Photonic Downconverting Link with Digital Linearization

Abstract — We experimentally demonstrate a digitally linearized high dynamic range downconverting microwave photonic link. The system is limited in frequency only by the 10 GHz 3-dB bandwidth of the optical modulators used and is demonstrated at 9 GHz. Digital linearization suppresses third order intermodulation distortion by as much as 39 dB. The linearization is shown for a single tone, a two tone, and a 1 MHz bandwidth input signal.

Index Terms — Analog systems, microwave photonics, optical fiber communication, optical modulation, digital linearization.

I. INTRODUCTION

Microwave photonic links with high dynamic range are useful for remoting antenna signals over long distances due to large available bandwidths, low propagation loss, and immunity to electromagnetic interference. Additionally, microwave photonic links can perform frequency downconversion to an intermediate frequency (IF) which eliminates electronic mixing. Many downconverting architectures have been proposed including a phase modulated coherent optical link [1], a traditional photonic link with an additional Mach-Zehnder modulator to perform mixing [2]−[4], and photonic subsampling of RF signals with pulsed optical sources [5]−[6].

Numerous architectures exist for correcting the nonlinearity introduced by the Mach-Zehnder modulator. Linearization techniques using two Mach-Zehnder modulators in series have been demonstrated [4], [7]. Digital signal processing (DSP) can be employed to reduce unwanted intermodulation distortion after the signal has been digitized.

In this work, a downconverting microwave photonic link is experimentally demonstrated at 9 GHz with a digital linearization technique that suppresses intermodulation distortion (IMD) by as much as 39 dB. The link uses a two Mach-Zehnder modulator configuration.

II. THEORY

A standard microwave photonic link consists of a laser source, electro-optic modulator, and a photodiode. The RF signal modulates the optical carrier, and a photodiode of sufficient bandwidth converts the optical power to electrical current. Mixing in a microwave photonic link can be achieved by introducing a second Mach-Zehnder modulator driven by a sinusoidal local oscillator (LO) signal. For the architecture shown in Fig. 1, the power gain of the downconverting link, assuming perfect bias conditions is given by:

$$G = \left(I_o \frac{\pi}{V_{\pi,1}} J_1 \left(\frac{\pi}{V_{\pi,2}} V_{LO} \right) \right)^2 R^2 \tag{1}$$

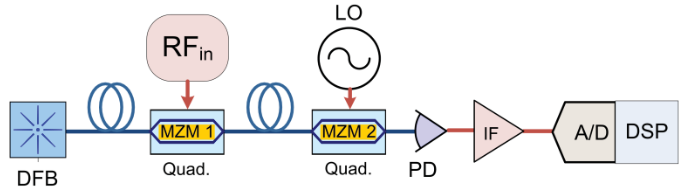

Fig. 1. Experimental setup. All fiber is polarization-maintaining. Abbreviations: DFB: distributed feedback laser, MZM: Mach-Zehnder modulator, Quad: quadrature, PD: photodiode, A/D: analog-to-digital converter, DSP: digital signal processing.

when using the small signal approximation for the RF encoding stage. In (1), I_o is the DC photocurrent at quadrature bias, $V_{\pi,1}$ and $V_{\pi,2}$ are the respective modulator responses, and J_1 is the Bessel function of the first kind. I_o is equal to $P_{las}T\eta/4$ where P_{las} is the source optical power, T is the total insertion loss of the link, and η is the photodiode responsivity. The input and output impedances are assumed to be matched with impedance R. Conversion gain is maximized with an LO drive amplitude of $0.6V_\pi$, at which point $J_1^2(V_{LO}\pi/V_{\pi,2})$ has a value of -4.7 dB.

In the downconverting link shown in Fig. 1, the LO modulator provides mixing without introducing any in-band distortion products. Higher order odd harmonics of the LO mix with the RF signal but can be easily electrically filtered at the output. Perfect isolation exists between the RF and LO ports because the signals are applied to separate modulators. Only the RF Mach-Zehnder modulator contributes to IMD so the distortion analysis can be simplified by ignoring the presence of the LO modulator. Distortion in a quadrature bias link is primarily attributed to the sinusoidal transfer function of the link given by:

$$i(t) = I_o \sin\left(\frac{\pi}{V_\pi} V_i + \phi \right) \tag{2}$$

where $i(t)$ is the AC-coupled output photocurrent, I_o is equal to $P_{las}T\eta/2$ which is the DC photocurrent at perfect quadrature bias, V_i is the input signal, and ϕ is the bias angle error from quadrature. For an AC-coupled output with a sinusoidal input of amplitude A and frequency ω_o, the output current can be expressed in terms of the Bessel function expansion:

$$\begin{aligned} i(t) = 2I_o \Bigg[&\cos\phi \sum_{n\,odd} J_n\left(\frac{\pi}{V_\pi}A\right)\sin(n\omega_o t) \\ &+ \sin\phi \sum_{n\,even} J_n\left(\frac{\pi}{V_\pi}A\right)\sin(n\omega_o t) \Bigg] \end{aligned} \tag{3}$$

The Bessel functions weight the harmonic terms with the even order harmonics only present with imperfect quadrature bias. (3) shows that the input third order intercept point (IIP3) only depends upon V_π and that the gain compresses according to the slope of the first-order Bessel function squared. Since the system has a known sinusoidal transfer function, the distortion terms can be removed, and the original undistorted input signal can be recovered by applying arcsine to the measured output current, as given by:

$$V_i = \frac{V_\pi}{\pi}\left[\sin^{-1}\left(\frac{i(t)}{I_o}\right) - \phi\right] \tag{4}$$

In this paper, the arcsine linearization is applied in DSP to the digitized IF signal and the suppression of third order intermodulation distortion (IMD3) is measured.

III. Experimental Setup

In this experiment, an RF input signal of 9 GHz is downconverted to 100 MHz with an applied 8.9 GHz LO. The experimental setup, shown in Fig. 1, consists of a distributed feedback laser (DFB), lithium-niobate Mach-Zehnder modulators for applying the RF and LO signals, a photodiode, an IF amplifier, and an analog-to-digital converter (ADC). The DFB laser has an output power of 18 dBm and relative intensity noise (RIN) of −165.3 dBc/Hz. The RF modulator has a measured V_π of 6.8 V at the 9 GHz operating frequency of the system. Both modulators are biased at quadrature. The photodiode has responsivity of 0.5 A/W and a 3-dB bandwidth of 5 GHz. The power incident on the photodiode is 4.4 dBm. The IF signal is amplified to prevent the ADC from setting the system's noise floor. The IF amplifier has a gain of 24.7 dB, an output third order intercept point of 38 dBm, and a noise figure of 2.7 dB. The ADC (Intersil KDC5512-50) has a sampling rate of 500 MS/s and a noise floor of −137.3 dBm/Hz. The capture length was 200 µs (100,000 samples).

With the optimal LO drive amplitude of $0.6V_\pi$, the overall system conversion gain is −15.2 dBm, which includes the 6 dB of loss due to the photodiode's internal 50 Ω termination. The system noise floor is measured to be −135.7 dBm/Hz. The spur free dynamic range (SFDR) is measured to be 99.3 dB $\text{Hz}^{2/3}$ before digital linearization.

IV. Experimental Results

The system's linearity is tested with two tones at 9.000 and 9.004 GHz and the LO at 8.9 GHz. Before digital linearization, IMD3 is present at the output as expected from (3). Arcsine digital linearization suppresses the IMD3 term across the testing input power range of −1 to 9 dBm, shown in Fig. 2(a). Fig. 2(b) and Fig. 2(c) show the original and digitally linearized spectra, respectively, for an input power of 9 dBm in each tone. The suppression is measured to be 39.6 dB.

The arcsine linearization was also tested with a single tone

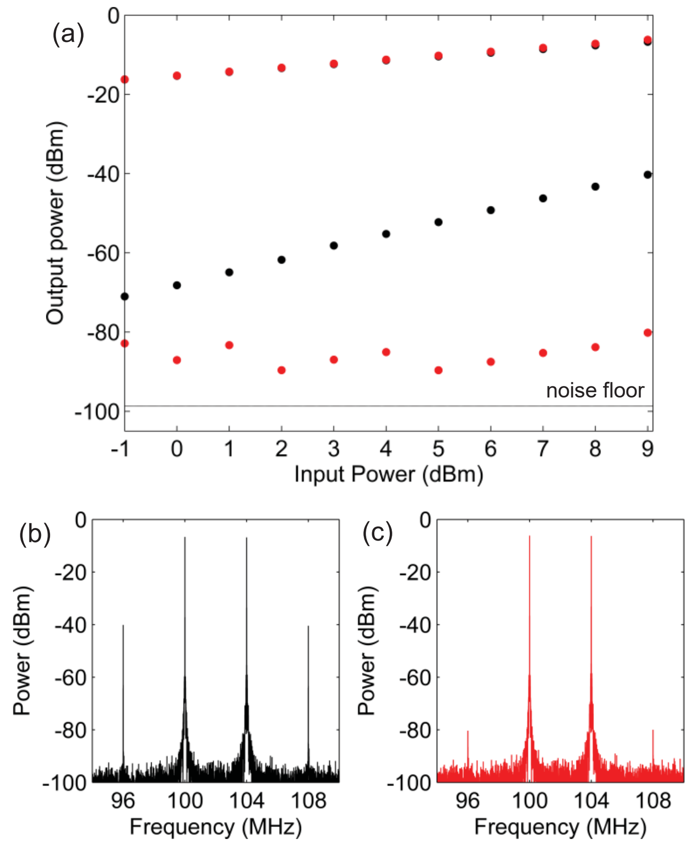

Fig. 2. (a) Plot of IMD3 and fundamental output power versus input power. Black: Original output. Red: Digitally linearized output. (b) Original two tone spectrum for input power of 9 dBm (c) Digitally linearized spectrum for input power of 9 dBm.

input signal at 9 GHz, and power gain compression due to the $J_1^2(V_{RF}\,\pi/V_\pi)$ scale factor of the fundamental was removed as shown in Fig. 3. The 1-dB compression point of the downconverting microwave photonic link occurs at a peak-to-peak drive amplitude of 0.6 V_π.

Finally, the system was tested with a quadrature amplitude phase shift keyed (QPSK) input signal with a symbol rate of 1 MHz and root-raised cosine pulse shape with a roll-off factor of 0.2 and integrated power of 12.6 dBm. The spectral features caused by the link's nonlinearity have been reduced to the level of the original input signal, as shown in Fig. 4.

V. Discussion

The arcsine linearization approach demonstrated is suitable for arbitrary input signals since the analytical inverse of the system transfer function is approximately known. Thus, arcsine linearization is not dependent on the nature of the input signal as long as the voltage of the input signal remains within the peak and null of the sinusoidal transfer function. Voltage excursions beyond these limits can result in *added* distortion by the arcsine operation since arcsine is defined only on the interval –1 to 1. A main limitation of the arcsine linearization approach is the imperfect sinusoidal system

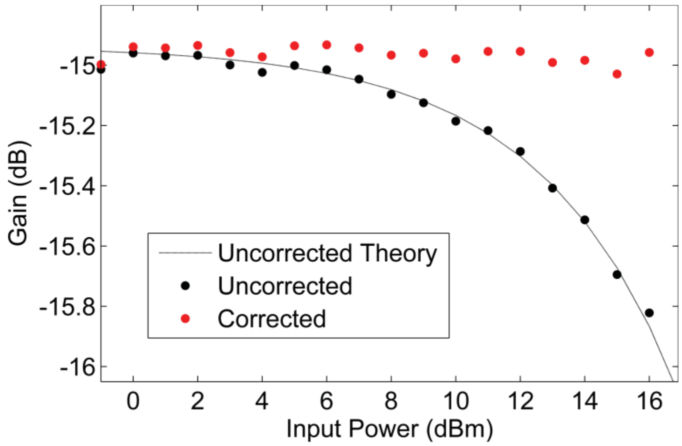

Fig. 3. Gain compression of the link before and after digital linearization.

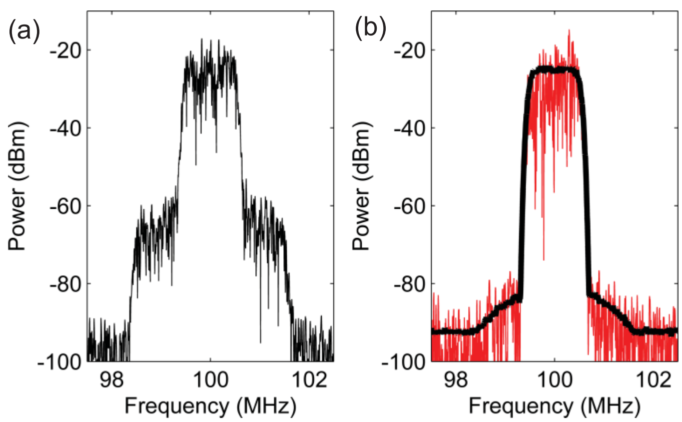

Fig. 4. (a) Original output. (b) Digitally linearized output with overlay of original input signal (black line).

transfer function encountered in a system with slightly nonlinear amplifiers and ADC front-end. The arcsine linearization does not completely remove distortion, and the effectiveness of the technique degrades at higher input power levels that stress the linearity of components.

The bias angle error from quadrature does not influence the performance of the arcsine linearization technique, as shown in (4). The bias angle error adds a DC term to the recovered AC-coupled signal and can safely be ignored. However, the bias angle error produces additional even order harmonics according to (3), which can be filtered in sub-octave systems.

Linearization can also be achieved when the system's transfer function is unknown but the distortion can be measured. In this case, orthogonal polynomial series can be used to remove distortion, but the statistics of the input signal must be known to properly select the orthogonal series for distortion compensation [8]. The technique of power series inversion does not require knowledge of the input signal and works for systems of arbitrary but known nonlinear transfer functions. Performance can be limited since cancelling a third order power series term does not eliminate IMD3 because higher order terms contribute to third order distortion.

Examining (1) reveals that the system gain can be improved. Currently, a significant improvement can be made by using an RF modulator with a lower V_π. For example, reducing the V_π by 50 percent would increase the gain by a factor of four. Increasing the photocurrent by improving the laser power, modulator loss, or photodiode responsivity also would increase the gain. The dynamic range of the system can be further improved with low bias techniques [4]. For a low bias offset from quadrature by ϕ, the gain of the system reduces by $\cos^2\phi$ while the average photocurrent reduces by $\sin\phi$. For RIN-dominated links the noise power decreases proportionally to the photocurrent squared, and for shot noise-dominated links the noise power decreases proportionally to the photocurrent. In either case, the noise power decreases faster than the gain. In practice, a low bias technique would require more optical power to compensate for the reduction in link gain while still matching the dynamic range of the ADC.

VI. Conclusion

We have experimentally demonstrated a high dynamic range downconverting microwave photonic link which was digitally linearized. Third order intermodulation distortion was suppressed by as much as 39 dB. The system was demonstrated at 9 GHz and using a single tone, a two tone, and a 1-MHz bandwidth signal.

References

[1] T. R. Clark, S. R. O'Connor, M. L. Dennis, "A phase-modulation I/Q-demodulation microwave-to-digital photonic link," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3039, 3058, Nov. 2010.

[2] A. C. Lindsay, G. A. Knight, and S. T. Winnall, "Photonic mixers for wide bandwidth RF receiver applications," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2311–2317, Sep. 1993.

[3] 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 Photon. Technol. Lett.*, vol. 43, no. 9, pp. 2318–2323, Sep. 1995.

[4] A. Karim, and J. Devenport, "High dynamic range microwave photonic links for RF signal transport and RF-IF conversion," *IEEE J. Lightw. Technol.*, vol. 26, no. 15, pp. 2718, 2724, Aug. 2008.

[5] P. W. Juodawlkis, J. J. Hargreaves, R. D. Younger, G. W. Titi, and J. C. Twichell, "Optical down-sampling of wide-band microwave signals," *IEEE J. Lightw. Technol.*, vol. 21, pp. 3116–3124, 2003.

[6] T. P. McKenna, J. A. Nanzer, M. L. Dennis, and T. R. Clark, "Mixerless 40 GHz wireless link using a photonic upconverting transmitter and a photonic downsampling receiver," in IEEE MTT-S Int. Microwave Symp. Dig., Seattle, WA, Jun. 2013, pp.1, 3.

[7] G. E. Betts and F. J. O'Donnell, "Microwave analog optical links using suboctave linearized modulators," *IEEE Photon. Technol. Lett.*, vol. 8, no. 9, pp. 1273–1275, Sep. 1996.

[8] J. Tsimbinos, K. V. Lever, "Nonlinear system compensation based on orthogonal polynomial inverses," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol.48, no.4, pp.406,417, Apr 2001.