Nonlinear Optical Loop Mirror for Waveband-Shift Free Optical Phase Conjugation

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Abstract: We experimentally demonstrate waveband-shift free optical phase conjugation by recombining signals and idlers at different output ports of a nonlinear optical loop mirror with idler-to-signal extinction ratio up to 18dB. © 2022 The Author(s)

1. Introduction

Optical phase conjugators (OPC) and other four-wave mixing based devices can play a crucial role in future optical communications for their unique signal processing abilities. Thus, optical phase conjugation allows to compensate for nonlinearities in communication links and thus to enhance their reach by up to 60% [1]. However, a common challenge for all four-wave mixing based devices is that phase conjugated signal copies, idlers, may occupy up to a half of the device operation range thus blocking these frequencies from being used by signals. Particularly, optical phase conjugators for nonlinearity compensation require phase-conjugated signal copies to occupy the same band as the input signals, i.e. waveband-shift free optical phase conjugation [2]. In this case it is necessary to separate signals and idlers occupying the same frequencies within the same band.

The waveband-shift free OPC has been realized in two ways. One way is to split the signal band in two halves and to perform phase conjugation of the band halves separately [3]. However, this requires two separate optical phase conjugators, and a band splitter introduces a noise penalty. Another way is to employ a pair of orthogonally polarized pumps to produce idlers which occupy the same frequencies as signals but have orthogonal polarizations with them and therefore can be demultiplexed from signals by a polarizing beam splitter. However, employment of two orthogonal pumps in this case leads to a gain coefficient reduction by a factor of 3 without facilitating polarization-insensitive operation.

In this paper, we experimentally demonstrate waveband-shift free OPC in nonlinear optical loop mirror (NOLM) allowing to demultiplex signals and idlers sharing the same frequency band by introducing a phase shift to the pump inside the NOLM. Although a similar concept has been proposed and simulated whilst using a gain medium with $\chi^{(2)}$-nonlinearity [4], and a rejection of an unwanted four-wave mixing product in NOLM has been experimentally demonstrated in [5], this is the first experimental demonstration performed in the context of a waveband-shift free OPC for WDM. We experimentally perform optical phase conjugation of a set of WDM probes occupying a 16 nm wide band in a NOLM and demonstrate that the signals and the phase conjugates occupying the same band can be recovered from different output ports of the NOLM. The achieved extinction ratio between the phase conjugates and residual signal is in the range between 7 dB and 18 dB across the examined band although the signal to idler conversion efficiency was only ~-9 dB. This proof-of-concept experiment shows feasibility of the proposed approach and can enable single pump waveband-shift free OPC or polarization-insensitive OPC employing only one pair of orthogonal pumps. Other four-wave mixing based devices can benefit from this concept as well, for example, fiber optic parametric amplifiers in NOLM can avoid a half of the gain spectrum band being blocked by idlers and thus amplify signals across the whole gain spectrum bandwidth.

2. Experimental setup

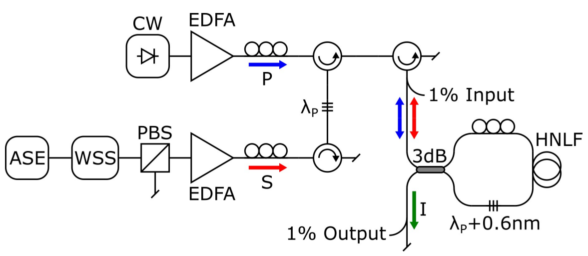

Fig. 1. Experimental setup of a waveband-shift free OPC in NOLM.

Figure 1 shows the experimental setup for examination of a wideband-shift free OPC in NOLM. A pump (P) for OPC is sourced from a 100 kHz linewidth external cavity laser at the frequency of 193.2 THz (1551.7 nm). Then, the pump is amplified with an EDFA to the power of 39 dBm (8 W). The pump is filtered and combined with 'signals' (S) by means of a pair of circulators and a 0.6 nm wide fiber Bragg grating (FBG) tuned to the pump wavelength. The 'signals' are emulated by the WDM probe comprising 11x200 GHz channels between 192.15 THz (1560.2 nm) and 194.15 THz (1544.1 nm) sourced from ASE noise shaped with a wavelength selective switch (WSS) and polarized with a polarizing beam splitter (PBS). Of course, the purpose of the waveband-shift free OPC in NOLM is to allow for generated phase conjugates, idlers (I), to occupy the same frequencies as original signals, but for this proof-of-concept demonstration the WDM probe is centered around the pump with a small shift of 50 GHz so that idlers and 'signals' are interleaved and therefore can be distinguished by an optical spectrum analyzer.

The combined pump and 'signals' are passed through an optical circulator to the NOLM representing a loop with a spectral response flattened 3 dB coupler at the input. The loop includes a polarization controller, a gain fiber where optical phase conjugation takes place and an FBG-based pump phase shifter. The gain fiber was a 52 m length of Al-doped HNLF having the SBS threshold of ~86 W·m, the nonlinear coefficient ~6.9 $W^{-1}\cdot m^{-1}$ and zero dispersion wavelength of ~1543 nm. The FBG was apodised with central wavelength of 1552.3 nm, bandwidth of 1 nm and reflectivity >99.9%, so the pump wavelength was ~0.1 nm away from the FBG reflection band edge. This FBG introduces a pump phase shift to the counter-clockwise pump. Consequently, this phase-shift is inherited by all counter-clockwise idlers and this facilitates constructive interference of the idlers at different output port then the 'signals'. The polarization controller inside the loop is tuned to minimize 'signal' transmission to the idler output port. Calibrated bidirectional 1% tap couplers are employed at the loop input and output (as shown at Fig. 1) and at both ends of the HNLF to monitor result of interference in the 3dB coupler and conversion efficiency inside the loop.

3. Results and Discussion

Figure 2 shows optical power spectra at the input and output of the loop designated at Fig. 1. There are 11 channels with power of ~-5.6 dBm emulating 'signals' and a pump with power of 35.9 dBm at the input of the loop. The small peaks at the idler frequencies observed at the input to the loop are phase-conjugates generated in SMF pigtails prior to the loop. At the output of the loop the 'signals' are suppressed and most of them have power <-30 dBm. On the other hand, the power of idlers at the output is ~-20 dBm. The extinction ratio between idlers and 'signals' ranges from 6.9 dB at the edges of the 16 nm signal band to 18 dB in the middle of the band. Although an extinction ratio >20 dB would be required for low penalty optical phase conjugation of QAM signals sharing frequencies with idlers, this proof-of-concept experiment shows that a relatively high idler-to-signal extinction ratios of up to 18 dB are possible for OPC in NOLM and there is a room for improvement.

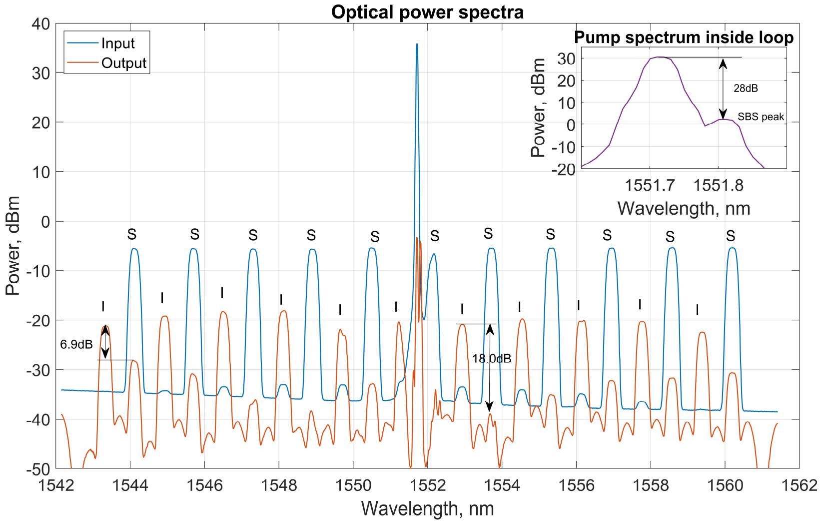

Fig. 2. Optical power spectra at the input and the output of the loop. Inset shows a zoomed pump spectrum measured inside the loop.

Figure 3 shows the key parameters for each 'signal' emulated by one of the probe channels and its corresponding idler at their respective frequencies. The idler internal conversion efficiency defined as the ratio between an idler power at the output of the HNLF and the corresponding 'signal' power at the input of the HNLF is around -9 dB for all idlers. It has been limited by the available pump power, but we estimate it could have been improved only by a few dB without additional mitigation of the stimulated Brillouin scattering. The net conversion efficiency defined as the power ratio between a 'signal at the loop input and the corresponding idler at the loop output is in the range between -17.7 dB and -12.7 dB across the full 16 nm range. The net conversion efficiency variation across the spectrum is caused by leak of the idler power to the input (signal) port of the loop, and it can be improved by tuning the pump phase shift in the loop. The signal transmission from the input to the output port of the loop is in the range between -34.9 dB and -22.6 dB. Since the passive insertion loss of the loop is ~2 dB, a signal rejection from the idler port of ~20…33 dB has been achieved. The position of the V-shaped signal transmission spectrum was defined by polarization controller in the loop, which implies the decrease of the signal rejection towards the edges of the 'signal' band was caused by birefringence in the loop. Hence, the bandwidth where 'signals' are efficiently rejected from the output port can be improved by mitigation or compensation of birefringence in the loop.

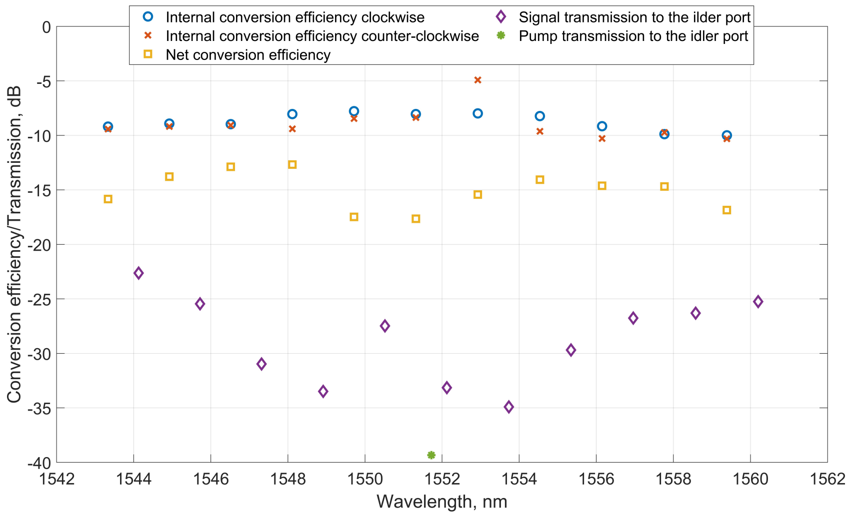

Fig. 3. Conversion efficiency in both directions inside the loop (blue circles and red crosses); Net conversion efficiency from the input to the output of the loop (yellow squares); and Signals and pump transmission from the input to the output of the loop (purple diamonds and the green star respectively).

4. Conclusion

This proof-of-concept experiment demonstrated an OPC in NOLM with idler-to-signal power extinction ratio up to 18 dB and thus confirmed that this arrangement can be employed for waveband-shift free OPC. A further conversion efficiency improvement can be achieved by improvement of the conversion efficiency and accurate tuning of the pump phase shift. A broadband rejection of signals from the output port can be achieved by mitigation or compensation of birefringence in the NOLM.

Acknowledgement

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