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System Impacts of Modulation Technology and Phase Noise on Coherent Analog Optical Links

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Abstract: We describe an analog optical link using amplitude modulation and coherent detection for high SFDR, gain, and low noise figure. We then address the dominant performance-limiting parameters and discuss several approaches to overcome these limitations.

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1. Introduction

Coherent detection in analog optical links offers several advantages, including increased linearity, heterodyne frequency conversion capability, and reduced link noise figure. The suppressed carrier modulation format can result in lower overall system noise and inherent signal carrying sideband gain, enabling signal distribution with minimal impacts on the link noise figure. Implementing a coherent link in a microwave communications system requires an optimized modulation platform while simultaneously understanding and mitigating coherence-related noise. This paper addresses specific lithium niobate Mach-Zehnder modulator (MZM) designs (X-cut, Z-cut, single-ended and dual-drive) and shows the dual-drive Z-cut design as being optimal for the suppressed carrier modulation format. We also show how the laser phase noise can be the dominant performance-limiting parameter in a coherent link and discuss several approaches to overcome phase noise-limited performance.

2. Link Architecture

Carrier suppression combined with coherent heterodyne balanced detection provides a microwave photonic link (see Figure 1) with increased linearity [1] and noise performance compared to an IMDD link [2]. Since the link gain and third-order intercept each depend on the product of modulator optical input power and local oscillator power, the amplitude of the sidebands can be increased by driving up the optical power into the modulator without saturating the detector.

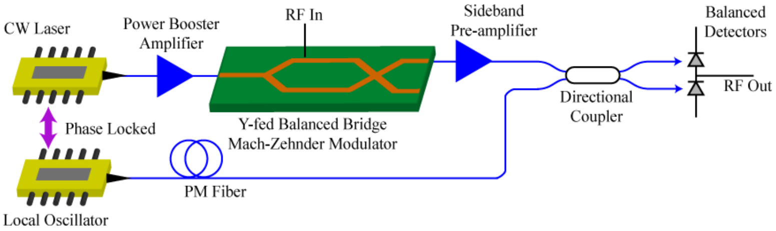

Figure 1. Block Diagram of suppressed carrier coherent analog optical link.

As the optical power into the modulator is increased, the link becomes limited by the power handling of the modulator, and can achieve low noise figure and high dynamic range at low DC photocurrent. Figure 2 shows contour plots of the link noise figure and spur-free dynamic range for a given modulator V_π and optical source power, assuming shot noise limited operation. The link noise figure can be dramatically improved using low V_π modulators. The Z-cut lithium niobate platform affords a lower V_π over the X-cut design. In the suppressed carrier modulation format, the MZM is biased at the null point in the transmission curve which results in the optical field now being linear with modulation voltage. At this bias point, the odd-order sidebands exit the dark leg which results in an inherent 3-dB increase in the sideband power [1]. In a single-ended Z-cut MZM, one is afforded a lower V_π but the MZM is not driven in a symmetric push-pull configuration. This leads to a phase imbalance in the optical fields and the sidebands no longer add coherently, hence no increase in the sideband power is observed. When a dual-drive, Z-cut MZM is chosen, the electrodes can be driven in a symmetric push-pull configuration using a wideband 180° microwave hybrid. In this configuration, the link performance is at an optimum with the benefits of a low V_π and increased sideband power.

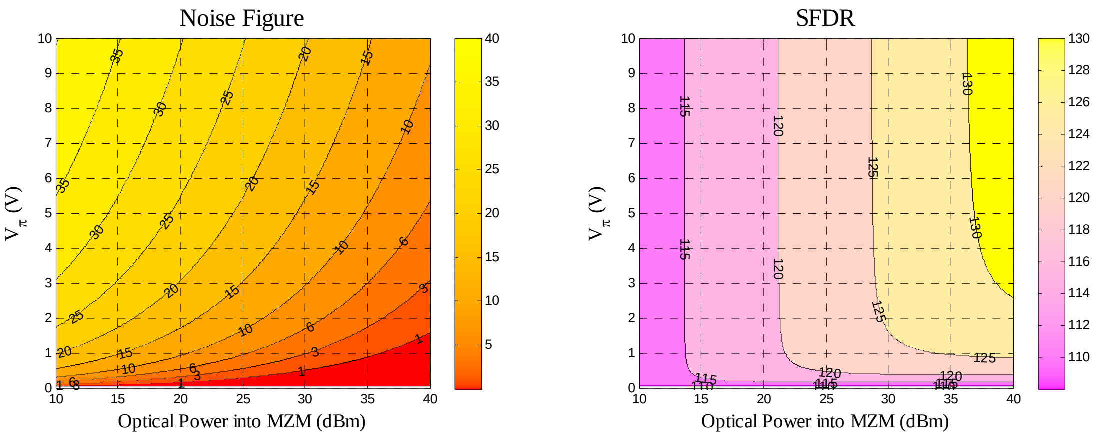

Figure 2. Contour plots of noise figure and spur-free dynamic range versus modulator half-wave voltage and optical power into the modulator.

3. Coherence-related Noise

In addition to the usual noise contributors in an analog optical link (thermal, RIN, shot noise, and ASE-related beat noise), one must also consider noise terms related to the coherent nature of the link [3]. We add to this list the contribution from the laser phase noise: $N_{\Delta\phi}\left(f\right)$. Phase noise can be converted to amplitude noise in the link, and must be reduced in the laser source and local oscillator. In the following, we will assume that the output signal is the tone produced by mixing the first signal sideband exiting the MZM with the LO. This process creates an electrical current at the output of the balanced receiver, and depends on the signal and LO optical powers $P_{sig}P_{LO}$ and the responsivity of the photodiodes $\Re$. Reaching low noise figures with these links requires special means to reduce the phase noise of the beat signal. This can be accomplished for example by locking the optical phase of the LO source to that of the signal laser. When the phase noise is low (i.e. when the total phase excursion of the beat note is well below 1 rad rms), the shape of the beat note spectrum reduces to the shape of its phase noise spectrum. Note that we do not consider here the possibly large phase variations at low frequency that could arise from differential variations of the separate optical paths traveled by both lightwaves. The phase noise single-sided power spectral density $S_{\Delta\phi,1}\left(f\right)$ [rad^2/Hz] is then twice the normalized power spectral density of the beat note on either side of the carrier $N_{\Delta\phi}(f-f_c)$. The noise arising from the phase noise contribution to the link is then given by

$$N_{\Delta\phi}(f-f_c)=\frac{S_{\Delta\phi}(f)P_{beat}}{2} \tag{1}$$

where P_{beat} is the RF power of the beat note. Phase noise requirements in RF communications systems can be challenging. The linewidth of the laser, the performance of a phase-locking loop, optical path mismatch and reflections in the link [4] can all degrade link performance. Power spreading reduces link gain, conversion of phase noise to amplitude noise increases noise figure, and phase noise by itself can produce spurious signals through reciprocal mixing. These noise terms can be reduced by using narrow-linewidth laser sources such as fiber lasers, and filtered frequency combs from a mode-locked laser.

Coherent laser fields used for the generation of RF signals can also be generated conveniently by phase modulating a single laser [5]. This process creates copies of the original laser field at multiples of the modulation frequency around the carrier frequency, with perfectly correlated noise properties. An RF signal at a multiple of the synthesizer frequency can be generated by interference of two sidebands (or one sideband and the carrier) on a fast photodetector. The power spectral density (PSD) of the beat note phase noise resulting from the laser carrier phase fluctuations is thus equal to

$$S_{\Delta\phi,l}(f)=4\sin^2\left(\pi f\tau\right)\frac{S_{f,l}(f)}{f^2} \tag{2}$$

where $S_{f,1}\left(f\right)$ is the PSD of the laser frequency noise (in Hz^2/Hz), and τ is the path mismatch. As mentioned above, low frequency phase noise can also be induced by vibrations and thermal fluctuations differentially affecting the optical fibers in which the fields propagate prior to their interfering at the photodetector. Finally, the frequency spacing between the interfering fields depends on the frequency of the RF synthesizer used to modulate the phase of the laser. As a result, the synthesizer phase noise, characterized by PSD $S_{\phi,RF}(f)$, contributes to the beat note phase noise even in the absence of any path mismatch. In this case, it adds $m^2 S_{\phi,RF}(f)$ to the beat note phase noise, m being the ratio of the beat note frequency to that of the synthesizer used to generate the modulation sidebands.

Two such modulation sidebands (or a sideband and the carrier) can be isolated by appropriate optical filters and sent into separate optical fibers. Such a system has been built by Menders et al. using a phase modulator and Fiber Bragg Gratings [6]. In this approach, it is important to match the path lengths traveled by both lightwaves before they are recombined in order to maintain their phase correlation at the photodetector and produce a very pure microwave signal. Although this was recognized by Menders et al. as an important issue, they did not achieve low phase noise because path lengths in their experiment were not equalized. Figure 3a shows that very low noise RF signals can be produced using the experimental set-up illustrated in Figure 3b, employing a commercial DFB laser. The beat note phase noise was measured for physical path mismatch varying from 0 to 1.1 m. This graph also includes the phase noise of the RF synthesizer at 3 GHz. Careful path matching reduces the high frequency phase noise to a very low level, indeed close to that of the RF synthesizer. Of course, the system will be more tolerant to a path mismatch for a laser exhibiting a lower level of frequency noise. As shown here, commercial DFB semiconductor lasers can be used in such systems to generate RF signals with a very low phase noise level.

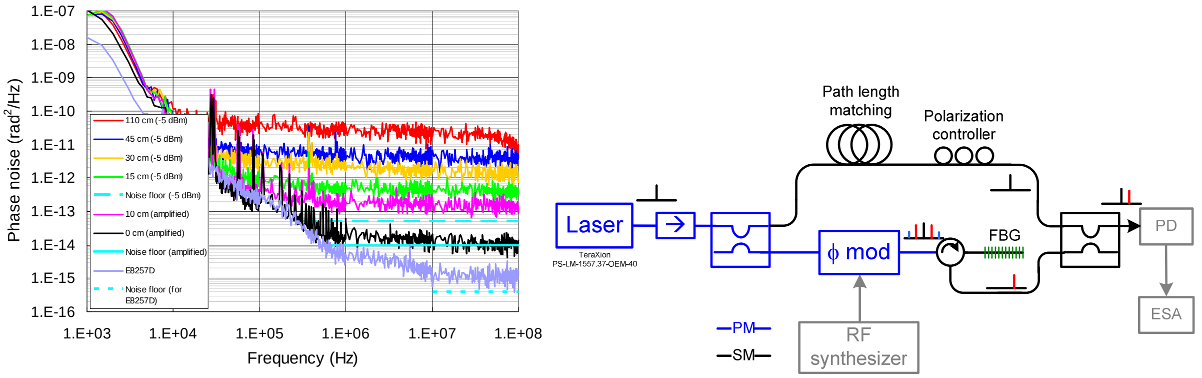

Figure 3: a) Measurement of the beat note and RF synthesizer phase noise. The power of the signal observed on the ESA is noted in parenthesis, b) the experimental set-up.

4. Summary

We describe an analog optical link using amplitude modulation and coherent detection for high SFDR, gain, and low noise figure. We then address the dominant performance-limiting parameters and discuss several approaches to overcome these limitations. The proper choice of modulator architecture can significantly improve the RF photonic link performance along with the implementation of a low phase noise source for coherent link applications.

5. References

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