View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Drexel Libraries E-Repository and Archives

College of Engineering

Drexel E-Repository and Archive (iDEA)
http://idea.library.drexel.edu/

Drexel University Libraries
www.library.drexel.edu

The following item is made available as a courtesy to scholars by the author(s) and Drexel University Library and may contain materials and content, including computer code and tags, artwork, text, graphics, images, and illustrations (Material) which may be protected by copyright law. Unless otherwise noted, the Material is made available for non profit and educational purposes, such as research, teaching and private study. For these limited purposes, you may reproduce (print, download or make copies) the Material without prior permission. All copies must include any copyright notice originally included with the Material. **You must seek permission from the authors or copyright owners for all uses that are not allowed by fair use and other provisions of the U.S. Copyright Law.** The responsibility for making an independent legal assessment and securing any necessary permission rests with persons desiring to reproduce or use the Material.

Please direct questions to archives@drexel.edu

Receiver for a coherent fiber-optic link with high dynamic range and low noise figure

Yifei Li, David Yoo, Peter Herczfeld, Arye Rosen, Asher Madjar and Sam Goldwasser
Center for microwave-lightwave engineering,
Drexel University, Philadelphia, PA 19104, USA.

Abstract — **Phase modulated coherent fiberoptic links can potentially provide exceptionally high spurious free dynamic range (SFDR) and low noise figure (NF). Critical issue is the development of a strictly linear phase demodulator. In this paper we describe a phase demodulator employing a phase locked loop discriminator. Implementing the PPLL on a single substrate using the state-of-the-art components could yield an SFDR better than 145 dB/Hz$^{2/3}$ and NF lower than 3dB.**

Index Terms — **Photonic phase locked loop, coherent fiberoptic link, high SFDR, low NF.**

I. INTRODUCTION

This paper concerns the transmission of an analog microwave signal from an antenna to a digital signal processing unit as shown in Fig.1. In addition to faithfully remote the microwave signal, we are also interested in performing the optical domain down-conversion the intermediate frequency (IF) range. In the current state of practice, the data modulates the intensity of the optical carrier emanating from a laser source, travels along the optical link and is converted back to electric signals at the optical detector. One of the bottlenecks in such an intensity modulated (IM) optical link is the limited spurious free dynamic range (SFDR) due to the nonlinear distortion incurred within the modulation and demodulation processes [1]. However, some critical applications require very high SFDR (larger than 145 dB·Hz$^{2/3}$) and a noise figure (NF) as low as 3 dB. It is for such applications that high quality coherent phase modulated (PM) optical links can play a critical role.

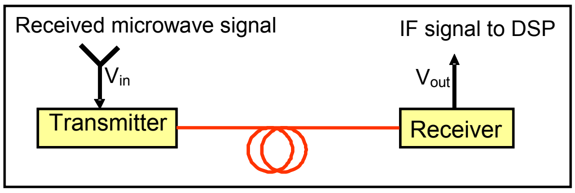

Fig.1. The input signal is, $V_{in} = A(t)\cos(\omega_m t + \phi(t))$, where A, ω_m and ϕ are the amplitude, frequency and phase of the microwave signal. The desired output signal is $V_{out} = A(t)\cos(\omega_{IF} t + \phi(t))$ where ω_{IF} is the IF frequency.

In the proposed coherent PM optical link, the output of the microwave antenna directly drives a high speed, linear and sensitive phase modulator that constitutes the optical transmitter. The emphasis of our work is on the optical receiver comprised of a strictly linear optical phase demodulator/down-converter. The novel concept presented here is an optical phase modulated (PM) link using a photonic phase locked loop (PPLL) demodulator/down-converter. The link being investigated enables PM signal demodulation and frequency down conversion to be accomplished *entirely in the optical domain*, resulting in a significant performance enhancement of the optical link, and more specifically, *improvement of its dynamic range and noise figure.*

II. PHOTONIC PHASE-LOCKED LOOP – PROOF OF CONCEPT EXPERIMENT

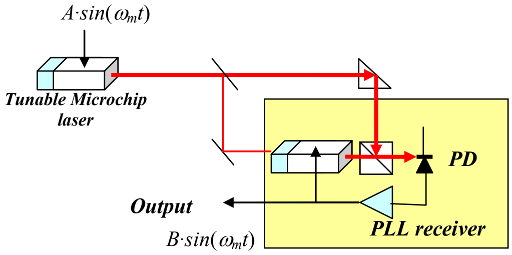

Fig. 2. FM fiber link at lower MHz

In the past years we have investigated the use of frequency modulated (FM) microwave photonic systems for lidar/radar, fiber radio and medical diagnostics [2,3]. Of a particular relevance to this paper, we initiated research of using a photonic phase locked loop to implement strictly linear coherent FM/PM optical link for RF over fiber applications. An example of such link employing highly linear electro-optical tunable microchip lasers is shown in Fig. 2. The FM sensitivity of the laser is set to be 20MHz/volt. The PPLL receiver was constructed using discrete component. A prove of concept experiment was performed to evaluate the linearity of this link at lower frequencies. The results are summarized in Fig. 3. The input vs. output characteristics are measured by applying a 3Volt 100kHz voltage ramp to the laser crystal. As shown in Fig. 3, an ideal linear transfer function is identified. Noted that, the applied ramp signal creates an optical phase change of over 300π and the link still remains strictly linear. A two tone inter-modulation test was also performed to verify the theoretical model we derived for the nonlinear distortion in the loop. We artificially reduced the loop gain to 20dB in order to observe the onset of the nonlinearity. We found that the two-tone third order intercept point at the output (IP3) around 23dBm, which agrees with our theoretical prediction. Considering the high frequency modulation index per volt (~20) in the experimental condition, this IP3 figure corresponds to an IP3 of 63dBm when the modulation index per volt is reduced to 0.2, the design parameter for the PPLL in the photonic IC form, as suggested in the following sections.

On the basis of this early experimentation we set out to design a coherent, PM fiberoptic link with very high dynamic range and low noise figure for the microwave and millimeter wave range.

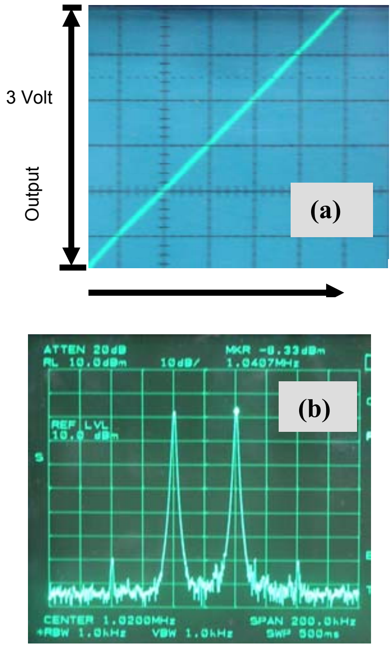

Fig. 3 Initial results of the strictly linear FM PLL link. (a) input vs. ouput, (b) two tone inter-modulation distortion

III. PHOTONIC PHASE-LOCKED LOOP (PPLL) LINEAR PHASE DEMODULATOR

In the coherent link architecture, the optical transmitter comprises of a remotely located high power (P_{TX}), narrow linewidth fiber or solid state laser and a linear phase modulator (with a high sensitivity: β_{TX}), which is directly driven by the antenna output.

The coherent optical receiver has two functions: i. linear demodulation of the optical carrier, and ii. optical domain down-conversion of the microwave signal to the IF band. In this paper, limited by space, the down-conversion will not be discussed. Instead, we will concentrated on describing our approach leading to the ultimate embodiment of the integrated PPLL, which performs faithful optical phase demodulation. First, we discuss the architecture and its requirements on the critical components.

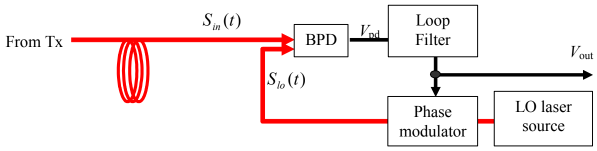

Fig. 4. Schematic representations of the PPLL phase demodulator. Abbreviations – BPD: Balanced Photo Detector. The phase modulated optical signal at the input is: $S_{in}(t)=\sqrt{P_{TX}}\cdot e^{j(\omega_0 t+\beta_{TX}V_{in})}+C.C.$ and the optical LO signal is $S_{LO}(t)=\sqrt{P_{LO}}\cdot e^{j(\omega_0 t+\theta(t))}+C.C.$

The phase demodulator, shown in Fig. 4., coined photonic phase locked loop (PPLL), relies on optical phase tracking to perform strictly linear phase demodulation. It comprises of balanced photodetector with responsivity R_{PD}, termination resistance R_{term} and saturated power P_{sat}, a loop filter with transfer function F(ω), an LO laser with power P_{LO} and a phase modulator with modulation sensitivity β_{LO}.

Initially, the optical signals from the transmitter, $S_{in}(t)$, and the local laser, $S_{LO}(t)$ are set at quadrature (90^o). When the transmitter optical signal undergoes a phase perturbation, the balanced PD will produce a nonzero error signal, which passes through a loop filter and modulates the optical phase of the LO laser to diminish the phase difference between the two optical signals. Ideally, if the loop latency is infinitely short and loop gain is infinitely high, the PPLL forces the phase of the LO optical signal to exactly mirror that of the input optical signal. Thus, its output, V_{out} is an faithful replica of the input (antenna signal, V_{in}). In reality, because of finite loop gain, there is a small but non-vanishing difference between the two phases, which may leads to small nonlinear distortion.

When the PPLL tracks the input optical phase, $\left|\beta_{TX}V_{in}(t)-\theta(t)\right|<<1$, and we can employ the small angle approximation: $\sin(\beta_{TX}V_{in}-\theta)\sim(\beta_{TX}V_{in}-\theta)$. The voltage signal passes through a loop filter and is applied to a phase modulator in order to modulate the LO laser. The self-consistent solution for θ yields the following relation:

$$\theta(\omega)=\frac{G(\omega)}{1+G(\omega)}\cdot\beta_{TX}\cdot V_{in}(\omega)$$

where the loop gain is:

$$G(\omega)=2\beta_{LO}\cdot R_{pd}\cdot\sqrt{P_{TX}\cdot P_{LO}}\cdot R_{term}\cdot F(\omega)$$

Consequently, the PPLL output voltage is given by:

$$V_{out}(\omega)=\frac{\theta}{\beta_{LO}}=G_{link}(\omega)\cdot V_{in}(\omega)$$

where $G_{link}(\omega) = \frac{G(\omega)}{1+G(\omega)} \cdot \frac{\beta_{TX}}{\beta_{LO}} \approx \frac{\beta_{TX}}{\beta_{LO}}$ is the PPLL link gain.

Therefore, in order to achieve the tight tracking critical for large dynamic range, the loop gain must be much greater than 1 in the signal band. However, due to the loop propagation delay (i.e., latency), if the loop gain is excessively high, it may acquire a negative phase margin at the critical frequency ω_c (where $|G(\omega_c)| = 1$), causing the PPLL receiver to oscillate. The maximum allowable propagation delay was calculated as a function of loop gain in the signal band, assuming a 500 MHz bandwidth and a RLC tank loop filter (see Fig. 5).

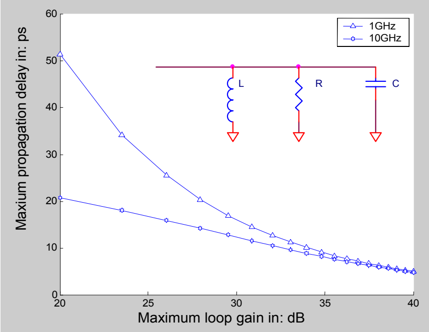

Fig. 5. Maximum propagation delay vs. the loop gain assuming the loop bandwidth is 500MHz.

For a 1 GHz carrier frequency, as the loop gain is increased from 20 dB to 40 dB, the allowable propagation delay is reduced from 51 ps to 5 ps.

When tracking is not ideal (i.e., $\beta_{TX} V_{in} - \theta \neq 0$), a small but finite nonlinear distortion will occur due to the sinusoidal response of the photodetector, which may be further intensified by the saturation characteristics of the photodiode. Active electronic components inside the loop can also be sources of nonlinear distortion.

If we operate the photodetector below saturation and avoid active electronic components in the loop then the third order intercept can be written as:

$$IP3 = \frac{4 \cdot [1 + G(\omega_{rf})]^3}{\beta_{LO}{}^2 R_{term}}$$

where we assumed for simplicity that $P_{TX}=P_{LO}=P$.

Besides nonlinear distortion, various noise sources also affect the PPLL receiver output. Including them into the model, the output noise floor can be calculated. For a coherent PM optical link employing high quality solid-state laser source (~-165dB/Hz relative intensity noise, ~1Hz Schawlow- Townes linewidth), the output noise floor can be estimated as:

$$N_{floor} \approx \frac{1}{2\beta_{LO}{}^2} \frac{(1/P_{TX} + 1/P_{LO}) \cdot e}{R_{pd} \cdot R_{term}} + \frac{2\delta\theta_n(\omega_{rf})^2}{\beta_{LO}{}^2 \cdot R_{term}}$$

The first term represents the shot noise of the photodetector while the second is due to the phase noise, where $\delta\theta_n(\omega_{rf})$ is the optical phase noise at the offset frequency, ω_{rf}. When the optical power is below 400 mW, the noise floor is dominated by the shot noise and is inversely proportional to the optical power. Above 400 mW, the phase noise dominates. It should be emphasized that due to the use of balanced photodetector, the relative intensity noise (RIN) was effectively canceled.

With the IP3 and noise floor determined, the link spurious free dynamic range (SFDR), noise figure (NF) and compression dynamic range (CDR) can all be calculated:

$$SFDR = \frac{2}{3} \cdot (IP3(dBm) - N_{floor}(dBm/Hz) - 3dB)$$

$$NF = N_{floor}(dBm/Hz) - G_{link} - (-174dBm/Hz)$$

$$CDR = P_{1dB}(dBm) - N_{floor}(dBm/Hz) - 3dB$$

where P_{1dB} is the 1 dB compression point of the PPLL output power.

These equations define the requirements to the PPLL parameters. First (and foremost), the loop gain must be maximized while maintaining a realizable loop propagation delay, or latency. The gain and the latency of the PPLL are determined by the characteristics of the individual components and their integration.

Next we investigated the optimal values for the critical components of the PPLL that will yield an optimized link in terms of SFDR and NF. Specifically, assuming an instantaneous bandwidth of .5 GHz, we arrived for critical component characteristics as listed in Table 1. In generating Table 1 we used device parameters that were currently attainable . These values yield a loop gain of 36 dB, which necessitates loop latency smaller than 8 picoseconds (see Fig. 5). Clearly, the PPLL must be tightly integrated on a single wafer.

TABLE 1. PRELIMINARY DESIGN SPECIFICATIONS FOR THE PPLL RECEIVER.

β_{TX}	β_{LO}	P_{sat}	R_{pd}	R_{term}
0.6rad/V	0.2 rad/V	600 mW	0.8 A/V	500 Ω

Theoretical study shows that when the transmitter and the LO laser powers are both set at 375mW, the coherent PM link employing the PPLL receiver shall attain the following performances specifications:

$$IP3 = 75dBm, SFDR = 157dB \cdot Hz^{2/3}, NF = 2.3dB$$

It should be noted that, for this preliminary design, the termination of photodiode was raised to 500 Ω via a simple transformer (commercially available at this ratio and bandwidth) outside the loop (i.e., *leaving the load impedance at 50 Ω*). This impedance transformation is not necessary if breakthroughs in key PPLL components are made. The key components of the PPLL are the high power photodetector that allows for the large loop gain, and the optical phase modulator that attains high sensitivity and low latency simultaneously. The latest development by Campbell [4] regarding high power photodetectors brings the very high saturation power into the realm of possibilities. The subsequent increase in the loop gain effectively relaxes the requirement on the phase modulator. In parallel, a novel optical phase modulator concept has been developed in Drexel University. Such modulator can achieve high modulation sensitivity while suffering negligible penalty in the loop latency. Thus, this is the key to unlock the full potential the PPLL receiver. At present, this concept is under careful evaluation and will be reported in near future.

IV. CONCLUSIONS

Fiber-optic links using amplitude modulation have been employed very successfully in communications, antenna remoting for radar and other similar applications require very high SFDR and low NF that AM links can’t provide. Coherent PM links have inherently better performance potential provided a linear phase demodulator can be developed. In this paper we discussed a linear phase demodulator and predicted the PM link performance.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of ONR and DARPA under contract N00014-00-1-0781 mod. 5.

REFERENCES

[1] R.F., Kalman, J.C. Fan, L.G. Kazovsky,, "Dynamic range of coherent analog fiber-optic links", Journal of Lightwave Technology, vol. 12, no. 7, July 1994, pp 1263 - 1277

[2] Y. Li, S. M. Goldwasser, A. J. C. Vieira, P.R. Herczfeld, “Rapidly Tunable Millimeter wave Optical Transmitter for Hybrid Lidar /Radar ", IEEE Transactions on Microwave Theory and Techniques, Oct 2001.

[3] Y. Li, S. M. Goldwasser, D. Yoo, P. R. Herczfeld, “Direct QAM Modulation of Microwave Subcarrier Using Electro-optically Tunable Microchip Lasers”, IEEE Microwave Photonics 2004 Technical Digest, Ogunquit, Maine, Oct. 2004

[4] Xiaowei Li, Ning Li, Xiaoguang Zheng, Stephane Demiguel, J. C. Campbell, David A. Tulchinsky, and Keith J. Williams, “High-saturation-current InP/InGaAs photodiode with partially depleted absorber,” IEEE Photon. Tech. Lett., IEEE Photon. Tech. Lett., vol. 15, pp. 1276-1278 (2003).