Overcoming Electronic Limits to Optical Phase Measurements with an Optical Phase-only Amplifier

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Abstract: We utilize four wave mixing to precisely multiply the modulation depth of a phase encoded signal, demonstrating 3-extra effective bits of resolution at 32GHz. The technique enables a new class of optical signal processing functions.
OCIS codes: (060.5060) Phase modulation ;(060.4370) Nonlinear optics, fibers; (190.2620) Harmonic generation and mixing

1. Introduction

Photonic signal processing is increasingly finding applications in several fields previously dominated by electronics, including analogue-to-digital conversion (ADC) [1], microwave and terahertz wave generation [2,3], radio-over-fiber (ROF) [4], and all-optical regeneration [5]. The benefits of utilizing photonic methods over the electronic equivalent are numerous, including low transmission loss, flat and broadband spectral response, and crucially for ADC applications, lower jitter sampling [1]. In most of these systems, a final optical to electronic conversion (generally incorporating digital sampling) is required. At high speeds, optical amplification is (almost always) utilized to raise the signal power above the optoelectronic receiver's noise floor, hereby maximizing signal-to-noise ratio (SNR). The optical power amplifier has therefore become ubiquitous, with doped fiber amplifiers (DFAs) commonly inserted prior to electro-optic receivers. DFAs by their very nature amplify the signal carrier and information-bearing sidebands equally and as such are very linear. This attribute is desirable when dealing with strong amplitude modulated optical signals. When precise measurement of an analogue signal is required however, such as in a ROF link, it is commonplace to perform only weak modulation in a single dimension such as phase, to ensure that the modulator itself is linear. In that instance, amplification of the signal in a DFA (and indeed in any optical power amplifier) is in fact an impediment, because the energy in the carrier is many orders of magnitude greater than that in the sidebands, and this 'DC' component can saturate, and even damage, the photo-receiver. This leads to a tradeoff between SNR and linearity. In RF, this compromise can be conveniently avoided by using AC-coupled amplifiers that preferentially amplify the sidebands over the redundant carrier. We propose and demonstrate here an optical equivalent of the RF AC-coupled amplifier, obtaining an extra 18 dB of sideband SNR that in our case led to a 3-bit increase in the effective number of bits (ENOB) for our photo-electric detection system operating at 32 GHz. In addition, we highlight how the concept lends itself to a next generation of ultrafast optically assisted ADCs.

2. Operation Principle and Experimental Set-up

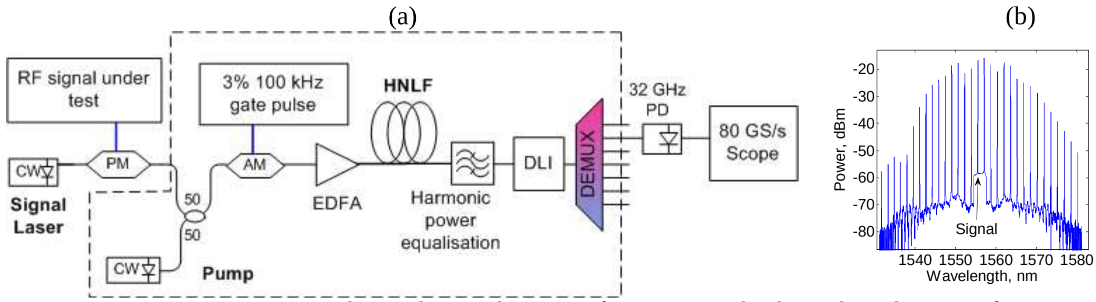

Figure 1: (a) Experimental setup. (b) Optical spectrum after HNLF, signal and pump located at centre of spectrum.

Our device is remarkably simple, and merely requires combining the phase-modulated optical signal with a frequency detuned continuous wave (CW) pump in a highly nonlinear fiber (HNLF). If the dispersion of the HNLF is low, a wideband cascade of four wave mixing (FWM) products is generated [6]. Given that the signal has a constant intensity, it can be written as $\exp(i\phi)$, where ϕ is the time varying phase information. Due to the phase matching property of FWM, the n^{th} harmonic (where n=1 corresponds to the signal) can be described as $\exp(in\phi)$ [6], and the modulation sidebands are enhanced by n^2 in power relative to those on the signal. In a system in which the limiting factor is the noise of the receiver electronics, and in which conventional optical amplification would only serve to saturate the detector (which we demonstrate below), demodulating the n^{th} harmonic rather than the signal would allow for n times better SNR. This holds true when the optical noise floor is lower than the electronic background noise level, which is often the case.

Our proof of principle setup is shown in Fig.1(a). An RF signal was phase modulated onto an optical carrier (laser operating at 1555.8 nm) using a $LiNbO_3$ phase modulator. The modulator was driven by various electrical test waveforms generated either from a 24 GS/s Arbitrary Waveform Generator (AWG) or a fast RF synthesizer. The modulated signal was then combined with the pump (1557.4 nm). The pump laser was actively controlled to ensure a 200 GHz (± 1 MHz) frequency offset between the two waves. The signal and pump were gated at 100 kHz with a 3% duty cycle before being amplified in an EDFA to increase their peak powers, filtered to suppress out of band amplified spontaneous emission (ASE), and coupled into a the nonlinear stage comprising two HNLFs connected by 12m of SMF-28. The total power at the HNLF input was 200 mW. The length, dispersion, dispersion slope, nonlinear coefficient and attenuation of the HNLFs at 1550 nm were as follows: 500 m, 0.06 ps/nm/km, 0.0035 ps/nm^2/km, 18 /W/km and 1.4 dB/km and 500 m, -0.09 ps/nm/km, 0.016 ps/nm^2/km, 11.5 /W/km and 0.8 dB/km, respectively. An example of the achieved spectrum is shown in Fig. 1(b), with more detail shown in Fig. 2(a) – the signal was modulation free at the time. The harmonics of interest were then filtered, simultaneously demodulated in a 10 GHz delay line interferometer (DLI) and characterized using a 32 GHz photo-detector and an 80 GS/s real time oscilloscope (also with 32 GHz bandwidth). The frequency offset stabilization at an integer multiple of the 10 GHz DLI free spectral range (FSR) meant that a single DLI could be used for all harmonics.

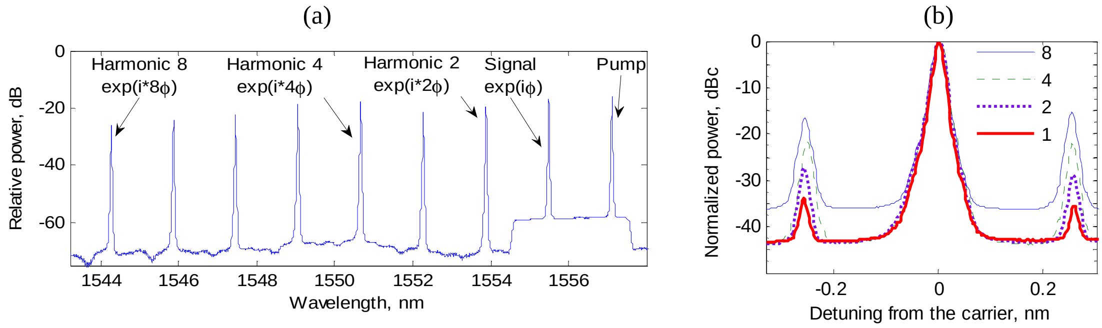

Figure 2: (a) Detail of the output optical spectrum with no phase modulation on signal. (b) Overlaid optical spectra of harmonics 1 (signal), 2, 4 and 8 when the signal was phase modulated at 32 GHz. These spectra were captured prior to the DLI, and are normalized to the carrier.

3. Results

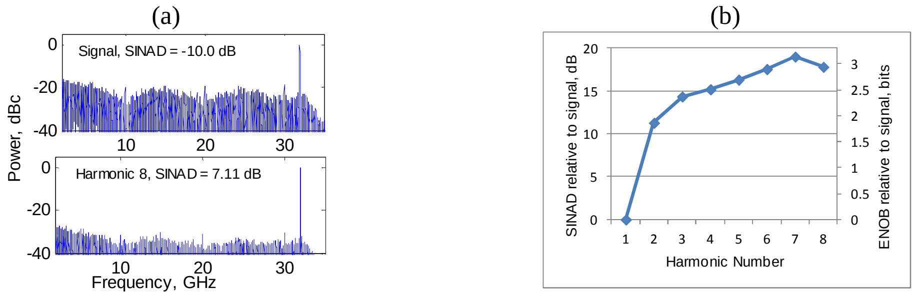

Figure 3: (a) RF spectra of the signal (top) and eighth harmonic (bottom) following detection of the 32 GHz phase modulated signal. (b) SINAD and ENOB of each harmonics 1 (signal) to 8 as calculated from the detected RF data at 32 GHz.

Fig. 2(b) shows overlaid optical spectral traces of the signal (n=1), 2^{nd}, 4^{th} and 8^{th} harmonics when a 32 GHz RF sine wave was applied to the modulator. The peak-to-peak voltage was approx 0.03 V_π. It is clearly observable that the modulation sideband on the 8^{th} harmonic is increased in power by 18 dB, with the sideband optical signal-to-noise ratio (OSNR) improved by up to 14 dB. The signal and harmonics were then all simultaneously demodulated in the DLI biased at 50% transmission, before being individually selected, amplified and coupled into the photo-detector. Note that the maximum possible signal power was coupled into the detector (as per the detector's specification), therefore further optical power amplification could not have been used to improve the optical-to-electrical conversion. The analog detector output was then captured with the oscilloscope and the data processed offline to calculate standardized figures of merit – signal to noise and distortion ratio (SINAD), as well as the ENOB, calculated from 1-40 GHz [7]. Note that the aggregate noise in the system was dominated by that originating in the receiver electronics due to the weak nature of the phase modulation. The results at 32 GHz are shown in Fig.

3. The SINAD increased by 18 dB in going from harmonics 1 to 8, improving the ENOB by approximately 3 bits. The slight reduction in performance in going from harmonic 7 to 8 is due to the reduced OSNR of the 8^{th} harmonic, Fig. 2(a); this can be easily remedied by increasing the power of the pump to boost the mixing process.

(a) (b)

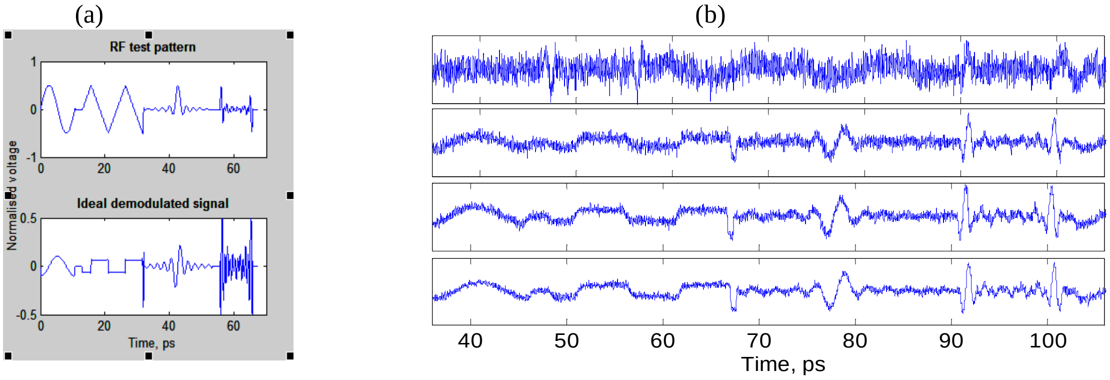

Figure 4: (a) RF test phase pattern, and expected detector output following demodulation in a 10 GHz FSR DLI. (b) Normalised data after demodulating signal, harmonic 2, 4 and 8 (from top to bottom respectively).

Finally, we show the system operating with a wideband input RF signal occupying 10 GHz. The chosen electrical pattern can be seen in Fig. 4 (a, top), and the ideal demodulated output (modeled) is shown in Fig. 4 (a, bottom). The various harmonics (1, 2, 4 and 8) after detection are shown in Fig. 4(b) with their powers normalized. The improvement in going from the signal (4b, top) to the 8^{th} harmonic is clearly visible. Calculating the ENOB in this instance is not directly possible due to the complex nature of the demodulating function.

4. Discussion and Conclusion

It is important to focus on the fact that this improvement is achieved by simply combining the signal with a CW laser in an optical fiber. In fact, the optical fiber could be integrated as part of the transmission channel, meaning zero additional latency. In contrast, other ENOB enhancement techniques, such as RF clock jitter reduction, require either an extremely low noise RF clock source and specially designed electronics, or the use of a mode-locked laser to perform pre-sampling [1]. Both these options will have significant cost and power implications. In addition, by either using a pulsed source as the pump, or optically sampling the harmonics after the FWM, the benefits of low jitter sampling can be combined with the significant power of phase amplification. Furthermore, the concept provides a route to building next generation optically assisted ADCs. Because the harmonics are precise integer multiples of the original channel, the device can be thought of as a modulo-2π calculator. Consequently, detecting each of the harmonics 1,2,4,8 …, using single bit electronic receivers, directly allows one to build ultra-high speed ADCs; at the moment this very modulo arithmetic is internally performed within the electronic ADC after detection.

In conclusion, we have used a cascaded FWM mixing process to generate the integer phase harmonics of a signal under test, and utilized this to achieve SNR enhancement without needing to deploy traditional optical amplification. This technique allowed us to improve the signal-to-noise-and-distortion-ratio performance of an optical-to-electrical converter by 18 dB, leading to 3 extra effective bits in detection. This technique will find many applications in photonic systems relying on optical phase to carry information, as well as future optically assisted ADCs.

5. Acknowledgement

This work is supported by the EPSRC grant EP/I01196X: Transforming the Future Internet: The Photonics Hyperhighway.

4. References

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