Mid-Span Pump Phase Shift Applied to WDM Wavelength Conversion for the Suppression of FWM Crosstalk

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Abstract: We apply mid-span pump-phase shifting to the wavelength conversion of a 9 channel WDM band in order to suppress inter-channel nonlinear crosstalk. SNR improvements between 3-6dB are observed through the use of the technique. © 2023 The Author(s)

1. Introduction

It is through the promise of ultra-wide bandwidth signal processing that many all-optical signal processing schemes are justified [1]; if these schemes can process a sufficient number of channels in parallel, then it is argued that they will become more cost- or energy- efficient than digital signal processing alternatives. Indeed, it is through this principle that all-optical amplifiers, such as the EDFA, were able to displace OEO regeneration. However, in the context of nonlinear signal processing with four-wave mixing (FWM), a difficulty arises in that the very process being relied upon to enable the processing of signals, is often simultaneously a cause of crosstalk in wavelength division multiplexed (WDM) bands. Furthermore, the dilemma often occurs that improving the efficiency of FWM to benefit idler generation will typically increase the generation of the spurious signals that are leading to crosstalk in the first place. Increasing pump to signal power ratios is a general treatment for this problem [2], however, in general, stimulated Brillouin Scattering will quickly present itself as a limit to pump power in many fiber-based systems, whilst loss and optical damage often mar waveguide-based systems.

As such, schemes that can mitigate the crosstalk and facilitate the use of higher signal powers to improve output idler optical signal to noise ratio (OSNR) are highly desirable. To this end, we proposed in a CW based proof-of-principle study, the mid-span pump phase shift (MPPS) scheme, wherein, the nonlinear processing medium is separated into two cascaded parts and a phase filter is placed in-between the two stages [3]. In the first nonlinear stage, wanted and unwanted (crosstalk inducing) idler generation takes place due to FWM as normal. The phase filter placed between the stages (which could be implemented using, for instance, a programmable filter or Bragg-

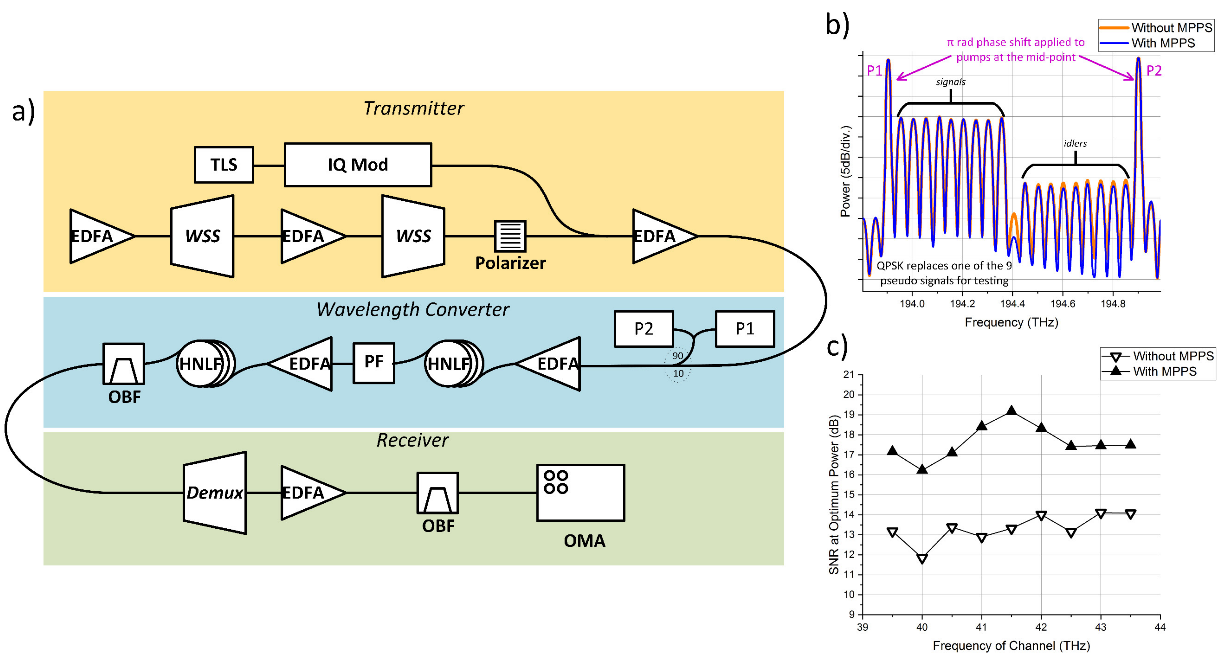

Fig. 1. a) Experimental setup, b) Output spectra of wavelength converter without and without MPPS, c) Output SNR of channels with and without MPPS.

grating) imparts a π radian phase shift to the pump (in a degenerately pumped system) or pumps (in a non-degenerately pumped system), the polarity of the phase shift is unimportant. In the second stage of FWM, newly generated unwanted idler waves are produced as in the first stage, but with a phase shift of π radians relative to the first stage, due to the MPPS applied. As such, the unwanted idler waves generated in the first stage interfere destructively with those generated in the second stage, reducing crosstalk with the wanted idlers that remain unaffected.

In this work, we apply the scheme to its originally intended use case – the mitigation of nonlinear crosstalk amongst WDM channels undergoing wavelength conversion. We build a wavelength converter testbed in which MPPS can be enabled or disabled and observe the improvement in signal quality that MPPS can provide when wavelength converting a 9-channel WDM band with 50GHz spacing. A 10GBd QPSK signal is used as the probe signal and an improvement in output SNR of 3-6dB is observed by applying MPPS.

2. Experimental Setup

Fig. 1-a provides a schematic of the experimental setup, with three distinct sections highlighted: the transmitter, the wavelength converter, and the receiver. As the objective of this experiment was to test the MPPS technique in a WDM setting, we needed to populate the conversion band with as many signals as possible. To achieve this, 9 channels of approximately 20GHz bandwidth and 50GHz channel spacing were carved out of EDFA-generated amplified spontaneous emission (ASE) using a wavelength selective switch (WSS). These channels shall be referred to by their 100GHz grid ITU designations (with non-integer indices, for example, CH43.5→194.35THz). These channels were then amplified before being re-carved with a second WSS to increase their OSNR. These pseudo-signals then passed through a linear polarizer so they could be multiplexed with a 10GBd single polarization QPSK signal which was generated using a CW laser and an IQ modulator. After multiplexing the signal-under-test, the WDM band was amplified to ~27dBm and passed through an attenuator so that its power could be varied. The signals were then passed into the wavelength converter, wherein they were first multiplexed with two, co-polarized CW pumps (P1 and P2) using a 90:10 coupler, biased to the pumps. The whole band then passed through an EDFA with a total output power of 18.5dBm before entering the first nonlinear stage, a strained 200m HNLF (with the following parameters: $\mathrm{L}= 0.2\mathrm{km}$, $\alpha = 0.83\mathrm{dB.km^{-1}}$, $\mathrm{D}' = 0.071\mathrm{ps.nm^{-2}.km^{-1}}$, $\gamma = 9.7\mathrm{W^{-1}.km^{-1}}$ and $\mathrm{D} = 0.60\mathrm{ps.nm^{-1}.km^{-1}}$, measured at 1550nm) whereupon they underwent the first stage of FWM. After exiting the first fiber, the pumps and WDM signal band entered a programmable filter (PF) that allowed us to apply the necessary dispersion compensation and mid-span pump phase shift that enables the MPPS technique. After exiting the PF, the WDM band passed through a second EDFA to prepare it for mixing in the second HNLF which nominally had the same parameters as the first, apart from a slightly different dispersion, since it was not strained ($\mathrm{D} = 0.67\mathrm{ps.nm^{-1}.km^{-1}}$). Mixing in this second stage not only boosted the conversion efficiency of the desired idlers, but it also suppressed unwanted idlers (to first order) on account of the π radian phase shift applied to the pumps. Fig. 1-b provides spectra just after the second HNLF, both with and without the application of MPPS. The 9 WDM signals and the generated idlers are labelled in the figure. Although it is not possible to see the evidence of in-band interference in the spectra, the benefit of MPPS can actually be seen at 194.4THz, in the form of an idler generated in the guard band between the idlers and signals. Application of MPPS results in a 6dB suppression in the power of this idler (which is only incidental, as it carries no data). After the band exited the second fiber, the pumps and signals were rejected using an optical band pass filter to select out the wavelength converted idlers. These were then delivered to the receiver where the channel to be tested was first demultiplexed, amplified using an EDFA, then the out-of-band ASE was rejected with an optical bandpass filter and the signal analyzed using a coherent receiver.

3. Results

The real data carrying signal was tuned, in turn, to all 9 channel locations in the WDM band and the total power into the wavelength converter swept from 0 to 16dBm, both with and without the MPPS technique being applied. Fig. 2 provides plots of the measured signal-to-noise-ratio (SNR), found with the receiver, after wavelength conversion for three selected channels corresponding to the two edges and center of the band to be wavelength converted: CH39.5, CH41.5 and CH43.5, which in turn were wavelength converted to channels: CH48.5, CH46.5 and CH44.5. These SNR plots show that peak SNR was achieved for peak launch powers of about 4-6dBm when MPPS was not deployed (open, downward pointing triangles), resulting in output SNRs of around 13-14dB. In contrast, enabling MPPS increased the optimum launch power to 10-14dB for the channels presented and increased SNR by 4-6dB.

Accompanying each plot are constellations both with and without MPPS, each for two scenarios: the optimum launch power, and a power slightly beyond this to help identify the cause of the degradation. In all cases, the benefit of utilizing MPPS is clear, with all signals experiencing an easy to observe improvement in their constellation diagrams. It is clear that MPPS results in a reduction of white noise, that is, the noise reduction is not biased to either of the quadratures nor to the amplitude or phase dimensions of the plot. This implies that the use of MPPS results in a reduction of FWM, not SPM or XPM, which would instead be characterized by a reduction in phase noise.

Finally, in Fig. 1-c, peak SNRs (found at the optimum launch power for each individual channel) are plotted for all channels both without and with MPPS presented. Although the improvement in SNR varies with channel, it is in excess of 3dB in all cases. The variation in SNR improvement is due both to the diversity of FWM interactions that can generate interference on each of the channels as well as stochastic variances between the fiber, notably chromatic dispersion, and polarization mode dispersion. We expect the variance of these parameters to change with the length of fiber samples used [4], so appropriate fiber length selection may improve the extent of suppression.

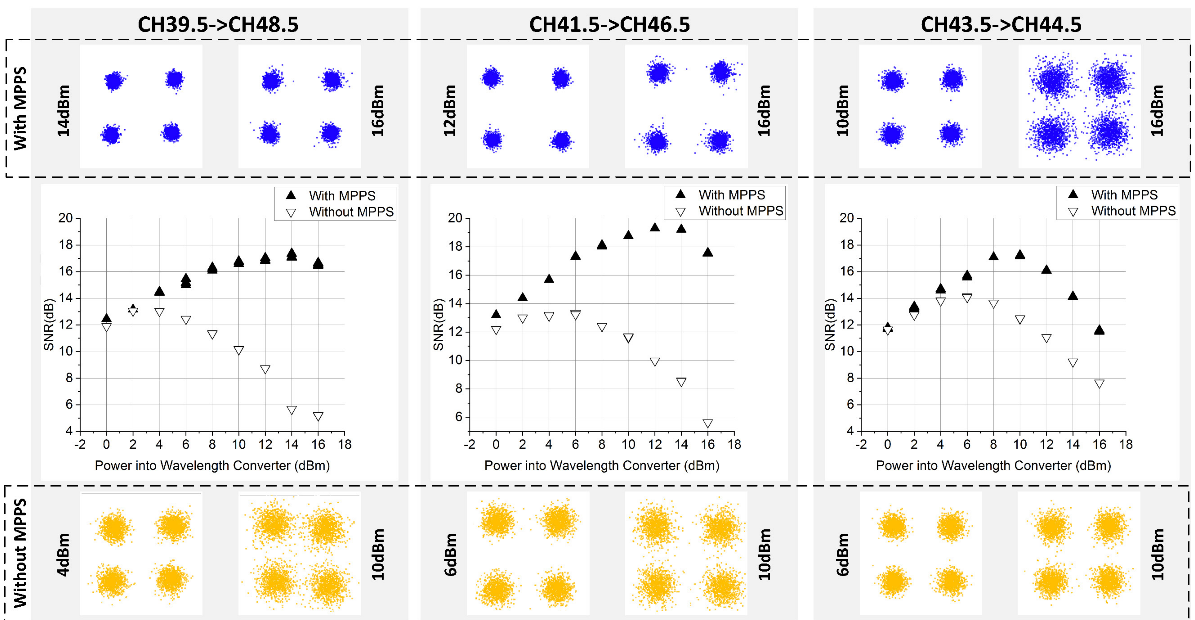

Fig. 2. SNR vs power input to the wavelength converter for three selected signals, with and without MPPS. Curves are accompanied by corresponding constellation plots.

4. Conclusion

We have applied the MPPS technique to the suppression of FWM induced crosstalk in a 9-channel WDM band with 50GHz spacing, confirming the validity of the technique when applied to data-carrying signals. An SNR improvement between 3 and 6dB was demonstrated in a wavelength converter otherwise offering modest performance. We expect the benefits of MPPS to be even greater when applied to more performant systems and understanding the limits of this technique will be an important future objective.

5. Acknowledgments

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6. References

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