Linear Coherent Receiver based on a Broadband and Sampling Optical Phase-Locked Loop

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***Abstract*—A novel coherent receiver for linear optical phase demodulation is proposed. The receiver, based on a broadband optical phase-lock loop is demonstrated to have a bandwidth of 1.45 GHz. Using the receiver in an analog link experiment, a spurious free dynamic range of 125dBHz$^{2/3}$ is measured at 300 MHz. Further, theoretical investigations are presented demonstrating receiver operation at high frequencies (>2GHz) using a sampling phase –locked loop.**

I. INTRODUCTION

Optical Phase-Lock Loops (OPLL) have diverse applications in future communication systems. They can be used in high sensitivity homodyne PSK receivers for phase noise reduction, provided sufficient loop bandwidth is maintained. Alternate phase lock loop applications include coherent synchronization of laser arrays [1] and frequency synthesis by offset locking [2].

In this work, a broadband optical phase lock loop is utilized in a coherent receiver for the linear demodulation of analog-phase modulated optical links. Demanding military communications require linear links with high dynamic range. Traditionally, linearity improvements in analog optical links have been focused on intensity modulated / direct detection (IMDD) links, with the addition of coherent and incoherent optical FM techniques. However, the performance of such links is constrained by the modulation depth (between 0 and 100%) and non-linear response of intensity modulators. Phase modulators, on the other hand, have no inherent limitation to their modulation depth and can be swung over many π. Hence, they result in improved SNR and have the potential to be utilized in high performance analog links. However, the challenge of constructing such a high linearity link resides in the receiver architecture. In standard interferometer based phase demodulation, a sinusoidal relation exists between the phase and detected current. This inherent non-linearity in the phase recovery process limits the available link dynamic range and consequently, the benefits of phase modulation are lost.

To overcome this problem, we proposed and demonstrated at low frequency, a novel coherent receiver with feedback that is capable of distortion suppression [3]. Subsequently, an integrated version of the receiver has been developed for operation at close to GHz frequencies [4].

In order to operate the receiver at frequencies greater than 2 GHz the baseband loop bandwidth has to be very large. For example, a loop operating at 20GHz requires a loop bandwidth >100 GHz [5]. This is impractical from the standpoint of overcoming physical delays in the feedback path as well as the challenge of designing electronics that operates beyond 100 GHz. Instead we have chosen to explore optical sampling as an alternate to baseband operation [6, 7]. The basic idea is to use a pulsed laser source at the receiver to down convert the received high frequency input RF signal to within the operating bandwidth of the receiver by sampling at a rate close to the pulse repetition rate of the laser source. Detailed numerical models that explore the feasibility of such systems have been developed [8].

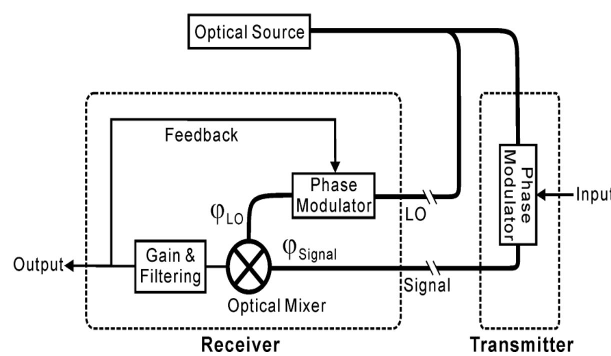

Figure 1. Concept of demonstrated coherent receiver with feedback. Thick lines: optical link; thin lines: electrical link

II. SYSTEM ARCHITECTURE

Figure 1 shows a schematic of the base receiver architecture. The received optical phase is mixed with an optical reference, producing a sinusoidal response to optical phase. The detected photocurrent is amplified and fed back to

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a reference phase modulator. The received phase is now given by standard control theory:

$$\varphi_S - \varphi_{LO} = \frac{\varphi_S}{1+G} \qquad (1)$$

Where φ_S and φ_{LO} are signal and reference optical phase, and G is the loop transmission gain. The reduction in the net detected phase results in the demodulator operating within its linear regime. Further, it should be noted that the feedback cannot discriminate between the detector shot noise and signal. As a consequence, the shot noise limited SNR remains unchanged despite the reduction in net phase.

The architecture of the receiver for sampled operation remains relatively unchanged. The only difference is that the c.w. optical source is replaced with a singled pulsed optical source in order to obtain an intermediate frequency (IF) component that falls within the bandwidth of the baseband phase demodulator.

III. INTEGRATED RECEIVER

To scale the operation of the receiver to microwave frequencies compact monolithic or hybrid integration of receiver elements is necessary for low loop latency. Our receiver consists of two integrated chips-one photonic and other electronic – mounted on a common microwave carrier. Figure 2 shows the photonic integrated circuit consisting of a balanced UTC photodetector [9], tracking phase modulators and a 2x2 MMI coupler. The receiver has the following features:

- Balanced (i.e. push-pull) modulator design that results in the cancellation of even order non-linearities and common-mode noise
- Exploitation of capacitances of photodiodes and modulators as circuit elements to perform the desired loop integrations in the feedback path.
- Electronic chip that enhances the phase margin of the system and also provides transconductance amplification to drive the modulators.

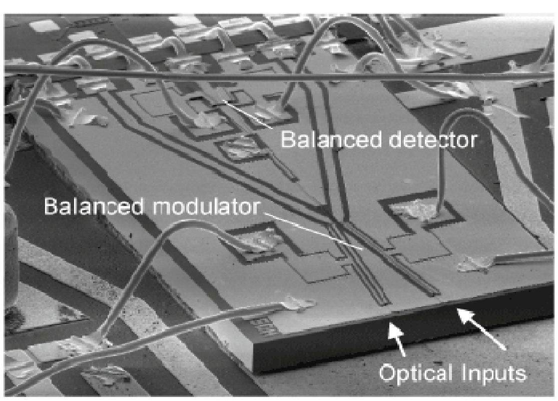

Figure 2. SEM of integrated Optoelectronic Receiver

IV. LINK DEMONSTRATION

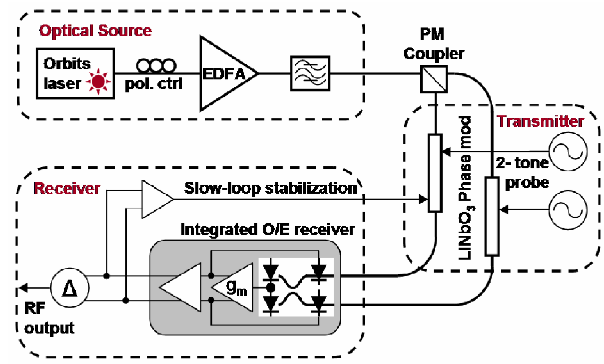

Figure 3. Schematic of Experimental Setup

The experimental setup is shown in Figure 3. The output of the optical source block is a high-power, amplified laser signal at 1537.40nm. The power emerging from the polarization maintaining (PM) coupler into the individual branches of the interferometer can be adjusted using the polarization controller. After the coupler, PM fiber and components are used for polarization management and stability.

Separate $LiNbO_3$ modulators are used in the transmitter block, in order to ensure that no mixing products are generated from the two-tone RF drive signal. A portion of the output signal from the receiver is tapped into a 'slow' feedback loop that generates a low frequency drive signal to one of the phase modulators for system stability against environmental drifts.

A. Link Response

The frequency response of the device for varying values of photocurrent is shown in Figure 4. The combination of high photocurrent and lower frequencies results in a sufficiently high loop transmission gain (G) such that the reference modulator is able to closely track the received signal phase. The optical link gain is now dependent on the ratio of drive voltage between source and reference modulator and in this link is -5dB.

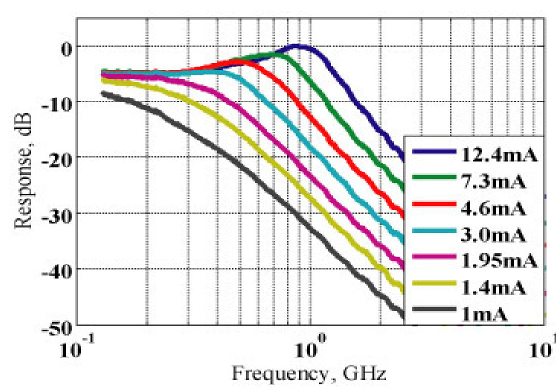

Figure 4. Link gain at different detected photocurrent values

At high frequencies or at low photocurrent values, loop transmission gain is low and hence, link gain is proportional to the photocurrent and loop filter transfer function as expected. The loop bandwidth, here defined by the 3dB point and approximately where the unity gain crosses over, is 1.45GHz at 12mA. The delay-limited bandwidth, within which the loop remains stable, is on the order of 4GHz.

B. *Spurious Free Dynamic Range (SFDR)*

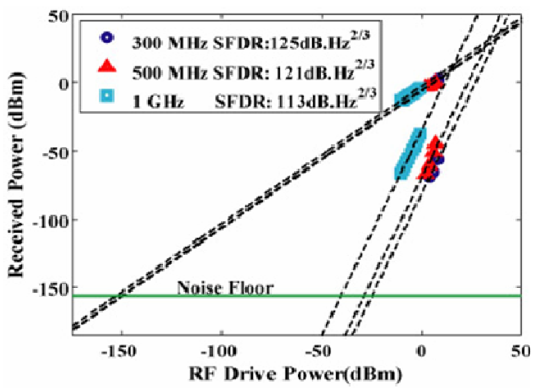

Figure 5. SFDR at different frequencies

Figure 5 shows SFDR data taken at 300 MHz, 500 MHz and 1 GHz. At 300 MHz, the high gain in the feedback loop results in enhanced linearity and consequently, an SFDR of 125dB.Hz$^{2/3}$ was measured. At higher frequencies, with reduced feedback (as seen in Figure 4), the SFDR degrades to the point where is there no reduction in net received phase. Consequently, the SFDR measured at 1GHz (113dB. Hz$^{2/3}$) with 12mA of photocurrent is close to the calculated shot noise limited SFDR at that frequency (116dB. Hz$^{2/3}$)

This is a fundamentally linear technique. However, further improvements in SFDR performance would require short feedback delay in order to sustain high, yet, stable loop gain at high frequency. Additionally, higher photocurrent in the detectors coupled with efficient, linear phase modulators will improve linearity performance of the receiver.

V. SAMPLING

In order to extend the frequency range of the receiver, the input RF signal has to be optically downconverted in order to fall within the bandwidth of the PLL. Standard optical downconversion for a balanced receiver involves using a frequency shifted optical reference tone, such that the frequency difference between one of the modulation sidebands and the RF signal is detected. However, in a phase modulated link, the signal, as obtained from the Bessel expansion, consists of several frequency components. Frequency shifting can access the information of only one of the tones and thus a severe limitation is placed on the linearity of the downconverted signal.

Optical sampling does not have this limitation. Using a pulsed laser source for signal and reference path, the input RF signal is sampled at a rate close to the RF period, and after detection, the resulting downconverted signal is obtained.

A. *Time Domain Analysis*

Previously, we reported a detailed time domain analysis of the baseband receiver operation [8]. The model has now been expanded to include sampled receiver operation as well [5]. The model suggests that to preserve linearity, a pulsed optical signal needs to be used. Moreover, by showing that the signal-to-intermodulation ratio (SIR) degrades with increased pulse width of the assumed Gaussian shape pulsed optical source, as shown in Fig. 6, it confirms that sampling induces extra non-linearities in the loop response. Further, by modeling the effect of loop gain on pulse width and taking into account the effective feedback delay of the sampled loop, it is found that for most efficient operation, very short pulses (<2ps) and high input signal frequencies are required [5].

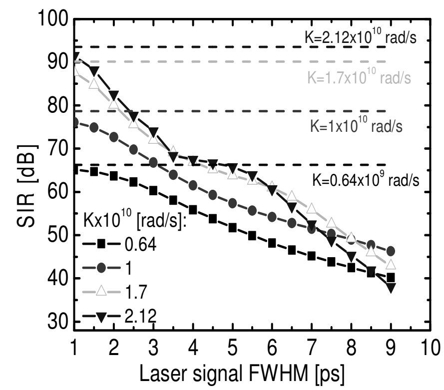

Figure 6. Signal to IR as a function of FWHM of the pulsed laser signal for selected values of the loop gain (K)

B. *Analysis Using Z-Transform Theory*

An elegant alternative to the computationally intense time domain model is to use Z transform theory for the analysis of sampled optical phase-lock loops [10]. In standard OPLL theory, the output phase and input phase are related thru equation 1. The Z-transform of the open loop transmission, G(Z), for a second order loop, taking into account delay is given as follows:

$$G(Z) = \frac{-S_n^2 T^2}{Z^n (Z-1)^2} \left[1 + (Z-1) \left(\frac{\tau_d}{T} + \frac{2i\xi}{S_n T} \right) \right] \qquad (2)$$

Here, Z is the Z transform variable and is given by $Z(f) = exp(2\pi ifT)$ where T is the sampling period. The delay, is expressed in the form $\tau = nT + \tau_d$ where the integer number of periods in the loop have the largest impact on loop behavior. The second term in the square bracket determines loop stability. It can be seen that increasing pulse period will decrease stability. Assuming a second order loop, a critical loop damping factor ($\xi = 1/\sqrt{2}$) and a loop natural frequency, f_n $(= s_n/2\pi i)$ adjusted to 10 dB loop gain margin for stability, we apply the Z-transform technique to the sampled receiver. Figure 7 shows the available stable loop gain as a function of input signal frequency assuming downsampling to 500 MHz. It is interesting to note that model predicts superior baseband performance below 1 GHz or sampled performance above 10GHz. The sampled gain does not vary with frequency at high frequencies and is a consequence of a transition from latency limited by pulse repetition rate to latency limited by physical delay in the feedback path.

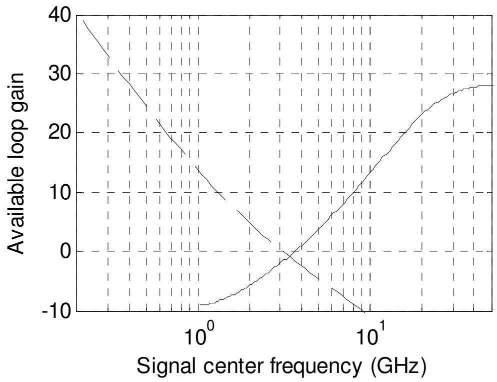

Figure 7. Available feedback gain in a linear tracking optical phase lock loop demodulator. The dashed line represents available stable feedback gain versus frequency of baseband tracking using a CW optical carrier. The solid line represents available stable feedback gain using a pulsed optical carrier and downconverting to 500 MHz.

VI. CONCLUSION

In this paper we have described and experimentally demonstrated the baseband operation of a novel coherent integrated receiver that is based on a broadband optical phase lock loop. We have shown that the receiver concept is a true linear technique, not realized by linearization or distortion cancellation and as such has the potential for high dynamic range. A loop bandwidth of 1.45 GHz and SFDR of 125dB.Hz$^{2/3}$ corresponding to 66dB in 500 MHz is reported. Additionally, we report an extremely low link loss: -5dB at low frequencies, when the loop is closed and the reference phase modulator is closely tracking the input signal phase.

We also explore the idea of porting the link to a much higher carrier frequency by using optical sampling. Two techniques 1) Time domain large signal model based on nonlinear differential equations and 2) Z transform theory; have been utilized to develop a comprehensive theoretical model of optical sampling in the context of the balanced receiver architecture. The results suggest that best performance is obtained at high RF to IF ratio. Put in another way, if the pulse widths of the pulsed optical source are shorter than 2ps and high input signal frequencies are used, the concept of optical sampling could become a practical reality for high-frequency analog optical links.

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