Electroptic Polymer Linear Modulators Based on Multiple-Domain Y-Fed Directional Coupler

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***Abstract*—We developed an analytical method to optimize the design of Y-fed direction couplers at large modulation depth from 10% to 50%. Simulation results indicate that three- and four-domain devices can obtain 45 dB higher distortion suppression than two-domain devices, which can potentially achieve 120 dB spurious free dynamic range. We also experimentally demonstrated that the two-domain electrooptic modulator obtained 94 dB distortion suppression at 20% modulation depth, which is 47 dB higher than a conventional Mach–Zehnder modulator.**

***Index Terms*—Integrated optics devices, modulators, optoelectronics, RF photonics.**

I. Introduction

The development of low loss, highly linear, and low-dispersion optical links coupled with the linear response of optical detectors to the intensity of incident light stream would make optical links an attractive alternative to microwave/millimeter links. Important applications include: 1) satellite receiver systems for distributed RF signals over long distances with high signal quality; 2) remote antenna and active phased array by means of high-quality, low-loss RF photonics without complicated digital processing equipment; and 3) CATV networks and local area networks (LANs) for low distortion distribution of RF signals in large building complexes, aircrafts, and television network systems [1], [2]. In these fields, highly efficient and linearized conversion from RF carrier-based signals to optical carrier-based signals is of paramount importance.

A substantial research work performed over the past years has resulted in a number of linearization techniques, which can be subdivided into two categories, namely, electronic compensation and optical techniques of linearization. Electronic compensation includes pre-distortion compensation [3] and feed-forward compensation [4]. Yet these techniques require expensive high-speed optoelectronic components, and have maximum bandwidth of only a few gigahertz. Optical techniques based on cascaded Mach–Zehnder (MZ) modulator [5], dual wavelength MZ modulation [6], or ring resonator assisted MZ modulator [7] can achieve high bandwidth linearization, however, with a common shortcoming of complex device structure. In addition, these complex devices require high thermal stability and precise bias voltage, which substantially limit its use in practical applications.

Y-fed direction couplers (YFDC) have been systematically studied by Tavlykaev [8], and are proven to possess intrinsic advantages over other integrated optical modulators in terms of large spurious free dynamic range (SFDR), thermally stable performance, bias free operation, and large fabrication tolerance. Some experimental results of YFDC with two domains have been demonstrated [9], [10] using electrooptic polymer materials, and achieved 22 dB higher distortion suppression than conventional MZ modulator. However, the potential of Y-fed directional couplers are far from being fully utilized. Optimized design through careful selection of device parameters will lead to much higher distortion suppression, and hence obtains over 120 dB SFDR for the RF photonic system.

In this paper, we will first optimize the design of YFDC with two domains in Section II based on an analytical method by Taylor series expansion. Three working areas of the device parameters were chosen for better distortion suppression across modulation range from 10% to 50%. In Section III, we investigate the design of YFDCs with three- and four- inverted domains through NELDER-MEAD simplex algorithm [11] to find the minimum value of the multi-variable function, which can significantly reduce the enormous computation work required for multiple dimensions scanning by orders of magnitude. The calculation results suggest that 80 dB higher distortion suppression can be obtained than conventional MZ modulator, and the system SFDR can potentially exceed 120 dB/Hz. In Section IV, an electrooptic (E-O) polymer (FTC/PU) YFDC modulator with two inverted domains are fabricated and characterized. Excellent fabrication uniformity enables the device to achieve 94 dB distortion suppression at 20% modulation depth, which is 47 dB higher than conventional MZ modulator. In the last section, a short conclusion and prospect are given.

II. Design of two-Domain YFDC

The YFDC consists of a single-mode Y-junction providing 3-dB power splitting for the two parallel and symmetric waveguide channels, which form the directional coupler, resulting in light beams oscillating between the two channels. The domain-inverted pair has two sections with opposite dipole orientation. In the domain-inverted sections, the electrooptic coefficients are

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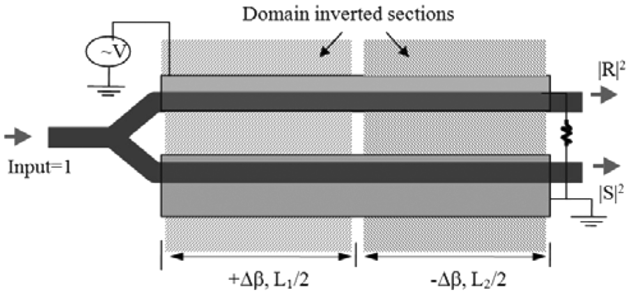

Fig. 1. Schematic of a domain-inverted Y-fed directional coupler.

inverted with respect to each other. The device schematic is depicted in Fig. 1.

We describe the light in the two guides by complex amplitudes $R(z)$ and $S(z)$, which vary slowly along the z-axis, i.e., the propagation direction. We assume that the energy exchanged between the two guides is governed by the coupled-wave equations, which is detailed in [12]

$$\frac{\partial R}{\partial z} - j\Delta\beta/2R = -j\pi S/2l_c \tag{1}$$

$$\frac{\partial S}{\partial z} + j\Delta\beta/2S = -j\pi R/2l_c \tag{2}$$

where $\Delta\beta = 2\pi/\lambda n_e^3 r_{33}\alpha V/d$, r_{33} is electrooptic coefficients, V is the applied voltage, λ is the optical wavelength, n_e is the extraordinary index of EO film, d is the electrode spacing, α is the overlap integral between the applied electrical field and the optical field $(0 < \alpha < 1)$, and l_c is the coupling conversion length, which is the minimum length required to obtain complete crossover in a directional coupler. For a normalized input, the amplitudes of the lossless input electric field of the guided wave $|R_i| = |S_i| = 1/\sqrt{2}$ in a Y-branch structure, the solution of the coupled-wave equations can be written in the matrix form [13]

$$\begin{aligned}\begin{bmatrix} R_o \\ S_o \end{bmatrix} &= M_2 M_1 \begin{bmatrix} R_i \\ S_i \end{bmatrix} \\ &= \begin{bmatrix} A_2 & -jB_2 \\ -jB_2^* & A_2^* \end{bmatrix} \begin{bmatrix} A_1 & -jB_1 \\ -jB_1^* & A_1^* \end{bmatrix} \begin{bmatrix} R_i \\ S_i \end{bmatrix}\end{aligned} \tag{3}$$

where matrix M_1 corresponds to the first domain, and M_1's coefficients are given by A_1 and B_1 shown at the bottom of the page,and matrix M_2 corresponds to the second domain with inverted polarity, and M_2's coefficients are given by A_2 and B_2, shown at the bottom of the page.

In (3), $s_1 = L_1/l_c, s_2 = L_2/l_c$, is the normalized length of the domain-inverted sections, where L_1 and L_2 is the electrode length. $x = \Delta\beta(L_1 + L_2)/\pi$ is the normalized driving voltage. With the guidance of these equations, the design of the linear modulator now becomes a problem of how to choose a good combination of (s1, s2), so that the transfer curve will obtain the best linearity.

It is quite difficult to precisely analyze the linearity of the modulator through (3), which describes the response of the modulator in time domain. Instead of widely used numerical method by fast Fourier transform (FFT) algorithms adopted in [8] to compute the frequency domain response, which usually requires longer computation, we developed an analytical method in this paper, which can clearly express the fundamental signals and all of the sprious signals. We expand (3) through Taylor series expansion

$$|R|^2 = f(V) = \frac{1}{2} + \sum_{n=1}^{\infty} h_n V^n \tag{4}$$

where $h_n = 1/n! d^n f(V)/dV^n$ are the coefficients of the Taylor series. At small modulation depth $(<5\%)$, expanding (4) into the third order can provide sufficient accuracy, but not for large modulation depth from 10% to 50%. For better accuracy, we expand (4) to the seventh-order polynomial. When a two-tone driving signal $V = a[\sin(2\pi f_1 t) + \sin(2\pi f_2 t)]$ is applied (a is the magnitude of the driving signal) to the YFDC, (4) generates various orders of harmonic and intermodulation distortion signals due to its nonlinearity. The coefficients of the triangular function will determine the magnitude of the fundamental signals as well as the nonlinear signals coming from the modulator. Table I gives the expression of the dc, fundamental, and several nonlinear signals based on the calculation delineated above. Note: (4) is an odd function when (0, 1/2) is set as the original point. All of the even-order polynomials of (4) have a coefficient of zero.

$$\begin{cases} A_1 = \cos\frac{\pi}{2}\sqrt{s_1^2 + \left(\frac{s_1 x}{s_1+s_2}\right)^2} + j\frac{x}{\sqrt{(s_1+s_2)^2+x^2}}\sin\frac{\pi}{2}\sqrt{s_1^2 + \left(\frac{s_1 x}{s_1+s_2}\right)^2} \\ B_1 = \frac{(s_1+s_2)}{\sqrt{(s_1+s_2)^2+x^2}}\sin\sqrt{s_1^2 + \left(\frac{s_1 x}{s_1+s_2}\right)^2} \end{cases}$$

$$\begin{cases} A_2 = \cos\frac{\pi}{2}\sqrt{s_2^2 + \left(\frac{s_2 x}{s_1+s_2}\right)^2} - j\frac{x}{\sqrt{(s_1+s_2)^2+x^2}}\sin\frac{\pi}{2}\sqrt{s_2^2 + \left(\frac{s_2 x}{s_1+s_2}\right)^2} \\ B_1 = \frac{(s_1+s_2)}{\sqrt{(s_1+s_2)^2+x^2}}\sin\sqrt{s_2^2 + \left(\frac{s_2 x}{s_1+s_2}\right)^2} \end{cases}$$

TABLE I
EXPRESSION AND AMPLITUDE OF THE SIGNALS FROM THE Y-FED DIRECTIONAL COUPLER

Signal	Frequency	Amplitude (up to the 7th order expansion)
DC	0	1/2
Fundamental	f_1, f_2	$\frac{1225}{64}h_7a^7+\frac{25}{4}h_5a^5+\frac{9}{4}h_3a^3+h_1a$
2nd Harmonic	$2f_1$, $2f_2$	0
IMD2	f_1-f_2, f_1+f_2	0
3rd Harmonic	$3f_1$, $3f_2$	$\frac{441}{64}h_7a^7+\frac{25}{16}h_5a^5+\frac{1}{4}h_3a^3$
IMD3	$2f_1$-f_2, $2f_2$-f_1	$\frac{735}{64}h_7a^7+\frac{25}{8}h_5a^5+\frac{3}{4}h_3a^3$
....		

To define the linearity of the optical modulator, most papers calculated the fundamental and IMD3 signal as a function of the input voltage or input RF power [5], [6], [8]. However, the input voltage or RF power strongly depends on the E-O coefficient, electrode lengths and other device configurations. Different devices may vary significantly from each other. In this paper, we will investigate the performance of the YFDC relating to the modulation depth, which is independent of individual device parameters. Of course, using input voltage or input RF power as the horizontal axis has the advantage of comparing the modulation efficiency of different modulators. However, as advanced E-O polymer materials with over 300 pm/V E-O efficiency [14], and E-O modulator with subvolt driving voltage [15] are reported, the concern of driving voltage and RF efficiency becomes less dominant. How to obtain a large SFDR for the RF photonic system is the most important consideration for the design of optical modulator, even it may require higher driving voltage. As a well known fact, MZ modulator can obtain higher distortion suppression at smaller modulation depth. The drawbacks associated with small modulation depth are extremely low efficiency and bad noise figure. For example, a MZ modulator with 1% modulation depth represents a 1:2500 RF to dc signal ratio. The noise figure may be improved through biasing the modulator near quadratic point [16], but it requires 500 mW optical input power to compensate the extremely high loss. To improve the optical efficiency and the noise figure at the receiver end, we target at a simple design philosophy in this paper: obtaining a high distortion suppression ratio at large modulation depth $(>10\%)$ to increase the power efficiency and noise figure.

Tavlykaev [8] calculated the relative level IMD3 of the two-domain YFDC at 4% modulation depth. He also pointed out that the YFDCs will demonstrate suppression dips at different modulation depth. This phenomenon is also observed in other optical linearization techniques. So there is a possibility that the YFDC with a particular (s1, s2) combination happens to have a suppression dip at 4% modulation depth, while performs not so well in other modulation depth. Here we simply do an arithmetic average of the distortion suppression ratio of the YFDC across a certain modulation depth range. Fig. 2(a) shows the average IMD3 suppression of YFDCs at modulation depth from 10% to 50%, as a function of the normalized section length (s1, s2). In Fig. 2(a), three optimized regions centered at P1(2.19, 1.03), P2(2.85, 2.85) and P3(4.55, 1.04) are selected because of their average performance. Fig. 2(b) shows the normalized output of the three YFDC modulators as a function of the modulation depth. It is seen that device P1 (2.19, 1.03 has the best average IMD3 suppression, especially a dip occurs at around 12% modulation depth. Device P2 (2.85, 2.85) also provides good IMD3 suppression with a dip at 20% modulation depth.

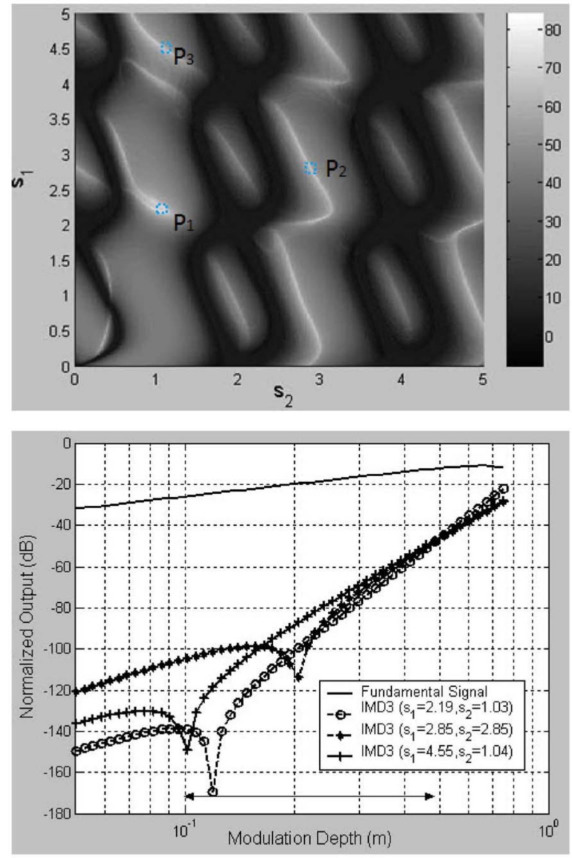

Fig. 2. (a) Average IMD3 distortion suppression of two-domain YFDCs. (b) Normalized output of selected YFDCs as a function of the modulation depth.

III. THREE- AND FOUR- DOMAIN YFDC

No research has been done with three- and four- domain YFDCs because of the following reasons. First, the design of three- and more domain YFDCs is much more difficult since adding variables into (4) will lead to exponential increase in the load of computation. Second, YFDCs with three- and more domains become more sensitive to geometry variation, which requires very high fabrication precision. Third, the device length is longer and the optical loss can be a concern to the device performance. In this Section, we will prove that YFDCs with three- and more domains can achieve much higher distortion suppression than two-domain devices through optimized numerical calculation. The tolerance to fabrication errors will also be investigated.

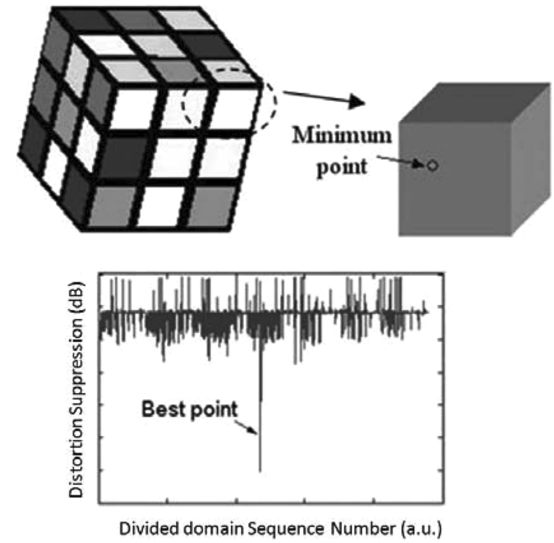

Fig. 3. Optimized algorithm to simulate a directional coupler with three- and more inverted domains.

TABLE II
PERFORMANCES OF YFDCS WITH DIFFERENT NUMBER OF DOMAINS

Name	Device 0	Device 1	Device 2	Device 3	Device 4
Type	1-domain	1-domain	2-domain	3-domain	4-domain
Normalized Section Length	s_1=0.7071	s_1=2.8595	s_1=2.85 s_2=2.85	s_1=1.8859 s_2=1.5131 s_3=2.5464	s_1=2.1884 s_2=2.2058 s_3=1.5383 s_4=2.6648
Average IMD3 Suppression at 10%~50% modulation depth (dB)	43.6	51.2	65.2	97.5	110.3
Normalized Driving Voltage	1.0	2.0	2.96	4.19	5.12
Maximum Modulation Depth	1.0	0.726	0.98	0.96	0.997
SFDR @-100dB/Hz noise level (dB/Hz)	68	75	81	87	88
SFDR @-120dB/Hz noise level(dB/Hz)	81	91	100	100	107
SFDR @ -145dB/Hz noise level(dB/Hz)	98	110	103	116	120

To find a feasible simulation method, we developed an algorithm as indicated by Fig. 3. First, we divide the 3-D space into N3 subspaces like a Rubik's cube, where N is the number of divisions along each dimension. In the next stage, we use a NELDER-MEAD simplex algorithm [11] to find the minimum (or maximum) value of the multi-variable function of (4) in each subspace, which takes much less time than conventional three-dimensional scanning method. At last, we compare all the minimum values we found and choose the best result.

The calculation results indicate that $(\mathrm{s1} = 1.8859, \mathrm{s2} = 1.5131, \mathrm{s3} = 2.5464)$ is the best combination for three-domain device, and $(\mathrm{s1} = 2.1958, \mathrm{s2} = 2.3372, \mathrm{s3} = 1.2255, \mathrm{s4} = 1.9732)$ is the best combination for four-domain device. To fully compare the performance of YFDCs with different number of domains, we listed the devices in Table II. The performances of those devices obtained through the following simulation works are also included in Table II.

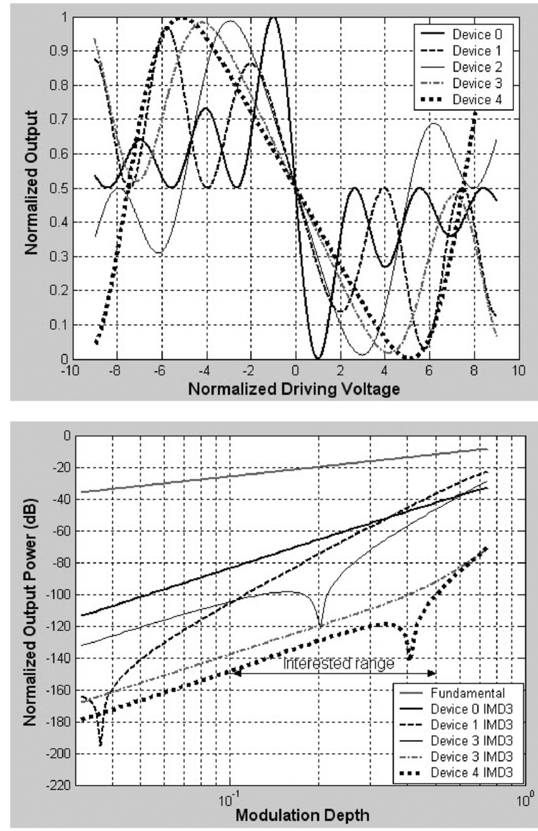

Fig. 4. (a) Transfer curve and (b) output powers of the fundamental and IMD3 signal of YFDCs with different number of inverted domains.

Device 0 is chosen because it has a sinusoidal transfer curve, which is identical to a MZ modulator. Device 1 has the best linearity as one-domain YFDC [8]. Device 2 has excellent linearity as two-domain YFDC, and also very large modulation depth. This device is fabricated and characterized in Section IV. Device 3 and Device 4 is the optimized design for three- and four- domain YFDC respectively. The driving voltages are normalized to the value of Deice 0, by assuming they have the same electrooptic efficiency and the same electrode length. Fig. 4(a) shows the transfer curve of the five devices, and Fig. 4(b) shows the normalized output power of the fundamental signals and IMD3 signals of the aforementioned devices. From Fig. 4(a), it is seen that as more domains are added to the YFDCs, higher driving voltage is needed; but in the mean while, better linearity is achieved as well. Fig. 4(b) indicates the improvement of linearity in a clearer manner. At large modulation depth (10%–50%), the IMD3 signal of Device 3 is more than 30 dB lower than that of Device 2. Device 4 can achieve even better distortion suppression than Device 3.

Table II also lists the SFDR of the YFDC at different noise level. Considering -150 dB/Hz relative intensity noise (RIN) of a typical distributed feedback (DFB) laser and shot noise from the photodiode, we find it very difficult to achieve a noise floor below -145 dB/Hz in real RF photonic system. If optical fiber amplifiers or trans-impedance amplifiers are used to compensate system loss, which is true in most RF photonic systems, the

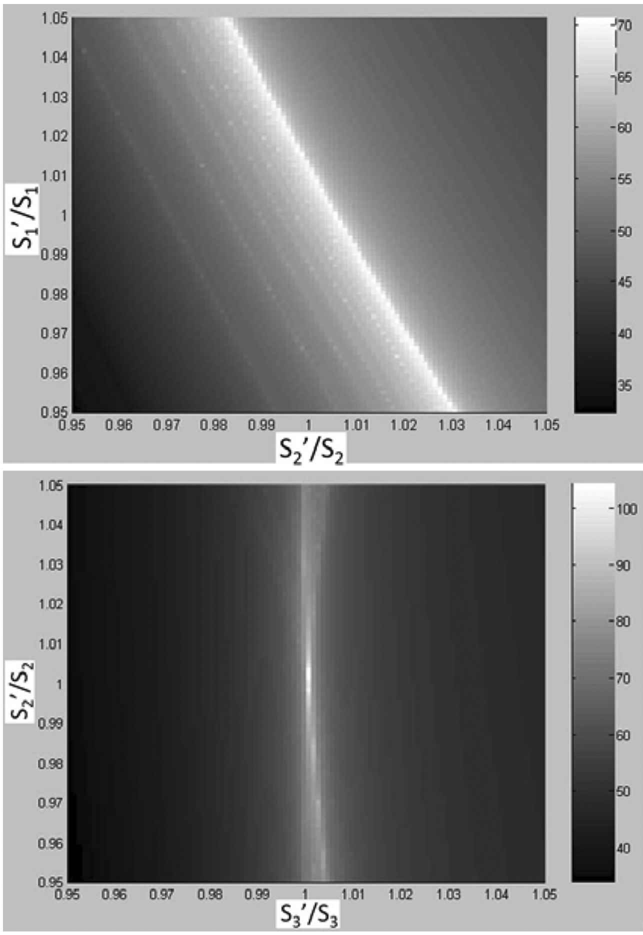

Fig. 5. Fabrication tolerance of YFDCs with (a) two inverted domains (Device 2) and (b) three inverted domains (Device 3).

noise floor can sometimes be as high as -100 dB/Hz. In these scenarios, YFDCs with two and more inverted domains show significant advantages over conventional MZ modulators.

The tolerance to fabrication errors can be the most critical concern for YFDCs with two and more domains. Tavlykaev [8] has shown that YFDCs with two domains actually has larger tolerance than one-domain YFDC. Fig. 5(a) depicts the average IMD3 distortion suppression of Device 2 relating to the fabrication error. s_1' and s_2' are the real fabrication sizes, and s_1 and s_2 are the optimized design value. The simulated window of 0.95 to 1.05 means the fabrication error range from -5% to $+5\%$. Fig. 5(b) represents that of Device 3 relating to s_2'/s_2 and s_3'/s_3. Further simulation results relating to s_1'/s_1 shows similar response as Fig. 5(b). It is seen that Device 3 has a much smaller fabrication tolerance than Device 2. However, the color-bar in Fig. 5(b) represents a much higher value than that in Fig. 5(a).

Even the performance of Device 3 degrades at a faster pace relating to the fabrication error, the average distortion suppression is still better than that of device 2. Hence, the investigation of YFDCs with three inverted domains has engineering merits. As for YFDC with four inverted domains, the fabrication tolerance is even smaller, and the performance improvement is very limited according to the simulation results in Table II. From the engineering point of view, YFDC with three inverted domains is probably the ultimate device this technology can achieve.

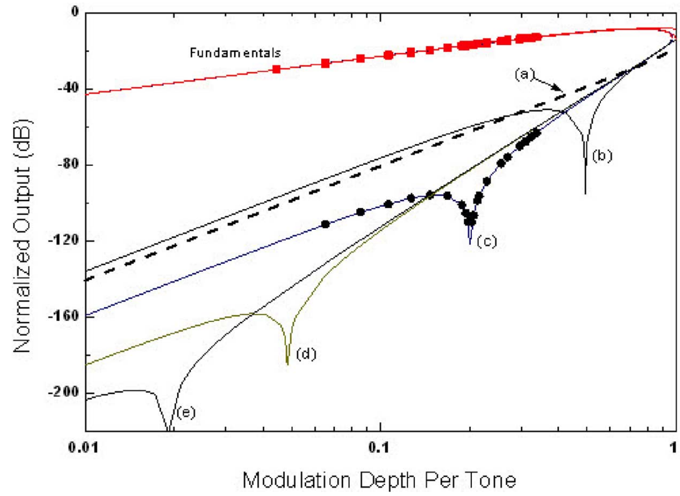

Fig. 6. Simulated and experimental output powers of the fundamental signals and IMD3 signals for YFDC modulators with (a) $(s_1 = 0.707, s_2 = 0)$; (b) $(s_1 = s_2 = 2.7715)$; (c) $(s_1 = s_2 = 2.8500)$; (d) $(s_1 = s_2 = 2.8600)$; and (e) $(s_1 = s_2 = 2.8605)$. The dots and squares in the figure are experimental data.

IV. Domain-Inverted YFDC-Based on Electrooptic Polymer Waveguides

The YFDC is based on U9020D:FTC/PU:UV11-3 E-O polymer materials. Detailed fabrication information can be found in [9]. In our design, both the first and the second domain are 1 cm long. The etching depth is fine tuned for obtaining the target normalized interaction length of 2.85. The device was poled by a domain inversion technique [9].

A light beam from an Nd:YVO4 laser (100 μW, $\lambda = 1.34\,\mu$m) polarized in the TM direction was coupled into and out of the modulator with two 60X objective lens respectively. The output light was received with a gain-switchable InGaAs detector (Thorlabs PDA400) connected to an HP8563E spectrum analyzer. Two sinusoidal modulating signals with equal amplitude at frequencies of 10 and 11 kHz from an HP 8904A multifunction synthesizer were combined and applied to the driving electrodes. The switching voltage of the YFDC was determined to be 12.5 V, resulting in a maximum modulation depth of 97.6%. The experimental results, shown in Fig. 6, with dots for the IMD3 signals and squares for the fundamentals, agreed very well with the fitting curves for the simulated modulator with $s1 = s2 = 2.85$, except for the narrow sharp dip areas which was due to the sensitivity limitations of our testing system.

To further confirm the suppression, we compared the experimental results of this YFDC to a conventional MZ modulator. Fig. 7(a) and (b) shows the outputs of these two modulators from a spectrum analyzer, where both devices were driven to 20% optical modulation depth with the same fundamental level. For the conventional MZ modulator, the IMD3 was 46.5 dB lower than the fundamental peak, while the IMD3 for the two-domain YFDC was 94 dB lower (close to the noise level). In other words, the IMD3 level of the two-domain YFDC was 47 dB lower than that of the conventional MZ modulator. Therefore, a suppression of 47 dB was obtained.

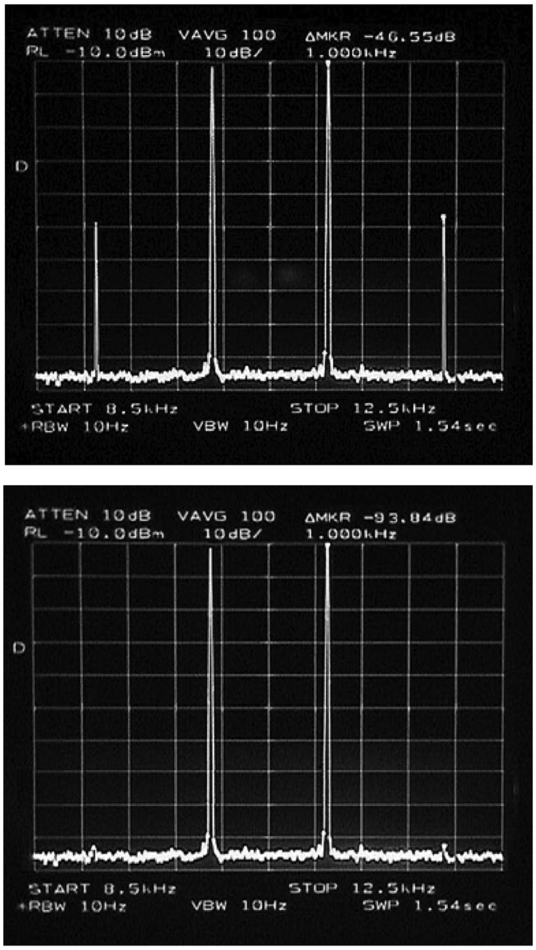

Fig. 7. Fundamental signals and IMD3 signals of (a) conventional MZ modulator and (b) two-domain YFDC modulator. Both devices are modulated at 20%.

From Fig. 7, we can see that noise level is about 105 dB/Hz (95 dB/10 Hz from the spectrum analyzer) lower than the fundamental signal. Since the fundamental signal is 14 dB lower than the optical carrier when modulated at 20%, the noise level is around 119 dB/Hz lower than the optical carrier wave. This high noise level is mainly attributed to the gain-switchable detector, which is indispensable to compensate the optical absorption of the E-O polymer modulator.

V. Conclusion

We developed an analytical method based on Taylor series expansion to investigate the design of YFDC modulators. With the adoption of an optimized algorithm to find the minimum values of multi-variable functions, we find that YFDCs with three- and four- domains can achieve 45 dB higher average distortion suppression than two-domain YFDC can do. This improvement can potentially increase the SFDR of real RF photonic systems above 120 dB/Hz. We also experimentally demonstrated that two-domain electrooptic YFDC modulator obtained 94 dB distortion suppression at 20% modulation depth, which is 47 dB higher than a conventional Mach–Zehnder modulator.

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