A Tutorial on Microwave Photonics

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Abstract – The broad bandwidth and low loss offered by modern photonics have led to an ever-increasing interest in the design and implementation of photonically assisted solutions for the generation, processing, control and distribution of microwave signals, an area called microwave photonics. In this article, a tutorial on microwave photonics is presented with an emphasis on optical generation of microwave signals and all-optical microwave signal processing.

Introduction

Microwave photonics is an area that studies the interaction between microwave and optical waves for application such as radar, communications, sensor networks, warfare systems and instrumentation. In the past few years, there has been an increasing effort in researching new microwave photonic solutions for these applications [1]. In general, the microwave photonics techniques cover the following topics: 1) photonic generation of microwave signals, 2) photonic processing of microwave signals, 3) photonic distribution of microwave signals, and 4) photonic analog-to-digital conversion. In this article, techniques developed in the last few years are reviewed with an emphasis on the system architectures to implement the functions for the photonic generation, and processing of microwave signals.

Optical Generation of Microwave Signals

A high frequency and frequency-tunable microwave signal can be generated by beating two optical waves at a photodetector (PD), as shown in Fig.1. Assume we have two optical waves given by

$$E_1(t) = E_{01} \cos(\omega_1 t + \phi_1), \qquad (1)$$

and

$$E_2(t) = E_{02} \cos(\omega_2 t + \phi_2), \qquad (2)$$

where E_{01}, E_{02} are the amplitude terms and ϕ_1, ϕ_2 are the phase terms of the two optical waves. The signal at the output of the PD is given by

$$I(t) = R \, |E(t)|^2 = R \, |E_1(t) + E_2(t)|^2 =$$

$$RP_1 + RP_2 + 2R\sqrt{P_1 P_2} \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)] \quad (3)$$

where R is the responsivity of the PD. Considering the limited bandwidth of the PD, the current at the output of the PD is given by

$$I_{RF} = 2R\sqrt{P_1 P_2} \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)], \qquad (4)$$

As can be seen from (4), a microwave signal with a frequency equal to the frequency difference between the two optical waves is generated. This technique is capable of generating an electrical signal with a frequency up to the THz band, limited only by the bandwidth of the PD. However, by beating two optical waves from two free-running LDs would lead to a microwave signal having high phase noise since the phase terms of the two optical waves are not correlated, and the beating process will transfer the phase noise of the two optical waves to the generated microwave signal. Numerous techniques have been proposed in the last few years to generate low-phase-noise microwave signals with the two optical waves being locked in phase. These techniques can be classified into three categories: 1) Optical injection locking, 2) Optical phase-lock loop (OPLL), and 3) Microwave generation using external modulation. In addition, a low-phase-noise microwave signal can also be generated using an opto-electronic oscillator (OEO).

Optical Injection Locking

To generate a high-quality microwave signal via heterodyning, the phase terms of the two optical waves used for heterodyning must be highly correlated. A solution is to lock the phase terms of two optical waves via optical injection locking [2] [3]. Fig. 2 shows a scheme to achieve optical injection locking, in which a master laser diode (LD) is frequency-modulated by an microwave at f_m, and the output from the master LD, consisting of an optical carrier at λ_0, two first-order sidebands and other higher-order sidebands, is injected into the slave LDs. The two slave LDs have a free-running wavelengths close to the wavelengths of two sideband, say -2nd and $+2$nd order sidebands, thus the two slave LDs are injection locked, and the optical waves at the outputs of the two slave LDs are phase correlated and the beating of the two waves would generate a microwave signal
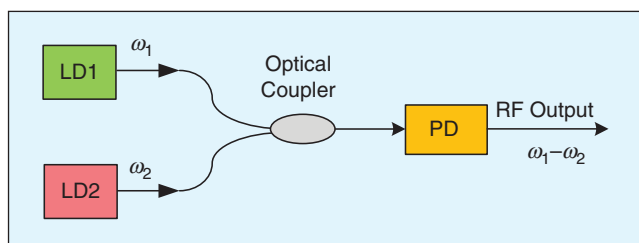

Figure 1. Beating of two optical waves at a PD for the generation of a microwave signal.
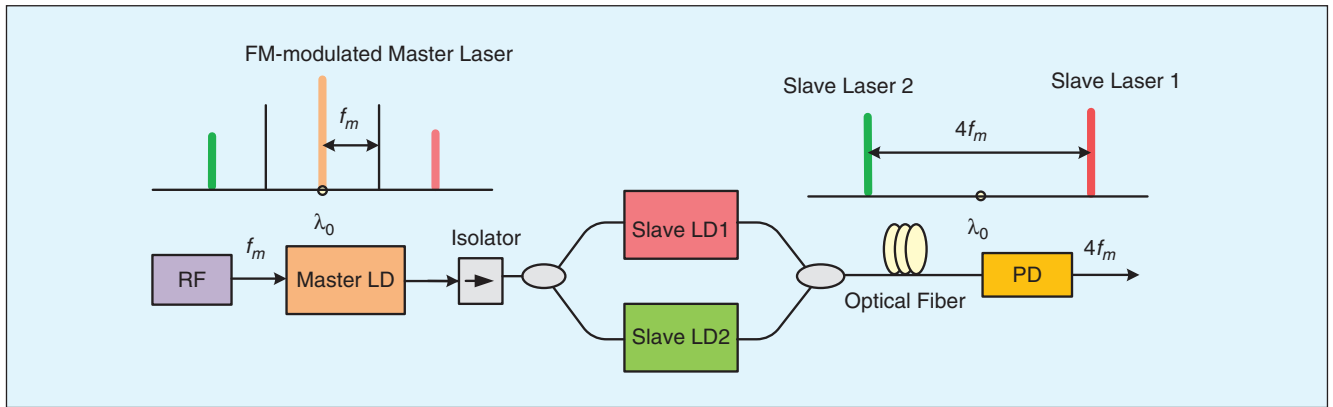
Figure 2. Optical injection locking of two slave LDs.

with its phase noise determined by the reference RF source. Note that the system can achieve frequency multiplying operation. For the configuration shown in Fig. 2, the generated frequency is four times the frequency of the reference RF source, a frequency quadrupling operation is thus achieved. Note also that the microwave signal can generated remotely. This is the key motivation of using such a technique for the optical distribution of microwave signals.

Optical Phase Lock Loop

Two free-running laser sources can also be phase locked using a phase lock loop [4]–[10]. Fig. 3 shows a scheme to achieve optical phase locking of two LDs. As can be seen two optical waves from two LDs are applied to a PD. At the output of the PD, a beat note with the frequency corresponding to the wavelength spacing is generated. The generated microwave signal is then sent to a phase detector consisting of an electronic mixer and a low-pass filter. The output voltage, which is proportional to the phase difference between the generated microwave signal and the reference signal, is sent to one LD to control the injection current, and thus its phase is accordingly changed, leading to the lock of the phase terms of the two optical waves.

The locking range is determined by the linewidth of the LDs and the loop length. To achieve affective phase locking, we need to use narrow linewidth LDs and also to make the loop length shorter. Again, similar to the injection locking scheme, the optical signal can be distributed over optical fiber for remote distribution. Note that it is not necessary that the frequency of the RF reference source is identical to the frequency of the generated microwave signal. In fact, if a harmonic generator is used, then a RF signal with different orders of harmonics can be sent to the mixer, thus a relatively low frequency RF reference signal can be used. For example, to generate a 60 GHz microwave signal, one may use a 15-GHz reference source, and the fourth harmonic will be mixed with the beat note to produce a voltage signal to control the phase of one LD.
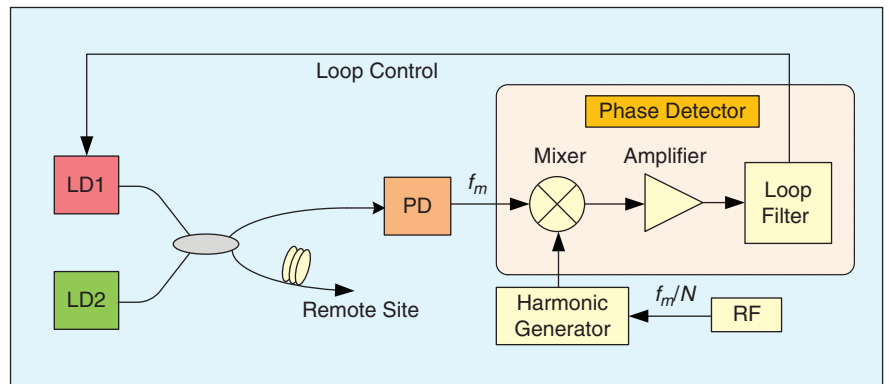

Figure 3. Optical phase locking of two LDs using a phase lock loop. The mixer, the amplifier and the loop filter forms a phase detection module.

Microwave Generation Based on External Modulation

Microwave signal generation can also be implemented based on external modulation, by which the frequency of a low-frequency microwave signal can be increased to a high frequency through frequency multiplication [11][12]. Fig. 4(a) shows a scheme to achieve frequency doubling using a Mach-Zehnder modulator (MZM). A RF signal is applied to the MZM via the RF port. The MZM is biased at the minimum transmission point (MITP) to suppress the optical carrier. At the output of the MZM, only two first-order sidebands are generated. By beating the first-order sidebands at a PD, a frequency doubled microwave signal is generated.

If the MZM is biased at the maximum transmission point (MATP), at the output of the MZM, an optical signal with an optical carrier and two second-order sidebands are generated. By using a notch filter to remove the optical carrier, and then beat the two sidebands at the PD, a frequency quadrupled microwave signal is generated.

To generate a microwave signal with a higher multiplication factor, a configuration that employs two cascaded MZMs may be used. The multiplication factor can be as high as 12, which enables the generation of a high frequency microwave or terahertz signal using a low-frequency microwave source. Different techniques have been proposed for the generation
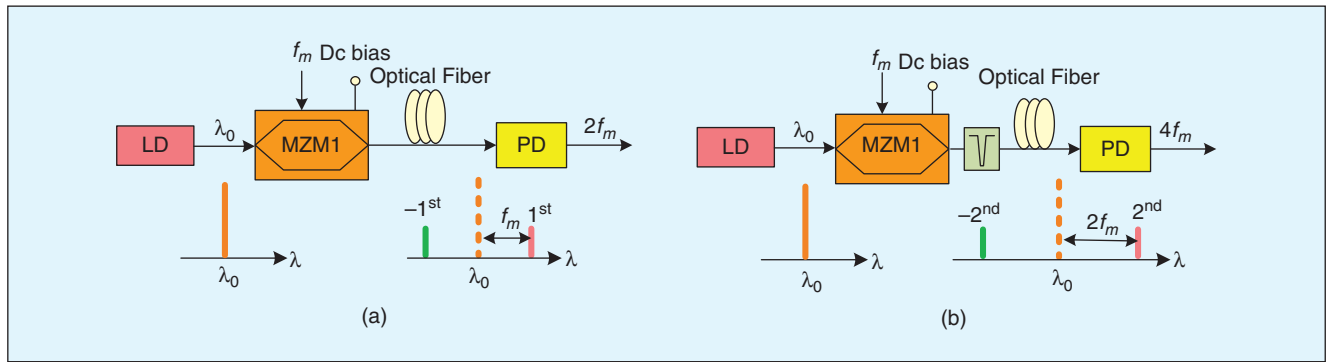
Figure 4. Microwave signal generation based on external modulation using a MZM. (a) Frequency doubling by biasing the MZM at the minimum transmission point. (b) Frequency doubling by biasing the MZM at the maximum transmission point. The optical carrier is removed by an optical notch filter.
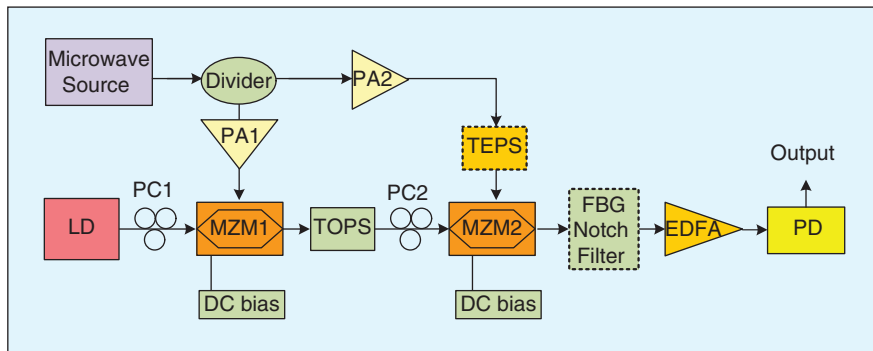

Figure 5. A generalized microwave frequency multiplication system using two cascaded MZMs. TOPS: tunable optical phase shifter, FBG: fiber Bragg grating, EDFA: erbium-doped fiber amplifier, TEPS: tunable electrical phase shifter, PA: power amplifier.
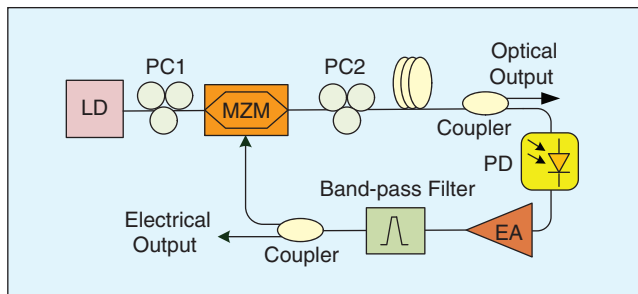

Figure 6. An opto-electronic oscillator.

Microwave Generation Based on an Electro-Optic Oscillator

In addition to the beating of two optical waves at a PD to generate a microwave signal, a high spectral purity microwave signal can also be generated using an opto-electronic oscillator (OEO) [24]. Compared with the techniques using injection locking, phase-lock loop or external modulation, the use of an OEO can generate a microwave signal without the need for a reference microwave source. Fig. 6 shows a typical OEO. If the gain in the loop is greater than the loss, the OEO will oscillate. The phase noise performance is determined by the Q factor of the OEO loop. To generate a microwave signal with low phase noise, the loop length should be long, from a few to tens of km. The use of a long loop length will, however, cause the OEO to generate a large number of closely spaced eigenmodes. To ensure a single-frequency oscillation, a high Q microwave filter with an ultra-narrow bandwidth must be used or high level of side modes will be generated. The use of multiple loops in an OEO would make the mode spacing greater, which would ease the requirement for a high Q microwave filter [25]–[27]. However, an OEO with multiple loops would have a poorer system stability and higher system cost. More importantly, the frequency tunability would be complicated if a multiple-loop structure is employed.

Recently, a technique to achieve an optically tunable OEO with a wide frequency tunable range incorporating a tunable microwave photonic filter implemented based on phase-modulation to intensity-modulation (PM-IM) conversion using a phase-shifted fiber Bragg grating (PS-FBG) was proposed [28], with the configuration shown in Fig. 7(a). When a microwave signal is applied to the PM, a phase-modulated optical signal consisting of an optical carrier and two first-order sidebands are generated. When the phase-modulated light wave is sent to the PS-FBG which has an notch in the reflection spectrum, if the optical wavelength is tuned such that one sideband of the modulated optical signal falls into the notch and is removed by the PS-FBG, the phase modulated signal

of a frequency-quadrupled [13]–[15], sextupled [16]–[18], octupled [19]–[22] and twelvetupled [23] microwave signal. All these approaches were implemented by biasing the MZMs at the MATP or MITP in conjunction with the use of an optical or microwave phase shifter and an optical filter. For two cascaded MZMs, there are four possible bias combinations: 1) MATP, MATP, 2) MITP, MITP, 3) MATP, MITP, and 4) MITP, MATP, with each combination corresponding to a specific multiplication factor under different operation conditions. Fig. 5 shows a microwave generation system using two cascaded MZMs. A theoretical analysis leading to the operating conditions to achieve frequency quadrupling, sextupling, and octupling was developed and verified experimentally [22].
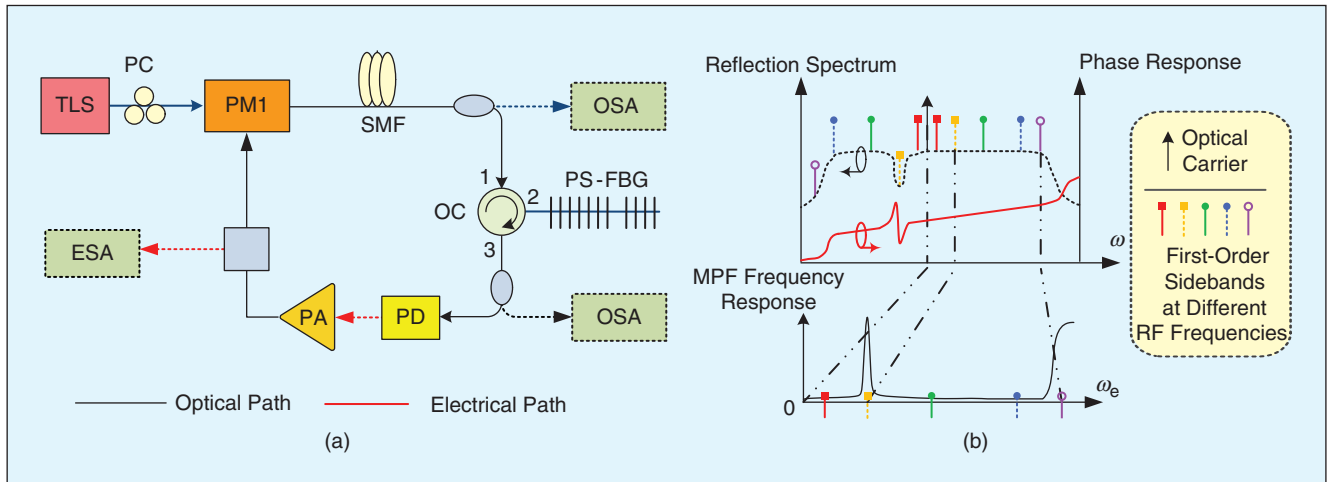
Figure 7. (a) An optically tunable OEO. (b) The Illustration of the operation of the microwave photonic filter. Upper: The reflection spectrum (dashed line) and phase response (solid line) of the PS-FBG. Lower: The frequency response of the microwave photonic filter.

becomes a single-sideband intensity-modulated signal, thus PM-IM conversion is achieved, and the joint operation of the phase modulator and the PS-FBG corresponds to a microwave photonic filter, with the filter bandwidth determined by the bandwidth of the PS-FBG. It is known that a PS-FBG can have a notch as narrow as a few MHz, thus the microwave photonic filter can effectively select one eigenmode, making the OEO operate in single frequency. The frequency tuning can be simply done by tuning the wavelength of the light wave from the tunable laser source (TLS). Thus, an OEO with a large frequency tunable range is achieved. The operation of the microwave photonic filter is shown in Fig. 7(b).

All-optical Microwave Signal Processing

Introduction to Photonic Microwave Delay-Line Filters

High-frequency and wideband microwave signals can also be processed in the optical domain. The key signal processing function is microwave filtering [29][30]. In this section, we will review the techniques to implement photonic microwave delay-line filters, with an emphasis on the generation of negative and complex coefficients to achieve bandpass filtering. The use of nonuniform time delays to generate equivalent complex coefficients to achieve photonic microwave delay-line filters with an arbitrary spectral response will also be discussed.

Fig. 8(a) shows a generic photonic microwave delay-line filter with a finite impulse response (FIR). As can be seen the filter consists of a light source, a modulator, a delay-line module, and a PD. Provided that the nonlinearity in the system is
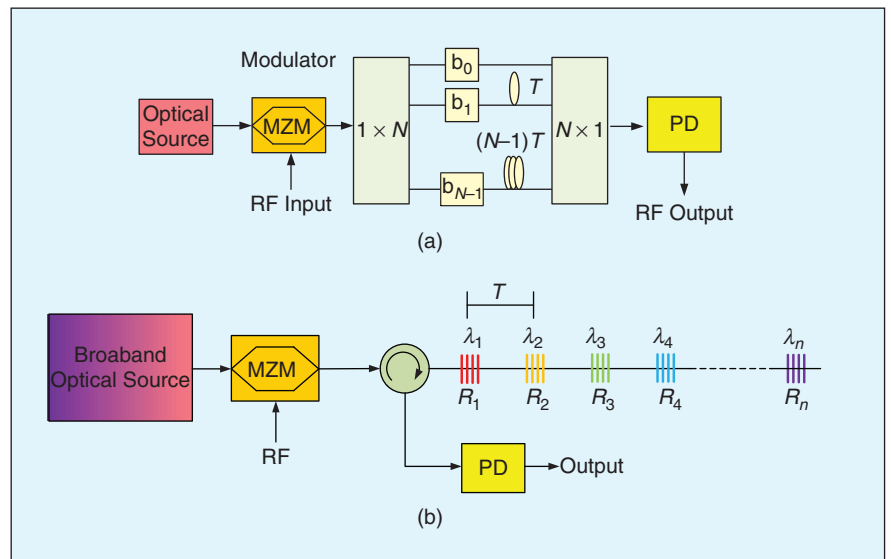

Figure 8. (a) A generic photonic microwave delay-line filter with a finite impulse response. (b) The implementation of a photonic microwave delay-line filter using an FBG array.

small and negligible, the entire system can be considered as a linear, time-invariant (LTI) system, in which the output $y(t)$ can be written as

$$y(t) = \sum_{k=0}^{N-1} a_k x(t - kT), \qquad (5)$$

where $x(t)$ is the microwave input signal, T is the time delay difference between two adjacent taps, and a_k is the coefficient of the k-th tap.

Applying the Fourier transforms to both sides of (5), the system transfer function is then obtained,

$$H(\omega) = \sum_{k=0}^{N-1} a_k \exp(-j\omega kT), \qquad (6)$$

The time delay unit T determines the free spectral range (FSR) of the microwave filter. The coefficient a_k is proportional
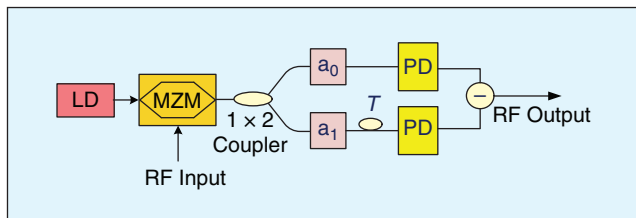
Figure 9. A photonic microwave delay-line filter with a negative coefficient using differential detection.

to the optical intensity of the k-th tap and cannot be negative. So the frequency response described by (6) is a typical transfer function of a FIR delay-line filter with all-positive coefficients.

Fig. 8(b) shows an incoherent photonic microwave delay-line filter using an FBG array. The microwave signal to be processed is modulated on an incoherent optical wave, such as a light wave from a light emitting diode (LED) or an amplified spontaneous emission (ASE) source, which is then sent to an FBG array. Due to the reflection of the FBGs in the FBG array, light waves with different time delays are detected at the PD. Since the optical source is incoherent, no optical interference will be generated at the PD. The time-delayed optical signals are then converted to time-delayed microwave signals. The overall function of the system is equivalent to a delay-line filter with the time delay difference determined by the physical separation of adjacent FBGs. The tap coefficients are set by controlling the reflectivitie of the FBGs.

Photonic Microwave Delay-Line Filters with Negative Coefficients

It is known a photonic microwave delay-line filter operating in the incoherent regime would have all-positive tap coefficients. Based on signal processing theory, an all-positive-coefficient microwave delay-line filter can only operate as a low-pass filter. To overcome this limitation, considerable efforts have been taken to design and implement photonic microwave delay-line filters with negative or complex coefficients, to achieve bandpass filtering functionality in the incoherent regime. A straightforward solution to generate negative coefficients is to use differential detection [31]. As shown in Fig. 9, a light wave from an LD is modulated by a microwave signal, which is then time delayed by optical fiber delay lines with a time delay difference of T. The output signals from the fiber delay lines are fed to a differential PD, which consists of two matched PDs with the detected microwave signals combined and subtracted electrically, leading to the generation of a positive and a negative coefficient. The two-tap photonic microwave delay-line filter shown in Fig. 9 can be extended to have N taps if the single-wavelength source is replaced by an N wavelength source and the 3-dB coupler is replaced by a $1 \times N$ WDM demultiplexer.

In Fig. 9, the negative coefficient is not generated directly in the optical domain. The limitation of this technique is that for a filter with N taps, N PDs are needed, making the filter complicated and costly. A few techniques have been proposed to implement an all-optical photonic microwave delay-line filter with negative coefficients using a single PD [32]–[37]. As

an example, negative coefficients can be generated using two MZMs that are biased at the quadrature points of the complementary transmission slopes [37], as shown in Fig. 10. The operation of the microwave phase inversion is shown in Fig. 10(a). As can be seen, the two MZMs are biased at the linear regions of the left and the right slopes of the transfer functions. When a microwave signal is applied to the two MZMs, the envelopes of the modulated optical signals are complementary. At the output of a PD, two complementary microwave signals are generated, leading to the generation of a negative coefficient. A similar technique using only a single MZM was proposed [38]. Considering the wavelength dependence nature of the transfer function of the MZM, a proper dc bias would make the modulator operate at the complementary slopes of the transfer functions when the optical wavelengths are at 1550 nm and 1310 nm windows.

All the filters discussed above are implemented based on the use of one or two MZMs. A photonic microwave bandpass filter with negative coefficients can also be implemented based on an optical phase modulator [39]. The negative coefficients are generated based on phase modulation (PM) and PM-IM conversion in two dispersive elements with complementary dispersion profiles, such as linearly chirped FBGs (LCFBGs), by reflecting the phase-modulated optical signals from the LCFBGs with complementary chirp profiles, microwave signals without or with a phase inversion are generated at the PD. An added advantage of using an optical phase modulator is that a phase modulator is not biased, which eliminates the bias drifting problem existing in a MZM-based system. The fundamental concept of the filter operation is shown in Fig. 11(a). An RF signal is applied to the optical phase modulator via the RF port to phase-modulate the multiple wavelengths at the phase modulator. Since a PD functions as an envelope detector, if a phase-modulated signal is directly applied to a PD, no modulating signal will be detected except a dc. This conclusion can also be explained based on the spectrum a phase-modulated signal. As shown in Fig. 11(a), a small-signal phase-modulated signal has a spectrum with the $+1$st and -1st order sidebands out of phase. The beating between the optical carrier and the $+1$st-order sideband exactly cancels the beating between the optical carrier and the -1st-order sideband. However, if the phase-modulated optical signal passes through a dispersive element, the phase relationship between the two sidebands and the optical carrier will be changed, leading to the conversion from phase modulation to intensity modulation. In addition, depending on the sign of the chromatic dispersion, a detected RF signal with or without a phase inversion would be obtained, leading to the generation of negative coefficients. The system configuration of the filter is shown in Fig. 11(b).

Photonic Microwave Delay-Line Filters with Complex Coefficients

The tunability of a photonic microwave delay-line filter is usually achieved by adjusting the time-delay difference. However, the change of the time-delay difference would lead to the change of the free spectral range (FSR), which results in the change of the 3-dB bandwidth as well as the entire shape of the frequency response. For many applications, it is highly
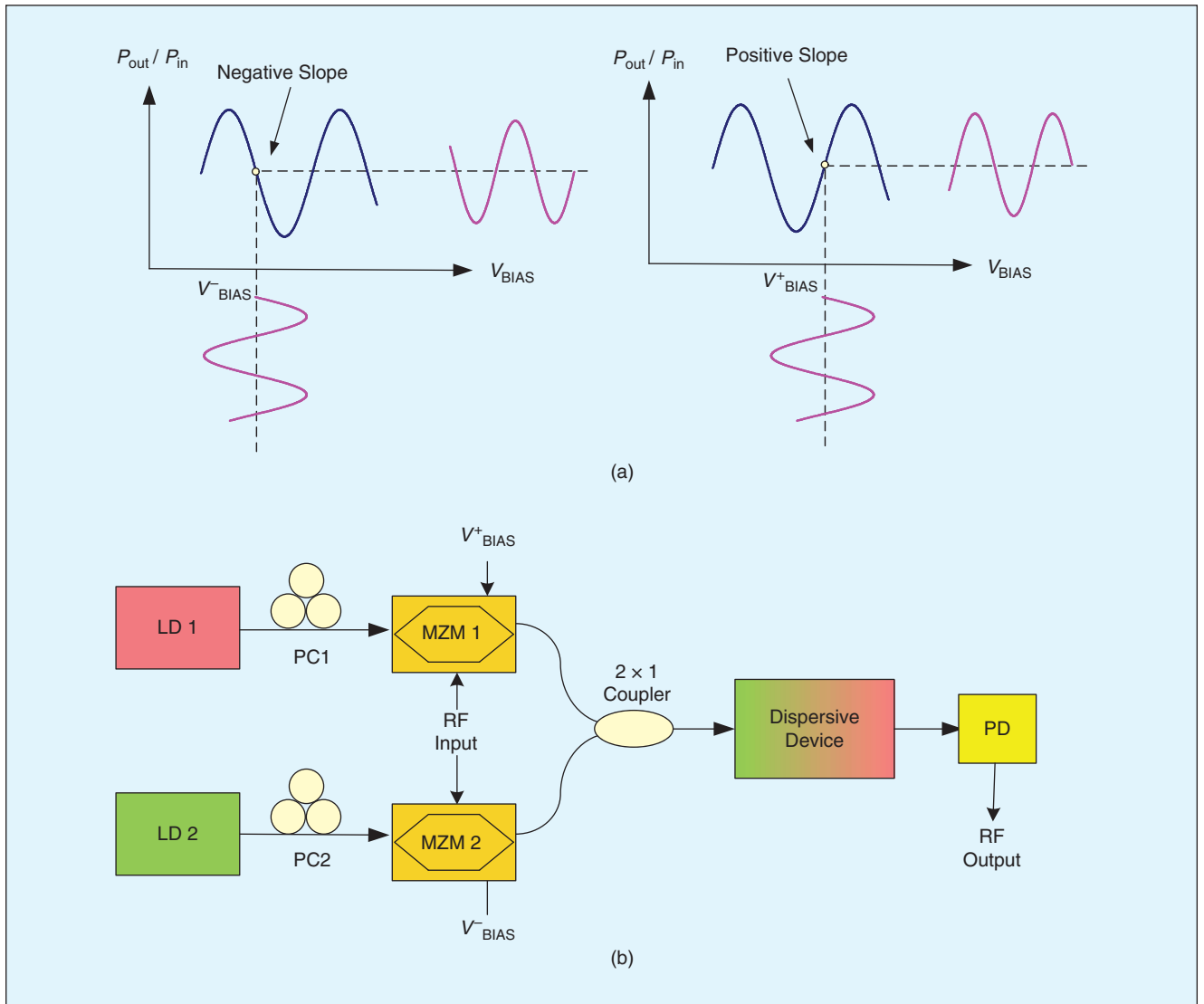
Figure 10. Photonic microwave delay-line filter with negative coefficients based on phase inversion using complementarily biased intensity modulators. (a) The operation of phase inversion, (b) the schematic of the filter.

desirable that only the center frequency of the passband or stop-band is changed while maintaining the shape of the frequency response unchanged. A solution to this problem is to design a photonic microwave delay-line filter with complex coefficients.

An N-tap microwave delay-line filter with complex coefficients should have a transfer function given by

$$H(\omega) = a_0 + a_1 e^{-j\theta} \cdot e^{-j\omega T} + \cdots + a_{N-1} e^{-j(N-1)\theta} \cdot e^{-j\omega(N-1)T}$$

$$= \sum_{n=0}^{N-1} a_n e^{-jn\theta} \cdot e^{-j\omega nT} \quad (7)$$

where T is again the time delay different between two adjacent taps. To tune the filter while maintaining the shape of the frequency response, the phase shifts of all the taps should maintain a fixed relationship, as can be seen from (7). Therefore, the phase shift of each tap should be tuned independently.

A photonic microwave delay-line filter with a complex coefficient using a wideband tunable optical RF phase shifter

was demonstrated. [40]. The RF phase shift is generated using two electro-optic MZMs by simply adjusting the bias voltages applied to the two MZMs, and the phase shift remains constant over the microwave frequency band of interest. A wideband phase shifter can also be realized based on a combined use of optical single-sideband modulation (SSB) and stimulated Brillouin scattering (SBS). It was demonstrated that the phase of a microwave signal carried by an optical carrier will experience microwave phase shift if the spectrum of the optical carrier or the sideband is falling in the SBS gain spectrum when passing through an optical fiber in which an SBS is resulted [41].

Nonuniformly Spaced Photonic Microwave Delay-Line Filters

The filters with complex coefficients in [40][41] have the potential to be extended to have multiple taps, but the filter complexity would be significantly increased since each tap needs a wideband phase shifter. To design a photonic

microwave delay-line filter with complex coefficients having a simple structure, a new concept was proposed by generating complex coefficients based on nonuniformly spaced taps [42][43]. It was demonstrated that the complex coefficients can be equivalently generated by introducing additional time delays to the taps.

As given in (6), the frequency response of a uniformly-spaced microwave delay-line filter has a frequency response is given by $H(\omega) = \sum_{k=0}^{N-1} a_k \exp(-j\omega kT)$. As can be seen $H(\omega)$ has a multi-channel frequency response with adjacent channels separated by an FSR, with the mth channel located at $\omega = m\Omega$.

In a regular photonic microwave delay-line filter based on incoherent detection, the coefficients are usually all positive, or special designs have to be employed to generate negative or complex coefficients. However, a phase term can be introduced to a specific coefficient by adding an additional time delay at the specific tap, which is termed time-delay-based phase shift. For example, at $\omega = m\Omega$ a time delay shift of $\Delta\tau$ will generate a phase shift given by $\Delta\varphi = -\Delta\tau \times m\Omega$. Note that such a phase shift is frequency-dependent, which is accurate only for the frequency at $m\Omega$, but approximately accurate for a narrow frequency band at around $m\Omega$. For most of applications, the filter is designed to have a very narrow frequency band, therefore, for the frequency band of interest, the phase shift can be considered constant over the entire bandwidth. As a result, if the mth bandpass response, where $m \neq 0$, is considered, one can then achieve the desired phase shift at the kth tap by adjusting the time delay shift by $\Delta\tau_k$. Considering the time delay shift of $\Delta\tau_k$, one can get

the frequency response of the nonuniformly-spaced delay-line filter at around $\omega = m\Omega$,

$$H_{\text{Non}}(\omega) = \sum_{k=0}^{N-1} a_k \exp\left[-j\left(k\frac{2\pi}{\Omega} + \Delta\tau_k\right)\omega\right]$$

$$\approx \sum_{k=0}^{N-1} [a_k \exp(-jm\Omega\Delta\tau_k)] \times \exp\left(-jk\frac{2\pi}{\Omega}\omega\right) \quad (8)$$

As can be seen from (8), an equivalent phase shift is generated for each tap coefficient. Specifically, if the desired phase shift for the kth tap is φ_k, the total time delay τ_k for the kth tap is $\tau_k = kT - \varphi_k/m\Omega$. As a result, if the time delay of each tap is adjusted, the filter coefficients would have the required phase shifts to generate the required passband with the desired bandpass characteristics.

The design of a nonuniformly-spaced photonic microwave delay-line filter to achieve a bandpass filter with a flat top was demonstrated [42]. The technique is particularly useful for advanced microwave signal processing. For example, the use of a nonuniformly spaced photonic microwave delay-line filter to achieve microwave phase coding [44], chirped microwave pulse generation [45], microwave pulse compression [46], microwave differentiation [47], and microwave Hilbert transformation [48] has been reported.

Conclusion

An overview about optical generation of microwave signals and all-optical microwave signal processing was presented. The key significance of using photonics to generate and process microwave signals is that high-frequency microwave signals can be generated and processed in the optical domain which may not be possible using the state-of-the-art electronics. In addition, the generated and processed microwave signals can be distributed over optical fiber for long distance distribution, to take advantage of the extremely low loss of the state-of-the-art fiber, which is an added advantage of photonic techniques for the generation and processing of microwave signals.

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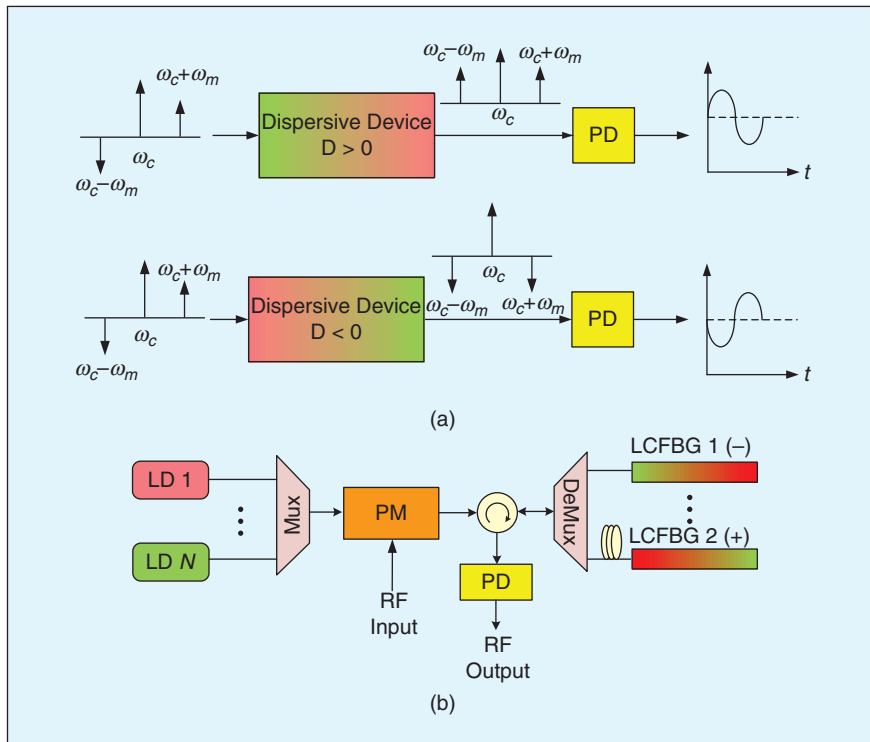
Figure 11. (a) RF phase inversion based on phase modulation and PM-IM conversion through opposite dispersions. (b) A photonic microwave delay-line filter with a negative coefficient based on PM-IM conversion in two LCFBGs with opposite dispersions.

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