A Simple, Linearized, Phase-Modulated Analog Optical Transmission System

Bryan M. Haas, *Member, IEEE*, and Thomas E. Murphy, *Senior Member, IEEE*

***Abstract*—We describe and experimentally demonstrate a new technique to suppress third-order intermodulation distortion (IMD) in a coherent phase-modulated RF optical link. The anisotropic electrooptic coefficient of lithium niobate is exploited to simultaneously modulate orthogonally polarized fields. These fields are then combined to eliminate the third-order distortion. This technique uses a single phase modulator, requiring no external bias or control, for a highly linear photonic microwave relay. The resulting suboctave dynamic range is limited by fifth-order IMD instead of third-order IMD.**

***Index Terms*—Distortion, heterodyning, intermodulation distortion (IMD), phase modulation, polarization.**

I. Introduction

FIBER optics offer a number of advantages over coaxial transmission lines for relaying microwave signals, including reduced attenuation, size, weight, and immunity to electromagnetic interference [1]. Most techniques for encoding an optical carrier with a microwave signal impose a nonlinear modulation transfer function that distorts the transmitted signal and limits the dynamic range of the link.

Phase modulation has recently attracted attention for analog optical communication, motivated by the observation that the electrooptic effect produces a phase shift that is linearly proportional to the applied field. Unfortunately, phase demodulation techniques require homodyne or heterodyne detection, which imposes a sinusoidal nonlinearity on the detected signal similar to that of an amplitude modulator. A few methods have been recently demonstrated to overcome this distortion at the receiver, either by using a fast phase-locked loop [2] or by postdetection digital-signal processing [3].

Although several techniques have been demonstrated for linearized modulation [4]–[8], most have focused exclusively on intensity modulation and direct detection. Compared to intensity modulators, phase modulators are simple, low loss, and do not require bias control. Moreover, although phase modulation necessitates a more complicated coherent receiver, the process of heterodyne detection can automatically convert the received signal to an intermediate frequency without the need of an electrical mixer [9], [10].

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B. M. Haas is with the Laboratory for Physical Sciences, College Park, MD 20740 USA (e-mail: bhaas@umd.edu).

T. E. Murphy is with the Electrical and Computer Engineering Department, University of Maryland, College Park, MD 20742 USA (e-mail: tem@umd.edu).

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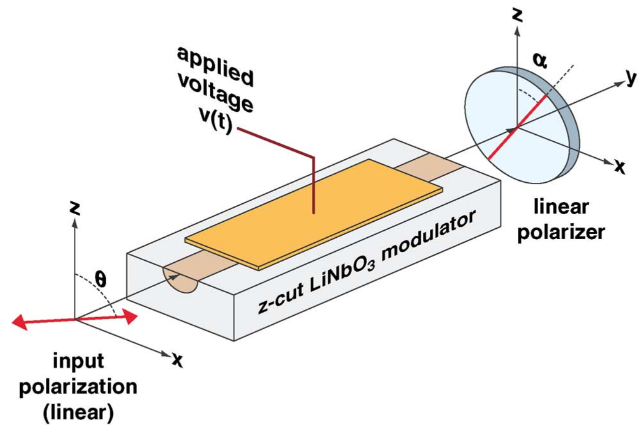

Fig. 1. Linearization scheme using a single phase modulator. The input optical signal is linearly polarized at an angle θ and the output polarizer is oriented at an angle α, which is chosen to eliminate third-order distortion in the signal.

We report here a new technique for linearized phase modulation that allows one to suppresses the third-order nonlinearity while preserving the simplicity of the transmitter. Unlike earlier linearization schemes, our proposed approach uses only a single unbiased electrooptic phase modulator driven by an unmodified input signal, and could entirely eliminate the third-order intermodulation distortion (IMD) that usually limits the dynamic range.

II. IMD Suppression Using Phase Modulation

$LiNbO_3$ exhibits an electrooptic coefficient r_{31} along the x- (TE) axis which is approximately 1/3 of the r_{33} coefficient on the z- (TM) axis, the ratio remaining constant over temperature. A similar anisotropy is seen in electrooptic polymers [11]. Our method makes use of this anisotropy to simultaneously phase modulate two orthogonal polarization states by different amounts. As shown in Fig. 1, if the optical signal entering a phase modulator is polarized at an angle θ with respect to the z-axis, it excites a superposition of TE and TM modes that will be modulated to different depths. In this way, a single device can simultaneously play the role of two phase modulators connected in parallel. When the output signal is projected onto a fixed polarization axis, it is possible to eliminate the third-order IMD, leading to improved dynamic range. The idea of using polarization mixing to achieve linearization was originally proposed and demonstrated in Mach–Zehnder intensity modulators [7], [8], but it has never been applied to the case of phase modulation.

To analyze the modulator shown in Fig. 1, we begin by assuming that the input electrical signal is a sinusoidal modulation at the microwave frequency Ω

$$v(t) = V_0 \sin \Omega t \tag{1}$$

and that the electric field of the input optical signal entering the device can be represented by

$$\mathbf{E}_{\rm in}(t) = E_0(\hat{\mathbf{z}}\cos\theta + \hat{\mathbf{x}}\sin\theta)e^{j\omega t} \tag{2}$$

where ω is the optical carrier frequency and θ describes the angle of polarization. If we neglect the birefringence of the device, the optical field of the phase-modulated signal emerging from the device is given by

$$\mathbf{E}(t) = E_0(\hat{\mathbf{z}}\cos\theta e^{jm\sin\Omega t} + \hat{\mathbf{x}}\sin\theta e^{jm\gamma\sin\Omega t})e^{j\omega t} \tag{3}$$

where $m = \pi V_0/V_\pi^{(z)}$ is the modulation depth for the z-polarized component of the field and γ is a dimensionless ratio (less than 1) that describes the ratio of the electrooptic modulation depth in the x direction to that in the z direction.

Phase modulation generates an infinite number of harmonic sidebands, but by properly choosing the frequency of the local oscillator and the bandwidth of the heterodyne receiver, one can ensure that the receiver responds only to the first upper sideband. Applying the Bessel function expansion to (3), and neglecting all but the upper sideband gives

$$\mathbf{E}(t) = E_0\left[\hat{\mathbf{z}}\cos\theta J_1(m) + \hat{\mathbf{x}}\sin\theta J_1(\gamma m)\right]e^{j(\omega+\Omega)t}. \tag{4}$$

After the microwave signal is modulated onto the two polarizations, the TM and TE fields are recombined at the output as in Fig. 1 with a linear polarizer set at angle α to the TM axis. The component of the electric field transmitted by the polarizer at angle α is then given by

$$\begin{aligned} E_\alpha(t) = E_0\,&[\cos\theta\cos\alpha J_1(m) \\ &+ \sin\theta\sin\alpha J_1(\gamma m)]\,e^{j(\omega+\Omega)t} + \dots \end{aligned} \tag{5}$$

The nonlinear components of the modulated signal are revealed by expanding the Bessel function $J_1(m)$ to third order in m

$$\begin{aligned} E_\alpha(t) =& \frac{E_0}{2}\left[\cos\theta\cos\alpha\left(m - \frac{1}{8}m^3\right)\right. \\ &\left. + \sin\theta\sin\alpha\left(\gamma m - \frac{1}{8}\gamma^3 m^3\right) + O(m^5)\right] \\ &\cdot e^{j(\omega+\Omega)t}. \end{aligned} \tag{6}$$

From (6), one sees that the terms proportional to m^3 can be eliminated under the following condition:

$$\cos\theta\cos\alpha + \gamma^3\sin\theta\sin\alpha = 0. \tag{7}$$

Although this equation does not have a unique solution for θ and α, one reasonable choice is to select the combination that maximizes the component proportional to m while canceling the components proportional to m^3. This yields the optimal solution

$$\theta = -\alpha = \pm\tan^{-1}(\gamma^{-3/2}). \tag{8}$$

A similar analysis with two tones (f_1 and f_2) reveals that, as expected, the third-order intermodulation products at $(2f_1 - f_2)$ and $(2f_2 - f_1)$ can be suppressed by choosing θ and α according to (7). Including higher order sidebands in the analysis will enable one to find conditions that suppress any other single distortion order, such as second-order.

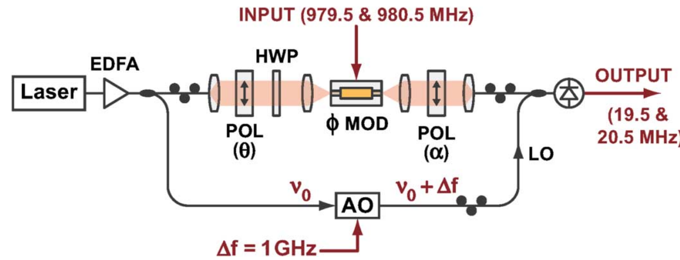

Fig. 2. Experimental setup for demonstrating linearized phase and polarization modulation and heterodyne detection and down-conversion.

As with most linearization schemes, the enhanced linearity comes at the expense of reduced efficiency. When θ and α are chosen according to (8), the transmitted amplitude is reduced by a factor of

$$\left[\frac{\gamma(1-\gamma^2)}{1+\gamma^3}\right] \tag{9}$$

compared to what it would be if the input signal were polarized in the z direction. This decrease is caused by the opposing transfer functions, which in addition to canceling the third-order terms, also reduce the linear terms. For the case of $\gamma = 1/3$, the linear signal amplitude is predicted to decrease by a factor of 2/7, or a power reduction of approximately 11 dB compared to the TM-polarized case.

III. Experimental Setup and Results

Fig. 2 depicts the experimental setup used to demonstrate linearized phase modulation. The electrooptic modulator was a standard Ti-diffused z-cut $LiNbO_3$ waveguide phase modulator, originally designed for digital operation up to 12.5 Gb/s. At a frequency of 1 GHz, the half-wave voltage $V_\pi^{(z)}$ of the modulator was measured to be 4.25 V. The housing was opened and pigtails removed to expose the crystal facets and enable free-space coupling into and out of the waveguide. Two equal-amplitude sinusoidal tones with frequencies of 979.5 and 980.5 MHz were combined and applied to the electrooptic modulator. Device birefringence at this frequency causes about 1% differential phase delay, with weak temperature dependence.

As shown in Fig. 2, the signal and local oscillator were generated from the same laser source, which ensures phase coherency in the heterodyne detector. The local oscillator was translated by 1 GHz using an acoustooptic frequency shifter, which places the local oscillator in the vicinity of the first upper sideband of the modulated signal. When the two-tone modulated signal and local oscillator are combined in the heterodyne detector, they produce downconverted electrical tones at the intermediate frequencies of 19.5 and 20.5 MHz.

A linear polarizer and adjustable half-wave plate were inserted at the input of the modulator to control the input polarization angle θ, while an adjustable linear polarizer at the output was used to project the modulated output signals onto an an axis α. The output polarization selection could also be accomplished

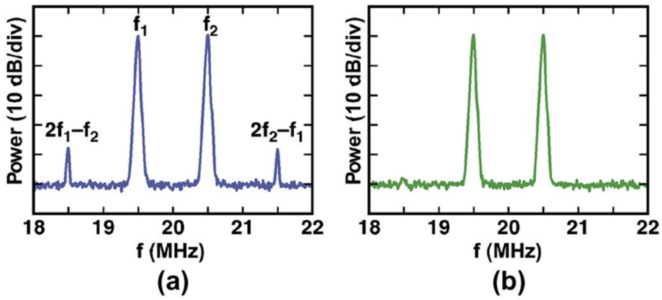

Fig. 3. Spectrum analyzer traces for two-tone IMD test for (a) traditional TM input polarization, and (b) mixed polarization. For (b), the input RF power was increased by ~10 dB to maintain identical tone output power, and the IMD products are suppressed to the noise level.

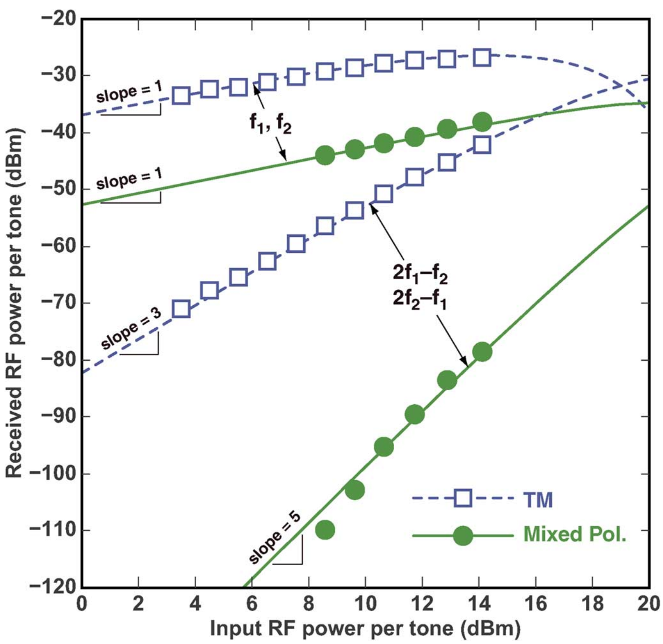

Fig. 4. Received versus input RF power for both TM (dashed) and mixed (solid) polarizations, plotted with calculated results. The upper points with slope $= 1$ are the linear signal powers while the lower points are third- and fifth-order IMD powers, respectively.

at the receiver by controlling the polarization state of the local oscillator.

The optimum input and output polarization angles were adjusted to be approximately $\pm 78°$, based upon (8), assuming $\gamma = 1/3$. Fine adjustments were made to the polarization angles while observing the detected output spectrum to locate the settings at which the IMD was minimized.

Fig. 3(a) plots the measured electrical spectrum of the downconverted output signal when the input signal was linearly polarized along the TM axis of the waveguide, whereas Fig. 3(b) plots the spectrum obtained when the input and output polarization angles were adjusted for optimal linearity. In the latter case, the input electrical power was increased by approximately 10 dB in order to maintain the same detected fundamental output power. Despite the stronger driving voltage, Fig. 3(b) clearly shows that the third-order IMD can be suppressed by using the mixed polarization state.

Fig. 4 plots the measured output tone and IMD power as a function of the input RF power applied to the modulator. The open squares show the performance obtained when the input signal was TM-polarized, while the filled circles show the results obtained by using a mixed polarization state described here. The dashed and solid lines indicate a theoretical fit to the measured data, based on a complete calculation of the two-tone spectrum. The calculated results have been adjusted in power and γ to account for inefficiencies and uncertainties in the experimental setup. As expected, the TM case exhibits third-order IMD similar to what is routinely seen in Mach–Zehnder amplitude modulators. For the mixed polarization case, the intermodulation tones at $2f_2 - f_1$ and $2f_1 - f_2$ increase by 5 dB for every 1 dB increase in the signal power, which indicates that the third-order distortion has been eliminated and that the linearity is instead limited by fifth-order distortion. Even though the linear tones have reduced power in the mixed polarization case, the dynamic range between the tones and IMD is still significantly improved for a given input power.

IV. Conclusion

We have developed the concept and experimentally shown that a single phase modulator can, with judicious choice of input and output polarizations, suppress third-order IMD. This is done by canceling the modulated third-order fields, leaving fifth-order distortion as the dominant IMD product. Advantages to this technique include a very simple and compact modulator with no requirement for external bias or any sort of processing or control at the transmitting end.

References

[1] A. J. Seeds, "Microwave photonics," *J. Lightw. Technol.*, vol. 50, no. 3, pp. 877–887, Mar. 2002.

[2] A. Ramaswamy, L. F. Johansson, J. Klamkin, C. Sheldon, H.-F. Chou, M. J. Rodwell, L. A. Coldren, and J. E. Bowers, "Coherent receiver based on a broadband optical phase-lock loop," in *Proc. OFC 2007*, Postdeadline paper PDP3.

[3] T. R. Clark, M. L. Dennis, and R. M. Sova, "Digital signal processing assisted coherent optical receiver for high dynamic range fiber optic networks," in *Avionics Fiber Optics and Photonics*. Piscataway, NJ: IEEE Press, 2005, pp. 69–70.

[4] S. K. Korotky and R. M. Ridder, "Dual parallel modulation schemes for low-distortion analog optical transmission," *IEEE J. Sel. Areas Commun.*, vol. 8, no. 7, pp. 1377–1381, Sep. 1990.

[5] W. Bridges and J. H. Schaffner, "Distortion in linearized electrooptic modulators," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pt. 1–2, pp. 2184–2197, Sep. 1995.

[6] M. Farwell, Z. Lin, E. Wooten, and W. Chang, "An electrooptic intensity modulator with improved linearity," *IEEE Photon. Technol. Lett.*, vol. 3, no. 9, pp. 792–795, Sep. 1991.

[7] L. M. Johnson and H. V. Roussell, "Reduction of intermodulation distortion in interferometric optical modulators," *Opt. Lett.*, vol. 13, no. 10, pp. 928–930, 1988.

[8] L. M. Johnson and H. V. Roussell, "Linearization of an interferometric modulator at microwave ferquencies by polarization mixing," *IEEE Photon. Technol. Lett.*, vol. 2, no. 11, pp. 810–811, Nov. 1990.

[9] R. F. Kalman, J. C. Fan, and L. G. Kazovsky, "A novel analog optical link with high dynamic range," *IEEE Photon. Technol. Lett.*, vol. 5, no. 6, pp. 725–728, Jun. 1993.

[10] R. F. Kalman and L. G. Kazovsky, "Demonstratin of an analog heterodyne interferometric phase-modulated (HIPM) link," *IEEE Photon. Technol. Lett.*, vol. 6, no. 10, pp. 1271–1273, Oct. 1994.

[11] K. D. Singer, M. G. Kuzyk, and J. E. Sohn, "Second-order nonlinear-optical processes in orientationally ordered materials: Relationship between molecular and macroscopic properties," *J. Opt. Soc. Amer. B*, vol. 4, no. 6, pp. 968–976, 1987.