An Optical Phase Quantiser Exhibiting Suppressed Phase Dependent Gain Variation

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Abstract: We experimentally demonstrate an all-optical phase quantiser based on phase-sensitive amplification which alleviates phase noise to amplitude noise conversion. Phase transfer functions are measured for the very first time using a novel scheme.
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1. Introduction

In an effort to address the continued growth of data traffic in optical networks, more spectrally efficient modulation formats, utilising both phase and amplitude, are being investigated [1]. These complex modulation formats suffer from a greater susceptibility to noise and thus a decreased reach, increasing the need for signal regeneration. The electronic methods currently used for this purpose do not scale well with increasing data rate and so optical methods, which potentially offer energy and cost reductions, format flexibility and ultra-fast processing rates are fast becoming a key technology to develop.

The behaviour of a signal regenerator can be described using a complex transfer function, which may be expressed in terms of separate intensity and phase components. The ideal system should possess a phase transfer profile in the form of staircase (quantised) function and a phase independent intensity transfer profile. Phase quantisation of an optical signal may be achieved through coherent addition with its phase harmonics, and is typically implemented by carefully mixing an M-ary PSK signal with its corresponding $(M-1)$ phase harmonic through phase sensitive four wave mixing (FWM) [2]. Despite successfully regenerating phase, such systems tend to exhibit a strong phase-dependent gain, partially converting phase noise into amplitude noise, which, upon forward propagation of the signal along a fibre optic channel, may be transferred back into phase noise through fibre nonlinearities, grossly limiting the benefit of the regeneration in the first place. This trade-off between phase noise and amplitude noise stands as a significant hurdle to realising practical phase regenerators based on this approach.

We have recently proposed and theoretically analysed a simple alteration to this scheme to suppress such phase-dependent gain, whilst maintaining good phase quantising ability [3]. This can be achieved by mixing not only the $(M-1)$ phase harmonic, but also the $-(M+1)$ phase harmonic with the original signal. In this paper we experimentally validate the technique and present a detailed analysis of its application to 4-level phase quantisation (as would be appropriate to the regeneration of a 4-PSK signal) by using a programmable optical filter and highly nonlinear fibre (HNLF) to synthesise the proposed system from an optical frequency comb. We characterise the system by mapping both its intensity and phase transfer functions and comparing them to the conventional single harmonic system. To this end, we propose and employ what we believe to be a novel technique to measure the phase difference between two signals by utilising an optical comb generator and a programmable optical filter to form a time sequential, balanced coherent receiver. We compare these results to those obtained through simulation and find them to be in very good agreement.

2. Concept

Figure 1 illustrates some possible phase sensitive amplifier (PSA) configurations that may be used to achieve the 4-level phase quantisation of a signal. In all cases, FWM processes are exploited to coherently add to the signal either one or two of its phase harmonics (referred to as single-harmonic and dual-harmonic systems, respectively) to achieve phase quantisation. The dual-harmonic system can be viewed as the combination of the other two, single-harmonic systems. The phase and intensity transfer functions of the dual-harmonic system depend upon the relative phase difference between the pumps, P1 and P3. The phase difference must be set in a way such that the intensity variations of the two underlying single-harmonic systems combine destructively, as this is the key to the phase dependent gain suppression.

The intensity and phase transfer functions for each system are given at the bottom of Figure 1. In these relations, m and n are mixing factors representing the degree to which the harmonics are added to the signal - the greater these coefficients, the greater the mixing (in the dual-harmonic case, the weighting of the two harmonics is assumed to be equal). For small values of m, we may apply the following approximation to the phase transfer functions in the single-harmonic systems: $\arctan\left(\frac{m \sin 4\phi_{in}}{1+m\cos 4\phi_{in}}\right) \simeq \arctan(m \sin 4\phi_{in})$. In this case, we find that by setting $n = \frac{m}{2}$, we may obtain similar phase transfer characteristics in both the 3rd single-harmonic system and the dual-harmonic system. It can be seen that the intensity transfer functions for the two single-harmonic systems are the same, each having a phase dependent gain variation of $\Delta G_{single} = 4m$ compared to $\Delta G_{dual} = 4n^2 \approx m^2$ for the dual-harmonic system. Therefore, the dual-harmonic system exhibits a smaller intensity variation than the single-harmonic systems for $m < 4$. Typical values of m to achieve optimal phase squeezing are lower than 1 so for all cases relevant to the present discussion, the dual-harmonic system provides a reduced gain variation.

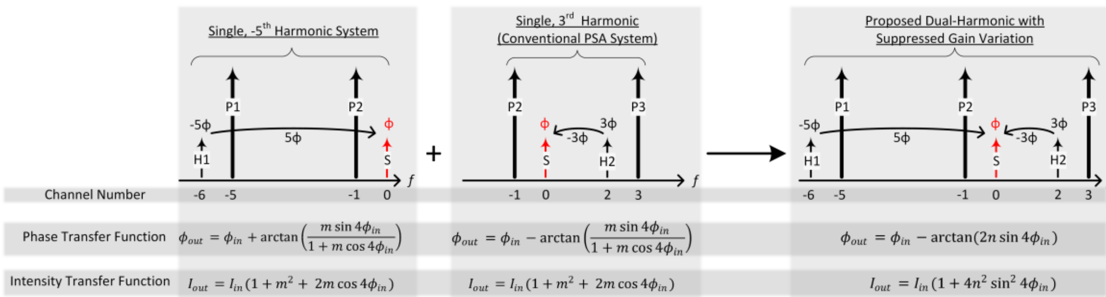

Figure 1: Some possible configurations for 4-level phase quantisation through FWM. Channels sit on an equally spaced frequency grid.

3. Experiment and Results

Figure 2 shows a schematic of the experimental setup used in this investigation to synthesise and perform measurements on the PSA systems to be studied. An overdriven Mach-Zehnder Modulator (MZM) was used to modulate a 17 dBm, 192.5 THz, continuous wave laser to produce an optical frequency comb with a 20 GHz spacing. The comb was then sent to programmable filter (Finisar Waveshaper), PF-A, which selected the phase-locked lines to be used as the test signal, the pumps and the harmonics for the desired quantiser under test and allowed for the per channel control of both attenuation and phase. The configurations were amplified up to a total power of 20.4 dBm and launched into a 300 m long HNLF with $D = -0.08$ ps nm^{-1} km^{-1}, $D' = 0.018$ ps^2 nm^{-1} km^{-1}, $\gamma = 11.6$ W km^{-1}, $\alpha = 0.88$ dB km^{-1} and $\lambda_0 = 1555$ nm.

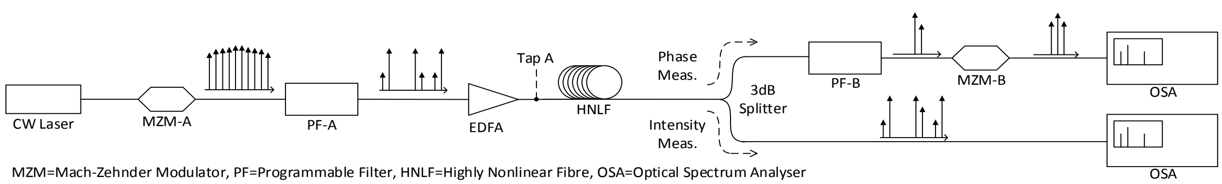

Figure 2: Schematic of experimental setup. Tap A is used for to measure the input to the HNLF.

The remainder of the setup was simply implemented to measure the phase and the intensity characteristics of the various phase quantisers. The lower branch of the 3dB splitter allowed for the measurement of the intensity through an optical spectrum analyser (OSA). The upper branch was used to measure the relative phase difference between the signal and the pump P2 (whose phase was found to be sufficiently uncoupled from the phase of the signal and harmonic lines). This was done by first selecting the pair of lines to be compared using the programmable filter, PR-B and then coherently mixing them using MZM-B (driven by the same frequency source as MZM-A). By applying a series of phase shifts to P2 using PR-B and each time measuring the output of MZM-B using an OSA, we may emulate a balanced coherent detector. To map the phase transfer and phase dependent gain characteristics of each system, we scanned the signal phase, ϕ, from 0 to 2π using PF-A, each time updating the harmonics so that they carried the correct multiple of the signal's phase (be it 3ϕ or -5ϕ). For each value of ϕ, we took measurements of the intensity of the signal line as well as its phase relative to pump P2.

Figure 3 shows the results for all three configurations detailed above in Figure 1. The experimental data (points), are plotted along with the corresponding numerical ones obtained using the split-step method (solid lines). In all cases, the numerical results show very good agreement with both the experimental phase and intensity transfer curves, confirming the concept and validating the method by which phase was measured.

For the single-harmonic systems, the pump powers were set to 17.4 dBm, the signal to 6.4 dBm and the harmonic lines to 4.4 dBm. This results in a value for m, the mixing coefficient, of approximately 0.38. The intensity transfer curves for both single-harmonic systems are very similar, as would be predicted from their analytical values (see Figure 1) with the magnitude of their gain variation being about 7 dB. We see that the system using the 3rd harmonic has broad, flat-topped steps and it is for this reason that most FWM based phase regenerators are based on this, $(M-1)$, harmonic: it is most similar to an ideal step function. In contrast, and in agreement to the expressions of Figure 1, the system that uses the conjugated 5th harmonic, exhibits a more jagged, saw-tooth-like phase transfer profile and as a result is less effective at phase quantisation.

For the dual-harmonic system, pumps were held at 15.3 dBm and the harmonics at 2.3 dBm with phase and intensity transfer functions being mapped for a range of signal powers from 2.3 dBm to 7.3 dBm (corresponding to a range for the mixing factor, n, of 0.14 to 0.31). In each case, the phase difference between P1 and P3 was optimised so as to minimise the amplitude of the oscillations in the intensity transfer function. Firstly, we note how the intensity transfer profile for the dual-harmonic case has 8 maxima, as opposed to the 4 maxima present in the single-harmonic cases, as predicted by their intensity transfer functions. Secondly, the lower the power of the signal and thus the higher the corresponding value of the mixing coefficient, n, the harsher the steps in the phase transfer function and the greater the magnitude of the intensity variation. Of the dual-harmonic phase transfer functions measured, the one obtained for $n = 0.14$ offers performance most similar to the presented 3rd harmonic, single-harmonic system. A direct comparison of these curves shows that, by using the proposed scheme, a reduction of the phase dependent gain from 7 dB down to <0.5 dB was achieved.

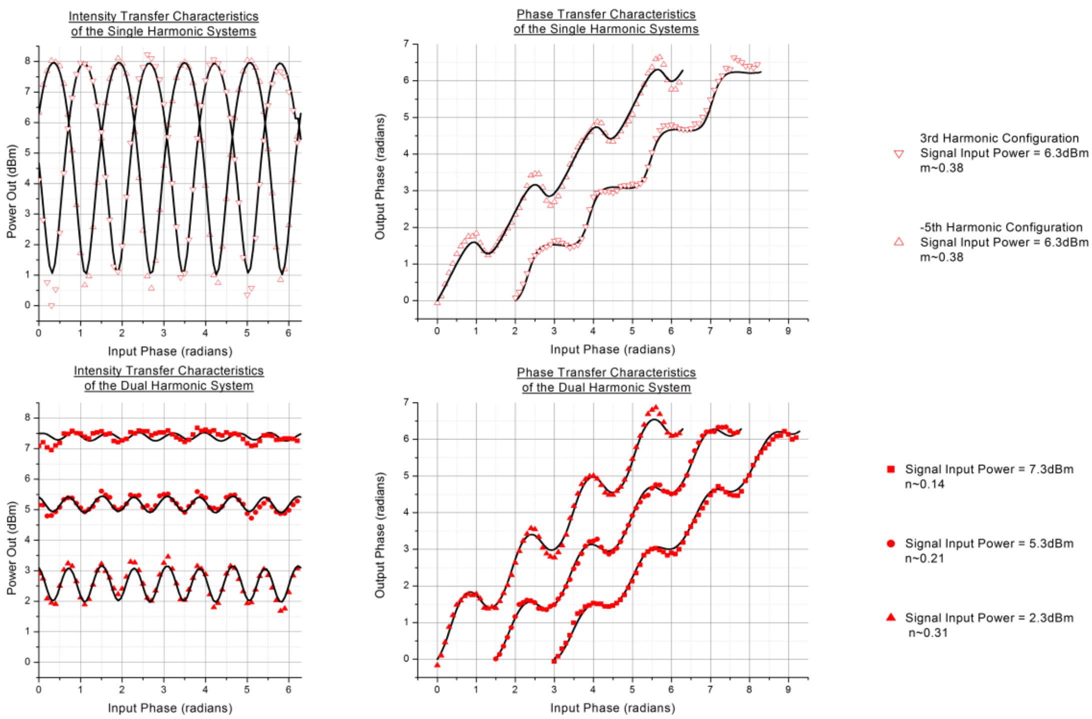

Figure 3: Plots of the measured intensity and phase transfer profiles for both the single- and dual-harmonic systems.

4. Conclusion

We numerically and experimentally characterised a newly designed, dual-harmonic, scheme for phase quantisation in terms of its intensity and phase transfer functions. It showed similar performance in terms of phase quantisation to the conventional single-harmonic system, whilst achieving a reduction in phase dependent gain variation of 6.5 dB, thus making it a much more ideal phase regenerator. To measure the various phase transfer functions, we proposed and implemented a novel technique using a programmable filter and an optical comb to emulate a time sequential, balanced coherent receiver. Experimental data are in very good agreement with results obtained through simulation.

4. References

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