Rapidly reconfigurable high-fidelity optical arbitrary waveform generation in heterogeneous photonic integrated circuits

SHAOQI FENG,1,2 CHUAN QIN,1,2 KUANPING SHANG,1 WEICHENG LAI,1 BINBIN GUAN,1 MATTHEW CLEMENTS,1 TIEHUI SU,1 GUANGYAO LIU,1 HONGBO LU,1 RYAN P. SCOTT,1 AND S. J. BEN YOO1,*

1Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA
2These authors contributed equally to the work.
sbyoo@ucdavis.edu

Abstract: This paper demonstrates rapidly reconfigurable, high-fidelity optical arbitrary waveform generation (OAWG) in a heterogeneous photonic integrated circuit (PIC). The heterogeneous PIC combines advantages of high-speed indium phosphide (InP) modulators and low-loss, high-contrast silicon nitride (Si$_3$N$_4$) arrayed waveguide gratings (AWGs) so that high-fidelity optical waveform syntheses with rapid waveform updates are possible. The generated optical waveforms spanned a 160 GHz spectral bandwidth starting from an optical frequency comb consisting of eight comb lines separated by 20 GHz channel spacing. The Error Vector Magnitude (EVM) values of the generated waveforms were approximately 16.4%. The OAWG module can rapidly and arbitrarily reconfigure waveforms upon every pulse arriving at 2 ns repetition time. The result of this work indicates the feasibility of truly dynamic optical arbitrary waveform generation where the reconfiguration rate or the modulator bandwidth must exceed the channel spacing of the AWG and the optical frequency comb.

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References and links


1. Introduction

Optical arbitrary waveform generation (OAWG) has been an area of active research where a Fourier synthesis of an optical waveform is made possible through line-by-line full field control of a coherent optical frequency comb (OFC) [1,2]. An OAWG waveform shaper separates optical comb lines from the OFC using a spectral demultiplexer (DEMUX), applies amplitude and phase modulation to each comb line with an array of modulators, and combines the modulated comb lines using a spectral multiplexer (MUX). The OAWG finds applications including microwave photonics [3], high-speed coherent communications [4–7] quantum optics [8–10], LIDAR [11], medical imaging and instrumentation systems.

The OAWG waveform shaper updates synthesized waveforms by altering amplitude and phase modulation on each comb line. Depending on the update speed, OAWG can be divided into two classes, namely static-OAWG and dynamic-OAWG. Static-OAWG imposes time-independent coherent modulation (amplitude and phase) on each comb line and thus generates arbitrary waveforms repeating at the OFC period. In spite of its repetitive nature, many interesting static-OAWG applications have been demonstrated in the literature [12–16]. On the other hand, dynamic-OAWG [1,4] imposes time-varying coherent modulation (in-phase
and quadrature-phase) to generate arbitrary optical waveforms with infinite record-length. There are two dynamic-OAWG approaches investigated to date: the rapidly-reconfigurable approach and the spectral-slice approach. In rapidly-reconfigurable dynamic-OAWG, the target waveform is synthesized on a pulse-to-pulse basis by updating the comb line modulations for each OFC period to change the output waveform. In spectral-slice dynamic-OAWG, the target waveform is analyzed over much longer time periods (temporal slices). While the spectral-slice dynamic-OAWG approach can result in truly dynamic OAWG, it imposes very stringent requirements on performances of highly linear modulators, high-resolution spectral MUX, high dynamic range digital-to-analog converters (DACs), and sophisticated algorithms. The rapidly-reconfigurable OAWG already has many applications including quantum communications [8–10], and we mainly focus on a rapidly reconfigurable OAWG.

In addition to the update speed, the waveform fidelity is another important figure of merit for OAWG. As regards static-OAWG, the fidelity depends on the crosstalk of spectral MUX and the precision of amplitude and phase settings. In contrast, the fidelity optimization of dynamic-OAWG is more challenging. To quickly reconfigure waveforms, frequency responses of modulators and electrical DACs have to be well considered. The fastest commercial DACs have 10-20 GHz of analog bandwidth and set an upper limit on the channel spacing. On the other hand, this sharp spectral resolution imposes a stringent requirement on the crosstalk of the spectral MUX, which sets a lower limit. This tradeoff leads to a compromise between spectral resolution and update speed [17]. A channel spacing of 20 GHz is near optimal considering current state-of-the-art electrical DACs and spectral MUX technologies.

Intensive research efforts have been made towards OAWG with high fidelity and fast update speed. The early demonstration and eventually commercialized technique is a bulk optical approach. It spatially disperses the OFC using gratings and alters amplitude and phase of different frequency components using a spatial light modulator (SLM) [18]. This approach has a limited update speed of milli-seconds, strict alignment requirements, low power efficiency and high sensitivity to environmental variations. To achieve improved stability, an integrated solution based on a silica platform has also been investigated. Silica OAWGs included silica-AWGs as spectral MUX and DEMUX and silica Mach-Zehnder interferometers (MZI) as amplitude and phase modulators [12,19]. Silica AWGs achieved relatively high contrast ratios and silica MZIs obtained well-controlled amplitude/phase modulation to realize high fidelity silica OAWGs. However, the relatively slow thermo-optical effect that governed the MZIs prohibited demonstrations of dynamic OAWGs in silica at meaningful speeds. Recent efforts for demonstrating truly dynamic-OAWG adopted an InP platform which supports dense arrays of high-speed modulators [20,21]. However, the fidelity of the OAWG was negatively affected by relatively large crosstalk in InP AWG MUX and spectral misalignment between the two AWG passbands [4]. So far, previous efforts failed to achieve high-fidelity and high-speed OAWG operation. On the other hand, the recently demonstrated high-contrast, low-loss Si$_3$N$_4$ AWGs are ideal as spectral dispersers [22], while InP modulators can achieve high-speed and high-fidelity modulation. The challenge of achieving both fidelity and speed requirements can be possibly overcome through heterogeneous integration of the two dissimilar material platforms.

In this article, we propose rapidly reconfigurable OAWG with a heterogeneous photonic integrated circuit [23]. As Fig. 1 illustrates, the proposed OAWG exploits high-speed InP modulators and low-loss, high-contrast Si$_3$N$_4$ AWGs; it consists of a Si$_3$N$_4$ AWG DEMUX, an InP modulator array, and a Si$_3$N$_4$ AWG MUX. The OAWG module separates each of the optical frequency comb lines using the Si$_3$N$_4$ AWG spectral DEMUX, imposes modulation on each line using the InP phase modulators, and coherently combines the modulated comb lines using the Si$_3$N$_4$ AWG spectral MUX. The Si$_3$N$_4$ and InP chips are actively aligned and then glued. Modulator electrodes are connected to high-speed printed circuit boards (PCBs) which
apply electrical signals for a target optical arbitrary waveform. By utilizing the heterogeneous platforms, we demonstrate that the OAWG module is able to offer high fidelity and 2-ns reconfigurable period, and this work takes a crucial step toward a truly integrated dynamic-OAWG.

The remainder of this article is organized as follows. Section 2 and 3 discuss design and fabrication of InP phase modulator arrays and Si$_3$N$_4$ AWGs, respectively. Section 4 presents the heterogeneous integration of modulator and AWG chips into an OAWG module. Section 5 demonstrates the ability of the OAWG module to generate various kinds of static and ultrafast reconfigurable waveforms with high fidelity.

2. InP phase modulator array

The optical waveform synthesis process in dynamic OAWGs involves the application of electrical signals to an array of optical modulators configured for line-by-line dynamic modulation of optical frequency comb. Ideally, the electrical-to-optical modulation transfer function should be linear and should achieve in-phase and quadrature-phase (IQ) modulations. For rapidly-reconfigurable OAWGs, amplitude and phase modulators can replace IQ modulators since the phase-reset can be achieved during the transient of waveform configuration. To this end, the InP/InGaAsP electro-optical modulator serves as an appropriate candidate for phase modulators capable of high-speed modulation and monolithic integration with InP/InGaAsP AWG MUX and DEMUX.

Our previous OAWG devices [4] utilized monolithic integration of InP/InGaAsP modulators and AWGs with epitaxial regrowth of an ion-doped InP over-cladding after defining waveguides by dry etching. The technique leads to promising photonic integration along with some disadvantages. The epitaxial regrowth for OAWG requires relatively complicated process steps, especially to overcome facet-dependency dictating typical epitaxial regrowth process. Here we utilized a regrowth-free InP waveguide modulator structure using Benzocyclobutene (BCB) instead of ion-doped InP as the waveguide over-cladding. The regrowth-free modulators expect to achieve lower parasitics, higher speed, higher power efficiency, and simpler process compared to the regrown modulators.

Figure 2(a) illustrates a cross-sectional schematic of the InP/InGaAsP phase modulator. The waveguide has a 4 µm core-width, a 0.5 µm core-height and a 0.35 µm rib-height. It is integrated with a vertical p-i-n diode including p-InP/i-InGaAsP/n-InP layers. The composition of the InGaAsP layer corresponds to a photoluminescence wavelength of 1150 nm, which gives a balanced tradeoff between absorption and refractive index change [24]. The thickness and the doping level of the constituent layers have been designed considering optical and microwave loss, velocity matching and modulation efficiency. The coplanar
traveling-wave electrodes are designed for matching the group velocity and minimizing the microwave loss. The signal and ground electrode widths are 12 µm and 30 µm, and the gap between signal and ground electrodes is 8 µm.

Fabrication of the InP phase modulator array utilized a 50-mm epitaxial InP wafer. The InP/InGaAsP layer stack was grown on an n-doped InP substrate. The SiO2 layer of 550 nm thickness was deposited by pressure-enhanced chemical vapor deposition (PECVD) to serve as a hard mask. The waveguides were patterned using g-line contact lithography followed by inductively coupled plasma (ICP) etching with CH4/H2/Cl2 gasses. BCB was coated and cured for InP waveguide over-cladding and planarization. The mesa structure was defined for implementing coplanar traveling-wave electrodes. The 1-µm thick metal stack layers Pt/Ti/Pt/Au were deposited as the electrodes.

Fig. 2. InP phase modulator array. (a) Cross-sectional schematic of an InP phase modulator. (b) Phase change of the InP modulator. Inset: Top-view micrograph of a fabricated InP phase modulator array chip.

The inset of Fig. 2(b) shows the top-view micrograph of a fabricated InP phase modulator array chip. The chip consists of ten InP phase modulators and six passive waveguides for testing. The phase modulator has a length of 2 mm. The waveguide width at both input and output sides of the chip is adiabatically tapered to match that of output ports of the Si3N4 AWG chip. The modulator electrodes are routed to north and south ends of the chip for wire bonding.

The fiber-to-fiber insertion loss of the InP modulator array chip is 8.7 dB, including the 3.1 dB per facet coupling loss and the 2.5 dB waveguide propagation loss. After assembling the OAWG module including the two Si3N4 AWGs described below, we characterized the transfer function with both amplitude and phase of the OAWG module using an optical vector analyzer (OVNA) [25]. Then we applied voltage on one of the OAWG channels and recorded the phase change of the transfer function on that channel. Figure 2(b) shows the measured phase response of one of the OAWG channel as a function of the reverse bias voltage. The \( V_{\pi} \) value is 2 V for a 2-mm long phase modulator.

We designed the traveling-wave modulator using an equivalent circuit model [26]. The simulated 3-dB E-O bandwidth of the modulator is 15 GHz. The group index of optical waves is 3.3, while the microwave index is 5.5. For the traveling-wave modulator with a length of 2 mm, the velocity mismatch limited bandwidth is calculated as 43 GHz. Thus, the E-O bandwidth of our modulator is mainly limited by the microwave loss. Our fabricated modulator has an E-O bandwidth of 500 MHz. We fabricated modulators on an N + doped InP substrate instead of a semi-insulating substrate, which contributes to the large microwave loss. We can improve the E-O bandwidth by better designing transmission lines on a semi-insulation substrate.

3. Si3N4 arrayed waveguide gratings

The fidelity of the OAWG largely depends on the optical crosstalk, which mainly comes from the spectral DEMUX, (e.g. AWGs used to separate optical frequency comb lines). Imperfect
isolation results in unintended optical frequency comb lines to be modulated by an unintended modulator and then coherently combined. The spectral MUX (e.g. AWG) can be wavelength-blind power couplers (e.g. star couplers) but a high-contrast spectral MUX can partly suppress intra-band crosstalk in OAWG. Hence employing high-contrast AWGs will help achieve high-fidelity OAWGs by mitigating impairments due to intraband crosstalk at each optical frequency comb line. One of the major challenges in realizing high-fidelity OAWG units is to design and fabricate AWG-pair devices with (1) high-contrast (i.e. high-extinction) ratios between adjacent and non-adjacent channels, (2) high spectral resolution and channel spacing (e.g. 20 GHz), and (3) matching spectral passbands between the MUX and DEMUX devices. The optical phase errors within the AWG primarily determine this crosstalk level and our previous InP OAWG devices employed phase tuners on each array arm of the AWG pairs to tune and to correct the phase errors to improve the crosstalk level by close to 10 dB [20]. For this work, we utilize Si$_3$N$_4$/SiO$_2$ AWGs designed for and fabricated by silicon CMOS compatible fabrication methods to achieve high-contrast AWG pair at 20 GHz channel spacing with nearly perfect spectral band matching without the need for phase error correction (PEC). To achieve even lower phase errors, we used a box-shaped AWG design which overcomes fabrication tolerance that depends on waveguide curvatures compared to typical horseshoe designs.

Figure 3(a) shows a cross-sectional schematic of the Si$_3$N$_4$/SiO$_2$ channel waveguide. The single-mode waveguide has a width of 2 µm and a height of 200 nm. We fabricated the Si$_3$N$_4$ device on a 150-mm silicon wafer. A 3-µm low-temperature oxide (LTO) layer as a bottom cladding was deposited by low-pressure chemical vapor deposition (LPCVD). Then a 200-nm stoichiometric nitride layer as a waveguide core was deposited by LPCVD at 800 °C. The waveguides and AWGs were patterned with projection lithography (248 nm) followed by ICP etching with C$_4$F$_8$ and H$_2$ gasses. Another 3 µm LTO layer as a top cladding was then deposited by LPCVD.

![Fig. 3. Si$_3$N$_4$ array waveguide gratings. (a) Cross-sectional schematic of a Si$_3$N$_4$ channel waveguide. (b) Top-view micrograph of a fabricated Si$_3$N$_4$ AWG. (c) Measured transmission of two Si$_3$N$_4$ AWG devices. Solid and dash lines indicate two AWG devices as spectral DEMUX and MUX. (d)-(e) A zoom-in microscopic view of arrayed waveguides and star coupler region in (b).](image-url)
Figure 3(b) shows the top-view micrograph of the fabricated Si$_3$N$_4$ AWG device. We designed a 12 channel $\times$ 20 GHz Si$_3$N$_4$ AWG with 28 arrayed waveguides. The designed AWG has a free spectral range (FSR) of 280 GHz and a path length difference $\Delta L$ of 600 $\mu$m. The AWG also has 4-$\mu$m wide waveguide apertures at the junctions between the slab and the arrayed waveguides and has a 100-$\mu$m long adiabatic taper from 4-$\mu$m wide aperture to the 2-$\mu$m wide single mode waveguide. The arrayed waveguides employ a combination of 2-$\mu$m wide single mode and 3-$\mu$m wide multi-mode waveguides with a bending radius of 100 $\mu$m at the curved waveguide region to maintain low phase errors.

We measured the transmission spectra of the fabricated Si$_3$N$_4$ AWG devices using an OVNA. The light is launched into the center input port, propagates through the AWG and is collected at all 12 output ports. Figure 3(c) shows the measured transmission of two Si$_3$N$_4$ AWG devices to be used as a MUX and DEMUX pair in the OAWG. In the legend, $I_{6Ox}$ represents that we chose the 6th input port and $x^th$ output port to test the passband. The passbands of the two AWG devices coincide nearly perfectly. The transmission spectra show a channel spacing of 20 GHz, neighboring-channel-crosstalk of $-12$ dB and background crosstalk of $-20$ dB. The crosstalk can be further reduced by the PEC technique [20].

4. Heterogeneous integration

The OAWG module consisted of the InP modulator array integrated between the Si$_3$N$_4$ AWG MUX and DEMUX pair. The InP and Si$_3$N$_4$ waveguides have dissimilar optical mode sizes and shapes as shown in Figs. 4(a) and 4(c), which result in a 2.1 dB optical coupling loss at the interface according to the three-dimensional finite-difference time-domain method (Lumerical FDTD solution). In order to reduce the coupling loss, the InP waveguides included adiabatic tapers with 2 $\mu$m width at the facet (see Fig. 4(b)) for optical mode matching. As Fig. 4(d) shows, the theoretical coupling loss can be as low as 1.4 dB. When the gap between the InP and Si$_3$N$_4$ waveguides increases, the coupling loss rises significantly. It is critical to maintain dust-free and planar surfaces on both facets, and to minimize the gap in order to achieve the heterogeneous integration with low-loss optical interfaces.

Fig. 4. Theoretical butt coupling between InP and Si$_3$N$_4$ waveguides. (a) Optical intensity distribution of a mode in the 4-$\mu$m wide InP waveguide. (b) Optical intensity distribution of a mode in the 2-$\mu$m wide InP waveguide. (c) Optical intensity distribution of a mode in the 2-$\mu$m wide Si$_3$N$_4$ waveguide. (d) Simulated InP-Si$_3$N$_4$ transmission as a function of the gap between 2-$\mu$m wide InP and 2-$\mu$m wide Si$_3$N$_4$ waveguides. The inset shows that InP waveguide is adiabatically tapered to match the mode of the Si$_3$N$_4$ waveguide.
We actively aligned the chips and bonded them using UV-curing epoxy. All three chips are 10-mm long and glued on an aluminum substrate. The active alignment process to complete the OAWG module was in two steps and utilized the amplified spontaneous emission (ASE) light source. During the first step, we actively aligned the Si$_3$N$_4$ AWG chip to the fixed InP modulator array chip, which was already glued onto the aluminum substrate. The emission from the ASE source was coupled into the InP modulator waveguide and then coupled into one of the input waveguides of the Si$_3$N$_4$ AWG. Since the ASE had a broad spectral range covering an entire FSR of the AWG and it lit up all twelve output waveguides at the output facet of the Si$_3$N$_4$ AWG. The infrared (IR) camera at the AWG output facet displayed twelve light spots. This alignment process utilized manipulation of the Si$_3$N$_4$ AWG chip on a 6-axis stage that allows x, y, z translational movements, and roll, yaw, and pitch rotational movements. Firstly, we monitored the top-view of the InP modulator array and Si$_3$N$_4$ AWG chip edges on a computer screen and optimized the yaw angle of the AWG chip to ensure that the two edges were parallel. Secondly, the input fiber was moved to launch light into one waveguide at a time. By moving the Si$_3$N$_4$ AWG chip vertically, we could see the brightness change of the AWG chip output on the IR camera, and we were able to decide how much roll angle optimization was needed. The lateral movement of the input fiber coupling light into different waveguides, the roll angle adjustment of the AWG chip and the vertical movement of the AWG chip were done iteratively until we saw the AWG output had approximately the same intensity no matter what input waveguide on the InP chip we launched light into. Thirdly, the pitch angle of the AWG chip was adjusted until we observed brightest and uniform twelve light spots on the IR camera. The waveguides of the two chip facets were brought close and aligned to minimize the coupling loss for all ten InP modulator element by aligning the north-end modulator and the south-end modulator against the corresponding AWG input waveguides. Once aligned, the UV-epoxy and UV-gun were used to securely bond the chips on the aluminum substrate without losing the optimized alignment. During the second step, the third chip (another Si$_3$N$_4$ AWG chip) was aligned against the securely bonded first and second chip completed in the first step above. The optimization procedure again utilized the 6-axis stage optimizing the alignment of the Si$_3$N$_4$ AWG chip against the InP modulator array chip using the ASE source with light launching from one of the input waveguides on the bonded AWG chip. Then we securely bonded the third chip on the aluminum substrate while maintaining the optimized alignment. Figure 5(a) shows the heterogeneous OAWG chip after the assembly.

![Figure 5(a)](image)

**Fig. 5.** Heterogeneous PICs for OAWG. (a) A photo of the heterogeneous PIC for OAWG. (b) Measured transmission of the PIC.

Figure 5(b) shows the fiber-to-fiber transmission of the OAWG module including the two Si$_3$N$_4$ AWG chips and the InP phase modulator array chip. The transmission shows twelve optical passbands including ten in the center of which we used eight channels for OAWG demonstrations and the two channels on the side as test channels. The fiber-to-fiber insertion loss is approximately 20 dB among the ten OAWG channels. The estimated breakdown of 20
dB loss is: 2.5 dB propagation loss for InP modulators, 9.5 dB propagation loss for two Si$_3$N$_4$ AWGs, $2 \times 2$ dB for InP-to-Si$_3$N$_4$ coupling loss and $2 \times 2$ dB for fiber-to-Si$_3$N$_4$ coupling loss. The fiber coupling utilized lensed fibers with 2.5-µm mode field diameter that attempts to match the mode field diameter of the Si$_3$N$_4$ waveguides. We observed Fabry-Perot fringes in the transmission of the heterogeneous PIC. We attribute these fringes to the optical reflection between two different chips. The optical power reflection is estimated as 13.5% by 3D FDTD simulation, assuming an epoxy-filled gap spacing of 0.5 µm between two different chips. The fringes will introduce non-uniform amplitude response between channels, which requires channel equalization.

The electrodes of InP phase modulator chip are wire bonded onto the two high-speed PCBs to electrically drive the modulator array. The coplanar waveguides on the PCBs are path length matched to avoid signal delay between the channels. The traveling wave modulators are matched with the on-board 50 Ω alternating current (AC) coupled termination. SubMiniature version A (SMA) cables are connected to the PCBs to feed driving signals onto the modulator chip.

5. Optical arbitrary waveform generation

By taking advantages of heterogeneous InP and Si$_3$N$_4$ platforms, the OAWG module can generate ultrafast waveforms reconfigurable with high fidelity. Figure 6(a) shows the experimental setup for OAWG and multi-heterodyne detection. We aligned the laser wavelength with the OAWG center passband, generated comb lines with 20 GHz spacing and sent them into the OAWG module with eight OAWG channels. The AWG DEMUX filtered eight comb lines and sent them to different spatial locations where comb lines were modulated by eight InP phase modulators driven by the electrical signals. The MUX AWG combined the modulated comb lines, and an EDFA amplified the signal before the comb lines entered a wavelength selective switch (WSS) for filtering out out-of-band comb lines. An acoustic optical modulator (AOM) shifted the signal spectrum by 35 MHz to avoid DC component overlapping with the center comb line. On the reference arm, we generated 19 GHz comb lines, and we also used a WSS to filter out eight comb lines. The beating between the reference and signal yielded 1 GHz comb lines. For the electrical part, we synchronized two synthesizers and pattern generators with a 10-MHz clock. The pattern generator’s output was a 500-MHz rectangular wave (see below). On the data negated port we inserted 1-bit delay so that the rectangular wave from the data and data bar was synchronized appropriately. We drove four out of eight OAWG channels by splitting each port from the pattern generator to two driving signals. The modulation power for each channel was 10 dBm. We chose pathlength matched RF cables to send signals to the chip such that the signals could arrive at the chip all at the same time. The electrical 5 GHz low-pass filters before the real-time scope removed the high-frequency noise outside −4 to 4 GHz range for the OAWG spectrum. Figure 6(b) shows the comb lines we generated on signal (blue) and reference (red) arm after the OFC.

![Fig. 6. (a) Experimental setup for rapidly reconfigurable OAWG and heterodyne measurement. ECL: external cavity laser; PC: polarization controller; OFC: optical frequency comb; WSS: wavelength selective switch; LPF: low-pass filter; EDFA: erbium-doped fiber amplifier; ATT: attenuator. (b) Spectra of signal and reference optical frequency comb lines.](image-url)
Fig. 7. Demonstration of quadratic phase chirp. (a), (c), (e), (g) and (i) Phase settings. (b), (d), (f), (h) and (j) Corresponding chirped waveforms.
Figure 7 demonstrates the module’s ability to change the phase on comb lines by generating quadratic phase with different quadratic coefficients in the frequency domain and shows the corresponding chirped pulses in the time domain. Manipulation of phases on comb lines provides an approach to increase the time-bandwidth product (TBWP) of the waveforms.

We generated static optical arbitrary waveforms repeating at 20 GHz by adjusting the phase on eight channels of the OAWG module. We used the multi-heterodyne detection with 20 GHz spacing comb lines beating with 19 GHz spacing reference comb lines, generating 1 GHz spacing comb lines as detected by the real-time coherent receiver. Figure 8(a) shows the spectrum of eight comb lines with flattened phase. Figure 8(c) shows the time domain pulses with a 1-ns period. Figure 8(e) shows the time-domain averaged waveform and comparison with the simulated waveform. The measured error vector magnitude (EVM) [27] is calculated as 16.4%. Figure 8(b) shows the spectrum of eight comb lines with a \([0, 0, 0, 0, \pi, \pi, \pi, \pi]\) phase pattern. Figure 8(d) shows the time domain waveform. Figure 8(f) shows the averaged time domain waveform and the comparison with the simulated waveform. The EVM is calculated as 18.7%. These waveforms with certain phase configurations exhibit the OAWG module’s ability to produce waveforms with high-fidelity. The EVM is limited by the phase-only modulation of the OAWG module and can be further improved if both amplitude and phase modulation are present in the module.
Fig. 9. Demonstration of optical CDM using 6 orthogonal phase configurations on 8 comb lines. The other two configurations are shown in Fig. 8. (a), (c), (e), (g), (i) and (k) Spectra of different phase configurations. (b), (d), (f), (h), (j) and (l) Time-domain waveforms for the corresponding phase configurations.
Figure 9 presents the demonstration of optical code division multiple-access (O-CDMA) using eight orthogonal phase configurations on eight comb lines. The eight comb lines support a total of eight orthogonal codes with Hadamard encoding scheme. The first two phase coding patterns are displayed in Fig. 8. Figure 9 presents the additional six phase coding configurations illustrated on top of each frequency spectrum. Both spectra and time-domain waveforms are displayed in two separate columns. The real-time waveforms all have a repetition period of 1-ns. The orthogonal spectra with high fidelity ensure reduced multi-user interference (MUI) for O-CDMA.

![Figure 9](image-url)

**Fig. 10.** Rapidly reconfigurable OAWG experimental results. (a) A 500 MHz rectangular wave as the electrical driving signal. (b) The reconfigurable fast-updating waveform between two optical arbitrary waveforms with a 2-ns period.

Figures 10(a) and 10(b) show a 5-ns time window of reconfigurable fast-updating waveforms with 500 MHz rectangular wave modulation creating alternating \([0, 0, 0, 0, 0, 0, 0, 0]\) and \([0, 0, 0, \pi, \pi, \pi, \pi]\) phase patterns on eight comb lines. For example, waveform 1 from 30 to 31 ns is a single sharp pulse, and waveform 2 from 31 to 32 ns is a pulse having two humps within a period. The target waveforms of waveform 1 and 2 are shown in Figs. 8(e) and 8(f). The fast-updating waveform exhibits a repetition rate of 2-ns. The updating speed of the OAWG module is currently limited by the low bandwidth of InP phase modulator, which is attributed to a large microwave loss due to the highly doped \(N\)-type InP substrate.

6. Summary

We proposed and demonstrated a heterogeneous PIC for rapidly reconfigurable OAWG. The heterogeneous PIC combines advantages of fast-speed InP modulators and low-loss, high-contrast Si\(_3\)N\(_4\) AWGs. We generated optical arbitrary waveforms with 160 GHz bandwidth (eight channels at 20 GHz channel spacing). The OAWG module can rapidly reconfigure optical arbitrary waveforms upon every pulse with a repetition period of 2 ns.

Currently, improvements on the OAWG performance are in progress in the following way. Firstly, in order to reduce the optical loss, we are including a spot size expander on the Si\(_3\)N\(_4\) waveguide to improve the mode matching with the InP waveguide and also to reduce the sensitivity to the optical misalignment between the two waveguides.

Secondly, in order to enhance the update speed limited by the modulator speed and parasitics, we are employing a semi-insulating substrate with velocity-matched modulators of improved design.

Lastly, the new OAWG design incorporates double Mach-Zehnder I/Q modulators that replace the phase modulators in the current OAWG module, aiming at even higher waveform fidelity in matching the desired arbitrary optical waveform. Through the three improvements mentioned above, we are making efforts to demonstrate a truly dynamic OAWG with high fidelity in the future.
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