Bias-free Y-branch waveguide modulator based on domain-inversed modulation of electro-optic polymer

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ABSTRACT

A Y-branch directional coupler modulator based on electro-optic (EO) polymer with domain-inversion is designed, fabricated, and characterized. The functional core material is LPD-80 chromophore in amorphour-polycarbonate (APC) host polymer which is cladded between UV15-LV and UFC-170A. The switching voltage of 4.4V and the electro-optic coefficient (r_{33}) of 90pm/V are measured from 4-domain directional coupler modulator and Mach-Zehnder modulator, respectively. A two-tone test of domain-inversed directional coupler modulator demonstrates the spurious-free dynamic range (SFDR) of 119dB/Hz$^{2/3}$, which is enhanced by 11dB compared with the conventional Mach-Zehnder modulator. The SFDR of Mach-Zehnder modulator shows good agreement with simulation result but the directional coupler modulator shows approximately 10dB lower value than simulation result, which is mainly due to the high sensitivity of directional coupler structure to the fabrication error. Further improvement can be achieved with completion of fabrication precision.

Keywords: electro-optic polymer, directional coupler, domain inversion, linear modulator, spurious free dynamic range

INTRODUCTION

One of the most demanding and promising applications of electro-opticl modulator is RF photonic link. In addition to the basic requirements such as lower driving voltage and higher bandwidth, high linearity of electro-optic conversion is a performance parameter of paramount importance. In RF photonic link, RF signals need to be transmitted and processed over optical fiber link without being digitized. Linearity of electro-optic conversion becomes important because non-linear electro-optic response will create undesirable spurious signals such as harmonics and intermodulations and hence degrade the system performance. This demand provoked efforts to develope linear modulators that can provide highly efficient and linearized conversion from RF carrier-based signals into optical carrier-based signals.

The most mature and widely used broadband modulator is Mach-Zehnder modulator based on lithium niobate. Lithium niobate has made success based on its high electro-optic coefficient (r_{33}=30pm/V) compared with III-V comopunds or silicon and the mature material process technology.[1] However, lithium niobate is facing barrier to further improvement of driving voltage and bandwidth that requires higher electro-optic efficiency. For this reason, electro-optic polymer has attracted significant interest as an alternative due to its ability to tailor electro-optic coefficient ten times that of lithium niobate or even higher.[2, 3] Unlike driving voltage or bandwidth that can be enhanced by improving the material properies, linearity is a purely structure-dependent parameter. Transfer curve that plots optical signal intensity versus input electrical signal is used to characterize the linearity of electro-optic response in a modulator. The transfer curve of Mach-Zehnder modulator is intrinsically sine-squared, which limits its application to highly linear modulator. Various linearization techniques have been proposed to overcome the limit.[4-7] Most of the techniques involve multiple number of Mach-Zehnder modulators in parallel and/or serial configuration. These schemes require strict balance of RF and bias control, i.e. complicated expensive circuitry needs to be implemented along with optical components.

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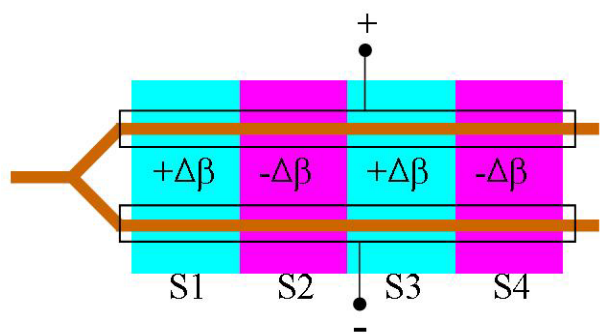
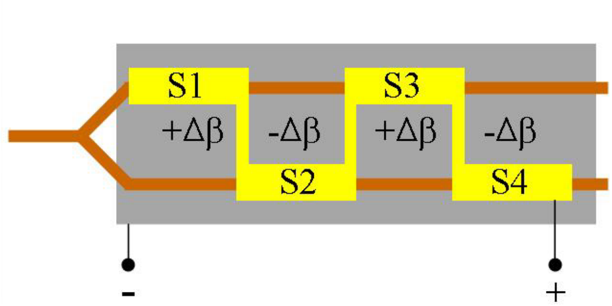
Directional coupler modulator is a purely optical linerization technique on the contratry to the electrical linearization of Mach-Zehnder modulator. Linear modulator based on directional coupler structure was first proposed by Kogelnik et al. [8] and was elaborated by Tavlykaev et al. [9]. Hung et al.[10] recently demonstrated two-domain directional coupler modulator based on photo-bleaching of electro-optic polymer. They achieved spurious free dynamic range (SFDR) of 115.5dB/Hz$^{2/3}$ which is 7.5dB higher than that of conventional Mach-Zehnder modulator. Theoretically, the linearity of transfer curve in a directional coupler modulator can reach 99% by employing domain-inversion technique.[9] Ease of employing domain-inversion technique is an additional advantage of electro-optic polymer over Lithium Niobate. Two- and four-domain Y-branch directional coupler modulators based on electro-optic polymer (LPD-80/amorphous polycarbonate) are designed and fabricated. Testing results of directional coupler modulators are compared with the conventional Mach-Zehnder modulator.

DESIGN

Figure 1 is a schematic layout of a Y-branch directional coupler structure. The advantage of directional coupler structure is its highly linear transfer curve unlike the sine-squared transfer curve of the conventional Mach-Zehnder structure. The linearity of directional coupler can be improved by designing a multi-section directional coupler with inverted domains, i.e. by poling neighboring sections along the waveguide in opposite direction as noted in different colors in Figure 1(a). As the light propagating along the waveguide is modulated by applied electric field, the propagation constant mismatch ($\Delta\beta$) between two arms of directinal coupler grows and degrades the linearity of modulator. One can compensate for this mismatch by poling EO polymer of the neighboring section in opposite direction. Instead of inversion-poling which takes complicated fabrication processes, an alternating electrode design is empolyed as shown in Figure 1(b). This electrode design can achieve the equivalent domain-inversion effect as inversion-poling while making the process simpler.



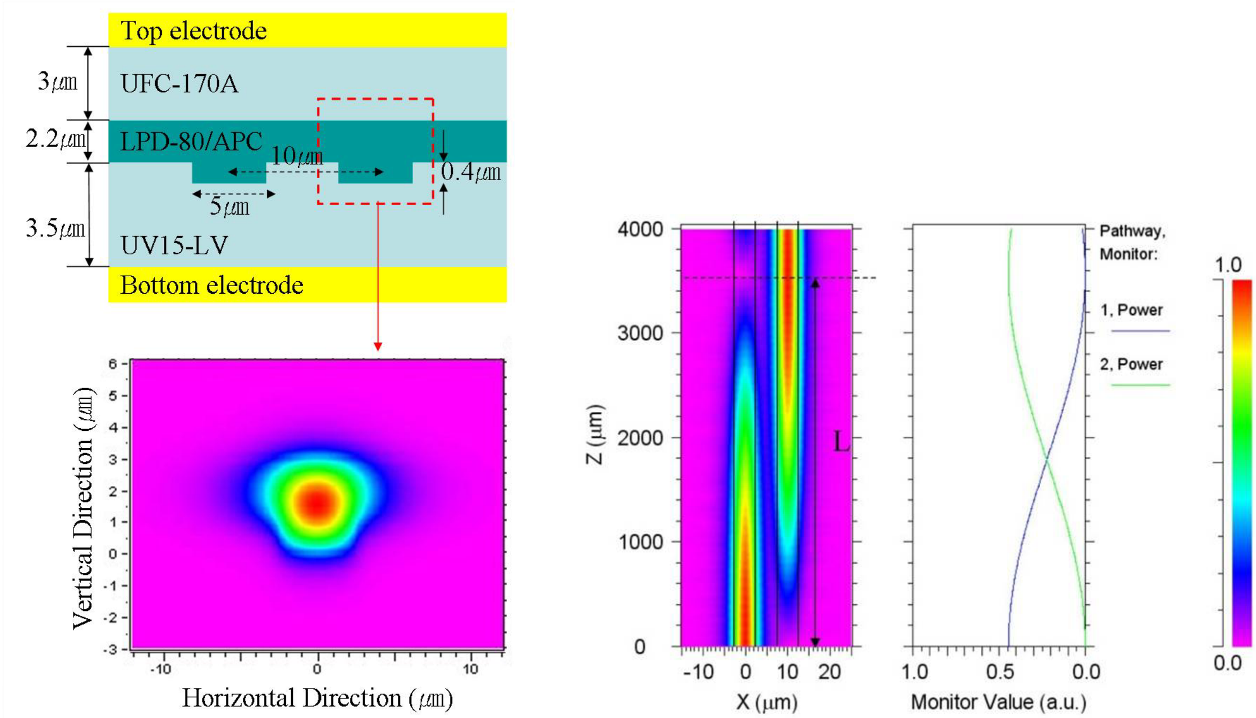
(a)



(b)

Figure 1. (a) Schematic layout of a Y-branch directional coupler with inverted-domains (b) Schematic electrode design

The design of directional coupler waveguide is illustrated in Figure 2. Waveguide parameters and the single-mode profile of one waveguide are depicted in Figure 2(a). Thicknesses of bottom cladding, core, and top cladding layer are 3.5 μm, 2.2 μm, and 3.0 μm respectively. Refractive index of bottom and top cladding layer is 1.50 and that of the core layer is 1.70. The width of waveguide is 5 μm and the center-to-center seperation between two waveguides is 10 μm. Inverted rib waveguide is defined by etching 0.4 μm of bottom cladding. Based on these waveguide parameters, the coupling length of directional coupler is calculated to be 3.55mm as illustrated in Figure 2(b).



(a) (b)

Figure 2. (a) Schematic cross-section of directional coupler waveguide and its single-mode profile (b) Calculated coupling length of directional coupler based on parameters in Figure 2(a).

Based on the design of directional coupler, the linearity of device can be tailored by adjusting the length of each section in Figure 1(b). The linearity of device can be characterized by measuring the suppression of the third order intermodulation distortion (IMD3) at certain modulation depth. We have previously reported 64dB distortion suppression at 25% modulation depth in a two-domain Y-branch directional coupler modulator, which is 22dB higher than the conventional Mach-Zehnder modulator.[11] Another parameter to characterize linearity is spurioud free dynamic range (SFDR) which is defined as the range between the smallest signal that can be detected in a system (i.e. a signal just above the noise floor of the system) and the largest signal that can be introduced in a system without creating detectable distortions. SFDR can be graphically determined by plotting the output power of fundamental signals and IMD3's as a function of modulation depth (or the input power). Figure 3 is calculation results of fundamental signals and IMD3's with various designs of two-domain directional coupler and Mach-Zehnder structure. One can estimate SFDR by comparing fundamental signal and IMD3 at the modulation depth where the noise floor of the system intersects IMD3 curve. S_1=S_2=2.86 is chosen for test in this paper. SFDR of this design is 130dB/Hz$^{2/3}$ assuming the system noise floor at -160dBm, which is 20dB higher than that of Mach-Zehnder structure. In case of four-domain directional coupler, the largest SFDR of 131dB/hz$^{2/3}$ can be achieved by designing S_1=2.188, S_2=2.206, S_3=1.538, and S_4=2.665.

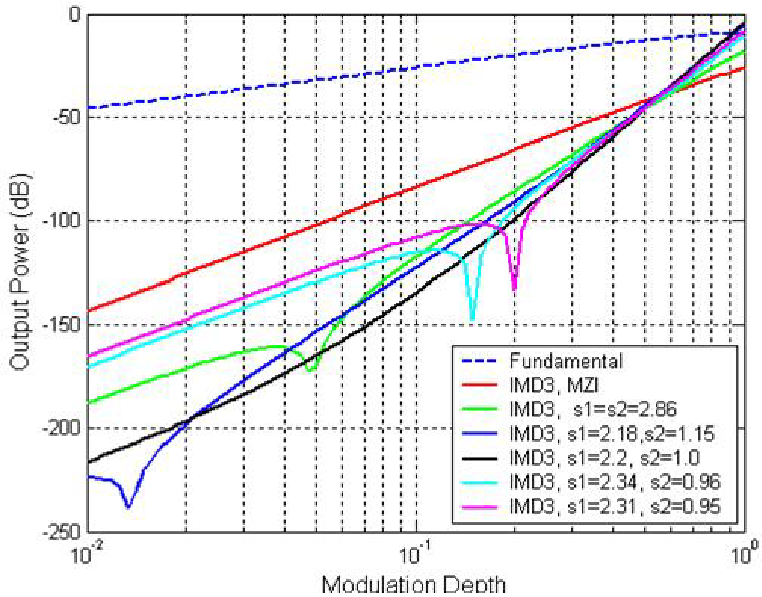


Figure 3. Calculated fundmental signals and IMD3's as a function of modulation depth. S: normalized section length=(interaction length of a section)/(normaliized coupling length).

FABRICATION

Device is fabricated using standard semiconductor processes in the following stpes.

(1) Bottom ground electrode (Aluminum, 2000Å) is deposited on a silicon substrate by sputtering deposition.

(2) Bottom cladding (UV15-LV, 3.5 ㎛) is spin-coated and cured by UV-exposure in nitrogen chamber.

(3) Inverted rib waveguides are patterned on bottom cladding layer by photolithography and Oxygen reactive ion etching (RIE).

(4) EO polymer (LPD-80, 50wt% in amorphous polycarbonate, 2.2 ㎛) is spin-coated and cured on hot-plate with nitrogen purging.

(5) Top cladding (UFC-170A, 3 ㎛) is spin-coated and cured by UV-exposure in nitrogen chamber.

(6) Top poling electrode (Chrome/Gold, 50Å/2000Å) is deposited by e-beam evaporation using shodow-mask.

(7) EO polymer is poled by contact poling technique.

(8) Top driving electrode is patterned by photolithography and wet-etching of the existing poling electrode.

(9) Device is cleaved and polished for testing.

Figure 4 is a cross-sectional scanning electron micrograph of a directional coupler modulator after polishing process. Top driving electrode is well aligned with one waveguide of the directional coupler. Epoxy layer is added on top to prevent polymer layers from peeling off during polishing process.

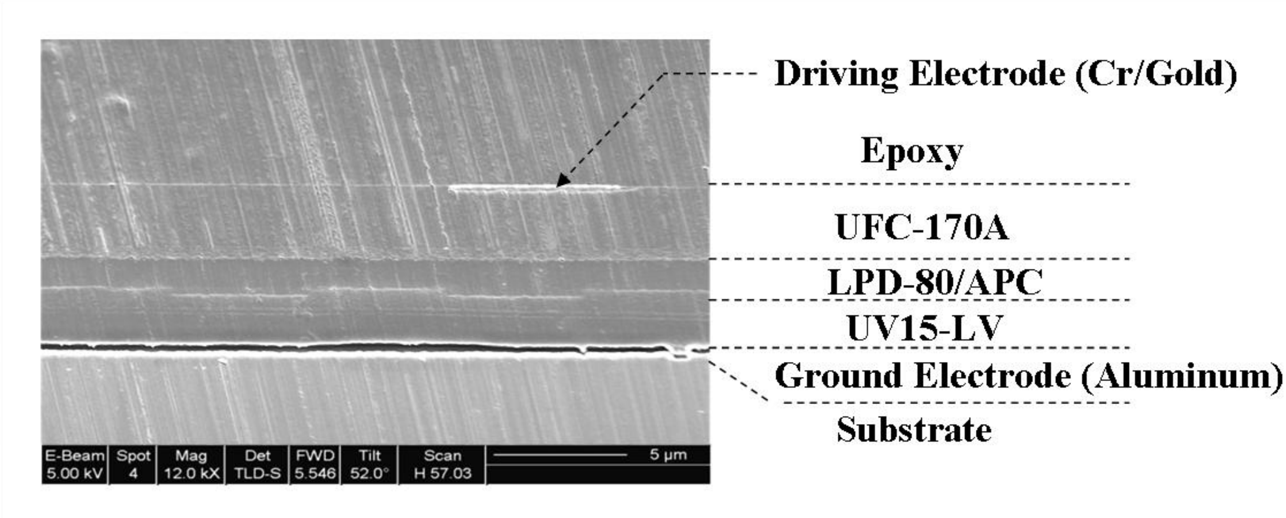


Figure 4. Cross-sectional scanning electron micrograph of Y-branch directional coupler modulator.

The most important step throughout the entire process is poling of EO polymer. The switching voltage and the electro-optic coefficient of device are determined by poling efficiency. Poling process begins by applying electric field of 100V/㎛ between top poling electrode and bottom ground electrode. Device is heated by computer-controlled hot-plate up to the glass transition temperature of EO polymer at the ramping speed of 10℃/min. Poling leakage current is monitored by pico-ammeter throughout poling process. Poling leakage current reaches its peak at the glass transition temperature. Upon reaching the glass transition temperature, hot-plate is turned off and cooled down to room temperature while maintaining electric field. Electric field is turned off at room temperature leaving the electro-optic chromophores frozen as aligned along the applied electric field. Figure 5 is a typical profile of the poling leakage current. Typical range of peak leakage current is 3~11$\mu A/cm^2$. Entire poling process is conducted in a nitrogen chamber to protect device from oxygen at elevated temperature.

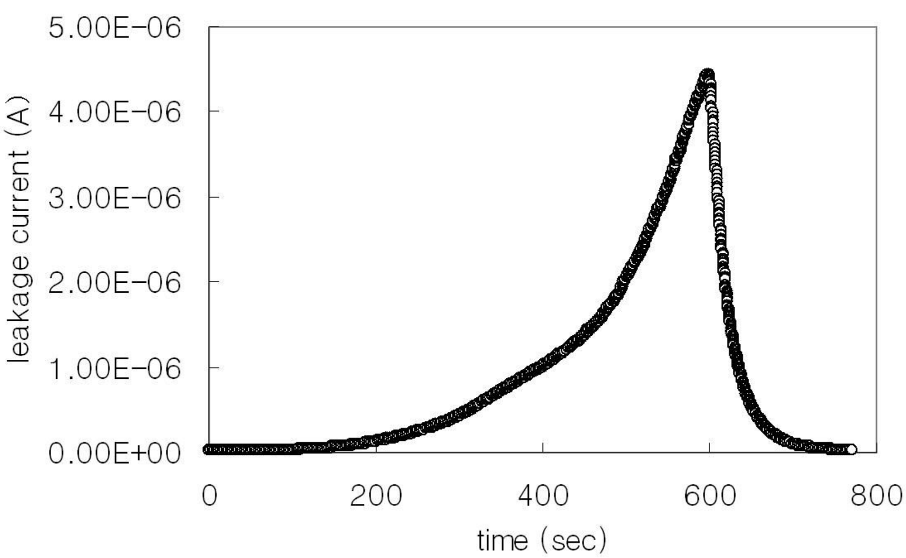


Figure 5. Leakage current profile during poling process.

CHARACTERIZATION

Fabricated devices are tested on a Newport six-axis autoaligner system. TM-polarized light from a tunable laser (MLS-2000, SANTEC) is coupled into the input waveguide through a polarization-maintaining (PM) fiber. Modulated optical signals are coupled into a single-mode butt fiber and delivered to a photodetector (PDA400, Thorlabs). Detected signals are characterized by an osciloscope (Agilent 86100A) and a spectrum analyzer (HP 8560E). Figure 6 is an over-modulated transfer curve of a four-domain directional coupler modulator. Input electrical signal is 10kHz triangular signal with peak-to-peak voltage of 10V generated by a function generator (Agilent 33120A). The switching voltage measured in this curve is 4.4V. In case of Mach-Zehnder modulator and two-domain directional coupler modulator, the switching voltage is measured to be 6.6V and 6.1V respectively. Based on the measured switching voltage, EO coefficient (r_{33}) can be calculated in the following equation. EO coefficient of Mach-Zehnder modulator is calculated to be 90pm/V using the device parameters shown in equation (1).

$$r_{33} = \frac{\lambda d}{n^3 V_\pi \Gamma L} = \frac{1.55\mu m \cdot 8.7\mu m}{1.7^3 \cdot 6.6V \cdot 0.65 \cdot 7.1mm} = 90\, pm/V \qquad (1)$$

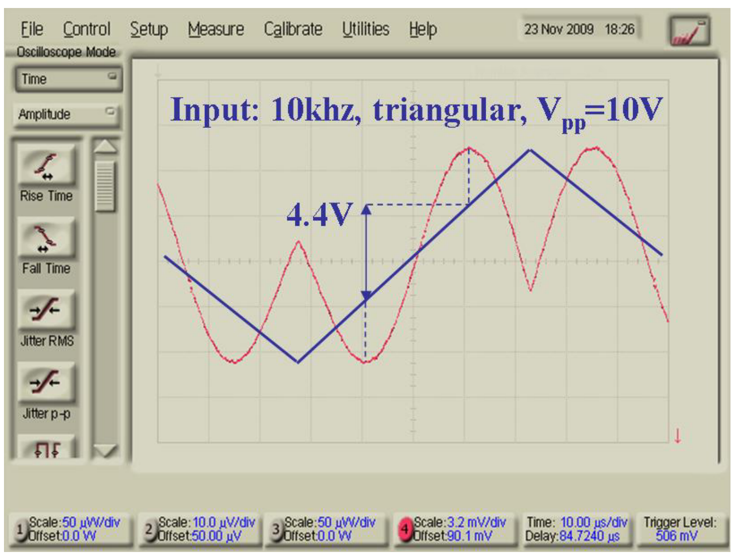
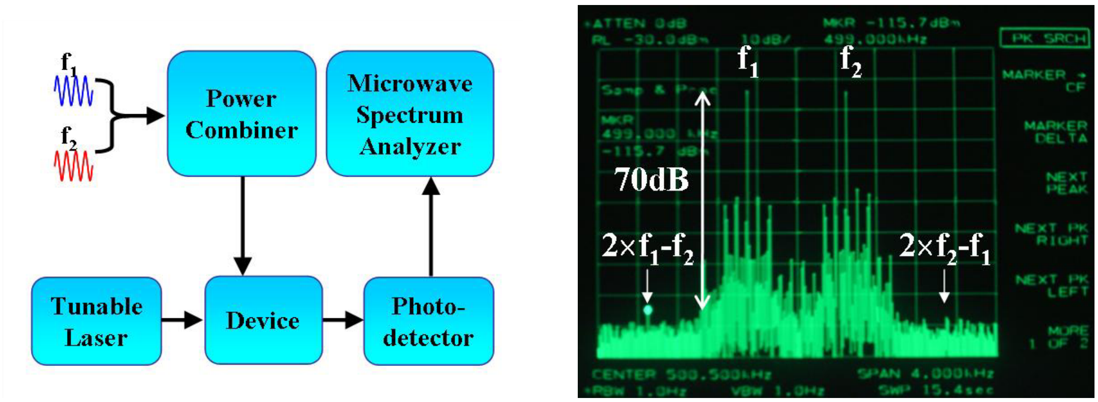


Figure 6. Over-modulated transfer curve of a 4-domain directional coupler modulator.

A two-tone test is performed to characterize the linearity of fabricated modulators. Figure 7(a) is a block-diagram of the two-tone test setup. Two input electrical signals with closely spaced frequencies (f1 and f2) are generated by a multifunction synthesizer (HP 8904A). Modulated optical signals are characterized by a microwave spectrum analyzer (HP 8560E). The purpose of a two-tone test is to evaluate the intermodulation signals originating from the non-linear electro-optic response of modulators. The third order intermodulation distortion (IMD3) signals are the most important among all distortion signals because they are positioned close to the fundamental signals and can be falsely detected as fundamental signals. Figure 7(b) is a screen capture of the spectrum analyzer. Input electrical signals (f1 and f2) are 500kHz and 501kHz and the resulting IMD3 signals (2·f1-f2 and 2·f2-f1) are 499kHz and 502kHz. IMD3 suppression of 70dB is achieved in this measurement. This achievement is limited by the intermodulation signal generated by the multifunction generator which is noted 70dB in the specification sheet.



(a) (b)

Figure 7. (a) Block-diagram of a two-tone test setup (b) Screen capture of spectrum analyzer.

IMD3 suppression in Figure 7(b) is measured at certain modulation depth (i.e. at a specific input power). One can measure IMD3 suppression as a function of input power and plot fundamental signals and IMD3 signals to eveluate spurious free dynamic range (SFDR) of modulator. Figure 8 is showing fundamental and IMD3 signals of Mach-Zehnder modulator and two-domain directional coupler modulator. Assuming the system noise floor at -160dBm, one can extrapolate IMD3 curve and find an intersecting point with the noise floor. SFDR is measured by comparing the output power of fundamental signal and IMD3 signal at the intersecting point. SFDR of Mach-Zehnder, two-domain directional coupler, and 4-domain directional coupler is measured to be 108, 119, and 118dB/Hz$^{2/3}$ respectively. Measred SFDR of Mach-Zehnder modulator is in good agreement with the calculated SFDR (110dB/Hz$^{2/3}$) from Figure 3. Directional coupler modulators, on the other hand, show approximately 10dB deviation between measurement and calculation. This may be due to the intrinsic nature of device structure. Mach-Zehnder modulator is not so sensitive to fabrication errors because it only relied on the phase difference between two arms. However, directional coupler is highly sensitive to fabrication errors because all design parameters are based on the coupling length of directional coupler. The coupling length of directional coupler is directly affected by small change in waveguide parameters that are caused by fabrication error, which in turn makes the optimum design of device deviate from its original one.

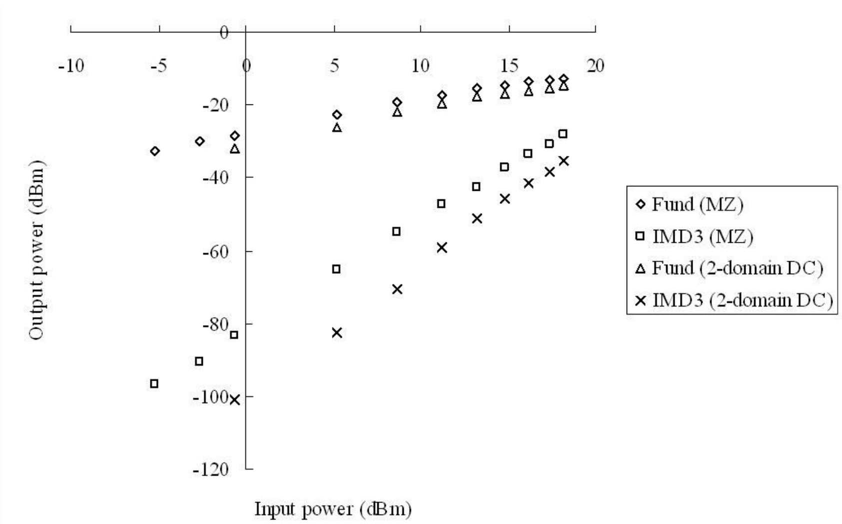


Figure 8. Plot of fundamental and IMD3 signals from Mach-Zehnder and two-domain directional coupler modulator.

CONCLUSION

In summary, we experimentally demonstrated two- and four-domain Y-branch directional coupler modulators and compared their performances with conventional Mach-Zehnder modulator. Switching voltage of 4.4V and electro-optic coefficient (r_{33}) of 90pm/V are measured from the transfer curve of devices. Spurious free dynamic range (SFDR) of device was evaluated by two-tone test. Measured SFDR of Mach-Zehnder modulator is 108dB/Hz$^{2/3}$, which is in good agreement with simulation result. Directional coupler modulators showed approximately 10dB enhanced SFDR compared with Mach-Zehnder modulator although the measured value is about 10dB lower than the simulation result due to fabrication errors. Further improvement in SFDR can be achieved by perfection of fabrication process.

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