higher k value but produce lower output power. The effect of the polarizer's ER on the k value of each SFS configuration is studied first. It can be shown that k values increase steadily with the polarizer's ER and then gradually roll off to asymptotic values for ERs larger than 10 dB and 15 dB for double-pass and single-pass SFSs, respectively. Although the maximum k values for all SFSs are slightly different (from ~ 1.8 to ~ 1.9), it indicates that a polarizer with modest extinction ratio (~ 20 dB) is sufficient for all SFSs to achieve its full effect. This is because the polarizer is needed only to attenuate the power in the unwanted polarization down to the spontaneous-emission power level.

It has been shown that k values are fairly sensitive to the insertion loss of a polarizer for SPB, DPF, and SPF SFSs.¹¹ For comparison, all four SFS results are shown in Fig. 4. The working parameters and optimal conditions of each SFS are the same as previously described. All the SFSs' k values decrease monotonically with increasing polarizer's insertion loss. The insertion of a polarizer causes attenuation of both ASE and the pump signals and thus reduces the single-pass SFSs' k values. For the DPF SFS, the backward ASE signal at the pump end will be attenuated twice owing to the polarizer's insertion loss, resulting in the degradation of k value. Noteworthy is the uniqueness of the DPB SFS, which is relatively insensitive to the polarizer's insertion loss. Such insensitivity arises because in the DPB configuration the output power decreases relatively slowly with mirror reflectance.¹⁰ The insertion of a polarizer at the mirror end is equivalent to the reduction of mirror reflectance. Since the reflected polarized ASE signal after passing again the EDF is amplified to a saturation level, the k value is relatively insensitive to the polarizer's insertion loss.

The polarizer's insertion loss also degrades the output ER. In the four configurations, the DPB SFS

Fig. 4. Dependence of k values on polarizer insertion loss for each optimal SFS.

has the least ER because the length between the polarizer and the output end is the longest. To increase ER, we may use a higher pump or a bidirectional pump.¹² Figure 5 shows that the ER of a polarized DPB SFS can be quite high at higher pumps. This is because the power is of approximately the noise level in the orthogonal polarization direction just past the polarizer, while the power in the desired polarization increases with pump power. k values also increase with pump power.

Although a polarized DPB SFS can provide good polarization power conversion, the mean-wavelength stability also needs to be conserved. It has been shown that a DPB SFS would have less mean-wavelength sensitivity to mirror reflectance.¹⁰ To insert a polarizer at the mirror end is equivalent to reducing the mirror reflectance, which then implies that the spectral stability shall not be changed sig-

Fig. 5. Dependence of k values and SFS output extinction ratio on pump power.

Fig. 6. Dependence of mean wavelength and linewidth on pump power for polarized and unpolarized DPB SFSs.

nificantly. It is indeed so, as shown in Fig. 6 for both polarized and unpolarized DPB SFSs. By inserting a polarizer, the mean wavelength shifts slightly to the shorter-wavelength sides. This is because the polarizer filters out half of the reflected ASE signal. The reflected ASE signal will pass longer EDF length and shift to L band. Thus the mean wavelength of polarized SFS shifts to the blue. Note that the $\partial\bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$ region still exists for a polarized DPB SFS.

3. Experiment

A 980-nm laser diode (263 JNG, Lucent) with maximum output power of 130 mW was used as the pumping source. The single-mode EDF had a cutoff wavelength of 945 nm with peak absorption of 9 dB/m and 13.5 dB/m at 979 nm and 1531 nm, respectively. The EDF length used in the experiment was 11 m rather than 13 m in the simulation for $\partial\bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$ operation because the parameters of the two EDFs are different. An in-line polarizer (Wave Optics 650/967-0700) with ~ 0.4 -dB insertion loss and with an ER of ~ 30 dB was used for polarization power conversion. Polarization-maintaining fibers were used in some optical paths for maintaining the polarization states. To reverse forward ASE to backward ASE, a fiber mirror with $\sim 85\%$ reflectance was employed. A precision tunable attenuator was incorporated next to the polarizer for controlling the polarizer's insertion loss. To prevent the SFS from lasing, a polarization-insensitive isolator was used to reduce optical feedback. Spectra ranging from 1500 nm to 1600 nm were measured by using an optical spectrum analyzer. A polarization analyzer was used for ER measurement, and a polarization controller was needed to transform the state of polarization of the SFS output into a linear polarization.

Figure 7 shows the output power variations of polarized and unpolarized DPB SFSs for the same op-

Fig. 7. Measured dependence of output power on pump power for polarized and unpolarized DPB SFSs.

timal conditions. When pumped at ~ 130 mW to maintain $\partial\bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$ operation, this polarized DPB SFS had 24.3-mW output power in the desired polarization, and the k value is thus calculated to be 1.88 [=24.3/(25.9/2)]. The measured ER was 13.3 dB. The polarized SFS power was almost twice as large as an unpolarized one when pump power was far beyond the threshold. Undesired polarization output power was nearly at the same low level over a wide pump range because it was approximately the noise level just after the polarizer. Since the parameters of EDF used in the simulation and experiments are not the same, the optimal EDF length for $\partial\bar{\lambda}_{\text{source}}/\partial P_{\text{pump}} = 0$ operation, and the optimal polarizer position for least sensitivity to insertion loss, had to be adjusted in the experiments.

Figure 8 shows the pump-power dependence of

Fig. 8. Measured dependence of mean wavelength and linewidth on pump power for polarized and unpolarized DPB SFSs.

Fig. 9. Measured dependence of k on polarizer insertion loss for DPB and SPB SFSs.

mean-wavelength stability and linewidth. It can be seen that $\partial\lambda_{\text{source}}/\partial P_{\text{pump}} = 0$ still exists at almost the same pump power (~ 100 mW) for the polarized SFS, indicating that stable pump-power-independent mean-wavelength operation can be obtained. Note that the mean-wavelength shifts to a shorter one, in agreement with the simulated result. The pump-power dependence of linewidth is also shown in Fig. 8. As expected, the polarized DPB SFS has the same trend as the unpolarized one. And the linewidth of the polarized SFS is slightly higher than that of the unpolarized one for a larger pump level.

In the simulation mentioned previously, it is seen that one unique advantage of using a polarized DPB SFS is due to its insensitivity to insertion loss. The SPB and DPB SFSs are experimentally compared and shown in Fig. 9. The total insertion loss including the splice of the EDF and the polarizer is less than 0.5 dB. The k -value degradation is $-0.06/\text{dB}$ for a polarized DPB SFS, much smaller than that of the SPB. This result agrees well with the simulated one in trend.

4. Conclusion

A polarized DPB SFS has been shown to deliver nearly twice the output power in the desired polarization as an unpolarized one, namely, exhibiting a high k value of ~ 1.88 and an ER of 13.3 dB. For a single pump, the optimal position of placing a polarizer to obtain such a high k value is found at the mirror end. Unlike the other configurations, a polarized DPB SFS is shown markedly insensitive to polarizer insertion loss, with a measured k -value degradation of $-0.06/\text{dB}$. Such low sensitivity arises from the low-reflectance requirement of a fiber mirror

to form the DPB SFS, since even a cleaved fiber end ($R \approx 4\%$) is enough to act as a mirror. Therefore when compared with the polarized SPB SFS, the polarized DPB SFS possesses better tolerance toward insertion loss, which is equivalent to the reduction of mirror reflectance. It has been also shown that a pump-power-independent mean-wavelength operation and broad bandwidth can still exist for a polarized DPB SFS, which are helpful for obtaining a mean-wavelength-stabilized source.

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