High Dynamic-Range Microwave Photonic Links using Maximally Linear FIR Optical Filters

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Abstract: We propose a microwave photonic link in which maximally linear FIR optical filters discriminate frequency modulation. Using a tenth-order filter, one can achieve a 127 dBm/Hz$^{2/3}$ SFDR with 1 mW of received optical power.

OCIS codes: (060.2360) Fiber optics links and subsystems; (060.2630) Frequency modulation

1. Introduction

Microwave photonic links have found applications in commercial and military antenna remoting, cable television and cellular communication links because of advantages in size, weight, immunity to electromagnetic interference, bandwidth and power over traditional coaxial links [1]. Analog link designers wish to minimize noise and distortion, while maximizing bandwidth and power efficiency. Optical frequency modulated (FM) photonic links are promising because FM distributed Bragg reflector (FM-DBR) lasers have been demonstrated with high modulation efficiency and with modulation bandwidths that are not limited by the laser relaxation frequency [2]. However, these links have high distortion due to nonlinearities in the FM-to-IM discrimination performed by optical filters. Previously, we analytically showed that one can achieve ideal linear discrimination with two complementary filters that have linear phase and *electric field transmission magnitude* that ramps linearly with optical frequency [3], and we proposed using optical finite impulse response (FIR) filters fabricated in planar lightwave circuits (PLC) to implement this system. Other authors have designed filters whose *optical power transmission magnitude* ramps linearly with frequency [4], which is not optimal due to coherent mixing of sidebands in the filter. In this current work, we study the effects of filter order and filter optimization criteria on the linearity of the overall photonic link. We find that a tenth-order filter designed using the maximal linear criteria can provide a spur-free dynamic range (SFDR) of 127 dBm/Hz$^{2/3}$ and a third-order output intercept point (OIP3) of 39 dBm with only 1 dBm of received optical power.

2. System

We implement our discriminator using FIR filters because symmetric filters can be designed for linear phase. Up to tenth-order FIR lattice filters have been implemented in planar lightwave circuits (PLC) for applications in dispersion compensation [5], but these devices allow for dynamic tuning and can instantiate any arbitrary coefficients for that particular filter order. The problem of discriminator design reduces to one of choosing the best coefficients. The frequency discriminator's transfer function is similar to that of a digital differentiator filter: a ramp with constant slope. Two sets of design criteria for digital differentiators known in the literature are the minimax relative error (MRE) criteria [6] and the maximally linear criteria [7]. The MRE criteria minimize the maximum relative error over a chosen band of frequencies. The maximally linear criteria fix a number of derivatives of the transfer function at a chosen frequency, guaranteeing high accuracy around a small frequency band. If this band is comparable to the bandwidth of our modulation, overall we expect high linearity. Below, we compare the linearity of optical frequency discriminators based on the MRE and maximally linear criteria and find that the both sets of filters surpass the Mach Zehnder interferometer (MZI) in performance, with the maximally linear filter the better of the two. We also present the tradeoffs between filter order, third-order nonlinearity and small signal gain.

A diagram of the photonic link is shown in Fig. 1. The complementary optical filters $H_a(f)$ and $H_b(f)$ are identical except for a shift in center frequency of one-half the filter's free spectral range (FSR) in order to obtain the opposite slope. The signal at the output of the link is simulated by creating a time domain waveform, $e(t) \propto \exp[2\pi f_c t + 2\pi\eta \int i(t)]$, where f_c is the optical carrier frequency, η is the modulation efficiency in MHz/mA, and *i(t)* is the input current. We use a 200 GHz sampling frequency and a 10,000 point FFT to convert this to the frequency domain. The link is tested with a number of filter orders. We obtain coefficients for MRE filters by numerically optimizing at half-band, over the range of normalized frequencies 0.45π to 0.55π (2π is the full FSR). The maximally linear filter is also optimized at half-band, at the point 0.5π. In Fig. 2, we compare the ideal transfer function to MRE and maximally linear filters of order $N = 6$, 10 and 14. For any given order, the maximally linear filter appears to more closely approximate the linear discriminator. An additional design parameter is the FSR of the filter, which is determined by the delay elements in the lattice implementation. A smaller FSR gives a larger slope, meaning better conversion efficiency from FM to IM and more link gain.

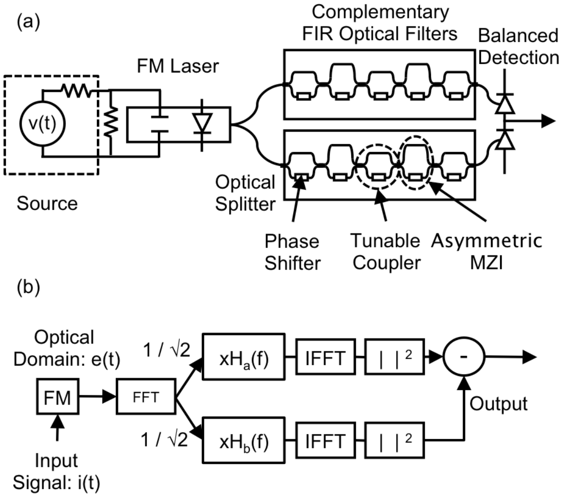

Fig. 1. (a) Schematic of frequency modulated photonic link. (b) Numerical model of photonic link used in simulation.

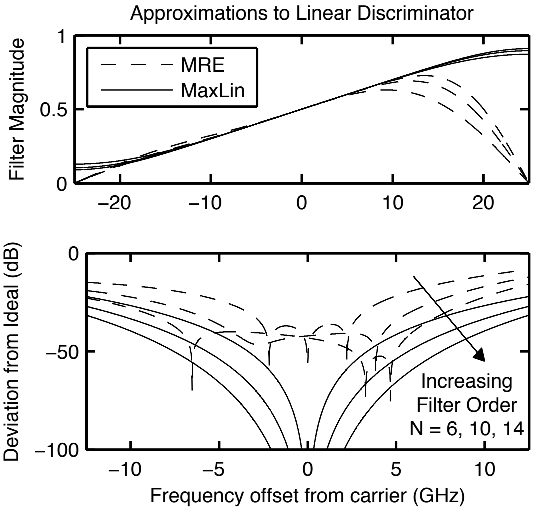

Fig 2. Transfer functions for MRE and maximally linear filters compared to ideal discriminator transfer function for 100 GHz FSR.

3. Results and Discussion

We fix the modulation to a two-tone waveform with $f_1 = 1.9$ GHz and $f_2 = 2.0$ GHz. For a FSR of 100 GHz, the output power at f_1 and the third-order distortion are plotted in Fig. 3. The noise floor is calculated using the small signal model in [3], assuming a 1 MHz laser linewidth. In general, higher order filters suppress the third-order distortion more than lower order filters. The third-order distortion of links using either type of filter increases much faster than 30 dB / decade for large modulation power. This can be explained by observing that in frequency modulation, the frequency deviation of the carrier increases with modulation depth, so more optical power is spread into higher order sidebands. For high modulation depths, most of the optical power lies outside of the range of frequencies for which the filter is optimized, creating more distortion than for low modulation depths.

We quantify the effect of changes in FSR on the OIP3 and SFDR in Fig. 4 and Fig. 5. For maximally linear filters with larger FSRs, the third-order distortion decreases faster than the gain decreases, so OIP3 monotonically increases. Higher order filters have increasingly better distortion characteristics: by increasing the filter order by four, the OIP3 increases by 20 dB or more. The maximally linear filters are much better than the MRE filters for a given filter order. The 14th-order MRE has higher OIP3 than the sixth-order maximally linear filter, but lower OIP3 than the tenth-order maximally linear filter. Our results suggest that a microwave-photonic link using a 250 GHz FSR, tenth-order maximally linear filter as a frequency discriminator provides 20 dB improvement in SFDR over a MZI discriminator. The expected SFDR is 127 dBm/Hz$^{2/3}$. There is an open question on the tolerance of these discriminator architectures to inexact realization of the filter coefficients and drifts in the laser wavelength. We speculate that MRE filters may be less susceptible to these issues, as they are optimized over a band of frequencies rather than a single point.

4. Conclusions

We have demonstrated by simulation that frequency modulated microwave-photonic links with very high linearity are obtainable by using optical FIR lattice filters to perform frequency discrimination. For a given filter order and large FSRs, links using filters designed with the maximally linear criteria surpass those designed with the MRE criteria. We have observed that linearity degrades for high modulation depths as power is spread into high-order optical sidebands far from the optical carrier. We find that a tenth-order FIR filter designed using the maximally linear criteria can obtain a 127 dBm/Hz$^{2/3}$ SFDR with only 1 dBm of received optical power.

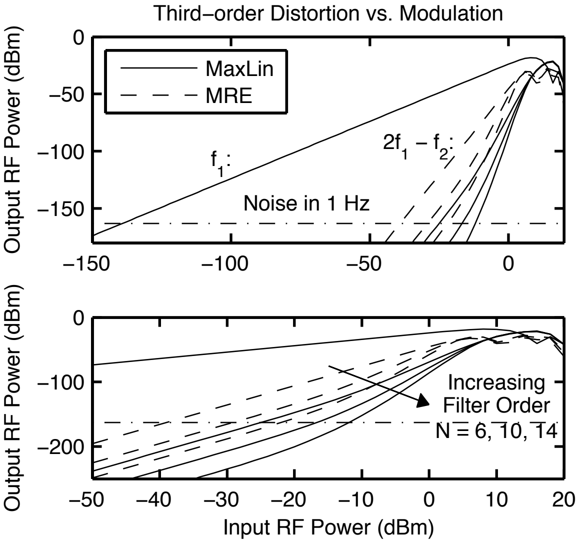

Fig 3. Third-order distortion versus modulation depth. We assume 1 GHz/mA modulation efficiency, 100 GHz filter FSR, 0.8 A/W detector responsivity and 1 mW received optical power.

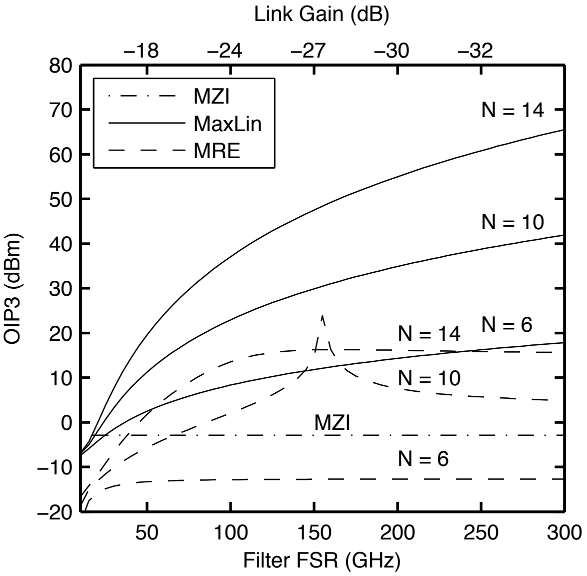

Fig 4. OIP3 for MZI, MRE and maximally linear filters versus FSR. We assume 1 GHz/mA modulation efficiency, 0.8 A/W detector responsivity and 1 mW received optical power.

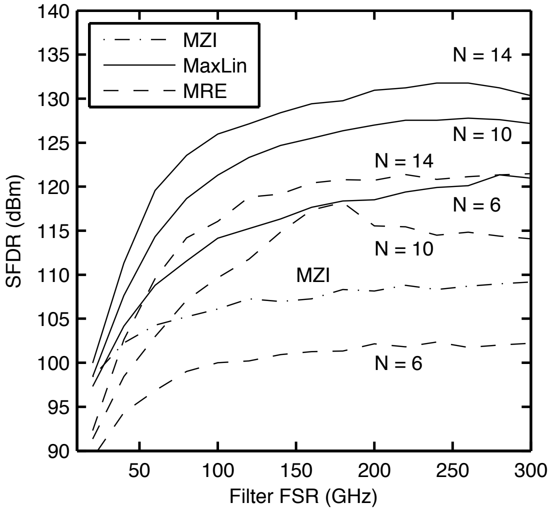

Fig 5. SFDR for MZI, MRE and maximally linear filters versus FSR. We assume 1 GHz/mA modulation efficiency, 0.8 A/W detector responsivity and 1 mW received optical power.

5. References

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