Microwave Photonic Systems

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(Invited tutorial)

***Abstract*—Recent advances in microwave photonic systems are reviewed, including system architectures for photonic generation of low-phase-noise microwave signals, linearly chirped microwave waveforms, and random microwave waveforms, photonic processing of microwave signals using microwave photonic filters based on incoherent and coherent detection, and radio over fiber links based on coherent detection with increased spectral efficiency and sensitivity. Microwave photonic systems for high-speed and high-resolution optical sensing are also discussed.**

***Index Terms*—Microwave generation, microwave photonic filters, microwave photonic sensing, microwave photonics, photonic integrated circuit, radio over fiber.**

I. Introduction

MICROWAVE photonics (MWP), a field that studies the use of photonics to implement microwave functions to take advantage of the wide bandwidth and low loss offered by modern photonics, has been heavily investigated for the past few years. New system architectures and their implementations have been well studied. The most important microwave photonics functions include photonic generation of microwave signals such as low-phase-noise microwave signals and frequency-chirped microwave waveforms, photonic processing of microwave signals such as microwave filtering and microwave frequency down or up conversions, radio over fiber for transmission of wideband microwave signals over optical fibers for broadband wireless communications, true time delays for broadband and squint-free phased array beamforming, and high-speed and high-resolution optical sensing. A few review articles on microwave photonics have been published for the past few years [1], [2], [3]. Thanks to the fast development in this field, new system architectures and their implementations have been proposed and reported. In this paper, a review on new system architectures including microwave photonic systems for photonic generation of microwave signals, linearly chirped microwave waveforms, and random microwave waveforms, photonic processing of microwave signals using microwave photonic filters implemented based on incoherent and coherent detection, and radio over fiber links based on coherent detection with increased spectral efficiency and receiver sensitivity is provided. Microwave photonic systems for optical sensing to translate the sensing information from the optical domain to the microwave domain with increased speed and resolution are also discussed.

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II. Recent Activities in Microwave Photonics

Recent research activities in microwave photonics can be divided into two main directions, 1) integrated microwave photonics, and 2) new microwave photonic system architectures for existing and new system functions. In terms of integrated microwave photonics, three major material systems have been studied for the integration of microwave photonic systems including Indium Phosphide (InP), Silicon on Insulator (SOI), and Silicon Nitride (Si_3N_4). InP and related ternary or quaternary compounds can be grown on a common InP substrate for monolithic integration of both passive and active optoelectronic components. As a direct bandgap material, InP is particularly important for light generation and amplification, to implement light sources and optical amplifiers. However, its high loss and large size (InP/InGaAsP, for example, the refractive index contrast is 3.4 vs 3.2, which is considered low) may make it less competitive with SOI for high density integration. SOI, a technology that allows optical devices to be made economically using the standard and well-developed CMOS fabrication process, has been well studied recently. Most of the optical components, both passive and active, are supported. The key advantages include much smaller footprint, low loss, and simple and low-cost fabrication process (for example, the refractive index contrast is 3.5 vs 1.5, which is considered very high). The key challenge is, as an indirect bandgap material, silicon does not support optical amplification and light generation, making it impossible for monolithic integration of microwave photonic systems. Si_3N_4, a material system with very low loss, is very attractive in implementing microwave photonic systems, especially for a system involving a large number of optical components, such as true time delay beamforming networks, in which a large number of tunable time delay lines and optical switches are needed. The key limitation is that no active components such as light sources, modulators, amplifiers, and photodetectors can be supported. Heterogenous integration, a technology that takes advantage of silicon-based processing while using III-V materials for light amplification and generation, has been studied as a solution for monolithic integration of microwave photonic systems. This is a direction that is being heavily studied, which is a promising solution for the implementation of microwave photonic systems on chip.

On the other hand, research efforts have also been made to the investigation of new system architectures and new functionalities of microwave photonic systems and a few new solutions have been reported recently. In this paper, the focus will be placed on the discussion of recent advances in microwave photonic systems, including new system architectures for the generation of low-phase-noise microwave signals, linearly chirped microwave waveforms, and wideband random microwave waveforms, photonic processing of microwave signals using microwave photonic filters based on incoherent and coherent detection, and radio over fiber links based on coherent detection with increased spectral efficiency and sensitivity. Microwave photonic systems for high-speed and high-resolution sensing are also discussed.

III. Photonic Generation of Microwave Signals

A low-phase-noise and high-frequency microwave signal can be used as a local oscillator (LO) source for a wireless system to increase the receiver sensitivity. The fundamental concept to generate a microwave signal in the optical domain is to beat two optical wavelengths at a photodetector (PD) to generate a microwave signal with its frequency corresponding to the wavelength spacing of the two optical wavelengths. For two wavelengths at the 1550 nm window, for example, a wavelength spacing of 0.8 nm corresponds to a beat frequency of 100 GHz, which is very high and is hard to generate electronically. However, heterodyne beating of two wavelengths from two free running laser sources will generate a microwave signal with a large phase noise, since the beating process will translate the phase noise terms from the two wavelengths directly to the beat frequency. To reduce the phase noise, a solution is to make the two wavelengths phase locked, to fully cancel the phase noise during the beating process. There are three techniques to generate two phase-locked optical wavelengths: 1) optical injection locking, 2) optical phase lock loop, and 3) external modulation.

For injection locking [1], one may generate an optical comb through direct or indirect modulation using a reference microwave signal. By injecting the optical comb into two slave laser sources, with one having a free running wavelength that is close to the wavelength of one comb line, then the wavelengths of the two slave lasers are phase locked. The schematic of an optical injection locking system is shown in Fig. 1. The beating of the two wavelengths will generate a low-phase-noise microwave signal with the phase noise from the two wavelengths fully cancelled. In the system, the two injection-locked slave lasers may be considered functioning as two ultra-narrowband optical filters. If the comb spacing is sufficiently large, then the two slave lasers may not be needed and can be replaced by two narrowband optical filters, to select two comb lines. The optical comb can be generated by using a directly modulated laser diode (LD) or using an external modulator such as an intensity modulator or a phase modulator.

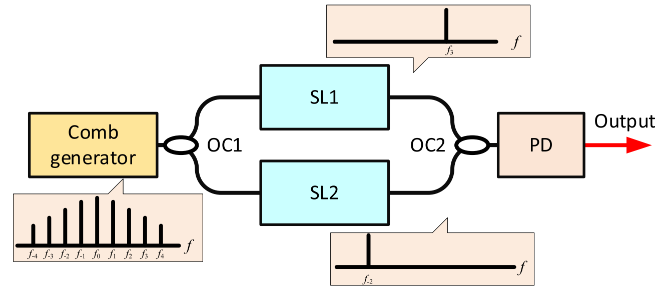

Fig. 1. An optical injection locking system for microwave signal generation. OC: optical coupler, SL: slave laser, PD: photodetector.

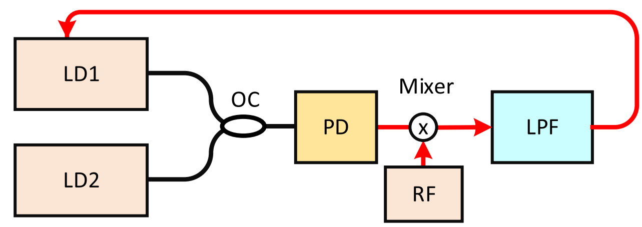

Fig. 2. An optical phase lock loop for low-phase noise microwave signal generation. LD: laser diode, OC: optical coupler, PD: photodetector, LPF: lowpass filter, RF: radio frequency.

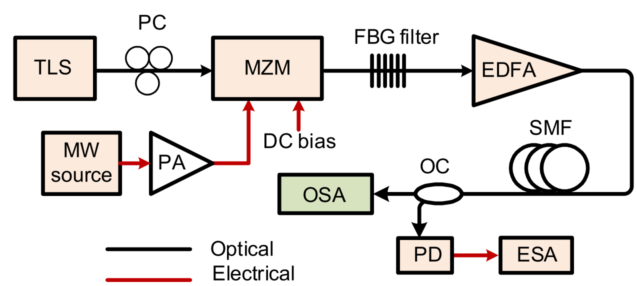

Fig. 3. Microwave signal generation based on external modulation. TLS: tunable laser source, MZM: Mach-Zehnder modulator, OC: optical coupler, SMF: single mode fiber, PA: power amplifier, FBG: fiber Bragg grating, EDFA: erbium-doped fiber amplifier, PD: photodetector, ESA: electrical spectrum analyzer, OSA: optical spectrum analyzer.

The phase terms of two free-running laser sources can also be locked using an optical phase lock loop [1]. As shown in Fig. 2, two wavelengths from two laser diodes are coupled and applied to a photodetector, where a beat note with its frequency corresponding to the wavelength difference is generated. If the two laser diodes are not locked in phase, the phase noise terms from the two laser diodes are translated to the beat signal, making it has a large phase noise. For wireless communications, for example, a microwave signal with a low phase noise is expected to make the wireless receiver have a high sensitivity. To make the two laser diodes phase locked, the beat note is mixed with a microwave reference signal at an electronic mixer and the output from the mixer is filtered by a low-pass filter (LPF). The joint operation of the mixer and the lowpass filter corresponds a phase detector with an output current or voltage proportional to the phase difference between the beat note and the reference signal, which is sent to one of the two laser diodes to control its phase, to make the two wavelengths phase locked. To achieve effective

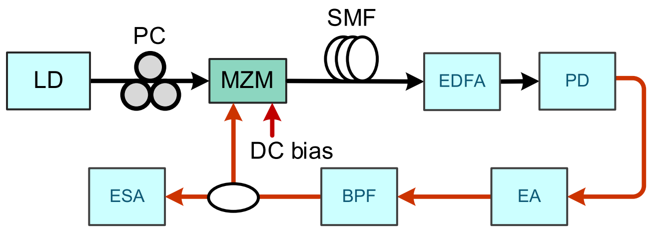

Fig. 4. Schematic of an optoelectronic oscillator (OEO). LD: laser diode, MZM: Mach-Zehnder modulator, SMF: single mode fiber, EDFA: erbium-doped fiber amplifier, PD: photodetector, EA: electronic amplifier, BPF: bandpass filter, ESA: electrical spectrum analyzer.

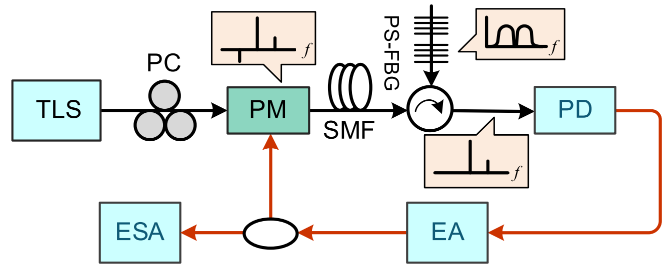

Fig. 5. A frequency-tunable optoelectronic oscillator (OEO) incorporating a frequency-tunable microwave photonic filter. TLS: tunable laser source, PM: phase modulator, PS-FBG: phase-shifted fiber Bragg grating, PD: photodetector, EA: electronic amplifier, ESA: electrical spectrum analyzer.

phase locking over a wide phase locking range, the bandwidth of the phase lock loop should be made large. A direct solution is to make the phase lock loop have a short loop length.

The limitation of the approaches based on optical injection locking and optical phase lock loop is that the frequency of the generated microwave signal is not tunable or with limited tunability. A solution to generate a microwave signal with a wide frequency tunable range is to use external modulation [1], [4], [5], [6]. For example, if a Mach-Zehnder modulator (MZM) is used to which a microwave signal is applied, by biasing the Mach-Zehnder modulator at the maximum transmission point, two second-order sidebands and an optical carrier are generated as shown in Fig. 3. By using a fixed optical stopband filter, such as a fiber Bragg grating (FBG) in transmission, the optical carrier is removed. By beating the two sidebands at a photodetector, a microwave signal with a frequency that is four times that of the microwave modulating signal is generated. The tunability can be achieved by tuning the frequency of the microwave modulating signal. Since the optical stopband filter is fixed, the system is simple in frequency tuning. The approach has been extended to have two cascaded Mach-Zehnder modulators for generation a microwave signal with a higher multiplication factor [7]. Depending on the biasing conditions, frequency quadrupling, sextupling, or octupling can be achieved.

The approaches based on optical injection locking, optical phase lock loop, and external modulation need a microwave reference source to achieve frequency multiplication, to generate a microwave signal at a higher frequency from a low-frequency microwave reference source. The negative impact is that the phase noise of a frequency-multiplied microwave signal is degraded due to that fact the phase noise is also multiplied by the same multiplication factor. Mathematically, the phase noise degradation is given by $20\log_{10}N$, where N is the frequency multiplication factor. If a microwave signal is frequency quadrupled, for example, the phase noise performance is degraded by 12 dB.

A solution to generate a high-frequency and low-phase-noise microwave signal without the need of a microwave reference signal is to use an optoelectronic oscillator (OEO) [8], [9]. An optoelectronic oscillator has an amplified hybrid feedback loop consisting of an optical path and an electrical path. The motivation to have an optical path is that a long low-loss fiber can be used in the loop, to increase the Q factor. Fig. 4 shows the schematic of an optoelectronic oscillator. As can be seen a Mach-Zehnder modulator is employed to perform electrical to optical conversion, to modulate a microwave signal on an optical carrier from a laser diode. The modulated optical signal is sent through a long single-mode fiber (SMF) and amplified by an erbium-doped fiber amplifier (EDFA) and applied to a photodetector, where the optical signal is converted to a microwave signal. An electronic amplifier (EA) is used to further increase the loop gain and an electronic bandpass filter (BPF) is connected at the output of the electronic amplifier to select the oscillation frequency before the microwave signal is fed back to the Mach-Zehnder modulator to close the optoelectronic loop. Once the gain is greater than the loss, oscillation will start and a microwave signal with its frequency equal to the center frequency of the electronic bandpass filter is generated.

To generate a microwave signal with a large frequency tunable range, the electronic bandpass filter in the loop must be frequency tunable, which is hard to achieved, especially for a large frequency tunable range. A solution is to use a microwave photonic filter (MPF), to translate the frequency response of an optical filter to the electrical domain and the central frequency of the microwave photonic filter is determined by the wavelength spacing between the optical carrier and the notch wavelength of the optical filter [10], [11], [12]. Thus, by tuning the wavelength of the optical carrier from the laser diode, the central frequency of the microwave photonic filter can be tuned, and the oscillation frequency is also tuned. Fig. 5 shows a frequency-tunable optoelectronic oscillator incorporating a microwave photonic filter. It is different from the optoelectronic oscillator shown in Fig. 4, the Mach-Zehnder modulator is replaced by a phase modulator (PM), and a phase-shifted fiber Bragg grating (PS-FBG) is connected at the output of the phase modulator. Note that the PS-FBG has an ultra-narrow notch. The microwave photonic filter is implemented based on phase modulation and phase-modulation to intensity-modulation (PM-IM) conversion in which the PS-FBG is employed to filter out one sideband of the phase-modulated optical signal from the phase modulator, to generate a single-sideband with carrier (SSB+C) signal. The detection of the SSB+C signal at the photodetector will generate a microwave signal. The entire operation is equivalent to a microwave photonic filter. If the notch of the PS-FBG is sufficiently narrow, single frequency selection can be realized, to ensure single-frequency operation of the optoelectronic oscillator. By tuning the wavelength of the optical carrier from the laser diode

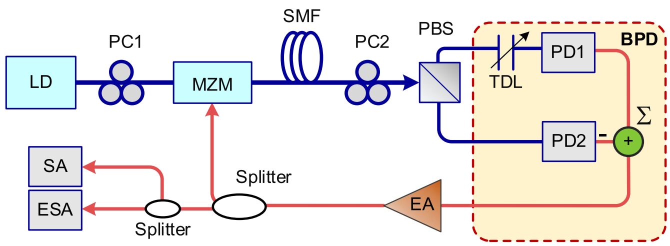

Fig. 6. A parity-time symmetric optoelectronic oscillator. LD: laser diode, PC: polarization controller, MZM: Mach-Zehnder modulator, SMF: single mode fiber, BPS: polarization beam splitter, PD: photodetector, EA: electronic amplifier, ESA: electrical spectrum analyzer, SA: signal analyzer.

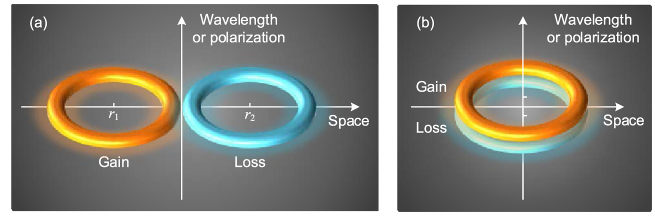

Fig. 7. (a) A parity-time symmetric system with two physical loops, and (b) a parity-time symmetric system with a single physical loop, but two equivalent loops based on wavelength or polarization division multiplexing [18].

or through thermal or mechanical tuning of the PS-FBG, the frequency of the generated microwave signal can be tuned.

The key challenge in using a long fiber in the optoelectronic loop is the small mode spacing, which is inversely proportional to the length of the loop length, making mode selection hard to achieve. For example, if the loop length is 10 km, the free spectral range (FSR) or mode spacing is only 20 kHz. To generate a microwave signal at tens of GHz, the Q factor of the microwave bandpass filter must be extremely high, and it is hard to achieve either by using an electronic bandpass filter or a microwave photonic filter.

Recently, a new concept to enhance the mode selection capability of a laser source [13], [14], [15] or an optoelectronic oscillator [16], [17] based on parity-time symmetry breaking was proposed. To implement parity-time symmetry, a laser source or an optoelectronic oscillator should have two mutually coupled resonators or ring loops with one having a gain and the other a loss, if the gain and loss coefficients are equal in magnitude, and the gain coefficient is greater than the coupling coefficient, parity-time symmetry is broken, and a mode that has the highest gain is enhanced, which would increase the mode selection capability.

Fig. 6 shows the schematic of a parity-time symmetric optoelectronic oscillator in which the two mutually coupled loops are implemented based on a polarization beam splitter (PBS) to split a linearly polarized intensity-modulated optical signal from a Mach-Zehnder modulator into two optical signals, with one having a gain and the other a loss by controlling the splitting ratio via tuning the polarization controller (PC) before the PBS.

Based on the coupled mode theory, we have

$$\frac{da_n}{dt} = -i\omega_n a_n + i\kappa b_n + \gamma_{a_n} a_n \tag{1}$$

$$\frac{db_n}{dt} = -i\omega_n b_n + i\kappa a_n + \gamma_{b_n} b_n \tag{2}$$

where a_n and b_n are the amplitudes of the n-th modes in the gain and loss loops, respectively, ω_n is the eigenfrequency of the longitudinal modes of the two loops without PT symmetry coupling, κ is the coupling coefficient between the two loops, and γ_{a_n} and γ_{b_n} are the gain coefficients of the gain and loss loops for the n-th mode. Solving (1) and (2), we can get the eigenfrequencies of the PT symmetric system, given by

$$\omega_n^{(1,2)} = \omega_n + i\frac{\gamma_{a_n} + \gamma_{b_n}}{2} \pm \sqrt{\kappa_n^2 - \left(\frac{\gamma_{a_n} - \gamma_{b_n}}{2}\right)^2} \tag{3}$$

For a mode, say $n = 0$, if the gain and the loss can be made balanced by tuning PC2, the parity-time symmetry condition, $\gamma_{a_0} = -\gamma_{b_0} = \gamma_0$, is satisfied. Then, (3) can be rewritten as

$$\omega_0^{(1,2)} = \omega_0 \pm \sqrt{\kappa_0^2 - \gamma_0^2} \tag{4}$$

If the gain/loss coefficient is smaller than the coupling coefficient, (4) has two real-valued solutions, corresponding to two frequencies, thus mode splitting is resulted. If the gain/loss coefficient is greater than the coupling coefficient, parity-time symmetry is broken, we have

$$\omega_0^{(1,2)} = \omega_0 \pm j\delta \tag{5}$$

As can be seen, the mode splitting no longer exists. Instead, the mode at ω_0 is experiencing a gain and a loss. Thanks to the gain, the mode is enhanced, which improves the capability of the system for mode selection.

The concept of using parity-time symmetry in an optoelectronic oscillator to enhance its mode selection capability has been extensively investigated since the first demonstration reported in [16]. For example, to simplify the implementation, the two physical mutually-coupled loops can be implemented using a single physical loop, but with two equivalent mutually coupled loops implemented based on wavelength division multiplexing [18] or polarization division multiplexing [19], as shown in Fig. 7. The implementation of a parity-time symmetric optoelectronic oscillator based on a hybrid integrated system, in which an integrated silicon photonic microdisk resonator was employed to implement two mutually coupled loops, was also reported [20].

Among the different techniques for low-phase-noise microwave signal generation, the one based on an optoelectronic oscillator is considered the most effective approach since a low-phase-noise and high-frequency microwave signal can be generated without the need of a reference microwave signal. In addition, the system architecture is very simple, which is particularly important for the implementation using photonic integrated circuits.

In addition to low-phase-noise and high-frequency microwave signal generation, the generation of linearly chirped microwave waveforms with a large time-bandwidth product (TBWP) is also an important topic, which can find applications in radar systems and microwave imaging systems to increase the range and imaging resolution through pulse compression. A large number of papers have been published. In general, all the approaches can be classified into three categories, 1) direct space-to-time (DST) pulse shaping, 2) temporal pulse shaping (TPS), and 3) spectral shaping and wavelength-to-time (SS-WTT) mapping. A comprehensive review of microwave arbitrary waveform generation based on microwave photonics can be found from [21]. The key limitation of these approaches [21] is that a generated microwave waveform has a small TBWP, although the bandwidth can be made very large, the temporal duration is usually very small, limited mainly by the limited dispersion which is needed to disperse an optical pulse, to extend the temporal width. Although the use of a sawtooth current to directly modulate a laser diode, to generate a linearly chirped optical waveform and to beat the chirped optical waveform with a fixed wavelength, can generate a linearly chirped microwave waveform with a large temporal duration, the phase noise performance of the generated microwave waveform is poor due to the fact that the laser diode when being tuned from one frequency to another needs a buildup time, causing phase disturbances at the new frequency [22]. Similarly, by electronically tuning an optoelectronic oscillator, a linearly chirped microwave waveform can also be generated, but the problem of phase disturbances existing in a laser diode when being tuned to a new frequency also exists [23].

A solution to generate a linearly chirped microwave waveform that is free from the phase disturbances when being tuned from one frequency to another is to use a Fourier domain mode-locked optoelectronic oscillator [25]. The mode locking concept is similar to an actively mode-locked optoelectronic oscillator in which all modes coexist in the optoelectronic loop and are phase locked [24]. For Fourier domain mode locking, instead of locking all modes using an active switch or an optical modulator, a frequency-tunable microwave bandpass filter is employed, in which the tuning frequency is an integer number of the free spectral range (FSR) of the optoelectronic loop, thus all modes are phase locked, and due to the narrow bandwidth nature of the frequency-tunable microwave bandpass filter, at one time, only a single mode is selected and sent to the output. Thus, at the output of the optoelectronic oscillator, a frequency chirped microwave waveform is generated. The concept of Fourier domain mode locking was previously reported to generate a frequency-chirped optical waveform for applications in optical coherence tomography [26].

The key challenge in implementing a Fourier domain mode-locked optoelectronic oscillator is to have a fast and frequency-tunable narrow bandwidth microwave bandpass filter. A solution to implement a fast and frequency-tunable narrow bandwidth microwave bandpass filter is to use photonics. In [25], a microwave photonic bandpass filter was implemented based on phase modulation and phase-modulation to intensity-modulation conversion using a narrow bandwidth optical notch filter. Through fast tuning the wavelength of the optical carrier from a laser diode by applying a sawtooth driving current, the filter can be fast tuned. Fig. 8 shows a Fourier domain mode-locked optoelectronic oscillator.

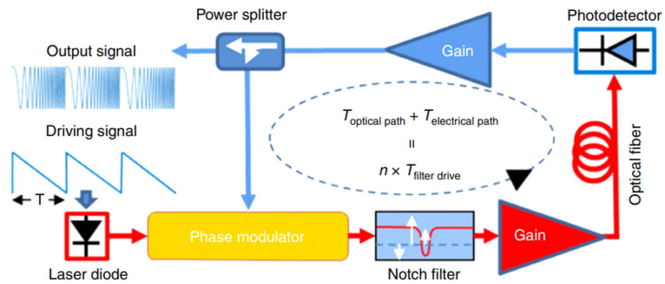

Fig. 8. A Fourier domain mode-locked optoelectronic oscillator [25].

Again, to generate a chirped microwave waveform with a low phase noise, the length of the optoelectronic loop has to be long to make the loop have a large Q factor. A long optoelectronic loop, however, would have a large number of closely spaced longitudinal modes, making the mode selection difficult. For example, if the loop length is 10 km, the mode spacing is only 20 kHz, which is very small. A microwave bandpass filter operating at a central frequency of a few to tens of GHz cannot have such a narrow bandwidth. Thus, at one time, not a single, but multiple modes are selected, this would cause performance degradation of the generated chirped microwave waveform.

Another approach to generate a frequency-tunable linearly chirped microwave waveform with a higher central frequency is to use a wavelength-tunable Fourier domain mode-locked laser source. Again, the Fourier domain mode locking is implemented using a frequency-tunable optical bandpass filter. Through beating a linearly chirped optical waveform generated by the Fourier domain mode-locked laser source with a fixed wavelength, a frequency-tunable linearly chirped microwave waveform at a high central frequency can be generated [27].

In addition to a linearly chirped microwave waveform, a random microwave waveform can have a large TBWP and can also be employed in radar systems to increase the range resolution. In addition, the use of a random microwave waveform in a radar system can improve the system performance in terms of electronic counter-countermeasures. A random microwave waveform can be generated based on microwave photonics. For example, by using a random fiber grating which has a spectral response that is randomly distributed, based on spectral shaping and wavelength-to-time mapping, a random microwave waveform can be generated [28]. The key component in the implementation is the random fiber grating, which can be fabricated in an optical fiber by pseudo-randomly varying the refractive index, to produce a randomly distributed spectral response. Using a random fiber grating as a spectrum shaper and a dispersive element such as a linearly chirped fiber Bragg grating (FBG) for wavelength-to-time mapping, a random microwave waveform with its shape identical to the random spectral response was generated [28]. The temporal duration of the generated microwave waveform is determined by the total dispersion of the dispersive element, which could be very large if the propagation loss is compensated, while the bandwidth of the generated waveform can be as wide as tens of GHz. A random microwave waveform with a temporal duration of 10 ns and a bandwidth of 32.24 GHz

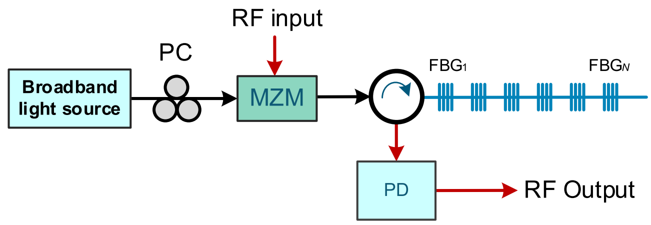

Fig. 9. A delay-line filter using a broadband light source and a fiber Bragg grating array. PC: polarization controller, MZM: Mach-Zehnder modulator, PD: photodetector, FBG: fiber Bragg grating.

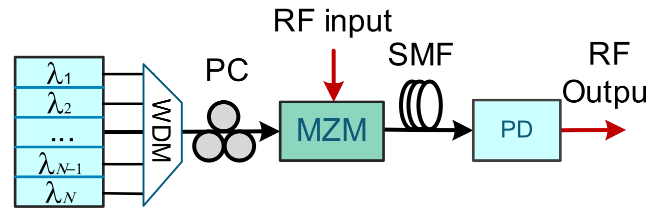

Fig. 10. A delay-line filter using a laser array having multiple wavelengths with an identical wavelength spacing. WDM: wavelength division multiplexer, MZM: Mach-Zehnder modulator, SMF: single-mode fiber, PC: polarization controller, PD: photodetector.

was generated experimentally. The TBWP was calculated to be 322.4.

IV. Microwave Signal Processing

Microwave signals can also be processed in the optical domain to take advantage of the wide bandwidth and low loss offered by photonics. In general, the processing of microwave signals in the optical domain belongs to analog processing, with the functionalities including microwave frequency up or down conversion, phase shift, time delay, and filtering. Among all these functionalities, photonic-assisted microwave filtering is considered an effective solution to implement microwave filters with large and flexible frequency tunability. A photonic-assisted microwave filter can also be designed and implemented to have a special spectral response such as a quadratic phase response for matched filtering [29] and flat-top magnitude response [30]. In this Section, photonic-assisted microwave filters will be discussed.

In general, the implementations of microwave photonic filters can be classified as two categories, 1) microwave photonic filters based on incoherent detection and microwave photonic filters based on coherent detection. Microwave photonic filters based on incoherent detection usually have a delay-line structure with a finite impulse response (FIR) or an infinite impulse response (IIR). A few review or tutorial articles have been published about delay-line filters based on incoherent detection [1], [31], [32], [33]. Here a few examples are provided and then more discussions about microwave photonic filters based on coherent detection will be provided.

A. Incoherent Microwave Photonic Filters

A microwave photonic filter based on incoherent detection can be implemented by either using an incoherent light source to avoid optical interferences at the photodetector or multiple wavelengths to allow a beat note between any two wavelengths to have a frequency that is beyond the bandwidth of the photodetector, thus the interferences are not detectable within the bandwidth of the microwave photonic filter. Fig. 9 shows a microwave photonic filter using an incoherent broadband light source, such a light emitting diode (LED) or an amplified spontaneous emission (ASE) source [34]. The broadband light source is modulated at a Mach-Zehnder modulator by a microwave signal to be processed and sent to a fiber Bragg grating (FBG) array. The modulated light from the modulator is sliced and time-delayed by the FBGs and detected at the photodetector. The coefficients of the delay-line filter can be determined by the reflection coefficients of the FBGs or if the FBGs are with identical reflectivities, the coefficients can be controlled by tailoring the shape of the spectrum of the broadband light source [34], and the time delays are determined by the physical locations of the FBGs. The limitation of the approach using a broadband light source is that the sliced and time-delayed optical signals have very low optical powers. After detection, the microwave powers are also very low, thus the filter has poor noise performance with a large noise figure (NF). A solution to the problem is to replace the broadband light source by a laser array with multiple wavelengths. Fig. 10 shows a delay-line filter consisting of a laser array having multiple wavelengths with an identical wavelength spacing. A microwave signal to be processed is modulated on the multiple wavelengths at a Mach-Zehnder modulator and the modulated light is sent through a dispersive fiber or a single-mode fiber, to introduce dispersion-induced time delays, and detected at a photodetector. For a standard single-mode fiber, the time delay between two taps with a wavelength spacing $\Delta\lambda$ is given by $\tau = D\Delta\lambda L$, where D is the dispersion coefficient (which is 17 ps/km. nm for a standard single-mode fiber at 1550 nm), and L is the length of the dispersive fiber. If the wavelength spacing is 1 nm, and the fiber length is 1 km, the time delay between two adjacent taps is calculated to be 17 ps. Note that the wavelength spacing must be large enough to make the frequency of the beat signal between two adjacent wavelengths higher than the maximum frequency of the photodetector, to avoid generating a beat signal at the output of the photodetector.

The microwave photonic filter using an FBG array shown in Fig. 9 is not frequency tunable since the time delay between two adjacent taps is fixed once the FBGs are inscribed in a fiber and the physical spacing between adjacent FBGs determines the time delay. This is the key limitation of this filter. The microwave photonic filter shown in Fig. 10 is frequency tunable, which can be done by tuning the wavelength spacing of the laser array. The tap coefficients can be tuned by tuning the optical powers of the wavelengths from the laser array. Clearly, the tuning is very complicated, especially the wavelength tuning, which must be done to ensure the spacing between any adjacent wavelengths identical, a very challenging task.

The fundamental limitation of a delay-line filter based on incoherent detection is that the tap coefficients are all positive, making the filter operate as a lowpass filter only. To implement a bandpass filter, the coefficients should have negative or complex

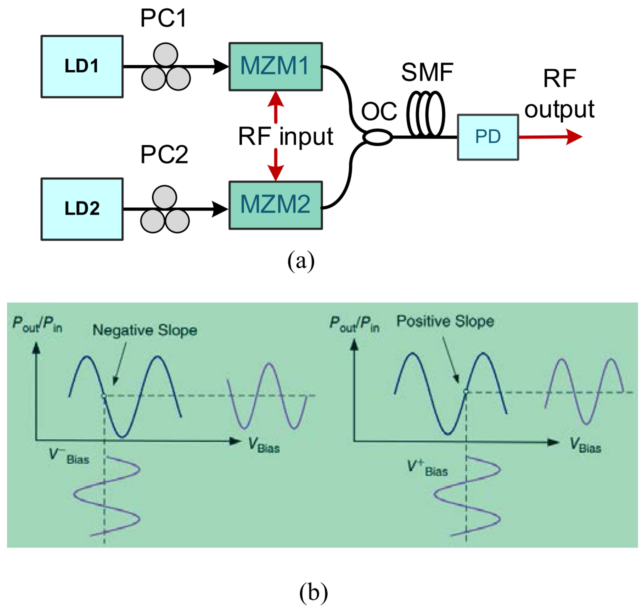

Fig. 11. (a) A two-tap delay-line filter with one negative coefficient. (b) Implementation of negative coefficient by biasing the Mach-Zehnder modulators at the complementary slopes of the transfer functions. LD: laser diode, MZM: Mach-Zehnder modulator, OC: optical coupler, PD: photodetector.

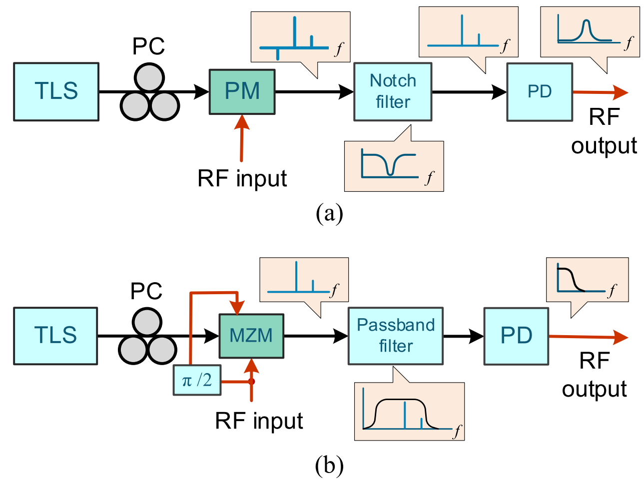

Fig. 12. Microwave photonic filter based on coherent detection. (a) A microwave passband filter implemented based on phase modulation and PM-IM conversion using an optical filter. (b) A microwave lowpass filter implemented based on single sideband plus carrier modulation. TLS: tunable laser source, PM: phase modulator, PD: photodetector, MZM: Mach-Zehnder modulator, PD: photodetector.

coefficients. A simple solution to implement a delay-line filter with negative coefficients is to use two Mach-Zehnder modulators that are biased at the quadrature points on the complementary slopes of the transfer function, as shown Fig. 11 [1]. The use of a semiconductor optical amplifier (SOA) to achieve signal amplitude inversion can also be used to achieve negative coefficients [1].

B. Coherent Microwave Photonic Filters

A microwave photonic filter based on coherent detection can be implemented using an optical filter, to translate the spectral response of the optical filter to the microwave domain. Instead of using a broadband light source or a laser array with multiple wavelengths, a single laser diode is used. Fig. 12(a) and (b) shows two microwave photonic filters based on coherent detection in which the light source is a laser diode. As can be seen from Fig. 12(a), the light from the laser diode is modulated at a phase modulator to generate a double sideband with carrier (DSB+C) optical signal. Note that the difference between intensity modulation using a Mach-Zehnder modulator and phase modulation using a phase modulator is that the two sidebands of a phase-modulated optical signal are out of phase. The beating between one sideband with the optical carrier will cancel completely the beating between the other sideband with the optical carrier. Thus, direct detection of a phase-modulated optical signal will not generate a microwave signal except a DC. However, if one sideband is removed by the notch of the optical filter, as shown in Fig. 12(a), then the DSB+C phase-modulated signal is converted to an SSB+C signal and the detection of the SSB+C signal at a photodetector will generate a microwave signal. The entire operation is equivalent to implementing a microwave passband filter with the shape of the passband determined by the spectral response of the optical filter. To have a narrow passband, the passband of the optical filter has to be narrow. For example, by using the notch of a PS-FBG, a narrow passband microwave filter with a bandwidth of 60 MHz can be implemented [35].

By using a Mach-Zehnder modulator and an optical passband filter, a microwave lowpass filter can be implemented. As can be seen from Fig. 12(b), by using a Mach-Zehnder modulator and a 90° hybrid, an SSB+C signal is generated. By placing the optical carrier within the passband of the optical bandpass filter, depending on the frequency of the microwave signal, the sideband will be within the passband of the optical filter or outside the passband of the optical filter, leading to the implementation of a microwave lowpass filter. The bandwidth can be tuned by tuning the wavelength of the optical carrier. The closer the optical carrier to the right edge of the passband, the narrower the bandwidth of the lowpass filter. The limitation of this approach is that only a lowpass filter can be implemented.

Based on the similar concept, a bandstop-to-bandpass microwave photonic filter based on a dual-drive Mach–Zehnder modulator (DD-MZM) and a PS-FBG was reported [36]. The dual-drive Mach–Zehnder modulator was employed to generate a phase-modulated or a quasi-single-sideband (QSSB) optical signal by controlling the bias voltages. By applying the phase-modulated or QSSB signal to the PS-FBG to suppress one sideband, a bandpass or a bandstop microwave photonic filter was implemented.

The same filter architectures shown in Fig. 12(a) and (b) can be implemented using photonic integrated circuits. Fig. 13 shows a silicon photonic integrated microwave bandpass filter [37]. All components including a phase modulator, an optical filter which is a microdisk, and a photodetector were implemented on the silicon chip. The light source was from external since silicon

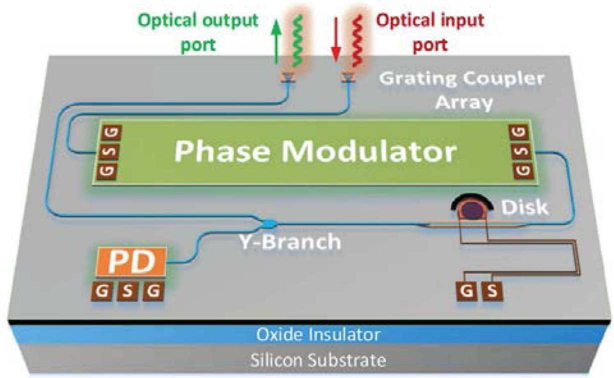

Fig. 13. A silicon photonic integrated microwave photonic filter. [37].

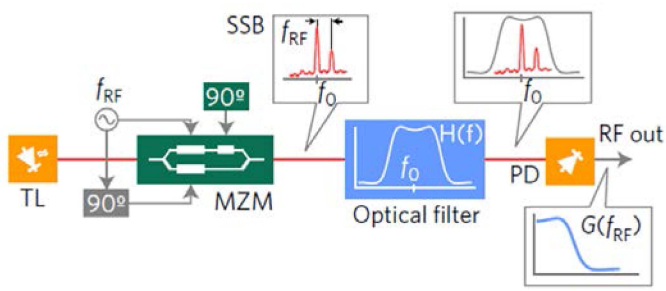

Fig. 14. A monolithically integrated microwave lowpass filter on InP [40].

is an indirect bandgap material and no light can be generated by silicon. To achieve monolithic integration, a laser source and analog electronics should also be integrated on the same silicon chip, heterogenous integration is thus needed [38], [39].

InP is a material system that can implement both active and passive optical components. Based on InP, a monolithically integrated microwave filter shown in Fig. 14 was demonstrated [40]. Due to a relatively high loss of InP, the bandwidth of the optical bandpass filter is very large (a few GHz), making the implemented microwave lowpass filter has a wide bandwidth of a few GHz. To implement a microwave lowpass filter with a narrow bandwidth, a narrow bandwidth optical filter is needed. Again, heterogenous integration may be needed. For example, the optical bandpass filter can be implemented using Si_3N_4 [41], which has a much lower loss than InP and SOI.

Between the two implementations, the use of coherent detection is advantageous in terms of flexibility in tailoring the spectral response of a microwave photonic filter. In fact, the spectral response of a microwave photonic filter based on coherent detection is translated from an optical filter. By controlling the spectral response of the optical filter, a microwave photonic filter with the required spectral response can be achieved. A microwave photonic filter based on coherent detection is particularly suitable for photonic integration due to the system simplicity. If heterogeneous integration is available using InP to produce a laser source, a modulator, and a photodetector, and Si_3N_4 to produce a high Q-factor optical filter, all on a

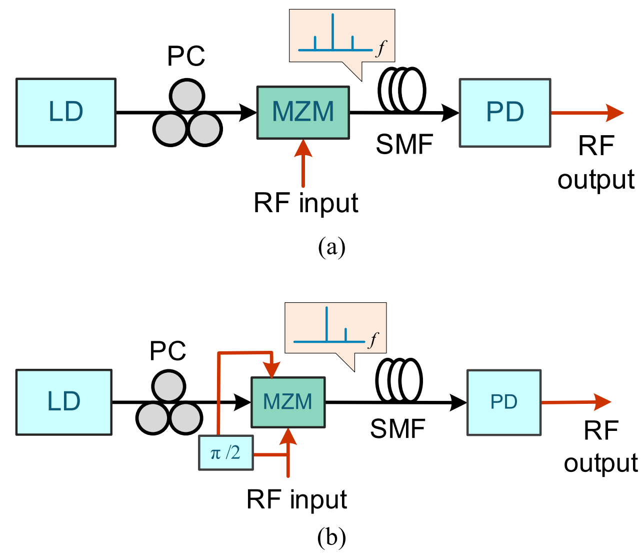

Fig. 15. An IM-DD RoF link. (a) DSB+C modulation, and (b) SSB+C modulation. LD: laser diode, MZM: Mach-Zehnder modulator, SMF: single mode fiber, PD: photodetector.

silicon platform, a high-performance microwave filter would be implemented.

V. Radio Over Fiber Based on Coherent Detection

Transmission of radio signal over fiber or radio over fiber (RoF) to take advantage of the low loss and wide bandwidth of state-of-the-art fibers has been intensively studied [42]. In general, RoF links are classified into two categories, 1) intensity-modulation and direct-detention (IM-DD) RoF links and 2) coherent detection RoF links. An IM-DD RoF link has a key advantage of simplicity, but the spectral efficiency is low. Although wavelength division multiplexing (WDM) and polarization division multiplexing (PDM) techniques, developed for optical fiber communications, can be employed in an IM-DD RoF link to increase the transmission capacity, the spectral efficiency can still be further increased if coherent detection and digital signal processing (DSP) is employed [43].

Fig. 15 shows an IM-DD RoF link in which a radio frequency (RF) signal is modulated on an optical carrier from a laser diode at a Mach-Zehnder modulator, to generate a DSB+C signal. The modulated optical signal is transmitted over a single-mode fiber and detected at a photodetector. Due to fiber chromatic dispersion, the two sidebands and the optical carrier will experience different time delays or phase shifts, which would cause partial or full cancelation of the beat signals resulted from the beating between upper sideband and the optical carrier, and the lower sideband and the optical carrier, leading to dispersion-induced power penalty. A simple solution to eliminate the dispersion-induced power penalty is to remove one sideband by either using an optical notch filter to filter out one sideband or using a dual-drive Mach–Zehnder modulator and a 90º hybrid to directly generate an SSB+C signal [44]. Since one sideband is eliminated, no cancellation would happen, making the RoF link immune to fiber chromatic dispersion.

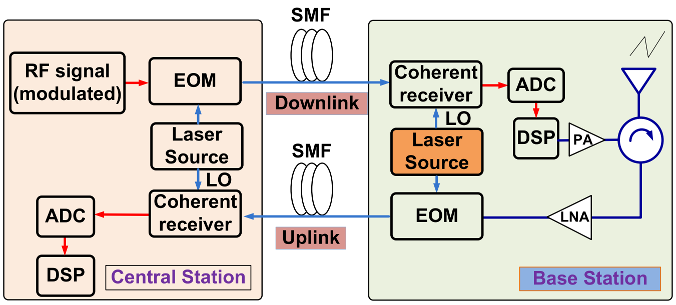

Fig. 16. A duplex RoF link with coherent detection. EOM: electrooptic modulator, SMF: single-mode fiber, ADC: analog-to-digital converter, DSP: digital signal processor, PA: power amplifier, LNA: low noise amplifier, LO: local oscillator.

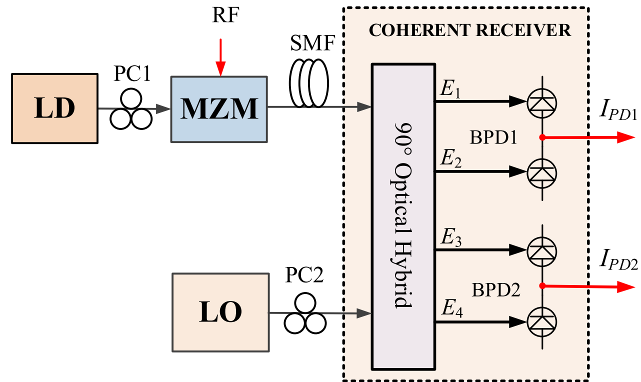

Fig. 17. A coherent RoF link with signal detection at an optical coherent receiver. LD: laser diode, BPD: balanced photodetector, MZM: Mach-Zehnder modulator, LO: local oscillator, PC: polarization controller, SMF: single-mode fiber.

In addition to an increased spectral efficiency, the use of coherent detection can also increase the receiver sensitivity. Fig. 16 shows a duplex RoF link connecting a central station and a base station via two single-mode fiber links (one for downlink and the other for uplink). At the central station, an RF signal is modulated at an optical modulator on an optical carrier from a transmitter laser source and sent to the base station via the downlink single-mode fiber. At the base station, the optical signal is detected at a coherent receiver, to which a local oscillator (LO) light is also applied. Since the transmitter laser source and the LO laser source are located at two different locations and are not phase locked, the coherent detection would translate the phase noise terms from the two laser sources to the detected RF signal, causing a joint phase noise. The unstable wavelengths would also cause an unstable offset frequency, which will also cause a frequency drift of the coherently detected RF signal. Therefore, solutions must be found to eliminate the joint phase noise and the unstable offset frequency from the two laser sources.

Coherent detection can also be applied to the uplink. As shown in Fig. 16, the transmitter laser source can be shared and used as an LO laser source for uplink coherent detection, and the LO laser source at the base station can be shared and used as a transmitter laser source for uplink transmission. A DSP unit is also needed at the central station to perform digital phase noise cancellation.

Fig. 17 shows a coherent RoF link with the optical signal detected at the optical coherent receiver. An RF signal is modulated on the optical carrier at a Mach-Zehnder modulator. The Mach-Zehnder modulator is biased at the quadrature point, and the optical field at the output of the Mach-Zehnder modulator is given by

$$E_s\left(t\right) = \sqrt{2P_sL_s}\cos\left[\pi s\left(t\right)/2V_\pi + \pi/4\right]e^{j\left[\omega_c t+\phi_c(t)\right]} \quad (6)$$

where P_s is the optical power of the light from the transmitter laser source and ω_c is its angular frequency, $s(t)$ is the input RF signal, $\phi_c(t)$ is the phase term of the transmitter laser source, V_π is the half-wave voltage of the Mach-Zehnder modulator, and L_s is the link loss between the coherent receiver and the transmitter.

Similarly, the optical field at the output of the LO laser source can be written as

$$E_{LO}\left(t\right) = \sqrt{2P_{LO}}e^{j\left[\omega_{LO}t+\phi_{LO}(t)\right]} \quad (7)$$

where P_{LO} is the optical power of the light wave from the LO laser source, $\phi_{LO}(t)$ is the phase term, and ω_{LO} is the angular frequency.

The optical signal from the transmitter and the light from the LO laser source are co-polarized and are sent to a 90° optical hybrid. At the four outputs of the optical hybrid, we have the electrical fields given by

$$E_1 = \sqrt{L}\left(E_s + E_{LO}\right) \quad (8)$$

$$E_2 = \sqrt{L}\left(E_s - E_{LO}\right) \quad (9)$$

$$E_3 = \sqrt{L}\left(E_s + E_{LO}e^{j\pi/2}\right) \quad (10)$$

$$E_4 = \sqrt{L}\left(E_s - E_{LO}e^{j\pi/2}\right) \quad (11)$$

where L is the loss caused of the 90° optical hybrid.

By applying E_1 and E_2, and E_3 and E_4 to two balanced photodetectors, we have two output photocurrents given by

$$I_{PD1} = 4RL\sqrt{P_sP_{LO}L_s} \times \left\{\cos\left[\pi s\left(t\right)/2V_\pi + \pi/4\right]\cos\left[\left(\Delta\omega\right)t + \phi\left(t\right)\right]\right\} \quad (12)$$

$$I_{PD2} = 4RL\sqrt{P_sP_{LO}L_s} \times \left\{\cos\left[\pi s\left(t\right)/2V_\pi + \pi/4\right]\sin\left[\left(\Delta\omega\right)t + \phi\left(t\right)\right]\right\} \quad (13)$$

where $\Delta\omega = \omega_c - \omega_{LO}$ is the offset frequency between the transmitter laser source and the LO laser source, $\phi(t) = \phi_c(t) - \phi_{LO}(t)$ is the joint phase noise introduced by the transmitter laser source and the LO laser source, and R is the responsivity of the photodetectors. Note that the power of the detected signal is proportional to the power of the LO laser source, thus coherent detection requires less optical power from the modulated optical signal than direct detection for a given signal-to-noise (SNR)

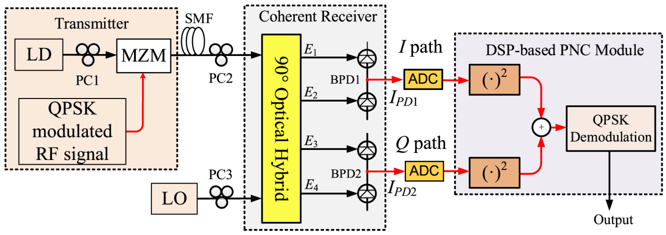

Fig. 18. A coherent RoF link with a DSP-based phase noise cancellation module. ADC: analog-to-digital converter, PC: polarization controller, LD: laser diode, BPD: balanced photodetector, MZM: Mach-Zehnder modulator, QPSK: quadrature phase shift keying.

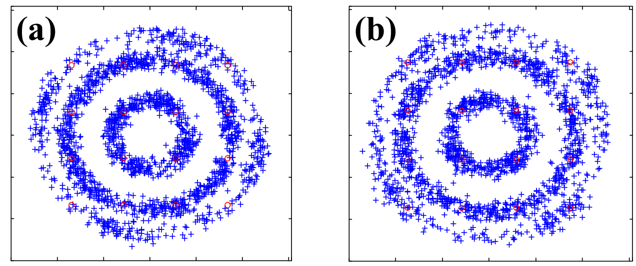

Fig. 19. The measured constellation diagrams of the microwave vector signals at the output of the coherent receiver. (a) The up-converted microwave signal, and (b) The down-converted microwave signal, and.

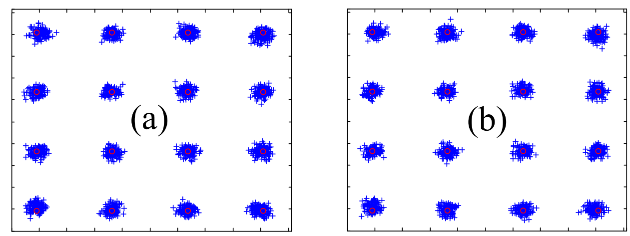

Fig. 20. Constellation diagrams for a recovered 16-QAM microwave vector signal corrupted by an OOK signal through phase modulation, to emulate a strong phase noise applied to the microwave signal. (a) OOK at 1000 Mbps, (c) OOK at 2000 Mbps.

ratio, thus the receiver sensitivity is increased. However, as can be seen in (12) and (13), to recover the RF signal, the unstable offset frequency $\Delta\omega$ and the joint phase noise $\phi(t)$ introduced from the transmitter laser source and LO laser source have to be eliminated, which can be done through signal processing using a high-speed DSP unit.

Fig. 18 shows a coherent RoF link in which an RF signal is directly modulated on an optical carrier at a Mach-Zehnder modulator. After transmission over a single-mode fiber, the intensity-modulated optical signal is detected at a phase-diversity coherent optical receiver, and two channels of signals corresponding to the I and Q components are obtained at the outputs of the coherent receiver, which are then sent to a DSP-based phase noise cancellation (PNC) module. By summing the squared magnitudes of the I and Q components, the phase noise is completely cancelled [45].

The two currents at the outputs of the coherent receiver I_{PD1} and I_{PD2} are given by (12) and (13), which are sampled and digitized by two analog-to-digital converters (ADCs). At the DSP unit, we can perform the following operation,

$$\begin{aligned} I_o^2 &= I_{PD1}^2 + I_{PD2}^2 \\ &= 8R^2L^2P_sP_{LO}L_s\left\{1-\sin\left[\pi s\left(t\right)/V_\pi\right]\right\} \\ &\approx 8R^2L^2P_sP_{LO}L_s\left\{1-\left[\pi s\left(t\right)/V_\pi\right]\right\} \end{aligned} \tag{14}$$

As can be seen, through this operation, the RF signal is free from the joint phase noise and the unstable offset frequency.

The effectiveness of the coherent RoF link for RF signal detection that is free from the joint phase noise and the unstable offset frequency was evaluated experimentally and shown in Fig. 18. For a standard 16 quadrature amplitude modulation (16-QAM) signal with a center frequency of 2.5 GHz and a symbol rate of 625 MSymbol/s, without phase noise cancellation, the constellation diagrams are shown in Fig. 19. Note that due to the offset frequency, the coherent receiver would generate two microwave signals at the up-converted and down-converted frequencies. The 16-QAM microwave vector signals were strongly affected by the joint phase noise and the unstable offset frequency introduced by the two laser sources and cannot be correctly recovered. If phase noise cancellation algorithm was applied, the joint phase noise and the unstable offset frequency could be fully eliminated, and the microwave vector signals were well recovered. Fig. 20 shows the constellation diagrams of the 16-QAM microwave vector signal which is corrupted by an OOK signal through phase modulation, to emulate a strong phase noise applied to the microwave signal. The results show that clear constellation diagrams are observed, and error-free detection is enabled.

The system shown in Fig. 18 can transmit only a single RF signal. Based on coherent detection and digital phase noise cancellation, multiple RF signals on a single optical carrier can be transmitted. For example, the spectral efficiency can be doubled to transmit two microwave vector signals on a single optical carrier through intensity modulation of one microwave signal and phase modulation of another signal [46]. Wavelength reuse in a symmetrical radio over wavelength division multiplexing passive optical network (WDM-PON) based on coherent detection was also demonstrated [47]. Thanks to the use of a developed digital phase noise cancellation algorithm, the data carried by the downlink optical signal can be fully eliminated when the downlink signal was reused for uplink transmission. To further increase the spectral efficiency, a data rate quadrupled RoF link to simultaneously transmit four microwave vector signals on a single optical carrier based on coherent detection and digital phase noise cancellation was also demonstrated [48]. More recently, an approach to transmit eight microwave vector signals based on coherent detection and polarization division multiplexing was reported [49].

The key challenge in implementing an RoF link based on coherent detection and digital phase noise cancellation is the need for a high-speed and low power consumption DSP unit. The recent advances in application-specific integrated circuits (ASICs) have made it possible to process microwave signals with a much wider bandwidth at a low cost and low power consumption [50].

VI. Microwave Photonic Sensing

Microwave photonics can also be employed for high-speed and high-resolution sensing. For an optical sensor, such as an FBG sensor, the interrogation is usually implemented using an optical spectrum analyzer (OSA) to monitor the wavelength shift. The speed is slow, and the resolution is poor. On the other hand, the interrogation can be done using microwave photonics with significantly increased speed and resolution. The fundamental concept is to translate the sensing information, such as an optical wavelength shift, from the optical domain to a microwave frequency change in the microwave domain, thus enabling the interrogation in the electrical domain with increased speed and resolution. There are, in general, three different approaches to implement microwave photonic sensing, 1) heterodyning two wavelengths of a dual wavelength laser source, to generate a microwave signal with the microwave frequency being a function of the sensing information, 2) spectral-shaping and wavelength-to-time mapping, to translate the optical spectrum in which the sensing information is embedded to the time domain, 3) optoelectronic oscillator, to translate the wavelength change of an optical sensing element to a microwave frequency change. A comprehensive review of these three approaches including the implementations of the sensing systems based on photonic integrated circuits has recently been reported [51].

The three approaches discussed in [51] can be used for sensing at fixed locations. Microwave photonics can also be employed to achieve distributed sensing [52]. It is widely known that Stimulated Brillouin Scattering (SBS) in an optical fiber can be employed for distributed sensing. Again, in a conventional Brillouin-based fiber-optic sensor, the sensing information is acquired through a time-consuming frequency-sweeping process using an optical spectrum analyzer to obtain a local Brillouin gain spectrum (BGS) and to calculate the local Brillouin frequency shift (BFS). Thus, it is only suitable for static or slow-varying measurements. Based on microwave photonics, truly distributed and ultra-fast fiber-optic sensing could be implemented based on an active and distributed microwave bandpass photonic filter through SBS. The operation principle is shown in Fig. 21. To obtain a truly distributed BFS, a counter-propagating single-shot pump pulse is launched into a fiber link and a microwave multi-tone (MMT) signal with a random initial phase distribution that is phase modulated on an optical carrier is launched into the fiber link from the other end. Due to the SBS effect, the -1st order sideband of the phase-modulated signal will experience Brillouin amplification while the $+1$st order sideband of the phase-modulated signal will experience Brillouin attenuation, and thus the phase-modulated signal is converted to an intensity-modulated signal. The entire operation is equivalent to a microwave bandpass filter. By detecting the optical signal at a photodetector, a regenerated MMT signal with its magnitude and phase that are shaped by the microwave bandpass filter is obtained. By evaluating the regenerated MMT signal, the Brillouin information corresponding to a temperature or strain change at a specific location is revealed. Fig. 22 shows the schematic diagram of the SBS-based distributed microwave photonic sensor. The key feature of the approach is that the time-consuming frequency-sweeping process is avoided, making distributed sensing at high speed possible.

The key advantage of using microwave photonics for optical sensing is the high speed and high resolution which is achieved by translating the sensing information from the optical domain to the microwave domain. By using a digital signal processor, the sensing information in the microwave domain can be fast and accurately measured.

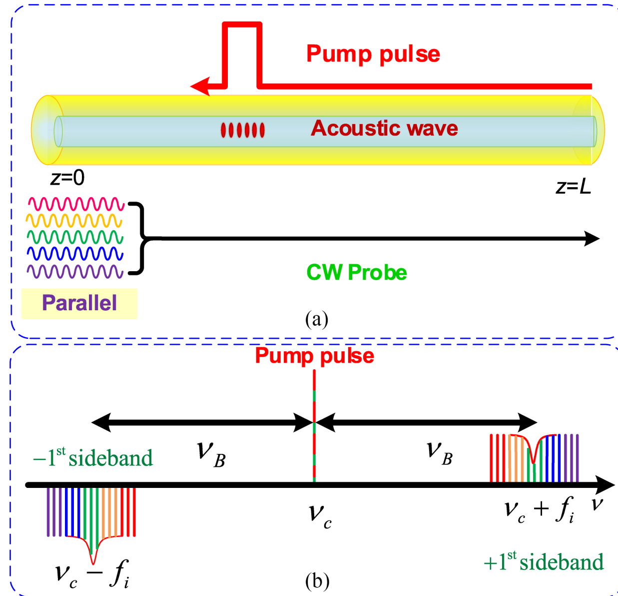

Fig. 21. Principle of an SBS-based distributed microwave photonic sensor. (a) A pump pulse launched into the fiber from the right end, to create SBS effect. A microwave multi-tone signal phase-modulated on an optical carrier is launched into the fiber from the left end. (b) The phase-modulated optical signal is experiencing phase modulation to intensity modulation conversion due to the Brillouin amplification and attenuation to the -1st and $+1^{st}$ sidebands [51].

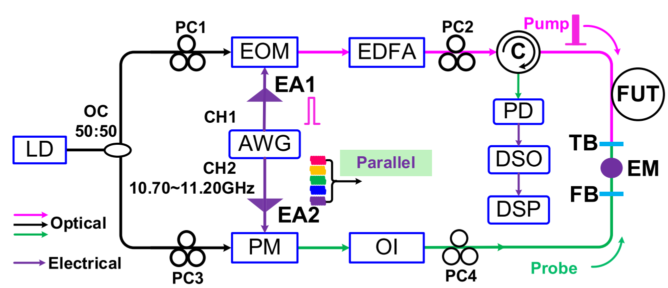

Fig. 22. Schematic diagram of an SBS-based distributed microwave photonic sensor. LD: laser diode, PC: polarization controller, PM: phase modulator, EOM: electro-optic modulator, AWG: arbitrary waveform generator, EDFA: erbium-doped fiber amplifier, OI: optical isolator; FUT: fiber under test, C: optical circulator, PD: photodetector, DSO: digital storage oscilloscope, DSP: digital signal processor, EA: electrical amplifier, EM: electro-motor, FB: fixed base, TB: tunable base [51].

VII. Conclusion

Microwave photonics has been topic of active research for over three decades and new system architectures have been proposed for the generation, processing, distribution, and measurements of microwave signals. In this article, recent advances in microwave photonic systems have been reviewed. Specifically, microwave photonic systems for the generation of low-phase-noise microwave signals, linearly chirped microwave waveforms, and random microwave waveforms were reviewed. Microwave photonic systems for the processing of microwave signals using microwave photonic filters were also reviewed. In general, microwave photonic filters can be implemented based on incoherent detection and coherent detection. The advantage of coherent detection is that the systems are much simpler with only a single laser source being needed, which would facilitate the system implementation, especially for integration using photonic integrated circuits. Microwave photonic systems for the transmission of radio signals based on coherent detection were also reviewed. The key advantages compared with IM-DD RoF links are that the spectral efficiency is much higher, and the receiver sensitivity is also significantly increased. The key difficulty in using coherent detection in an RoF link is the joint phase noise and unstable offset frequency which would make the microwave signals at the receiver heavily embedded in noise, making error-free detection impossible. Through digital phase noise cancellation, the joint phase noise and unstable offset frequency can be fully eliminated, and error-free detection is enabled. Microwave photonic systems for optical sensing can increase the interrogation speed and sensing resolution since the sensing information (usually wavelength shift in the optical domain) is translated to a microwave frequency change in the microwave domain. The use of a DSP unit could process the microwave signal or waveform at a high speed and high resolution.

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