Time-Sampled Linear Optical Phase Demodulation

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Abstract: Time-sampled optical phase demodulation is proposed, based on heterodyne detection of a phase modulated signal, digital frequency division and measurement of the timing of zero-crossings using an XOR-gate. 30dB improvement in intermodulation terms is measured.

OCIS codes: (060.1660) Coherent communications; (120.5060) Phase modulation

1. Introduction

Phase modulated optical links hold great promise for analog link applications. It allows large SNR for a given optical power by increasing the phase modulation depth well beyond 2π. Low noise and high power lasers [1] together with linear, low $V\pi$ and bias-free optical $LiNbO_3$ phase modulators [2] will potentially allow passive antenna-remoting with high linearity and low noise figure. Currently, the limiting factor is the optical receiver. Standard balanced receiver configurations have a nonlinear sinusoidal response. Notable efforts to generate a linear response include a feedback loop to a linear tracking phase modulator [3] or linearization of the receiver response using digital signal processing [4].

The common assumption in these approaches is that the optical phase information must be linearly converted to current amplitude. The information is then typically obtained by digitizing the electrical waveform. This conversion is not required. Phase information can be viewed as a variation of time encoding, and as such is better demodulated using a time measurement. This paper proposes this type of optical receiver.

2. Phase Demodulator Architecture

The architecture of the proposed receiver is shown in Fig. 1, left. The received radio signal phase-modulates an optical signal in the remote antenna unit. Heterodyne detection then downconverts the optical signal to RF using an offset phase-locked local oscillator laser. The resulting RF signal is passed through a limiting amplifier. Each zero crossing of the RF signal is now represented by a digital transition from low to high voltage or reverse. The phase information is encoded as a time shift of the transition, which can be recovered by comparison to the clock signal used to phase-lock the LO laser.

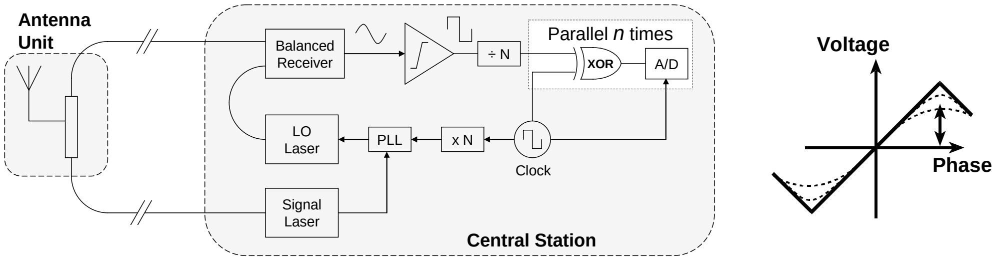

Fig. 1. Left: Schematic of proposed linear phase-modulated optical link. Right: Response of XOR-gate. Dashed lines indicate the effect of increasing risetime of the input waveforms.

Several methods can be used to recover the timing information of the received signal, such as comparing the signal and clock using an XOR-gate. This generates a linear response within the $\pm \pi/2$ range when integrated over one clock-cycle, as illustrated by Fig. 1, right. The linear range of the phase detection is increased using a digital frequency divider, where every n^{th} transition selected. The linear range is now $\pm n \cdot \pi/2$ and can be sufficiently large to avoid any distortion in the recovered waveform due to clipping. Using n XOR gates and n complementary divided signals, the information of all transitions can be recovered while benefiting from the larger linear range. The output of each XOR gate is sampled and digitized at a rate determined by the divided clock.

One concern using the digital frequency divider is aliasing. For example, for a clock division by a factor of two, f_{signal} and $f_{signal}+\frac{1}{2}f_{clock}$ will overlap. This aliasing problem can be resolved by adding or subtracting the samples from the two complementary divided signals. In a similar manner, a division by n can be resolved by processing the outputs from n complementary channels. This indicates the potential broadband nature of the proposed receiver, where an n-GHz broadband received signal can be channelized into n 1-GHz parts.

3. Proof-of-Concept Demonstration

Figure 2, left shows a schematic of a limited proof-of-concept demonstration. No phase-locked optical local oscillator source was available and a free-running LO had to be used. For this reason, the clock signal is recovered by tapping off part of the optical heterodyne beat signal before phase modulation is applied. Further, no digital frequency division is used so that the input frequency to the XOR gate is directly determined by the laser heterodyne. The output is now integrated using a simple low-pass filter.

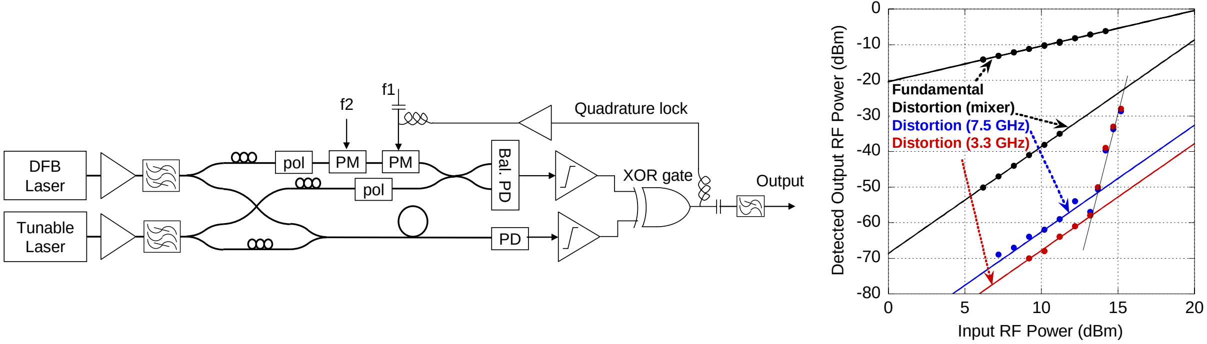

Fig. 2. Left: Schematic of the experimental arrangement for the proof-of-concept demonstration. (pol: polarizer, PM: phase modulator, PD: photo detector). Right: Measured power of fundamental and distortion compared to a mixer based receiver.

Figure 2, right shows the detected fundamental power and the power of intermodulation distortion ($2f_1$-f_2) as a function of modulator drive power. Data for two heterodyne frequencies are presented, around 7.5GHz and 3.3GHz. As a comparison, data obtained using a simple double-balanced mixer is included, replacing the limiting amplifiers and the XOR gate. The mixer data has been shifted to compensate for the different receiver gain and to directly provide a baseline comparison to a sinusoidal response.

Several observations can be made in Fig 2, right. First, using the XOR gate receiver, the intermodulation terms increases with the cube of input power up to a point, from which a break-down in linearity occurs. This is due to clipping as the peak phase modulation exceeds $\pi/2$. A second observation is the reduced linearity at larger heterodyne frequencies. The effect arises from the finite risetime of the output of the limiting amplifiers and the XOR gate, resulting in a more non-linear response and is relatively larger at 7.5GHz, as illustrated by Fig. 1, right. Using digital frequency division, both these limitations can be alleviated. At 3.3GHz heterodyne frequency, there is a ~30dB improvement in linearity compared to the mixer based receiver translates to an equivalent 10dB improved SFDR assuming shot-noise limited performance. This improvement is robust and does not require any precise control of bias points, input frequencies, etc. The measured SFDR of these measurements were severely limited by the residual noise from the free-running laser heterodyne, which grows larger at lower heterodyne frequencies. This explains the larger measured SFDR at 7.5GHz (96dBHz$^{2/3}$) than at 3.3GHz (95dBHz$^{2/3}$) despite the lower distortion of the latter.

4. Summary

In this paper, a linear method to demodulate optical phase modulation is presented. This approach uses heterodyne detection of a phase modulated optical signal and recovers the information by measuring the timing of zero crossings in the heterodyne frequency using an XOR gate. A proof-of-concept demonstration has been performed showing a robust 30dB improvement in the power of intermodulation terms. It is expected that the introduction of digital frequency division and a phase-locked high performance local oscillator laser will greatly improve the performance of this approach, both in linearity and in noise performance, which is now limited by the stability and phase noise of the free-running laser heterodyne used.

Acknowledgment

This work was supported by the DARPA PHOR-FRONT program under the United States Air Force Contract FA8750-05-C-0265.

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