Waveband-Shift-Free Optical Phase Conjugation in Fiber Loop Mirror Across 35-nm Bandwidth

Vladimir Gordienko*, Sonia Boscolo, Mariia Bastamova, Nick J. Doran, and Andrew D. Ellis
Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, United Kingdom
**v.gordienko1@aston.ac.uk*

Abstract: We experimentally demonstrate waveband-shift-free optical phase conjugation across the full C-band by employing a nonlinear optical loop mirror to demultiplex signals and phase-conjugated copies with an extinction ratio of at least 17dB across 35nm. © 2024 The Author(s)

1. Introduction

Optical phase conjugators (OPCs) and other parametric devices are researched actively because of their ability to improve capacity and efficiency of future optical communications. The employment of OPCs in communication links allows for mitigation of signal distortions caused by nonlinear effects in the transmission fiber, thereby improving the signal-to-noise ratio (SNR), hence the link's reach and capacity [1,2]. State-of-the-art OPC in multi-span links with wavelength-division multiplexed (WDM) signals has been demonstrated to outperform digital backpropagation [3], enhance the reach by up to 60% [4] or 40% [5], or bring about increasing *Q*-factor benefit as more OPCs are added into the link [6,7]. Numerical simulations have also shown that the employment of OPC in an unrepeated link can improve the SNR by up to 4dB [8].

One of the key OPC challenges is that practical optical communication links usually require waveband shift-free OPC, wherein the phase-conjugate copies are transmitted in the same wavelength band as the signals. However, a typical OPC is inherently transparent to the input signals, which leads to crosstalk between signals and their phase conjugates unless additional measures are taken. The state-of-art waveband shift-free OPC is achieved by performing phase conjugation separately for each signal half-band [4] or polarization [9]. These approaches either introduce upfront band splitter loss reducing the OPC noise figure or double the component count. In [10], it was demonstrated that four-wave mixing (FWM) wave generation with high suppression of the input pump and signal waves can be achieved in a nonlinear optical loop mirror (NOLM) [11] configuration by introducing a relative phase difference between the counterpropagating FWM waves through a dispersive element asymmetrically placed in the loop. Therefore, OPC within a NOLM setup enables in principle waveband-shift-free OPC with a single pump, a single nonlinear optical medium and less upfront loss than the currently used approaches. However, as the phase difference caused by chromatic dispersion depends quadratically on the frequency detuning of the signal from the pump, the parametric NOLM scheme of [10] works well only on a per wavelength channel basis. In our proof-of-concept experiment [12], we demonstrated WDM compatible waveband shift-free OPC by using a fiber Bragg grating (FBG) based phase shifter asymmetrically placed in the loop. But the relative suppression of signals against phase conjugates was around 7dB, insufficient for practical use, and the bandwidth was limited to 16nm.

This paper extends our previous work [12,13] by demonstrating experimentally waveband shift-free OPC with an extinction ratio between phase conjugates and signals of 17 to 25dB across a bandwidth of 35nm. This is achieved by improving the dispersion symmetry around the gain medium [10] in the NOLM loop and finely adjusting the asymmetric pump phase shift and polarization required [14].

2. Experimental Setup and Principle

Figure 1(a) shows the experimental setup. The pump (P) was sourced from a 100-kHz linewidth external cavity laser and its wavelength was adjusted in the range 1548.6nm to 1550.0nm during the experiment. The pump was amplified by an erbium-doped fiber amplifier (EDFA) with the output power 38.5dBm (~7.1W), and then filtered and combined with the signals (S) via a pair of circulators and a tuneable FBG set to the pump wavelength. The WDM signals were emulated by 22x 10GHz-wide, 200-GHz spaced channels between 1532.7nm and 1566.3nm, shaped from amplified spontaneous emission (ASE) noise by a wavelength selective switch (WSS) and polarized with a polarization beam splitter (PBS). Whilst the purpose of waveband shift-free OPC is to allow signals and their phase conjugates (S*) to occupy the same band at the same frequencies, for demonstration purposes, in our experiment the signals were intentionally spaced coarsely to create phase conjugates in the same band but at detuned frequencies, thereby enabling extinction ratio measurements of phase conjugates against signals at the OPC-NOLM output.

The combined pump and signals were passed to the NOLM input via an optical circulator. The NOLM loop comprised an Al-doped highly nonlinear fiber (HNLF) as the nonlinear medium, a FBG based phase shifter, and two polarization controllers for better control over birefringence induced phase-shifts [15], connected through a spectral response flattened 3-dB coupler. The HNLF was 52-m long and had a stimulated Brillouin scattering (SBS) threshold of ~86 W·m, the nonlinear coefficient ~6.9 $W^{-1}·m^{-1}$ and a zero-dispersion wavelength of ~1543 nm. The pump phase shifter was an apodised FBG with a reflectivity of >99.9% across the band 1548.1±0.5nm, which induced a phase shift of $\leq \pi/2$ within a ~nm range around its reflection band (inset of Fig. 1). In case of the perfect dispersion symmetry and ideal polarization settings inside the loop, the input pump and signals always return to the original input ('reflection') port of the NOLM and never go through the output ('transmission') port [11]. By contrast, the asymmetric position of the FBG means that only the counterclockwise conjugated signals inherit a phase shift from the input pump that has propagated through it. Therefore, a fine tuning of the pump wavelength adjusts the relative phase difference between counter-propagating conjugated signals, hence facilitating their constructive interference at the output port. Two pairs of calibrated bidirectional 1% tap couplers were employed at both ports of the NOLM and ends of the HNLF for monitoring purposes.

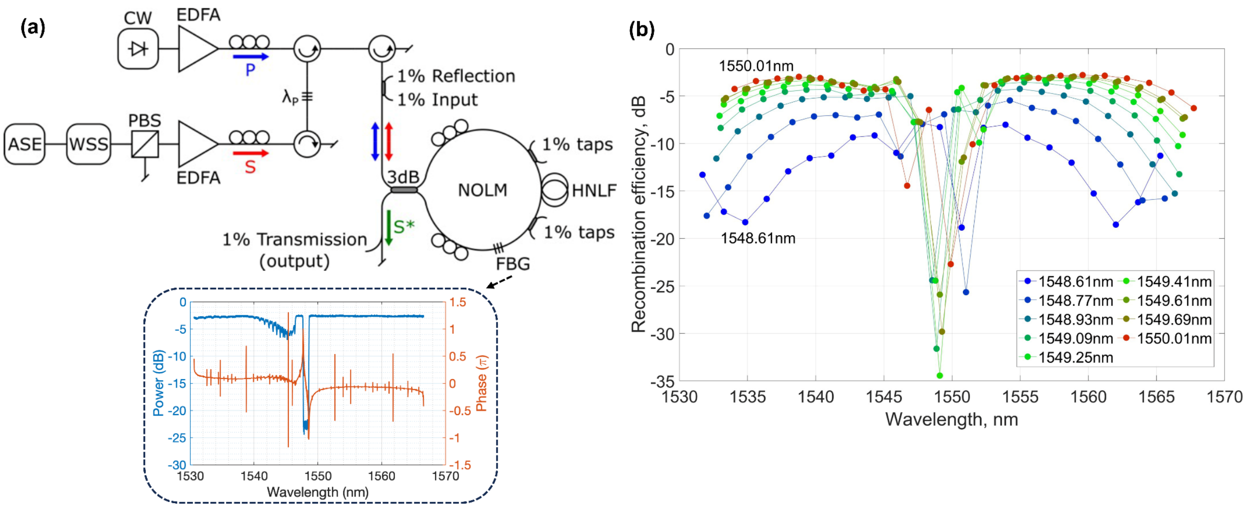

Fig. 1. (a) Schematic diagram of the experimental setup of the waveband-shift-free OPC. The inset shows the power and phase responses of the FBG. (b) Recombination efficiency of the signal conjugates at the NOLM output port as the pump wavelength is adjusted from 1548.6nm to 1550nm (see the legend for the exact values).

3. Results and Discussion

The results reported in [12] show a significant wavelength dependence of the signal rejection at the NOLM output port. This was due in part to the accuracy of the birefringent bias [14], and in part also to asymmetric dispersion inside the loop, which is known to induce wavelength sensitivity in optical parametric loop mirror performance [10]. To address these issues, we included an additional polarization controller within the loop and equalized the path lengths in the two arms to an accuracy of several cm by adding a length of standard single-mode fiber to one arm, respectively.

To achieve efficient transmission of all the conjugated signals through the NOLM output port, we also adjusted the pump phase shift by tuning the pump wavelength around the FBG. Figure 1(b) shows the signal conjugates' recombination efficiency at the NOLM output port as the pump wavelength was varied between 1548.6nm and 1550nm. The recombination efficiency is the fraction of the total phase conjugates' power recombined at the NOLM output port as a result of interference in the 3dB coupler. We can see that the recombination efficiency above −5dB is achieved across the 35-nm range for pump wavelengths near 1550nm. This optimum spectral position of the pump relative to the FBG is explained by the fact that the phase conjugation is not symmetric with respect to the FBG and, thus, a pump phase shift less than $\pi/2$ is required for constructive interference of the signal conjugates at the output port. The peak recombination efficiency was limited to ~−3dB by a combination of insertion loss and a slight directional asymmetry in conversion efficiency. Overall, the pump wavelength of 1549.72nm was chosen as it allowed for the signals and their conjugates to be on the ITU grid. The low values of recombination efficiency measured around 1550 nm were caused by a signal or a signal conjugate reflection from the phase shifter and consequent interruption of the interference process. While the FBG employed in this experiment was 1-nm wide, in principle a phase shifter with much narrower reflection band could be used.

The overall optimum results are summarized in Fig. 2(a), which shows the internal conversion efficiency measured at the HNLF ends in both directions, the net conversion efficiency defined as the ratio of the conjugated signal power at the NOLM output to the signal power at the NOLM input, and the signal transmission through the output port defined as the ratio of the signal powers at the NOLM output and input. We can see that an internal conversion efficiency of −13…−10dB has been achieved across the range of 35nm. It was limited by the pump power in each direction in the HNLF being 32dBm (1.6W) and restricted by the 1% SBS threshold. The net conversion efficiency which includes the insertion loss and the phase conjugate's recombination efficiency at the NOLM output is in the range −18.5…−14dB, if we neglect the two signal conjugates near the pump that are distorted by the FBG. The signal transmission through the output port is largely <−35dB, which means >99.9% reflection across the 35-nm range. This was achieved after adjusting the polarization inside the loop. The resulting extinction ratio between the phase conjugates and the signals was in the range −17…−25dB, which is a tolerable level of crosstalk for basic modulation formats. This can be further improved by up to 10dB via an increase of the internal conversion efficiency to 0dB as shown in [9] to enable the employment of QAM signals. Figure 2(b) shows the calibrated optical power spectra at the NOLM input and output. It highlights that the input signals are almost non-existent at the output except for the signal at ~1547nm whose rejection is disrupted by reflection from the FBG. The phase conjugates (new wavelengths) have a high extinction ratio with the signals at the output.

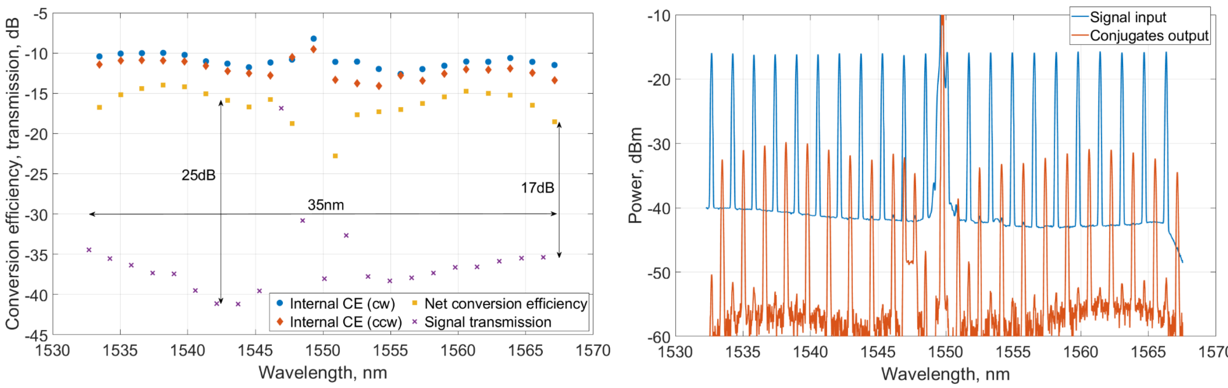

Fig. 2. (a) Overall optimized internal (clockwise – blue, counter-clockwise – red) and net (yellow) conversion efficiencies and signal transmission (purple). (b) Optical power spectra at the NOLM input and output.

4. Conclusion

We have demonstrated that OPC within a NOLM setup is capable of broadband waveband shift-free OPC by showing a relative suppression of signals against phase conjugate copies of at least 17dB across a spectral range of 35nm. We believe this is a promising technology for waveband shift-free OPC and related parametric devices such as parametric amplifiers and wavelength converters, where it may be required to avoid crosstalk between signals and idlers or wavelength converted copies, occurring at the same wavelengths.

Acknowledgements. The work was supported by the UK EPSRC projects EP/R024057/1 (FPA-ROCS), EP/S003436/1 (PHOS), EP/S016171/1 (EEMC), and EP/X019241/1 (CREATE). Data underlying the results presented in this paper are available at: https://doi.org/10.17036/researchdata.aston.ac.uk.00000614.

References

[1] S. Watanabe *et al*, "Long-haul fiber transmission using optical phase conjugation," Opt. Fiber Technol. **2**, 169-178 (1996).
[2] A. D. Ellis *et al.*, "Performance limits in optical communications due to fiber nonlinearity", Adv. Opt. Photon. **9**, 429-503 (2017).
[3] I. Sackey *et al.*, "Kerr nonlinearity mitigation: Mid-link spectral Inversion versus digital backpropagation in 5×28-GBd PDM 16-QAM signal transmission," J. Lightwave Technol. **33**, 1821-1827 (2015).
[4] A. D. Ellis *et al.*, "4 Tb/s transmission reach enhancement using 10 × 400 Gb/s super-channels and polarization insensitive dual band optical phase conjugation," J. Lightwave Technol. **34**, 1717-1723 (2016).
[5] T. Umeki *et al.*, "Simultaneous nonlinearity mitigation in 92 × 180-Gbit/s PDM-16QAM transmission over 3840 km using PPLN-based guard-band-less optical phase conjugation," Opt. Express **24**, 16945-16951 (2016).
[6] M. E. McCarthy *et al*, "PMD tolerant nonlinear compensation using in-line phase conjugation", Opt. Express **24**, 3385-3392 (2016).
[7] H. Hu *et al.*, "Fiber nonlinearity mitigation of WDM-PDM QPSK/16-QAM signals using fiber-optic parametric amplifiers based multiple optical phase conjugations," Opt. Express **25**, 1618-1628 (2017).
[8] P. M. Kaminski *et al.*, "All-optical nonlinear pre-compensation of long-reach unrepeatered systems," in 2020 European Conference on Optical Communications (ECOC), Brussels, Belgium, 2020.
[9] I. Sackey *et al.*, "Waveband-shift-free optical phase conjugator for spectrally efficient fiber nonlinearity mitigation," J. Lightwave Technol. **36**, 1309-1317 (2018).
[10] K. Mori, T. Morioka, and M. Saruwatari, "Optical parametric loop mirror", Opt. Lett. **20**, 1424-1426 (1995).
[11] N. J. Doran and D. Wood, "Nonlinear-optical loop mirror," Opt. Lett. **13**, 56-58 (1988).
[12] V. Gordienko *et al.*, "Nonlinear optical loop mirror for waveband-shift free optical phase conjugation," in Optical Fiber Communication Conference (OFC), San Diego, CA, 2023, paper Th2A.12.
[13] V. Gordienko *et al.*, "Design of an interferometric fiber optic parametric amplifier for the rejection of unwanted four-wave mixing products," Opt. Express **31**, 8226-8239 (2023).
[14] B. Ibarra-Escamilla *et al.*, "Experimental investigation of the nonlinear optical loop mirror with twisted fiber and birefringence bias," Opt. Express **13**, 10760-10767 (2005).