Dynamic Linearity Improvement of Phase and Frequency Modulated Microwave Photonic Links Using Optical Lattice Filter Discriminators

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Abstract— **A phase modulated (PM) microwave photonic link (MPL) with linearity improvement is presented. The link demodulates the PM using a phase discriminator based on a dynamically tunable, integrated, sixth-order optical lattice filter in planar lightwave circuit (PLC) technology. The linearity of the demodulation process is optimized by using electrical spectrum monitoring and a feedback algorithm to automatically choose the filter coefficients. For a 2 GHz modulation frequency, the link achieves a 6.7 dB improvement in the third-order output intercept point (OIP3) for intermodulation distortion (IMD) over a Mach-Zehnder interferometer (MZI).**

Keywords—Analog photonics, microwave photonic filter, microwave photonics, RF photonics, radio-over-fiber (RoF)

I. Introduction

Microwave photonic links (MPLs) which use phase modulation (PM) are promising candidates for high-performance microwave signal distribution systems because phase modulation is highly linear. Modulators based on the linear electro-optic effect, including those fabricated in lithium niobate, are intrinsically linear, and authors have also reported linear, integrable phase modulators fabricated in indium-phosphide which use the quantum confined Stark effect (QCSE) in multiple quantum wells [1]. While nonlinearities are inherent to the demodulation process, demodulation performed using an optical filter based phase discriminator and direct detection (PM-DD) (also called slope or interferometric detection) can be engineered for low nonlinearities by optimizing the transfer function of the filter [2]. Thus, phase modulated microwave photonic links could be used in systems requiring large dynamic range and low signal distortion.

Discriminators for PM-DD links can also be used to discriminate optical frequency modulation (FM), because FM is identical to PM but with a modulation depth that is linearly dependent on modulation-frequency. FM lasers, where a phase modulator in the optical cavity varies the optical frequency with applied RF power, have been demonstrated with high modulation efficiency [3, 4]. The combination of a high efficiency FM laser with a discriminator filter for low-distortion demodulation leads to a MPL with signal gain, low noise figure and large dynamic range.

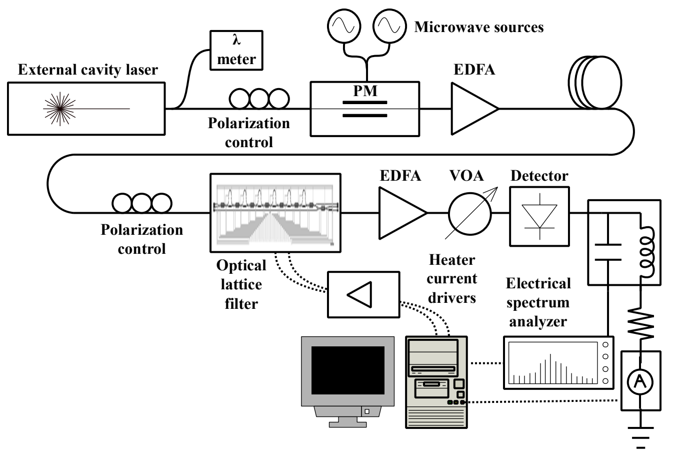

Fig. 1. Diagram of phase modulated microwave photonic link discriminated with an optical lattice filter and with feedback optimization of the filter taps

To control the nonlinearity of the link, authors have proposed PM-DD links using discriminators realized with tunable integrated filters [5]. Recent experiments have demonstrated the concept using filters based on micro-ring resonators [6]. However, normalized to the same received photocurrent, the third-order and second-order nonlinearities measured by [6] were significantly worse than just a simple asymmetrical Mach Zehnder interferometer (A-MZI) [7], while the link had much added complexity.

Theoretical frequency-domain analyses of phase modulated MPLs [8, 2] give insight on this problem. While many authors have explored using filters with a linear power transmission-versus-frequency curve [6, 9, 10], this transfer function does not result in ideal linear discrimination. Instead, filtering should be done coherently with a linear electric-field transmission-versus-frequency curve, and the phase of the filter's transfer function also should be linear. This results in

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linear PM to amplitude modulation (AM) discrimination, rather than IM. A pair of complementary filters and balanced detection can be used to cancel second harmonics produced when directly detecting the AM [2]. In this paper, using a discriminator filter fabricated in planar lightwave circuits (PLC) implementing a linear-field transfer function, we experimentally demonstrate nonlinearity improvement over the MZI.

II. Optical Lattice Filter Discriminators

The phase discriminator used in our experiments is a 6th-order finite impulse response (FIR) lattice filter fabricated in a silica-on-silicon, planar lightwave circuit (PLC) process by Alcatel-Lucent Bell Labs. Optical lattice filters are low-loss integrated devices that can be used to implement arbitrary filter transfer functions [11]. They are coherent devices and thus act upon the phase and magnitude of the light's electrical field. They are analogous to digital filters used in signal processing. Optical lattice filters are ideal for discriminators because they predictably can be tuned after fabrication to adjust the transfer function aiming for one that produces low signal distortion by the link.

This type of lattice filter has been extensively studied in other applications, such as dispersion compensation and gain equalization, and up to 10^{th}-order filters have been demonstrated in silica and silicon waveguide processes [12-13]. Our filter has 6 stages of symmetrical MZIs (switches) and asymmetrical MZIs (delay line interferometers) which are tunable using chromium heaters deposited on the waveguides. The free spectral range of the filter is 120 GHz. The goal of the experiments is to set the multi-purpose filter's transfer function for low distortion phase discrimination.

III. Procedure

In our experiment the discriminator filter is dynamically tuned to minimize the link distortion. The filter has 13 degrees-of-freedom to adjust. If the filter is ideal, one can in principle choose all the parameters a-priori to implement desired filter coefficients. However, it is difficult to characterize precisely the correspondence between currents applied to each waveguide heater and the resulting optical phase shift. Imperfections in the filter fabrication also make the characterization difficult. Therefore, feedback is used to choose the correct biases to the heaters.

Fig. 1 shows a system diagram for the experiment. Two radio frequency synthesizers are used to generate tones at 2 GHz and 2.0001 GHz with equal RF powers, and they are combined with a microwave coupler. Light from an external cavity laser is modulated with a lithium niobate phase modulator. The light is passed through the tunable filter and photodetected, and then the signal is viewed on an electrical spectrum analyzer. Two polarization controllers are used to ensure linear polarization into the phase modulator and filter. A computer program reads off the dc photocurrent and peak power at each modulation frequency and distortion product.

We use an optimization routine employing a downhill-

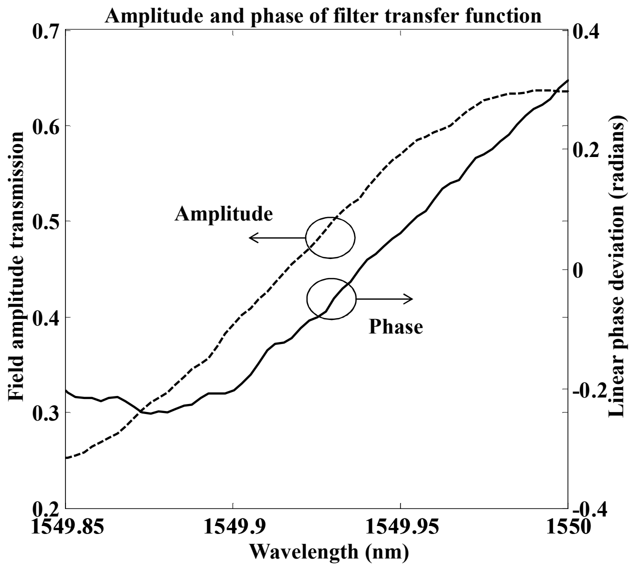

Fig. 2. Amplitude and phase responses of the optical filter after the optimization procedure

simplex algorithm to tune the heater settings for the discriminator filter. The error signal for the optimization routine is the third-order intermodulation distortion term at 1.9999 GHz, normalized to the dc photocurrent and the fundamental signal power. The start point for each heater is randomly chosen within an acceptable range of currents which will not cause damage to the device. The routine varies the heater settings to minimize the error signal, thus maximizing the OIP3. The routine reaches a minimum error value after less than 100 iterations.

IV. Results

In Fig. 2 shows the amplitude and phase response of the optical filter after tuning, measured using an optical vector network analyzer. To the accuracy of the instrument, both the amplitude response and phase response appear to be linear ramps versus optical frequency. This is the desired transfer function for linear FM to AM discrimination. The plotted amplitude response is normalized to the 7 dB insertion loss of the filter. The insertion loss could be improved by better fiber coupling into the filter. The waveguide loss for silica PLC is not a significant loss mechanism.

Fig. 3 shows the fundamental power and third-order nonlinearity as a function of carrier wavelength. We vary the wavelength of the external-cavity laser and for each step record the RF power at the output of the link at each frequency of interest. The distortion remains low over a wavelength span of 10 pm. A 1549.937 nm carrier wavelength gives an optimal ratio of fundamental to IMD3 power. The optimal operating wavelength corresponded with a point where the filter has 50% amplitude transmission. For a system with a fixed wavelength of operation, the filter itself can be tuned in wavelength by adjusting the phase delays in each stage. A single filter could also be tuned to accommodate a variety of sources at different wavelengths, such as wavelength division multiplexing channels, since the filter transfer function repeats over each

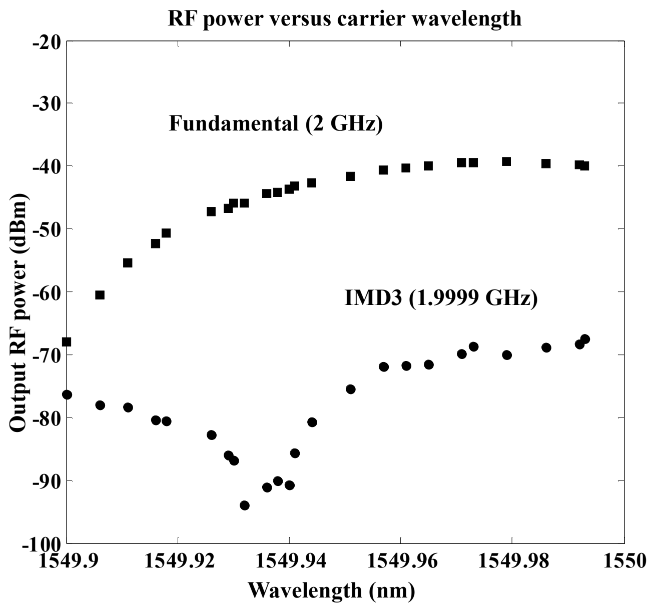

Fig. 3. Measurement of link response versus carrier wavelength

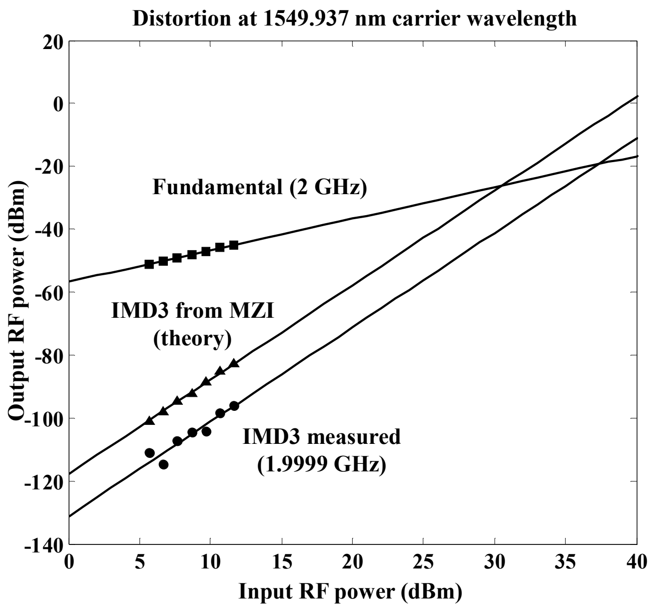

Fig. 4. Measurement of link response versus modulation power

free-spectral range.

At the optimal wavelength, we varied the RF power input into the link and measured the IMD3 and fundamental power. The data is shown in Fig. 4. The distortion clearly showed a cubic dependence with input power. For a photocurrent of 0.11 mA, we measured an OIP3 of -19.5 dBm. The OIP3 of a PM link using an MZI discriminator and the same photocurrent is -26.2 dBm. This particular transfer function displayed a 6.7 dB OIP3 performance improvement over the MZI. For shot-noise limited noise performance, the link has a spurious free dynamic range (SFDR) of 112 dB $Hz^{2/3}$. If the light is amplified to produce 10 mA of photocurrent, OIP3 increases to 19.7 dBm and the shot-noise limited spurious free dynamic range is 125 dB $Hz^{2/3}$.

V. CONCLUSION

These initial results using optical lattice filters to discriminate phase modulation show appreciable improvement in third-order nonlinearity over the MZI, achieving 6.7 dB improvement in OIP3 at 2 GHz modulation frequency, for a 10 pm (1.25 GHz) span of carrier wavelengths. Because electrical spectrum monitoring and a feedback algorithm are used to optimize the filter coefficients, the system is robust to fabrication imperfections and other variations in the devices. Our particular FIR lattice filter had variations in switch contrast and waveguide loss that were corrected by the optimization. No assumptions were made about the mapping of the heater settings for the filter to its transfer function to run the optimization routine, so the technique could be used for any optical filter architecture.

Theory and simulation suggest that much larger improvements in linearity are possible through careful adjustment of the filter transfer function [5]. Filter coefficients could be chosen by rules such as the maximally linear criteria to achieve minimal distortion. The use of sets of complementary filters and balanced photodetection can also increase the signal gain and achieve low second-harmonic distortion. We predict improvement in the linearity performance of the discriminator with increasing filter order. Increasing the order of the filter from sixth-order to tenth-order could improve third-order non-linearity by as much as 20 dB [5]. Increased photonic integration should lead to improved performance.

Besides just further improvement in nonlinearity, the optimization goal can also be changed to seek improvement in signal gain, or nonlinearity improvement over chosen carrier wavelengths or modulation frequency spans. High-order filters could also be optimized to correct for gain equalization and fiber dispersion. For these reasons, using general purpose, tunable filters for phase discrimination is a very promising technique and suitable for much further study.

REFERENCES

[1] Yifei Li, Renyuan Wang, A. Bhardwaj, S. Ristic, and J. Bowers , "High Linearity InP-Based Phase Modulators Using a Shallow Quantum-Well Design," *Photonics Technology Letters, IEEE* , vol. 22, no. 18, pp. 1340–1342, Sep. 15, 2010

[2] J. M. Wyrwas and M. C. Wu, “Dynamic Range of Frequency Modulated Direct-Detection Analog Fiber Optic Links,” *J. Lightw. Technol.*, vol. 27, no. 24, pp. 5552–5562, Dec. 2009.

[3] Q. S. Xiang, Y. Zhao, and F.-S. Choa, “A high-performance RF-lightwave transmitter for analog fiber links,” in *Proc. LEOS 2000, 13th Annu. Meeting*, vol. 1, pp. 138–139.

[4] X. Xie, J. Khurgin, F. S. Choa, X. Yu, J. Cai, J. Yan, X. Ji, Y. Gu, Y. Fang, Y. Sun, G. Ru, and Z. Chen, "A model for optimization of the performance of frequency-Modulated DFB semiconductor laser," *IEEE J Quantum Electron*, 2005, 41, 473-482.

[5] J. M. Wyrwas and M. C. Wu, "High Dynamic-Range Microwave Photonic Links Using Maximally Linear FIR Optical Filters," *in Optical Fiber Communication Conference, OSA Technical Digest* (Optical Society of America, 2010), paper JWA43.

[6] D. Marpaung, C. Roeloffzen, A. Leinse, and M. Hoekman, “A photonic chip based frequency discriminator for a high performance microwave photonic link,” *Opt. Express*, vol. 18, no. 26, pp. 27359–27370, Dec. 13, 2010.

[7] V. J. Urick, F. Bucholtz, P. S. Devgan, J. D. McKinney, and K. J. Williams, “Phase Modulation With Interferometric Detection as an Alternative to Intensity Modulation With Direct Detection for Analog-Photonic Links,” *Microwave Theory and Techniques, IEEE Transactions on* , vol. 55, no. 9, pp. 1978–1985, Sep. 2007.

[8] P. Driessen, T. Darcie, and J. Zhang, “Analysis of a class-B microwave-photonic link using optical frequency modulation,” *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2740–2747, Aug. 1, 2008.

[9] X. Xie, J. Khurgin, J. Kang, and F.-S. Choa, “Ring-assisted frequency discriminator with improved linearity,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1136–1138, Aug. 2002.

[10] T.E. Darcie, J. Zhang, P.F. Driessen, and Jae-Jeong Eun, “Class-B Microwave-Photonic Link Using Optical Frequency Modulation and Linear Frequency Discriminators,” *J. Lightw. Technol.*, vol. 25, no. 1, pp. 157–164, Jan. 2007.

[11] C. K. Madsen and J. H. Zhao, *Optical Filter Design and Analysis*. John Wiley & Sons, Inc., New York, 1999.

[12] K. Takiguchi, K. Jinguji, K. Okamoto, and Y. Ohmori, “Variable group-delay dispersion equalizer using lattice-form programmable optical filter on planar lightwave circuit,” *Selected Topics in Quantum Electronics, IEEE Journal of*, vol. 2, no. 2, pp. 270–276, Jun. 1996.

[13] F. Horst, R. Germann, U. Bapst, D. Wiesmann, B. J. Offrein, and G. L. Bona, "Compact tunable FIR dispersion compensator in SiON technology," *Photonics Technology Letters, IEEE* , vol. 15, no. 11, pp. 1570–1572, Nov. 2003