Brillouin Random Fiber Lasing Oscillation with Enhanced Noise Suppression for 64-QAM Coherent Communications

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***Abstract*—Brillouin random fiber lasing oscillation with superior noise suppression was proposed to incorporate in dual-polarization 64-QAM coherent optical communications, highlighting the potential of the bit error rate reduction by more than one-order of magnitude.**

Keywords—noise suppression; stimulated Brillouin scattering; coherent optical communications

I. Introduction

Higher-order quadrature amplitude modulation (QAM) format is very attractive for high-capacity optical transmission systems [1], in which highly coherent laser sources with narrow linewidth are basically required as the carrier laser sources. Otherwise, a broad linewidth laser source with high frequency noise (FN) will deteriorate the bit error rate (BER) in 64-QAM systems [2]. Recently, lasers with narrow linewidth and high optical signal-to-noise ratio (OSNR) have been intensively investigated for coherent communications. For instance, a III-V/silicon hybrid external cavity laser on a silicon-on-insulator, which has a 55 dB side-mode suppression ratio and a linewidth of 37 kHz, shows no additional penalty compared to commercially available narrow linewidth lasers for dual-polarization (DP) 16-QAM [3]. Thanks to superior FN suppression based on Brillouin fiber lasing resonance, a long-cavity laser output with linewidth suppression from ~3 MHz down to less than 20 kHz for coherent optical communications is achieved [4]. Although corporately utilization of an additional multifrequency-selection element can maintain single-longitudinal-mode operation to some extent, a dilemma between the long-cavity-based FN suppression and single-longitudinal laser mode capability still exists in conventional fiber cavity-based laser systems, which limits their potentials in coherent communications. Alternatively, Brillouin random fiber lasing oscillation (BRFLO), using randomly distributed Rayleigh scattering as a feedback mechanism, intrinsically eliminates cavity modes while emitting a single-mode laser with low FN and high OSNR [5], playing crucial roles in future high-capacity optical coherent communications.

In this paper, we proposed and demonstrated a laser FN suppression approach based on high-OSNR BRFLO, benefitting a significant BER reduction for DP 64-QAM coherent optical communications. Experimental results show that the proposed

BRFLO can produce a 520 Hz ultra-narrow linewidth laser output at 214 kHz linewidth pumping, achieving ~20 dB FN suppression, whilst the OSNR is improved by more than 20 dB as the OSNR of the pump varies from 38 dB to 53 dB. By means of the BRFLO, the BER of a DP 64-QAM system is expected to be significantly reduced from 1.4×10^{-2} to 9.3×10^{-4} at a pump laser of 38 dB OSNR, which is well below the threshold limit of 3.8×10^{-3} for the forward error correction (FEC).

II. Configuration and Principle

Fig. 1(a) illustrates the experimental configuration of the proposed BRFLO, including an off-the-shelf half-open fiber cavity, which is constructed from two optical circulators (CIRs), a 20 km single-mode fiber (SMF) acting as a Brillouin gain fiber, and a 10 km Rayleigh scattered fiber. The laser is output through an isolator (ISO) that is placed at the back end of the Rayleigh fiber to block any Fresnel reflections. A commercial laser with a linewidth of ~200 kHz is amplified by an erbium-doped fiber amplifier (EDFA) and launched into the proposed half-open fiber cavity. As the pump power is boosted above the stimulated Brillouin scattering (SBS) threshold, the Stokes light can be generated by the SBS process with a slight wavelength up-shift. The Stokes light shows ultra-narrow linewidth performance due to the slow attenuation of the excited acoustic phonon via SBS. Moreover, the 10 km Rayleigh fiber backscatters the Stokes light to the gain fiber through CIR2 to provide random distributed feedback for lasing oscillation, which essentially contributes a Lorentzian envelope over laser FN. Hence, the output laser linewidth compression formula can be derived in terms of the combined effect of Brillouin gain and random Rayleigh feedback [5]. In addition, the effective Brillouin gain spectrum $g_B^{eff}(v)$, *i.e.*, the convolution of the natural Brillouin gain spectrum and the pump spectrum, is introduced to comprehensively characterize the broadening of the SBS gain profile, particularly in the case of the pump laser with up to megahertz linewidth. Thus, the Stokes linewidth Δv_{BRFLO} after the BRFLO can be modified as:

$$\Delta v_{BRFLO} = (\Delta v_p + \alpha \Delta v_B^{eff})/[\beta(1 - \frac{\pi \Delta v_B^{eff}}{c \ln R / n L_r})^2], \quad (1)$$

where R denotes the Rayleigh random feedback parameter. c/n is the light velocity in the fiber. Considering the BRFLO without a fixed resonant cavity, the random cavity length L_r can be equated with $L_g + 2L_R^{eff}$, where L_g is the length of the gain fiber and the effective length of the Rayleigh fiber is expressed as L_R^{eff}. α is the linewidth correction factor. $g_B^{eff}(v)$ remains Lorentzian shape with the effective bandwidth Δv_B^{eff} equaling the sum of the pump linewidth Δv_p and the natural Brillouin gain bandwidth Δv_B in the case where the pump spectrum exhibits a Lorentzian line shape. Note that, the proposed BRFLO with Rayleigh scattering random feedback allows an enhanced laser linewidth compression, which is introduced as the compression factor β in Eq. (1). It indicates that the Brillouin random lasing oscillation with enhanced noise suppression would be beneficial to the QAM system. To evaluate it, a DP 64-QAM system based on the proposed BRFLO technique was simulated, as shown in Fig. 1(b). The polarization beam splitter (PBS) injects a laser in two orthogonal linear polarization states

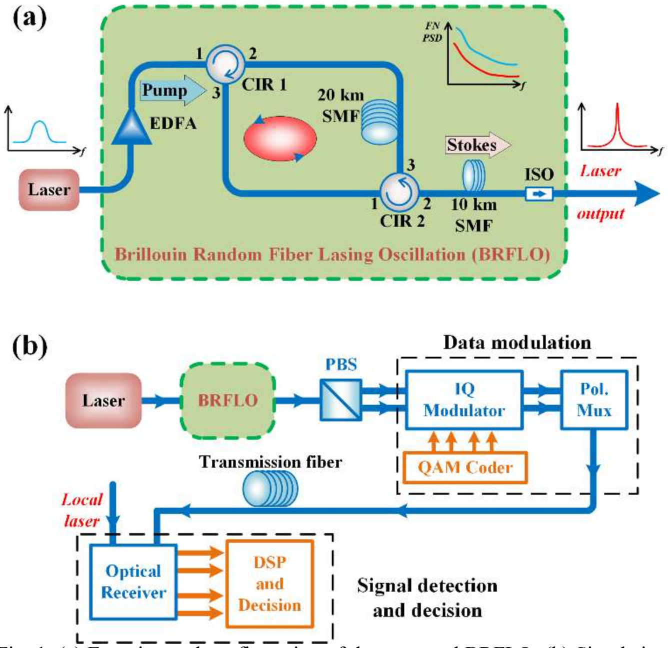

Fig. 1. (a) Experimental configuration of the proposed BRFLO. (b) Simulation schematic of the DP 64-QAM system.

into the data modulation module, which contains the IQ modulator driven by the QAM coder. The 120 Gb/s DP 64-QAM signals are obtained by the polarization multiplexing (Pol.-mux) simulator serving to combine the two signals in DP states. Then, the signals are launched into the signal detection and decision module over 60 km of transmission fiber. The optical receiver is responsible for the coherent detection of the signals passing through the Gaussian optical filter. Finally, the DP 64-QAM signals are recovered under the operation of the digital signal processing (DSP) and symbol decision.

III. Results and Discussions

The laser linewidth was characterized by the delayed self-heterodyne (DSH) method with 80 MHz frequency shift. Considering the difference in magnitude between the pump and Stokes linewidths, 3 km and 100 km delay fibers were used for the linewidth measurements, respectively. The obtained results can be well fitted with the Lorentz curve, from which the 3-dB linewidths can be calculated, as shown in the insets of Fig. 2(a). The Stokes exhibits a 3-dB linewidth of 520 Hz, while its pump shows a 3-dB linewidth of 214 kHz, indicating a linewidth compression ratio of up to ~412 for the proposed BRFLO. To characterize the relationship between Stokes and pump linewidth, according to Eq. (1), the theoretical curve shown in Fig. 2(a) can be derived in the case of the Rayleigh feedback parameter R of 1.2×10^{-4} and Δv_B of 20 MHz. When the pump linewidth is 214 kHz, the Stokes has a linewidth of 520.6 Hz with the linewidth correction factor α of 0.04 and Rayleigh-induced factor β of 0.002, showing a good agreement with the results of DSH. The FN power spectral densities (PSDs) of the Stokes and the pump were measured by an imbalanced Michelson interferometer composed of a 3×3 optical fiber coupler, where a 1 km SMF acted as a delay fiber. In Fig. 2(b), the FN PSD of the Stokes is significantly reduced by ~20 dB at the Fourier frequencies between 400 Hz and 60 kHz compared to that of the pump, which demonstrates the pronounced

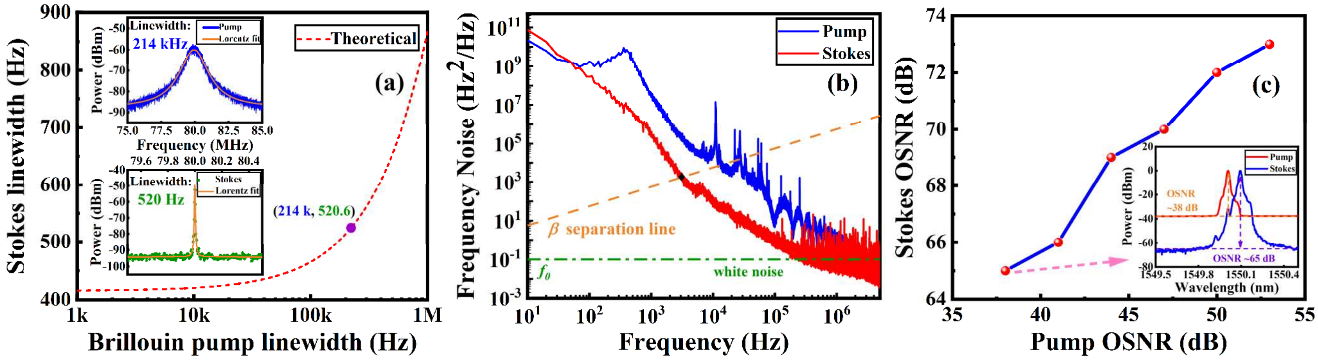

Fig. 2. (a) The Stokes linewidth versus the Brillouin pump linewidth. Insets: the linewidth measurement of pump and Stokes. (b) The FN PSDs of the pump, and the Stokes. The β separation line ($8\,f\,\ln(2)/\pi^2$) and white noise limit line are drawn by orange and green dashes, respectively. (c) The Stokes OSNR versus the pump OSNR. Inset: optical spectra of 38 dB OSNR pump, and Stokes.

suppression of the FN by the BRFLO. The Brillouin gain drift due to ambient temperature fluctuations results in relatively high FN in the low-frequency domain. The intrinsic linewidth of the Stokes is ~0.31 Hz calculated from $\Delta v = f_0\pi$ at the white noise $f_0 = 0.1\ \mathrm{Hz}^2/\mathrm{Hz}$. In addition, the β separation line approach can be utilized to evaluate the linewidth of the Stokes [6]. As the measurement time is set to be 0.35 ms, the linewidth of 448 Hz is obtained, which basically coincides with the measured linewidth using the DSH method.

To evaluate the impact of the pump OSNR variation, the laser coupled with adjustable amplifier spontaneous emission noise from another EDFA was injected into the BRFLO. Then, the corresponding Stokes spectra at different pump OSNRs were measured by an optical spectrum analyzer. In Fig. 2(c), as the OSNR of the pump increases linearly from 38 dB to 53 dB, the OSNR of the Stokes increases accordingly, from 65 dB to 73 dB. The inset in Fig. 2(c) shows the spectrogram of the 38 dB OSNR pump and its corresponding Stokes. The generated Stokes features a wavelength up-shift of 0.08 nm from the pump, corresponding to the Brillouin frequency shift of ~11 GHz, which is negligible in coherent communication.

Figure 3(a) shows the constellation diagrams for both polarizations without and with the BRFLO at the commercial laser with the 214 kHz linewidth and 38 dB OSNR. Without the BRFLO, the system suffers a certain distortion, reaching the BER of 1.4×10^{-2} , which is not conducive to signal demodulation. On the other hand, by employing the BRFLO, a concentrated data code distribution can be achieved, and the BER can be as low as 9.3×10^{-4}, well bellowing the FEC limit.

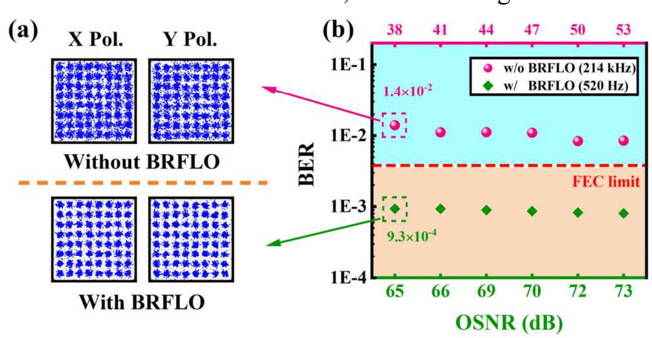

Fig. 3. (a) The constellation diagrams without and with the BRFLO. (b) The calculated BER versus the OSNR without and with the BRFLO.

The calculated BER versus the OSNR of the laser without and with the BRFLO, as depicted in Fig. 3(b), indicates that the BER based on the BRFLO wanders below the FEC limit, yet the BER is higher than the FEC limit without the BRFLO. Note that, the BER will fall gently as the OSNR of the laser source increases.

IV. Conclusion

To summarize, the proposed BRFLO technique brings crucial advantages in terms of FN suppression and OSNR improvement for application in QAM systems. Take advantage of the BRFLO, the FN of the laser source is suppressed by ~20 dB, correspondingly a linewidth compression ratio of up to 412. Additionally, the OSNR is further improved by over 20 dB. Consequently, a low BER of 9.3×10^(-4) in the DP 64-QAM system is expected. These findings suggest that the proposed BRFLO technique exhibits great potential for future long-haul coherent optical communications.

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