A robust and dither-free technique for controlling driver signal amplitude for stable and arbitrary optical phase modulation

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Abstract: We propose a robust and dither-free technique using a delay line interferometer, a balanced detector and simple signal processing to adjust the amplitude of the driver signal of an optical phase modulator automatically for stabilizing the modulated phase of an optical carrier at any arbitrary value. The technique is analytically shown to be robust against practical device imperfections. A stable 45 degrees phase shift with deviation less than ± 0.8 degrees is experimentally demonstrated.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.5060) Phase modulation.

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1. Introduction

Advanced modulation formats have been one of the enabling technologies for high spectral efficiency (SE) and ultra-large-capacity long distance fiber communication systems [1, 2]. Quadrature-phase-shift-keying (QPSK) with polarization-division-multiplexing [3, 4] has been studied to obtain SE of 2.0 b/s/Hz in 100 Gb/s dense wavelength-division-multiplexing (DWDM) systems. To meet the requirement of growing bandwidth demand, higher-order phase-shift-keying (PSK) [5–7] and quadrature amplitude modulation (QAM) [8–10] are investigated to increase the SE further to achieve beyond 100 Gb/s capacity in each DWDM grid. In practical QPSK/PSK/QAM transmitters, the bias voltages and/or the driver signal amplitudes should always be stabilized at the specified operating points for generating optimal signal constellations. However, temperature fluctuation, device aging and amplifier heating will all lead to the drift of the above operating parameters and thus distort the signal constellations. Therefore, automatic control of these key parameters in these multi-level optical transmitters [5–10] is essential for implementing future high SE systems. Up to now, the reported automatic control schemes focus on automatic bias control in dual-parallel Mach-Zehnder modulator (MZM) for QPSK signal generation [11, 12], arbitrary optical signal generation [13–15] and orthogonal frequency division multiplexing (OFDM) signal generation [16, 17]. In these schemes, different feed-back signals are monitored, including optical output power [11–14] or its statistics [17], RF power spectrum [11] and differential phasor [15]. Meanwhile, automatic control of the driver signal amplitude of the phase modulator (PM) are also essential to ensure the long-term stability of the transmitter in the implementation of multi-level PSK systems [5, 18] or QAM system [8]. To the best of our knowledge, however no automatic control technique has ever been proposed to date to achieve stable and arbitrary optical phase modulation.

In this paper, we propose and demonstrate a dither-free control technique for controlling the driver signal amplitude of a phase modulator. Using a delay line interferometer (DLI), a balanced photo-detector (BPD) and simple signal processing, the resultant phase shift from a phase modulator can be stabilized at an arbitrary value using dither-free feedback. The proposed technique is analytically shown to be insensitive to devices imperfections from the DLI and the BPD. This can reduce the implementation cost as a result of lower requirements for devices qualities. Furthermore, this control scheme is dither-free and hence the phase distortion induced by a dither signal is avoided. This advantage is especially beneficial for the multi-level modulator implementations because the modulated signal will be more sensitive to phase errors for higher-order modulation formats. In particular, a stable phase shift of 45 degrees is experimentally demonstrated and may help pave the way for practical and stable setups for 8PSK/8QAM transmitter realizations [5, 8].

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2. Operating principle

Figure 1 shows the block diagram of the proposed technique for controlling the driver signal amplitude of a phase modulator. The control module is shown in the gray box. A typical multi-level transmitter consists of a PM cascaded with a subsequent MZM-based modulator. A portion of the output light from the PM is tapped and sent to a DLI. The DLI has a delay of symbol period T and a phase offset φ tuned by an external applied voltage V_p. A balanced photo-detector then converts the optical signal from the DLI into an electrical signal, which is then sampled asynchronously with a low-speed sampler. The samples are then collected to construct a histogram. In this scheme, φ is switched between 0 and 90 degrees alternatively. In the histograms, the peak locations for $\varphi = 0$ and $\varphi = 90$ degrees are calculated and sent to the control module as the input parameters. With these input parameters monitored, the control module adjusts the output parameter of the gain voltage V_g of the driver amplifier automatically, which in turn adjusts the driver signal amplitude V_{pp} so that the generated phase shift of the PM is stabilized at a specified value.

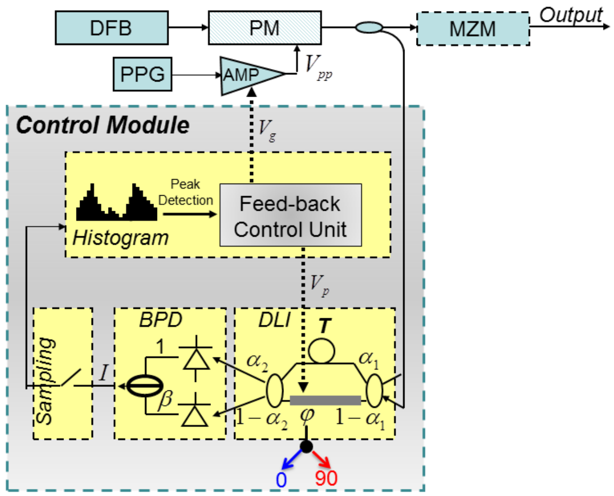

Fig. 1. Block diagram of the proposed control technique for a phase modulator. DFB-Distributed Feedback Laser; PM- Phase Modulator; MZM- Mach-Zehnder Modulator; PPG-Pulse Pattern Generator; BPD- Balanced Photo-Detector; DLI- Delay Line Interferometer; AMP- Amplifier.

To analytically illustrate the operating principle of the proposed technique, let $E(t)$ be the optical field after the PM with constant power P. The two couplers included in the DLI have their respective splitting ratios of α_1:(1-α_1) and α_2:(1-α_2), and the responsivities of the upper and lower photo-detector (PD) in the BPD are 1 and β respectively. In this case, the output signal I of the BPD is given by:

$$\begin{aligned} I &= \left\{\alpha_1(1-\alpha_2)+\alpha_2(1-\alpha_1)-\beta\left[\alpha_1\alpha_2+(1-\alpha_1)(1-\alpha_2)\right]\right\}P \\ &\quad +2\sqrt{\alpha_1\alpha_2(1-\alpha_2)(1-\alpha_1)}\,(1+\beta)\,\mathrm{Re}\{E(t-T)\cdot E^*(t)\cdot e^{-i\varphi}\} \\ &= C_1P + C_2\,\mathrm{Re}\{E(t-T)\cdot E^*(t)\cdot e^{-i\varphi}\}. \end{aligned} \tag{1}$$

In the above expression, C_1 and C_2 are two constants determined by α_1, α_2 and β only. The first term C_1P is a DC component and will become zero when one of the two splitting ratios is ideal (0.5:0.5) and the responsivities of the two photo-detectors are identical. Assuming that the phase shift generated by the PM is θ, the phase difference between the two consecutive symbols after the PM will be one of the three possible values of $-\theta$, 0 or θ. Therefore, $E(t-T)\cdot E^*(t)$ can be $Pe^{-i\theta}$, P, or $Pe^{i\theta}$ and the BPD output signal I in Eq. (1) has three possible values:

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$$\mu_1 = C_1P + C_2P\cos(\theta+\varphi), \mu_2 = C_1P + C_2P\cos(\varphi) \text{ or } \mu_3 = C_1P + C_2P\cos(\theta-\varphi). \quad (2)$$

In this scheme, the phase offset φ should be switched between 0 and 90 degrees. Since the phase offset φ drifts because of temperature fluctuations in practice, V_p should be controlled adaptively to stabilize φ at zero or 90 degrees. With μ_2 monitored as the error signal, the phase offset φ can be stabilized at 0 degree by maximizing $\mu_2=C_1P+C_2P\cos(\varphi)$. For the case of φ=90 degrees, one can monitor $(\mu_1+\mu_3)/2-\mu_2 = C_2P\cos\varphi\cdot(\cos\theta-1)$ as the error signal. By tuning V_p so that the error signal approaches zero, φ can be stabilized at 90 degrees.

In Eq. (2), μ_1, μ_2 and μ_3 depend on the phase shift θ generated by the PM and the phase offset φ in the DLI. We use $\mu_{i,x}$ (i = 1,2,3) to represent the values of μ_i (i=1,2,3) when the phase offset φ = x degrees.

If φ = 90 degrees in Eq. (2), the three levels $\{\mu_1, \mu_2, \mu_3\}$ will be given by:

$$\mu_{1,90} = C_1P - C_2P\sin(\theta), \mu_{2,90} = C_1P \text{ and } \mu_{3,90} = C_1P + C_2P\sin(\theta). \quad (3)$$

If φ = 0 degree in Eq. (2), the three levels $\{\mu_1, \mu_2, \mu_3\}$ will be given by:

$$\mu_{1,0} = \mu_{3,0} = C_1P + C_2P\cos(\theta) \text{ and } \mu_{2,0} = C_1P + C_2P. \quad (4)$$

From Eqs. (3) and (4), the phase shift θ generated by the PM can be estimated by:

$$\tan\theta = \frac{\mu_{3,90} - \mu_{2,90}}{\mu_{3,0} - \mu_{2,90}} \quad (5)$$

Based on Eq. (5), the driver signal amplitude V_{pp} can be tuned adaptively to achieve a stable phase shift θ_0 by monitoring the error signal $\varepsilon = (\mu_{3,90}-\mu_{2,90})-\tan\theta_0\cdot(\mu_{3,0}-\mu_{2,90})$ and driving it to zero.

It should be noted that in the above derivations, the effects of both the non-ideal splitting ratios for the two couplers and the responsivity difference between the two PDs have been taken into account. Consequently, with the proposed control scheme based on Eq. (5), no phase error will be induced by the non-ideal splitting ratios and the responsivity difference. Therefore, the performance of the scheme is inherently robust against these imperfections of practical devices.

3. Experimental results and discussions

The proposed driver signal amplitude control technique is experimentally realized to control a PM to generate a stable 45 degrees phase shift. This module would be essential in the implementation of 8PSK/8QAM transmitter [5,8], in which a dual-parallel MZM modulator is cascaded with a PM having a phase shift of 45 degrees. In the experiment, the PM is driven by a 10.7 Gb/s binary electrical signal with an adjustable amplitude, ranging from 1.00 V to 1.30 V. Part of the output light from the PM is coupled to the control module shown in Fig. 1. The DLI (Optoplex: Optical DPSK demodulator) has a fixed delay time of 85.4 ps and a tunable phase offset controlled by the external applied voltage V_p. The output electrical signal of the BPD (u2t:BPDV2120) is then measured and asynchronously sampled by an Agilent Digital Sampling Oscilloscope (86100A). The samples are used to construct the histograms.

In the experiment, V_p is adjusted to switch the phase offset φ of the DLI between 0 and 90 degrees alternatively. Figure 2 shows the measured eye diagrams of the BPD output signal when the phase offset is 0 or 90 degrees respectively. The theoretically predicted values in Eq. (3) and Eq. (4) are indicated in these eye diagrams for comparison. In the 0 degree case, only two voltage levels are present since $\mu_{1,0} = \mu_{3,0}$. In the 90 degree case, the upper level $\mu_{3,90}$ and the lower level $\mu_{1,90}$ are symmetrical with respect to the middle level $\mu_{2,90}$.

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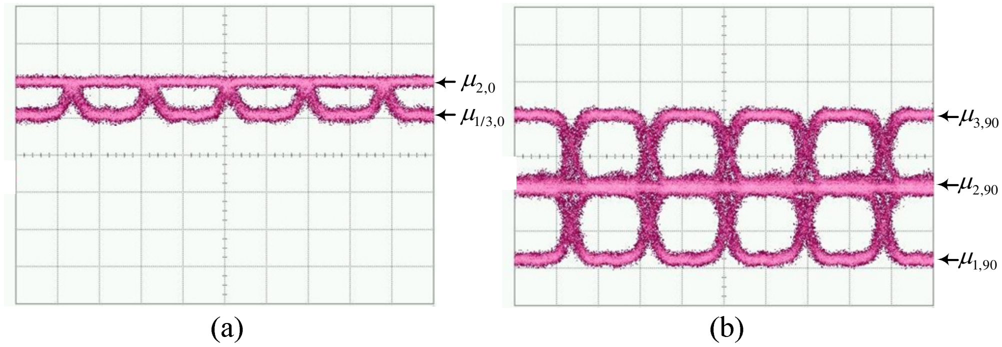

Fig. 2. Eye diagrams of the BPD output signal when the DLI has the phase offset φ of (a) 0 degree, and (b) 90 degrees.

For the targeted phase shift of 45 degrees, the error signal ε is simplified to $\mu_{3,90}$-$\mu_{3,0}$ by setting $\tan\theta_0 = 1$ in $\varepsilon = (\mu_{3,90}-\mu_{2,90})-\tan\theta_0\cdot(\mu_{3,0}-\mu_{2,90})$, where θ_0 is the desired phase shift of 45 degrees. Figures 3(a), 3(b), and 3(c) show the histograms plotted for three particular driver signal amplitudes V_{pp} of 1.00 V, 1.12 V and 1.26 V, respectively. The voltage levels $\mu_{1,90}$, $\mu_{2,90}$, $\mu_{3,90}$, $\mu_{1,0}$, $\mu_{2,0}$, and $\mu_{3,0}$ are obtained by finding the peak locations in the histograms. For V_{pp} = 1.00 V, the error signal is negative which is a direct consequence of $\mu_{3,90}$ being smaller than $\mu_{3,0}$. Based on Eq. (5) it can be inferred that the actual phase shift is below 45 degrees. The error signal is close to zero when V_{pp} is around 1.12 V. The error signal becomes positive when V_{pp} = 1.26V, indicating that the resultant phase shift is larger than 45 degrees.

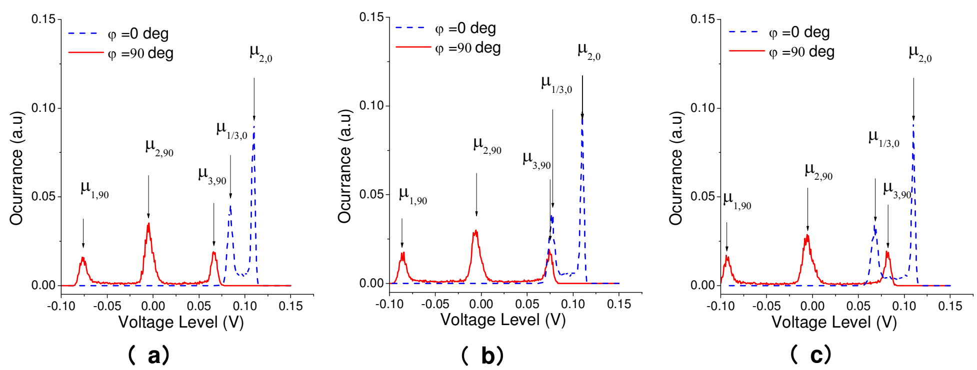

Fig. 3. Histograms of the sampled BPD output signal when the driver signal amplitude is: (a) 1.00 V, (b) 1.12 V, and (c) 1.26 V. The histograms for the DLI phase offset φ of 0 and 90 degrees are plotted in blue and red respectively.

Figure 4a depicts the monitored error signal of $\varepsilon = \mu_{3,90}$-$\mu_{3,0}$ as a function of the driver signal amplitude V_{pp} ranging from 1.00 to 1.30 V. Figure 4(b-d) show the superimposed eye diagrams including the cases for both 0 and 90 degrees phase offsets for three V_{pp} values of 1.26, 1.14, and 1.00 V, respectively. The balance between $\mu_{3,90}$ and $\mu_{3,0}$ can be directly identified in these eye diagrams. As shown in Fig. 4a, the monitored error signal of $\varepsilon = \mu_{3,90}$-$\mu_{3,0}$ increases monotonically with V_{pp}. When V_{pp} is around 1.14 V, the error signal is approximately equal to zero, indicating that the resultant phase shift approaches the targeted value of 45 degrees. As shown by the two vertical blue lines in Fig. 4(a), the detectable amplitude error is less than ± 0.02 V. Therefore, its corresponding phase deviation is estimated to be $\pm\, 0.02 \times (45.0/1.14) \approx \pm\, 0.8$ degrees. By increasing the number of samples used in constructing the histograms, the phase precision of the control scheme can be potentially improved. It is worth noting that the proposed technique can be used for stabilizing the phase modulation at an arbitrary value besides the case of 45 degrees demonstrated in this paper. Therefore, the scheme has wide applications in transmitters implementations for various advanced modulation formats [5, 8, 18], in which stable phase modulation at any arbitrary value is necessary.

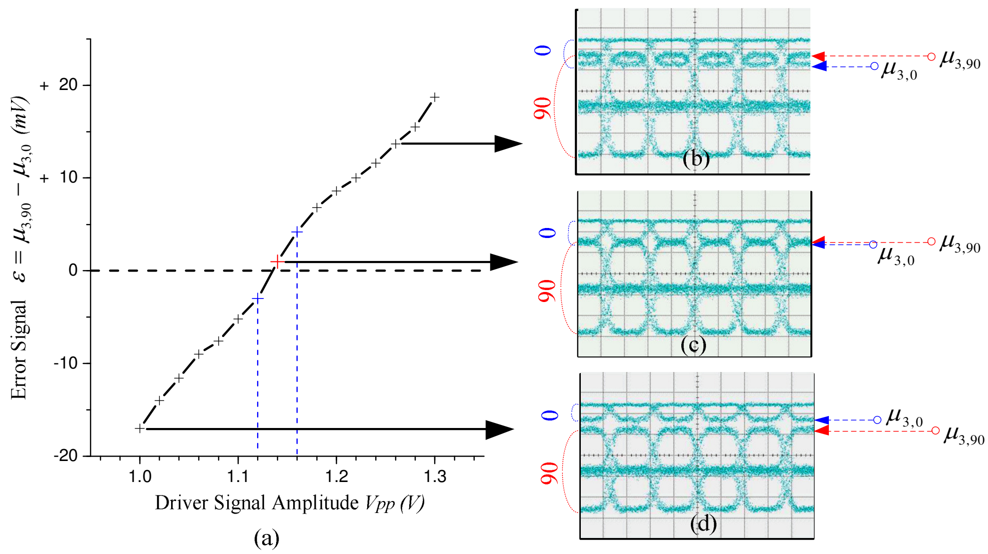

Fig. 4. (a) Error signal $\varepsilon = \mu_{3,90}$-$\mu_{3,0}$ as a function of the driver signal amplitude V_{pp} of a phase modulator. Superimposed eye diagrams (for φ of 0 and 90 degrees) when V_{pp} is (b)1.26 V, (c)1.14 V, and (d)1.00 V.

4. Conclusions

A dither-free and robust technique is proposed for automatic control of the driver signal amplitude of an optical phase modulator to generate a stable phase shift at any arbitrary value. The proposed technique is analytically proven to be robust against the device imperfections from the delay line interferometer and the balanced photo-detector. The experimental results for stable 45 degrees phase modulation with a phase error of less than ± 0.8 degrees have been successfully demonstrated. The scheme can be used to stabilize the phase shift of a phase modulator at any arbitrary value for optical communication systems employing higher-order modulation formats.

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