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UWB Signal Generation and Modulation Based on Photonic Approaches

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Abstract

Demands for efficient and reliable wireless communications between computers, mobile phones, and other portable electronic devices in short distances are increasing very fast. Ultra-wideband impulse radio is one of the promising techniques, which has gained much research interests in recent years. It covers a wide scope of applications in short-range wireless communications. Conventionally, the low-bandwidth electronics can process the UWB signals very well. More recently, microwave photonics has enabled a new paradigm for developing UWB techniques in photonic domain. The photonic approaches offer much higher bandwidth and seamless compatibility with optical fiber networks, which allow for scaling the UWB technology to more advanced application scenarios. This chapter is included because photonic approaches have become a unique and effective technique in microwave signal processing. We do not attempt to offer a comprehensive review of UWB photonics, but rather to introduce the typical photonic solutions for UWB signal generation, modulation, transmission, down conversion, and so on.

Keywords: UWB generation, UWB modulation, UWB-over-fiber, microwave photonics

1. Introduction

Ultra-wideband impulse radio (UWB-IR) shows great promise in short-range high-throughput wireless communications and sensor networks owing to its intrinsic properties, such as immunity to multipath fading, extremely short time duration, being carrier free, and having low duty cycle, wide bandwidth, and low power spectral density [1–8]. While mature microelectronics can generate the impulse signals with perfect quality [9–11], the increasing demands for wireless bandwidth have driven the UWB-IR moving to higher frequency like W band (100 GHz). Besides, UWB is limited to coverage of its immediate surrounding area

(up to 10 m) because of its low radiation power. Due to its light weight, low power consumption, low latency, and large bandwidth, optical fiber is considered to be an optimal solution to distribute the wireless signal over several tens of meters or kilometers. As such, it is no longer an economical way to process the UWB signals in electrical domain since an additional electrical-to-optical conversion (EOC) is needed, which increases the cost and power budget of the whole system. Alternatively, an all-optical UWB transmitter that includes impulse generation and data encoding will be highly desirable as no EOC is required. The signal generated in optical domain can be directly fed into the local optical fiber network for distribution. Such UWB-over-fiber solution can be fully compatible with the infrastructure of the current passive optical network (PON). It means that the wireless signal and the wired signal can share the same optical fibers, which further reduce the costs.

Due to the advantages of optics, such optical approaches have been widely studied for microwave applications, and it has become a promising research area—microwave photonics (MWP). Over the past two decades, the wireless communication community holds the continuous demands for low power consumption, larger transmission capacity, flexibility in signal distribution, and so forth. Particularly, the optical communications have advanced significantly, and it gives rise to a plethora of mature device and system technologies, which can handle many problems with frequencies from microwave to millimeter wave and THz range. MWP has been reported to offer a wide range of promising solutions to arbitrary microwave signal generation, modulation, multicasting, beam forming, filtering, phase shift, interference cancelation, frequency conversion, and so on. Compared with components working at radio frequencies, optical and electrooptic devices in MPW have nearly no bandwidth limitation, which allow for very high-speed microwave signal processing. The MWP device platform mainly includes fiber optics, integrated materials like silicon or III–V semiconductors, electrooptic crystals, and other material systems. The principal idea for MWP is to manipulate the optical wave using optical techniques, which includes optical nonlinear effects, electrooptic effects, optical filtering, optical spectrum shaping, and so on. After proper optical processing, the optical signal can be downconverted to microwave domain by photodetection.

MWP has a wide scope of topics like signal generation, modulation, distribution, photonic analog-to-digital conversion, and many other signal processing applications. It should be noted that signals with frequencies located in a wide spectral band spanned from several GHz to one millimeter can be handled by MWP. Among such a broad area, UWB signal processing in optical domain is one of the most interesting research topics within the MWP community due to its intrinsic advantages of low power density and high data rate. To make it work, a handful of approaches have been proposed, and some of the excellent results have been demonstrated so far. In this chapter, we will provide some technology introduction, literature review, and insight of application prospect that are related to UWB photonics.

2. UWB signal generation

UWB-IR is regulated by the Federal Communications Commission (FCC) for indoor wireless access operating in the frequency range from 3.1 to 10.6 GHz [1]. Based on the FCC definition,

a UWB signal should have a spectral bandwidth that is greater than 500 MHz or a fractional bandwidth that is greater than 20% [1]. The UWB-IR can be generally classified into two categories: (1) the direct sequence UWB-IR [7] and (2) the multiband UWB-IR [8]. Direct sequence impulse radio is a simple and widely accepted form for UWB communications since it is carrier free. Thus, there is no need for complicated frequency mixers and local oscillators to up- or downconvert the carrier frequency. The generation of UWB pulses is one of the most important considerations within a UWB transmitter because the impulse quality will affect the system performance significantly [12].

Gaussian pulses are the most widely used waveforms in UWB-IR communications as they offer the advantages like simplicity and achievability. In principle, different orders of UWB-IR waveforms can be generated by using different orders of frequency differentiator filter with a Gaussian pulse input [2]. The optical band-pass filter is normally able to act as a first- or second-order frequency discriminating filter. However, it has been demonstrated that the frequency spectra of both UWB monocycle and doublet pulses have significant components in the low frequency range (<2 GHz) and thus violate the dip in the FCC spectral mask [13, 14]. Higher-order derivative of Gaussian pulses like triplet, quadruplet pulse, and some other waveforms that are more power efficient are highly desirable but rather difficult and expensive to achieve [15–17]. Here, we introduce the typical UWB signal generation techniques that relied on electrooptic components. These approaches include [2]: (1) phase modulation to intensity modulation (PM-IM) conversion, (2) optical nonlinear effects, (3) optical spectral shaping and frequency-to-time mapping, (4) microwave delay-line filter, and (5) injection locking.

2.1. PM-IM conversion

PM-IM conversion is one of the earliest methods that developed for UWB-IR generation, which was realized by changing the phase relationships among all the frequency components of the optical phase-modulated signal. A frequency discriminating filter is normally needed to convert the phase to intensity, and thus, it can also be considered as optical filtering technique. A single-stage filter can generate the monocycle pulses when the optical carrier is biased at the linear slope of the filter. Higher-order Gaussian derivative pulses can be generated by using multiple filter and superimposing their outputs. **Figure 1** illustrates how a single filter produces the monocycle pulses. An electrical Gaussian pulse should be first converted to the optical domain using a phase modulator. The phase-modulated signal is then applied to a frequency discriminating filter. The laser wavelength can be adjusted to either side of the linear region of the filter spectrum slope. The operation of phase modulation and frequency discrimination is equivalent to a first-order differentiation of the input Gaussian pulses encoded on the optical phase. The phase-modulated signal with a constant intensity will be converted to an intensity monocycle waveform through the PM-IM process as shown in **Figure 1**. The converted signal is then detected at a PD, which serves as an envelope detector.

The normalized optical field being phase-modulated by the Gaussian pulse train can be expressed in the form of

$$E_{PM}(t) = \exp[j\omega_c t + \beta_{PM} \cdot s(t)] \quad (1)$$

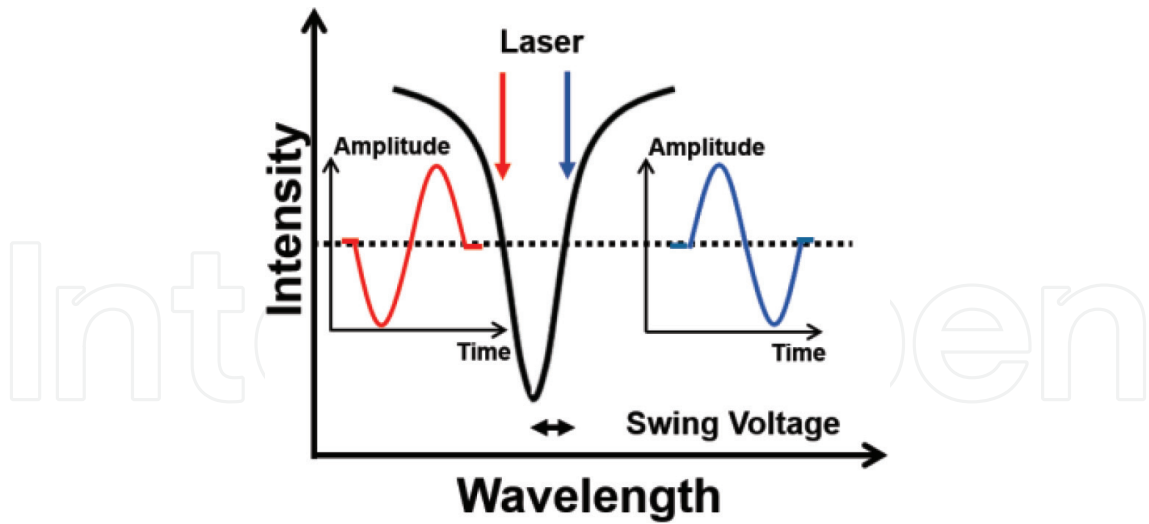


Figure 1. The schematic diagram of the monocycle pulse generation based on PM-IM conversion.

where ω_c is the angular frequency of the optical carrier, β_{PM} is the phase modulation index, and $s(t)$ is the pulse train represented by

$$s(t) = \sum_{n=-\infty}^{+\infty} \Omega(t - nT_T) \tag{2}$$

Based on the configuration shown in Figure 1, when the phase-modulated light is located at the linear region of the filter spectral slopes, as shown in Figure 1 at A, the ac part of the recovered signal at the output of the PD can be written as [7].

$$\tau(t) \sim RP\beta_{PM}K \cdot s'(t) \tag{3}$$

where R is the responsivity of the PD, P is the optical power after the filter, K is the slope steepness factor of the filter transmission spectrum, and $s'(t)$ is the first-order derivative of the modulating signal $s(t)$. Then, the UWB monocycle pulses are obtained.

Monocycle UWB-IR is the simplest waveform that can be directly generated from a single optical filter, but the power spectrum of the monocycle is not efficient. Here, we introduce a more advanced PM-IM conversion scheme with multiple filters, which allows for more power-efficient UWB-IR generation. The principle is described in Figure 2(a and b) where the laser wavelength can be biased at different nonlinear slope of the filter spectrum. Different types of asymmetric monocycle pulses can then be generated with different polarities due to the intensity peaking effect. Based on such asymmetric monocycle waveforms, we can superimpose them into higher-order Gaussian derivative pulses using the configuration shown in Figure 2(c). The generation of a doublet or triplet pulse can be implemented via two identical optical filters in parallel with each producing an asymmetric monocycle first. By introducing an appropriate group delay to one of the pulses, a simple combination of the two pulses can generate the target doublet pulse or triplet pulse. As indicated in Figure 2(c), quadruplet pulses can also be generated using such delay and superimpose method if three identical filters and two optical delay lines are used.

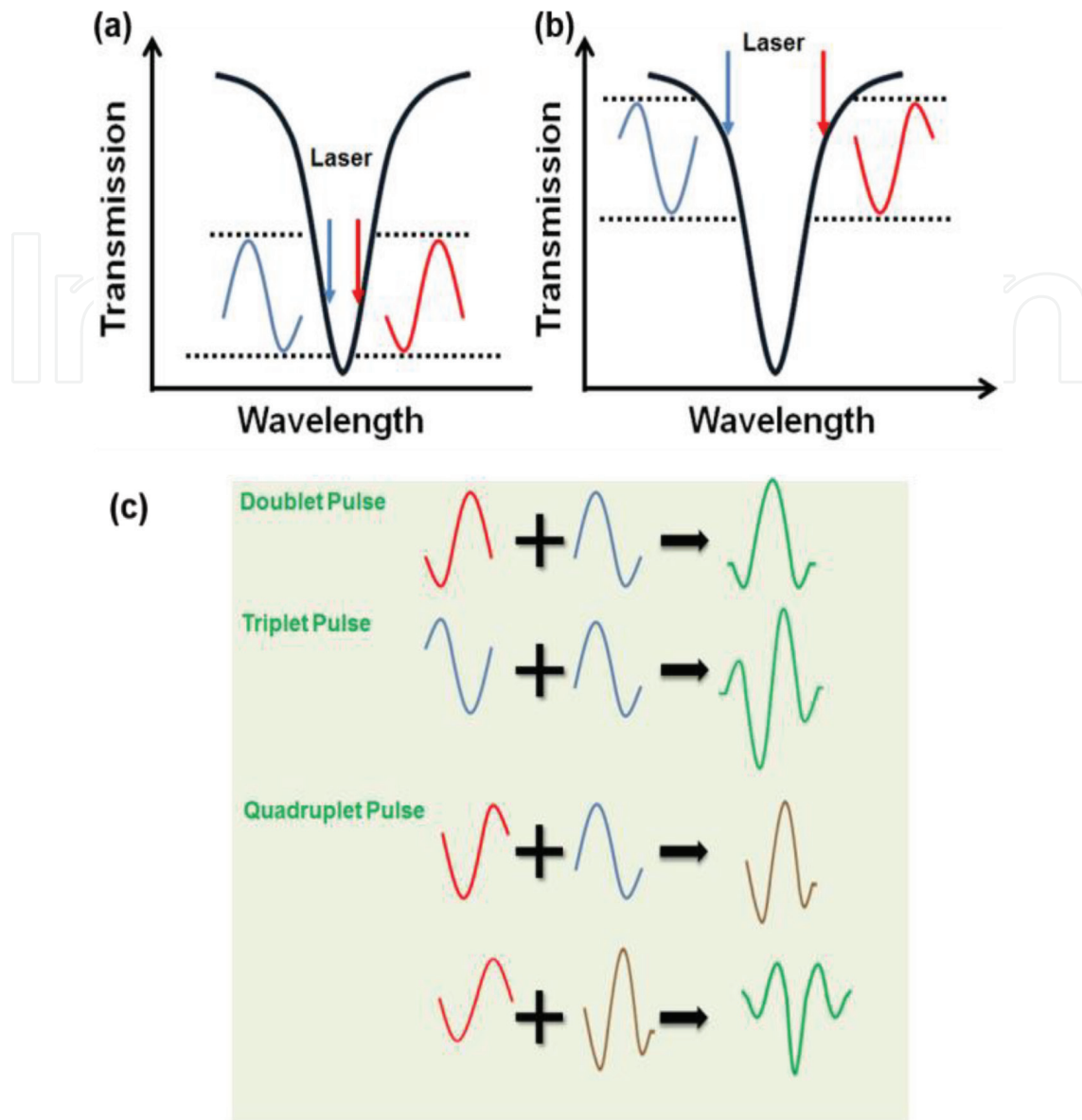


Figure 2. The schematic diagram of the (a and b) generation of asymmetric monocyte pulses; (c) generation of higher-order Gaussian pulses using combination of different asymmetric monocyte pulses.

The selection of an optical frequency-discriminating filter is important in the PM-IM conversion process. In optics, the fiber Bragg grating (FBG), thin-film band-pass filter, arrayed waveguide grating (AWG), Sagnac filter can be the excellent candidate. For example, FBG, a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others, can be flexibly designed and a frequency discriminator with the desired optical spectrum that is suitable for PM-IM conversion. A typical setup for FBG-based UWB-IR generation is shown in **Figure 3**. Light from a laser diode is fiber coupled to an electrooptic PM, which is driven by a sequence of Gaussian pulses.

The phase-modulated optical signal is then applied to an FBG via an optical circulator. The PM-IM conversion is achieved by using the FBG serving as a frequency discriminator. The converted UWB signal is then detected at a PD, which serves as an envelope detector.

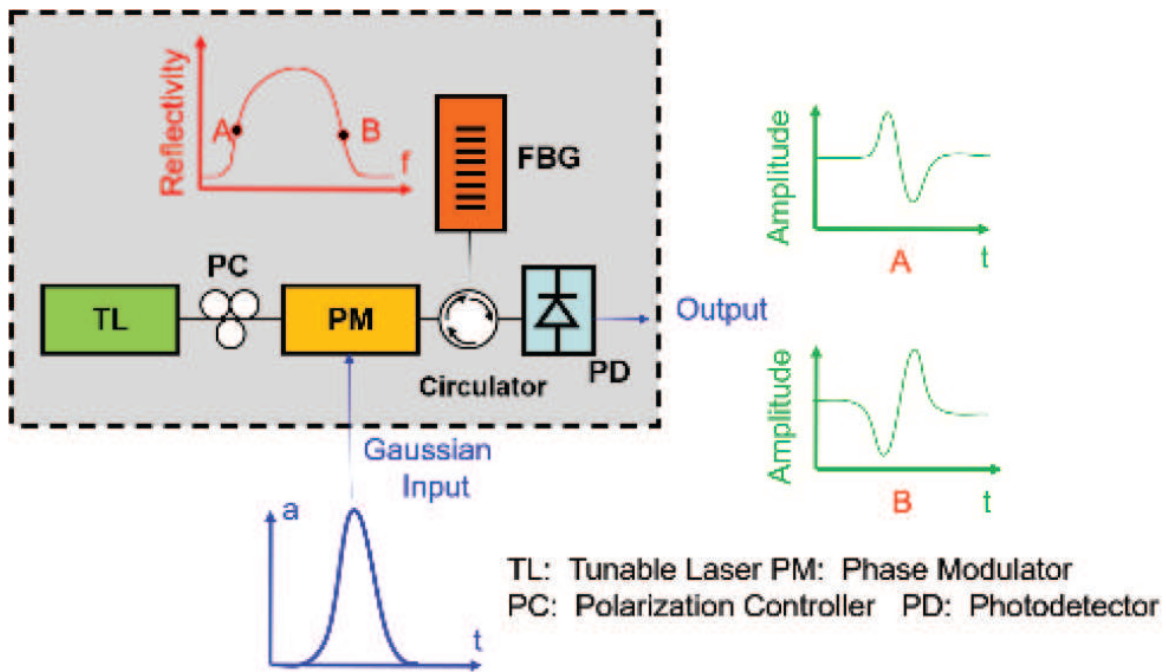


Figure 3. The schematic setup of a typical FBG-based monocycle pulse generation system.

2.2. Optical nonlinear effects

Optical nonlinear effects in optical waveguides like optical fiber, periodically poled lithium niobate, integrated nanowire waveguide are ultrafast processes that can be highly functional in many areas. Here, we introduce several nonlinear processes that can be applied to UWB-IR generation [18, 19]. It is important to point out that most of such techniques are associated with the PM-IM conversion. We still consider them as a new class of technique due to their unique mechanisms compared with the typical PM-IM approaches.

Typically, by sending a phase-modulated Gaussian pulse to a frequency-discriminating filter, a Gaussian monocycle pulse can be generated via frequency discrimination. Higher-order Gaussian pulses can be obtained by combining time-delayed UWB monocycles at different wavelengths with inverted polarities [20, 21]. Alternatively, for example, triplet pulses can be generated through four-wave mixing effect combined with an optical band-pass filter. In this scheme, the high-order Gaussian triplet pulse is directly generated by performing the first-order derivative of a phase-modulated Gaussian doublet pulse without complicated superposition of different pulses.

A general schematic block diagram of such four-wave mixing (FWM)-based UWB generation is depicted in Figure 4. The two paths of input optical continuous waves (CWs) are phase modulated. The phase modulators are driven by two sets of electrical Gaussian pulses that can be divided from a single-pulse pattern generator. For the upper electrical path, the Gaussian pulse is processed by an electrical Mach-Zehnder interferometer (MZI) before driving to the phase modulator. An optical delay is between the two light waves. The two light waves are then combined together and fed into the nonlinear medium such as highly nonlinear fiber, silicon waveguide, or chalcogenide waveguide to perform FWM. The output signal is converted

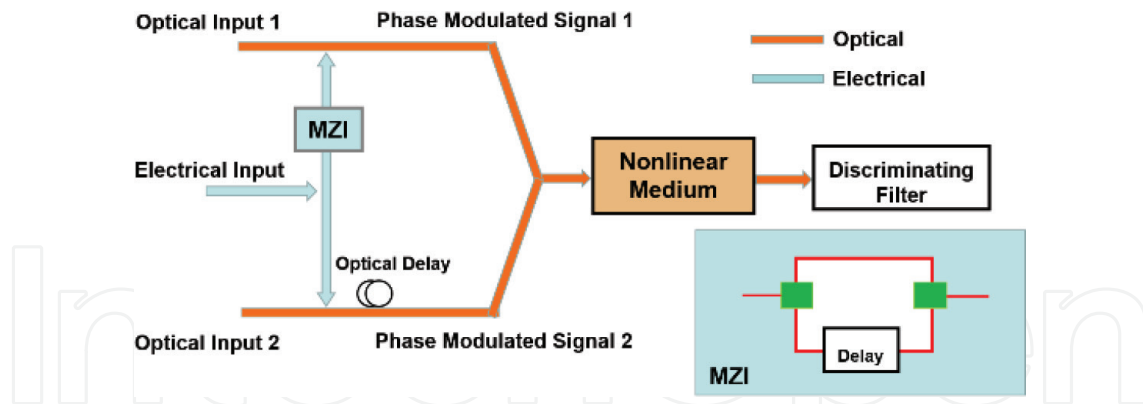


Figure 4. The schematic block diagram of the four-wave mixing (FWM)-based triplet pulse generation.

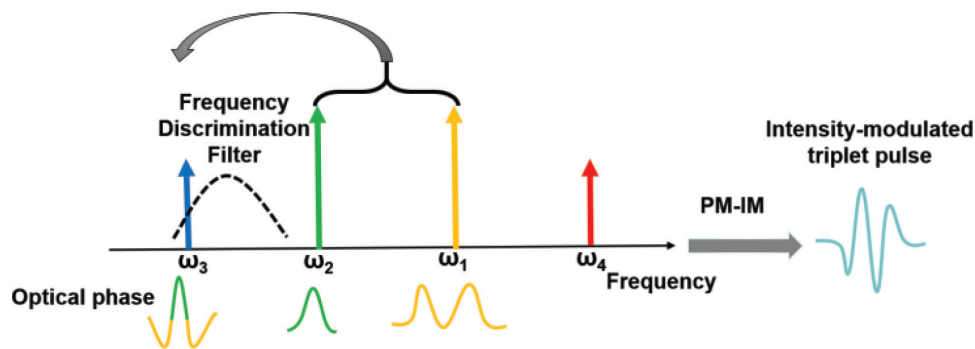


Figure 5. The schematic illustration of the working principle for triplet pulse generation using FWM.

to the triplet pulses by a discriminating filter via PM-IM conversion. An UWB triplet can be generated by converting the signal into the electrical domain using a photodetector.

The working principle of this method is shown in **Figure 5** where the electrical MZI modulated the light wave (ω_1) with a modified Gaussian pulse and the other carrier (ω_2) with a normal Gaussian pulse. An FWM process will function as a phase conjugation that modulates the idler phase with a triplet Gaussian pulse as shown in the inset of **Figure 5**. Then, an optical band-pass filter will translate this phase response into intensity triplet pulses. Compared with the monocycle pulse, triplet pulse has a suppression in the low frequency range that makes the spectrum fit the FCC mask better.

Two-photon absorption (TPA) is another optical nonlinear effect that can be used for UWB signal generation. The schematic block diagram of the all-optical UWB monocycle pulse generation using non-degenerated TPA in a nonlinear WG is shown in **Figure 6**. A CW probe and a pulse pump are aligned to the Si waveguide's TE-like mode and coupled together. After propagation through the long waveguide, the CW probe is inversely modulated by the pulse pump during the non-degenerated TPA process in the nonlinear WG. By properly controlling the delay and power relation between the attenuated pump and inversely modulated probe, positive and negative UWB monocycle pulses with different shape can be generated in the optical domain after their recombination. With the optical-to-electrical conversion at a photodetector, a UWB monocycle pulse is obtained in the electrical domain.

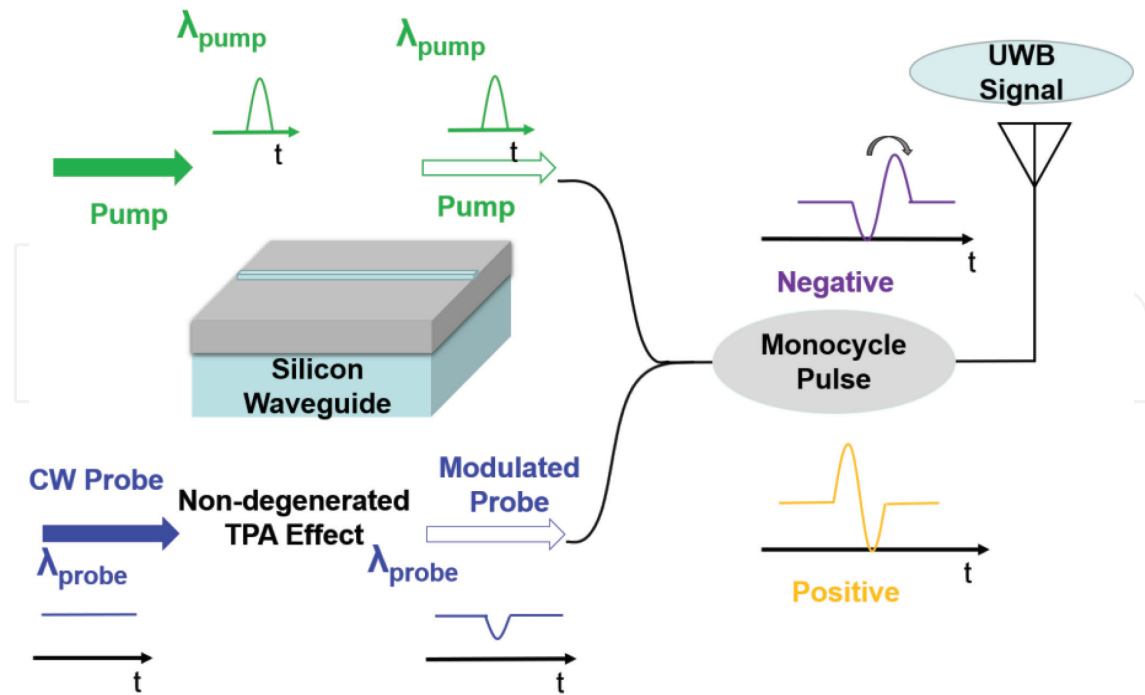


Figure 6. The schematic diagram of the working principle for TPA-based monocycle pulse generation.

2.3. Optical spectral shaping and frequency-to-time mapping

UWB pulses can also be generated based on optical spectral shaping and frequency-to-time conversion using a Fourier transform device. Fourier transform optical spectral shaping and dispersive stretching were implemented to generate adaptive broadband microwave arbitrary waveforms [22, 23]. UWB pulse generation has been widely demonstrated via spatial-light-modulator (SLM)-based spectrum shaper and frequency-to-time mapping [24–26]. But in this approach, the pulse shaping is implemented in free space, which makes the system bulky and complicated. UWB pulses can also be generated based on spectral shaping and frequency-to-time conversion using pure fiber-optic components [27]. The use of fiber-optic components instead of free space optics has the advantage of smaller size, light weight, and the potential for integration using the photonic integrated circuit (PIC) technique.

Figure 7 shows a UWB pulse generation system based on spectral shaping and frequency-to-time mapping using all-fiber components. In the system, the optical power spectrum of a femtosecond pulse from a mode-locked fiber laser (MLFL) is shaped by optical spectral shaper to obtain a spectral shape corresponding to a UWB monocycle or more power-efficient waveform. The wave shaper based on MEMS can act as an excellent spectral shaper for this



Figure 7. The block diagram of a UWB-IR generation system based on optical spectral shaping and frequency-to-time mapping. MLFL, mode-locked fiber laser.

scenario. A certain length of single-mode fiber (SMF) acting as a dispersive element can be used to perform the frequency-to-time mapping. In the meantime, the SMF can also distribute the UWB signals to a remote site. A UWB-IR pulse is then obtained at the output of a high-speed PD. The UWB pulse has a shape that is a scaled version of the user-designed power spectrum. The pulse width is determined by the total dispersion of the SMF. In fact, an ultra-short pulse from the MLFL source can also be divided into two paths by an optical coupler. When the input pulse spectrum from one port is shaped by a reflection filter, the input pulse from the other port is spectrally shaped by a transmission filter. The spectra shapes of the two filters are complementary, which ensures that the time-domain pulses are polarity reversed. Similar to PM-IM conversion, this technique can generate more complicated pulses other than monocycle pulse by applying asymmetric spectral shaping in the complementary filters. Then, the spectrum-shaped pulse is then sent to a length of dispersive fiber to perform frequency-to-time mapping.

2.4. Microwave delay-line filter

We have discussed the generation of monocycle, doublet and triplet pulse generation in the previous section. It is known that monocycle, doublet, and triplet represent the first-, second-, and third-order derivative of the Gaussian pulse. In principle, different order derivatives can be approximated by first- or higher-order differences, which can be implemented via a photonic microwave delay-line filter, with two or three taps, with one negative tap. For a photonic microwave delay-line filter, the filter should operate in the incoherent regime using incoherent detection to avoid optical interference. A photonic microwave delay-line filter with incoherent detection normally has positive coefficients only [28–30]. Thus, it is necessary to design filter with negative coefficients while maintaining the incoherent detection.

The general working principle can be described in **Figure 8**. UWB-IR can be generated by such a system that consists of an N-tap photonic microwave delay-line filter, a light source, an optical modulator, a time delay element, and a PD. The microwave signal is modulated onto the light wave using an optical modulator. The modulated light wave is then sent to an N-tap

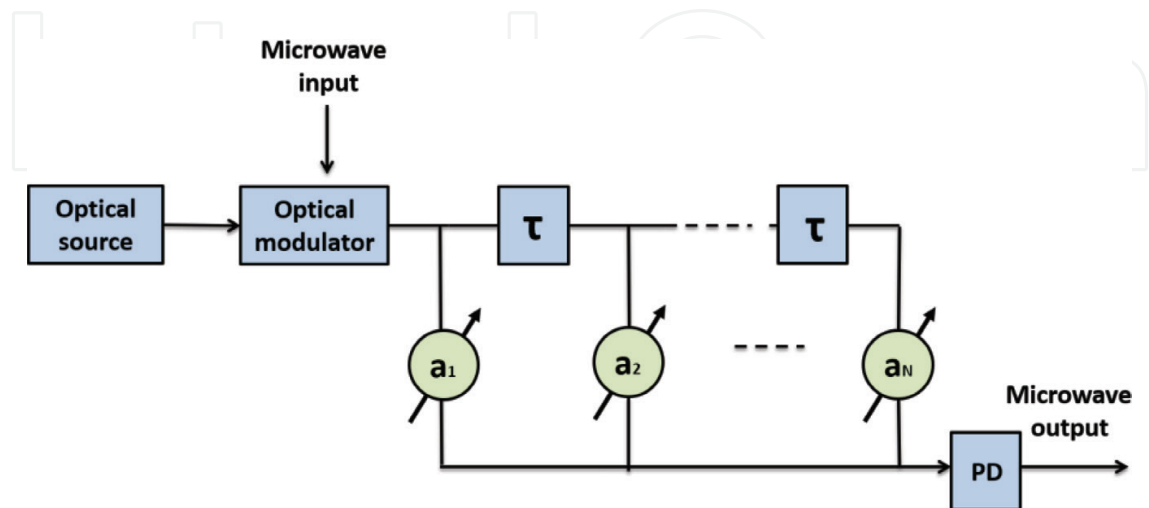


Figure 8. The schematic diagram of the UWB signal generation principle based on microwave delay-line filter.

delay-line device to introduce different time delays with an identical time delay difference between each adjacent tap. The time-delayed signals are then converted to electrical signal via a PD. The multitap delay-line device acts as a multitap RF filter in the electrical domain. The free spectral range (FSR) and the tap coefficients can be designed by introducing appropriate time delay difference. Thus, the desired frequency response of the RF filter can be realized using the photonic devices.

2.5. Photonic integrated circuits

We have mentioned a handful of approaches that can generate the UWB-IR in optical domain. Most of the systems relied on the discrete packaged components like optical fiber, lithium niobate electrooptic modulator, thin-film filter, fiber Bragg grating, spatial light modulator, and so on. Such system is quite bulky and requires sophisticated control on optical phase, polarization, optical intensity, wavelength, and many other parameters. Some of these parameters are extremely sensitive to the environmental variations and thus are difficult to stabilize. From the economical point of view, the UWB system based on many discrete packaged components will suffer from additional losses at the interface between different devices and also suffer from high packaging costs.

Photonic integrated circuits (PICs) have become a new paradigm for on-chip subsystem with a plethora of applications like optical computing, interconnection, sensing, microwave photonics, and so on. Similar to the electronic integrated circuits, the idea of PIC originates from the large-scale integration of various photonic devices and functionalities on a single chip. The benefits from on-chip system based on PIC include low cost, low power consumption, stable performance, and small footprint. Silicon and III–V material systems have been widely used for integrated photonic devices. While III–V material has limited wafer dimension and high cost, silicon is now considered as the most promising photonic integration platform. The past two decades have witnessed the huge success of silicon photonics that advanced from scientific research to commercialization.

Here, we introduce a UWB-IR generation technique using silicon microring resonator, which consists of a bus waveguide and a microring waveguide. The working principle of a microring resonator is shown in **Figure 9**. The bus waveguide and the microring are coupling with each other via a coupler. When light of the resonant wavelength is passed through the bus waveguide, it will cross couple into the microring and builds up in intensity over multiple round trips due to constructive interference. Once it travels through a round trip, it is output to the output bus waveguide. Because only a selected few wavelengths will satisfy the resonance condition within the cavity, the optical ring resonator can function as a filter. If only one bus waveguide is implemented as shown in **Figure 9**, the microring will serve as a notch filter with the output spectrum shown as the inset of the figure. The microring resonance spectrum normally has a Lorentz shape with very large extinction ratio, and the resonance dip of the notch filter induces an abrupt phase change. Thus, microring resonator is a good candidate for a frequency discrimination filter, which can be used for PM-IM conversion. By generation of different types of monocycle pulses as described in **Figure 1**, a delay and superimpose method can produce much more complicated and power-efficient UWB pulses.

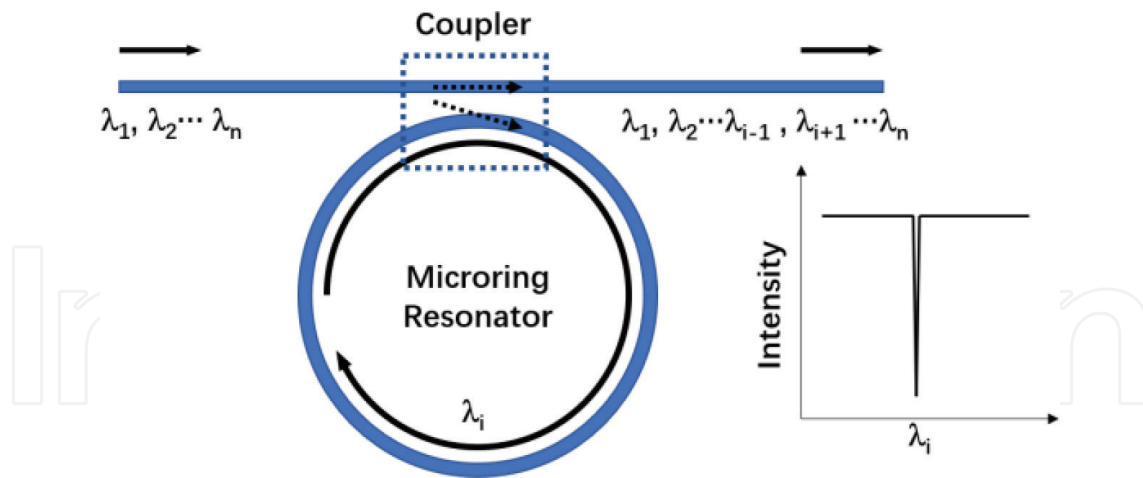


Figure 9. The schematic diagram of a microring resonator. Inset: the schematic optical spectrum at the through port of the microring.

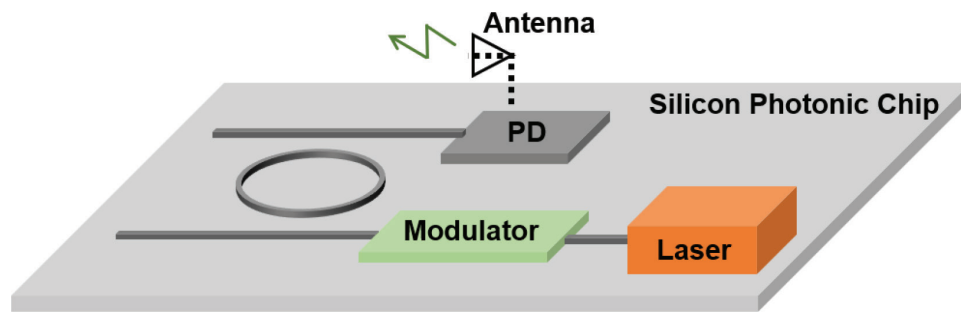


Figure 10. Experimental setup of the UWB generation using MRR and integrated Ge photodetector. PD, photodetector.

The advantages of using silicon microring are the possibility of integration and the extremely small footprint. A possible system setup of the on-chip monocycle UWB-IR generation can be depicted in **Figure 10**.

If we recall the principle illustrated in **Figure 2**, doublet and triplet UWB waveforms can be generated by using a pair of identical filters. In a nonintegrated system, we need to double the efforts and costs to set up another set of filter, cables, connectors, and so forth. In contrast, PIC holds one of the most exciting features of just copying the circuit layout and sharing the same fabrication process. Importantly, the cost is not necessarily doubled since many expenses are shared in a multiproject wafer [31]. A PIC layout for doublet or triplet pulse generation is shown in **Figure 12** where two identical microring resonators produce two asymmetric monocycle pulses. The microring pair can be electrically controlled to adjust the working wavelengths. The microscope image of the tunable microring pair is shown as the inset. After PM-IM conversion via the ring resonator, one of the light waves is time-delayed by a certain length of long waveguide. Then, two paths of optical waves are combined and superimposed by a coupler. Finally, the optical to electrical conversion is performed in the photodiode and hence the electrical doublet or triplet UWB-IR is generated. The microscope images of the long waveguide and the photodiode are shown in the inset of **Figure 11**.

3. UWB signal modulation

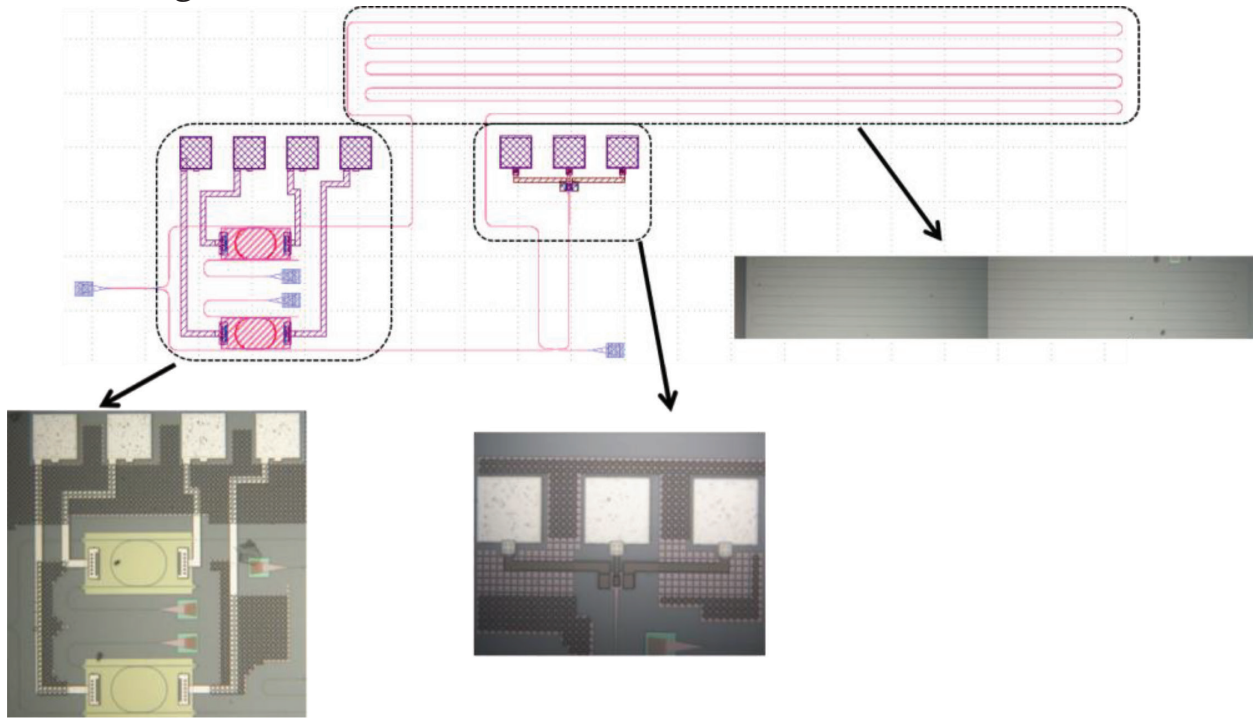


Figure 11. The PIC layout of the on-chip UWB generation system. The inset are the microscope images of the microrings, photodetector, and long waveguides.

UWB-IR is a wide band RF spectrum with extremely low power spectral density. It actually functions as a wireless carrier to deliver information in a short reach scenario. The modulation of UWB-IR is also a fundamental issue in the transmitter design. One of the most intuitive modulation formats that can apply for UWB-IR is the on-off keying (OOK). This format is easy to implement, but it suffers from intensity noise. Pulse position modulation and biphasic modulation are alternative formats apart from OOK. Here, we introduce a novel UWB signal modulation scheme using the tunable filter, which can be compatible for both OOK and biphasic modulation.

In **Figure 12**, we illustrate the working principle of how to generate and modulate the UWB monocycle pulse using a single tunable filter. Such a tunable filter should have a large extinction ratio and fast tuning speed. Electrooptic silicon microring is one of the perfect candidates for this scheme. As shown in **Figure 12(a)**, when the laser wavelength is set at the center of the linear slope of the ring resonance, a monocycle pulse with a certain intensity is generated. When a driving voltage is applied to the ring resonator, the ring resonance is shifted and its resonance dip is shifted to match the laser wavelength. As a result, the pulse will vanish due to the low intensity at the ring resonance dip and the OOK modulation is achieved.

If the driving voltage is larger, a larger wavelength shift will be introduced to the ring resonance as shown in **Figure 12(b)**. First, the laser wavelength is set to a midpoint at one side of the resonance slope center. Without the electrooptic tuning, a monocycle pulse will be generated. By applying an appropriate swing voltage, the laser wavelength can be just located to the other side of the resonance slope. As a result, the polarity of the monocycle pulse will be reverted since it experiences a π phase shift. The biphasic modulation can be

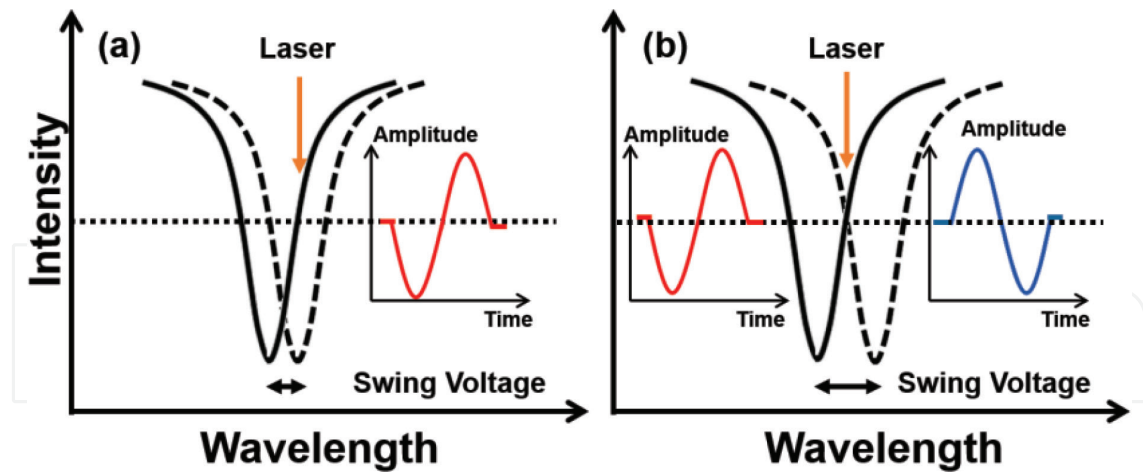


Figure 12. The schematic principle of the tunable-filter-based (a) UWB OOK modulation and (b) UWB biphas modulation.

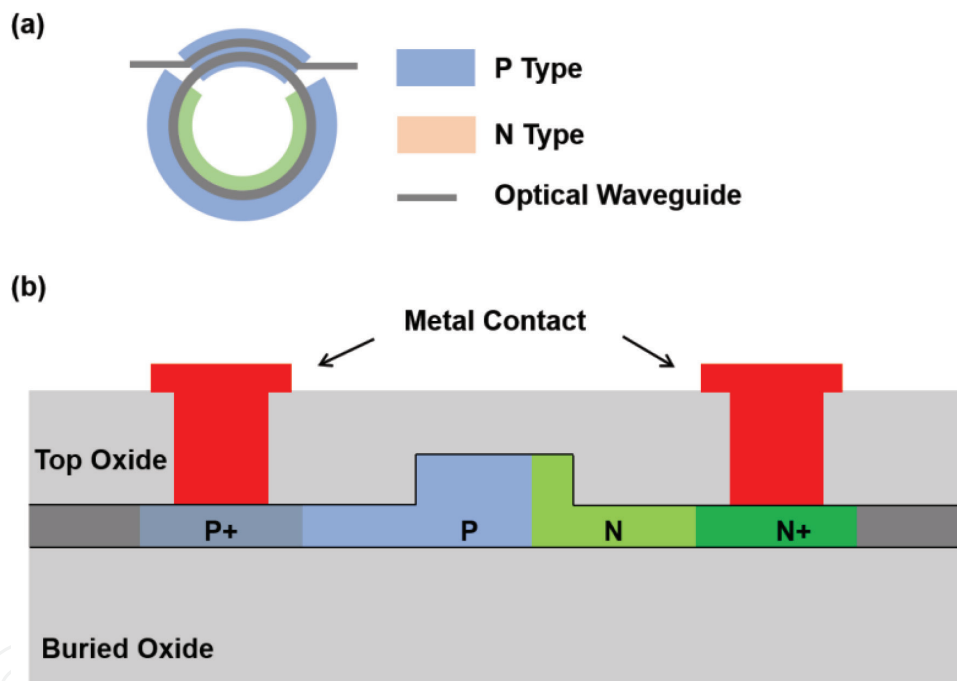


Figure 13. (a) The top-view schematic diagram of the silicon microring modulator and (b) the schematic diagram of the P-N silicon waveguide.

realized if the driving voltages are well controlled with equal intensity for the polarity-reverted monocycle pulse.

An active microring resonator (microring modulator) can be used to simultaneously generate and modulate the UWB-IR. The top view and cross section schematic structure of a silicon ring modulator are shown in **Figure 13(a)** and **(b)**. The resonance wavelength tuning is achieved by modifying the resonance condition, which is expressed by

$$n_{eff}L = m\lambda_i \tag{4}$$

where n_{eff} is the waveguide effective refractive index, L is the round-trip length, m is an integer, and λ_i is the resonance wavelength. The cavity waveguides are normally doped with P- and N-type implantations as shown in **Figure 13**. Silicon is a semiconductor; the doping improves the conductivity of the waveguides, which introduces the free carriers inside the waveguides. The P- and N-type doping forms a P-N junction inside the waveguide with several hundreds of nanometers width. By electrical tuning, the effective index of the waveguide changes due to the variations in carrier distribution, which is called free carrier dispersion effect [32]. The index change results in the resonance shift indicated in Eq. (4), and thus, it could be utilized for UWB-IR generation and modulation.

4. UWB-over-fiber

UWB-over-fiber (UWBoF) has been proposed to effectively distribute UWB-IR signals while keeping the wireless transmission within tens of meters range. For such optical distribution, it can be more cost-effective to implement the generation and distribution of UWB-IR in optical domain, thus avoiding the need for multiple electrical to optical to electrical conversions. An interesting idea is to integrate the UWB signal distribution networks into the existed access networks. By sharing the same fiber, optical UWB-IR and wired downstream signal coexist in the access fiber networks. The fiber to the home brings the wireless UWB signal to the home as well. There are many UWBoF architectures discussed in the literatures. Among those access network solutions, wavelength division multiplexed-passive optical network (WDM-PON) is one of the most promising systems as it has extremely large data capacity. Though it has not been commercialized yet due to the cost issues, it has a bright future since it can fully utilize the nearly infinite optical bandwidth. Here, we introduce a hybrid solution of UWB-IR wireless service that is integrated with a WDM-PON. It provides a wired baseband data service and a UWB-IR signal distributed from the other remote antenna unit (RAU).

The schematic system configuration is shown in **Figure 14**. In such a WDM distribution system that integrates the UWB-IR and wired baseband signal, a silicon PIC is implemented in an optical network unit (ONU) within the WDM-PON architecture. The silicon chip serves as a wireless access point and a wired signal receiver. Centralized light sources are located at the central office, and there are two laser diodes with wavelength close to each other for each transmitter (Tx). This is a trick that is used for separation of the UWB and wired signal at the ONU side. For Tx1, laser diode1 (LD1) is intensity modulated with wired signal, while LD2 is phase modulated with the UWB wireless data. The wavelengths of LD1 and LD2 occupy two adjacent channels of the AWG. All the channels are multiplexed and transmitted in the distribution fiber. At the remote node, the wavelength channel allocated to wired signal is sent to the receiver directly. The other channel is separated into two branches with a portion of the signal remodulated by the upstream data. Since the UWB signal is a phase-modulated CW, the phase information will not affect the upstream data if intensity modulation format is used. Another part of the signal is coupled onto the silicon chip through

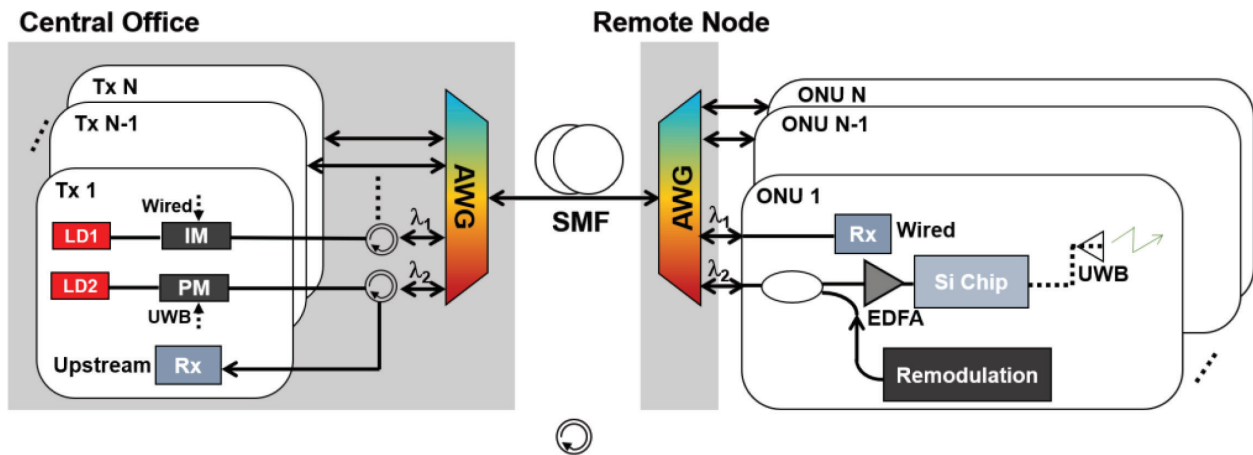


Figure 14. The schematic diagram of the UWBoF system, which is compatible with WDM-PON.

a grating coupler. The on-chip microring resonator performs the PM-IM conversion. The UWB monocycle pulse is generated and converted to electrical signal by a waveguide germanium photodetector, which can be fabricated using fully CMOS compatible process. If the photodetector has enough responsivity, its output can be directly fed into the antenna for wireless emission.

5. Conclusion

Though UWB has not been so widely implemented as Wi-Fi, Bluetooth, and other narrow-band services, its broadband nature and intrinsic advantages make it extremely suitable for some particular applications like indoor positioning and tracking. The UWB service has much higher precision and less interferences than other radio systems, which make it promising for Internet of things in the near future. MWP is emerging as an alternative technology for other UWB signal generation and processing in electrical domain. Over the past decade, we have witnessed a lot of lab demonstrations of UWB photonics like UWB waveform generation, UWB signal modulation, UWB-over-fiber, and so on. There are many other topics that remain open to the whole community such as the study on impact of fiber channel impairments, integration of UWB antenna and photonic chip, more power-efficient UWB pulse generation, advanced formats of UWB signal modulation, and so on.

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