

Coherent Optical Receiver for Linear Optical Phase Demodulation

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Abstract — A novel optical coherent receiver architecture for linear optical phase modulation is presented. A proof-of-concept demonstration has been performed using discrete components and at low frequency. High dynamic range has been confirmed at 3.13mA average photocurrent; 124.3 dBHz^{2/3}, corresponding to a 131.5 dBHz^{2/3} if a shot-noise limited noise floor were achieved (here limited by low-frequency 1/f-type noise). Further, efforts to increase the operating frequency to the GHz region and beyond has been outlined in the efforts to develop compact, low latency integrated chip technology and the development of novel sampling downconversion receiver architectures.

Index Terms — Optical phase locked loops, Optical communication, Integrated optoelectronics, Optical receivers.

I. INTRODUCTION

Optical modulator-based analog optical links has the potential for high performance. The combination of a high power, low noise optical source and a low $\sqrt{\pi}$ modulator results in a link with gain and low noise figure [1,2]. The linearity of an intensity modulated, direct detection (IMDD) link has been limited by full and zero transmission, between which a linear transfer function is difficult to fit. At best the transfer function can be linearized. This can result in a large SFDR in 1 Hz bandwidth [3], however the high order dependence of intermodulation terms still limits the available linear modulation depth.

Up to date, most analog links have used IMDD. This despite the fact that other modulation formats may be more suited for high performance analog transmission. Phase modulation is not limited in modulation depth in the same way as intensity modulation, it is in practice limited by the drive signal that can be applied to the modulator. This leads to the availability of highly linear modulators such as LiNbO3 phase modulators, which predominantly relies on the linear electro-optic effect. Further, a higher signal-to-noise ratio (SNR) can be supported in a phase modulated link than is possible using intensity modulation. This can be understood in terms of a tradeoff between SNR and spectral width of modulated optical signal.

The main challenge in constructing a linear phase modulated optical link is the problem of how to linearly convert the optical phase into an electrical current. The conventional phase receiver mixes the phase modulated

optical signal with an optical reference, producing a sinusoidal relation between photocurrent and optical phase, resulting in a link performance similar to that of a Mach-Zehnder modulated link [4]. In this work, we will show how a linear optical phase receiver can be built.

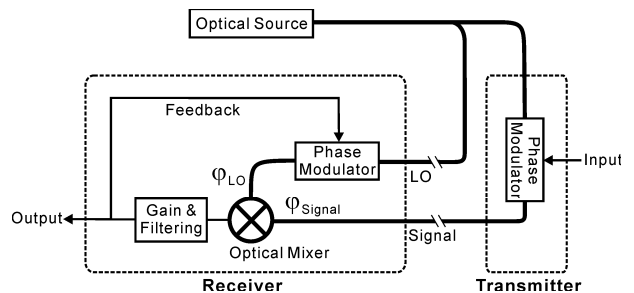


Fig. 1. Concept schematic of the proposed coherent receiver with feedback. Thick lines: optical link; thin lines: electrical link.

II. APPROACH

We are proposing a feedback receiver concept. The base function of the receiver is illustrated in Fig.1, above. Like in a conventional PM receiver, the received optical phase is mixed with an optical reference, producing a sinusoidal response to optical phase. The detected photocurrent is now amplified and fed back to a reference phase modulator. The received phase is now given by standard control theory:

$$\varphi_S - \varphi_{LO} = \frac{\varphi_S}{1+T} \quad (1)$$

Where φ_S and φ_{LO} are signal and reference optical phase, and T is the loop transmission gain. It can be observed that for high loop gain, the reference phase will closely track the received signal phase. Linear operation can be understood in two ways, the net detected phase gain will fall within the linear range of the sine transfer function of the optical mixing process, or using a linear reference phase modulator, or the driving signal must be linearly related to the received optical phase. It should be noted that the feedback reduces receiver noise sources just as much as net detected signal, such that the SNR remains unchanged when the loop is closed.

A common limitation in any feedback system is bandwidth limitations due to latency in the loop. The delay

will subtract a frequency dependent phase, and the loop bandwidth is limited by the requirement to keep the feedback phase away from -180° at unity loop gain to retain stability. To reach linear operation at 1 GHz, the loop bandwidth must approach 10 GHz, which require the loop delay to be in the 10-20ps range. This corresponds to only 3-6mm roundtrip path length in vacuum. For this reason fiber coupled components, or even LiNbO₃ based optics cannot be used. Only a very compact optical components material base, such as InP, can deliver this short latency.

Even using compact InP based technology, the high gain operating frequency of the receiver is limited to frequencies below 2GHz. To access higher RF frequencies, photonic RF downconversion is required. Simple photonic mixing, applying a sinusoidal modulation on the optical carrier converting the received RF signal to a detected IF signal, falling within the bandwidth of the loop, is a nonlinear process when closing the feedback loop. Instead, a pulsed optical source can be used where the pulse duration is short compared to the RF period, approximating an ideal sampling process. The baseband signal is then recovered by the integration in the loop.

III. PROOF-OF-CONCEPT DEMONSTRATION

To demonstrate the feasibility and validity of the concept, a proof-of-principle demonstrator experiment has been built. This is built using fiber-coupled optical components with up to four order of magnitude longer path-length than the equivalent integrated parts. For this reason, the operating frequency is limited to the 100 kHz range. The experimental arrangement used is outlined in Fig. 2. A more detailed description of the experiment can be found in [5]. The output from the optical source is split into a signal and reference path using a polarization beam splitter and polarization maintaining fiber. A two-tone RF probe signal (140 and 160 kHz) is applied to the signal path using separate phase modulators. In the receiver signal and reference is mixed and photodetected. The output from the balanced detector pair is then directly connected to the reference modulator to provide the feedback path. The feedback gain and filter function is regulated by the detector load, converting photocurrent to modulator drive voltage.

The power of detected fundamental and intermodulation terms from the buffer output is plotted in Fig. 3 against the link input power. With the feedback path disabled, a SFDR of 104.5 dBHz^{2/3} is obtained, limited by the sine response of the optical mixing. Closing the loop, a number of effects can be observed. First, we see that the detected power at the

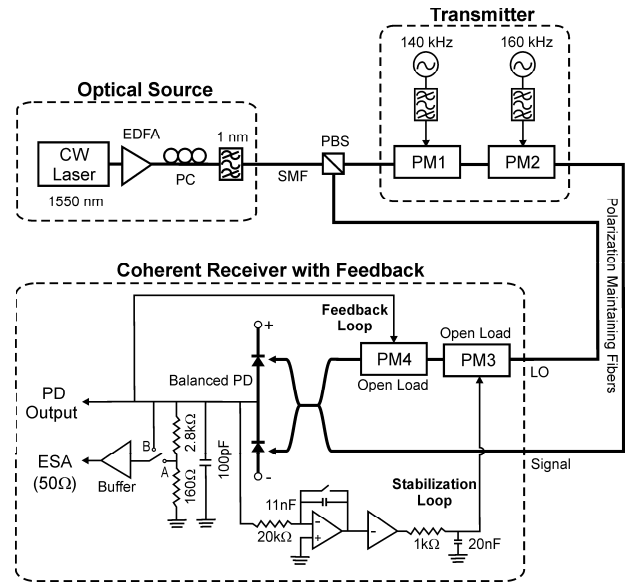


Fig. 2. Experimental setup. PC: polarization controller; SMF: single-mode fiber; PBS: polarization beam splitter; PM#: phase modulator; PD: photodetector; ESA: electrical spectrum analyzer

signal frequency is reduced as a result of the reduced net phase difference between signal and LO. However, as predicted the SNR remains unchanged as the noise floor is suppressed as much. The second effect is a dramatic reduction in intermodulation terms, appearing at 120 and 180 kHz. In fact, more than 20 dB increase in input drive power is required to generate detectable intermodulation terms. All in all, this translates in an improvement in SFDR of about 20 dB to 124.3 dBHz^{2/3}.

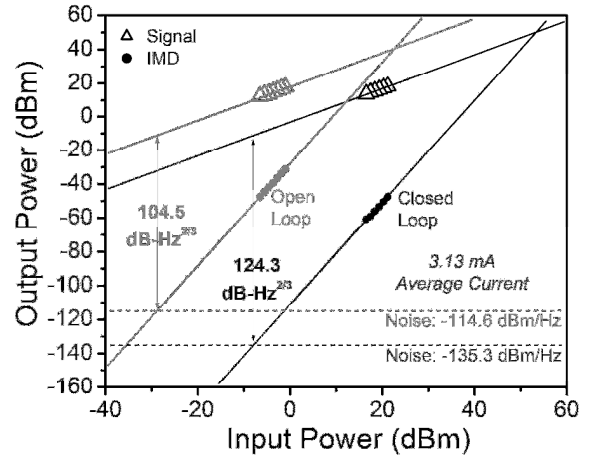


Fig.3. SFDR measurements at 3.13 mA of average photocurrent. Gray: open loop; Black: closed loop. IMD: 3rd-order intermodulation distortion.

The improvement in SFDR is dependent of the available loop transmission gain, T , and is proportional to $1/(T+1)^3$. Therefore, increasing the loop gain by increasing the optical power should show a strong effect on the dynamic range. This is also observed in Fig. 4, where the dynamic range increases to a peak value at 3.13mA of received photocurrent, after which the dynamic range degrades. This degradation can in part be attributed to nonlinearities of the photodetectors. These are terminated by a high impedance to provide the full voltage swing to the reference modulator ($4.4V V_{\pi}$).

At several mA of photocurrent, shot-noise dominates over thermal noise, representing the theoretical limit of noise level. As a consequence of operating at these low frequencies, shot noise limited operation has not been reached due to $1/f$ -type noise contributions from the optical source, etc. The currently measured noise levels are approximately 10 dB above the theoretical shot noise level, leading to about 6.7 dB penalty in SFDR, as indicated in Fig. 4. In a system operating at higher frequencies, shot noise limited operation should be available, particularly in this configuration where both laser intensity and phase noise is being cancelled when the signal and reference paths are matched. The projected shot noise limited performance corresponds to $131.5 \text{ dB}\cdot\text{Hz}^{2/3}$ at 3.13 mA.

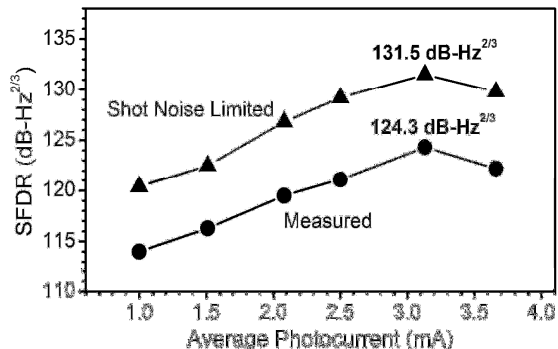


Fig. 4. SFDR with measured and shot-noise-limited noise levels for the closed loop case.

The sampling downconversion receiver approach has been demonstrated using the proof-of-principle demonstration outlined above in section III. For this demonstration, the received IF signal remained 140 and 160 kHz, while the received RF frequency was 110 MHz. Similar effects can be observed as for the baseband loop; closing the loop simultaneously reduces the noise floor, the signal and the intermodulation terms in a manner that increases the SFDR by 14 dB, from $85.9 \text{ dB}\cdot\text{Hz}^{2/3}$ to $100 \text{ dB}\cdot\text{Hz}^{2/3}$. The reduced dynamic range can mainly be attributed to increased noise of the amplified Mach-Zehnder based pulsed source used.

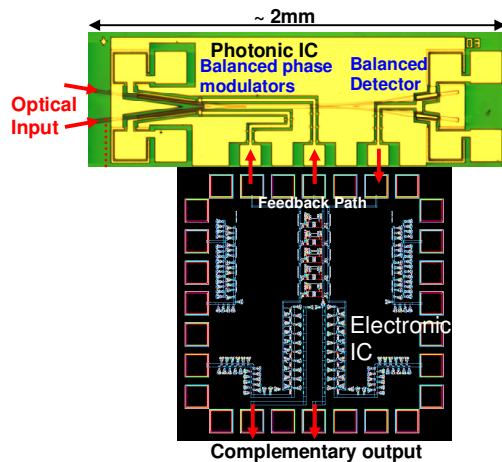


Fig. 5. Low-latency feedback receiver arrangement for linear demodulation of microwave phase-modulated optical links, showing electronic and photonic ICs.

IV. INTEGRATED RECEIVER DEVELOPMENT

The proof-of concept demonstration was performed at frequencies in the 100 kHz region, limited by the delay of the discrete components used in the feedback receiver. To reach an operating frequency of 1-2GHz, a low latency (10-25ps) receiver must be built. Figure 5 shows a current effort to realize this, based on close integration of an electronic integrated circuit, shown in schematic form and a photonic integrated circuit shown as a photograph. The photonic IC consists of a balanced detector pair, a coupler and optical phase modulators in a balanced configuration. The electronic chip is fundamentally a transimpedance amplifier, converting the differential output current from the detectors to modulator drive voltage. Additionally, it provides stability adding loop filtering and a buffer function for the output signal.

As the received photocurrent increases, lower amplifier transimpedance is required to provide feedback in the phase-lock loop. In fact, for sufficiently high photocurrent the modulator impedance can be tailored to provide adequate filtering and stable phase feedback, forming a feedback path on a single chip. The electronic IC is still needed to provide a buffered output.

To fully take advantage of the potential performance of a phase-modulated optical link, stringent performance requirements for modulator and detector performance must be met. In the proof-of-concept demonstration above, the obtained dynamic range was limited by the amount of photocurrent that could be detected without degradation, 3.13mA per detector at peak dynamic range. It is predicted that if this number can be increased to 100mA, potentially 90dB SFDR in 500MHz noise bandwidth should be available. Although, to support this performance, the output IP3 of a single detector must be higher than 50 dBm at this photocurrent.

A second critical performance requirement is the linearity of the phase modulators. While the closed-loop operation suppresses nonlinearities from the optical interferometer as well as of the amplifier, any nonlinear response of the phase modulator will remain. Since the feedback loop will force the reference phase to closely track the signal phase, a nonlinear phase modulator will consequently be modulated by a nonlinear drive signal. Using LiNbO3 modulators, this is not a limiting problem. However, Stark effect InP phase modulators predominantly rely on the more efficient quadratic electro-optic effect. The high efficiency leads to very short modulator structures and low latency, but the linearity of a single modulator will limit the available receiver performance.

An improved modulator configuration is obtained by placing two phase modulators, one in the signal arm and one in the LO arm, in a push-pull configuration. These are now driven in antiphase. The compound response is now given by:

$$\begin{aligned}\varphi_m &= \varphi_1(v_m) - \varphi_2(-v_m) = \sum_n a_n v_m^n - \sum_n a_n (-v_m)^n = \\ &= \sum_{n'} 2a_{2n'+1} v_m^{2n'+1}\end{aligned}\quad (2)$$

Where φ_m and v_m is the modulation phase and drive voltage and a_n are the Taylor expansion terms around the modulator bias point. It is seen that the quadratic term along with any higher even order terms are cancelled using this configuration. A second beneficial effect is that the amplitude modulation from the phase modulators is to a first order approximation cancelled using the balanced modulator approach.

VII. SUMMARY

The continuing work to realize a linear optical phase demodulating receiver has been summarized. It is shown that the feedback receiver concept not only allows the analog link designer to take advantage of the existence of linear optical phase modulators to generate highly linear optical links, it also supports optical links where the

available signal to noise ratio exceeds what is possible using standard intensity modulation links.

A proof-of-concept demonstration has been performed using discrete components and at low frequency. High dynamic range has been confirmed at 3.13mA average photocurrent; 124.3 dBHz^{2/3}, corresponding to a 131.5 dBHz^{2/3} if a shot-noise limited noise floor were achieved (here limited by low-frequency 1/f-type noise).

Further, efforts to increase the operating frequency to the GHz region and beyond has been outlined in the efforts to develop compact, low latency integrated chip technology and the development of novel sampling downconversion receiver architectures.

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