Band Selection in Broadband Loop ASE Source Using Seed Signal Injection

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***Abstract*—Band selection in a broadband $(C + L)$ loop amplified spontaneous emission (ASE) source using C-band seed signal injection is experimentally demonstrated and compared with conventional double-pass bidirectionally pumped ASE source designs. Significant suppression in C-band and increase in L-band ASE powers were observed for increasing C-band seed signal power. This enables C-, $C + L$-, and L-band operations in the loop ASE source with the seed signal power of less than -12 dBm, between -12 and -3 dBm, and higher than -3 dBm, respectively.**

***Index Terms*—Amplified spontaneous emission (ASE) source, erbium-doped fiber amplifier (EDFA), superfluorescent fiber source.**

I. Introduction

BROADBAND amplified spontaneous emission (ASE) light sources with high power, low spectral ripple, and short coherence length have recently become desirable in several applications such as light sources for dense wavelength-division-multiplexing (DWDM) device and erbium-doped fiber amplifier (EDFA) characterization [1], spectrum-sliced DWDM sources [2], fiber-optic gyroscopes [3], optical sensor systems [4], and low coherence tomography [5]. However, in general it is difficult for an erbium-doped fiber (EDF) ASE source to simultaneously achieve broad bandwidth, low ripple, and high output power by simply varying the pumping power as the bandwidth quickly narrows with increasing pump power. Using various schemes of double-pass configuration, high-power ASE sources have previously been realized to operate in either the C-band [6] or L-band [7]. Various different methods have also been demonstrated to provide broadband operation in an ASE up to 80 nm within $C + L$-band such as double-pass dual pumping with 1480/980-nm laser diodes [8] or a two-stage configuration with dual pumping and spectral flattening using a long period fiber grating filter [9]. Recently, an ASE source design enabling us to operate in a selective C- or L-band region have been proposed through the selection of the pumping scheme using an optical switch [10]. In this letter, a band selectable broadband loop ASE source is experimentally demonstrated operating in C-, L-, or $C + L$-band through a C-band seed signal injection. The loop design of C and L-band EDFAs have been demonstrated previously [11], [12]. In the loop ASE source design, the output ASE spectral evolution as a function of the seed signal power shows a significant C-band ASE suppression while L-band ASE power increases. This enables C-, $C + L$-, and L-band operations in the loop ASE source with nearly equal output powers. The output spectrum of the loop ASE source is also compared with conventional double-pass ASE source designs.

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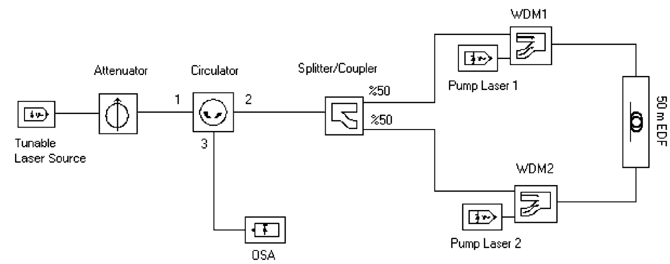

Fig. 1. Band selectable broadband loop ASE source.

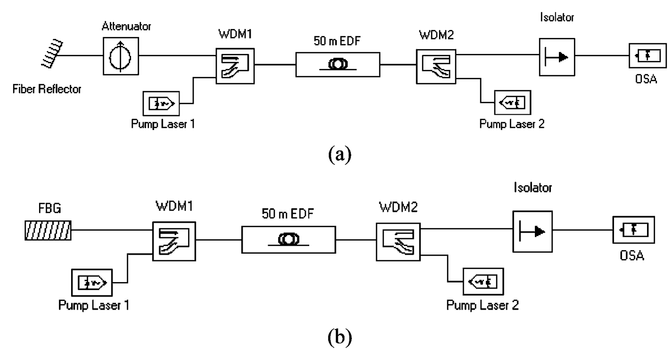

Fig. 2. Conventional bidirectionally pumped double-pass ASE source design with (a) gold-coated broadband fiber reflector and (b) C-band FBG reflector.

A. Experimental Setup

The band selectable loop design of bidirectionally pumped EDF ASE source is shown in Fig. 1. In this configuration, a tunable laser source (TLS) tuned at 1550 nm with a variable optical attenuator was used as C-band seed signal. The TLS used in the setup has a bandwidth of 0.04 nm and a long-term stability of ±0.01 dB. C-band seed signal is directed through a wideband circulator and a 3-dB coupler and applied to the EDF loop pumped bidirectionally at 980 nm. On the other hand, in conventional double-pass ASE source designs shown in Fig. 2(a) and (b), either a gold-coated broadband fiber reflector with a variable attenuator to optimize the reflection ratio or a C-band fiber Bragg grating (FBG) reflector operating at 1525–1565-nm window with a flat reflection spectrum was used to perform the double-pass operation. In conventional designs, an isolator was also used only at the output of the ASE source to suppress lasing

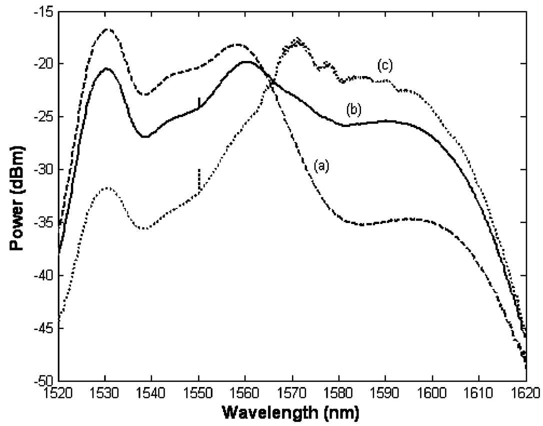

Fig. 3. Band selected output spectra of the loop ASE source for different seed signal powers (a) C-band without seed signal, (b) $C+L$-band with a seed signal power of -8 dBm, and (c) L-band with a seed signal power of 0 dBm.

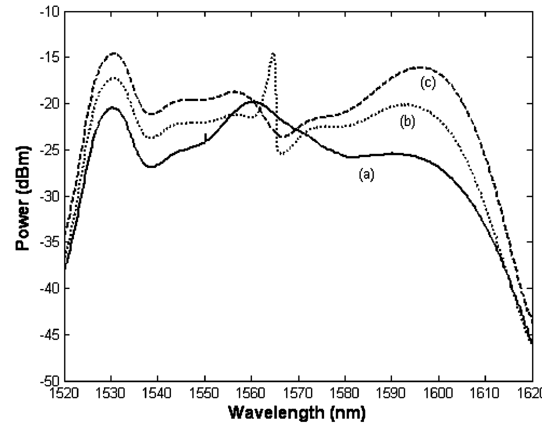

Fig. 4. Measured output spectra for different configurations (a) $C+L$-band loop ASE source with a seed signal power of -8 dBm. (b) Conventional double-pass ASE source with a C-band FBG reflector. (c) Conventional double-pass ASE source with a fiber reflector and optimized reflection.

oscillations. The EDF used in this experiment was 50 m long and its NA is 0.21, cutoff wavelength is 960 nm, core radius is 1.75 μm, and background loss at 1310 nm is 8 dB/km, absorption loss at 980 nm is 10.46 dB/m, and emission loss at 1530 nm is 16.59 dB/m. The ASE output signal is observed with an Anritsu MS9710B optical spectrum analyzer. The pump power applied in all configurations is 230.6 mW, with 103 mW in Pump Laser 1 and 127.6 mW in Pump Laser 2.

II. Results and Discussion

First, the output ASE spectrum measurements were performed for the loop ASE source as a function of seed signal power. The measured output ASE spectra of the loop ASE source are shown in Fig. 3 for three different seed signal powers. As shown in Fig. 3(a), C-band backward ASE generated at both sides of the loop ASE source was observed at the source output without applying a seed signal. When a seed signal power of -8 dBm is applied, C-band ASE is partly suppressed and its energy is transferred to L-band resulting in a $C+L$-band ASE output [Fig. 3(b)]. If the seed signal power is further increased to 0 dBm, C-band ASE is then significantly suppressed and the output ASE spectrum narrows covering only L-band as shown in Fig. 3(c). The effect of C-band seed signal injection at 1550 nm as a control signal in a loop design can be explained by two mechanisms: First, the C-band backward ASE is suppressed at the input section of the EDF so that the pump power can be converted more efficiently to the L-band ASE power. The pump power to L-band ASE power conversion efficiency enhancement provided by the C-band seed signal injection depends on both of the seed signal wavelength and the injected power level. C-band backward ASE at around 1535 nm is significantly suppressed when the C-band seed signal wavelength is varied from 1540 to 1560 nm [12]. Second, the injected C-band seed signal is strongly amplified at the input section which is then used as a secondary pumping source at 1550 nm to the system. It has been shown [13] that an L-band EDFA or ASE source can efficiently be pumped using a 1530–1550-nm band pumping source. The efficient operating limits of the seed signal is sufficiently wide to tolerate small bandwidth and power deviations in the C-band source. Using a longer length of EDF and higher pumping powers, maximum energy transfer from the C-band to the L-band can be achieved, resulting in an extended ASE spectrum at the source output.

TABLE I
Comparison of the Loop ASE Source and Conventional Double-Pass Design ASE Sources

	C Band Loop ASE source	C+L Band Loop ASE source	DP design with a FBG reflector	DP design with a fiber reflector
ΔP	6 dB	7.6 dB	11.2 dB	9 dB
Po	+11.3 dBm	+10.5 dBm	+15.27 dBm	+15.27 dBm
Δλ	41.2 nm	85 nm	79.8 nm	85.6 nm
λm	1545.8 nm	1566.4 nm	1564.8 nm	1566.6 nm

Fig. 4 shows the comparison of the output spectra for the loop and conventional double-pass broadband ASE sources. Fig. 4(a) shows the output ASE spectrum of the loop design with a seed signal power of -8 dBm. Fig. 4(b) and (c) show the output spectra of conventional double-pass ASE sources with a C-band FBG reflector and a broadband fiber reflector, respectively. The reflection ratio of the fiber reflector was optimized using the attenuator about $\sim$ %30 to obtain a maximum bandwidth at the ASE spectrum. Although the conventional double-pass designs with FBG and fiber reflector give higher output powers, the proposed loop design has resulted in relatively less power variation and a different spectral shape at the output spectrum. Specifically, the conventional double-pass design with a broadband fiber reflector results in a large peak at 1530- and 1600-nm regions and a deep valley at 1565-nm region. The conventional double-pass design with a C-band FBG reflector also exhibits an additional large peak at around 1564.8 nm as lasing oscillations due to the insufficient sharpness of the filter response and the signal gain provided within the loop. On the other hand, the loop design exhibits relatively small peaks at 1530- and 1560-nm regions. The output power decrease in loop design, however, can be explained by extra signal losses resulting from the 3-dB coupler and the circulator. The conventional designs given in Fig. 2(a) and (b) can only allow $C+L$- and L-band operations without and with the injection of a sufficient seed signal through a circulator inserted at the output side, respectively. Therefore, C-band operation by simply varying the seed signal injection will not be possible. Table I shows comparison of their specifications for different ASE source configurations namely power

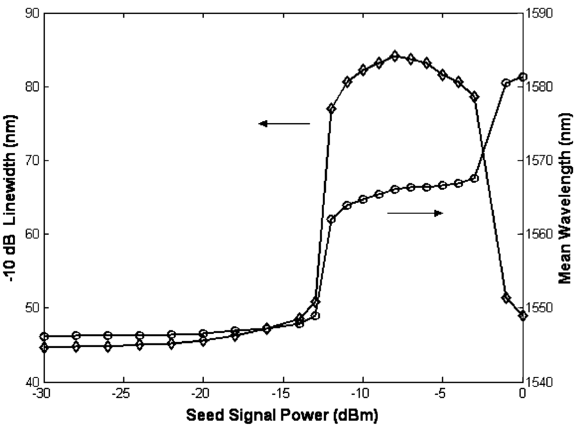

Fig. 5. The -10-dB linewidth and mean wavelength of the loop ASE source as a function of the seed signal power. ($P_{\rm p.tot} = 230.6$ mW).

variation defined as the difference between the peak and valley power in the 1525–1600-nm region (ΔP), mean output power (Po), -10-dB linewidth $(\Delta\lambda)$ defined as the spectrum width at level down by the 10 dB from the peak level and mean wavelength (λm) defined as the mean value of -10-dB cut points.

Fig. 5 shows the measured -10-dB linewidth and mean wavelength of the loop ASE source output as a function of the seed signal power. For the seed signal powers smaller than -12 dB, the output ASE spectrum is mostly within C-band. When the seed signal power is varied between -12 and -3 dBm, the linewidth of the ASE source reaches at the highest value and $C+L$-band ASE operation is achieved. The maximum linewidth was obtained as 85 nm for a seed signal power of -8 dBm. The output power of the ASE source slightly decreases from $+11.3$ dBm in C-band operation to $+10.5$ dBm for $C + L$ and $+10.6$ dB for L-band operations. The mean wavelength of the output spectrum in $C + L$-band operation is quite stable being 1566.4 nm with a maximum deviation of ± 2.7 nm for the seed signal powers from -12 to -3 dBm. The stability of the ASE source mean wavelength determines the accuracy of rotation detection and a broader linewidth provides a higher signal to noise ratio in fiber-optic gyroscopes [3], [6]. For seed signal powers higher than -3 dBm applied to loop ASE source, the output spectrum mostly shifts to longer wavelengths and, therefore, a complete L-band ASE source operation is realized. Due to the limited output power available from the TLS, the measurements have been performed for the seed signal powers from -30 to 0 dBm.

III. CONCLUSION

Band selection in a broadband $(C + L)$ loop ASE source through C-band seed signal injection as a control signal input was experimentally demonstrated and its performance was compared with the performance of conventional double-pass bidirectionally pumped ASE source designs. In the loop ASE source design, a significant suppression in the C-band backward ASE power and increase in the L-band ASE power were observed for increasing C-band seed signal power. This has enabled C-, $C + L$-, and L-band operations in the loop ASE source with the seed signal power of less than -12 dBm, between -12 and -3 dBm, and higher than -3 dBm, respectively. The proposed design also allows the user controlled sweeping of the output spectrum from C- to L-band. The band selection feature of a loop ASE source can be used in various applications such as all-optical switching in L-band and band-selected DWDM device characterization.

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