High-frequency characterization of an optical phase modulator with phase modulation-to-intensity modulation conversion in dispersive fibers

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We propose a new method for characterizing optical phase modulators based on phase modulation-to-intensity modulation (PM-to-IM) conversion in dispersive fibers. The fiber dispersion spectrally alters the relative phasing of the phase-modulated signal and leads to the PM-to-IM conversion, which is extended to measure the modulation efficiency of optical phase modulators. In the demonstration, the frequency-dependent modulation index and half-wave voltage are experimentally measured for a commercial phase modulator. Compared with conventional methods, the proposed method works without the restriction of small-signal operations, and allows swept-frequency measurement with high resolution and accuracy by using a vector network analyzer.

electro-optic modulators, microwave photonics, optical fiber dispersion, phase modulation

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Optical phase modulation can eliminate bias drifting and generate inherent out-of-phase sidebands compared with Mach-Zehnder intensity modulation, which has attracted significant interest in microwave photonic signal processing [1], such as photonic microwave filtering [2,3] and photonic microwave frequency measurement [4,5]. In phase-modulation-based microwave photonics systems, the modulation efficiency of the optical phase modulator, the modulation index and the half-wave voltage influence the overall high-frequency performance. This is especially true at broadband microwave operation, which should be critically characterized to evaluate and optimize the system. However, optical phase modulators only change the optical phase, which makes it difficult to measure directly the modulation efficiency with developed intensity-sensitive instruments [6].

Many measurement techniques have been proposed such as optical spectrum analysis [6], optical frequency discrimination [7], self-heterodyne method [8], and Sagnac loop

method [9]. Optical spectrum analysis has a very simple configuration, which is to measure the optical spectrum of the phase-modulated signal. Nevertheless, it is a point-to-point measurement, and its resolution is limited by the optical spectrum analyzer (about 0.01 nm) [9]. Optical frequency discrimination uses a Fabry-Perot (FP) interferometer to make a frequency-to-amplitude conversion. However, it suffers from the nonlinear slope of the optical frequency discriminator. The Sagnac loop method is based on the delayed interference of bidirectional modulations and achieves swept-frequency measurement with high resolution, and is applicable to small-signal operation and requires an envelope extraction.

As is known, phase-modulated signals can be converted to intensity modulation by inserting a dispersive device after phase modulation [1–5,10]. Phase modulation-to-intensity modulation (PM-to-IM) conversion has been widely used to demodulate the phase-modulated optical signal in the receivers of microwave photonic systems [1]. In this paper, we investigate PM-to-IM conversion in the context of char-

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acterizing optical phase modulators, and propose a new method for measuring the modulation efficiency through the PM-to-IM conversion in fold-back dispersive fiber paths. We theoretically analyze the evolution of phase-modulated signals in the dispersive fiber and present the measurement principle with a fold-back configuration to demonstrate our method. The frequency-dependent modulation index and half-wave voltage are experimentally measured for a commercial phase modulator. Our method works without the restriction of small-signal operation, and allows swept-frequency measurement with high resolution and accuracy by using a network analyzer, which avoids using an unstable interferometer or additional envelope extraction.

1 Operating principle

As is shown in Figure 1(a), an optical carrier at an angular frequency ω_0 is phase-modulated by an electrical sinusoidal signal at an angular frequency ω_e . The phase-modulated optical signal can be expanded in terms of the Bessel functions

$$e_1(t) = e^{j\omega_0 t + jm \cos(\omega_e t)} = \sum_{n=-\infty}^{+\infty} j^n J_n(m) e^{j\omega_0 t + jn\omega_e t}, \quad (1)$$

where $J_n(\bullet)$ is the n th-order Bessel function of the first kind and m is the modulation index of the phase modulator. It is obvious that phase modulation generates multiple optical sidebands at both sides of the optical carrier with frequency spaced by ω_e and phase shifted by $\pi/2$.

After dispersion propagation, an additional phase shift is introduced to each optical sideband depending on its frequency offset relative to the optical carrier. The phase shift induced by the fiber dispersion with length L can be approximately represented by

$$\phi(\omega_0 + n\omega_e) = (\beta_0 + \beta_1 n\omega_e + \beta_2 n^2 \omega_e^2 / 2) L. \quad (2)$$

In the expansion, the first two terms give rise to a fixed

phase shift and propagation delay, and the third term denotes the group velocity dispersion, in which the dispersion coefficient β_2 relates to the fiber dispersion parameter D by $D = -2\pi\beta_2 c \omega_0^2$. Assuming fiber loss contributes only with a constant factor α , the optical signal after dispersion propagation can be written as

$$e_2(t) = \sum_{n=-\infty}^{+\infty} j^n J_n(m) e^{\alpha/2} e^{j\phi(\omega_0 + n\omega_e)} e^{j\omega_0 t + jn\omega_e t}, \quad (3)$$

and the optical intensity after dispersion propagation is given by

$$i(t) = e_2(t) \cdot e_2^*(t) = e^{\alpha} \sum_{k=-\infty}^{+\infty} j^k e^{jk\omega_e t + j\phi_1 + jk\phi_2} \sum_{n=-\infty}^{+\infty} J_{n+k}(m) J_n(m) e^{j2n\phi_2}, \quad (4)$$

with $\phi_1 = \beta_1 L k \omega_e$ and $\phi_2 = \beta_2 L k \omega_e^2 / 2$. Applying Graf's additional formula of Bessel functions [10,11], the expression for the received optical intensity can be further reduced to

$$i(t) = e^{\alpha} \left[1 + 2 \sum_{k=1}^{+\infty} (-1)^k J_k(2m \sin \phi_2) \cos(k\omega_e t + \phi_1) \right]. \quad (5)$$

It can be seen from eq. (5) that the fiber-dispersion-induced phase shift alters the phase spectrum of the phase-modulated signal, and leads to PM-to-IM conversion. To develop a practical method, we focus on the fundamental component in eq. (5). We define the ratio of the first-order harmonic component to the dc component as the strength of the first-order harmonic (SFH) given by

$$I_1 = 2 \left| J_1(2m \sin(\beta_2 L \omega_e^2 / 2)) \right|, \quad (6)$$

which shows that the SFH function periodically achieves null at the notch frequencies corresponding to

$$\omega_{nu}^2 = 2u\pi / |\beta_2 L|, (u = 0, 1, 2 \dots). \quad (7)$$

The notch frequency only depends on the fiber dispersion, and so it can be used to indicate the fiber dispersion. Once

Figure 1 (a) Scheme of dispersion-induced PM-to-IM conversion and (b) diagram of the proposed fold-back configuration for measuring the modulation efficiency of phase modulators. PM, phase modulator; ESA, electrical spectrum analyzer; Cir, circulator; OC, optical coupler; PD, photodiode.

the fiber dispersion is determined from the characteristic notch frequency, the modulation index can be determined from the measured SFH, and its high-frequency degradation can be obtained by the swept-frequency measurement with a vector network analyzer owing to the fundamental component measurement [12].

For the measuring accuracy, we investigate the error dependence of the modulation index on the dispersion uncertainty by the error transfer factor

$$F = \left| \frac{\Delta m}{m} / \frac{\Delta L \beta_2}{L \beta_2} \right| = \left| \frac{\beta_2 L \omega_e^2}{2} \operatorname{ctg} \left(\frac{\beta_2 L \omega_e^2}{2} \right) \right|, \quad (8)$$

which is deduced from the total differential of the SFH function. For $F < 1$, the uncertainty of the modulation index is less than that of the fiber dispersion, whereas for $F > 1$, the uncertainty is larger and gives rise to a large error of the modulation index. Therefore, the fiber dispersion should be carefully chosen to feature $F \leq 1$ as $|\beta_2 L \omega_x^2| \leq 4.0575$ with a maximum angular frequency ω_x . That is to say, all the non-zero-frequency notches should be out of the measuring frequency range, which does not agree with the requirement of determining the fiber dispersion according to eq. (7).

To deal with the problem, we introduce a fold-back configuration in Figure 1(b), where the round-trip dispersion is double the single-trip dispersion. The fiber length is set as

$$\pi \leq |\beta_2 L \omega_x^2| \leq 4.0575 \quad (9)$$

to allow an optimum single-trip dispersion for measuring the modulation index. Meanwhile, the fiber length also ensures enough round-trip dispersion for accurately determining the fiber dispersion from the non-zero-frequency notch within the measuring frequency range.

2 Experiment and results

To demonstrate our scheme, we experimentally characterize a commercial phase modulator using the setup shown in

Figure 1(b). According to eq. (9), the optimum fiber dispersion should be $199 \text{ ps}^2 \leq |\beta_2 L| \leq 257 \text{ ps}^2$ in the frequency range of 20 GHz, which corresponds to a 9.2- to 11.8-km standard single-mode fiber operated at 1550 nm. In our experiment, the optical carrier from a DFB laser diode at 1550.2 nm is first sent to a LiNbO₃ phase modulator. The phase-modulated optical signal is then coupled into an 11.5-km single-mode fiber via an optical circulator (Cir1). At the end of the fiber, another optical circulator (Cir2) is terminated to loop back the optical signal. In the case of single-trip dispersion, the measured signal comes from port 1 of Cir2 via an optical coupler (OC2). In the case of round-trip dispersion, we measure the optical signal at port 3 of Cir1. The optical coupler (OC1) is used to compensate for the fold-back path to keep the relationship between the single-trip and round-trip dispersions.

The optical intensity after fiber propagation is detected by a New Focus 45-GHz photodiode, which has a flat responsivity within a 20-GHz frequency range and its error factor is negligible. With a full two-port calibration, an HP8720D vector network analyzer is used to generate a swept-frequency signal and measure the first-order harmonic component of the optical intensity. As the dc component is the same for all swept frequencies, we measure it with an R&S FSU43 electrical spectrum analyzer at one frequency e.g., at 8 GHz, as reference, from which the measured SFH is obtained.

As is shown in Figure 2(a), the measured SFHs under the single-trip dispersion achieve only a dc notch, while the results under the double-trip dispersion achieve a non-zero-frequency notch at 17.87 GHz besides a dc notch, which indicates a round-trip dispersion of 498.4 ps² and a single-trip dispersion of 249.2 ps². The error transfer factor for both cases is calculated and plotted in Figure 2(b). One can see that the error transfer factor reaches maximum at 17.87 GHz (notch frequency) in the round-trip case, whereas it keeps no more than 1 within the whole frequency range in the single-trip case. It is worth noting that the error transfer factor approximately equals 1 around zero frequency;

Figure 2 (a) Measured SFH and (b) error transfer factors for different cases of dispersion, where a 11.5 km standard single-mode fiber is used.

that is to say, the dc notch has little influence on the measuring accuracy of the modulation index. The error factor reaches minimum at 12.63 GHz for the round-trip case and 17.87 GHz for the single-trip case, which indicates the minimum error of the modulation index at these frequencies.

The frequency-dependent modulation index is determined from the measured SFH based on eq. (6), and results for the single-trip and round-trip dispersions are shown in Figure 3 for comparison. We see that the errors around the notch frequency in the round-trip case are largely suppressed, and the single-trip case shows obvious improvement without any unreasonable error. The modulation index of the phase modulator decreases from 0.55 to 0.21 rad when the modulation frequency increases from 0.05 to 20 GHz. The phase modulator is also measured using the conventional optical spectrum analysis for comparison, as shown in Figure 3, where the frequency space of about 1 GHz and lower frequency of about 4 GHz are limited by the resolution of the OSA and the linewidth of the laser source, respectively. Nevertheless, our results are in good agreement with those obtained using the conventional method.

Furthermore, the half-voltage of the phase modulator is characterized with the same setup. The electrical reflection coefficient Γ_L of the phase modulator is simultaneously measured with the calibrated vector network analyzer, and the input impedance Z_L of the modulator and its electrical driving amplitude V_e are obtained using $Z_L = 50 (1 + \Gamma_L) / (1 - \Gamma_L)$ and $V_e^2 = 2|Z_L|P_e$, respectively. Therefore, the half-wave voltage of the modulator can be determined with the help of $V_\pi = \pi V_e / m$, which increases from 3.2 to 7.7 V with a modulation frequency up to 20 GHz.

3 Conclusion

During the experiment, our measurements had stable and

Figure 3 Measured modulation index under single-trip dispersion (open circles) and round-trip dispersion (filled circles), where filled squares represent the results obtained using optical spectrum analysis.

repeatable results because the optical carrier and its sidebands are affected by the same fiber impairments. We did our measurement at an electrical power of 7 dBm, which is applicable to other driving levels since our method does not assume any small-signal operation [10,11]. Moreover, the method can be extended to other wavelengths and other dispersive fibers as long as the operation meets the dispersion requirement.

The frequency-dependent modulation index and half-voltage confirm the aforementioned degradation of modulation efficiency at high-frequency modulation. It has been noted that the degradation is mainly due to (1) the phase-velocity mismatches between the optical wave and the microwave and (2) the impedance mismatches between the microwave source and the modulator [13,14]. Our measurement obviously provides much detailed information for characterizing and optimizing both phase modulators and phase-modulation-based systems.

In summary, we proposed and demonstrated a simple and effective method to characterize phase modulators based on PM-to-IM conversion in fold-back dispersive paths. The frequency-dependent modulation index and half-wave voltage can be accurately obtained by measuring the optical intensity of the phase-modulated signal after experiencing dispersion propagation. Our method benefits from the high resolution and swept frequency of developed electrical-domain measurement techniques, which largely enhance the characterization of electro-optic phase modulators.

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