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REVIEW ARTICLE

Recent progresses on optical arbitrary waveform generation

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Abstract This paper reviews recent progresses on optical arbitrary waveform generation (AWG) techniques, which could be used to break the speed and bandwidth bottlenecks of electronics technologies for waveform generation. The main enabling techniques for optically generating optical and microwave waveforms are introduced and reviewed in this paper, such as wavelength-to-time mapping techniques, space-to-time mapping techniques, temporal pulse shaping (TPS) system, optoelectronics oscillator (OEO), programmable optical filters, optical differentiator and integrator and versatile electro-optic modulation implementations. The main advantages and challenges of these optical AWG techniques are also discussed.

Keywords optical arbitrary waveform generation (AWG), wavelength-to-time mapping, optoelectronics oscillator (OEO), temporal pulse shaping (TPS) system, optical differentiator and integrator, electro-optic modulation

1 Introduction

Ultrafast optical/microwave waveforms with a bandwidth up to tens/hundreds of Gigahertz could find applications in numerous fields, such as high speed optical communications, biomedical imaging, and coherent control in chemistry [1–16]. Photonics-assisted techniques have attracted much attentions thanks to their applications in many fields [17–31], such as microwave frequency measurement, analog-to-digital conversion, microwave photonics sensing, broad bandwidth radar and microwave photonics filter. The state-of-the-art digital electronics has a very limited sampling speed due to its narrow signal processing bandwidth, the sampling rate of currently available arbitrary waveform generation (AWG) systems based on electronics technologies is limited to about 50 Gb/s. Thanks to the inherent high-speed and broad bandwidth offered by rapidly developed optical techniques, the photonic-assisted generation of ultrafast arbitrary optical/microwave waveforms in the optical domain has been a hot topic of interest in the past few years [32–40].

Over the decades, many kinds of optical techniques from free-space-based [4], fiber-based [34] to integrated optics [40] have been proposed to generate wideband and ultrafast optical/microwave waveforms. Microwave waveform is in general generated in the optical domain and then converted into microwave waveform with optical-to-electrical conversion in a photodetector (PD). Different techniques have their unique features for generating specific optical/microwave waveforms.

Among these reported techniques, the spectral shaping and wavelength-to-time mapping (SS-WTT) method is a very simple but powerful technique for AWG. In particular, SS-WTT method can be implemented based on pure fiber optics, which offers the advantages such as smaller size, lower loss, better stability and higher potential for integration [41–51]. SS-WTT technique is particularly suitable for AWG based on pure fiber optics. However, a major limitation of this technique, is the poor reconfigurability, since the spectral response of the optical spectral shaper is hard to be tuned once the filter is fabricated. To generate a reconfigurable waveform based on the SS-WTT method, a few optical spectral shaper with reconfigurable/programmable spectral responses have been reported, for example, the commercially available programmable optical processor based on the liquid crystal on silicon (LCOS) technology.

Direct space-to-time (DST) pulse shaping technique is a counterpart technique of SS-WTT implemented in the spatial domain [52–58]. A general DST waveform generator is implemented using a spatial or fiber-based diffraction grating by converting a spatially distributed

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pattern to a temporally distributed pattern. The spatially distributed pattern could be exactly mapped into a waveform in the time domain. At the initial investigation stage, the DST technique is realized using a pure spatial diffraction grating, a lens and a thin slit. However, the waveform generator becomes bulky and lossy due to spatial implementation and high coupling loss. Later on, the DST is implemented based on pure fiber optics using fiber Bragg grating (FBG) and long period grating (LPG). In particular, a superluminal space-to-time mapping can be realized in an LPG based on mode coupling, which could generate ultrafast arbitrary waveform with a bandwidth 3 orders higher than using an FBG. Recently, a DST waveform generator based on integrated optics using a modified arrayed waveguide grating was reported [12].

Temporal pulse shaping (TPS) system is another widely investigated technique for AWG. In a TPS system, two conjugate dispersive elements are connected before and after an optical modulator. The waveform at the output of the TPS system is a Fourier-transformed version of the modulation signal, which was used to implement microwave spectrum analysis [59–65]. The key feature of an optical AWG based on a TPS system is that an ultra-high speed waveform can be generated using a low speed waveform. In addition, the output waveform could be updated in real time by changing the low speed microwave waveform which makes the system reconfigurable with large flexibility. TPS system based AWG is first proposed and investigated by A. M. Weiner from Purdue University [4]. Arbitrary waveform in the picosecond and femtosecond regime has been successfully generated. However, an spatial liquid modulator (SLM)-based pulse shaping system is mainly limited by its large size, poor stability and high loss due to the implementation involving free-space optics. With the rapid development of fiber optics, a TPS system can be practically realized based on pure fiber-optics. Recently, Li and Yao experimentally demonstrated a purely fiber-based TPS system for the generation of symmetric waveforms [63]. In addition, they proposed an unbalanced TPS system for continuously tunable photonic microwave frequency multiplication and chirped microwave waveform generation.

Optoelectronics oscillator (OEO) is a classic microwave photonics system that produces repetitive electronic sine wave and modulated optical continuous wave signals. OEO has attracted great interests recently thanks to its numerous potential applications, such as wireless communications, optical signal processing, radar, and modern instrumentation. Recently, OEO has not only been used to generate single-frequency microwave waveform, but also arbitrary waveform such as arbitrarily phase coded, chirped and triangular microwave waveforms and high repetition-rate optical pulse train. The key feature of an OEO-based AWG is that an external waveform generator is not required which makes that waveform generator compact and low cost [66–68].

Programmable optical processor provides a powerful platform for the generation of high speed arbitrary waveform [69,70]. This kind of AWG is mainly implemented by linearly filtering the magnitude and phase of an input optical signal. The major advantage of this technique is that the magnitude and phase could be arbitrarily tuned by adjusting the phase distribution of LCOS-based SLM. Recently, Hu et al. employed the optical processor to generate an optical airy pulse for studying the nonlinear interaction between an airy pulse and the dispersion of an optical fiber [70]. Note that, there still exists two main specifications that needs to be improved. The first one is the limited spectral resolution. Currently, the state-of-art frequency resolution of an programmable optical processor is about 5 GHz, which in turn means that it could not be used to shaping the spectrum of an optical signal with a spectral resolution narrower than 5 GHz. By using two-dimensional LCOS-based SLM, the frequency resolution could be largely improved, but the system will become very complicated due to the requirement of a two-dimensional disperser. The second one is its bulky size and high cost. In particular, the high cost would be very important factor which determines whether the optical processor could be widely applied for AWG.

As mentioned above, although a programmable optical processor can be used to generate arbitrary waveform with broad bandwidth [71–81], its cost is very high. In some applications, only one or a few specific waveforms are needed, e.g., only a flat-top waveform is required as an optical gating signal for a time-division multiplex (TDM) system. In these cases, a waveform generator with an unique processing functionality and low cost is preferred by customers. Optical differentiator and integrator, as a kind of novel optical signal processor, have been proposed and experimentally demonstrated to generate flat-top and Hermite-Gaussian pulse in recent years. A low cost waveform generator with an unique functionality, such as optical differentiator or integrator, is particular attractive for some specific applications.

To increase the transmission capacity, different kind of advanced modulation formats have been widely investigated. Among them, various electro-optic modulators have been designed and fabricated, such as phase modulator, intensity modulator, polarization modulator, dual-parallel/dual-drive Mach-Zehnder modulator and quadrature amplitude modulation (QAM) modulator, etc [82–95]. Advanced format modulators allow us to control the magnitude and phase of an input optical signals by adjusting the modulation strategy. Based on a polarization modulator, many waveforms, such as ultrawideband waveform and phase coded microwave waveform, have been reported. Based on continuous wave (CW)-light intensity-only modulation, a sequence of arbitrarily chirped Gaussian-like optical pulses and complex-modulation (16-QAM) optical telecommunication data streams were generated.

This paper reviews recent progresses on optical AWG techniques, which could be used to break the speed and bandwidth bottlenecks of electronics technologies. The main enabling techniques for optically generating optical and microwave waveforms are introduced and reviewed in this paper, such as wavelength-to-time mapping techniques, space-to-time mapping, TPS system, OEO, programmable optical processors, optical differentiator and integrator and versatile electro-optic modulation implementations. This paper is organized as follows. In Section 1, the main waveform generation techniques are simply introduced. From Sections 2 to 8, recent progresses on optical AWG based on different techniques are presented in detail. A conclusion is drawn in Section 9.

2 Frequency-to-time mapping

SS-WTT mapping is an important technique, which has been recently employed to generate arbitrary waveform, and some specific waveforms such as chirped microwave waveforms and ultrawideband signal. As shown in Fig. 1, an arbitrary waveform is generated in an SS-WTT mapping system by shaping the spectrum of an ultrashort optical pulse using a spectral filter with reconfigurable spectral response, followed by WTT mapping in a dispersive element. Thanks to the linear WTT mapping, an arbitrary microwave waveform with a shape that is a scaled version of the shaped optical spectrum is generated. The WTT mapping relation between the frequency and time is given by $t = \ddot{\phi}\omega$, where t denotes the time, ω denotes the angular frequency and $\ddot{\phi}$ presents the dispersion. The key device in an SS-WTT system for an arbitrary microwave waveform generation is the optical spectral filter. Such an optical spectral shaping can be implemented using various optical filters such as FBGs, interferometers and ring resonator arrays with programmable spectral response within the bandwidth of a pulsed laser.

As shown in Fig. 2, a chirped microwave waveform is generated using a tilted FBG (TFBG) based on SS-WTT mapping [51]. A transform-limited ultrashort optical pulse from a mode locked laser (MLL) is sent to the TFBG that is working in the transmission mode. The TFBG is used to shape the power spectrum of the input optical pulse to have a spectrum that has linearly increasing wavelength spacing for the cladding mode resonant wavelengths. After the TFBG, a dispersive element with a linear group delay response is used to perform the dispersion-induced wavelength-to-time mapping. A microwave waveform with its shape that is a scaled version of the shaped optical power spectrum is then generated at the output of a PD. Note that, since the spectral response of the TFBG is not easy to change once it was fabricated, the generated chirped microwave waveform is not reconfigurable.

As shown in Fig. 3, an interesting approach to generating a chirped microwave waveform with continuously tunable chirp rate based on temporal interferometry

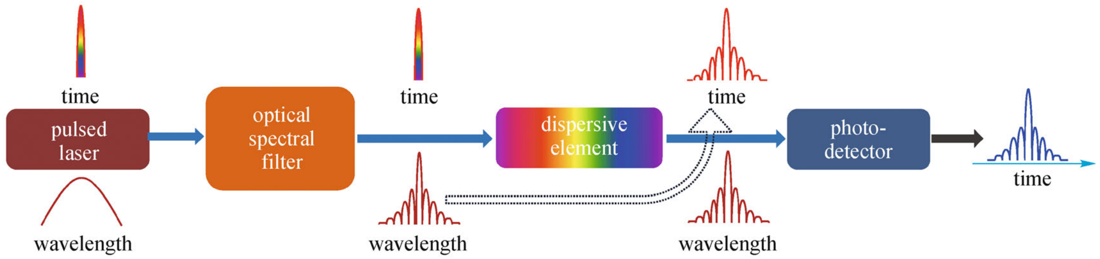


Fig. 1 Schematic showing of a microwave arbitrary waveform generation (AWG) system based on optical spectral shaping and wavelength-to-time mapping (SS-WTT) technique

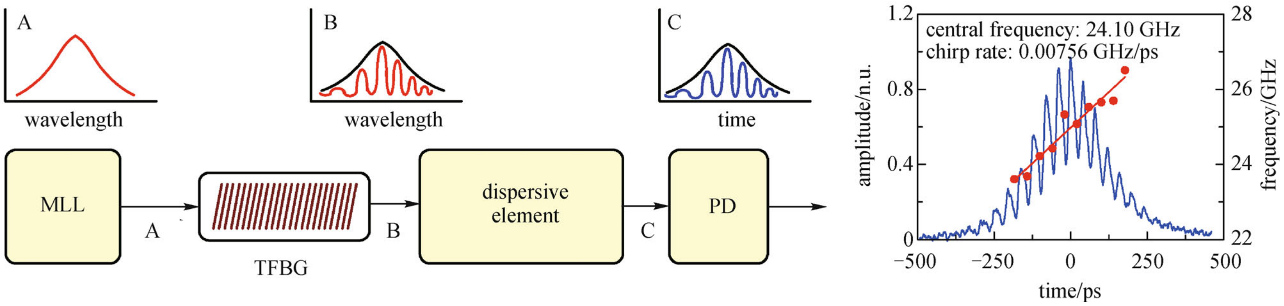
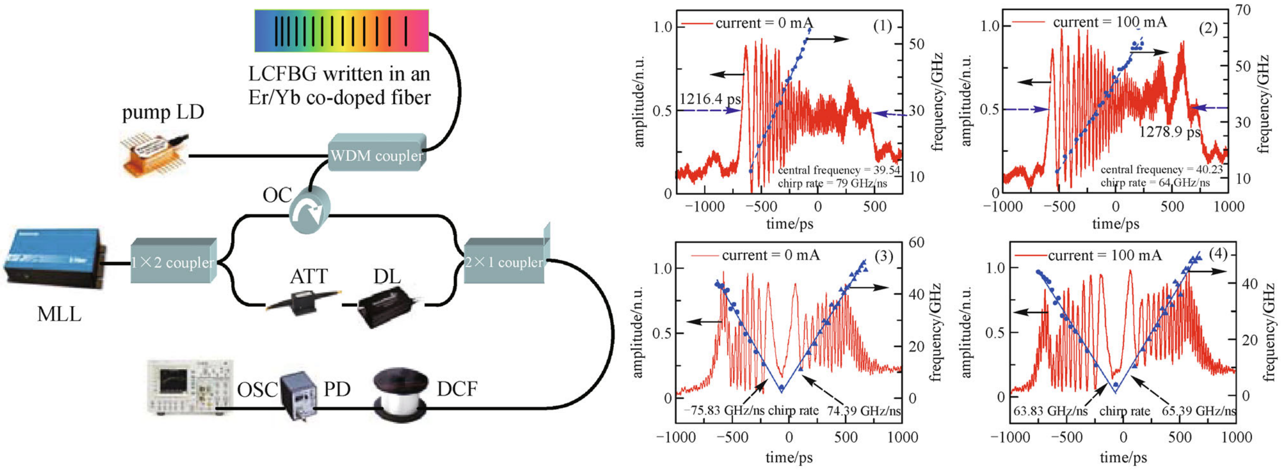


Fig. 2 Schematic of a chirped microwave waveform generator using a TFBG based on spectral shaping and wavelength-to-time mapping (SS-WTT) mapping. MLL: mode-locked laser; TFBG: tilted fiber Bragg grating; PD: photodetector [51]



(a) (b)

Fig. 3 (a) A temporal interferometer for a chirped microwave waveform generation. An LCFBG is incorporated in the interferometer, and a DCF is used to stretch the two pulse from the interferometer. (b) Experimental result (ΔL = 4 cm): the generated linearly chirped microwave waveform (solid + red line) and the instantaneous frequency (blue dots) (1) without pumping, and (2) with optical pumping. Dashed line: linear curve fitting of the instantaneous frequency. Experimental results (ΔL = 0 cm): the generated linearly chirped microwave waveform (solid + red line) and the instantaneous frequency (blue dots) (3) without pumping, and (4) with optical pumping. Dashed line: linear curve fitting of the instantaneous frequency. LCFBG: linearly chirped fiber Bragg grating, LD: laser diode; MLL: mode-locked laser; ATT: attenuator; DL: delay line; OSC: oscilloscope; PD: photodetector; DCF: dispersion compensating fiber; OC: optical circulator [60]

was proposed and experimentally demonstrated [60]. The key feature of this proposed chirped microwave waveform generation system is that an optically pumped LCFBG is employed in a Mach-Zehnder interferometer (MZI) serving as the spectral filter. The spectral response of the MZI has an increasing or decreasing free spectral range (FSR), which is tunable by pumping the LCFBG. After the WTT mapping in a dispersion compensating fiber (DCF), a temporal interference pattern with an instantaneous frequency that is linearly increasing with time is generated. The detection of the temporal interference pattern at a PD would generate a linearly chirped microwave waveform. The optically pumped LCFBG is written in an erbium-ytterbium (Er/Yb) co-doped fiber. By pumping the LCFGB with different pump power, the group delay response will be changed, leading to the change of the FSR of the spectral response. The key advantage of using optical tuning over an external thermal or mechanical tuning to tune the dispersion of the LCFBG is that the dispersion can be tuned at a high speed and controlled remotely. In addition, the undesirable birefringence effects existing in the mechanical tuning technique can also be avoided. A linearly chirped microwave waveform with a tunable chirp rate from 79 to 64 GHz/ns by changing the injection current of the pump laser diode (LD) from 0 to 100 mA is experimentally demonstrated. In addition, the central frequency of the generated chirped microwave waveform can be changed by tuning the longitudinal offset of the MZI.

3 Space-to-time mapping

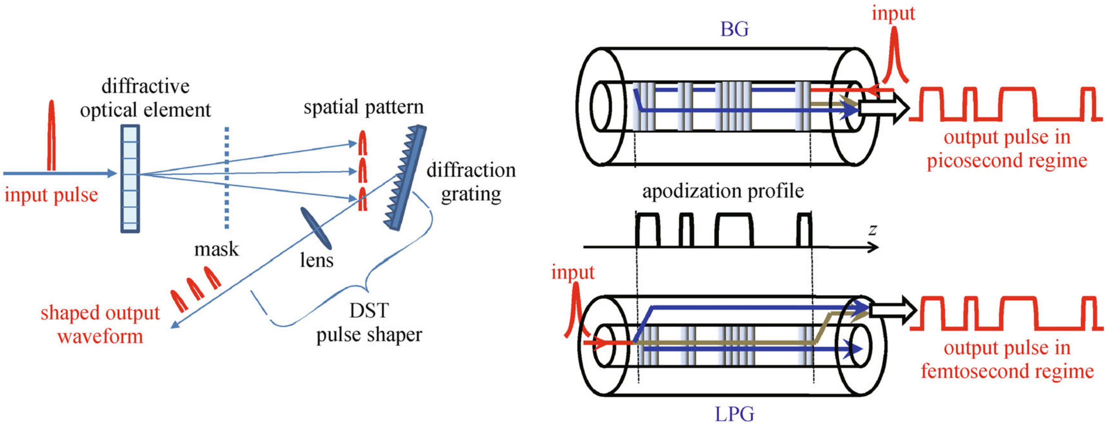
Figure 4 shows the schematic showings of DST pulse shaping techniques. As shown in Fig. 4(a), a DST pulse shaper implemented in the spatial domain consists of an input diffraction grating, a lens and an output thin slit. The basic principle of a DST pulse shaper is to convert a spatially distributed pattern to a temporally distributed waveform. An arbitrary waveform could be generated by tuning the spatial mask response. The amplitude, pulse-to-pulse spacing, and repetition rate of the pulse sequence can be controlled after the space-time mapping. However, a DST implemented in the spatial domain has the disadvantages of bulky and high coupling loss.

To reduce the size and loss of DST in a free-space-based system [52,53], the arbitrary waveform can also be generated using fiber optic components such as FBGs and LPGs, as shown in Fig. 4(b). The advantages of these solutions are associated with their intrinsic compact, low-loss all-fiber implementations. FBG was first used to realize waveform generation based on DST mapping technique. An optical input pulse is reflected back by each section of the Bragg gratings. When the FBG working in reflection under weak-coupling conditions, i.e., so-called first-order Born approximation, multiple reflection of the optical signal in FBG could be neglected. The apodization profile of the FBG can be converted to the profile of output waveform. In other words, the output time-domain filter response is directly proportional to the complex grating apodization profile with a space-to-time scaling factor. However, an FBG operates in a counter-propagation coupling mode. The ratio (v) between the space (Δz) and time (Δt) variables is necessarily lower than the propagation speed of light in vacuum (c), i.e., $v = \Delta z/\Delta t = c/2n_{\mathrm{eff}} < c$, where n_{eff} denotes the effective index of the FBG. It means that space-to-time mapping speed is much lower than light speed, which in turn determines that the generated waveform cannot reach very high speed, limited in the picosecond regime [54–58].

Recently, Ashrafi et al. reported an experimental demonstration of a DST based pulse shaping approach based on the first-order Born approximation in LPGs [55–58], referred to as superluminal space-to-time mapping. In contrast to counter-directional coupling devices such as FBGs, LPG is a co-directional coupling device. The space-to-time mapping speed is given by $v = \Delta z/\Delta t = c/(n_{\mathrm{clad}} - n_{\mathrm{core}}) > c$, where n_{clad} denotes the effective index of cladding modes, n_{core} presents the effective index of fiber core. It is obvious that the space-to-time mapping speed in an LPG is much higher (about 3 orders) than the one in an FBG. An LPG is fabricated using the standard single-mode fiber (Corning SMF28) and is designed for generation of 4-symbol data stream patterns, i.e., “1”0”0”1”. The separation length between the first and last apodization-bits of fabricated LPGs is 7.12 cm. As shown in Fig. 5, when a nearly transform-limited Gaussian-like optical pulse with a FWHM of ~200 fs is launched into the LPGs, a 4.6-TBaud data stream sequence with a pattern of “1”0”0”1” is successfully generated.

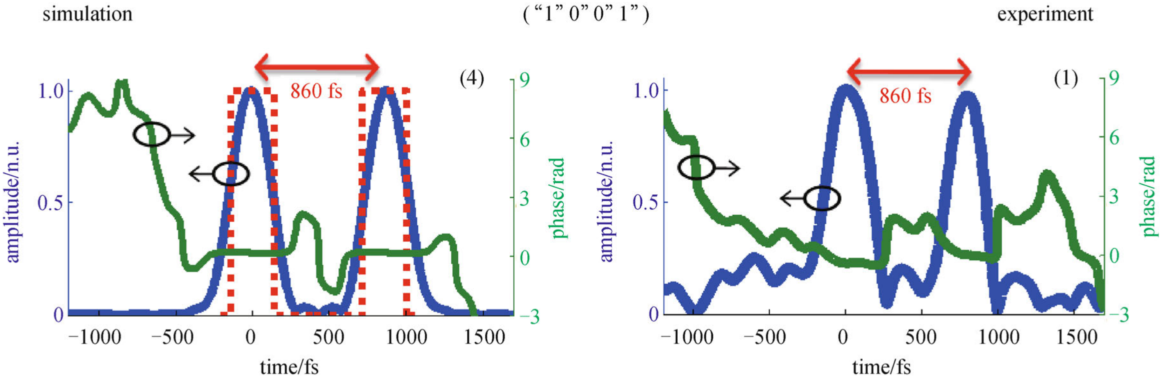
4 Temporal pulse shaping system

Figure 6 shows a schematic diagram of a TPS system for AWG. TPS techniques have been widely used for arbitrary microwave waveform generation, thanks to the advantageous features such as simple configuration and real-time reconfigurability [59–65]. In a TPS system, two conjugate dispersive elements are connected before and after an



(a) (b)

Fig. 4 Schematic showing of an arbitrary waveform generation (AWG) system based on direct space-to-time (DST) techniques: (a) based on free space optics; (b) based on fiber Bragg gratings (FBGs) and long period gratings (LPGs) [55]



(a) (b)

Fig. 5 Simulated (a) and experimentally (b) measured output time-domain amplitude (solid blue curves) and phase (solid green curves) responses of the fabricated long period gratings (LPGs) [55]

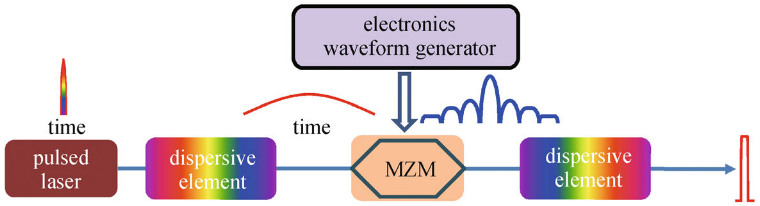


Fig. 6 Schematic showing of an arbitrary waveform generation (AWG) techniques based on a temporal pulse shaping (TPS) system. MZM: Mach-Zehnder modulator

optical modulator. The waveform at the output of the TPS system is a Fourier-transformed version of the modulation signal, which can be used to generate a fast waveform using a relatively slow waveform. The same concept has also been used to implement microwave spectrum analysis. The key advantage of the TPS technique is that a high-speed pulse can be generated using a relatively low-speed waveform. The major difficulty of the approach is that the input waveform is usually complex valued, and the modulation of a complex-valued waveform requires an intensity modulator and a phase modulator with precise synchronization. A TPS system based on pure fiber-optics was proposed by Chi and Yao in Ref. [59], but the technique was studied numerically with no experimental demonstration performed.

Recently, an experimental demonstration of a purely fiber-based TPS system for the generation of symmetric waveforms was presented [63]. Figure 7 shows the TPS system for the generation of a symmetric waveform. A transform-limited Gaussian pulse is generated by a MLL. Two conjugate dispersive elements, connected before and after the MZM, are a SMF and a DCF. The dispersion of the SMF and DCF is conjugated. The output of the system is a scaled version of the Fourier transform of the modulation signal from an electronic arbitrary waveform generator. The target symmetric waveform can be generated by programming the signal from the electronic arbitrary waveform generator.

When the target output is a rectangular waveform, the optical signal at the output of the MZM should be a Sinc waveform. The input modulation signal is designed with a Sinc-like function, as shown in Fig. 8(a). The spectrum of the optical signal at the output of the MZM is measured by an optical spectrum analyzer (OSA), as shown in Fig. 8(b). Figure 8(c) shows the calculated waveform at the output of the DCF, which is a rectangular wave with a 3-dB time width of 15.3 ps. The ripples on the top of the rectangular waveform are caused by the truncation of the Sinc waveform at the MZM. Since the output waveform is too fast to detect using a PD, an autocorrelator is employed to measure the output waveform. It is known that the correlation of a rectangular waveform is triangular. The measured correlation output and the recovered output signal (i.e., the rectangular waveform) are shown in Fig. 8 (d). As can be seen, a triangular waveform is observed. Based on the autocorrelation output, the width of the experimentally generated rectangular waveform is calculated, which is 18.8 ps. A good agreement between the simulated and the experimental results is reached.

As shown in Fig. 9, an unbalanced TPS system for chirped microwave waveform generation is proposed and demonstrated [64]. The proposed system consists of an ultrashort pulsed source, a MZM and two dispersive elements. The dispersions of the two dispersive elements are opposite in sign, but not identical in magnitude. The entire system is equivalent to a conventional balanced TPS system with two complementary dispersive elements for real-time Fourier transformation and a third dispersive element to achieve a second real-time Fourier transformation. The key significance of this proposed technique is that a high-frequency and frequency-chirped microwave waveform can be generated using a relatively low-frequency CW microwave source with a simple system structure, which can find many applications in radar, high-speed communications and modern instrumentation. In addition, the chirp rate of the generated microwave waveform can be tuned by changing the third-order dispersion of the dispersive element.

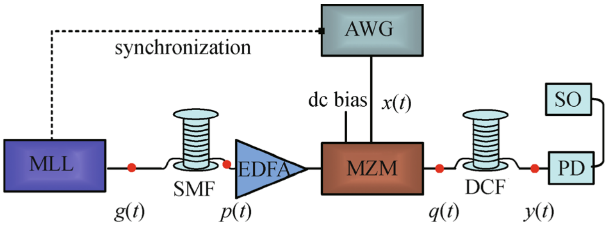


Fig. 7 Experimental setup of a temporal pulse shaping (TPS) -based symmetric arbitrary waveform generation (AWG) sytem. AWG: arbitrary waveform generator; MLL: mode-locked laser; SMF: single mode fiber; EDFA: erbium-doped fiber amplifier; MZM: Mach-Zehnder modulator; DCF: dispersion compensating fiber; SO: sampling oscilloscope; PD: photodetector [63]

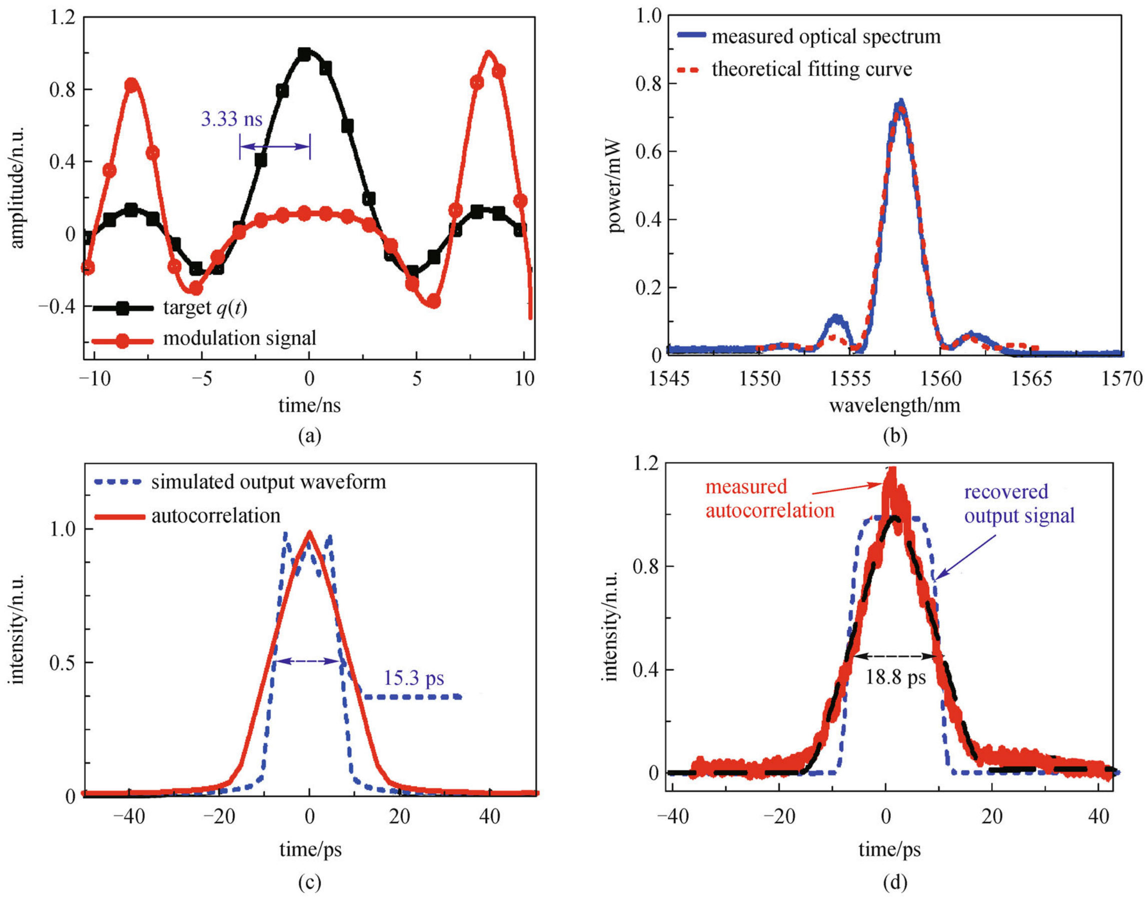


Fig. 8 (a) Target optical waveform at the output of the Mach-Zehnder modulator (MZM) and the calculated modulation signal; (b) measured spectrum of the optical signal at the output of the MZM and its fitting curve with the square of a Sinc function; (c) simulated waveform at the output of the dispersion compensating fiber (DCF) and its autocorrelation; (d) measured autocorrelation (solid line) at the output of the DCF, the recovered waveform (dotted line) from the measured optical autocorrelation, and its simulated autocorrelation (dashed line) [63]

5 Optoelectronics oscillator

As shown in Fig. 10, OEO is an oscillator with a resonant loop formed by optical and electrical components. In this loop, an optical signal is converted to an electrical signal using a photodetector, and the electrical signal is modulated onto the optical signal using an electro-optic modulator. An optical delay line, such as a long length of SMF or a whisper gallery mode (WGM) device, is used to increase the loop length for achieving a high Q factor of the oscillator. An electrical filter is used to select the oscillating frequency of the oscillating loop [68].

OEO has been employed to generate pure-frequency microwave waveform, frequency-hopping-free microwave waveform, linearly chirped microwave waveform and arbitrary phase-coded microwave waveform. Recently, a novel approach to achieving a frequency-tunable OEO using a photonic microwave transversal filter is proposed and experimentally demonstrated [68]. The schematic of the proposed frequency-tunable OEO is shown in Fig. 11. it is the first time to implement an all-optical tunable OEO based on a spectrum-sliced photonic microwave filter. In this proposed technique, a broadband amplified spontaneous emission (ASE) optical source is coupled to a programmable multichannel optical filter, which is employed to slice the broadband spectrum into multiple channels. The spectrum-sliced broadband source is then fiber coupled into a MZM, which is biased at the quadrature point. The MZM is connected to a dispersive element which can be a DCF, a SMF or an LCFBG. The optical output from the dispersive element is converted to an electrical signal at a photodetector and then fed back to the MZM to form the OEO loop. An electrical amplifier (EA) is used in the loop to provide sufficient electrical gain. The generated microwave signal exhibited a good phase noise performance with a phase noise of −120 dBc/Hz at an offset of 10 kHz as shown in Fig. 12. The key significance of the proposed technique is that no electronic microwave filters are needed which ensures a large frequency tunable range through all-optical tuning.

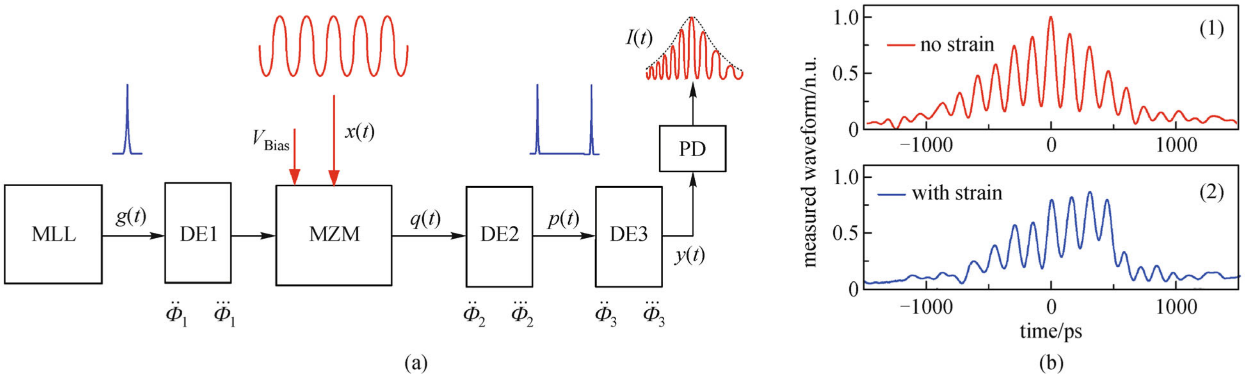


Fig. 9 (a) Schematic showing of a proposed unbalanced temporal pulse shaping (TPS) system for chirped microwave pulse generation; (b) generated chirped microwave waveform with different chirp rates. MLL: mode locked laser; DE1: the first dispersive element; MZM: Mach-Zehnder modulator; DE2: the second dispersive element; DE3: the third dispersive element; PD: photodetector [64]

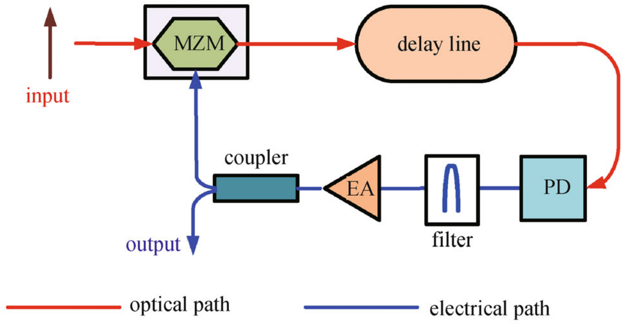


Fig. 10 Schematic showing of an OEO for microwave waveform generation. MZM: Mach-Zehnder modulator; PD: photodetector; EA: electrical amplifier

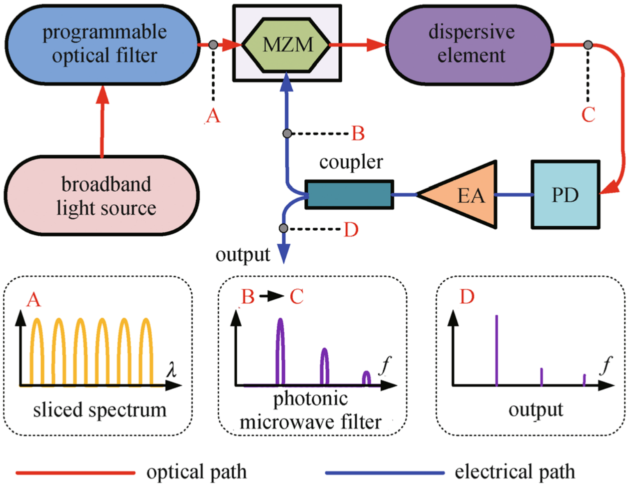
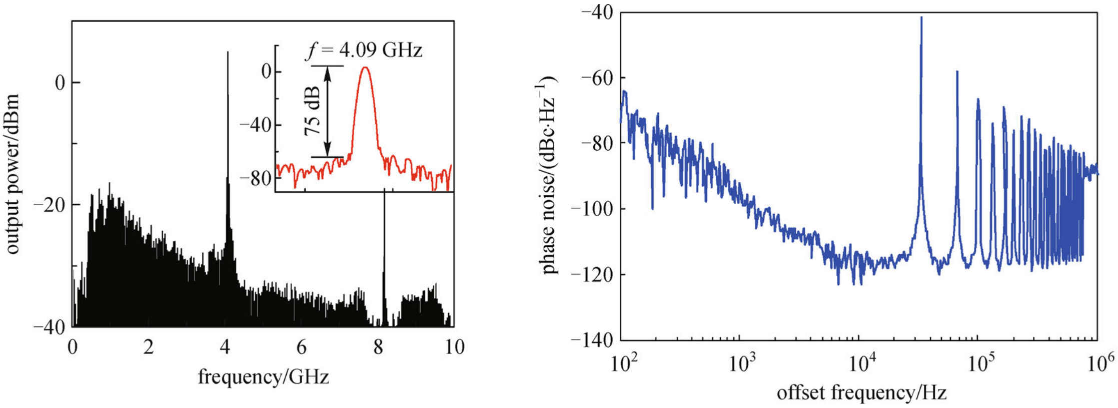


Fig. 11 Schematic diagram of the proposed frequency-tunable optoelectronic oscillator (OEO). MZM: Mach-Zehnder modulator; PD: photodetector; EA: electrical amplifier [68]

6 Programmable optical filter

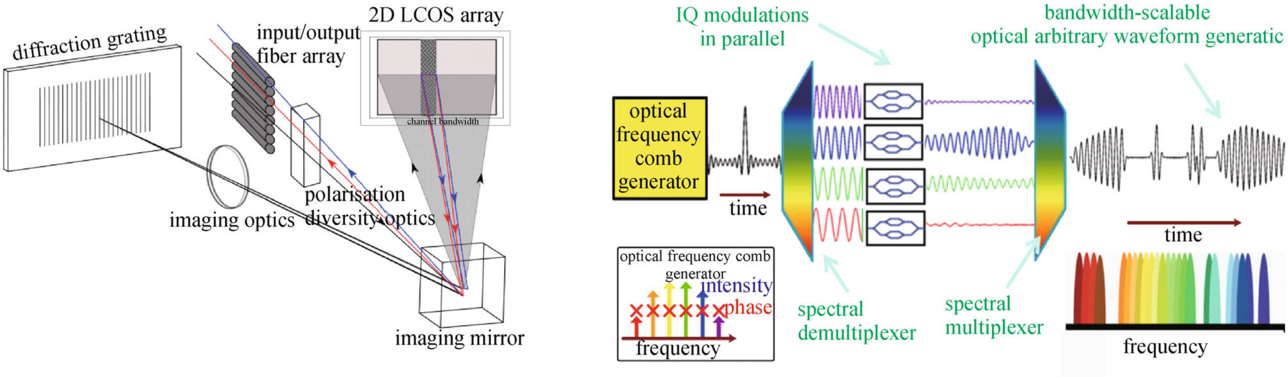
Programmable optical filter has been widely used to implement spectral shaping of an input optical signal for achieving optical AWG. There are two kinds of techniques for shaping the optical spectrum.

The first kind of programmable filter is based on a LCOS array, as shown in Fig. 13(a). Based on this technique, the



(a) (b)

Fig. 12 (a) Electrical spectrum of the generated 4.09 GHz microwave signal. The frequency span is 10 GHz and the resolution bandwidth (RBW) is 1 MHz. The inset gives a zoom-in view of the 4.09 GHz microwave signal; (b) phase noise measurement of the generated 4.09 GHz microwave signal [68]



(a) (b)

Fig. 13 Schematic showing of optical arbitrary waveform generation (AWG) system based on (a) a liquid crystal on silicon (LCOS)-based programmable optical signal processor; (b) in-phase/quadrature (IQ) modulation of an optical frequency comb [69]

input signal can be an optical signal with arbitrary shaped spectrum. By tuning the amplitude and phase of the input optical signal, an arbitrary waveform can then be generated. However, this technique is mainly limited by the spectral resolution of the LCOS-based optical filter [96]. Currently, the commercially available programmable optical filter has a limited resolution of about 5 GHz. The spectral resolution could be further improved by using a two dimensional LCOS. However, the two dimensional alignment is much complicated, which in turn leads to high insert loss and unstable filtering performance coving a broad bandwidth. Recently, as shown in Fig. 14, we theoretically and experimentally study the phenomena related to self-phase modulation of Airy pulses in fibers. During nonlinear evolution, most spectral components of the Airy pulses concentrate into one or two peaks for normal and anomalous dispersion, respectively. The Ariy pulse is generated by shaping an optical Gaussian pulse using a LCOS-based programmable optical filter [70].

The second kind of programmable waveform generation technique is based on in-phase/quadrature (IQ) modulation in parallel [69]. In this technique, an optical frequency comb must be used as the light source, as shown in Figs. 13(b) and 15. Each comb is distributed to each channel in a spectral demultiplexer and is modulated in amplitude and phase. The modulated combs are combined in a spectral multiplexer. The key feature of an IQ-modulation based AWG method is that the whole system can be integrated into a photonics chip and the output waveform can be widely reconfigurable by tuning the amplitude and phase modulation profile of the input optical frequency combs. However, the phase stability between each combs is a big issue that makes the generated waveform unstable. In particular, when the whole system is integrated onto a chip, the temperature on the chip will be arbitrarily changed in operation due to the generated heat during the IQ modulation. The temperature fluctuations on chip will highly affect the phase stability, which in turn makes the output waveform unstable.

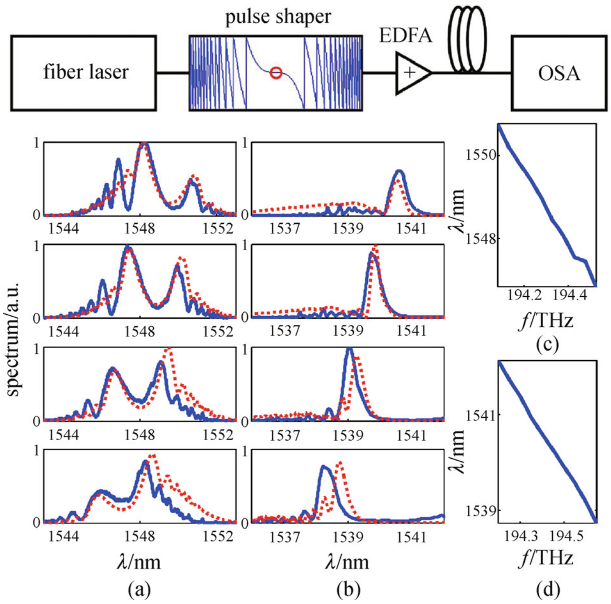


Fig. 14 Experimental setup for Airy pulses generation based on a programmable optical filter. The plot in the pulse shaper schematically shows the cubic phase structure wrapped between –π and π where the circle indicates its center. Experimental results (blue solid curve) and theoretical prediction (red dashed curve) of frequency shift control in (a) large-effective area fibers (LEAFs) and (b) dispersion shifted fibers (DSFs); (c) and (d) plot the positions of the spectral notch and peak relative to the center of the cubic phase structure, corresponding to (a) and (b), respectively. EDFA: erbium doped fiber amplifier; OSA: optical spectrum analyzer [70]

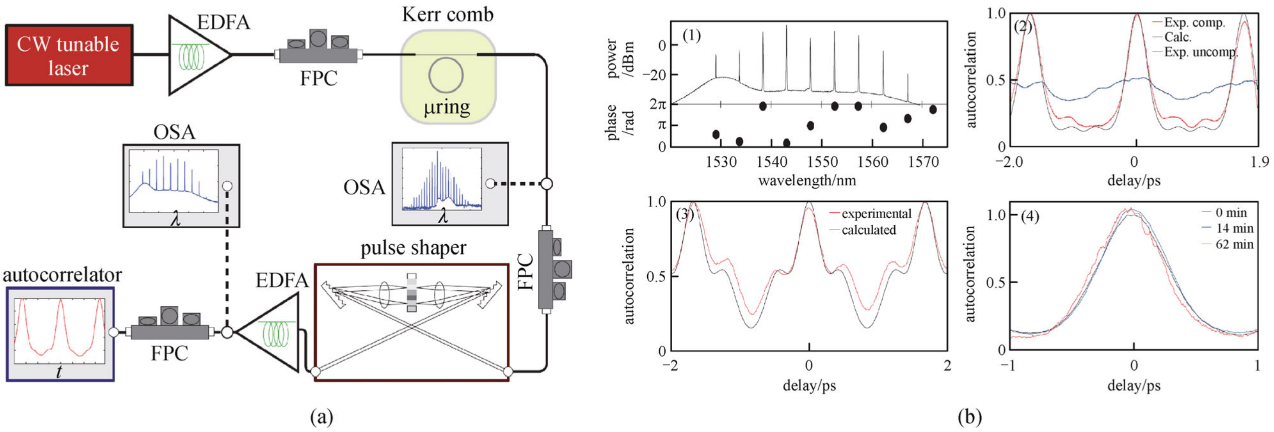


Fig. 15 (a) Scheme of the experimental set-up for LCOS-based programmable optical filtering of a frequency comb from a silicon nitride microring; (b) experimental results of the optical arbitrary waveform generation (AWG) [96]. FPC: fiber polarization controller; µring: silicon nitride microring; EDFA: erbium doped fiber amplifier; OSA, optical spectrum analyzer

7 Optical differentiator and integrator

Optical differentiator and integrator as two fundamental optical processors have been investigated in the past few years [71–81]. Thanks to the intrinsic advantages of broad bandwidth based on an optical implementation, optical differentiator and integrator have an extremely large bandwidth comparing to the electronics based signal processors. Optical differentiator was used to generate ultrawideband signals and flat-top pulse in the optical domain, which have very important applications in optical and wireless communications. Optical integrator has the potential applications to all-optical memory and flat-top pulse generation with a widely tunable time width. The basic principle of an optical differentiator and an optical integrator is schematically shown in Fig. 16.

Recently, an on-chip complemeritary metal-oxide semiconductor (CMOS)-compatible MZI is used for flat-top pulse generation by linearly re-shaping an input Gaussian-like optical pulse [75]. As shown in Fig. 17, the input

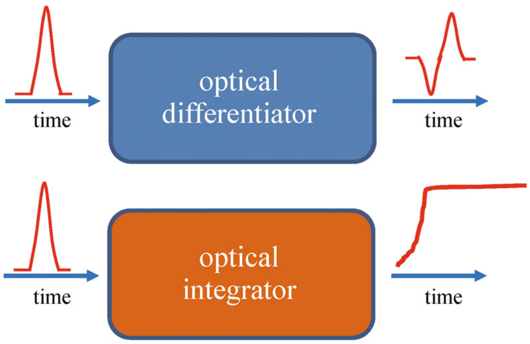


Fig. 16 Schematic showing of the input and output signals of an optical differentiator and integrator

section of the fabricated MZI has a FSR of 100 GHz. The input pulses in the experiments were nearly transform-limited Gaussian-like optical pulses generated from a passively mode-locked wavelength-tunable fiber laser. An flat-top pulse generation is implemented by re-shaping the input Gaussian-like optical pulse with a slightly wavelength-detuned optical differentiator. When the wavelength shifting between the pulse carrier wavelength and the MZI notch wavelength is tuned to 0.37 nm, as shown in Fig. 17 (e), a nearly chirp-free flat-top pulse with a time-width of 20 ps is generated, as shown in Fig. 17(f).

In addition, an all-optical temporal differentiator with a record operation bandwidth of ~25 THz (~200 nm, at least one order of magnitude larger than any previously reported temporal differentiation technology) was experimentally demonstrated based on a simple and compact all-fiber wavelength-selective directional coupler [74]. The fabricated directional coupler can be used to process optical signals with time features as short as a few tens of femtosecond. The schematic diagram of the wavelength-selective directional coupler is given in Fig. 18(a). The magnitude and phase spectral responses of the directional coupler is shown in Fig. 18(b). It can be seen that there is a π-phase-shift at the resonance wavelength and the total bandwidth of the differentiator has a bandwidth of 25 THz. When the wavelength shift between the pulse carrier wavelength and the directional coupler's central notch wavelength is tuned to ~8 nm, as shown in Fig. 18(c1), a

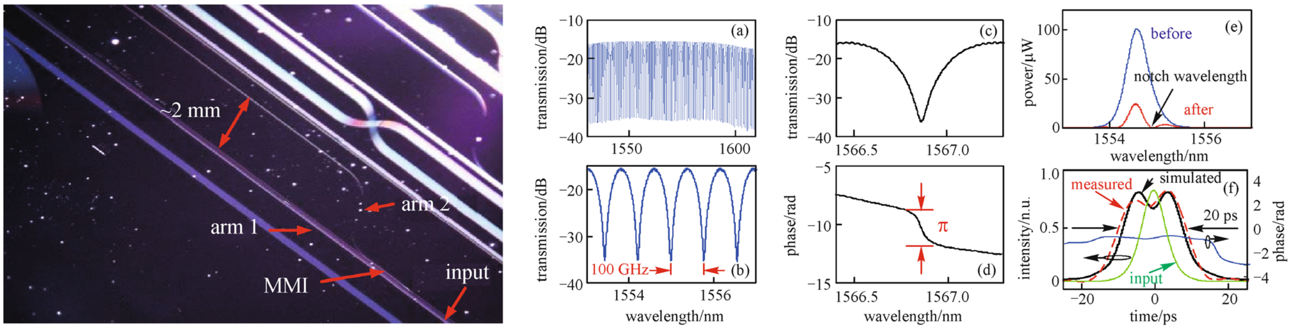
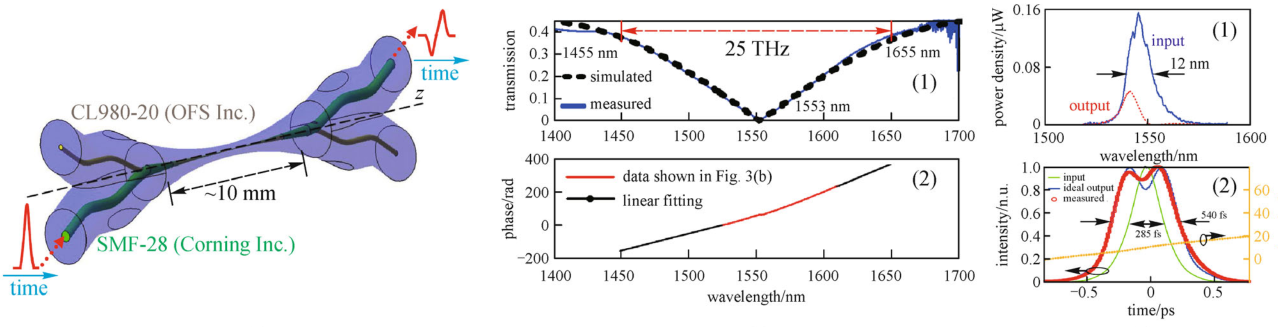


Fig. 17 Part of the fabricated on-chip complemeritary metal-oxide semiconductor (CMOS)-compatible Mach-Zehnder interferometer (MZI) based optical differentiator and the experimental results. (a) Transmission spectrum and (b) its zoom-in view of the fabricated MZI; (c) spectral magnitude and (d) phase responses along one of the device's resonances; (e) optical spectrum of an optical pulse before and after the optical differentiator; (f) generated flat-top pulse [75]



(a) (b) (c)

Fig. 18 (a) Schematic diagram of a wavelength-selective directional coupler; (b) magnitude and phase responses of the fabricated directional coupler; (c.1) spectra of a femtosecond pulse before and after propagation through the fabricated directional coupler when the pulse carrier wavelength is shifted from the central resonance wavelength by ~8 nm; (c.2) time-domain intensity profiles of the input pulse, the measured output pulse and the numerical ideal output [75] nearly chirp-free flat-top pulse with a full width at half maximum (FWHM) of 540-fs is generated at the directional coupler's output, as shown in Fig. 18(c2). The flat-top pulse is very useful for de-multiplexing of a time division multiplexing (TDM) signal with a high time-jitter tolerance for the gating signal.

8 Electro-optic modulation

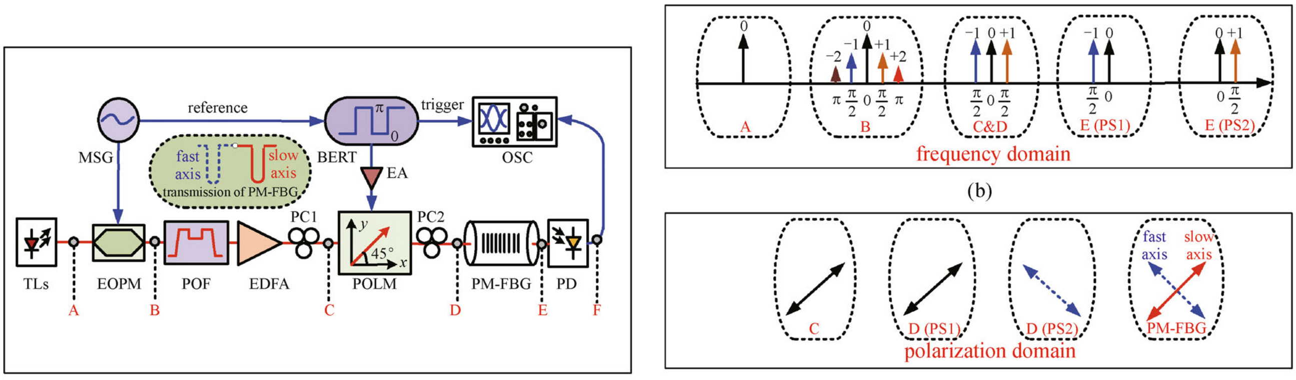
Different kind of advanced modulation formats have been widely investigated for increasing the transmission capacity of optical analog/digital transmission system. Among them, various electro-optic modulators have been designed and fabricated, such as phase modulator, intensity modulator, polarization modulator, dual-parallel/dual-drive Mach-Zehnder modulator and QAM modulator, etc [82–95]. Advanced format modulators allow us to control the magnitude and phase of an input optical signals. Based on a polarization modulator, ultrawideband waveform and phase coded microwave waveform could be easily generated. Rosario et al. reported an approach to generate an optical waveforms with arbitrary, user-defined complex (amplitude and phase) modulation patterns, e.g., a sequence of arbitrarily chirped Gaussian pulses or a 3-Gbps 16-QAM modulated data pattern, by using a extremely simple setup involving intensity-only modulation of a CW-light source and band-pass filtering [93].

As shown in Fig. 19, a novel photonic approach to generating a precisely π phase shifted binary phase-coded microwave signal is proposed and experimentally demonstrated [94]. In the proposed approach, a phase modulator (PM) is employed to generate two ±1st-order sidebands and an optical carrier. Thanks to the inherent ±π/2 phase shifts of the two ±1st-order sidebands, a binary phase-coded microwave signal with a precise phase shift of π is generated by beating one sideband with the optical carrier at a time, which is realized by the use of a polarization-maintaining fiber Bragg grating (PM-FBG) and a polarization modulator (POLM) to select one of the two sideband and the optical carrier. The experimental setup and basic principle are introduced in Fig. 19.

As can be seen from Fig. 20, a binary phase-coded microwave signal at 18 GHz is generated. Figure 20(b) shows the phase information recovered from the phase-coded signal which is also a 4.5-Gb/s "0101" digital sequence. An exact π phase shift is achieved. The pulse compression capability at this new frequency is evaluated. The phase-coding signal is a 4.5-Gb/s PRBS with a length of 128 bits. Figure 20(c) shows the generated 18-GHz phase-coded signal with a time duration of 28.44 ns. Figure 20(d) shows the autocorrelation. The autocorrelation peak has an FWHM of about 0.22 ns. The compression ratio is about 126.96 and the PSR is about 8.2.

9 Conclusions

Recent progresses on optical AWG techniques were introduced and analyzed in detail. Optical implementation of arbitrary waveform generation could be effectively used to break the electronics limitations of speed and bandwidth. However, most of the enabling techniques reported are based on bulky and fiber optics system. The cost and performance should be further improved. To solve this problem, a fully programmable optical arbitrary waveform generator based on photonics integrated circuits would be the most promising solution in the near future.



(a) (b) (c)

Fig. 19 (a) Schematic showing of the proposed binary phase-coded microwave signal generation system; illustration of operation principle in (b) frequency domain and (c) polarization domain. TLs: tunable lasers; EOPM: electro-optic phase modulator; MSG: microwave signal generator; POF: programmable optical filter; EDFA: erbium doped fiber amplifier; PC: polarization controller; POLM: polarization modulator; BERT: bit error rate tester; EA: electrical amplifier; PM-FBG: polarization maintaining fiber Bragg grating; PD: photodetector; OSC: oscilloscope; PS: polarization state [94]

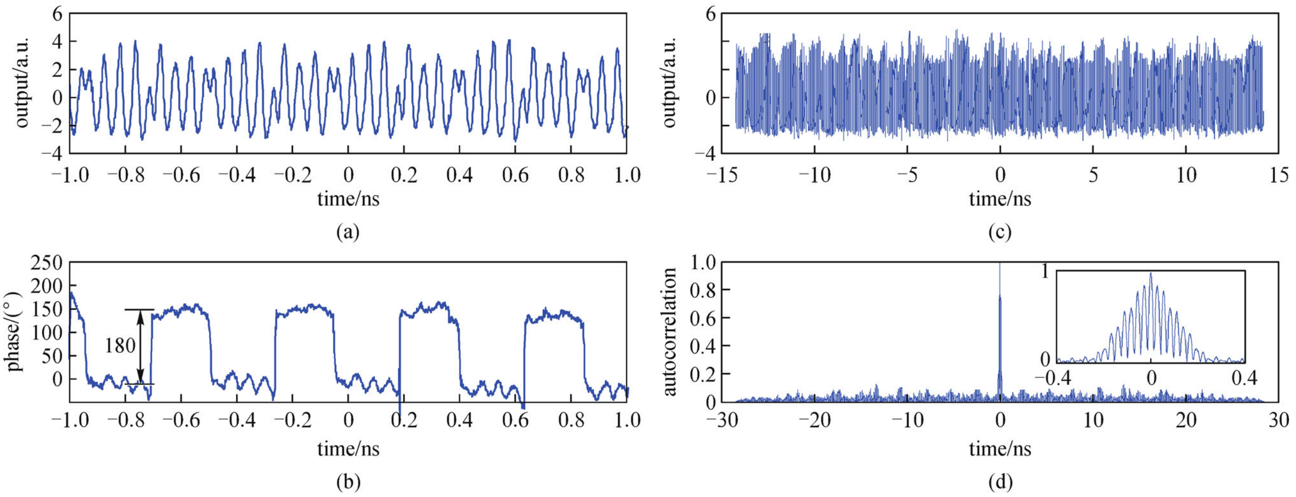


Fig. 20 (a) Generated 18-GHz binary phase-coded signal; (b) recovered phase information from the binary phase-coded microwave signal in (a); (c) binary phase-coded signals and (d) calculated autocorrelation of the signal with a carrier frequency of 18 GHz [94]

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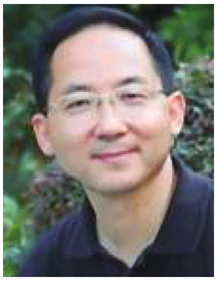

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