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Carrier-to-signal Ratio Reduction of Radio-over-fiber Transmission Links using Combination of Optical Parametric Amplification and Stokes Wave Feedback-assisted Stimulated Brillouin Scattering

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Abstract: Radio-over-fiber (RoF) is an attractive technology to implement high-speed mobile fronthaul networks in a cost-effective manner. In analog RoF transmission, high signal-to-noise ratio (SNR) is required, and thus lower carrier-to-signal ratio (CSR) is preferable. Nevertheless, increasing modulation depth to reduce CSR produces signal distortions during electrical-optical conversion due to nonlinear characteristics of optical modulators. The authors previously reported CSR reduction of RoF links using optical parametric amplification. Meanwhile, CSR reduction of RoF systems has been also reported using amplified Brillouin scattering. In this paper, we report CSR reduction experiments using a combination of parametric amplification in a 15-km long RoF link and stimulated Brillouin scattering (SBS) assisted by Stokes wave feedback. Reduction of CSR up to 10 dB was achieved by the proposed system, though the reduction was limited by SBS threshold of the transmission fiber without Stokes wave feedback.

Keywords: Optical communications, Nonlinear optics, Fibers, Analog RoF, Optical modulation.

1. Introduction

Global mobile data traffic is expected to be increased by seven-fold between 2017 and 2022 [1]. The 5th generation (5G) mobile communication systems which are currently being deployed around the world are predicted to handle 11.8 percent of this total traffic by 2022. Small cell mobile network architecture has been studied for 5G and beyond 5G mobile networks where the peak throughput per cell is going to be ten times or higher than the current 4th generation (4G) systems [2-4]. In small cell architecture-based mobile networks, mobile fronthaul networks which interconnects centralized base band units with massive number of remote radio heads must be capable of handling Gigabit/s scale transmission speeds while fulfilling stringent latency requirements. Analog Radio-over-fiber (RoF) technology has been studied as a cost-effective solution to satisfy the demand for high capacity in mobile fronthaul networks [5]. Even though analog RoF benefits high bandwidth, low transmission-latency and digital-to-analog converter (DAC)-free transmission, high signal-to-noise ratio (SNR) is required at the reception.

SNR of transmission signal can be increased by simply increasing optical modulation depth, thus reducing carrier-to-signal ratio (CSR) in the optical spectrum. However, in analog RoF transmission, increasing modulation depth results signal distortions due to the nonlinear electrical-optical conversion characteristics of the optical modulator [6].

The authors previously proposed a solution to reduce CSR of RoF signals using optical parametric amplification during transmission [7]. Meanwhile, CSR reduction of RoF systems has been reported using stimulated Brillouin scattering (SBS) enhanced by feedback of the Stokes wave [8].

We experimentally study CSR reduction of RoF signals using a combination of parametric amplification and amplified SBS by means of the Stokes wave feedback. In this paper, extending our previous report of [9], we compare CSR reduction of RoF signals with and with no Stokes wave feedback.

The rest of this paper is organized as follows: In Section 2, effects of optical parameteric amplification on CSR reduction of RoF transmission is discussed after presenting experimental results. In Section 3, we report experimental results of CSR reduction when amplified SBS is used with in combination of optical parametric amplification. Conclusions are drowned in Section 5.

2. Carrier-to-signal Ratio Reduction by Optical Parametric Amplification

2.1. Experimental Setup

The experimental setup which was used to study the effect of optical parametric amplification on CSR reduction is portrayed in Fig. 1. Light of 1559.6 nm from a distributed feedback (DFB) laser was intensity modulated by a microwave tone in an LN ($LiNbO_3$) Mach-Zehnder modulator (EOspace X-cut 12.5 Gb/s).

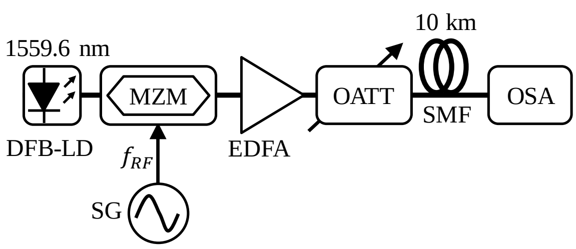

Fig. 1. Experimental setup: DFB-LD, distributed feedback laser diode; EDFA, Erbium-doped fiber amplifier; MZM, LN Mach-Zehnder intensity modulator; OATT, optical attenuator; OSA, optical spectrum analyzer; SG, signal generator; SMF, singlemode fiber.

Intensity modulated light was amplified by an Erbium-doped fiber amplifier (EDFA; Keopsys KPS-BT2-C-30-PB-FA). Amplified light was transmitted over 10-km standard single mode fiber (SMF). An optical attenuator (OATT) was placed between the EDFA and the transmission fiber to adjust fiber launch power, P_{IN}.

We measured optical power spectra of the transmitted signal using an optical spectrum analyzer (OSA; Advantest Q8384) under wavelength resolution of 0.01 nm. During the measurements, the frequency of the microwave tone f_{RF} and P_{IN} were varied.

2.2. Results and Discussion

Measured power spectra are presented in Fig. 2 for comparison. The upper row and the lower row of Fig. 2 depict the optical power spectra when f_{RF} were 7 and 15 GHz, respectively. Back-to-back spectra are shown in the 1st column. 2nd - 4th columns show the spectra after 10-km SMF transmission. The spectra of the 1st and 2nd columns were measured for the same power levels. Modulation depth is defined as the ratio between the peak-to-peak voltage of microwave tone and V_π where V_π is the half-wave voltage of the LN modulator. Modulation depth was kept at 0.5 and 0.2 for the microwave tone frequencies of 7 and 15 GHz, respectively. V_π of the LN modulator was 3.75 V.

A slight power increase was noticed in the transmitted signal spectrum of Fig. 2 (a) for P_{IN}=3.04 dBm, compared with the back-to-back spectrum of the 1st column. This power increase is apparently a measurement artifact caused by high-resolution operation of the OSA.

For the convenience of explanation, changes of spectra after fiber transmission are explained for the microwave frequency of 15 GHz. Comparing the spectra of the 1st and the 2nd columns of Fig. 2 (b), two spectral peaks which were not seen in the back-to-back spectrum were noticed in the transmitted signal spectrum for fiber input power of 13.80 dBm. Since these two spectral components are the 2nd order harmonics, optical parametric amplification is assumed saturated at the fiber launch power of 13.80 dBm.

For fiber launched powers greater than 15 dBm, a spectral peak was noticed at the 0.083 nm (10 GHz) downshihted frequency from the optical carrier frequency (3rd column of Fig. 2 (b)). This spectral peak is identified as an anti-stokes wave of SBS. A rapid growth of anti-stokes wave was noticed for further increase of fiber launched powers. Further increase of fiber launch power results another two spectral peaks with unequal peak powers between the signal side lobe and the 2nd order harmonic (4th column of Fig. 2 (b)). Among these two spectral components, the one appeared in the low frequency side can be inferred as the four-wave mixing component of the optical carrier, lower side sideband and the anti-stokes wave [10]. The spectral component appeared in the high frequency side is assumed as the idler of the low frequency side component, as its peak power is less than the low frequency side component.

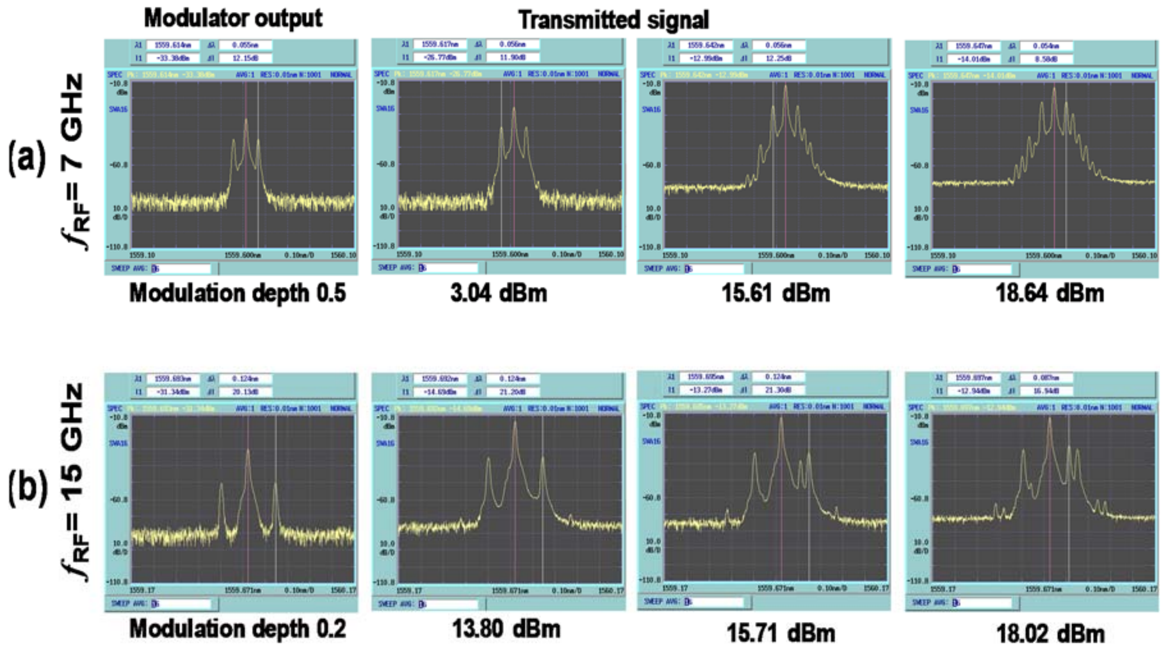

Fig. 2. Measured optical spectra. Upper row: f_{RF}= 7 GHz. Lower row: f_{RF}= 15 GHz. Corresponding fiber input powers of each measurement are shown below spectra. The 1st column shows the corresponding back-to-back spectra of the 2nd column. Horizontal 0.1 nm/div, Vertical 10 dB/div.

CSR of the transmitted signal is plotted against fiber launch power and presented in Fig. 3. For both 7 and 15 GHz microwave frequencies, no distinguishable variation of CSR was seen until fiber launch power became greater than 15 dBm. For fiber launch powers greater than 15 dBm, CSR started to decrease gradually. This CSR reduction can be inferred as a result of carrier suppression by SBS, because the fiber launch power exceeded SBS threshold of the system for fiber launch powers greater than 15 dBm.

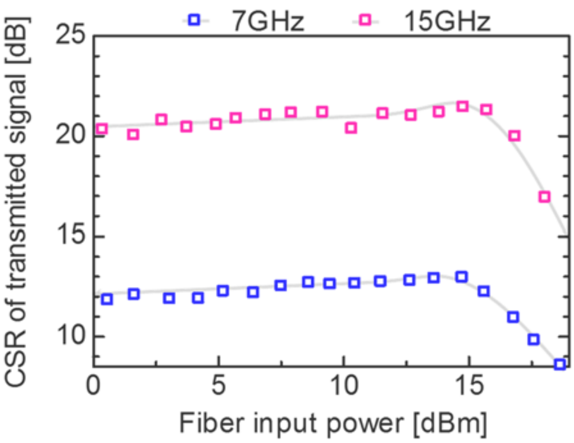

Fig. 3. Carrier-to-signal ratio (CSR) variations of 10-km SMF transmitted signal.

The initial difference in CSR of two microwave frequencies was due to the frequency dependence of the LN modulator.

3. Combined Effect of Optical Parametric Amplification and Stimulated Brillouin Scattering with Stokes Wave Feedback on Carrier-to-signal Ratio Reduction

3.1. Experimental Setup

Combined effect of optical parametric amplification and Stokes wave feedback-assisted SBS was studied using the experimental setup depicted in Fig. 4.

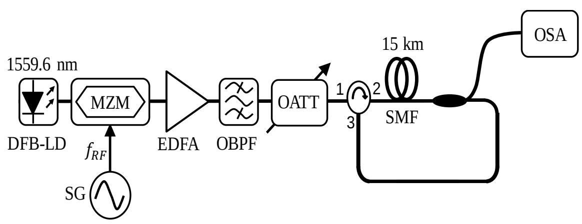

Fig. 4. Experimental setup: DFB-LD, distributed feedback laser diode; EDFA, Erbium-doped fiber amplifier; MZM, LN Mach-Zehnder intensity modulator; OATT, optical attenuator; OBPF, optical bandpass filter; OSA, optical spectrum analyzer; SG, signal generator; SMF, singlemode fiber.

As described in Section 2, light of 1559.6 nm from the DFB laser was intensity modulated by a microwave tone in the LN Mach-Zehnder modulator. Modulated signal was amplified and filtered for outband amplified spontaneous noise using the EDFA and an optical bandpass filter (OBPF) respectively. Power of OBPF output signal was adjusted using the variable optical attenuator. Modulated optical signal was then launched into a SMF and transmitted over 15-kms.

In order to amplify Brillouin scattered light, backscattered Stokes wave was extracted using an optical circulator and feedbacked to the SMF from the opposite end [8]. The optical circulator used in the experimental setup had no light path from port 3 to port 1. Optical power spectra of modulated signal were measured at port 1, port 3 of the circulator and at the end of the 15-km fiber.

3.2. Results and Discussion

Measured optical spectra are presented in Fig. 5. The spectra shown in the first and the third columns of Fig. 5 were measured at the port 1 and port 3 of the optical circulator, respectively. Spectra of 15-km SMF transmitted signal are presented in the second column. In Fig. 5, (a) and (b) were measured for modulation frequency of 7 GHz and fiber input powers of 0 dBm and +20 dBm respectively. Spectra shown in (c) and (d) of Fig. 5 were measured for the same fiber power levels as (a) and (b) respectively where the modulation frequency was 15 GHz.

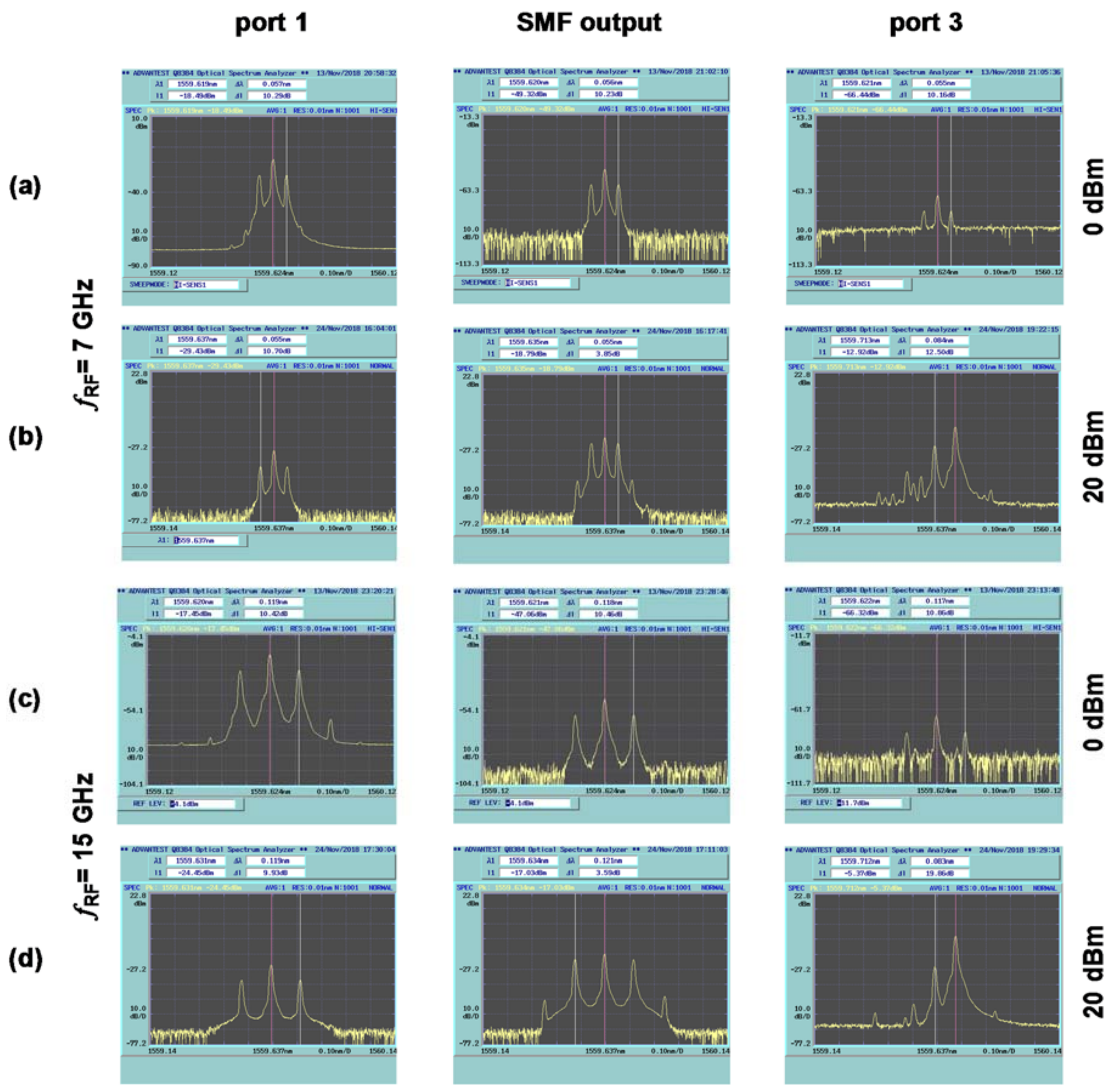

Fig. 5. Measured optical spectra. Fiber input powers of (a) and (b) are 0 dBm and 20 dBm respectively. (c) and (d) also correspond to the same fiber input powers as (a) and (b) respectively. Horizontal 0.1 nm/div, Vertical 10 dB/div.

While Fig. 5 (a) and (c) (fiber input power of 0 dBm) show little differences between the first (input) and the second (output) columns, Fig. 5 (b) and (d) (fiber input power of +20 dBm) clearly shows CSR reduction. The second column of Fig. 5 (b) and (d) also shows the second order harmonics of the modulation sidebands, indicating the saturation of parametric gain. Meanwhile, spectrum peak shifted from the carrier wavelength by 0.083 nm (10 GHz) is clearly observed in the third column of Fig. 5 (b) and (d).

For both modulation frequencies, with increased fiber input power, increases in sideband power levels relative to carrier power levels were noticed after fiber transmission. However, after fiber input power reached a certain value, the growth of sidebands seemed to be stopped and CSR reduction was saturated.

Measured CSRs of transmitted signal are plotted against fiber input power and presented in Fig. 6 for microwave frequencies of 7 GHz and 15 GHz.

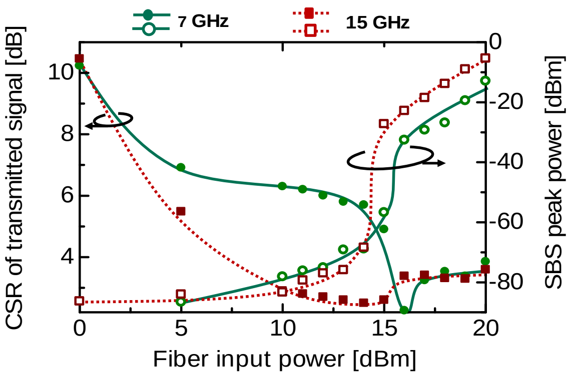

Fig. 6. Carrier-to-signal ratio (CSR) of transmitted signal and SBS peak power characteristics.

For both modulation frequencies, CSR of transmitted signal decreased with increasing fiber input power up to +5 dBm. The authors previously reported modulation depth enhancement of RoF transmission by means of optical parametric amplification only [7]. In the previous report on parametric amplification, enhancement in modulation depth became significant for the fiber launched power greater than +5 dBm. Thus, the CSR reduction in this power regime would be mainly because of carrier suppression by the amplified SBS.

Comparing the CSR reduction for fiber launched power of +5 dBm and +10 dBm, the 15 GHz case showed larger reduction than did the 7 GHz case. This difference can be attributed to the dependence of parametric gain on the modulation frequency.

For fiber input power greater than +16 dBm, CSR reduction became saturated. In the same graph, we plotted peak power of Stokes wave created by SBS for each fiber input power. For fiber input power greater than +16 dBm, an exponential growth of Stokes wave power (in linear scale) was noticed for both modulation frequencies of 7 and 15 GHz. It can be inferred that the transmission power became so strong to reach the SBS threshold of the transmission fiber without feedback. CSR reduction in the proposed system is then considered to be limited by the SBS threshold of the transmission fiber.

4. Conclusions

Firstly, we experimentally studied the effect of optical parametric amplification on CSR reduction of RoF transmission. In 10-km transmission link, no distinguishable CSR reduction caused by optical parametric amplification was seen for both 7 and 15 GHz microwave signals.

However, some noteworthy changes were found in the optical spectrum caused by optical parametric amplification. After the saturation of optical parametric amplification, high order harmonics appeared in the spectrum. Because of four-wave mixing of the optical carrier, lower side signal sideband and the anti-Stokes wave, two new conjugate frequency components were produced.

Secondly, an experiment was carried out to examine the combined effect of optical parametric amplification and Stokes wave feedback-assisted SBS on CSR reduction of RoF links. CSR reduction was studied for the same RoF signals used in the first experiment in a 15-km fiber link. For intensity-modulated signal, CSR reduction up to 10 dB was achieved. For fiber input power greater than +16 dBm, the reduction was saturated due to the exponential growth in Stokes wave intensity.

Acknowledgements

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