Demonstration of Wavelength-Insensitive Biasing Using an Electrooptic Polymer Modulator

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***Abstract*—Wavelength-insensitive biasing (WIB) of an optical intensity modulator was demonstrated using the photobleaching technique to control the initial phase difference of the electrooptic polymer modulator. The WIB technique reduced the wavelength sensitivity of the bias point at 1550 nm by a factor of 17.**

***Index Terms*—Laser trimming, optical modulators, radio frequency photonics, wavelength-division multiplexing (WDM).**

I. Introduction

THE WAVELENGTH response of a Mach–Zehnder (MZ) optical intensity modulator plays an important role in systems where a single variable wavelength or multiple fixed wavelengths may be modulated by a single modulator. Examples of such systems include wavelength-division-multiplexing (WDM) configurations used in telecommunications networks [1], photonic time stretch and WDM sampling techniques currently being investigated for enhancing the performance of analog-to-digital converters [2], and photonic true-time-delay systems [3].

Changes in the carrier wavelength shift the modulator bias away from the optimum $\pi/2$ bias point and cause a strong increase in the second-order distortion. At a certain detuning from the center wavelength, the second-order distortion begins to exceed the third-order distortion. In systems with greater than one octave bandwidth, this begins to degrade the spur-free dynamic range (SFDR) of the system. To prevent SFDR degradation due to second-order distortion one, therefore, must limit the optical bandwidth of the system.

In a recent publication, Dubovitsky *et al.* [4] proposed a novel technique to make the quadrature bias point of an MZ modulator insensitive to changes in the optical wavelength. The wavelength-insensitive bias (WIB) technique is based on compensation of the bias shift due to the nature of the dispersion of the half-wave voltage, V_π, and the difference in the optical pathlength in the arms of the MZ. The method requires building a modulator with a specific pathlength difference. This could be achieved by a specially designed photomask, but this method requires careful simulation and fabrication because the photolithography is irreversible. For electrooptical polymer modulators, it is possible to adjust the optical pathlength after the fabrication. The chromophores inside the polymer can be decomposed or rearranged by radiation at wavelengths within their absorption band, which is usually referred as photobleaching [5]. A drop in the refractive index is introduced with the photobleaching. This phenomenon had been widely used to fabricate and trim optical waveguides [6], [7]. In this letter, we used the photobleaching technique to trim the pathlength of the polymer modulator and demonstrated wavelength-independent biasing.

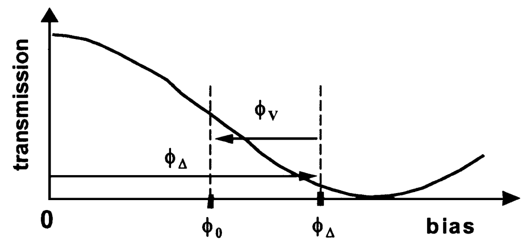

Fig. 1. Illustration of the WIB technique. The modulator is trimmed away from quadrature ϕ_0 to the point ϕ_Δ. An external voltage is applied to bring the bias back to ϕ_0. The wavelength dispersion and the values of ϕ_Δ and ϕ_V are such that the bias point remains at ϕ_o independent of the wavelength changes.

II. Basics of WIB Technique

As shown in Fig. 1, the transmission of an MZ modulator is given by

$$T(\lambda) = \frac{1}{2}\left[1 + \cos\left(\pi \frac{V}{V_\pi(\lambda)} + \phi_B(\lambda)\right)\right] \tag{1}$$

where $\phi_B = \phi_\Delta + \phi_V$ is the phase bias of the modulator and

$$\phi_\Delta = 2\pi \frac{\Delta_{nL}}{\lambda} \tag{2}$$

$$\phi_V = \pi \frac{V_B}{V_\pi} \tag{3}$$

Δ_{nL} internal pathlength mismatch between two arms of the MZ interferometer;
V_B applied bias voltage.

In order to suppress the second-order distortion, the bias point must be independent of the wavelength or

$$\frac{d\phi_B}{d\lambda} = \frac{d\phi_\Delta}{d\lambda} + \frac{d\phi_V}{d\lambda} = 0. \tag{4}$$

The dispersion of ϕ_Δ can be calculated from (2)

$$\frac{d\phi_\Delta}{d\lambda} = -\frac{1}{\lambda}\phi_\Delta = -0.65\phi_\Delta\ \mu\text{m}^{-1} \tag{5}$$

at $\lambda = 1550$ nm.

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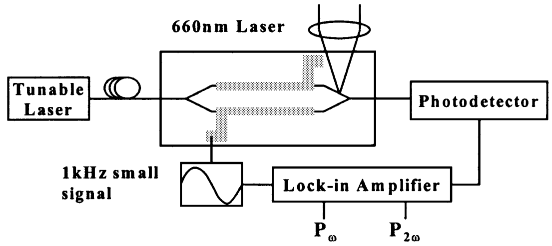

Fig. 2. Schematic illustration of the experimental setup. A 660-nm laser beam was focused on one arm of the MZ interferometer to perform the photobleaching. A 1-kHz small sinusoidal signal was applied on the electrode to modulate the transmission. Detected output was sent to the lock-in amplifier to obtain the first- and second-harmonic signals for bias measurement.

For the APC/CLD-1 (an amorphous polycarbonate doped with a phenyitetraene-bridged chromophore) polymer modulator used in these experiments, V_π is 7.5 V at 1550 nm and 5.4 V at 1310 nm [8]. This gives the dispersion of V_π of about 8.75 V/μm. Using this value, the dispersion of ϕ_V is

$$\frac{d\phi_V}{d\lambda} = -\frac{1}{V_\pi}\frac{dV_\pi}{d\lambda}\phi_V = -1.17\phi_V \ \mu\text{m}^{-1} \tag{6}$$

at $\lambda = 1550$ nm. Combining (4)–(6) and the condition of quadrature bias, we find the equations which can be solved for ϕ_Δ and ϕ_V

$$\begin{aligned} 0.65\phi_\Delta + 1.17\phi_V &= 0 \\ \phi_\Delta + \phi_V &= \phi_0 = (2n+1)\frac{\pi}{2} \end{aligned} \tag{7}$$

where n is the integer that gives the quadrature point selected.

III. Experimental Setup

The experimental setup is shown in Fig. 2. A modified Mitutoyo FS-50 microscope is used to perform the photobleaching. The beam from a collimated 660-nm laser diode is fed though the objective lens of the microscope. The 660-nm laser was chosen to be within the absorption peak of the CLD chromophore (630–690 nm). The spot size and the position can be monitored by the charged-coupled device camera with color filters to reduce the intensity at the laser wavelength. The beam diameter can be adjusted by changing the objective lens or defocusing the laser.

The modulator is driven with a small sinusoidal signal at 1 kHz and a peak-to-peak magnitude equal to $0.1V_\pi$, corresponding to a modulation index of $\pi/20$. The sinusoidal signal also served as the reference signal of the lock-in amplifier for the bias measurement. The output signal is detected by a photodetector and delivered to the lock-in amplifiers to measure the intensities of the first- and second-harmonic signals. The measurement was made at 1550 nm.

For a small sinusoidal modulation at fixed frequency ω, the ratio of the first and second harmonics of the optical output signal is given by

$$\frac{P_{2\omega}}{P_\omega} = \frac{\pi}{8}\frac{V_m}{V_\pi}|\cot\phi_B| \tag{8}$$

where P_ω and $P_{2\omega}$ are the amplitude of the first- and second-harmonic signals, and V_m is the peak-to-peak modulation voltage.

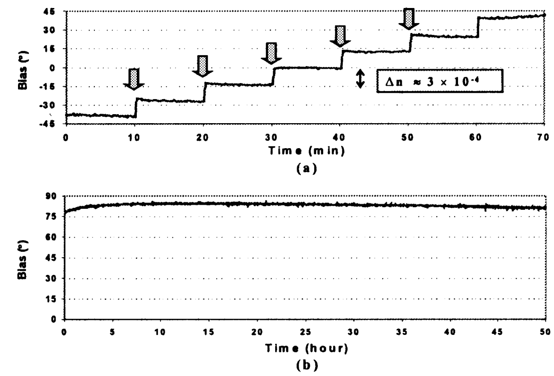

Fig. 3. (a) Index change due to photobleaching. Each arrow pointing at the rising edge indicates a single scan with the same exposure condition. (b) Stability of the induced bias shift by photobleaching. Test was performed in N_2 environment to prevent further photobleaching due to the guided light in the waveguide. Results shows no further bias change after 50 hours.

The bias ϕ_B can be obtained by measuring the ratio between $P_{2\omega}$ and P_ω. This technique has also been widely used for bias control of MZ modulators [9].

The modulator is placed on a computer-controlled motorized moving stage to control the trimming length. By varying the power of the bleaching laser and the moving speed of the stage, we can change the intensity and overall energy of the exposure.

IV. Results of Photobleaching

The bias change during the trimming is shown in Fig. 3(a). The bleaching beam scanned a length of the waveguide of 220 μm at a rate of 116 μm/s. The beam shape is elliptical with axes of 70 and 25 μm. The bleaching laser power is 1 mW. After each scan, the bias point was allowed to stabilize. There is a slight overshot after each exposure before settling to a steady-state change of bias phase of 13 $\pm$ 1° corresponding to an effective index change of (2.5 $\pm$ 0.2) $\times$ 10^{-4} per exposure. With this constant small index change and micrometer motorized stage, a phase shift of 1/100 of the wavelength can be easily achieved.

The trimming was performed in air, because oxygen is required for the photobleaching. After trimming close to the quadrature point, a bias stability test was performed at 1550 nm with the modulator inside a nitrogen-filled box to prevent photobleaching by the 15 mW of input laser power. Fig. 3(b) shows no significant drift of the bias over 50 hours.

V. Demonstration of WIB

The wavelength sensitivity of MZ modulators increases at successively higher quadrature points [$n > 0$ in (7)]. In order to get easily distinguishable results with our limited wavelength range, we demonstrated the WIB technique at the $n = 1$ (270°) bias point. After the desired quadrature bias point ϕ_0 was reached by photobleaching, a wavelength scanning from 1520 to 1580 nm was performed to measure the bias dispersion $d\phi_0/d\lambda$ without WIB, as shown in Fig. 4(a). The measured dispersion is about 10% lower than predicted by (5). The difference could be due to dispersion in the effective index of the waveguide, which is a second-order effect and not be considered in the analysis. The additional bias shift due

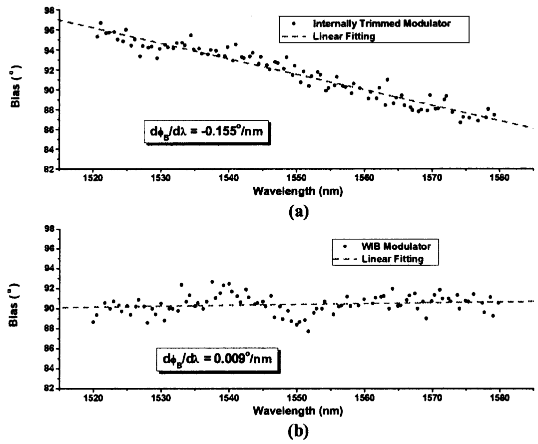

Fig. 4. Comparison of wavelength-dependent bias shift between internally trimmed modulator and WIB modulator. (a) Internally trimmed modulator. (b) WIB modulator. An improving factor of 17 on bias dispersion was achieved using WIB technique.

to path mismatch required to implement WIB was calculated from (7), and the bias was adjusted to that point by additional photobleaching. The final step was to apply the negative bias voltage to bring the bias back to ϕ_0. A wavelength scanning was again used to compare the bias dispersion with and without WIB.

The measured dispersion at ϕ_0 without any bias voltage was about $155^\circ/\mu$m. Fig. 4(b) shows that the WIB techniques reduced the dispersion to $9^\circ/\mu$m. We believe the scatter of the data is mainly due to polarization fluctuation of the laser and higher order terms in harmonic distortion. The data shows that the WIB technique reduces the wavelength sensitivity of the bias point by a factor of 17.

VI. Conclusion

We have demonstrated a WIB electrooptic polymer modulator. Using a focused laser beam with wavelength at the absorption peak of the chromophore, we can accurately control the index change of the polymer to adjust the pathlength mismatch. The photobleaching is performed after the fabrication and can be monitored during the process. This gives the advantage over the photolithography. Because of the small path difference required for WIB, $\sim\lambda$, the bias point is expected to be stable for small temperature fluctuations. The WIB technique could be demonstrated in $LiNbO_3$ modulators using a similar *in situ* trimming by excimer laser ablation [10].

The experimental result shows a reduction by a factor of 17 in bias dispersion, which can significantly increase the usable wavelength range of an MZ modulator before the second-order distortion effects start to limit the SFDR.

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