

# An all-fiber low-noise hybrid Erbium-Brillouin amplified laser source

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**Abstract:** We demonstrate a novel all-fiber hybrid erbium-Brillouin amplified laser source, and achieve 8-dB reduction of RIN compared with an EDFA based source. The resulting spurious-free dynamic range in an analog system is improved by 6.8 dB.

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## 1. Introduction

High-power laser sources with low relative intensity noise (RIN) are desired for applications in analog photonic links. The conventional method is to use an erbium-doped fiber amplifier (EDFA) to boost the output power of a semiconductor laser. However the strong signal-spontaneous beat noise from the EDFA degrades the RIN performance and limits the spurious-free dynamic range (SFDR) of the photonic link. A solid-state laser has high power and low RIN, however is bulky and expensive. To obtain a low-cost, high-power and low-noise laser source, a hybrid erbium-Brillouin amplifier was demonstrated [1,2], in which a phase modulator is employed to generate a sideband of the light from a DFB laser as the seed signal of a Brillouin amplifier. However the modulation frequency of the phase modulator must be exactly equal to the Brillouin frequency shift of the gain fiber to ensure the effective Brillouin amplification. With the temperature variation of the environment, the Brillouin frequency shift of the fiber could change [3]; therefore, such a hybrid amplifier would need monitoring and temperature control in practical applications. Furthermore, the hybrid amplifier requires the high-speed modulator and the associated radio-frequency (RF) source, which incur added cost. In addition, the other sidebands of the phase-modulation and the DC component are also included as the input to the Brillouin amplifier, which could affect the quality of the output signal of the amplified laser source.

In this paper, we propose the use of a single longitudinal-mode Brillouin/erbium fiber laser [4] as the seed source of a hybrid erbium-Brillouin fiber amplifier to avoid the problems discussed above, and demonstrate such a low-noise, highly stable, and low-cost laser source. Since the single-mode fibers (SMFs) used in the seed-signal generator and the fiber amplifier are identical, the frequency difference between the seed-signal and the Brillouin pump is exactly equal to the Brillouin frequency shift, despite of the temperature variation of the environment. In addition, this method eliminates the need of a phase modulator and a high frequency RF source as used in [1,2], thus greatly reduces the cost. The all-fiber hybrid erbium-Brillouin amplifier takes advantage of the narrow bandwidth of the Brillouin amplification to suppress noise. The noise floor of the hybrid amplified source is  $\sim 8$  dB lower than that of the EDFA based laser source, which leads to  $\sim 6.8$  dB SFDR enhancement in an analog photonic link. Such an all-fiber low-noise hybrid erbium-Brillouin amplifier would be a candidate towards practical applications in high-performance photonic links.

## 2. The hybrid erbium-Brillouin amplified laser source

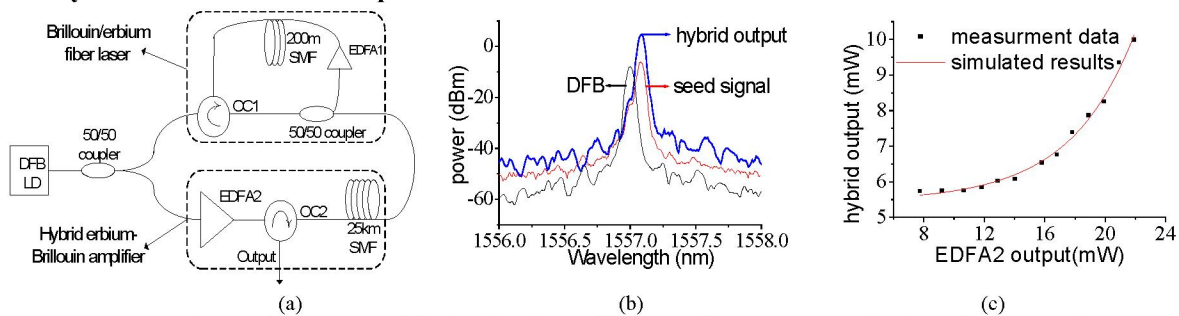


Fig.1 (a) The experimental setup of the hybrid erbium-Brillouin amplified laser source; (b) The optical spectra of the DFB laser, the Brillouin/erbium fiber laser and the hybrid erbium-Brillouin amplified source, respectively, measured by an OSA with a 0.07-nm resolution; (c) The output power of the hybrid amplified source vs. the pump (EDFA2) power.

The experimental setup of the hybrid erbium-Brillouin amplified source is shown in Fig.1 (a). A 0-dBm light output from a 1557-nm DFB laser is divided into two paths by a 50/50 coupler. In the upper path, the -3-dBm light serves as a Brillouin pump to generate the seed signal in the Brillouin/erbium fiber laser, in which a 200m piece of SMF is used as the Brillouin gain medium. The EDFA1 includes a 5-m EDF with 240ppm erbium ion concentration and a 30-mW 980nm pump LD. In the EDFA1, the pump power cannot be set too high; otherwise multiple Brillouin lasing lights would be produced. The EDFA1 provides most of the cavity-gain. At the output port, a 1557.088-nm lasing light with a 2-dBm output power is obtained. The laser exhibits single longitudinal-mode operation and the linewidth is in the kilohertz regime or less [4]. An optical circulator (OC1) ensures the counter-clockwise propagation of the light in the Brillouin/erbium laser, with an output at the second 50/50 coupler. In the lower path, the DFB laser output is amplified to 14 dBm by an EDFA2 and then injected into a 25-km SMF through another circulator (OC2) to pump the seed-signal from the Brillouin/erbium fiber laser. Because the two pieces of SMFs are of same type, the Brillouin frequency shifts of the two fibers are equal regardless of the environmental temperature change. The 14-dBm output power from the EDFA2 is well above the 1.5-mW SBS threshold of the 25-km SMF at the wavelength of 1557 nm, thus the 2-dBm seed signal at 1557.088 nm is efficiently amplified to 10 dBm. The optical spectra of output signals from the DFB laser, the Brillouin/erbium fiber laser and the hybrid-amplified source with a 0.07-nm resolution are shown in Fig. 1 (b). The 10-dBm output power is limited by the pump power of the EDFA2. The output power of the hybrid amplifier increases exponentially with the increasing of the pump power (EDFA2) as depicted in Fig.1 (c). Higher output power could be achieved if the pump were stronger.

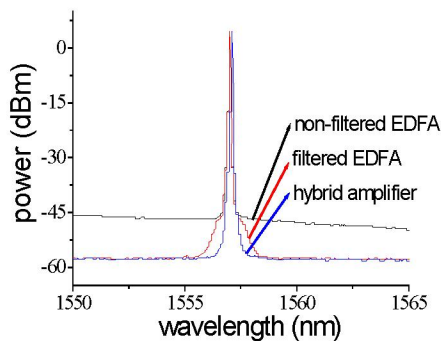


Fig.2. The output optical spectra of the DFB LD, EDFA and hybrid amplified laser source. Both sources were measured with 10dBm output power.

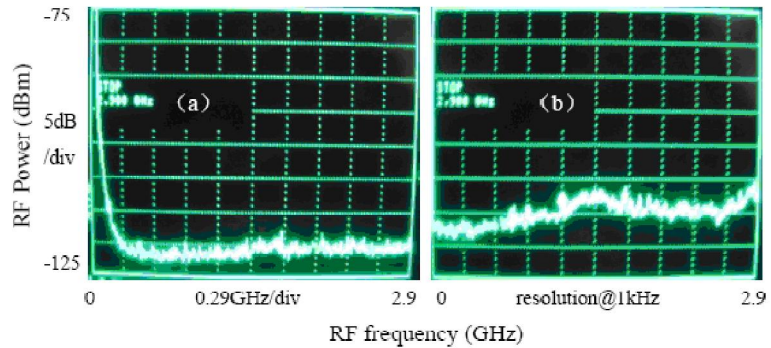


Fig.3. The RF spectra with a 2.9GHz frequency span and a 1kHz resolution. (a) the hybrid amplified source and (b) the filtered, EDFA-amplified source.

To verify the low-noise characteristic of the hybrid erbium-Brillouin amplified source, in Fig. 2 we provide optical spectra of three different sources, including the DFB, the EDFA amplified source, and the hybrid erbium-Brillouin amplified laser source. The output powers of all the sources are set to 10 dBm. The EDFA amplification results in ASE noise, which leads to high noise floor. Although the ASE power can be suppressed using an optical filter, the filter bandwidth is still wide in frequency domain. In this measurement, we used an optical filter with a 100-GHz bandwidth. While for the hybrid erbium-Brillouin amplified laser source, the Brillouin amplifier serves as a narrow band filter ( $\sim 35$  MHz), which filters most of the ASE power from the EDFA.

By using a 10-GHz photodetector (PD), we also compare their noise performance by observing the electrical spectra on a RF spectrum analyzer (RF-SA) as shown in Fig.3. The output noise of the PD includes the shot-noise, the signal-spontaneous beat noise and the spontaneous-spontaneous beat noise, among which the signal-spontaneous beat noise is dominant. An optical filter can filter most ASE from the EDFA, however within the bandwidth of the filter, the beat noise is almost unchanged compared with the case of the EDFA without a subsequent filter. While for the hybrid erbium-Brillouin amplifier with the narrow Brillouin gain bandwidth, the high frequency signal-spontaneous and the spontaneous-spontaneous beat noise are greatly reduced. The noise power of the hybrid-amplified laser is  $\sim 8$  dB lower compared with the EDFA amplified source, which is seen in Fig. 3. In this figure, the 2.9-GHz span is the maximal display range of the RF-SA. Within this frequency range, the measured RIN of the hybrid erbium-Brillouin amplified laser source is  $\sim -150$  dBm/Hz, which is limited by the RF-SA and would be close to the shot-noise limitation [1]. While for the measurement of the EDFA based source, the noise spectrum is non-flat and the RIN was read around the central frequency of the span, which is  $-142$  dBm/Hz. At RF frequency  $< 200$  MHz, the noise power of the hybrid amplifier is larger than that of the EDFA amplified source because of the strong Brillouin amplification noise and the spontaneous Brillouin scattering that covers about ten times the bandwidth of SBS [5]. The latter could be reduced by enhancing the Brillouin pump

power. It is worth noting that the higher power EDFA2 could increase the beat noise of the EDFA amplified laser source, however it does not increase that of the hybrid erbium-Brillouin amplified laser source because of the filtering characteristic of the Brillouin amplification.

### 3. The SFDR measurement

To demonstrate the advantages of this low-noise hybrid erbium-Brillouin amplified laser source, we measured a critical parameter SFDR in an analog system. SFDR is defined as the dynamic range of the input RF power where the minimal required RF power is determined by the noise performance of the source, and the maximum RF signal power level is limited by the inter-modulation products [6]. The experimental setup is shown in Fig. 4 (a). In the measurement, we intensity-modulated the output of the laser source through a Mach-Zehnder modulator (MZM) using two RF signals at 1.8GHz (GSM frequency) and 1.9GHz (PHS frequency) with the same powers, which are combined by a RF combiner. A 2.5-GHz PD with a  $-7\text{dBm}$  saturated power is used to receive the signals. A variable optical attenuator (VOA) is inserted before the PD to ensure the linear reception of the PD. The hybrid erbium-Brillouin amplified laser source and the EDFA amplified source with a  $10\text{-dBm}$  output power are used for the analog fiber link, respectively. The third-order inter-modulation distortion (IMD3) effect is produced when the strong input RF power leads to nonlinearity, which generates RF components at 1.7 GHz and 2.0 GHz. We measure the RF power at 1.7 GHz as the power of IMD3. The SFDR measurements of both sources in the same link are provided in Fig.4 (b). The SFDR of the fiber link using the hybrid erbium-Brillouin amplified source is  $81.4\text{dB}\cdot\text{Hz}^{2/3}$ , which is improved by 6.8 dB compared with that of the link employing DFB-EDFA source. Note that  $-150\text{dBm/Hz}$  noise floor of the hybrid-amplified source is the measurement limitation, and the real noise floor of the source could be lower. In this 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.

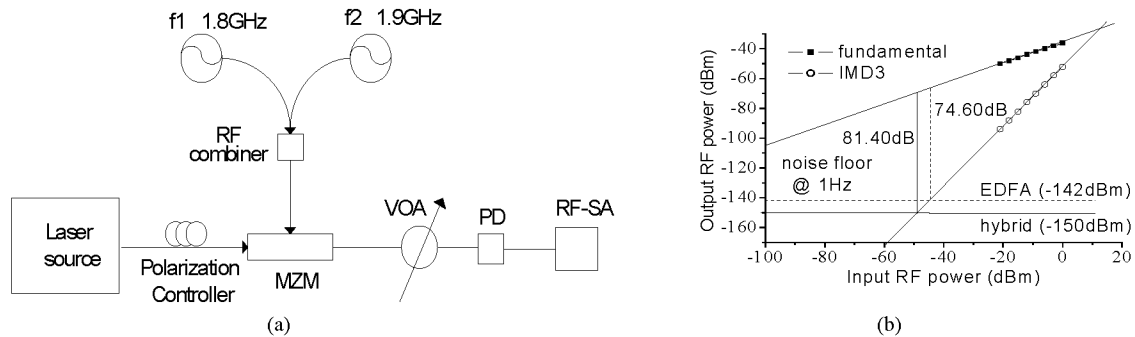


Fig.4 (a) The experimental setup of the analog fiber link; (b) Two-tone SFDR measurement results.

### 4. Conclusion

An all-fiber low-noise hybrid erbium-Brillouin amplified laser source is experimentally demonstrated, which eliminates the need for a high frequency phase modulator and RF source, and is insensitive to temperature change in the environment. The hybrid amplifier achieves  $\sim 8\text{-dB}$  RIN reduction relative to a DFB-EDFA source, which leads to  $\sim 6.8\text{dB}$  SFDR enhancement in an analog fiber link.

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