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Silicon-photonics-based wideband radar beamforming: basic design

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Abstract. Proposed is silicon-photonics-based phased array antenna beamforming for high-resolution long-range radars with wide instantaneous radio frequency (rf) bandwidth. Specifically, the proposed silicon-photonics beamformer platform offers the potential for cost-effective monolithic chip-scale integration of photonic delay lines, 2×2 optical switches, variable optical attenuators, and optical amplifiers that form the base unit of a rf transmit/receive array signal processor. In effect, the proposed silicon-photonics devices empower the design of a powerful proposed photonic beamformer with one time-delay unit per antenna element. Device-level designs studies are shown that promise meeting the high-resolution radar mission-critical requirements via time delays of up to 2.5 ns, switching times of less than 100 ns, optical isolations as good as 50 dB, and optical gains of up to 6 dB. Longer delays are achieved off chip using optical fibers. *© 2010 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3280286]

Subject terms: Fourier optics and signal processing; analog optical signal processing; continuous optical signal processing.

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1 Introduction

Photonics has long been recognized as a viable technology for distribution and processing of millimeter and microwave signals in modern phased-array antennas (PAAs).[1] Advantages of photonics over electronics for these beamforming control systems include reduced weight and size, immunity to electromagnetic interference (EMI) and electromagnetic pulses (EMP), and low rf transmission loss. In particular, photonic technologies have been successfully employed to demonstrate true time-delay beam steering, which is essential for squint-free wide-instantaneous-bandwidth operation of high-performance radar systems.

A typical advanced wideband radar beamforming system design is shown in Fig. 1, where each antenna element uses an independent rf signal-conditioning unit. Note that a beamformer is a complex interconnection of rf waveguides (splitters and combiners) that can produce different time-delay errors per antenna element depending on system conditions such as the beamformer temperature and stresses and strains in different parts of the waveguides. Therefore, any robust beamformer architecture such as the Fig. 1 design involves an independently controllable time-delay unit (TDU) per antenna element. Electronically, a beamformer system includes high-power amplifiers (HPAs), low-noise amplifiers (LNAs), rf attenuators, and transmit/receive (T/R) rf switches. In addition, if optical fibers are deployed in the rf signaling control system, such as for distribution and rf-optical-rf links, then again temperature changes and stresses can put strains in the fibers that can independently affect the different rf time-delay paths in the beamforming network. Thus, any practical deployed wide-instantaneous-bandwidth radar beamformer for demanding outdoor environments must use an independently controllable TDU per antenna element, and this TDU should produce both long delays (e.g., 10 ns) and high-resolution delays (e.g., 10 ps), equivalent to 1000 settings, or 10 bits. In addition, the TDU should have other general features such as wideband rf operation [e.g., S/C band 2 to 8 GHz or X band (8 to 12 GHz)], low loss (e.g., <5 dB optical), low crosstalk (e.g., <50 dB optical), and fast (submicrosecond time delay) reset.[2] To date, such a desired TDU is altogether lacking in the all-electronic domain.

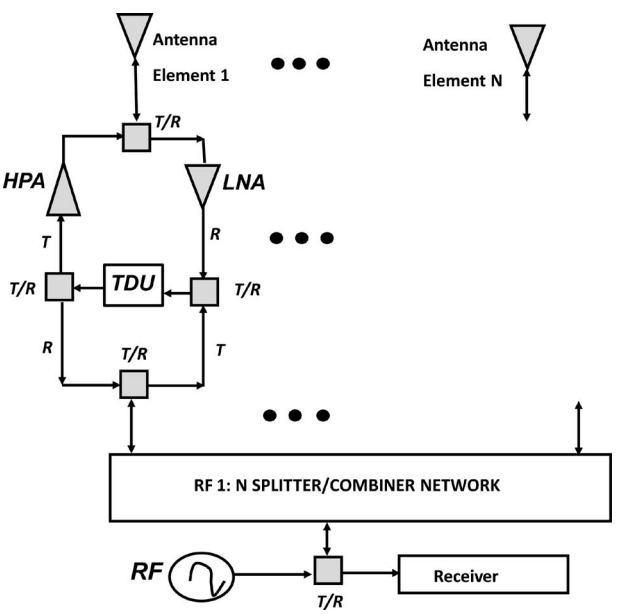


Fig. 1 An advanced rf PAA beamformer design using one variable TDU per antenna element. HPA: high-power amplifier; LNA: low-noise amplifier; T/R: rf transmit/receive switch; TDU: time-delay unit with rf in and rf out.

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A wide variety of schemes and device technologies have been proposed and used for realizing optical beamformers,[3–25] including silica glass, III-V semiconductors, polymers, electromechanical and microelectromechanical systems (MEMS), lithium niobate, and nematic and ferroelectric liquid crystals. However, these proposed and implemented systems do not meet the requirements mentioned for advanced TDUs. Recently, it was shown that acoustooptic switching[26] can indeed meet the desired TDU requirements, but this device technology, like many others before it, is presently limited in capability of cost-effective scaling to practical PAA TDU counts (e.g., >500) required in large PAAs. Given this motivation, this paper uses silicon photonics as the base platform to propose the desired design of a superperformance (e.g., 10 bits), superfast (e.g., $<1\ \mu$s) optical TDU design that can realize the wideband PAA radar control mission. Shown are basic device design and simulation studies indicating the performance expected from the proposed silicon photonic TDUs.

Many years ago, silicon photonics was proposed for optical switching at 1300 nm.[27] Meanwhile, silicon photonics has matured in the last few years as a viable technology for a host of applications, particularly for passive and active integrated optics.[28] Silicon-based delay lines with subpicosecond time-delay accuracy have been demonstrated, although with very short time delays of the order of tens of picoseconds.[29] A new CMOS-compatible material named Hydex®, allowing delays as high as 2 ns, has also been reported.[30] Compared to competing technologies based on nonlinearity in fibers and the electro-optic (EO) effect in lithium niobate and III-V semiconductors, silicon photonics has several key advantages, which include:

(a) *Cost-effectiveness*: Lots (e.g., thousands) of TDUs per large-aperture advanced phased-array radar (e.g., Aegis class) are required, particularly for a fully agile three-dimensional (3-D) electronic or e-scan system with complete beam power. A monolithic technique capable of processing all these TDUs simultaneously would substantially reduce manufacturing costs.

(b) *CMOS compatibility*: Unlike competing materials, silicon has the great advantage of compatibility with silicon integrated circuit (IC) technology required to electrically drive the devices. In addition, compatibility of silicon photonics with CMOS processing and integration with variable optical attenuators (VOAs) and rf-to-optical modulators also implies further cost reduction and high-yield manufacturing.

(c) *Compactness*: The high refractive index contrast between silicon and SiO_2 provides a platform for submicron waveguide dimensions in silicon-on-insulator (SOI) waveguides, leading to a smaller footprint and reduced weight for a silicon photonic beamformer.

(d) *Integration*: Compact ($\sim$1 cm), fast ($<1\ \mu$s), high-attenuation (>40 dB) VOAs have been recently demonstrated[31] and can be monolithically integrated with the optical switches, photonic delay lines, and optical amplifiers of the proposed TDU. In addition, the rf-to-optical modulator that provides the PAA's rf signal can also be integrated on the same silicon chip, a feature presently hard to achieve in the competing material technologies.

Another vital component of an optical TDU is a high-speed rf-band photodetector. Because of its optical transparency in the 1300 and 1550-nm wavelength bands typically used for rf EO modulation, silicon is not a suitable material for rf demodulation via photodetection. With a smaller bandgap, germanium (Ge) has strong absorption at these wavelengths, and Ge photodetectors can be integrated on silicon chips. High-performance hybrid Ge(Si)-on-Si photoreceivers have been demonstrated[28]—for example, a Ge-on-SOI photodetector with a 6.6-GHz bandwidth.[32]

2 Proposed Beamsteering System

Figure 2 shows the proposed basic silicon-based TDU for implementing PAA beamsteering. The unit employs a classic serial digitally switched N-bit TDU scheme using the proposed silicon 1×2 and 2×2 routing switches. Using an N-bit delay line, one can produce 2^N-1 independent relative time delays. The delay lines can be on chip, using long integrated waveguides for shorter delays (<2.5 ns), or can be external optical fibers (for 2.5- to 20-ns delays). One advantage of silicon photonics is that the losses caused per TDU bit stage can be partly compensated by Raman optical amplification. In addition, a VOA can be monolithically integrated on the chip per TDU for signal conditioning required for antenna pattern control as well as rf loss calibration within the beamforming network.

Critical to the design of any TDU is the realization of low-loss, high-speed, low-crosstalk 1×2 and 2×2 optical switches to meet the mentioned TDU requirements. Due to the lack of a linear EO effect in silicon, the free-carrier plasma effect has been the most popular mechanism for achieving EO modulation. Specifically, the principle of EO operation involves the modulation of the free-carrier density in which the optical loss and/or refractive index is rf modulated by injection, depletion, accumulation, or inversion of free carriers.[28] The very first silicon photonic device was a 2×2 switch based on n-type waveguides fabricated on n^+ substrate.[27] More recently, EO switches based on SOI substrates have been demonstrated[33] that exhibit high 5-MHz switching speed but lack the TDU's required low (e.g., >40 dB) crosstalk.

To realize the TDU switching goal, Fig. 3(a) shows the proposed novel 1×2 fast ($<1\ \mu$s) switch based on the free-carrier plasma effect using carrier injection via lateral *pn* junction diodes that straddle SOI waveguides. The design of these devices is optimized for the targeted beamforming control application, i.e., fast switching time ($\sim$0.1 to 1 ns) and high on/off extinction ratio, leading to 50-dB interchannel optical isolations. The proposed 1×2 switch design uses a silicon Mach-Zehnder interferometer (MZI). At the output of the MZI, the phase-shifted signals are directed into a multimode interference (MMI) coupler that selects the desired output channel. To control the phase-shifting process, refractive index variation is induced by carrier injection (i.e., the plasma effect) via the electrical biases applied to the two *pn* junction diodes. Shorter de-

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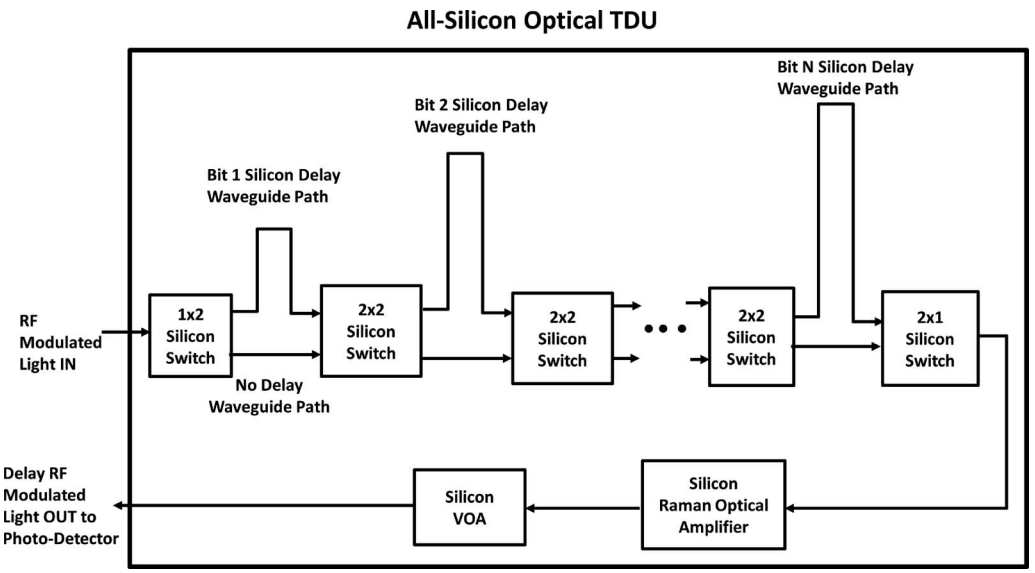


Fig. 2 Proposed *N*-bit programmable silicon photonic TDU module.

vices can be achieved at the expense of higher carrier injection (slower switching operation) via the *pn* junctions. This trade-off can be optimized according to the specific beamforming system requirements, another useful feature of silicon photonics. Note that low-crosstalk switching cannot be obtained merely based on MMI couplers, and reported optical extinction ratios are on the order of −22 dB.[34] To overcome this shortcoming, the design in Fig.

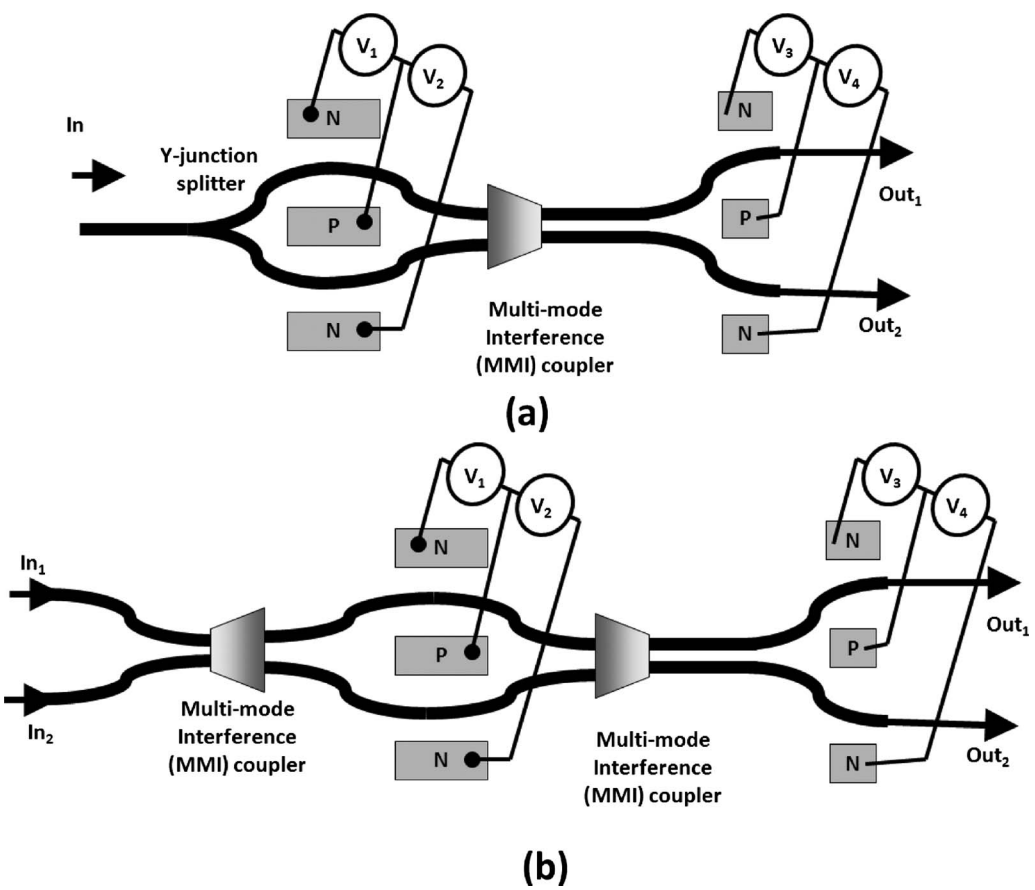


Fig. 3 Proposed (a) 1×2 and (b) 2×2 silicon optical switch designs to be used to realize the TDU design in Fig. 2.

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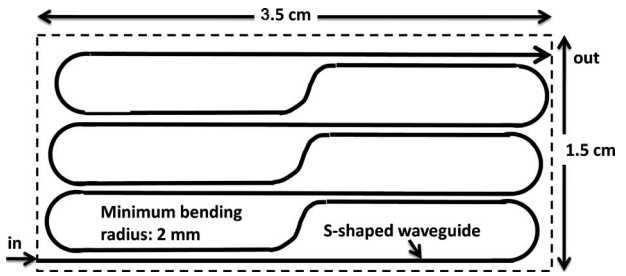


Fig. 4 Proposed S-shaped waveguides for achieving long on-chip photonic delay lines in the silicon TDU of Fig. 2.

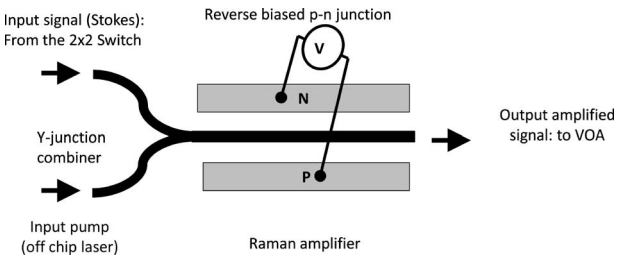


Fig. 5 Proposed method for integrating a photonic delay line and a silicon Raman amplifier needed for the TDU design of Fig. 2.

3(a) proposes inserting two 1×1 photonic switches at the output arms of the integrated device. Specifically, by applying a forward bias to the off arm, the 1×1 switch essentially acts like a VOA and can provide an extra 40 dB or more extinction ratio at high biases, leading to the desired high-isolation photonic switch for routing the no-delay and delay rf signals on the light carrier. It is emphasized that the *pn* junctions in the MZI arms and those in the output arms serve different purposes. In essence, with the appropriate choice of bias, the same device, consisting of a silicon waveguide with a straddling *pn* junction, is employed as a phase modulator in the MZI arms, while it is employed as an intensity (loss) modulator in the 1×1 switches following the MZI.

To realize the desired 2×2 optical switch required for TDU assembly, a second MMI coupler is inserted at the input of the MZI as depicted in Fig. 3(b). The working principle remains similar to that of the 1×2 switch. The choice of biases V_1 and V_2 allows selecting one of the input ports to be routed to one of the output ports via phase modulation. Similar to the 1×2 switches, two 1×1 switches (biases V_3 and V_4) are inserted at the output arms to provide more than 40-dB extra isolation via intensity (loss) modulation in the off port.

Guided-wave optical delay lines on the TDU silicon chip in Fig. 2 provide high precision for rf beamforming systems, because the waveguides are defined using photolithography, by which waveguide lengths can be controlled with submicron precision with accuracy limits typically set by processing variations or the mask quantization. The higher refractive index of silicon than that of silica (3.4 versus 1.45) suggests that a larger time delay per waveguide length ($\approx$12 ps/mm) is possible in silicon. Figure 4 shows how long (2.5-ns) time delays are achievable in a 20-cm-long S-shaped waveguide. The footprint of such a chip is 3.5×1.5 cm^2. Note that the proposed silicon photonic delay lines would induce a typical waveguide linear loss of 0.3 dB/cm,[35] and thus the overall loss can be as high as 6 dB for a 2.5-ns waveguide delay. Given that beamforming requires cascaded delay lines, a 6-dB loss is considered high. Given that silicon Raman amplifiers have proven successful,[36,37] we propose their use for optical loss recovery in the silicon TDU chip. Note that stimulated Raman scattering (SRS) has been long exploited in optical fibers to create amplifiers and lasers. However, several kilometers of fiber are typically required to create a useful device. The gain coefficient for SRS in silicon is approximately 10^3 to 10^4 times higher than that in silica fiber. Additionally, silicon waveguides can confine the optical field to an area that is approximately 100 times smaller than the modal area in a standard single-mode optical fiber. Combined, these facts make it possible to observe SRS over the interaction lengths encountered on a chip. To achieve net cw gain, a *pn* junction diode can be used to sweep the carriers out of the waveguide core region. Up to 6.5 dB of optical gain has been demonstrated,[38,39] which is sufficient to compensate for the loss of a 2.5-ns silicon waveguide delay. Hence, we propose the integration of such Raman amplifiers in the silicon TDU. For these optically pumped amplifiers, an off-chip laser source is required, whose beam ought to be combined with the rf-modulated signal for the PAA. As shown in Fig. 5, a Y-junction combiner can achieve this goal.

3 Performance Predictions

Next, the critical performance parameters of the silicon photonic devices used to realize the proposed TDU are presented. First, the diode waveguides shown in Fig. 3 are analyzed using the lateral geometry shown in Fig. 6, with ridge height $H=2.0$ μm, waveguide width $W=1.5$ μm, slab height $h=1.1$ μm, and ridge-to-contact spacing $d=2$ μm used in the numerical simulations. The model used in the calculations follows Ref. 40. The dependence of free-carrier absorption (FCA), α_{FCA}, on carrier density is given by

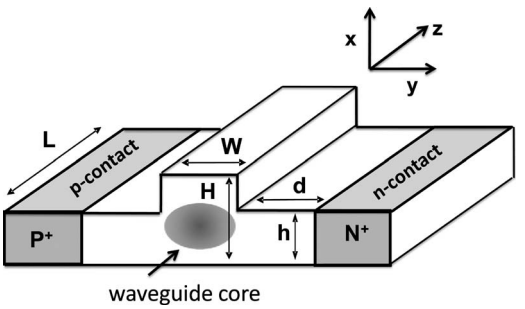


Fig. 6 Schematic of the proposed silicon EO modulator with a straddling *pn* junction diode. Modulation of carriers (electrons and holes) in the waveguide core region via the *pn* junction allows phase or intensity modulation of the guided light. Ridge height $H=2.0$ μm, waveguide width $W=1.5$ μm, slab height $h=1.1$ μm, and contact-to-ridge spacing $d=2$ μm are used in the numerical simulations.

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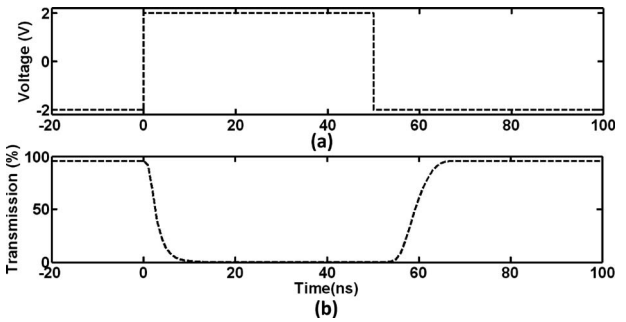


Fig. 7 Simulated switching results for a silicon intensity (loss) modulator, showing: (a) applied electrical signal; (b) output optical transmission with ≈50-dB extinction ratio.

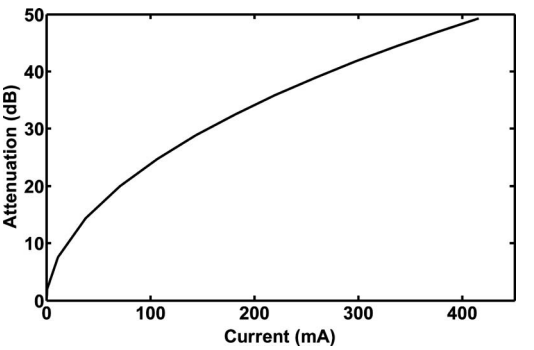


Fig. 8 Attenuation versus bias current of the ridge waveguide with *pn* junction diode under forward bias for intensity (loss) modulation.

$$\alpha_{\mathrm{FCA}} = 8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P, \tag{1}$$

where ΔN and ΔP are the free-electron and hole concentrations, respectively. In the presence of FCA and two-photon absorption (TPA), the propagation of optical intensity $I_p(z)$ along the z direction (Fig. 6) is given by the following nonlinear differential equation:

$$\frac{\mathrm{d}I_p(z)}{\mathrm{d}z} = -[\alpha + \alpha_{\mathrm{FCA}}(z)]I_p(z) - \beta I_p^2(z), \tag{2}$$

where β=0.7 centimeter per gigawatt (cm/GW) is the TPA coefficient, and α is the linear absorption coefficient of the waveguide. Here α_{FCA} is a function of the optical intensity I_p and bias voltage V. The device was simulated using a commercial drift-diffusion simulator (ATLAS by Silvaco International). TPA was emulated by specifying a carrier generation rate G at the waveguide core with $G=\mathrm{d}N/\mathrm{d}t = -(1/2E)\mathrm{d}I_p/\mathrm{d}z = \beta I_p^2/2E$, where E=0.8 eV is the photon energy and N is the carrier density. The values of the electron and hole bulk recombination lifetimes were 3 and 10 μs, respectively. A surface recombination velocity of 200 cm/s was used for both types of carriers. The simulator provides the carrier concentration as a function of V, from which, by using Eq. (1), the output optical intensity and modulation depth are obtained. The optical transmission and modulation depth can be extracted from $I_p(L)/I_p(0)$ as a function of V. In order to accommodate the 3-D nature of the problem, a quasi-3D model is developed in which the 2-D results of ATLAS at several optical intensities are interpolated to numerically solve Eq. (2). The simulator also provides the diode current per unit length, J (A/μm).

The switching speed of intensity EO modulators is a key figure of merit for rf photonics. Up to 10-GHz bandwidth has been reported in EO (carrier injection type) silicon optical modulators.[41] Figure 7 shows a summary of the conducted switching (intensity modulation) simulation results in a 0.4-cm-long waveguide. A 10-MHz (100-ns period) square waveform electrical signal with $t_{\mathrm{rise}}=t_{\mathrm{fall}}$=200 ps is applied to the diode. An external resistance of 5 Ω cm^2 was assumed. The simulated optical response shows t_{on} =12.9 ns, t_{off}=5.6 ns, giving $f_{\mathrm{max}} \approx 54$ MHz (≈18.5-ns switching time) achievable in this particular bias case of V_{off}=−2.0 V and V_{on}=2.0 V. Up to 49.3-dB modulation depth (i.e., extinction ratio) is attainable by this choice of biases.

The characteristic (static attenuation versus bias current) of the diode waveguide is shown in Fig. 8. By trading off some of the 18.5-ns switching time, one can achieve higher extinction ratios, which can be beneficial for noise suppression in the TDU.

To estimate the performance of the MZI-based Si switches (phase modulation), a 5-MHz (200-ns period) square-waveform electrical signal with $t_{\mathrm{rise}}=t_{\mathrm{fall}}$=35.5 ps is applied to the diodes. In a 0.5-cm-long waveguide, a π phase shift is achievable for V_{off}=0.75 V and V_{on}=0 V, that is, V_π=0.75 V. An optical loss of 0.9 dB loss in the off state (0.75 V) is obtained. Figure 9 shows the transient response of phase shift under these conditions. The transient optical response shows t_{on}=6.2 ns, t_{off}=24.2 ns, indicating that $f_{\mathrm{max}} \approx 33$ MHz (or ≈30-ns TDU switching time) is attainable. These initial design studies of the proposed silicon-photonics-based TDU indicate the road to achieving the desired numbers for loss, crosstalk, delay range, and switching speed.

4 Conclusions

Over the years, the stringent rf beamformer system requirements have impeded deployment of an optically controlled PAA. Silicon photonics is a promising technology for fulfilling this elusive goal. For the first time, to our knowledge, this paper proposes, analyzes, and simulates a silicon-

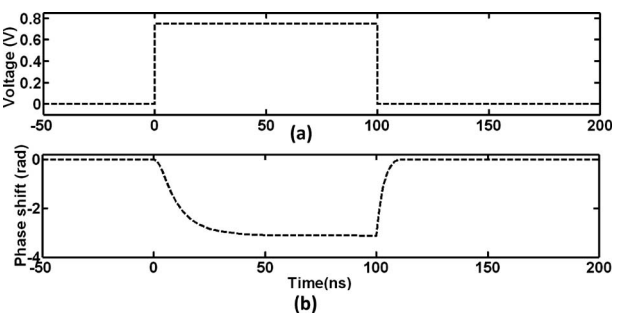


Fig. 9 Simulated switching results of a silicon phase modulator, showing: (a) applied electrical signal; (b) transient response for attaining π phase shift. The result confirms that ≈30-ns switching time is attainable in the proposed switches.

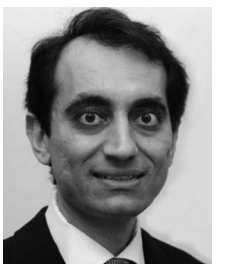
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photonic TDU design to enable an element-level wideband beamformer.[42] The novel chip-scale TDU uses silicon 2 $\times$2 switches, photonic delay lines, integrated Raman amplifiers, and VOAs. The reported design simulations suggest that it is feasible to obtain a high-performance all-silicon TDU that provides the low crosstalk (50 dB optical), high speed (<1 μs), long delays (up to 2.5 ns), and low insertion loss (<6 dB) required for an advanced beamforming TDU.

Future work relates to the fabrication of the proposed silicon TDU.

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