Coherent, Phase Modulated (PM) Fiber-optic Link Design

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***Abstract* — This paper is concerned with a coherent, phase modulated optical link for microwave applications, such as antenna remoting. The optical transmitter employs a low noise high power solid state laser and a sensitive phase modulator. The demodulator/detector in the optical receiver utilizes a newly developed and tested photonic phased locked loop (PPLL). All signal processing, including down-conversion to intermediate frequency (IF) range, is executed in the optical domain. The link design predicts a spurious free dynamic range up to 157 dBHz$^{2/3}$ and noise figure below 3dB. The requirements on key photonic components to attain these results are described in detail.**

***Index Terms* — Coherent optical link, high dynamic range, photonic phased locked loop, antenna remoting.**

I. Introduction

Modern military platforms containing on-board communications, radar, and electronic warfare (EW) systems benefit from the ability to 'remote' the microwave sensors from the central processing unit (CPU). For example, the antenna elements and T/R modules and the control unit of a phased array antenna are often not co-located. An analog data link provides the required connectivity between such components, thus potentially becoming a system performance limiting factor. Continued and ongoing research and development efforts focus on analog data links with higher dynamic range, broader bandwidth, and lower noise [1]. Optical links are attractive due to their high bandwidths, low attenuation, and immunity to electromagnetic interference.

In a typical analog fiber optic data link the data modulates the intensity of the optical carrier emanating from a laser source, travels along the optical link and is converted back to an electric signal at the optical detector. The signal demodulation is done directly, typically through the use of a photodetector. One of the bottlenecks in such an optical link is the limited spurious free dynamic range (SFDR) due to the nonlinear distortion associated with the optical modulation and demodulation processes.

The next generation of optical links will rely on coherent, phase and frequency modulated techniques and void of electronic components. The continued development of high power, low noise and extremely narrow linewidth lasers, combined with highly sensitive and linear phase modulators, will enable the realization of excellent optical phase modulated (PM) transmitters. Coherent phase and frequency modulated optical links will also require the development of highly sensitive, extremely linear optical phase demodulator/detectors and optical domain down-converter that can accommodate very high frequency microwave carrier signals. The principal candidate for a high performance phase demodulator/detector is a **photonic phased locked loop** (PPLL). As with any phased locked loop, stability is an issue and our previous work indicates that the latency of the PPLL must be reduced to a few picoseconds to ensure stability for signal bandwidths on the order of a GHz [2]. This latency requirement represents a major PPLL challenge that cannot be met using traditional loop filter design techniques even if the implementation uses the highest component integration possible. A new approach is clearly needed.

In this paper we address the design of a coherent phase modulated fiber-optic link that uses a novel PPLL with cutting edge photonic components. The PPLL also incorporates a built in optical domain down-converter to accommodate very high frequency microwave carrier signals. We believe that this new approach will make high frequency coherent PM fiber optic links a practical reality.

Figure 1 illustrates our novel fiber-optic link architecture, which directly routes the microwave output signal from the antenna, V_{in}=A(t)exp(iω_mt)+c.c., down-converts it to the IF range, V_{out}=A(t)exp(iω_{IF}t)+c.c., and provides the down-converted electronic signal, to the digital processor without the employment of a single electronic component.

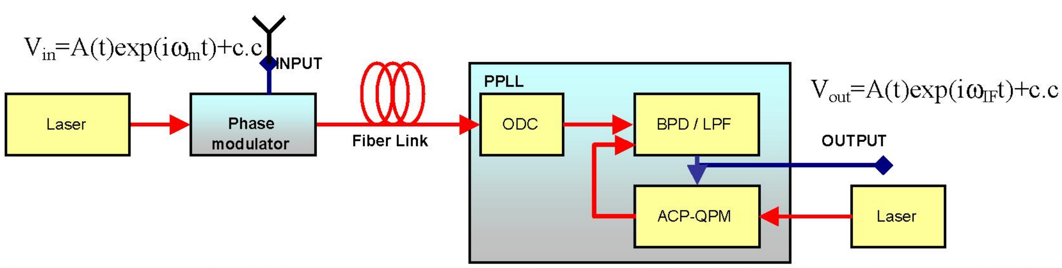

Fig. 1. PM fiber-optic link with PPLL phase demodulator/detector, ODC - Optical Down Converter, BPD - Balanced Photo Detector with Low Pass Filter, ACP-QPM Attenuation-Counter-Propagating Quadratic Phase Modulator. ADD Vin and Vout on the figure

II. PM OPTICAL LINK CONFIGURATION

In this section we describe the overall link architecture, as shown in Fig.1, and describe the requirements on components. The two lasers, at the optical transmitter and receiver, are very narrow linewidth, high power (P_{TX} and P_{LO}), and low noise solid state devices. The linear phase modulator in the optical transmitter can be a long device with very low V_π, that assures high transmitter sensitivity. The output of the transmitter is a phase modulated optical carrier described by the equation:

$$S_{TX}(t) = \sqrt{P_{TX}} \cdot \cos(\omega_o t + \beta_{TX} \cdot V_{in}(t))$$

where β_{TX} is the sensitivity of the phase modulator, ω_o is the optical frequency, P_{TX} is the optical power, and $V_{in}(t)$ is the microwave signal received by the antenna:

$$V_{in}(t) = A_{in}(t) \cdot e^{i\omega_m t} + c.c.$$

where $A_{in}(t)$ is the complex envelope of the microwave carrier that contains the signal information and c.c. is the complex conjugate. In general, $A_{in}(t)$ is narrow band compared with the microwave carrier frequency, ω_m.

The optical domain frequency down-converter (ODC) is comprised of an optical amplitude modulator (such as MZ modulator) and a balanced photodiode*. The ODC modulator amplitude modulates the optical signal, S_{TX}, at the IF frequency producing an AM signal of the form:

$$S_{TXIF}(t) = \sqrt{P_{TX}} \cdot m_1 \cos\omega_{IF} t \cdot \cos(\omega_o t + \beta_{TX} \cdot V_{in}(t)) \cdot$$

It should be noted that this modulation does not affect the phase of the optical carrier that contains the microwave signal. This optical signal is fed into the balanced photodetector. The phase tracking system, shown in Fig. 1., coined photonic phase locked loop (PPLL), relies on optical phase tracking to perform linear phase demodulation. The PPLL is comprised of the balanced photodiode, a low pass filter (BPD/LPF) and a quadratic phase modulator (QPM). The locally generated feedback optical signal impinging on the photodiode is:

$$S_{LO}(t) = \sqrt{P_{LO}} \cdot \sin(\omega_o t + \theta(t))$$

where P_{LO} is the optical power of the LO laser.

In the case of no microwave signal modulation, the PPLL adjusts the optical signals from the transmitter and the local laser to be in quadrature (90°). When the transmitter optical signal undergoes a phase perturbation, the balanced PD will produce a down-converted nonzero error signal, given by,

$$V_C(t) = m_1 \cdot \cos\omega_{LO} t \cdot 2R_{PD}\sqrt{P_{TX}P_{LO}} \cdot R_{term} \cdot \sin(\beta_{TX} \cdot V_{in}(t) - \theta(t))$$

where m_1 is the conversion gain of the down-converter, R_{PD} is the responsivity of the photodiode, R_{term} is the terminal resistance. This error information passes through a loop filter, up-converts at the quadratic phase modulator (QPM) and modulates the optical phase (i.e. θ(t)) of the LO laser to effectively track the phase difference between the two optical signals.

When the loop is tracking the input phase, $\beta_{TX} \cdot V_{in}(t) - \theta(t)$ is very small and the down-converted output is given by

$$V_{down}(t) = A_{out}(t) \cdot \exp^{i(\omega_m - \omega_{LO})t} + c.c.$$

where $A_{out}(t)$ is the complex envelope of the down-converted signal. In frequency domain, the self-consistent solution yields this complex envelope as:

$$A_{out}(\omega) = \frac{\beta_{TX}}{m_2 \cdot \beta_{LO}} \cdot \frac{G(\omega + \omega_{LO})}{1 + G(\omega + \omega_{LO})} \cdot A_{in}(\omega)$$

where m_2 is the up-conversion loss, β_{TX} and β_{LO} are the sensitivities of the transmitter and receiver phase modulators, respectively, $G(\omega) = \beta_{LO} \cdot m_1 \cdot m_2 \cdot R_{PD}\sqrt{P_{RX}P_{LO}} \cdot R_{term} \cdot \tilde{F}(\omega)$ is the PPLL loop gain, and m_1 is down-conversion loss. We also define the link gain as:

$$G_{link} = \frac{\beta_{TX}}{m_2 \cdot \beta_{LO}} \cdot \frac{G(\omega + \omega_{LO})}{1 + G(\omega + \omega_{LO})}$$

In order to retain high fidelity down-conversion, which requires the output envelope A_{out} to be a scaled replica of the input microwave envelope A_{in}, the loop gain must be set as high as possible. This can be achieved by significantly increasing the optical power level of the lasers and employing a very high saturation photodetector. At the same time the loop propagation delay (i.e., latency) of the PPLL must be kept low to avoid oscillations.

III. SYSTEM PERFORMANCE

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 will be further intensified by the saturation characteristics of the photodiode. Since the PPLL does not contain electronic components, all nonlinearities are photonic in nature.

If we assume for simplicity that $P_{TX}=P_{LO}=P$, then the third order intercept, IP3, can be derived as:

$$IP3 = \left(\frac{P_{1dB}^2 - 0.3P^2}{P_{1dB}^2 + 0.3P^2}\right) \cdot \frac{4 \cdot [1 + G(\omega_{rf})]^3}{\beta_{LO}{}^2 R_{term}},$$

* A paper describing in detail the optical domain transmission is being submitted to the IEEE-MTT transaction.

where P_{1dB} is the 1 dB saturation optical power of the photodetector.

Aside from nonlinear distortion, the PPLL output is also affected by various noise sources within the loop, which are: i. optical phase noise, ii. laser RIN, iii. thermal noise and iv. photodetector shot noise. The contribution of these noise sources to the PPLL output is shown in Fig. 2,

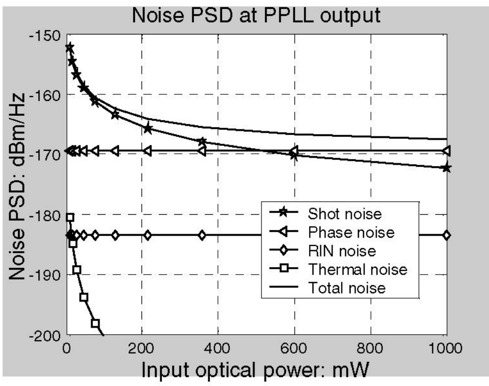

Fig. 2. Noise power spectral density (PSD) of various noise sources at PPLL output.

To calculate the noise floor, we let 20 dB of cancellation of the laser RIN by the BPD. The phase noise at a 1MHz offset -110 dBc/Hz is derived from previous measurements of solid state microchip lasers [3].

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 governed by the shot noise and is inversely proportional to the optical power. Above 400 mW, the phase noise dominates.

With the IP3 and noise floor determined, the link spurious free dynamic range (SFDR), and noise figure (NF) can all be calculated. They are given by:

$$SFDR = \frac{2}{3} \cdot (IP3(dBm) - N_{floor}(dBm/Hz) - 3dB)$$
$$NF = N_{floor}(dBm/Hz) - G_{link} - (-174dBm/Hz)$$

where G_{link} is the link gain of the coherent PM optical link defined above.

In summary, the high level roadmap for the PPLL design is: i. avoid using active electronic components inside the loop, ii. maximize the loop gain, and iii. minimize loop latency.

IV. HIGH PERFORMANCE PM OPTICAL LINK

Given the generalized analysis of the coherent PM fiber optic link using the PPLL presented in the previous sections, it is now important to address two fundamental questions: 1 Does this architecture support link performance that would far exceed the capabilities of the best possible electronic or optical AM links, and 2. What are the component requirements to achieve this goal? We will address the component requirements first and then use them to calculate the link performance.

Solid state lasers can provide narrow line width, very low RIN and phase noise with optical output powers approaching 1W. The sensitivity of the system is determined by the phase modulator in the transmitter. Considering great progress in new electro-optic materials and advances in device fabrication, a value of .6rad/V for β_{TX} is within reach.

Perhaps the most critical component of the PPLL is the BPD. For most radar and electronic warfare operation the carrier frequency is high, but the information bandwidth is usually .5GHz or less. Once the signal is down-converted to the IF or baseband range in the optical domain, the required BPD bandwidth is .5 GHz or less. Based on current research we concluded that a balanced photodiode with saturation power of P_{sat}=.6W and responsivity of Rpd=.8A/V at .5GHz is attainable [4] . Furthermore, the BPD can functions as a low pass filter (LPF), eliminating the need for an electronic filter in the PPLL.

Table I show critical component values that we believe are achievable in the near-term given the current state-of-the-art and reasonable technology development efforts.

Table I. Component specifications for for the PM link design. V_{max} is the peak voltage applied to the phase modulator, R_L is the load resistance.

β_{TX}	β_{LO}	V_{max}	P_{sat}	R_{pd}	R_L
.6rad/V	.2 rad/V	>5 V	.6 W	.8 A/V	500 Ω

The above components' characteristics were used to generate a set of system performances depicted in Fig. 3. As an example, for an optical input power of 375 mW, we expect a loop gain of 36 dB that would assure a very high IP3 and hence a large dynamic range. At this power level the link characteristics are as follows:

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

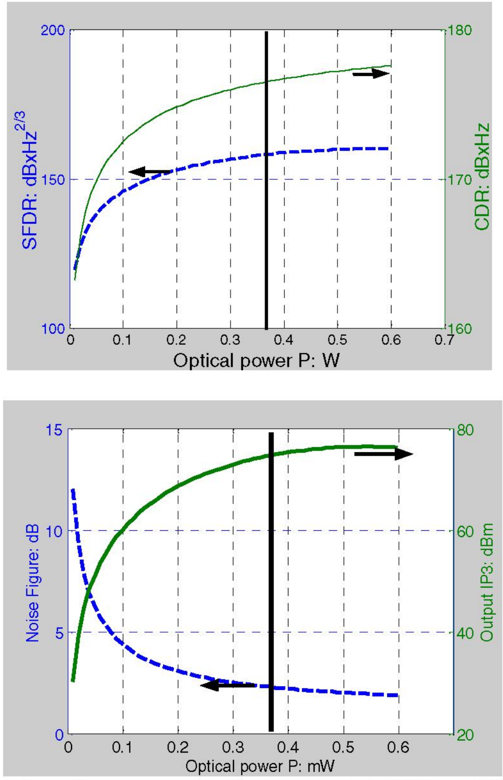

Fig. 3. Link performance vs. optical power. (a) SFDR and CDR, (b) NF and IP3.

It needs to be emphasized that the values listed above represent reasonable goals. It should be noted that if we reduce the optical power level to 100 mW, which is within the reach of currently available photodetectors, we still expect excellent link performance (145dBHz$^{2/3}$ SFDR and less than 5dB NF).

If the loop gain is excessively high in the signal band, 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 latency (delay margin) was calculated to be t_{loop}=8psec assuming a loop bandwidth of .5GHz, and loop gain of 36dB (i.e P=375 mW). In fact, the latency requirement represents the most formidable challenge to the implementation of the high performance PM link.

Specifically, to attain very low latency two challenges must be considered: i. very tight integration of the photonic components, namely the BPD and the QPM, and ii. reduction of the latency of the QPM. Rapid advances in nano-photonics fabrication technology makes chip level integration of the BPD and QPM a real possibility. Recently we designed and carried out proof-of-concept experiment on an attenuation-counter-propagating quadratic phase modulator (ACP-QPM) that substantially reduces the latency [5]. In the ACP-QPM the optical and microwave signals travel in the opposite direction and the propagating microwave signal is attenuated. If the device is sufficiently long it acts like a lumped element low pass filter with diminishing latency.

V. Conclusion

In the past three decades considerable research has been conducted on optical antenna remoting and optical signal distribution in phased array antennas for radar and EW. Initially, significant progress was achieved; however, recent improvements have been incremental due to the inherent performance limitations associated with the non-linearities of AM modulation and direct detection. It is time to recognize the need for fundamentally different approaches for high performance analog fiber optic links. In this paper we analyzed a new, coherent (PM) optical link architecture that can provide very high SFDR and low NF. While a complete link has yet to be built, the key component of this link, the photonic phased locked loop (PPLL) has been demonstrated experimentally in previous work to validate proof-of-concept. We also defined the component requirements necessary in order for this new link architecture to exceed current AM/direct detection link performance by 30 dB in SFDR. The incorporation of a high fidelity PM link into radar and EW systems will significantly improve their performance.

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