Pilot-aided Pump Dithering Removal in Degenerate FWM-based Optical Phase Conjugation Systems with Higher-order QAM

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Abstract: A pump dithering removal algorithm, based on pilot sequence-aided DSP, is proposed and experimentally validated in dual polarization 64 QAM optical phase conjugation system. A 4.2 dB SNR improvement was observed due to the SBS suppression.

1. Introduction

In an ultra-wideband transmission scenario, multiple optical bands are used to increase the bandwidth and the total throughput. Wavelength conversion between optical bands and adaptive nonlinearity compensation become critical techniques when processing the wideband signal. Four-wave mixing (FWM) in highly nonlinear fiber (HNLF) has been shown to be a promising method to achieve wavelength conversion and optical phase conjugation (OPC) for fiber nonlinearity compensation [1].

Non-degenerate FWM with two orthogonally-polarized pumps has been investigated for parametric amplification and OPC [1,2] due to its polarization insensitive property. In contrast, degenerate FWM systems are simpler in design, requiring only a single pump and a polarization-diversity loop [3]. Accurate phase matching and polarization alignment between two pumps are no longer required. Therefore, many studies have focused on single-pump FWM for optical fiber parametric amplification and OPC [4,5]. However, pump dithering, essential for stimulated Brillouin scattering (SBS) suppression, is directly transferred to the idler in this case, and conventional receiver DSP fails to recover the higher-order quadrature amplitude modulation (QAM) idler, because the least mean square (LMS)-based adaptive equalizer does not work for phase-dithered symbols. One approach to avoid idler dithering is to use a co-phase dithered pump and signal such that the phase modulations cancel each other [6]. However, the system setup includes an additional polarization diversity loop to dither the signal and it requires accurate phase matching among the loops. Unlike the non-degenerate FWM where a pair of counter phase-dithered pumps are deployed and the residual phase transferred to the idler could be eliminated digitally [2,7], the idler dither in single-pump FWM is much stronger and cannot be removed with conventional phase noise estimation. This is why most experiments using degenerate FWM avoid using pump dithering [8,9].

In this paper, we propose a pilot-aided DSP algorithm to remove the pump dithering transferred to the idler, which enables the suppression of SBS in single-pump polarization-diversity loop OPCs. To the best of our knowledge, this has not previously been investigated for dual polarization (DP) higher-order QAM modulation. Pilot sequences and equally-spaced pilot symbols are commonly used in coherent receiver DSP for equalization and carrier phase estimation [10], and in our proposed scheme, the sequence is also utilised for pump dithering estimation, without the need for additional overhead. Constrained LMS fitting is applied to determine the amplitude and frequency of the dithering signal, and the conventional DSP is modified to handle phase-dithered OPC signals.

2. Proposed Algorithm

In FWM-based OPC, a strong pump laser is often used to guarantee a high conversion efficiency and sufficient idler power for transmission. In most cases, the pump power is greater than the SBS threshold and the SBS can have a detrimental effect on the idler quality. A common approach to suppress the SBS is by modulating the phase of the pump with a single- or multi-tone sinusoidal signal:

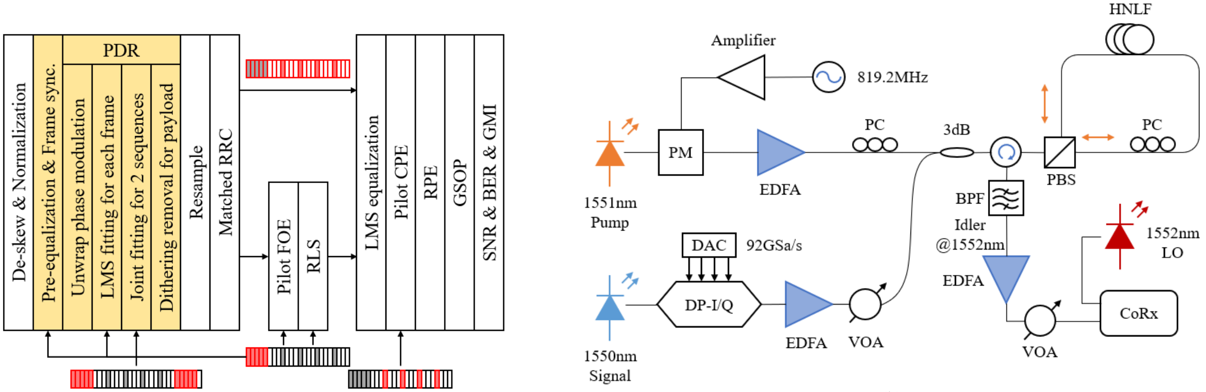
$$\Phi_{\text{Pump}}(t) = \sum_{i=1}^{n} A_i \sin(2\pi f_i t + \phi_i) \tag{1}$$

Here, A_i, f_i, ϕ_i denote the amplitude, frequency and initial phase for the i-th sinusoidal signal, respectively. According to the phase transfer relation in FWM, the dither that is transferred to the idler in degenerate FWM (not considering the signal modulation or laser phase noise) becomes:

$$\Phi_{\text{Idler}} = 2\Phi_{\text{Pump}} - \Phi_{\text{Signal}} = \sum_{i=1}^{n} 2A_i \sin(2\pi f_i t + \phi_i) \tag{2}$$

Note that this phase dither is much stronger than laser phase noise and the modulation frequency could reach several hundred MHz. Therefore, the phase dither should be removed from the signal by multiplying $e^{-j\Phi_{\text{Idler}}}$ at the beginning of DSP to ensure the successful operation of the following symbol recovery. In our proposed DSP, we use the embedded pilots to calculate the sinusoidal phase waveform by comparing the pilot sequence with the pre-equalized signal, and LMS fitting is applied to estimate the coefficients A_i, f_i, ϕ_i.

As the above PDR algorithm is included in the pilot-aided DSP [10], some modifications have to be made, as shown in Fig. 1a. Since the idler occupies a broader spectrum than the symbol rate, due to the phase modulation, the pump dithering removal (PDR) cannot operate on 2 samples per symbol after resampling and matched root-raised-cosine (RRC) filtering as is commonly the case with Rx DSP. We upsample the expected pilot sequence to the analog-to-digital converter (ADC) sampling rate and filter it to coincide with the received signal sampling rate and waveform. However, without polarization de-multiplexing or equalization, it is impossible to extract the signal at the pilot position, and the data-aided equalization cannot work with the phase-modulated signal. Therefore, a constant modulus algorithm-based pre-equalizer is applied to every N samples to demultiplex the two polarization signals and synchronize the frames before PDR. The step size N depends on the rational approximation of the ADC sampling rate and symbol rate. During the PDR, two data frames are captured, and at the beginning of each frame, the signal sequence is extracted and compared with the upsampled pilot, giving the phase modulation waveform. After removing the noise-induced phase jumps by excluding samples where the phase increment exceeds a threshold value, the constrained LMS fitting is performed on both polarizations, and the coefficients of the phase sine wave are estimated. If an additional linear term is included in the optimization function, the frequency offset can be estimated at the same time. Following the PDR, the signal is resampled to 2 samples per symbol, recursive least square (RLS) and LMS equalization, pilot-based carrier phase estimation (CPE) and residual phase estimation (RPE) are carried out. Finally, the recovered symbols are de-mapped, and the SNR, bit error rate (BER) and generalized mutual information (GMI) are calculated on the payload symbols.



(a) (b)

Fig. 1: (a) Proposed DSP for OPC signal with pump dithering. Highlighted blocks are the additional operations for PDR. Red sequences or symbols are active units in corresponding DSP blocks. FOE: frequency offset estimation. GSOP: Gram-Schmidt orthogonalization procedure. (b) Experimental setup. CoRx: coherent receiver.

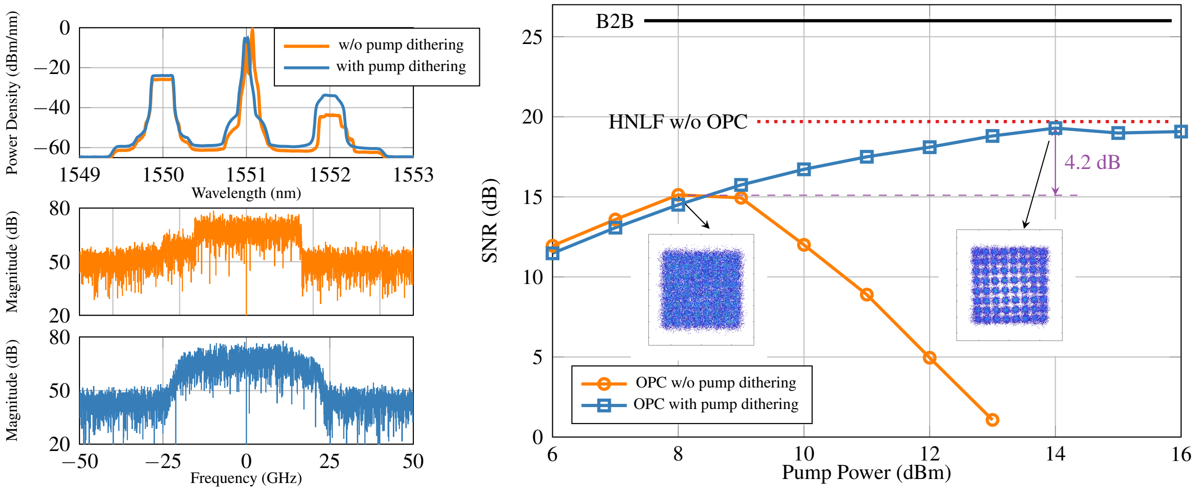
3. Experimental Setup

Fig. 1b shows the experimental setup of the 32 GBaud DP 64 QAM OPC system. An external cavity laser emitting at 1550 nm was modulated by a DP-I/Q modulator which was driven by 92 GSa/s 8-bit digital-to-analog converters (DACs). The modulated signal was amplified by an erbium-doped fiber amplifier (EDFA) followed by a variable optical attenuator (VOA) before being combined with the 1551 nm pump. The pump was phase modulated by an 819.2 MHz sine wave to introduce the pump dithering, and the following polarization controller (PC) was adjusted such that the pump power was evenly distributed to the two polarization outputs after the polarization beam splitter (PBS). Inside the polarization-diversity loop, horizontally- and vertically-polarized signals propagated in opposite directions through the HNLF and were combined together. The 2 km HNLF had a nonlinear coefficient of $10\,\mathrm{W}^{-1}\mathrm{km}^{-1}$ and a zero-dispersion wavelength of 1551 nm. The input signal power to the HNLF was 0 dBm, and the pump power was adjusted from 6 dBm to 16 dBm. The phase-conjugated and wavelength-converted idler was then filtered using an optical band pass filter (BPF). The coherent receiver was configured with a local oscillator (LO) at 1552 nm, a polarization-diverse optical 90-degree hybrid, 100 GHz balanced detectors and an oscilloscope with 256 GSa/s sampling rate.

4. Results

Figure 2a shows the optical and electrical spectra of the OPC signal. The SBS threshold for the HNLF is approximately 8 dBm, the SBS peak becoming significant at pump powers above this value. With 14 dBm pump power, when the pump dithering was not applied, the SBS peak was extremely strong and the OPC signal suffered severe distortion, as the orange spectrum shows. The same SBS peak could be seen in the electrical spectrum of the received OPC signal. When the pump was phase modulated by the sine wave, the SBS threshold was increased by at least 8 dB, and the SBS peak was no longer observed in the optical spectrum. The blue trace also shows the OPC signal spectrum with the pump phase transferred to the idler, giving rise to the broader spectrum due to the dithering, as expected. The received idler power after BPF was -16.1dBm.

Figure 2b presents the SNR as a function of input pump power to the HNLF. With dithering and PDR DSP, the pump power could be increased to 14 dBm. The maximum achievable SNR was 19.3 dB, a 4.2 dB improvement, and the corresponding constellations of the recovered symbols are shown in the inset. The net GMI also increased from 9.03 to 10.83 bit/4-D symbol, and the gap between OPC and back-to-back was 0.63 bit/4-D symbol. Compared with the signal transmitted through the HNLF without OPC, a conversion penalty of only 0.4 dB was observed. Although an intrinsic gap between the loop configuration and back-to-back transmission still exists, due to the back-scattered light and the extinction ratio of the PBS, the experiment demonstrated that PDR-assisted DSP provides a promising solution to the suppression of SBS by enabling pump dithering in degenerate FWM configuration, which could benefit OPC-based nonlinearity compensation and wavelength conversion.



(a) (b)

Fig. 2: Experimental results. (a) Top: optical spectrum before BPF, pump power=14dBm; Middle: electrical spectrum of received signal w/o pump dithering, pump power=12dBm; Bottom: electrical spectrum of the received signal with pump dithering, pump power=14dBm. (b) SNR as a function of pump power. Inset: recovered constellations.

5. Conclusion

We have presented a pilot-aided pump dithering removal algorithm for optical phase conjugation systems, which enables stimulated Brillouin scattering suppression in degenerate four-wave mixing configuration. Experiments with dual-polarization 64 QAM demonstrated 4.2 dB higher SNR compared with the idler without pump dithering.

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