Improved Radio Over Fiber Performance Using Predistortion Linearization

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***ABSTRACT* ? This paper describes improvements to *Radio Over Fiber* photonic links obtained by increasing the linearity of Mach Zehnder modulators using predistortion. The work was conducted at the Ku and X-band satellite uplink frequencies with a 1550 nm laser, but should be applicable to any microwave or even millimeter frequency band and any externally modulated laser. Link performance was evaluated for 2-tone intermodulation distortion, noise power ratio (NPR) and WCDMA adjacent channel power. Intermodulation distortion was reduced by more than 15 dB, and more than a 6 dB increase in effective signal power was demonstrated for typical system requirements.**

I. INTRODUCTION

Radio Over Fiber is a technique that modulates RF/microwave signals on an optical carrier to take advantage of the relatively low loss of optical fibers [1,2]. Many Radio Over Fiber systems employ a Mach Zehnder modulator (MZM) to amplitude modulate the light carrier [3]. MZMs typically have tremendous bandwidth that can easily exceed 40 GHz. While this bandwidth is necessary for conventional fiber optic communications, only a gigahertz or so of bandwidth is needed for radio over fiber applications. In most cellular telephone and multi-point video/data distribution systems, information is routed at baseband to the local transmission nodes, where it is up converted. The signals are in analog form and often involve many individual digitally modulated carriers spread over a GHz or more of bandwidth. Since only a fraction of the MZM bandwidth is utilized in Radio over Fiber systems, linearization is a practical and attractive method to achieve performance enhancement.

II. MZM OPERATION/CHARACTERIZATION

The MZM operates on the principle of optical phase interference. The optical carrier is split into two equal amplitude signals, the phase of one of these signals is shifted via the linear electro-optic effect, and the signals are recombined. When the optical carriers are set to a 0 ° phase difference, they sum to give a signal of maximum amplitude. When the carriers are set to a 180 ° phase difference, they cancel. V_p is defined as the change in voltage between these two points. For Radio over Fiber applications the MZM is biased to a point midway between these two extremes ($V_p/2$), and the RF/microwave information signal, V_{in}, is added to this bias voltage. Thus, the amplitude of the RF/microwave signal (V_{in}) controls the phase difference between these two optical signals. The optical signal amplitude (L_{out}) is simply

$$L_{out} = L_{mx}\,[1 + \sin(kV_{in})]^{½} \,, \qquad (1)$$

where L_{mx} is the conversion gain of the MZM and k is a conversion constant. kV_{in} equals p/2 when L_{out} is at maximum. The voltage out of the optical detector (V_{out}) is proportional to L_{out}^2; thus after removal of the dc term,

$$V_{out} = L_{mx}^2 \sin(kV_{in}) \,. \qquad (2)$$

Figure 1 shows how the gain [20 log(V_{out}/V_{in})] corresponding to this transfer response varies as the RF/microwave input level is increased from small signal to the point of maximum output level. This characteristic is not unlike the response of a microwave solid state power amplifier (SSPA) that typically displays 2.5 to 3.5 dB of compression at saturation compared to the 3.9 dB displayed by the MZM optical system [4,5]. However, SSPAs normally maintain a constant output level when driven beyond saturation, while the MZM decreases in output level. A similar response is displayed by traveling wave tube amplifiers (TWTAs).

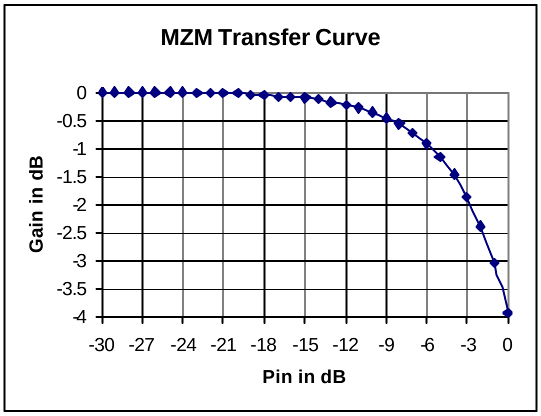

Fig. 1. MZM Gain compression at saturation is 3.9 dB.

Another difference between SSPA and MZM non-linearity is the level of phase distortion. The MZM transmission process introduces no phase distortion because envelope detection used in the photo detection process is insensitive to phase change. Thus ideally, a predistortion linearizer should introduce no phase correction. However, phase distortion introduced prior to the MZM by the microwave driver amplifiers will affect the performance and should be minimized. In practice available MZMs require about +25 dBm to drive them to saturation. Sizing a driver amplifier for minimal contribution to the distortion requires an output power backed off (OPBO) of more than 5 dB resulting in a requirement of almost a watt of saturated power. Even at this OPBO, most available amplifiers still introduce a few degrees of phase change. A predistortion linearizer can correct for this phase change and other non-linearities introduced by the driver circuitry.

III. PREDISTORTION DESIGN APPROACH

A predistortor was designed to linearize commercially available MZMs. The transfer characteristics of the JSD Uniphase SITU 3000 MZM and associated driver amplifiers used during testing were characterized experimentally to provide data for the predistortion unit design and are shown for applied Ku-band microwave signals in Figure 2.

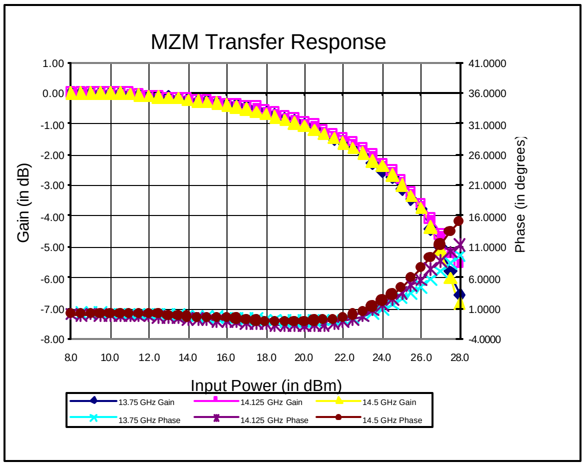

Fig. 2. MZM measured transfer response at Ku-band.

Very similar results were achieved at X-band. [Only Ku-band results will be shown unless there was a significant difference between bands.] The Pin corresponding to saturation is about 26 dBm. The MZM maintains the response of equation (2) independent of frequency. The differences between Figures 1 and 2 are primarily due to frequency dependent effects of the microwave driver amplifiers. MZMs can change in small signal gain with frequency, but over both the X and Ku satellite bands the test MZM's gain was near constant as seen in Figure 2.

Techniques for designing microwave predistortors have been well documented [6,7,8,9]. Because of the similarity of an MZM's non-linear characteristics to that of a microwave high power amplifier (HPA), it was decided to start with an existing SSPA linearizer design and modify its characteristics to match the MZM. The response of a relatively simple predistortor was modeled and is shown in Figure 3.

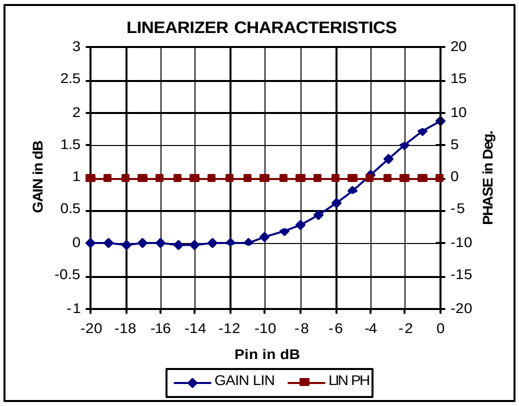

Fig. 3. Modeled linearizer response required 2 dB of gain expansion and no phase correction.

Figure 4 shows the calculated response of the modeled linearizer when combined with the MZM (L/MZM). The linearizer moves the 1 dB compression point (CP) almost 5 dB closer to the saturation point. This corresponds to a major improvement in linearity and was closely matched by the experimental linearizer.

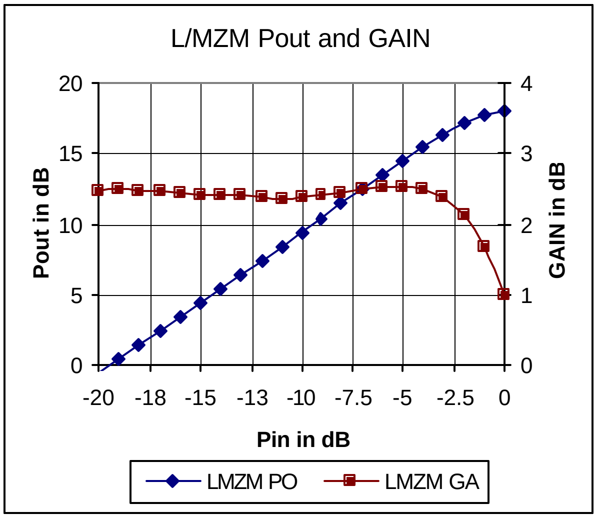

Fig. 4. The modeled L/MZM response moved the 1 dB CP very close to saturation.

IV. MZM LINEARIZER PERFORMANCE

Figures 5 and 6 show respectively the measured response of the test linearizer at Ku-band, and the response when it is combined with the MZM. As in the model, the 1 dB CP is moved to within a few tenths of a dB of saturation (Pin = 8 dBm in Figure 6). Unlike the modeled case, where zero phase change was assumed, the experimental linearizer was adjusted to reduce the phase distortion introduced by the MZM's imperfect driver amplifiers.

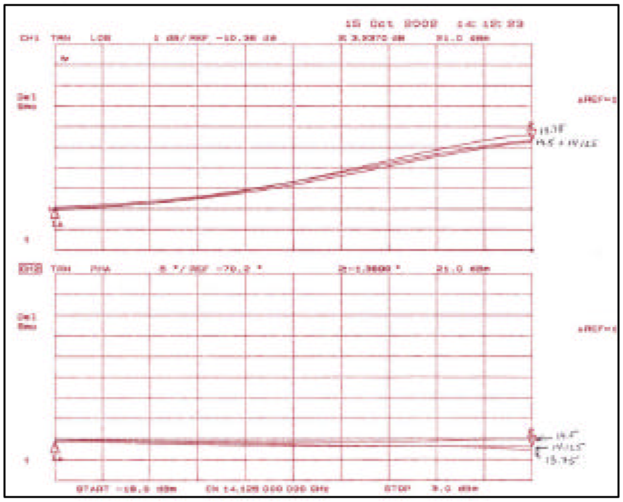

Fig. 5. The experimental linearizer response requires a minimal phase change.

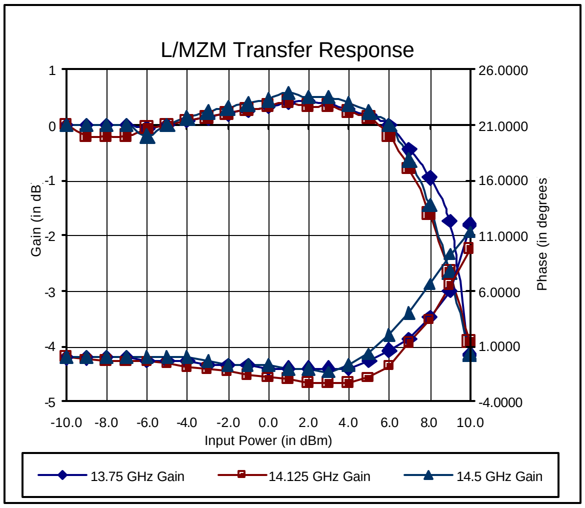

Fig. 6. The L/MZM's measured response shows the 1 dB CP very near saturation.

The modeled and measured 2-tone carrier-to-intermodulation ratio (C/I) corresponding to this response and that of the MZM without linearization (measured) is shown in Figure 7. More than a 15 dB improvement in C/I was achieved over much of the dynamic range. More importantly, the effective signal power at high C/I (> 40 dB) was increased by more than 6 dB. This improvement was maintained across the full satellite band.

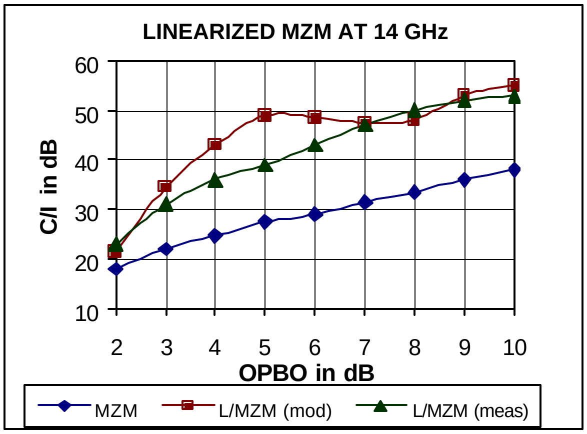

Fig. 7. Measured Ku-band performance of MZM and L/MZM, and modeled performance of L/MZM.

The measured X-band C/I performance is shown in Figure 8. Interestingly, the X-band system yielded even better C/I performance. This result is probably due to better control of the 8 GHz linearizer characteristics. Similar results should be achievable at Ku-band as well.

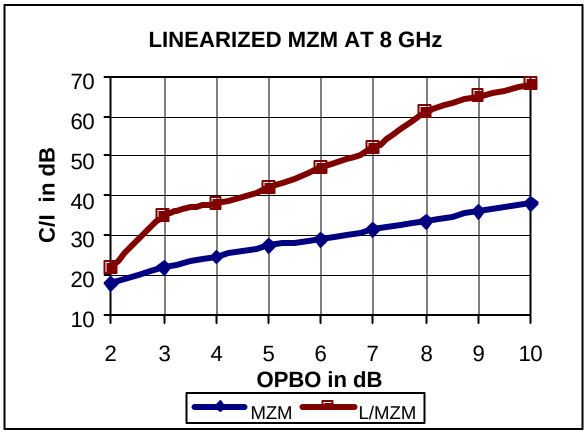

Fig. 8. Measured C/I performance of MZM and L/MZM at X-band shows > 25 dB reduction of intermodulation at high OPBO.

Multi-carrier and wideband code division multiple access (WCDMA) signal performance was also investigated. The performance of high power amplifiers with many carriers is normally evaluated using noise power ratio (NPR) measurements [10]. In this test white noise is used to simulate the presence of many carriers of random amplitude and phase. A 40 MHz noise pedestal was used; this bandwidth is typical of most satellite transponders. The results of these measurements at Ku-band are shown in Figures 9 and 10. For an NPR of 30 dB, the linearizer achieves an increase in effective signal power of about 3 dB. Figure 10 shows the NPR notch achieved by the L/MZM at 6 dB OPBO. CDMA, in addition to cellular telephones, is starting to be used with satellites. The adjacent channel power levels (ACPL) in response to a 3G WCDMA signal produced by the MZM and L/MZM at 2.5 and 5 MHz offsets are shown in Figure 11. (Figures at higher OPBO were limited by test equipment.)

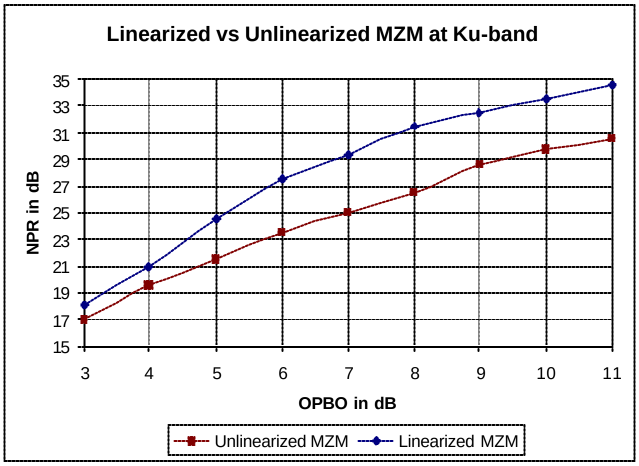

Fig. 9. NPR of MZM and L/MZM with 40 MHz noise pedestal.

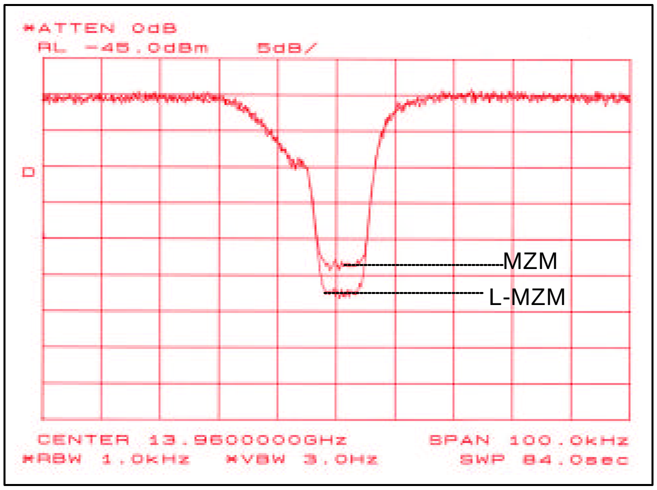

Fig. 10. NPR improvement with L/MZM at 6 dB OPBO.

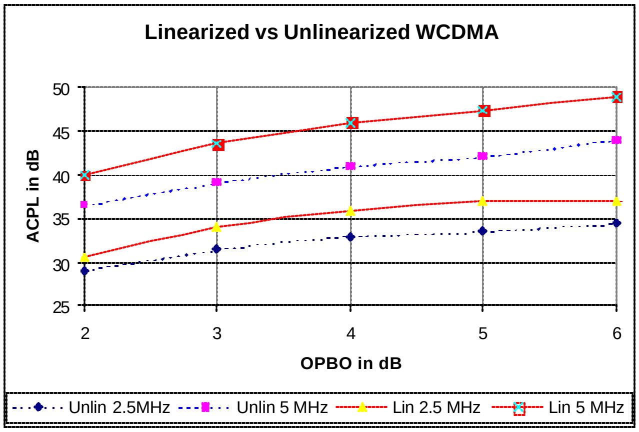

Fig. 11. ACPL of MZM and L/MZM with WCDMA signal.

V. CONCLUSION

The results in this paper clearly illustrate the value of combining an MZM with a linearizer in Radio Over Fiber photonic link applications. This combination can provide more than 6 dB increase in effective laser power at the high linearity levels required for both present and future communication requirements. Such systems should be highly attractive for both commercial and military communications applications where the losses of optical conversion can be a major limitation. The linearization of an MZM provides both higher power and linearity. The linearizer allows an MZM to provide 4 times the output power for C/Is > 40 dB, and more than a 15 dB improvement in 2-tone C/I over much of its power range.

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