

# A Downconverting, Linearized Phase-Modulated Fiber Optic Link Optimized for K-Band Microwave Signals

Bryan M. Haas (*member, IEEE*) and Thomas E. Murphy (*senior member, IEEE*)

Laboratory for Physical Sciences, College Park, MD and University of Maryland, College Park, MD

**Abstract** — We demonstrate a new technique to simultaneously downconvert and linearize a phase-modulated radio-over-fiber link that does not require a frequency-stabilized optical local oscillator. A 20GHz microwave signal is downconverted to a 250MHz intermediate frequency with a 14dB improvement in spur-free dynamic range over the nonlinearized link configuration. The method uses a single lithium niobate phase modulator at the transmitter, modulating two different wavelengths on orthogonal polarizations. These wavelengths are modulated again in the receiver to impart a local oscillator tone, then each upper sideband is filtered with a fiber bragg grating to present the beat IF at the photodetector.

**Index Terms** — analog optical links, frequency conversion, intermodulation distortion, microwave photonics, phase modulation, polarization

## I. INTRODUCTION

One of the problems faced by RF engineers is how to efficiently transfer a high frequency microwave signal between the antenna and receiver (or transmitter) when they are separated by some significant distance. There is a large body of literature discussing the merits and handicaps of using fiber optic links to perform this function, usually using intensity modulated links with direct detection (IMDD) links [1], [2].

A growing number of efforts have recently focused on phase-modulated links as another alternative because of the highly linear modulation it provides and simpler modulator/transmitter. Several recent efforts at developing linear, or linearized, optical receivers are bearing fruit although they are limited in bandwidth [3], [4] or require additional digital processing [5].

Another problem is how to recover the high-frequency signal in a way that it can be digitized with high resolution. This usually requires the signal to be downconverted to an intermediate frequency (IF), often in the VHF band, that is more easily digitized. A fiber optic link that does not downconvert the signal must use an electronic mixer to accomplish this, either before or after the link. If the mixer is placed after the link, the photodetectors and mixers must have enough bandwidth to accommodate the full-spectrum microwave signal which can add significant cost.

We describe here a new method that instead uses electrooptic mixing in a Local Oscillator (LO)-driven phase

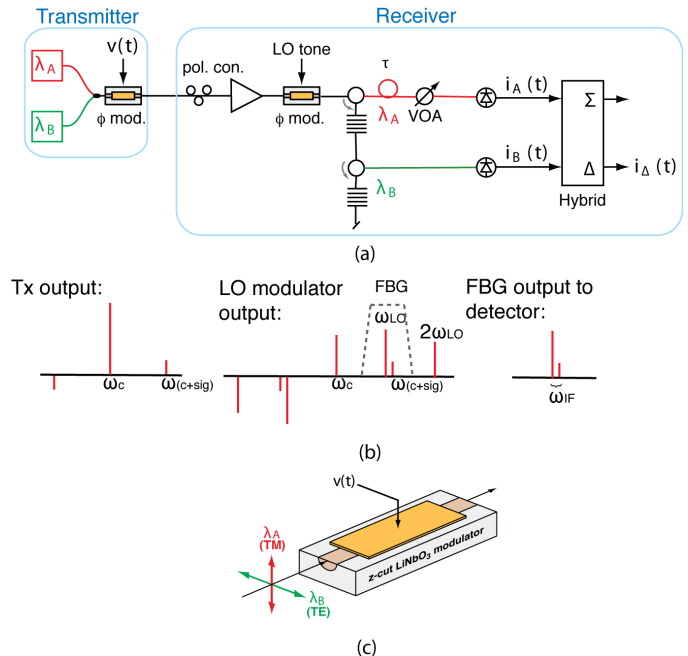


Fig. 1. (a) Schematic diagram of dual-wavelength linearized downconverting link. (b) Simplified spectrum, showing the LO and filter placement to achieve direct detection of the IF. (c) For linearized operation the two wavelengths are polarization multiplexed and launched along the TM and TE axes of the modulator.

modulator. The method presented here is limited in that the optical filter must be able to provide significant rejection between the signal sideband and its carrier and other sidebands, placing a practical lower frequency limit at a few GHz with conventional filter technology (e.g. FBGs). Thus this link works most effectively at higher GHz frequencies, where it becomes easier to spectrally filter the sideband. This technique is uniquely suited for burgeoning applications that utilize the K and Ka bands (18-40GHz).

## II. THEORY

Fig. 1(a) shows the layout used for this experiment. The high-frequency RF signal (near 20GHz for this experiment) is phase modulated onto an optical carrier. The phase modulator requires no external bias circuitry and requires no external power to operate, making it an attractive option for antenna

remoting scenarios. At the receiver, the optical signal is amplified and then phase modulated again, this time with a very strong single tone that becomes the Local Oscillator (LO) analogously to [6]. Illustrated in Fig. 1(b), this tone is placed near the signal of interest and follow-on optical spectral filtering rejects all other products, leaving only the LO tone and the original signal to be recovered. Since the lower, antiphased, sideband has been removed, the beat between the LO and signal at the desired Intermediate Frequency (IF), typically between 50-300MHz, is directly detected by a photodetector. The detector only requires enough bandwidth to cover the IF range, significantly lowering the component cost of the link.

The linearization technique used here exploits the fact that the electrooptic coefficient of LiNbO<sub>3</sub> is different for the z (TM) and x (TE) polarization states. This effectively causes a single modulator to act as two modulators with different transfer functions that can be set in opposition to suppress a single order of distortion. A different wavelength is used for each polarization, and each is separately recovered with the filtered sideband method and the detected currents combined.

#### A. Nonlinearized (TM-only) link characteristics:

The optical carrier is phase modulated with the RF signal, generating the usual spectrum:

$$E(t) = \sqrt{P_0} e^{j\omega t} \sum_{n=-\infty}^{\infty} J_n(m_s) e^{jn\Omega t} \quad (1)$$

$P_0$  is the optical power before spectral filtering,  $m_s$  is the signal modulation depth defined as  $m_s = (\pi V_{0s})/V_\pi$ ,  $\omega$  is the optical frequency, and  $\Omega$  is the microwave signal frequency.

The field from (1) is presented at the input of the second phase modulator. The Local Oscillator (LO), with frequency  $\Omega_{LO}$  is a single microwave tone modulating this field, and its output is:

$$E(t) = \sqrt{P_0} e^{j\omega t} \sum_{p=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} J_p(m_{LO}) J_n(m_s) e^{j(p\Omega_{LO} + n\Omega)t} \quad (2)$$

When the LO is modulated onto the carrier, unintended distortion products are generated between the LO frequency and all frequencies present in the original signal and its sidebands, according to (2). This is IMD between the signal and LO, and is not the IMD created by multiple signal frequencies we are primarily concerned with. This signal-LO IMD is not of concern if the signal is suboctave at the IF, which is often the case.

If we assume a suboctave (at the IF) signal and ignore the IMD caused between the LO and signal, the RF gain of the nonlinearized link can be found to be:

$$G_{RF} = \Phi^2(m_{LO}) \left( \frac{J_0(m_{LO})}{J_1(m_{LO})} \right)^2 \left( \frac{\pi^2}{V_\pi} \right)^2 Z_i Z_o i_{DC}^2 \quad (3)$$

where  $\Phi^2(m_L)$  is a calculated parameter that accounts for imperfect filtering causing some of the DC photocurrent to arise from residual carrier and harmonics.

The suboctave dynamic range is then limited by third-order intermodulation (IMD3) products at  $(2\Omega_1 - \Omega_2)$  and  $(2\Omega_2 - \Omega_1)$  that are naturally created by (1) when more than one signal frequency is present. By setting the extrapolated linear and third-order amplitudes equal to each other, the input-referenced intercept point is:

$$P_{IIP3} = \frac{4}{\pi^2} \left( \frac{V_\pi^2}{Z_i} \right) \quad (4)$$

and when the noise power spectral density  $S_0$ , is known, the third-order Spur-Free Dynamic Range (SFDR) is given by:

$$SFDR = \left( \frac{G_{RF} P_{IIP3}}{S_0 B} \right)^{2/3} \quad (5)$$

#### B. Linearized Link Characteristics:

The conditions for linearization (suppression of third-order distortion) when two separate photocurrents are present have been set forth in [7] and [3] for MZM and phase-modulated links with interferometric detection, respectively. As in [3] the signal here is modulated to two different depths in what are effectively two different modulators. The LiNbO<sub>3</sub> modulator, as well as many other electrooptic materials, has different electrooptic coefficients for the TM (vertical, in a Z-cut device) and TE (horizontal) polarizations. One wavelength is present on each polarization axis in the modulator, these wavelengths are spectrally separated by the FBGs, detected separately, and the resulting photocurrents are subtracted in an RF 180° hybrid. When the two currents are combined in the proper ratio the third order distortion can be suppressed. This ratio is [7]:

$$i_{\lambda(TM)} = \gamma^3 i_{\lambda(TE)} \quad (6)$$

For LiNbO<sub>3</sub>, third-order suppression is expected to occur when approximately 95% of the current is from the detected TE wavelength and 5% is from the TM wavelength. At this point, the dominant distortion is proportional to  $m^5$ , the fifth-order.

Using separate wavelengths, standard WDM components can be used to demultiplex and individually control each color, and PM fiber is not required on the return fiber between

the modulator and receiver. The current can be controlled either by adjusting the optical powers or the currents themselves.

Most of the received current is from the “wrong” or weakly-modulated polarization, and the linearized RF gain is reduced by a factor of  $(\gamma(1-\gamma^2))^2$ , about 10.5dB lower than the “normal” gain from (3) where all the optical power and therefore current is from the strongly-modulated TM axis of the modulator. In calculating gain, the current used is TE wavelength's detector current.

As with the third order, the input-referenced fifth-order intercept point (IIP5) is found by including fifth-order terms and equating linear and fifth-order amplitudes when the currents are according to (6). This yields

$$P_{IIP5} = \frac{P_{IIP3}}{\gamma} \sqrt{\frac{3}{5}} \quad (7)$$

and the fifth-order limited SFDR is (using the gain from (3))

$$SFDR5 = \left( \frac{(\gamma(1-\gamma^2))^2 G_{RF} P_{IIP5}}{S_o B} \right)^{4/5} \quad (8)$$

The birefringence of LiNbO<sub>3</sub> can cause significant differential group delay between the signal modulated on the TM and TE axes. In order for the linearization to work, the IF phases must match. The extraordinary index of refraction in LiNbO<sub>3</sub> (TM in a z-cut device) is 2.14, whereas the ordinary (TE) index is 2.22. This can be largely ignored at low signal frequencies, but causes significant phase mismatch in the X- or K-band and must be compensated for. For instance, a 5cm long modulator will cause approximately 13.3 ps relative delay, the TE mode being retarded with respect to the TM mode. This delay is directly translated to the respective IFs.

A simple method to remove this effect is to insert an identical modulator into the signal path immediately after the signal phase modulator, as a passive compensating waveplate. If the signal modulator has a PM output, a 90-degree splice or connection between the two modulators will reverse the axes and remove the differential delay at its output for all frequencies. The output of this second phase modulator can be SMF. Alternately, the TM-wavelength portion of the receiver can have a delay line inserted to equalize the paths.

### III. EXPERIMENT

Two external cavity tunable lasers were polarization multiplexed onto the slow (TM) and fast (TE) axes of the signal modulator's input PM fiber. The TE wavelength was launched onto the fast axis by means of a 90-degree PM splice. Isolation between the two wavelengths (polarizations), measured at the output of the modulator, was >24dB. The

signal tones were 19.95 and 19.98GHz. Each wavelength at the output thus carried the same signal, modulated to different depths.

Less-than-perfect polarization or spectral isolation in the modulator or at the detectors does not preclude linearization, as long as the net modulation depth on each wavelength is different. Any crosstalk will effectively change the  $\gamma$  ratio, thereby changing received TE and TM currents needed for linearization according to (6) and changing the received gain and SFDR.

The signal modulator in this experiment did not have a PM output fiber so a compensating modulator was not used to remove the birefringent group delay since the polarization state between the modulators could not be fully preserved. Instead, a fiber delay was placed in the TM wavelength's path at the receiver.

The output of the modulator traveled through a length of SMF to a polarization controller, then into a single-polarization EDFA with an 11dB optical noise figure. The controller was adjusted to ensure sufficient power from each wavelength entered the EDFA, and the single-polarization output from the EDFA was aligned to ensure all optical power launched into the LO modulator was along the TM axis. This ensured that both wavelengths experienced the same LO modulation depth.

The LO modulator was driven by a single 19.7GHz tone at a modulation depth of 1.08 to maximize the signal gain from (3), corresponding to an input power of 18.1dBm; this depth was verified by measuring the power in the first optical sidebands as measured on an optical spectrum analyzer. Both the signal and LO modulators were 40GHz bandwidth Z-cut, Ti-indiffused phase modulators, 5cm in length with measured TM  $V_\pi$  of 7.4V at 20GHz. The signal modulator's TE  $V_\pi$  was measured to be 20.5V at 20GHz, for a  $\gamma$  of 0.361, or 1 / 2.77.

After both wavelengths were modulated with the LO, they were passed through a thermally stabilized FBG with nominal 30GHz 1dB bandwidths to separate out one of the wavelength's upper sidebands (1<sup>st</sup> sideband of the signal and LO) on the reflective path. The remainder of the signal was transmitted through the FBG to a second FBG that selected the other wavelength's upper sidebands. This filtering both spectrally separated the two signals and effected the IF downconversion. The FBGs used in this experiment were not particularly well-suited to this application; the attenuation of the carrier and second upper sidebands were measured to be only 6dB, causing  $K(m_L)$  to be 0.466, a Gain penalty of almost 6.6dB. The first lower sideband, which is in antiphase with the upper sideband and would further diminish signal recovery, was attenuated by 18dB and therefore does not have any significant effect on the results or analysis.

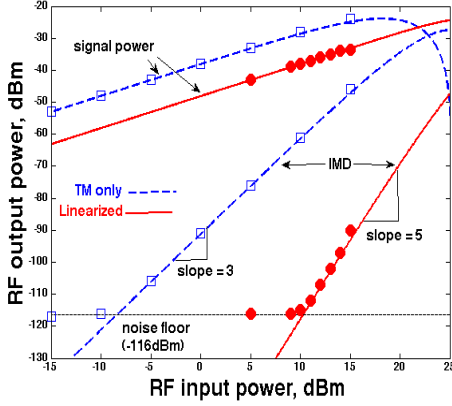


Fig. 2. Measured received vs input RF power for the TM-only (blue squares) and linearized (red circles). The lines indicate the results from theory. The signal tones were at 19.95GHz and 19.98GHz with the recovered IF at 250MHz and 280MHz. All measurements used a resolution bandwidth of 10KHz.

TABLE I  
PREDICTED / MEASURED LINK PERFORMANCE

predicted/measured	TM-only	Linearized
<b>Gain</b>	-37 / -38dBm	-49 / -48dBm
<b>SFDR</b>	97 / 96.5dB/Hz <sup>2/3</sup>	110.5 / 110dB/Hz <sup>4/5</sup>

Once separated, each signal was sent to a PIN photodetector. The photodetector outputs were combined in a 180° RF hybrid, with its output sent to a microwave spectrum analyzer via a bandpass filter and LNA preamplifier to ensure the link noise floor was visible above the spectrum analyzer's floor.

#### IV. RESULTS AND DISCUSSION

Results from the two-tone testing described above are presented in Fig. 2 and Table 1. Recovered tones were at 250MHz and 280MHz, and the IMD products at 220MHz and 310MHz. The LO-signal IMD level was not measured in this experiment. All calculations consider the 3dB power loss from the hybrid combiner and 6dB loss from the parallel 50-Ohm resistor in each photodiode. The 2.5mA current for the linearized case is the current measured from the TE wavelength.

Although the linearized SFDR itself is not particularly impressive at 110dB/Hz<sup>4/5</sup>, the 13.5dB improvement in dynamic range over the TM-only baseline is in agreement with theory. The TM-only Gain, NF, and SFDR also agree with the predicted values. Calculations show that in the shot limit and with the same  $V_{\pi}$  for the signal modulator, the linearized SFDR for the same received current improves to 122dB/Hz<sup>4/5</sup>. Better FBG filters help as well; a nominal 20dB

rejection further increases the SFDR to 124dB/Hz<sup>4/5</sup>. It must also be recalled that the signal has already been downconverted from 20GHz to a 250MHz IF; cascade analysis of a non-downconverting link with an electronic mixer to downconvert would show that the overall SFDR is lower than that of the non-downconverting link's SFDR.

#### V. CONCLUSION

We have presented the theory for, and experimentally demonstrated, a new phase-modulated fiber link to simultaneously downconvert and linearize a K-band microwave signal to a VHF IF with improved SFDR. The link does not require a separate optical local oscillator, which greatly simplifies and can improve the reliability of the receiver in comparison to optical heterodyne approaches. This design is especially amenable to higher frequency links, where downconversion is essential and optical filtering can be applied to isolate modulation sidebands.

#### References

- [1] C. H. Cox, *Analog Optical Links: Theory and Practice*, New York: Cambridge Univ. Press, 2004.
- [2] A. J. Seeds, "Microwave Photonics," *IEEE Trans. Microwave Theory & Tech.*, vol. 50, no. 3, pp. 877-887, March 2002.
- [3] B. M. Haas, V. J. Urlick, J. D. McKinney, and T. E. Murphy, "Dual-Wavelength Linearization of Optically Phase-Modulated Analog Microwave Signals," *J. Lightwave Technol.*, vol. 26, no. 15, pp. 2748-2753, Aug 2008.
- [4] L. A. Johansson, H. Chou, A. Ramaswamy, J. Klamkin, L. A. Coldren, M. Rodwell, and J. E. Bowers, "Coherent Optical Receiver for Linear Optical Phase Demodulation," *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, pp.47-50, June 2007.
- [5] T. R. Clark, and M. L. Dennis, "Photonic Downconversion and Linearization of an X-Band Fiber Optic Link Using Optical I/Q Demodulation," *Proc. CLEO, CtuAA2*, pp1-2, May 2007.
- [6] G. K. Gopalakrishnan, R. P. Moeller, M. M. Howerton, W. K. Burns, K. J. Williams, and R. D. Esman, "A Low-Loss Downconverting Analog Fiber-Optic Link," *IEEE Trans. Microwave Theory & Tech.*, vol. 43, no. 9, pp. 2318-2323, September 1995.
- [7] E. I. Ackerman, "Broad-Band Linearization of a Mach-Zehnder Electrooptic Modulator," *IEEE Trans. Microwave Theory & Tech.*, vol. 47, no. 12, pp. 2271-2279, December 1999.