

A Highly Stable Low-RIN Hybrid Brillouin/Erbium Amplified Laser Source

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Abstract—We demonstrate a low-noise all-fiber hybrid Brillouin/erbium amplified source consisting of a Brillouin/erbium fiber laser with a subsequent Brillouin amplifier to boost the power and reduce the noise. The same single-mode fibers used in the fiber laser and the amplifier lead to the same amount of Stokes frequency shifts in spite of the environmental variation, ensuring stable Brillouin amplification. The hybridly amplified source features temperature insensitivity, low noise, potentially high power, and low cost. The relative intensity noise of the hybridly amplified source is ~ 10 dB lower than that of the erbium-doped fiber amplifier (EDFA)-based source at radio frequencies > 200 MHz due to the filtering characteristics of the Brillouin amplification. Compared with an EDFA amplified fiber system, the spurious-free dynamic range of an analog transmission system employing such a laser source is improved by 7.7 dB owing to the lower RIN.

Index Terms—Amplifier, beat noise, dynamic range, erbium, relative intensity noise (RIN), stimulated Brillouin scattering.

HIGH-POWER laser sources with low relative intensity noise (RIN) are desired for applications in analog photonic links. To achieve high output power, an erbium-doped fiber amplifier (EDFA) is usually used to boost the power from a semiconductor laser. However, due to the amplified spontaneous emission (ASE) noise, the EDFA degrades the RIN performance of the laser source. Though solid-state lasers can achieve high output power and low RIN simultaneously, they are bulky and expensive. Hybrid Brillouin/erbium amplifiers have been proposed to achieve high power and low RIN [1], [2], taking advantage of the narrow bandwidth of the Brillouin amplification and the high output power of the EDFA. In these hybrid amplifiers, the first low-frequency sideband of a phase-modulated distributed feedback (DFB) laser is used as the seed signal of a Brillouin amplifier, while the amplified DFB laser output serves as the Brillouin pump. The driving frequency of the phase modulator must be exactly equal to the Stokes frequency shift of the Brillouin amplifier to ensure effective amplification. However, the Stokes frequency shift of the fiber could change with the temperature variation of the environment [3], [4], while the bandwidth of the Brillouin gain

Manuscript received January 9, 2006; revised February 11, 2006. This work was supported by National Natural Science Foundation of China under Grants 60577048/10474064/60407008/90304002, and by the Science and Technology Committee of Shanghai Municipal under Grants 022261003/04DZ14001/04DZ05103.

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Digital Object Identifier 10.1109/LPT.2006.873484

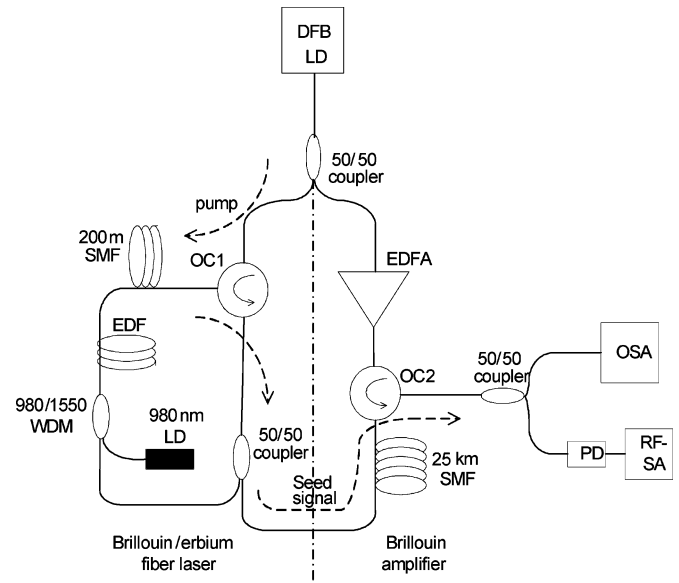


Fig. 1. Experimental setup of the hybrid Brillouin/erbium amplified laser source.

is limited to several tens of megahertz [4]. Therefore, such a hybrid amplifier would need signal monitoring and temperature control in practical applications. Besides, the hybrid amplifier requires a high-speed modulator and a high-frequency RF source. In addition, the phase modulation produces unwanted multiple sidebands, which are output with the amplified signal.

To improve the performance of the hybrid Brillouin/erbium amplifier, we propose a new all-fiber hybrid amplifier, in which a Brillouin/erbium fiber laser [5] is used to generate the seed signal of the Brillouin amplifier. Since the characteristics of the single-mode fibers (SMFs) used in the fiber laser and the amplifier are identical, the frequency difference between the seed-signal and the Brillouin pump is equal to the Stokes frequency of the Brillouin amplifier in spite of the temperature variation. The scheme uses a low-cost Brillouin/erbium fiber laser to replace a high-speed phase modulator and its RF source/driver [1], [2]; therefore, it is potentially cost-effective. Furthermore, the Brillouin/erbium fiber laser operates in a single longitudinal mode [5], which ensures the single frequency output of the amplifier. This hybrid amplifier utilizes the narrow-bandwidth feature of the Brillouin amplification to suppress the RIN.

Fig. 1 shows the experimental setup of the new hybrid Brillouin/erbium amplified laser source, which mainly consists of a Brillouin/erbium fiber laser and a Brillouin amplifier. The 0-dBm output power from a 1557-nm DFB laser is divided into

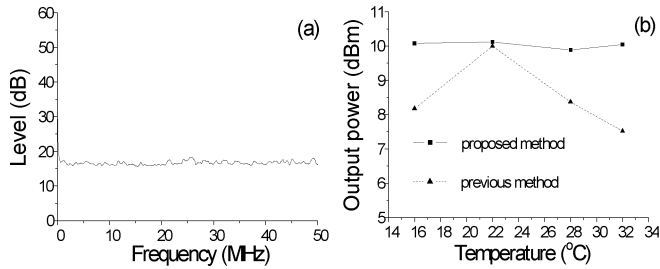


Fig. 2. (a) Single-longitudinal-mode operations of the hybridly amplified laser source. (b) Temperature dependency of the output powers of the previous and the proposed methods.

two paths by a 50/50 coupler. In the left part, the light serves as the Brillouin pump of the Brillouin/erbium fiber laser, in which a 200-m standard SMF is used as the Brillouin media to generate the backward Brillouin signal, and an EDFA with a 5-m EDF of 240-ppm erbium ion concentration is used as the primary gain media to amplify the Brillouin signal. In the EDFA, the pump power is kept low to avoid multiline Brillouin lasing [6]. The -3 -dBm Brillouin pump power is above the Brillouin threshold of the Brillouin/erbium fiber laser and the EDFA provides most of the cavity gain. Lasing at 1557.088 nm is formed once the gain is larger than the cavity loss. The optical circulator (OC1) ensures the counterclockwise propagation of the Brillouin lasing signal, and a 2-dBm output power exits the cavity through the second 50/50 coupler. In the right part, the DFB laser output is amplified to 14 dBm by another EDFA and then injected into a 25-km SMF through a second circulator (OC2) to serve as the pump of the Brillouin amplifier. The output from the Brillouin/erbium fiber laser is Brillouin-frequency shifted; therefore, it can serve as the seed-signal to the Brillouin amplifier, where it is amplified to 10 dBm. The amplified signal is output from the OC2 and then divided by the third 50/50 coupler. One part is sent to an optical spectrum analyzer (OSA) and the other is detected by a photodetector (PD) followed by an RF spectrum analyzer (RF-SA).

Typically, an erbium-doped fiber laser exhibits multiple longitudinal modes because of the inhomogeneous broadening of the EDF. However, in the Brillouin/erbium fiber laser, the homogenous Brillouin gain of the SMF suppresses the free run process of the EDF. As a result, the combined nonlinear gain in the SMF and the EDF gain lead to single-mode operation, and the linewidth is in the kilohertz range or less [5]. Fig. 2(a) shows the single-longitudinal-mode operation of the Brillouin/erbium fiber laser, which is measured by a PD followed by an RF-SA. No longitudinal mode beating is observed at ~ 1 MHz, which corresponds to the free spectral range of the fiber-ring length of ~ 210 m. As the SMFs used in the Brillouin/erbium fiber laser and the Brillouin amplifier are of the same type, the Brillouin Stokes shifts of the two SMFs are equal regardless of the temperature change, which ensures the stable power output of the hybrid amplifier. Fig. 2(b) shows the temperature dependency of the output powers using the previous and our proposed methods, respectively. We used a tunable LD to mimic the sideband produced by a phase modulator in [1], and the powers and wavelengths of the Brillouin pump and the signal are set to be the same values as those in our proposed method. It can be clearly

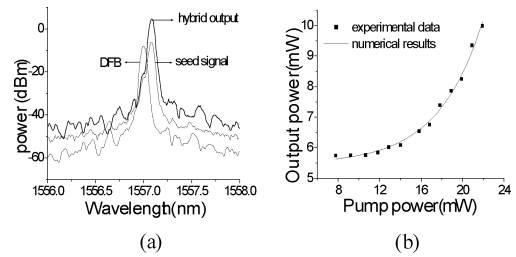


Fig. 3. (a) Optical spectra of the DFB laser, the Brillouin/erbium fiber laser, and the hybrid Brillouin/erbium amplified source at 0.07-nm resolution bandwidth. (b) Output power of the hybrid amplifier versus the pump power.

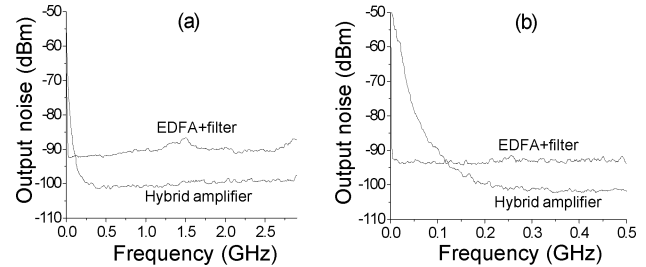


Fig. 4. Output noise power spectra (at 100-kHz resolution bandwidth) of the hybridly amplified source and the EDFA amplified source with a filter. The RF frequency span is (a) 2.9 GHz and (b) 500 MHz, respectively.

observed that the output power changes with the environmental temperature variation because of the temperature dependency of the fiber Brillouin frequency shift. However, with our proposed method, the output power is almost constant in spite of the temperature change.

We present in Fig. 3(a) the optical spectra of the output signals from the DFB laser, the Brillouin/erbium fiber laser, and the hybrid amplifier, respectively, at 0.07-nm resolution bandwidth to show the generation and amplification process of the Brillouin laser. It is shown experimentally that the 10-dBm maximum output power is limited by the EDFA with a 14-dBm maximum power. It is also found that the output power of the hybrid amplifier increases exponentially with the Brillouin pump power both in the experimental and the numerical results, as shown in Fig. 3(b). The pump conversion efficiency at the maximum output level is about 40%. This high conversion efficiency can be attributed to the exact and self-sustained frequency match between the seed signal and the Stokes frequency of the Brillouin amplifier in our proposed method. Higher output power could be achieved if a high-power EDFA were available.

We compare the noise performance of the hybridly amplified source and a DFB followed by an EDFA by measuring the RIN using an RF-SA, as shown in Fig. 4. After a 10-GHz PD, the electrical noise includes the shot noise, the spontaneous-spontaneous beat noise, and the signal-spontaneous beat noise. Among them, the last one is dominant. An optical filter can remove most ASE power from the EDFA; however, the signal-spontaneous beat noise is nearly unchanged within the filter bandwidth. In the hybrid amplifier, owing to the narrow Brillouin gain bandwidth, the high-frequency signal-spontaneous and the spontaneous-spontaneous beat noises are greatly reduced. The noise power of the hybridly amplified laser is ~ 10 dB lower at frequencies > 200 MHz than the EDFA amplified source, as shown in Fig. 4(a). In this figure,

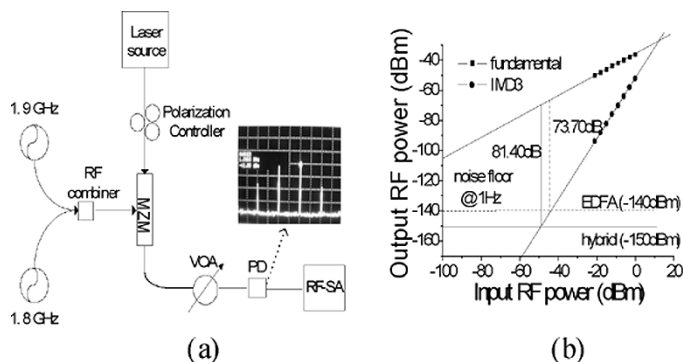


Fig. 5. (a) Experimental setup of the analog system. (b) Two-tone SFDR measurement results.

2.9 GHz is the maximal frequency range of the RF-SA. Within this range, the measured RIN of the hybrid Brillouin/erbium amplified laser source is ~ -150 dB/Hz, which is limited by the RF-SA and would be close to the shot-noise limitation [1] as the high-frequency signal-spontaneous beat noise out of the Brillouin amplification bandwidth is filtered. At frequencies < 100 MHz, the noise power of the hybrid amplifier is larger than that of the EDFA amplified source, as shown in Fig. 4(b), because of the strong Brillouin amplification noise [2] and the spontaneous Brillouin scattering [7].

To demonstrate the applications of this hybrid Brillouin/erbium amplified laser source in an analog photonic link such as radio-over-fiber, we measured a critical parameter in analog transmission systems: spurious-free dynamic range (SFDR). SFDR is defined as the dynamic range of the input RF power with the minimal required RF power determined by the noise performance of the source, and the maximum signal level limited by the nonlinearity [8]. A lower RIN of the source would lead to a larger SFDR based on the definition. The measurement setup is shown in Fig. 5(a). In the measurement, both the laser sources are intensity modulated through a Mach-Zehnder modulator (MZM) using two RF signals at 1.8 and 1.9 GHz, which have the same power and are combined by an RF combiner. A 2.5-GHz PD with -7 -dBm saturation power is used to receive the signals. Before the PD a variable optical attenuator (VOA) is inserted to ensure linear operation of the PD. After the PD, an RF-SA is used to measure the RF spectrum. The hybridly amplified laser source and the EDFA amplified source with a 10-dBm output power are used consecutively as the sources of the analog fiber system. The received RF power is linearly increased with the input RF power and the third-order

intermodulation distortion (IMD3) effect is produced when the strong input RF power results in spurious components due to the nonlinearity of the system, which is shown in the inset of Fig. 5(a). The SFDR measurements of the two sources are shown in Fig. 5(b), respectively. The SFDR of the hybridly amplified fiber system is 81.4 dB \cdot Hz $^{2/3}$, which is extended by 7.7 dB compared with that of the EDFA amplified system because of the ~ 10 -dB reduction in the noise floor. In this particular demonstration, the SFDR is clearly improved by using the low-noise source, while the upper bound of the SFDR is limited by the linearity of the PD and the MZM.

In summary, we have experimentally demonstrated an all-fiber low-noise hybrid Brillouin/erbium amplifier with a highly stable low-RIN laser source. This Brillouin/erbium amplified laser source eliminates the need for a high-speed phase modulator or an RF source, and is insensitive to the temperature variation. Meanwhile, the single-longitudinal-mode operation of the Brillouin/erbium fiber laser ensures the single-frequency output of the hybrid amplifier. The hybridly amplified laser source exhibits ~ 10 -dB reduction in the RIN compared with the conventional EDFA-based source at frequencies > 200 MHz, which leads to ~ 7.7 -dB SFDR improvement in an analog system. This stable, low-noise, and low-cost fiber amplified source would be attractive for analog photonics applications.

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