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Abstract *A polarization modulator together with a polarizer can implement phase modulation, intensity modulation with tunable chirp, and frequency-doubling intensity modulation. If an optical filter is incorporated, frequency-quadrupling and frequency-sextupling intensity modulations and a microwave photonic phase shifter can also be realized. By using a polarization modulator to replace the intensity modulator in an optoelectronic oscillator, various new features are enabled. In this article, an analytical model for the polarization modulator-based systems is established. The recent development in employing polarization modulators for constructing optoelectronic oscillators is discussed. The emerging applications enabled by the polarization modulator-based optoelectronic oscillators and the possible future development are also discussed.*

Keywords microwave photonics, optical signal processing, optoelectronic oscillator, polarization modulation

1. Introduction

Generation of microwave signals is essential for high-speed wireless communications, software-defined radios, multi-function radars, high-accuracy time/frequency reference, modern instrumentation, and many other emerging applications [1–6]. The key performance criterion for a microwave signal generator is the spectral purity or the frequency stability of the generated signal, which can be evaluated mainly by a parameter called phase noise. Due to the lack of high-frequency and high-Q electronic resonators at room temperature, it was very difficult to generate signals with very low phase noise at high-frequency bands using pure microwave oscillators until the invention of the optoelectronic oscillator (OEO) in 1994 [5–9]. A typical OEO is an optoelectronic feedback loop consisting of an electro-optic modulator (EOM), an optical fiber delay line, a photodetector (PD), an electrical or optical amplifier, and an electrical bandpass filter. The EOM is used to convert the oscillating signal from the electrical domain to the optical domain so that it can be transmitted in the optical fiber. The optical microwave signal after

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transmission is converted back to a microwave signal by the PD and directed to the radio frequency (RF) port of the EOM. If the gain of the optoelectronic feedback loop is greater than unity, which can be guaranteed by either optical or electrical amplifiers, the OEO begins to oscillate. By applying a very long fiber to store a large amount of energy with very little loss in the loop, a high-spectral-purity X-band microwave signal with a phase noise as low as –163 dBc/Hz at a 10-kHz offset is achieved at room temperature [10].

Early works on OEOs were mainly focused on improving the phase noise performance [11, 12], suppressing the sidemodes [13–15], minimizing the size [16-18], increasing the long-term stability [19–21], and enabling the frequency tunability [22–25]. For these objectives, the measures were to propose innovative architectures, optimize the parameters of the components, replace the long fiber delays by integratable high-Q optical energy storage elements, or change the frequency-fixed electrical filter to frequency-tunable electrical filters or microwave photonic filters (MPFs). As a key component, the EOM in the OEOs was usually implemented simply by a conventional intensity modulator (IM) or a phase modulator (PM). Few efforts were devoted to obtain the added values from the introduction of new modulation schemes. Recently, with the increasing interests to apply OEOs for millimeter-wave applications or analog/digital signal processing [26–31], OEOs based on polarization modulators (PolMs) [32] became attractive. Different from the single-dimension (either amplitude or phase) modulation implemented by the conventional IMs or PMs, a PolM can support both TE and TM modes with opposite phase modulation indices, so it actually performs two-dimensional modulation. With the increased dimension for modulation, various new features of the OEOs can be enabled, such as effective spurious level reduction through polarization-multiplexed dual loops, frequency multiplication to operate the OEO at the millimeter-wave band, and phase shifting to let the OEO act as arbitrary waveform generator.

In this article, an analytical model for photonic systems based on polarization modulation is established. The added values by introducing polarization modulation to the OEO are discussed, which include effective sidemode suppression, frequency multiplication, and widely frequency tuning. The applications of the polarization-modulated OEO in digital signal processing, photonic frequency up- and down-conversion, optical comb generation, and arbitrary microwave signal generation are described. Challenges and possible future development are also discussed.

2.   Analytical Model for Photonic Systems Based on Polarization Modulation

It is well known that any polarized light can be expressed as a Jones vector:

$$\mathbf{E} = \begin{bmatrix} E_{\mathrm{x}} \\ E_y \end{bmatrix} = E_0 \begin{bmatrix} \cos \alpha \cdot \exp\left(j\frac{\phi}{2}\right) \\ \sin \alpha \cdot \exp\left(-j\frac{\phi}{2}\right) \end{bmatrix}, \tag{1}$$

where E_0 is the magnitude of the optical field, angle α is defined as $\tan\alpha = |E_y/E_x|$, and ϕ is the phase difference between E_x and E_y. From Eq. (1), the polarization of a light can be altered by controlling either the amplitude or phase of the vector components. This can be accompanied by mechanical (e.g., waveplate rotators and fiber squeezers [33]), magneto-optical (e.g., Faraday rotators [34]), electro-optical (e.g., integrated LiNbO$_3$ [35], polymer [36], or GaAs [32] devices), or all-optical (e.g., nonlinear polarization rotation and cross-polarization modulation in optical fibers or semiconductor optical amplifiers [37–40]) approaches. Considering that the mechanical and magneto-optical approaches have a
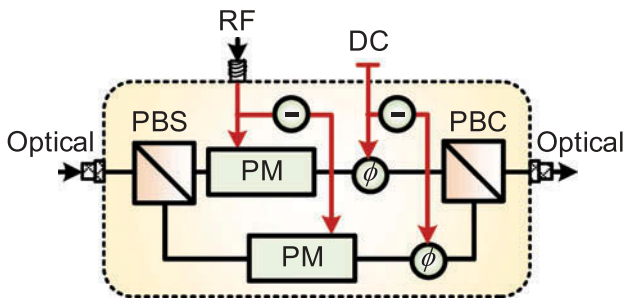
Figure 1. Equivalent scheme for modeling a PolM.

limitation in speed, and the all-optical approaches demand complicated configurations and stringent control of the incident lights, electro-optical devices are the most promising candidates to implement polarization modulation with a large bandwidth.

Since the electro-optical effects in $LiNbO_3$, polymer, or GaAs mainly operate on the phase of a light, electro-optical PolMs are generally realized by introducing phase differences to the vector components according to the driving RF signal. As a result, the equivalent scheme of an electro-optical PolM can be seen in Figure 1, which consists of two PMs, a polarization beam splitter (PBS), a polarization beam combiner (PBC), and two optical phase shifters. The two vector components of an incident light are split into two paths by the PBS, with E_x, for example, directed to the upper path and E_y transmitted along the lower path. Then, the two components achieve phase modulations with complementary phase modulation indices in the PMs driven by an RF signal. The PolM should also have a DC bias port, which is used to introduce a static phase difference between the two vector components. Finally, E_x and E_y are combined by the PBC, composing a polarization-modulated signal. From the above analysis, the Jones matrix of the PolM can be written as

$$\mathbf{J} = \begin{bmatrix} \exp\left(j\frac{\beta\phi(t)}{2} + j\frac{\phi_0}{2}\right) & 0 \\ 0 & \exp\left(-j\frac{\beta\phi(t)}{2} - j\frac{\phi_0}{2}\right) \end{bmatrix}, \tag{2}$$

where β is the phase modulation index, ϕ_0 is the static phase that can be controlled by the DC bias, and $\phi(t)$ is the modulating signal. As an example of the polarization modulation, if a linearly polarized light having an angle of 45° to one of the principal axes of the PolM is introduced to the PolM, letting $\beta\phi(t) + \phi_0 = \pi/4$, the linearly polarized light is converted to a circularly polarized wave, or letting $\beta\phi(t) + \phi_0 = \pi/2$, the polarization direction of the incident light is rotated by 90°.

When a polarizer with its polarization direction aligned to have an angle of θ to one of the principal axes of the PolM is followed, the signals along the two polarization directions will interfere with each other, and thus

$$E_{out} = \frac{\sqrt{2}}{2} E_{in} \left\{ \cos\theta \exp\left[j\left(\frac{\beta\phi(t)}{2} + \frac{\phi_0}{2}\right)\right] + \sin\theta \exp\left[-j\left(\frac{\beta\phi(t)}{2} + \frac{\phi_0}{2}\right)\right] \right\}. \tag{3}$$

In Eq. (3), the incident light to the PolM is assumed to be a linearly polarized light having an angle of 45° to one of the principal axes of the PolM. From Eq. (3), if θ is 0° or 90°, the

phase modulation with a positive or negative phase modulation index is implemented, and if θ is 45°, one obtains

$$E_{out} = E_{in} \cos\left(\frac{\beta\phi(t) + \phi_0}{2}\right). \tag{4}$$

As can be seen from Eq. (4), intensity modulation is realized. For other values of θ, a mixture of both the phase and intensity modulation can be realized. Therefore, the PolM introduces more flexibilities than conventional IMs and PMs, because any optical systems based on phase modulation and intensity modulation can be implemented using a PolM together with a polarizer.

Supposing the modulating signal is a single-frequency signal, i.e., $\phi(t) = \cos\omega_c t$, where ω_c is the angular frequency. Based on the Jacobi–Anger expansion, the signal in Eq. (4) can be rewritten as

$$
\begin{aligned}
E_{out} = E_{in} \Bigg\{ &\cos\left(\frac{\phi_0}{2}\right)J_0(\beta) + 2\cos\left(\frac{\phi_0}{2}\right)\sum_{n=1}^{\infty}J_{2n}(\beta)(-1)^n\cos(2n\omega_c t) \\
&+ 2\sin\left(\frac{\phi_0}{2}\right)\sum_{n=1}^{\infty}J_{2n-1}(\beta)(-1)^n\cos((2n-1)\omega_c t) \Bigg\},
\end{aligned}
\tag{5}
$$

where J_n is the nth-order Bessel function of the first kind. When ϕ_0 is controlled to be 0, $\pi/2$, or π, the obtained optical fields are equivalent to the output of a Mach–Zehnder modulator (MZM) biased at the maximum transmission point, quadrature point, and minimum transmission point, respectively.

When $\phi_0 = \pi/2$, and assuming that the modulation index is small enough to ignore the higher orders harmonics (>1), from Eq. (5), only the optical carrier and the two first-order sidebands are left. If the three sidebands are sent to a PD, a microwave signal with the fundamental frequency can be generated.

When $\phi_0 = \pi$, the output optical field becomes

$$E_{out} = 2E_{in}\sum_{n=1}^{\infty}J_{2n-1}(\beta)(-1)^n\cos((2n-1)\omega_c t). \tag{6}$$

From Eq. (6), only odd-order sidebands are presented. For a small modulation index, only the ±1st-order sidebands are left. By beating the two ±1st-order sidebands at a PD, a frequency-doubled microwave signal can be generated. The output current of the generated frequency-doubled electrical signal is written as

$$I(t) \propto A\Re J_1^2(\beta)\cos(2\omega_c t), \tag{7}$$

where $\Re$ is the responsivity of the PD, and A is a parameter related to the input optical power.

If the modulation index β is large enough, the third-order sidebands in Eq. (6) could not be ignored. By inserting a wavelength-fixed optical notch filter to remove the two first-order sidebands, only the ±3rd-order sidebands are left. Beating the two sidebands at a PD, a frequency-sextupled microwave signal is generated [41]. The current of the generated microwave signal is given by

$$I(t) \propto A\Re J_3^2(\beta) \cos(6\omega_c t).$$ (8)

If the DC bias is controlled to let $\phi_0 = 0$, the output of the PolM together with the polarizer becomes

$$E_{out} = E_{in}\left(J_0(\beta) + 2\sum_{n=1}^{\infty} J_{2n}(\beta)(-1)^n \cos(2n\omega_c t) \right).$$ (9)

As can be seen, all the odd-order sidebands are suppressed. Again, if the modulation index β is well controlled, only the optical carrier and second-order sidebands are left. By using a wavelength-fixed notch filter to remove the optical carrier, two phase-correlated optical wavelengths with a wavelength spacing corresponding to $4\omega_c$ are obtained [42]. By beating the two wavelengths at a PD, a high-quality microwave signal with a frequency that is four times the driving RF signal is generated:

$$I(t) \propto A\Re J_2^2(\beta) \cos(4\omega_c t).$$ (10)

From Eqs. (3)–(10), all the fundamental frequency, frequency-doubling, frequency-quadrupling, and frequency-sextupling intensity modulations can be realized by a PolM and a polarizer, although the latter two require an optical notch filter. Because a polarization controller (PC) can not only adjust the angle θ between the polarization direction of the polarizer and the principal axes of the PolM, but can also introduce a phase difference ϕ_0 between E_x and E_y, a PolM together with a PC and a polarizer can perform any type of modulation that can be realized by an IM or a PM. In addition, since the PC and polarizer are devices external to the PolM, the output of the PolM can be split into several paths, and in each path, a PC and a polarizer incorporated. As a result, different types of modulation can be implemented in parallel using a single PolM.

One interesting type of modulation that can be realized by the PolM together with a PC and a polarizer is the mixed phase modulation and intensity modulation with tunable power ratio between the two modulations [43], i.e., intensity modulation with tunable chirp. The mixed modulation provides a new solution to reduce the dispersion-induced power fading and intermodulation distortion in an analog photonic link [43–45]. In addition, if this chirp interacts with fiber dispersion, a frequency-tunable MPF can be achieved.

To show this special type of modulation, Eq. (3) is rewritten as

$$E_{out} = \frac{\sqrt{2}}{2} E_{in}\left\{ \cos\theta \cos\left(\frac{\beta\cos\omega_c t}{2} + \frac{\phi_0}{2}\right) + (\sin\theta - \cos\theta)\exp\left(-j\frac{\beta\cos\omega_c t}{2}\right) \right\}.$$ (11)

As can be seen from Eq. (11), both intensity modulation and phase modulation are performed. The ratio between the two modulations can be adjusted by changing θ, i.e., the angle of the polarization direction of the polarizer to the principal axis of the PolM. If the signal is introduced to a dispersive element, assuming that small-signal modulation is performed, one obtains

$$E_{out} = \frac{\sqrt{2}}{2} E_{in} \left\{ J_0\left(\frac{\beta}{2}\right) \left\{ \cos\theta \exp\left[j\left(\frac{\phi_0}{2} + \theta_0\right)\right] + \sin\theta \exp\left[j\left(-\frac{\phi_0}{2} + \theta_0\right)\right] \right\} \right.$$
$$+ J_1\left(\frac{\beta}{2}\right)\cos\theta \left\{ \exp\left[j\left(\omega_c t + \frac{\pi}{2} + \frac{\phi_0}{2} + \theta_{+1}\right)\right] - \exp\left[j\left(-\omega_c t - \frac{\pi}{2} + \frac{\phi_0}{2} + \theta_{-1}\right)\right] \right\}$$
$$\left. + J_1\left(\frac{\beta}{2}\right)\sin\theta \left\{ \exp\left[j\left(\omega_c t + \frac{3\pi}{2} - \frac{\phi_0}{2} + \theta_{+1}\right)\right] - \exp\left[j\left(-\omega_c t - \frac{3\pi}{2} - \frac{\phi_0}{2} + \theta_{-1}\right)\right] \right\} \right\},$$

$$(12)$$

where θ_0, θ_{-1}, and θ_{+1}, are the dispersion-induced phase shifts of the optical carrier, the lower first-order sideband, and the upper first-order sideband, respectively. Expanding the propagation constant in the Taylor series, the dispersion induced phase shifts becomes

$$\begin{cases} \theta_0 = z\beta(\omega_o), \\ \theta_{-1} = z\beta(\omega_o) - \tau_0\omega_c + \frac{1}{2}D_\omega\omega_c^2, \\ \theta_{+1} = z\beta(\omega_o) + \tau_0\omega_c + \frac{1}{2}D_\omega\omega_c^2 \end{cases} \tag{13}$$

where ω_o is the angular frequency of the optical carrier, z is the transmission distance, τ_0 equals $z\beta'(\omega_o)$, D_ω equals $z\beta''(\omega_o)$, and β' and β'' are the first- and second-order derivatives of the propagation constant with respect to ω_o. Beating the optical signal at a PD and setting the phase difference ϕ_0 to be $\pi/2$, the AC current is given by

$$I(t) \propto 2J_0\left(\frac{\beta}{2}\right)J_1\left(\frac{\beta}{2}\right)\sin\left(2\theta + \frac{1}{2}D_\omega\omega_c^2\right)\cos[\omega_c(t - \tau_0)]. \tag{14}$$

The transmission response of the entire system can then be written as

$$|h(\omega)| \propto \left|2J_0\left(\frac{\beta}{2}\right)J_1\left(\frac{\beta}{2}\right)\sin\left(2\theta + \frac{1}{2}D_\omega\omega_c^2\right)\right|. \tag{15}$$

As can be seen, an MPF with a periodic response is constructed. When $2\theta + \frac{1}{2}D_\omega\omega_c^2 = (2k+1)\frac{\pi}{2}, k = 0, \pm1, \pm2 \cdots$, the transmittance achieves its maximum value, so the center frequencies of the MPF present at

$$\omega_m = \sqrt{((2k+1)\pi - 4\theta)/D_\omega} (k = 0, \pm1, \pm2, \ldots). \tag{16}$$

By simply controlling θ by tuning the PC placed between the PolM and the polarizer, the center frequencies of the MPF can be shifted to any desired frequency. This filter can be incorporated into a frequency-tunable OEO to coarsely select the oscillation mode [46].

Another interesting feature of the PolM is that it can realize an ideal microwave photonic phase shifter together with an optical filter, a PC, and a polarizer [47]. Based on the Jacobi–Anger expansion, Eq. (1) can be rewritten as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \exp\left(j\frac{\phi_0}{2}\right)\left[J_0\left(\frac{\beta}{2}\right) + jJ_1\left(\frac{\beta}{2}\right)\exp(j\omega_c t) - jJ_{-1}\left(\frac{\beta}{2}\right)\exp(-j\omega_c t)\right] \\ \exp\left(-j\frac{\phi_0}{2}\right)\left[J_0\left(\frac{\beta}{2}\right) - jJ_1\left(\frac{\beta}{2}\right)\exp(j\omega_c t) + jJ_{-1}\left(\frac{\beta}{2}\right)\exp(-j\omega_c t)\right] \end{bmatrix}. \tag{17}$$

In Eq. (17), small-signal modulation is assumed so that the higher-order (>1) sidebands are ignored. An optical filter is then followed to remove one of the first-order sidebands. Therefore, two optical single-sideband (SSB) signals with a phase difference of π is obtained:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \exp\left(j\frac{\phi_0}{2}\right)\left[J_0\left(\frac{\beta}{2}\right)+J_{-1}\left(\frac{\beta}{2}\right)\exp(-j(\omega_c t+\frac{\pi}{2}))\right] \\ \exp\left(-j\frac{\phi_0}{2}\right)\left[J_0\left(\frac{\beta}{2}\right)+J_{-1}\left(\frac{\beta}{2}\right)\exp(-j(\omega_c t-\frac{\pi}{2}))\right] \end{bmatrix}. \tag{18}$$

Then the polarizer with its polarization direction aligned to have an angle of θ to one principal axes of the PolM is followed to combine the two orthogonally polarized SSB signals. Sending the combined signal to a PD for square-law detection, the output current can be written as

$$\begin{aligned} I(t) \propto\ & (1+\sin 2\theta\cos\phi_0)J_0^2\left(\frac{\beta}{2}\right) + (1-\sin 2\theta\cos\phi_0)J_{-1}^2\left(\frac{\beta}{2}\right) \\ & -2(\cos 2\theta\sin\omega_c t+\sin 2\theta\cos\omega_c t\sin\phi_0)J_0\left(\frac{\beta}{2}\right)J_{-1}\left(\frac{\beta}{2}\right) \end{aligned}. \tag{19}$$

When $\phi_0 = \pi/2$, which can be implemented by tuning the DC bias of the PolM, Eq. (19) becomes

$$I(t) \propto \cos\left(\omega_c t+2\theta+\frac{\pi}{2}\right)J_0\left(\frac{\beta}{2}\right)J_{-1}\left(\frac{\beta}{2}\right). \tag{20}$$

By changing θ in the range of $[0, \pi]$, the phase of the signal would be varied in $[0, 2\pi]$ and the amplitude remains unchanged. As a result, a full-range tunable microwave photonic phase shifter is achieved.

3. Polarization-Modulated OEO with New Features

As discussed in Section 1, the two-dimensional modulation performed by the PolM, together with a PC and a polarizer, can perform frequency multiplication, phase shifting (with an optical filter), and tunable microwave photonic filtering (with a dispersive element). If it is used to replace the conventional IM in the OEO, various new features can be enabled, including sidemode suppression through polarization multiplexed dual loops, frequency multiplying, and wideband frequency tunability.

3.1. Sidemode Suppression

In general, the Q factor of an OEO can be expressed as $Q = 2\pi f\tau$ [8], where f is the oscillation frequency, and τ is the energy decay time. To achieve a high Q value, a long fiber is always needed to ensure a large energy decay time. However, the frequency spacing of the oscillating modes in the OEO cavity is inversely proportional to the fiber length; i.e., a long fiber will lead to the generation of many densely spaced sidemodes. When the oscillation frequency of an OEO reaches several GHz, it is difficult to suppress the unwanted sidemodes using an electrical bandpass filter. One effective method to solve this problem is to employ the Vernier effect by incorporating multiple loops in the OEO

[13–15]. With the Vernier effect, only the modes that satisfy the oscillating conditions of all the loops can oscillate. By carefully choosing the fiber lengths in the loops, the sidemodes would be effectively suppressed.

In a conventional dual-loop scheme [13], the optical signal after the modulator is split into two paths in the optical domain that undergo different fiber delays in the two paths. To form the Vernier effect, the signals in the two paths must be combined before being fed back to the modulator. There are two possible ways to combine the two signals: (1) combining the two signals in the optical domain and then performing optical-to-electrical conversion by a PD and (2) performing optical-to-electrical conversion of the two optical signals using two separated PDs and then combining the two signals in the electrical domain. The first approach is cost effective, but the system suffers from serious optical interference and is therefore very sensitive to the mechanical vibrations or temperature changes. The second approach is robust, but two or more PDs are required that not only demand more complex driving circuits but also increase power consumption and noise. In addition, the electrical combining of the two loops would introduce additional power losses because the electrical power combiner has an intrinsic 3-dB loss.

These problems can be ideally solved by implementing an optical domain coupled with dual loops based on polarization modulation and polarization multiplexing [48]. Figure 2 shows the schematic diagram of the dual loops formed by polarization modulation and polarization multiplexing. A PolM in conjunction with a PC and a PBS functions as a dual-output IM, which generates two complementary intensity-modulated signals. The two signals are directed into two paths with different lengths of single-mode fiber (SMF). The two paths are combined by a PBC. Since the lightwaves in the two paths are orthogonally polarized, there is no optical interference in the PBC. As a result, a single PD can perform simultaneously the optical-to-electrical conversion and summation of the two delayed signals from the two paths. The key advantage for this configuration is that only a single PD is needed, which can reduce the noise of the generated signal and the cost of the system. Another advantage is that all the energy from the PolM is utilized, reducing at least a 4.5-dB optical or 9-dB electrical power budget as compared with the conventional dual loops based on MZMs. This includes 3 dB (optical) from the modulation scheme, since the MZMs biased at the quadrature point have an intrinsic 3-dB loss, and 3 dB (electrical) from the polarization multiplexing, because it would not introduce the 3-dB combining loss. In addition, the net loss of each loop can be adjusted easily by adding a PC in each path, making the system flexible.

By connecting the output of the PD to the RF port of the PolM, and inserting an electrical amplifier and an electrical bandpass filter, a dual-loop OEO would be constructed. Figure 3 shows the electrical spectrum of the dual-loop OEO. As can be seen, the sidemode suppression ratio (SMSR) of the generated microwave signal is less than 60 and
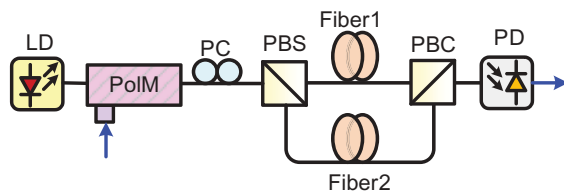
Figure 2. Schematic diagram of the dual loops formed by polarization modulation and polarization multiplexing.
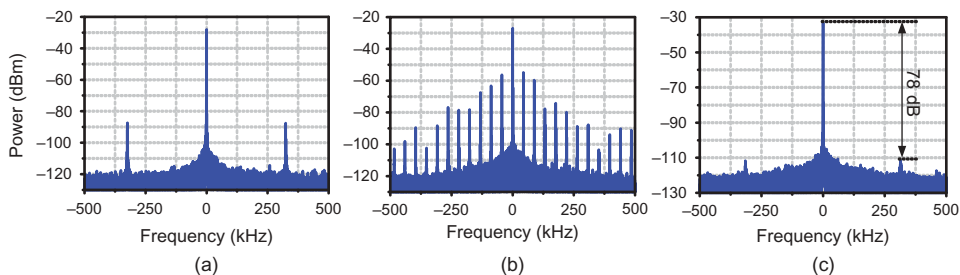
Figure 3. Electrical spectrum of single-loop and dual-loop OEOs: (a) single-loop with 600-m SMF, (b) single-loop with 4.74-km SMF is enabled, and (c) dual-loop with 600-m and 4.74-km SMFs.

30 dB, respectively, for single-loop configurations, while it reaches 78 dB if both loops are enabled, confirming that the polarization multiplexing-based dual-loop structure can effectively suppress the undesired sidemodes.

3.2. *Frequency Multiplying*

In a conventional OEO, many electrical and electro-optical devices are used, such as EOMs, PDs, electrical amplifiers, electrical couplers, electrical cables, and electrical bandpass filters, so the maximal achievable frequency of the OEO is inevitably limited due to the electronic bottleneck. An approach to extend the operational frequency range is to perform frequency multiplication in the OEO. Based on the frequency-multiplying OEO, signals with frequencies as high as hundreds of GHz are obtainable if an ultra-wideband (UWB) PD is available [49]. The key challenge to realize a frequency-multiplying OEO is to maintain the oscillation of the fundamental frequency in the loop while generating a frequency-multiplied signal out of the loop at the same time.

Compared to conventional IMs or PMs [26, 27], a PolM has the inherent advantages in realizing the frequency-multiplying OEO. As described in Section 2, if the PolM is followed by a PC and a polarizer, by properly setting the PC, fundamental frequency or frequency-doubling intensity modulation can be realized. In addition, frequency-quadrupling or frequency-sextupling intensity modulation is also achievable if an optical notch filter is used to remove the undesirable optical sidebands. Therefore, the output of the PolM can be split into several paths and a PC and polarizer inserted to each path. The fundamental frequency, frequency-doubling, frequency-quadrupling, or frequency-sextupling intensity modulations can be then implemented simultaneously. Applying the fundamental frequency modulation to maintain the oscillation, the frequency-multiplied signal can be generated at other paths. The schematic diagram of a typical PolM-based frequency-multiplying OEO is shown in Figure 4.

The frequency-doubling OEO based on polarization modulation was demonstrated in 2009 [50]. In the frequency-doubling OEO, a PolM and two polarizers together form a two-port IM with the equivalent bias points being tuned separately. One of the two-port IMs (PolM+PC2+Pol1) is set to operate at the quadrature point to maintain the oscillation of the fundamental frequency in the OEO loop. The other (PolM+PC3 +Pol2) is set to selectively operate at the quadrature point or the minimum transmission point by simply tuning PC3. Therefore, the fundamental or second harmonic frequency of the oscillation signal can be generated at PD2. Figure 5a shows the optical spectrum of the generated 10-GHz optical microwave signal. Its electrical
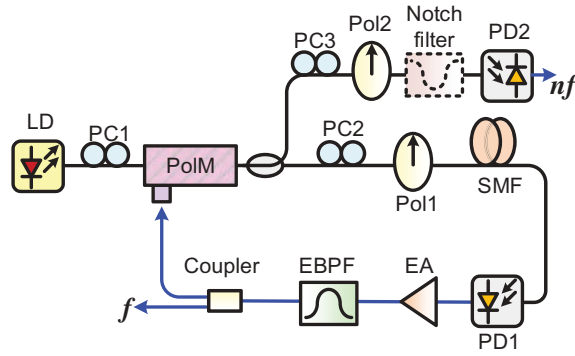
Figure 4. Schematic diagram of PolM-based frequency-multiplying OEO.
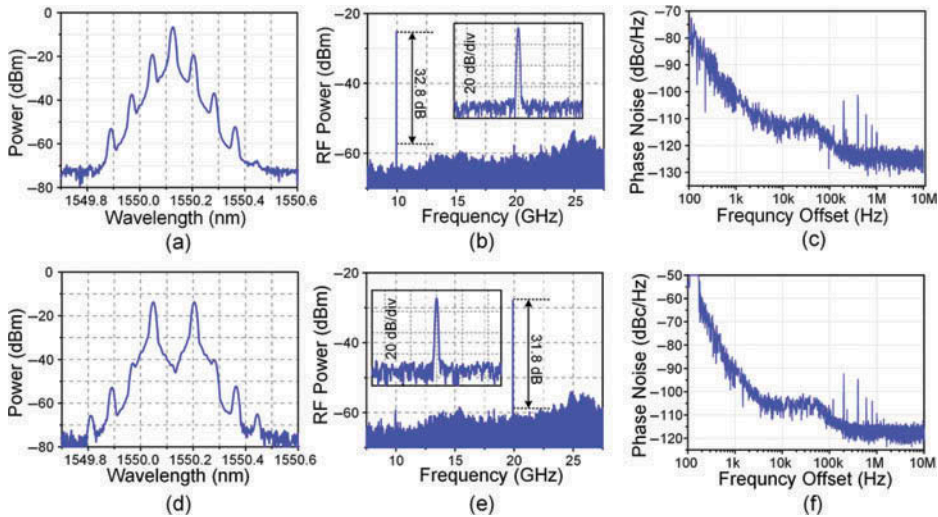
Figure 5. Generation of 10- and 20-GHz signals using the PolM-based FD-OEO: (a) and (d) optical spectra; (b) and (e) electrical spectra at a span of 20 GHz and a resolution bandwidth (RBW) of 3 MHz; inset: electrical spectra at a span of 1 MHz and an RBW of 9.1 kHz; and (c) and (f) phase noise spectra.

spectrum is shown in Figure 5b. The power of the 10-GHz signal is 32.8 dB higher than its second harmonic frequency. The zoom-in view of the 10-GHz signal at a span of 1 MHz is shown in the inset of Figure 5b. The SSB phase noise of 10-GHz signal is –112.52 dBc/Hz at a 10-kHz offset, as shown in Figure 5c. The frequency-doubled signal at 20 GHz is also generated. As can be seen from the optical spectrum shown in Figure 5d, the optical carrier is more than 30 dB lower than the first-order sidebands. Correspondingly, the generated 20-GHz electrical signal is 31.8 dB higher than the 10-GHz component, as shown in Figure 5e. Figure 5f shows the SSB phase noise spectrum of the frequency-doubled signal, which is –106.11 dBc/Hz at a 10-kHz offset.

Another frequency-doubling OEO based on polarization modulation was demonstrated in [51]. In this scheme, the equivalent IM consisting of a PolM and a polarizer is

operating at the minimum transmission point, where optical carrier and even-order side-bands are suppressed. To maintain the oscillation of fundamental frequency in the loop, a stimulated Brillouin scattering (SBS) effect is employed to recover the optical carrier.

The first frequency-quadrupling OEO based on polarization modulation was reported in [52]. The PolM-based two-port IM is also incorporated. Differently from [50], the output branch is operating at the maximum transmission point rather than the minimum transmission point. Therefore, odd-order sidebands are suppressed. An optical notch filter is employed to suppress the optical carrier. A frequency-quadrupled signal is then gener-ated at PD2. Similar frequency-quadrupling OEOs were reported in [53, 54]. In [54], the PolM is placed in a Sagnec loop. Instead of suppressing the optical carrier by an optical notch filter, the optical carrier is suppressed due to the destructive interference between the clockwise and counter-clockwise optical signals.

The frequency-multiplying OEO based on polarization modulation can also be rea-lized by cascading a second EOM [55]. The first PolM and two polarizers together form a two-port IM. One output is used to maintain the oscillation of the fundamental frequency in the loop, and the other is connected to a second PolM-based IM, which is driven by the generated fundamental frequency microwave signal shifted by a phase of 90°. A fre-quency-quadrupled optical microwave signal is generated if the second PolM-based IM is operated at the minimum transmission point. The key advantage of this approach is that no optical filter is applied, so the scheme can produce optical microwave signals at multiple wavelengths.

It should be noted that the polarization extinction ratio of the polarization elements determines the suppression ratio of the undesirable frequency components in the fre-quency-multiplying OEOs based on polarization modulation. Larger polarization extinc-tion ratio of the polarization devices leads to better spectral purity of the generated microwave signal. Currently, the commercially available polarization elements can achieve polarization extinction ratios of more than 35 dB. As a comparison, the typical extinction ratio of an MZM is only around 25 dB because it is very difficult to achieve an ideal 50/50 splitting ratio in the Y-splitter of the MZM due to the fabrication tolerance. Thus, the spurious suppression of the PolM-based OEOs was demonstrated to be preferable [50, 52].

3.3. *Frequency Tunability*

Frequency tunability is an interesting feature for a practical OEO, which always needs a high Q tunable bandpass filter implemented in the electrical or optical domain. Compared to the tunable electrical bandpass filter, an MPF is more attractive thanks to the relatively large frequency tuning range. However, the center frequency tuning of the MPF is usually realized by changing the wavelength of the injected lightwave, so very precise frequency tuning cannot be implemented due to the large linewidth and poor wavelength stability of a tunable laser source.

An OEO based on a PolM and a chirped fiber Bragg grating (CFBG) can solve this problem [46]. Figure 6 shows the schematic diagram of the tunable OEO based on polarization modulation. According to [43], a PolM in conjunction with a dispersive element, a PC, and a PBS is equivalent to a tunable MPF with the peak of the frequency response controlled by simply tuning the PC. Therefore, a coarse selection of the oscilla-tion mode is realized. The PBS is also used to form dual loops to finely select the oscillation mode through the Vernier effect. Figure 7a shows the open-loop response of the OEO. By closing the loop, a microwave signal with the frequency tunable from 5.8 to 11.8 GHz is generated, as shown in Figure 7b.
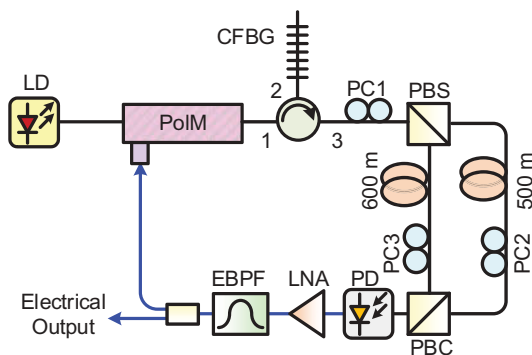
Figure 6. Schematic diagram of the tunable OEO based on a PolM and a CFBG.
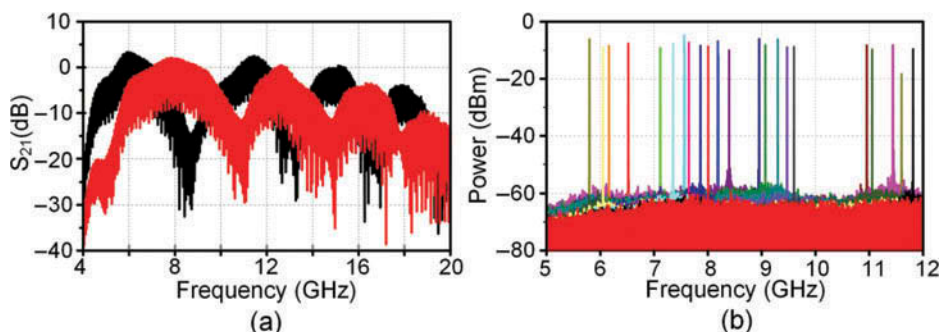
Figure 7. (a) Open-loop response of OEO and (b) measured electrical spectra of the generated microwave signals.

4. Applications of the PolM-Based OEOs

Taking advantage of the PolM-based OEO, various applications, such as digital signal processing [56, 57], photonic frequency conversion [58–62], optical comb generation [63, 64], and arbitrary microwave signal generation [65, 66], can be realized.

4.1. Digital Signal Processing

Optical digital signal processing, including clock recovery, nonreturn-to-zero (NRZ) to return-to-zero (RZ) or carrier-suppressed RZ (CSRZ) format conversions, serial-to-parallel conversion, and signal regeneration in NRZ systems, is important to the future high-speed and large-capacity optical networks. Frequency-multiplying OEOs based on polarization modulation can implement all these signal processing functions [56, 57] using the same scheme.

Figure 8 shows a typical setup for implementing the optical signal processing in an NRZ system using a frequency-doubling OEO based on polarization modulation [56]. When an optical NRZ signal with a data rate of f_m and a weak continuous wave (CW) optical probe are injected into the frequency-doubling OEO, a very small $f_m/2$ component could be occasionally introduced by the randomization of the NRZ data signal and the noise in the OEO. Once the $f_m/2$ component is present, it would be
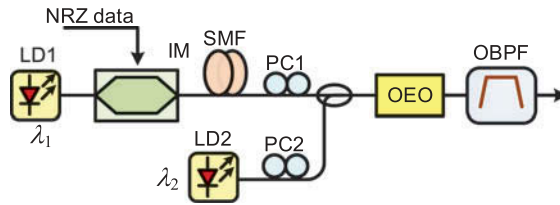
Figure 8. Experimental setup for implementing optical signal processing in an NRZ system using a frequency-doubling OEO based on polarization modulation.

captured and amplified by the OEO. The amplified $f_m/2$ component is then fed back into the PolM-based IM and modulates the later injected NRZ data signal. With this modulation, the $f_m/2$ and f_m components in the injection signal are mixed to generate a new $f_m/2$ component, so the existing $f_m/2$ component is enhanced. This positive feedback would finally lead to an oscillation at the frequency of $f_m/2$. Once the OEO is oscillating at $f_m/2$, the frequency-doubling operation on the probe wavelength at the output port would generate an optical clock at f_m. Meanwhile, the NRZ signal is re-modulated by the extracted clock, carved to be an RZ signal if the equivalent intensity modulation at the output port is biased at the maximum transmission point or a CSRZ signal if it is biased at the minimum transmission point. The re-modulation of a data signal by the extracted clock is also known as synchronous modulation, which can be used for 2R signal regeneration (re-amplification and re-timing). On the other hand, if the equivalent intensity modulation at the output port is biased at the positive or negative quadrature point, the NRZ signal is re-modulated by an $f_m/2$ clock, therefore carved to be an RZ signal with a bit rate of $f_m/2$. Therefore, optical serial-to-parallel conversion is realized.

4.2. Frequency Conversion

Frequency conversion is essential for microwave or millimeter-wave systems. The performance of the frequency-converted signal is highly dependent on the quality of the local oscillators (LOs), because the noises and sidemodes around the LO signals would be converted to the desired frequency band. For a high-frequency system, the LOs should have high frequencies. However, the generation of a high-frequency LO in the electrical domain usually involves multiple stages of frequency multiplications, leading to severe phase noise and poor spectral purity. A dual-loop PolM-based OEO is one of the most effective solutions to solve these problems, thanks to the distinct features of high sidemode suppression and low phase noise.

Several frequency up-conversion systems were demonstrated by employing the PolM-based OEO [58–60]. In [58], the frequency-doubling PolM-based OEO was used to up-convert a baseband signal with a bandwidth as high as 5 or 10 GHz to a 10- or 20-GHz RF carrier. Because the PolM together with a PC and a polarizer can be used to reduce the dispersion-induced power fading by [43], a dispersion-free multi-channel up-conversion system was demonstrated in [59]. In some specific application, such as the microwave beamforming in phased array antennas, the phase shifting is always required in addition to the frequency up-conversion. By employing the phase shifting based on an SSB polarization-modulated OEO [45], a scheme was reported that realized signal up-conversion and phase shifting simultaneously [60].

The frequency down-conversion can also be realized by the PolM-based OEO [61, 62]. Since the OEO can extract the RF carrier from the incoming RF signal, it can automatically track the phase of the received RF signal. As a result, no phase estimation or compensation components are needed in the down-conversion system, which makes the receiver simple and stable. In [61], by employing a frequency-doubling OEO, the oscillating frequency of the OEO is half of the frequency of the RF carrier, so the frequency components around the RF carrier (always have higher powers) could not directly leak to the oscillating signal, which ensures a high-performance microwave down-conversion. The frequency down-conversion based on a polarization-modulated OEO was also successfully applied in a radio-over-fiber link for the wireless distribution of a 3-Gb/s uncompressed HD video [62].

4.3. *Optical Comb Generation and Arbitrary Waveform Generation*

OEOs based on polarization modulation have also shown its potential for the generation of optical frequency comb (OFC) and microwave arbitrary waveform signals. Conventionally, the generation of an OFC always requires external RF reference sources. Since the high-quality external RF sources are expensive for practical applications, the OFC without using the external RF reference is attractive. Previously, Wang and Yao proposed a tunable OFC generator based on a dual-loop PolM-based OEO [63] using two cascaded PolMs. To simplify the scheme, Li et al. proposed another PolM-based OEO to generate the flat OFC using a single PolM with the assistance of a Brillouin-assisted power equalizer [64].

Another interesting application of the PolM-based OEO is the arbitrary waveform generation. For instance, a frequency-hopping microwave waveform was generated based on a frequency-tunable PolM-based OEO [65]. A PolM together with a polarization-maintaining phase-shifted fiber Bragg grating (PM-PSFBG) functions as a bandpass MPF, which has different transmission passbands along the two polarization axes. By quickly controlling the polarization state of the optical signal injected into the OEO loop, a frequency-hopping microwave signal is generated. Microwave signal with a hopping speed of 10 MHz and a time–bandwidth product of 700 was generated. In addition, Zheng et al. successfully used a PolM-based OEO to generate a chaotic UWB signal [66].

5.　Conclusion and Discussion

An analytical model has been established for polarization modulation-based photonic systems. By connecting a polarizer to a PolM, various types of modulation can be realized, such as the phase modulations with complementary modulation indices, fundamental frequency or frequency-doubling intensity modulations, and intensity modulation with tunable chirp. Frequency-quadrupling and frequency-sextupling intensity modulations and a microwave photonic phase shifter can also be implemented if an optical filter is used to remove the optical carrier or some of the sidebands. These functions can be switched in the same scheme simply by adjusting the polarization direction of the polarizer and the DC bias of the PolM or by inserting a PC between the PolM and the polarizer. In addition, by splitting the output of the PolM into several paths and incorporating in each path a PC and a polarizer, different functions can be implemented simultaneously using a single PolM.

The efforts to apply the PolMs in the OEOs during the past 5 years are reviewed. Special attention has been paid to describe the approaches developed to enable new

features or new applications, which are difficult or impossible to achieve through conventional IM-based OEOs. These new features include effective sidemode suppression, frequency doubling and quadrupling, and wideband frequency tunability. The schemes to perform flexible digital signal processing, high-performance photonic frequency up- and down-conversion, OFC generation, and arbitrary microwave signal generation by the PolM-based OEOs are also developed.

Although the PolM-based systems are flexible in functionality, they require precise polarization manipulation to achieve high modulation efficiency, sufficient suppression of the spurious, or accurate transmission peak. Considering that the initial polarization states can be accurately adjusted according to the performance (e.g., the spurious levels in the electrical spectrum), the misalignment of the polarization angles usually results from the polarization instability in the realistic applications. Fortunately, the PolM and the polarizer in the OEOs are placed very close to each other, so the environmental vibration will not induce fast and large variations of the polarization states if the system is well packaged. In addition, the polarization tracking circuits are commercialized, and the cost is greatly reduced, which can be employed to lock the polarization states. It should be noted that the angle of the polarization axes of the PolM and the polarization direction of the polarizer in most of the PolM-based OEOs is fixed at 0°, 90°, or ±45°. Therefore, the PolM splitter multi-polarizer structure can be possibly implemented using integrated photonic circuit. Any work on the integration of the PolM splitter multi-polarizer structure would promote the practical application of the PolM-based OEOs since it would greatly reduce the size and improve the stability of the entire system. Another possible future direction is to apply the PolM-based OEOs for multi-channel digital or analog signal processing thanks to the broad bandwidth of the polarization devices. Some works were reported [54, 56, 59], but the potential is still insufficiently developed.

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