Linearization of a Broadband Analog Optical Link Using Multiple Wavelengths

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Abstract

Instead of balancing the RF signal voltage on two modulator electrodes, broadband linearization of a link can be more easily achieved when two wavelengths are simultaneously modulated using a standard single-electrode Mach-Zehnder modulator.

Introduction

It is possible to operate either a Mach-Zehnder or a directional-coupler modulator around a DC bias voltage at which the second derivative of the transfer function is zero; doing so eliminates distortion at the second-harmonic and second-order intermodulation frequencies, causing third-order distortion products to dominate and thus limit the dynamic range [1], [2]. Third-order distortion limits the broadband dynamic range achievable using commercially available $LiNbO_3$ modulators to roughly 110 dB•$Hz^{2/3}$. To improve upon this, recent efforts have focused on the development of broadband "linearized" modulators, in which third-order distortion is minimized at the same DC bias voltage where no even-order distortion occurs. Figure 1 shows three previously proposed broadband linearized modulators (after [3]–[5]).

For frequencies above 2 GHz or so, where the modulator electrodes must be configured as transmission lines whose effective refractive index at RF frequencies closely matches the optical refractive index [6], there are inherent challenges associated with implementing any of the architectures shown in Fig. 1. Two of these approaches [Fig. 1(a) and(b)] require that the RF signal be split and applied in precise proportion to two different RF electrodes. To achieve broadband linearization at frequencies of 2 GHz or higher, therefore, the RF characteristics of the modulator's two traveling-wave electrodes (including RF attenuation per unit length, characteristic impedance, and guided wave velocity as determined by the effective RF refractive index) must match each another over the entire band of interest. This RF signal balancing gets progressively more difficult to accomplish with increasing signal frequency and/or percentage bandwidth.

To my knowledge the only broadband (greater than an octave bandwidth) linearized electro-optic modulator proposed thus far that does not require application of the RF signal to more than one electrode is the modified directional coupler design shown in Fig. 1(c). This configuration is the same as a straightforward directional coupler modulator [2], except for the incorporation of two additional DC-biased electrodes that impose controlled mismatches in the propagation constants between the optical waveguides in the coupling region [5]. In the 500-1000 MHz band a dynamic range of 111 dB•$Hz^{4/5}$ has been demonstrated using this type of modulator [7]. Recently, an analytical model [8] has shown that modulator could achieve a dynamic range of 129 dB•$Hz^{4/5}$ across a broad band and at high frequencies, but only if the mismatch between the RF and optical refractive indexes is counteracted by "re-phasing," which is essentially splitting of the RF among multiple shorter electrode segments—leading back to the electrode characteristic-matching issue.

Technical Approach

Figure 2 shows a new broadband linearization approach that uses a straightforward commercially available Mach-Zehnder electro-optic modulator with a single traveling-wave RF electrode and a single DC bias electrode. The Mach-Zehnder modulates two wavelengths of light simultaneously, and at the other end of the link a wavelength-division multiplexer (WDM) routes the two modulated wavelengths to separate detectors whose outputs are combined in an RF hybrid coupler. At the correct modulator bias voltage and the correct ratio of photodetector currents, both second- and third-order distortion are cancelled.

The curves in Fig. 3(a) show how the photocurrents at the individual detectors vary with modulator bias voltage (dashed lines), and how the current at the Δ output of the RF hybrid coupler varies with modulator bias (solid line). Figures 3(b) and (c) show second and third derivatives of these curves, respectively.

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These plots reflect the case where the ratio of photocurrents is maintained such that, at the modulator bias where both detector outputs have zero even-order distortion, the detectors deliver equal levels of third-order distortion to the hybrid coupler. Therefore, at this modulator bias and photocurrent ratio, the strongest distortion products at the hybrid coupler's Δ port are fifth-order.

This new linearization architecture is analogous to the dual-parallel Mach-Zehnder modulator configuration shown in Fig. 1(b), in which the RF signal is split in a specific proportion between two Mach-Zehnders that are fed a single optical carrier that has also been split in a specific proportion. In the new configuration only one Mach-Zehnder modulator is required because it has a different halfwave voltage (V_π) at the two wavelengths, so that an RF signal of magnitude v_M applied to the one electrode results in a different modulation depth v_M/V_π at the two wavelengths. Conceptually this dual-wavelength approach more closely approximates one described by Johnson and Roussell, who cancelled third-order (but not second-order) distortion by balancing two different *polarizations* of light that have different halfwave voltages in a lithium niobate Mach-Zehnder modulator [9].

An important advantage imparted by the new multiple-*wavelength* linearization approach is that inexpensive, commercially available fiber wavelength-division multiplexers can be used to route the two modulated wavelengths of light to separate photodetectors whose outputs are combined electrically (as in Fig. 2). Wavelength multiplexing to separate detectors enables precise maintenance of the desired ratio of RF signal powers to achieve distortion cancellation, even in the presence of unpredictable environmental factors such as stresses on the fiber that might induce variability in the relative losses at the two wavelengths [10].

Experimental Results

Using only commercial components I assembled a link in a configuration similar to the one shown in Fig. 2. For the optical sources I used an ATx Nd:YAG laser with 200 mW output power at 1320 nm and an Ortel InGaAsP DFB laser with 30 mW output power at 1550 nm. Both lasers had polarization-maintaining fiber pigtails. A WDM manufactured by PIRI coupled the inputs at the two different wavelengths into one polarization-maintaining fiber so that both optical carriers could be fed into the modulator. The modulator I used was a $LiNbO_3$ Mach-Zehnder device with one traveling-wave RF electrode and one DC bias electrode. At 1320 nm the manufacuterer (UTP) specified V_π of 4.7 V at DC and a 3 dB bandwidth of 3 GHz. A second WDM demultiplexed the modulated optical carriers, each of which I routed to a separate BT&D InGaAs photodiode detector. I was careful to match as closely as possible the lengths of the two fiber paths from the WDM to the detectors. I also followed both detectors with RF line stretchers and adjusted these to equalize the group delay measured (using a network analyzer) from the modulator input to either input of the RF hybrid coupler.

Before attaching the hybrid coupler (manufactured by Anzac, and specified for 2-2000 MHz operation) I connected the detector outputs to separate RF spectrum analyzers, and the modulator input to an RF signal generator set to 750 MHz. I varied the modulator's DC bias voltage and observed minima at the second-harmonic frequency (1.5 GHz) about every 4.7 V for the 1320 nm detector, and about every 6.8 V for the 1550 nm detector. At a modulator bias voltage of about –5.0 V it happened that the 1.5 GHz output from either detector was very near one of its minima.

With the modulator bias fixed at this second-order minimum, the next step was to set the ratio of RF powers at the hybrid coupler input ports. Figure 2 suggests one method involving amplifiers [10] for maintaining the two coupler inputs at the proper ratio for distortion cancellation. To achieve the proper ratio in the initial experiment I used a precision variable optical attenuator between the YAG laser and the 1320 nm input of the WDM. Feeding a two-tone RF input to the modulator, I varied the 1320 nm carrier attenuation until I observed a minimum in the measured output power from the Δ port of the hybrid coupler at the third-order intermodulation frequency.

Varying the link input power at the two RF tones (f_1, f_2), I measured the link output power at these tones, their sum frequency (f_1+f_2), and the third-order intermodulation frequencies ($2f_1-f_2$, $2f_2-f_1$). Fig. 4(a) shows the measured results for 499 and 501 MHz input tones, along with the measured noise output in a 1 MHz instantaneous bandwidth. Figure 4(b) shows results of the same measurement for input tones at 999 and 1001 MHz. In these plots hollow squares and circles represent measured data at the fundamental and third-order intermod frequencies for the link with only the 1550 nm laser on (this yields better performance than the link with only the 1320 nm laser). When power at the second wavelength is present in proper proportion to the first wavelength, third-order distortion is suppressed, as shown by the solid triangles in the plots.

The plots show four of additional features worth mentioning: first, and most significantly, the spurious-free dynamic range is greater for the two-wavelength link, in accordance with its design; second, the two-wavelength link suppresses second-order distortion (represented on the plots by solid circles) incompletely, but to a degree sufficient to ensure that the dynamic range is third-order distortion limited; third, there is some noise figure penalty associated with the linearization, which has been true for every broadband linearized link that uses Mach-Zehnder modulators [11]; fourth, the same control settings (modulator bias and photocurrent ratio) yield linearization across an octave of bandwidth—i.e., at 500 MHz and 1 GHz, as shown in Fig. 4 (a) and (b), respectively. Amplification of the 1550 nm carrier, and a corresponding decrease in attenuation of the 1320 nm carrier, would enhance the link's dynamic range more profoundly.

Summary and Acknowledgments

Proposals for linearization of a fiber-optic link across more than an octave bandwidth have required precise balancing of the signal voltage levels on multiple electrodes in a custom modulator, which represents a significant implementation challenge. I have described a new link linearization method that uses a standard Mach-Zehnder $LiNbO_3$ modulator with only one RF and one DC bias electrode to linearize across greater than an octave bandwidth. Instead of balancing the voltages on two RF electrodes, this new technique uses the standard traveling-wave electrode to modulate two optical carriers, and it is the ratio of these optical carrier powers that is adjusted for distortion cancelling.

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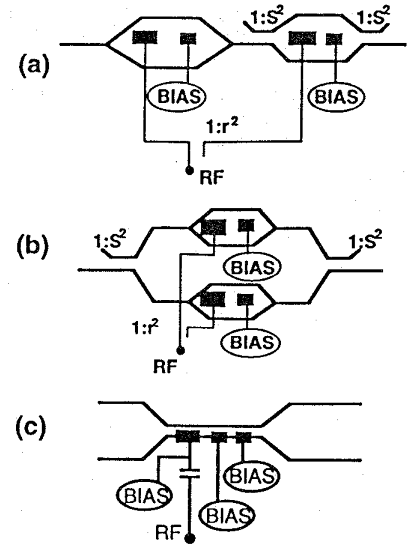

Fig. 1 Broadband linearized electro-optic modulator configurations: (a) series Mach-Zehnders [3]; (b) parallel Mach-Zehnders [4]; (c) modified directional coupler [5].

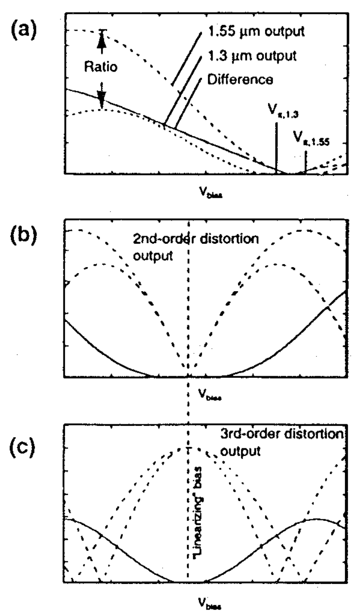

Fig. 3 (a) Photocurrent at the two individual detectors (dashed lines), and the current at the output of the RF hybrid coupler (solid line), as a function of the modulator bias;

(b) Second derivative of the photocurrent at the individual detectors (dashed lines), and at the output of the RF coupler (solid line), as a function of the modulator bias;

(c) Third derivative of the photocurrent at the individual detectors (dashed lines), and at the output of the RF coupler (solid line), as a function of the modulator bias.

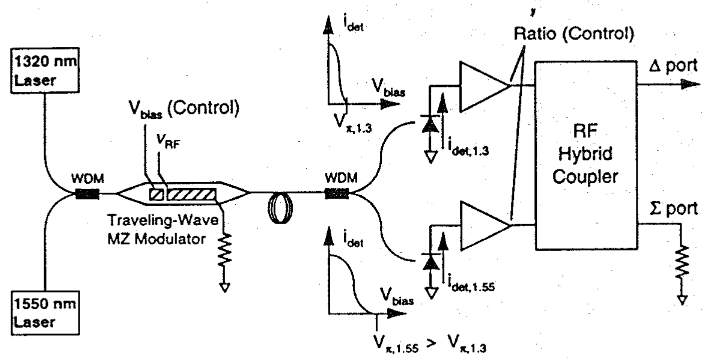

Fig. 2 New linearization architecture. Second- and third-order distortion are simultaneously minimized by precise control of the modulator bias and the ratio of signal powers carried by the two optical wavelengths.

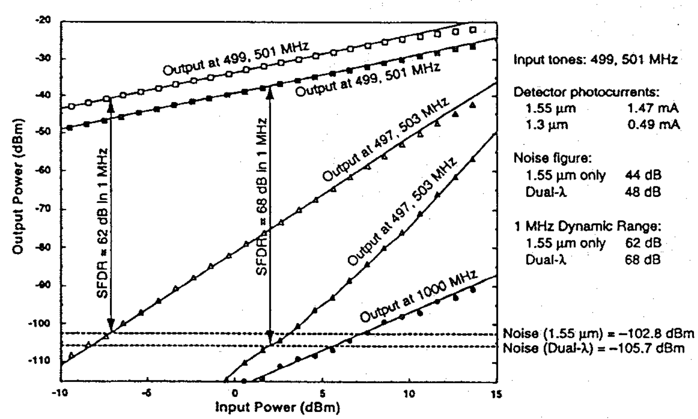

Fig. 4 (a) Link output noise (dashed line) and RF power measured at the fundamental (squares), second-order intermod (circles), and third-order intermod (triangles) frequencies as the RF input power at the fundamental frequencies (499 and 501 MHz) is varied. Hollow symbols represent the situation where only one of the wavelengths (1550 nm) is present; solid symbols represent two-wavelength operation at the proper ratio of detector photocurrents.

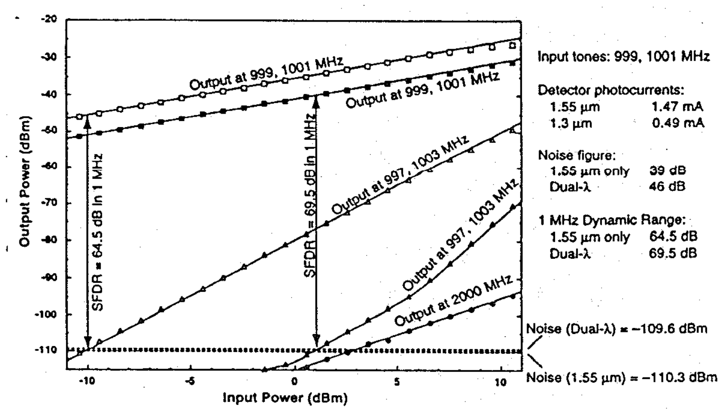

Fig. 4 (b) Same as (a), but with fundamental frequencies of 999 and 1001 MHz. Modulator bias and photocurrent ratio settings are unchanged from the 499 and 501 MHz measurement..