Coherent Optical Receiver with Linear XOR Phase Detection and Frequency Down-Conversion

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Abstract — A novel optical coherent receiver architecture for linear optical phase modulation based on mixed signal circuit concepts is presented. This approach relies on heterodyne optical-to-RF down-conversion and linear RF phase demodulation using an XOR gate, generating a linear phase response over +/-pi/2 modulation depth. Adding digital frequency division by a factor *n* before the phase detector increases the linear range *n*-fold. Further, the coherent receiver is shown to perform frequency down-conversion in a linear manner. A first proof-of-principle discrete components demonstration has been performed to verify the frequency division architecture.

Index Terms — Ceramics, coaxial resonators, delay filters, delay-lines, power amplifiers.

I. 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 Vπ 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 work demonstrates an intermediate optical-to-RF down-conversion stage, after which the RF phase can be linearly recovered. This is achieved by a mixed-signal circuit approach using digital frequency division and an XOR-gate.

We have previously demonstrated a proof-of-concept demonstration using free-running laser heterodyne phase demodulation, using wide-linewidth lasers [5]. It was found that the XOR receiver improved linearity by 30dB compared to a conventional mixer based phase demodulation. However, a noise floor was obtained due to the laser linewidth. In this paper, this concept is extended using two phase-locked low-linewidth lasers and extended linear range phase demodulation using digital frequency division and XOR gate phase detectors.

II. APPROACH

The architecture of the proposed receiver is shown in Fig. 1, left. The received radio signal directly drives an optical phase modulator in the remote antenna unit. In the central station, heterodyne detection down-converts 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 the other way around. 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. This is done in a linear manner using an XOR-gate, which has a linear range of +/-pi. Further, using digital frequency division by a factor *n*, the linear range of the XOR demodulator is similarly increased by a factor *n*. This is illustrated in figure 2 for a division factor of four.

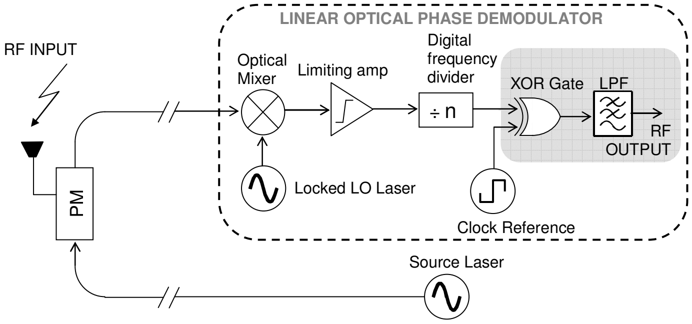

Fig. 1. Concept schematic of the proposed coherent receiver with linear XOR RF phase modulation. Shaded area is duplicated *n* times for *n* frequency division factor.

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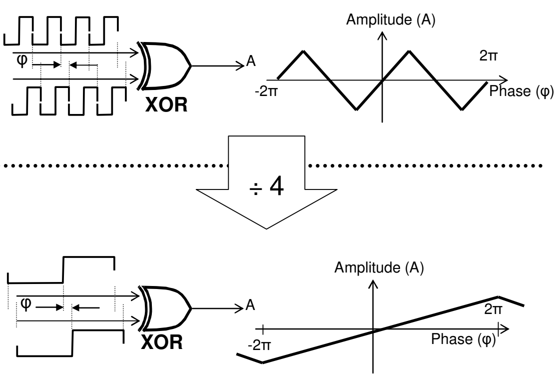

Fig. 2. Illustration of linear RF phase modulation using an XOR gate, and increasing the linear range using digital frequency division.

With the frequency division, there will be a penalty in signal-to-noise ratio, corresponding to the loss in information encoded in the zero transitions lost in the frequency division. To recover this information, *n* parallel outputs from the frequency division circuit must be captured. The full phase information is then recovered when recombining the outputs.

An attractive property of this optical receiver is the potential for frequency down-conversion using sampling concepts. The received RF phase modulation after limiting is contained alone in the timing of the zero-crossings. These represents sampling points, and as in any sampling system, an input RF frequency at $f_{clock} \pm f_{IF}$ will result in a down-conversion to f_{IF}. Similarly, if the XOR gate is preceded by a digital frequency division of *n*, an input RF frequency of $f_{clock}/n \pm f_{IF}$ will result in a direct down-conversion to *IF*. This is illustrated in Fig. 3 where a factor-of-eight frequency division is applied. The eight divided outputs can now be digitized, and the different Nyquist bands in the DC-to-RF frequency range can then be digitally accessed by the appropriate summation of the eight digitized signals.

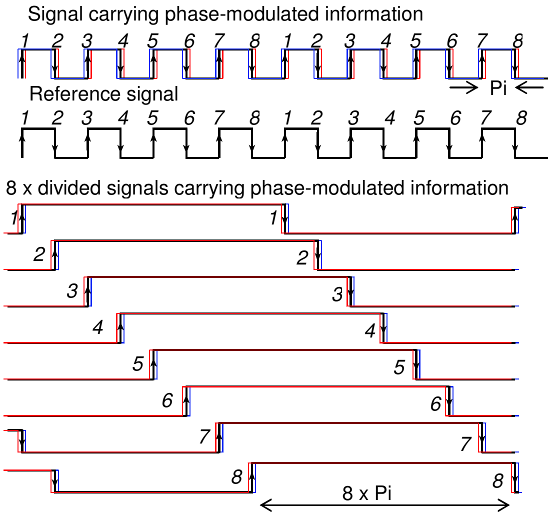

Fig. 3. Illustration of factor-of-eight frequency division with eight complementary outputs containing the full-band phase information of the received optical signal.

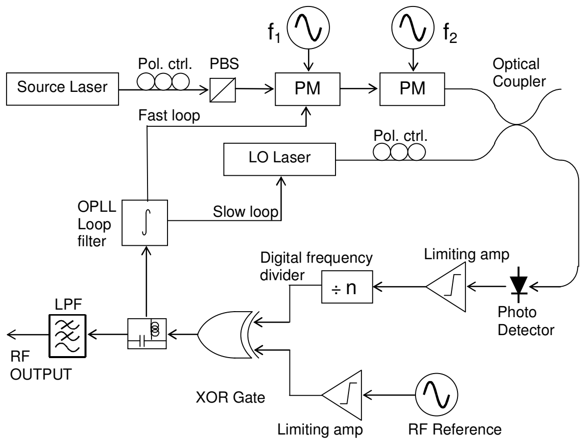

Fig. 4. Schematic of the experimental arrangement for the proof-of-concept demonstration. (PBS: polarizing beam splitter, PM: phase modulator, LPF: Low-pass filter).

III. PROOF-OF-CONCEPT DEMONSTRATION

Figure 4 shows a schematic of a limited proof-of-concept demonstration. The polarization of the output of an Orbits Lightwave fiber laser is matched to two $LiNbO_3$ phase modulators using a polarizing beam splitter and a polarization controller. The optical signal is then modulated by a two-tone probe signal. To avoid RF cross-talk between the two tones, two separate optical phase modulators are used to optically perform the RF signal combination. The received optical phase modulated signal is mixed with the LO laser at an offset frequency. The heterodyne signal is then detected, amplified using a limiting amplifier, to generate a square-wave, and frequency divided by a factor of four using an Inphi digital frequency divider. The divided signal is compared to a clock reference in the XOR gate, generated by an RF signal synthesizer and a second limiting amplifier. The output of the XOR-gate is passed through a bias-tee. The DC output is used to provide a feedback signal to phase-lock the LO laser. This is divided into a slow loop for laser wavelength tuning and a fast loop phase modulator. The fast loop is required to overcome a ~20kHz resonance in the laser piezo tuning element. An oscilloscope trace of the locked laser heterodyne signal is shown in Fig. 5, triggered by the microwave reference. Coherence is clearly observed. The RF output from the bias-tee carries the demodulated RF signal, which is then low-pass filtered to remove the divided optical heterodyne carrier frequency. The demodulated two-tone signal is then connected to a spectrum analyzer to detect the power of fundamentals and intermodulation terms.

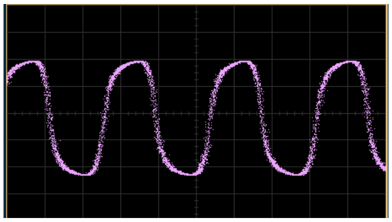

Fig. 5. Locked laser heterodyne signal

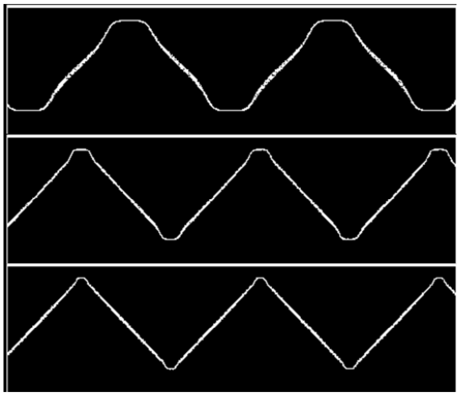

Fig. 6. XOR gate response after low-pass filtering for 10GHz input carrying continuous-ramp linear phase-modulation. Without frequency division (top), with factor-of-two division (middle), and with factor-of-four division (lower).

Figure 6 shows the response of the XOR gate for a 10GHz input without frequency division (top), with factor-of-two division (middle), and with factor-of-four division (lower). A clear improvement in linearity is clearly visible with higher division factors. The distortion in the response, most clearly seen in the top curve, is caused by the impulse response of the limiting amplifiers, the divider and the XOR gate. The distortion grows less visible at higher division factors, as the linear phase range increases.

Initial results of frequency division architecture have been obtained using an unlocked LO laser. To recover the RF reference for the XOR-gate, the laser beat-signal with no phase modulation was detected using a second photodiode. Figure 7 shows the detected fundamental power and the power of intermodulation distortion ($2f_1$-f_2) as a function of receiver input modulation depth. The RF frequency was kept close to 4GHz, resulting in a ~1GHz divided signal. The two-tone probe signal was centered around 500MHz with a +/-1 MHz separation.

We can clearly observe the more linear behavior of the XOR phase demodulator, as compared to the calculated response of a pure sinusoidal phase demodulation, green curve. Using an XOR demodulator with no division, we can observe an ~18dB reduction in intermodulation terms for smaller phase modulation depths. For modulation depths exceeding π rad peak-peak swing, clipping occurs, and the intermodulation terms rapidly approaches the same level as for using a sinusoidal phase demodulator. Adding frequency division to the XOR receiver, the suppression of the intermodulation terms are further suppressed (>22dB improvement). The improvement also remains up to modulation depths exceeding π rad peak-peak swing, where linearity remains in the response even at this very deep received optical phase modulation depth.

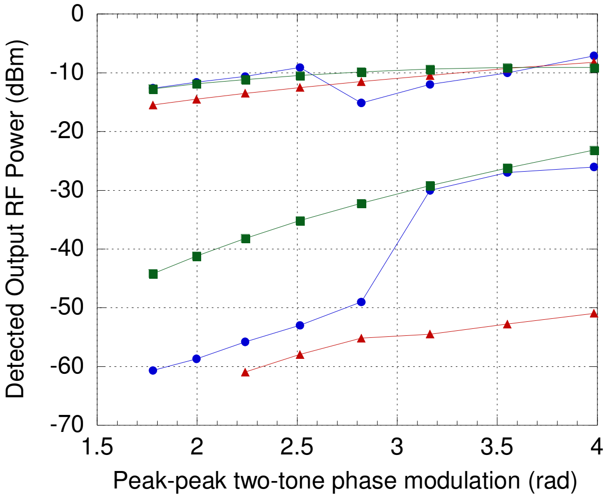

Fig. 7. Power of fundamental (f1) and distortion (2f1-f2) after phase demodulation using the XOR gate with (red), and without (blue) frequency division and compared to a calculated sinusoidal demodulator response (green). The divided signal has been shifted in power to compensate for the division loss, for easy comparison.

VII. SUMMARY

In this paper, a novel optical coherent receiver architecture for linear optical phase modulation based on mixed signal circuit concepts is presented. The receiver generates linear optical phase demodulation, in contrast to conventional mixer-based phase demodulation with a sinusoidal response. The phase demodulator relies in optical-to-RF down-conversion and RF phase demodulation using an XOR-gate, linear in the +/-pi/2 range. Further, it is shown that the linear range can be extended using digital frequency division. Finally, the phase demodulator has the potential to perform sampling down-conversion of higher received phase modulation frequencies, aided by the intermediate RF down-conversion, and further aided by frequency division.

An initial receiver demonstration has been performed using an offset-locked local oscillator laser, illustrating the improved linear range with XOR demodulation, and enhanced by frequency division.

ACKNOWLEDGEMENT

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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