Highly Linear Electro-optic Polymer Based Traveling Wave MMI-fed Directional Coupler Modulator

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Abstract: We demonstrate an EO polymer based traveling-wave MMI-fed directional-coupler modulator. High-speed and linear operation is demonstrated with bandwidth-length product of 125GHz·cm, the 3-dB electrical bandwidth of 10GHz, and the SFDR of 110 ± 3dB/Hz$^{2/3}$.

OCIS codes: (230.4110) Modulators; (230.7020) Traveling-wave devices; (200.4650) Optical interconnects; (250.2080) Polymer active devices

A 1×2 multi-mode interference (MMI) 3-dB coupler (176.6nm×15nm) is designed to equally split the input optical power into two waveguides of a directional coupler, as shown in Fig.1 (a), and hence the device is automatically set at 3-dB operation point with zero bias. The MMI has shorter length and higher fabrication tolerance than traditionally used Y-junction [1]. Therefore, unlike the sine-squared transfer curve of the conventional Mach-Zehnder structure, a proper design of coupling length of directional coupler can provide a linear transfer function [2]. The linearity of this MMI-fed directional coupler can be further improved to suppress IMD3 by multi-domain inversion poling [3]. Considering the fabrication and poling complexity, in this paper we use a 2-domain inversion directional coupler for demonstration. The interaction length of the directional coupler is calculated using FIMMWAVE to be 3517.5um for TM mode. Push-pull poling can be done at the inverted domains, with silicon dioxide as the protection layer to prevent dielectric breakdown. Then, a single uniform traveling wave electrode designed for high speed operation can create $\Delta\beta$-reversal [4], as shown in Fig.1 (a). A refractive index taper is designed at the passive regions of the waveguides so that the optical mode profile at the input/output (I/O) sides of the waveguide can better match that of the I/O optical fiber to reduce the coupling loss.

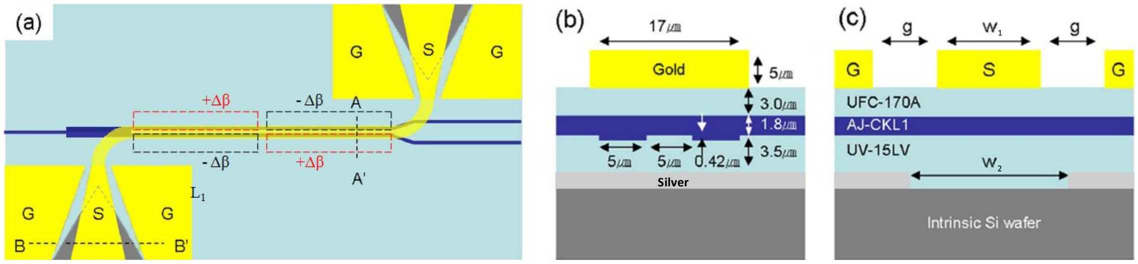

Fig. 1. (a) Schematic top view of traveling wave MMI-fed directional coupler modulator with 2-domain-inversion poling, (b) Cross section corresponding to A-A' in (a), (c) Cross section corresponding to B-B' in (a). (S: signal electrode, G: ground electrode).

As shown in Fig. 1, a velocity-matched gold traveling wave electrode is designed for high speed modulation. Frequency dependence of the characteristic impedance is calculated to match 50ohm using Ansoft HFSS. A 17μm wide, 5μm thick and 2cm long microstrip line is designed to provide uniform modulation electric field and good alignment. A 1 mm long tapered quasi-coplanar waveguide with partial ground is designed to couple the RF power from an RF microprobe into the microstrip line with minimum coupling loss. The shape of the silver ground is designed to not only match 50ohm impedance but also to match the electric field profiles between the microstrip line and quasi-coplanar waveguide.

Device is fabricated on an ultra high intrinsic silicon wafer. A 1 μm thick silver film is patterned using the lift-off process. Silver is chosen here as the bottom electrode material to reduce waveguide sidewall roughness due to scattering of UV in the photolithography process as well as to suppress the RF loss because of the low resistivity of silver. The polymer trench waveguide consists of three layers (top: UFC-170A, core: AJ-CKL1, and bottom: UV-15LV) and is fabricated by photolithography and oxygen RIE. The Electro-optic polymer here, AJ-CKL1, is formulated by doping 25 wt% of AJY chromophore into amorphous polycarbonate. A refractive index taper can be fabricated at the passive regions of the waveguides by UV photo-bleaching using a gray scale photo mask. For push-pull domain-inversion poling, 150nm thick gold electrodes [indicated by the dashed lines in Fig. 1(a)] are patterned by lift-off process. A thick silicon dioxide layer (300nm) is deposited above the electrodes and between the gap of electrodes using e-beam evaporation process, so that push-pull poling can be done with applied poling electric field as high as 150V/um at the glass transition temperature of EO polymer. After poling is done, the poling electrodes are removed and finally a 5nm thick traveling wave electrode is fabricated by gold electroplating process. The cross-sections of the device are shown in Fig. 1(b) and (c).

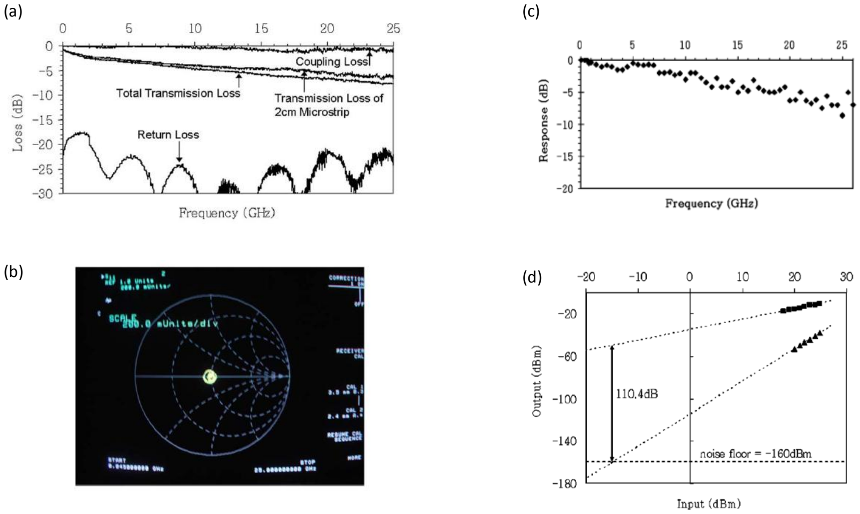

Fig. 2. (a) Measured loss of the fabricated traveling wave electrode. (b) Characteristic impedance of the fabricated traveling wave electrode on Smith chart. (c) Frequency response of the small signal modulation measured at 4%. modulation depth. (d) Plot of fundamental and third-order intermodulation distortion signals measured at 8 GHz used to calculate spurious free dynamic range.

The performance of the fabricated traveling wave electrode is characterized by a network analyzer. It can be seen from Fig. 2(a) that the return loss is well below -17dB. Square root frequency dependence of transmission loss implies that RF loss is dominated by the conductor loss, which is measured to be 0.65 ± 0.05 dB/cm/GHz$^{1/2}$. It is shown in Fig. 2(b) that the characteristic impedance is well centered at on the Smith chart. The velocity matching between RF wave and optical wave is evaluated by the time domain measurement of the reflection loss. The resulting index mismatch between the RF wave and optical wave is 0.06, resulting in the bandwidth-length product of 125GHz·cm, so the modulation frequency limit corresponding to 2cm interaction length would be 62.5GHz.

The frequency response of the device is evaluated by the small signal optical modulation measured at 4% modulation depth. The measured optical insertion loss is 25dB. The measured 3-dB electrical bandwidth of the device is 10 GHz as shown in Fig.2 (c). A two-tone test is performed to evaluate the linearity of the device. Since the IMD3 suppression of the fabricated device is out of the measurable range in our two-tone test setup, SFDR is indirectly measured by extrapolating the IMD3 plot to find an intercept point with the noise floor, which is assumed at -160 dBm considering the typical fiber-optic link parameters [5], and then measuring the difference with the extrapolated fundamental signal as illustrated in Fig. 2(d). The measured SFDR is within 110 ± 3dB/Hz$^{2/3}$ over the modulation frequency range of 2–8GHz.

[1] B. Lee, C. Lin, X. Wang, R. T. Chen, J. Luo, and A. K. Y. Jen, "Bias-free electro-optic polymer-based two-section Y-branch waveguide modulator with 22 dB linearity enhancement," *Opt. Lett.*, vol. 34, no. 21, pp. 3277–3279, 2009.
[2] S. Thaniyavarn, "Modified 1 2 directional coupler waveguide modulator," *Electron. Lett.*, vol. 22, no. 18, pp. 941–942, 1986.
[3] X. Wang, B. Lee, C. Lin, D. An, and R. T. Chen, "Electroptic polymer linear modulators based on multiple-domain Y-fed directional coupler," *J. Lightw. Technol.*, vol. 28, no. 11, pp. 1670–1675, 2010.
[4] H. Kogelnik and R. V. Schmidt, "Switched directional couplers with alternating ," *IEEE J. Quantum Electron.*, vol. QE-12, no. 7, pp. 396–401, Jul. 1976.
[5] W. B. Bridges and J. H. Schaffner, "Distortion in linearized electrooptic modulators," *IEEE Trans. Microw. Theory Tech.*, vol. 43, no. 9, pp. 2184–2197, Sep. 1995.