

# Silicon thermo-optic phase shifters: a review of configurations and optimization strategies

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**Abstract.** Silicon photonics (SiPh) has emerged as the predominant platform across a wide range of integrated photonics applications, encompassing not only mainstream fields such as optical communications and microwave signal processing but also burgeoning areas such as artificial intelligence and quantum processing. A vital component in most SiPh applications is the optical phase shifter, which is essential for varying the phase of light with minimal optical loss. Historically, SiPh phase shifters have primarily utilized the thermo-optic coefficient of silicon for their operation. Thermo-optic phase shifters (TOPS) offer significant advantages, including excellent compatibility with complementary metal-oxide-semiconductor (CMOS) technology and the potential for negligible optical loss, making them highly scalable. However, the inherent heating mechanism of TOPS renders them power-hungry and slow, which is a drawback for many applications. In this review, we thoroughly examine the principal configurations and optimization strategies that have been proposed for achieving energy-efficient and fast TOPS. Furthermore, we compare TOPS with other electro-optic mechanisms and technologies poised to revolutionize phase shifter development on the SiPh platform.

**Keywords:** thermo-optic, phase shifter, silicon photonics.

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## 1 Introduction

The use of silicon photonics (SiPh)<sup>1,2,3,4</sup> has witnessed exponential growth over the past decade. This increase is driven by the relentless and explosive expansion of consumer data, the necessity for real-time processing of wideband signals, and the significant energy demands of the data center industry, which consumed between 1% and 5% of the global power in 2020.<sup>5</sup> Photonic integrated circuits (PICs) present effective solutions to these challenges, offering solutions where there is a demand of energy efficiency and high computational throughput in disruptive technologies, including optical communications transceivers,<sup>6,7</sup> LiDAR systems,<sup>8</sup> quantum optics devices,<sup>9</sup> and optical sensors.<sup>10</sup> Additionally, emerging computing architectures for artificial intelligence and neuromorphic computing, leveraging SiPh, have shown numerous benefits such as multiwavelength capabili-

ties, ultra-high speeds, and low power consumption that address the limitations of complexity, cost, and footprint associated with traditional electronic computing components.<sup>2</sup>

Both mainstream and emerging applications necessitate the development of highly complex PICs that incorporate an extensive library of on-chip components such as (de)multiplexers, phase shifters, modulators, laser sources, photodetectors, and fiber-to-chip couplers. Among these, phase shifters stand out as a pivotal component in the majority of PICs, enabling the manipulation of the real part of the effective refractive index with minimal ideally zero alteration to the imaginary part. The demand for components that combine ultra-low optical loss with a compact footprint is critical for ensuring the scalability of advanced PICs and meeting the rigorous requirements of emerging applications. In this context, silicon thermo-optic phase shifters (TOPS) have emerged as the prevalent method. TOPS utilize the variation in silicon's refractive index where light is predominantly confined due to changes in temperature. Silicon TOPS have become the cornerstone for the development of sophisticated PICs, showcasing the vast potential of SiPh technology across various application domains. Notable examples include optical reconfigurable and multipurpose photonic circuits,<sup>3,4</sup> phased arrays for LiDAR systems,<sup>5</sup> optical neural networks,<sup>6</sup> and Fourier transforming for optical spectrometry,<sup>7</sup> with demonstrators integrating from approximately 50 to 176 TOPS.<sup>8</sup> However, the intrinsic heating mechanism of TOPS often results in high power consumption and slow operation. As a consequence, various optimization configurations and strategies have been proposed to enhance power efficiency and switching speed, or both, making the topic of TOPS a blooming area of research over the past decade.

In this review, we explore the configuration and optimization strategies that have been proposed for TOPS in silicon photonics. Our discussion begins with an examination of the fundamental principles underlying thermo-optic tuning in silicon waveguides, along with basic design guide-

lines and the trade-offs required for achieving optimal performance. Subsequently, we delve into the advancements in various TOPS technologies, highlighting developments in metallic heaters, transparent heaters, doped silicon, folded waveguide structures, and multi-pass waveguide configurations. Finally, TOPS are compared with alternative technologies, providing a comparative analysis. A concluding section is dedicated to discussing prospective technological advancements and the future outlook for TOPS in silicon photonics.

## 2 Fundamentals

Thermo-optic phase tuning in silicon waveguides is achieved by applying localized heat and exploiting the large thermo-optic coefficient of silicon, approximately  $1.8 - 1.9 \times 10^{-4} \text{ K}^{-1}$ .<sup>3,7</sup> It is important to note that for devices utilizing  $\text{SiO}_2$  as the waveguide cladding, the thermo-optic effect of  $\text{SiO}_2$  is typically disregarded since it is an order of magnitude lower than that of Si, approximately  $9 \times 10^{-6}$ .<sup>7</sup> The phase shift variation  $\Delta\phi$  in a waveguide can be expressed as:

$$\Delta\phi = \frac{2\pi}{\lambda} \Delta n_{\text{eff}} L \quad (1)$$

where  $\lambda$  is the wavelength,  $\Delta n_{\text{eff}}$  is the variation in the effective refractive index, and  $L$  is the path length. When the phase shift is induced by a change in the waveguide temperature, it is described by:

$$\Delta\phi = \frac{2\pi}{\lambda} \frac{\partial n_{\text{eff}}}{\partial T} \Delta T L \quad (2)$$

where  $\partial n_{\text{eff}}/\partial T$  is the thermo-optic coefficient of the optical mode, and  $\Delta T$  represents the temperature increase.

According to Joule heating, the temperature increase is directly proportional to the power con-

sumed by the microheater, denoted as  $\Delta T \propto P_{\text{elec}}$ . Consequently, the power consumption of TOPS, specifically the power required to induce a phase shift of  $\pi$  ( $P_\pi$ ), can be formulated as:

$$P_\pi = \frac{\lambda}{2L} \left( \frac{\partial n_{\text{eff}}}{\partial P_{\text{elec}}} \right)^{-1} \quad (3)$$

where  $\partial n_{\text{eff}}/\partial P_{\text{elec}}$  represents the variation of the effective refractive index with the electrical power applied to the microheater. For thermo-optic phase shifters that are invariant in the propagation direction, such variation is proportional to the active length of the heater. Hence, in Eq. (3), the value of  $P_\pi$  does not significantly vary with the length of the phase shifter. This implies that the same phase shift can be achieved by using either short but intensely heated active heaters or longer but mild heaters, with the electrical power required to reach the desired temperature remaining constant. However, if the phase shift architecture is designed to vary with the direction of light propagation, it is possible to disrupt this relationship and achieve higher thermo-optic efficiencies while maintaining the same active footprint.

To assess the performance of TOPS, the following figure of merit (FOM) is commonly employed and aimed to be minimized:

$$FOM = P_\pi \tau \quad (4)$$

where  $P_\pi$  represents the power required to induce a phase shift of  $\pi$ , typically expressed in milliwatts (mW), and  $\tau$  denotes the switching time, measured in microseconds ( $\mu\text{s}$ ). On the other hand, to experimentally determine the performance metrics of the phase shifters, these devices are often integrated into interferometric structures, such as Mach-Zehnder interferometers (MZIs), microring resonators (MRRs), or multimode interferometers (MMIs).

### 3 Basic configurations

The fundamental design of a thermo-optic phase shifter typically involves a straight silicon waveguide accompanied by a parallel heater, resulting in a device that is invariant along the propagation direction. The heater is constructed from an electrically conductive material, designed to allow the flow of an electrical current and consequently generate Joule heating, described by the equation  $P_h = I_h^2 R_h$ , where  $I_h$  represents the current flowing through the heater, and  $R_h$  denotes the resistance of the heater. Additionally, an alternative approach to heater design involves doping the silicon waveguide itself, thereby enabling the waveguide to function as the heater by facilitating electrical conductivity and heat generation directly within the silicon.

In the context of a propagation-invariant configuration for thermo-optic phase shifters, the power consumption can be analytically approximated, as detailed by Jacques et al.,<sup>2</sup> by the equation:

$$P_\pi \approx \Delta T_\pi G A \quad (5)$$

where  $G$  represents the thermal conductance between the heated waveguide and the surrounding materials, and  $A$  denotes the area through which the heat flow occurs. Similarly, an analytical expression for the switching speed,  $\tau$ , can be derived, indicating its dependence on the thermal properties and geometry of the system:<sup>2</sup>

$$\tau \approx \frac{H}{G} \propto \frac{AL}{G} \quad (6)$$

in which  $H$ , the heat capacity of the heated waveguide, is proportional to the product of the area,  $A$ , and the length,  $L$ , of the waveguide ( $H \propto AL$ ).

To minimize power consumption in TOPS, it is crucial to incorporate waveguides with materials of low thermal conductivity and to minimize the distance between the waveguide and the heater. However, reducing the distance between the heater and the waveguide often results in a trade-off, as it may increase optical loss due to heater absorption. Conversely, using materials with low thermal conductivity can indeed reduce power consumption but at the cost of slower switching speed. Therefore, unless the gap between the heater and the waveguide is diminished, a distinct trade-off between power consumption and switching speed exists. According to Eqs. (5) and (6), one potential strategy to achieve faster switching speeds without escalating power consumption involves decreasing the heat capacity of the waveguide, which suggests the use of shorter active lengths. However, this approach entails challenges. By analyzing Eq. (2), it is evident that  $L_\pi \propto 1/\Delta T_\pi$ . In this regard, opting for short heater lengths can give rise to critical temperature values. High temperatures can compromise the performance of the heater caused by the self-heating phenomenon produced by the increase of the heater resistance with the temperature.<sup>2</sup> Therefore, the actual temperature increase is lower than the expected assuming a constant heater resistance, and thereby yield a different phase shift. Additionally, employing such compact phase shifters increases the susceptibility of adjacent structures to thermal crosstalk, potentially affecting the overall device performance.

Several optimization strategies to enhance power consumption, switching speed, or both have been explored in the literature, as we discuss in the sections that follow. Initially, we examine the use of metallic heaters to decrease power consumption by reducing the thermal conductance of the surrounding waveguide environment. This approach, however, results in a longer switching speed. Subsequently, we explore the application of transparent heaters, which aim to diminish the gap between the heater and the waveguide, i.e., the area  $A$  traversed by the heat flow [refer to Eqs.

(5) and (6)], without penalizing the optical loss of the device. The final approach involves direct heating of the silicon waveguide through doping, thereby transforming it into a resistive element. This technique offers significant improvements in both power consumption and switching speed by minimizing the value of  $A$ , though it introduces optical loss due to free carriers. It is important to note that this direct heating approach is specific to the silicon photonics platform and is not applicable to other emerging photonics platforms, such as silicon nitride. Unless specified otherwise, the results discussed herein pertain to transverse electric (TE) polarization at a wavelength of approximately 1550 nm.

### 3.1 *Metallic heaters*

The most commonly employed method for inducing localized heating in a silicon waveguide or structure involves the use of metallic heaters and the principle of Joule heating (Fig. 1a). Such resistive heaters are typically configured as metal wires placed atop the silicon structure, separated by an intermediate dielectric layer, such as  $\text{SiO}_2$ , to mitigate optical loss (Fig. 1b). The thickness of these heaters is generally on the order of  $\sim 100$  nm, determined by standard fabrication techniques, including lift-off procedures. Additionally, a diverse range of metals or metallic compounds compatible with complementary metal-oxide-semiconductor (CMOS) fabrication technology can be utilized for the heaters. These materials include copper (Cu), nickel silicide (NiSi), platinum (Pt), titanium (Ti), titanium nitride (TiN), and tungsten (W). Figure 1c shows the temperature distribution within a typical TOPS based on a metallic heater, featuring a 1- $\mu\text{m}$ -thick oxide cladding layer situated between the silicon waveguide and the metallic heater.

Table 1 surveys the experimental works that have employed metallic heaters alongside various generic optimization strategies to develop phase shifters in straight silicon waveguides. It is impor-

tant to note that while the focus of these studies is on the use of metallic heaters, the optimization strategies outlined are versatile and can be applied to other methodologies discussed in subsequent sections.

Table 1: Summary of basic experimental thermo-optic phase shifters using metallic heaters in silicon photonics.

Ref.	Structure / Heater metal	Optimization strategy	Loss (dB)	$P_\pi$ (mW)	Switching time ( $\mu\text{s}$ )*	FOM (mW $\mu\text{s}$ )	Length ( $\mu\text{m}$ )
?	MZI / CrAu	None	32 <sup>+</sup>	50	3.5	175	700
?	MZI / N/A	None	12 <sup>+</sup>	235	60	$14 \times 10^3$	2500
?	MZI / N/A	None	22 <sup>+</sup>	90	100	9000	140
?	MRR / Ti	Air trenches	N/A	$\sim 10$	$\sim 10$	$\sim 100$	$\sim 30$
?	MZI / Pt	None	16 <sup>+</sup>	40	30	1200	40
?	MRR / Ni	Pulse preemphasis	$< 1$	16	$4^\ddagger / < 1^\ddagger$	$64^\ddagger / < 16^\ddagger$	$\sim 60$
?	MZI / Pt	Free-standing	2.8 <sup>+</sup>	0.54	141	76	100
?	MRR / Ti	Free-standing	$< 1$	1.2	170	204	50
?	MZI / NiSi	Close heater	$< 1$	20	3	60	200
?	MZI / TiN	Free-standing	$< 1$	0.49	144	71	1000
?	MRR / NiSi	Free-standing	$< 1$	2.9	358	1038	50
?	Microdisk NiCr	Close heater and pulse preemphasis	$< 1$	12	$2.9^\ddagger / 0.085^\ddagger$	$35^\ddagger / 1^\ddagger$	$\sim 60$
?	MZI / W	None	$< 1$	22	45	990	200
?	MZI / TiN	Geometry	$< 1$	30	7	210	320

\* We consider the limiting switching speed of the switch in the case that the value of the phase shifter is not reported, i.e., the highest value between the rise and fall time constants.

<sup>+</sup> The value corresponds to the entire switching device. The optical loss of the phase shifter is not reported.

<sup>†</sup> Without preemphasis. <sup>‡</sup> With preemphasis.

N/A = Not available; MZI = Mach-Zehnder interferometer; MRR = Microring resonator.



Espinola et al. provided one of the pioneering experimental demonstrations of TOPS on silicon nearly two decades ago.<sup>2</sup> The design featured a silicon waveguide with a Cr/Au heater measuring 14- $\mu\text{m}$  in width and 100-nm in thickness, positioned atop the waveguide. The phase shifter spanned a length of 700  $\mu\text{m}$ , separated from the heater by a 1- $\mu\text{m}$ -thick layer of  $\text{SiO}_2$ . Integrated within a Mach-Zehnder interferometer (MZI) to function as a switch, the device exhibited significant optical loss (32 dB), which the authors attributed primarily to scattering caused by considerable sidewall roughness in the waveguide. Despite its status as one of the initial experimental reports in this field, the device demonstrated a power consumption of 50 mW and a switching time of 3.5  $\mu\text{s}$ , resulting in a figure of merit (FOM) of 175 mW  $\mu\text{s}$ . Notably, subsequent studies have reported similar or at times inferior performance metrics.<sup>3,4</sup>

On the application side, the capabilities of TOPS have been harnessed for switching purposes by cascading  $1 \times 2$  MZI switches to implement  $1 \times N$  configurations.<sup>2</sup> A significant advantage of these switches lies in their compact design, with the phase shifter elements measuring only 40  $\mu\text{m}$  in length. Nonetheless, these devices were characterized by considerable power consumption and slow switching speeds, reported at 90 mW and 100  $\mu\text{s}$ , respectively. The primary factor contributing to such a suboptimal performance is the substantial width of the heaters, approximately 20  $\mu\text{m}$ , which enlarges the cross-sectional area  $A$  of the phase shifter, as discussed in Eqs. (5) and (6). A notable improvement in power consumption and switching speed to 40 mW and 30  $\mu\text{s}$ , respectively can be achieved by reducing the heater width to 5  $\mu\text{m}$ , as demonstrated in subsequent studies.<sup>2</sup>

Atabaki et al. have highlighted the substantial influence of the heater width and the intermediate layer on the performance of thermo-optic phase shifters equipped with metallic heaters atop silicon waveguides.<sup>2</sup> Narrow heaters, with widths of less than approximately 2  $\mu\text{m}$ , are shown to enable

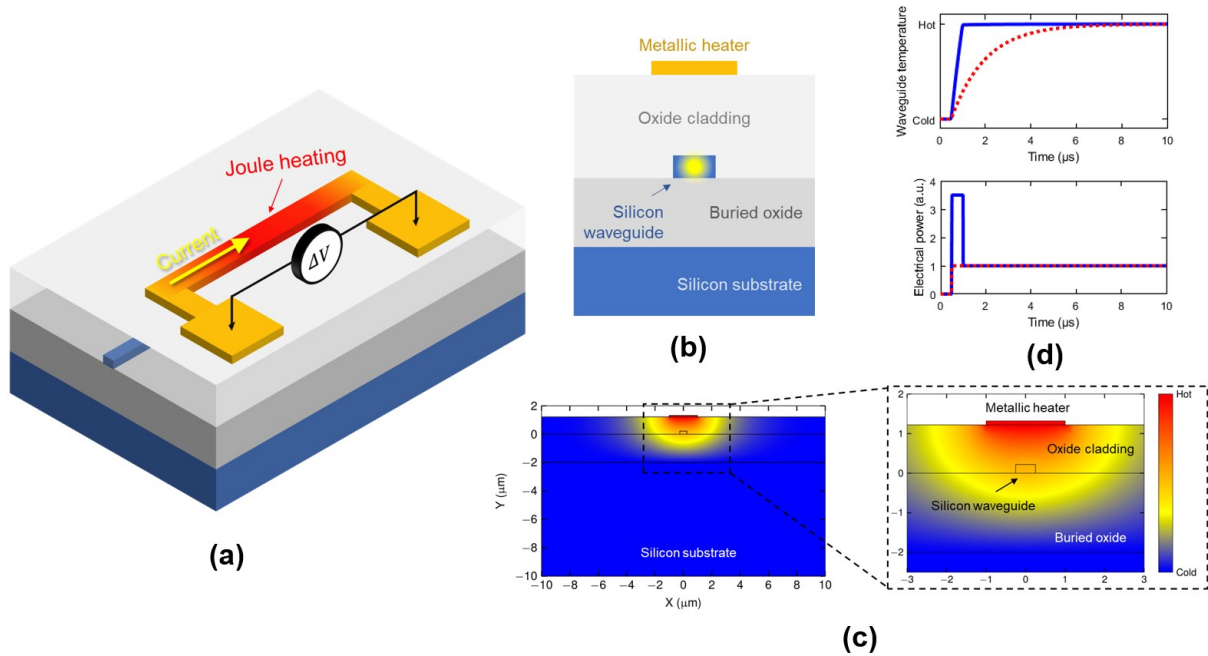


Fig 1: (a) Illustration of a TOPS using a metallic heater on top of the waveguide. (b) Cross-section of the TOPS. (c) Simulated temperature distribution of the TOPS. (d) Temporal response of the TOPS upon a square electrical signal applied to the heater with (solid blue line) and without (dotted red line) employing pulse preemphasis. The considered TOPS comprises a  $500 \text{ nm} \times 220 \text{ nm}$  Si waveguide with a  $2 \text{ }\mu\text{m} \times 100 \text{ nm}$  Ti heater on top. The gap between the waveguide and the heater is  $1 \text{ }\mu\text{m}$ . The temperature distribution in the cross-section was obtained by solving the conductive heat equation using COMSOL Multiphysics simulation tool. We considered the thermal constants reported in literature.<sup>7</sup> A non-uniform tetrahedral mesh, with element sizes ranging from  $1 \text{ nm}$  to  $500 \text{ nm}$ , was employed. A conductive heat flux boundary condition with a heat transfer coefficient of  $5 \text{ W}/(\text{m}^2 \text{ K})$  was set on the surface. The temperature of the remaining boundaries was fixed at  $293.15 \text{ K}$  (cold).

faster switching times ( $\sim 4 \mu\text{s}$ ) and lower power consumption ( $\sim 16 \text{ mW}$ ), attributed to the reduced volume of heating. However, reducing the heater width below  $2 \mu\text{m}$  does not yield significant further improvements, primarily due to the lateral heat diffusion, which spans about  $1\text{-}2 \mu\text{m}$ , thus becoming comparable to the microheater's dimensions.

Furthermore, the selection of material for the waveguide cladding plays a critical role in modulating both power consumption and switching speed, establishing a trade-off with the thermal conductivity of the cladding material. Enhancing the thermal conductivity, while keeping the specific heat capacity constant, accelerates the phase shifter's response but increases power requirements [refer to Eqs. (5) and (6)]. Substituting  $\text{SiO}_2$  with  $\text{SiN}$  is one strategy to enhance switching speed. Moreover, applying high-energy-pulsed drive signals can further decrease switching times, potentially to sub-microsecond scales, as demonstrated by the use of a preemphasis pulse (illustrated in Fig. 1d). This approach swiftly achieves the steady-state operation, although the inherent delay in heat transfer from the heater to the silicon waveguide sets a lower bound on achievable switching times.

The employment of parallel heaters alongside the silicon waveguide has been showcased as a method to realize low-loss, energy-efficient, and fast phase shifters.<sup>?</sup> This approach utilizes a rib waveguide configuration instead of the conventional strip design, with heaters positioned on both sides of the waveguide's thin bottom slab. In ref.<sup>?</sup> the heaters were composed of a 20-nm-thick  $\text{NiSi}$  layer, featuring widths varying from 500 nm to  $3 \mu\text{m}$ . Notably, a layer of  $\text{SiN}$  is deposited atop the silicon waveguide prior to heater formation to inhibit silicide development within the waveguide structure. By setting the distance between the heaters and the waveguide at 500 nm, a balance between low optical loss and a remarkable FOM of  $60 \text{ mW } \mu\text{s}$  was attained, accompanied by a power consumption of 20 mW and a switching time of  $3 \mu\text{s}$ . Despite the phase shifter's

relatively high propagation loss of 25 dB/cm, its compact length (40  $\mu\text{m}$ ) resulted in an insertion loss of less than 1 dB.

Lower FOM values have also been reported through the strategic placement of metallic heaters directly atop the silicon structure, leveraging silicon's thermal conductivity,<sup>7</sup> achieving power consumptions of merely 12 mW and switching times of 2.9  $\mu\text{s}$ . To circumvent optical losses associated with NiCr heaters, a microdisk with a 4  $\mu\text{m}$  diameter was utilized as the phase-shifting element, minimizing metal-light interactions to less than 1 dB of loss due to the evanescent nature of the optical mode towards the device's center.

The application of the preemphasis technique, as previously mentioned,<sup>7</sup> further reduces the switching time to 85 ns ( $\text{FOM} \approx 1 \text{ mW } \mu\text{s}$ ), enhancing the responsiveness of ON/OFF switching devices based on thermal phase shifters. Such devices benefit from differential or balanced architectures, enabling optical changes by selectively heating one of the optical paths. However, the primary challenge lies in the cooling period required for the heaters, as simultaneous cooling of both paths is essential before initiating the next switch to prevent continuous device heating.

The selection of an appropriate metal for the heaters is crucial not only from the perspective of minimizing optical loss but also to ensure that electrical power dissipation occurs predominantly within the heater rather than in the interconnections. While the optical loss may not be significantly affected by the choice of heater metal, the efficiency of power dissipation is paramount. The integration of the heater metal into a CMOS process flow is a critical consideration when selecting the optimal material for the heater. Although tin- and nickel-based alloys can be patterned as heaters within a CMOS process, foundries often prefer copper and tungsten due to their more desirable characteristics.

Tungsten, in particular, is favored for its relatively high resistivity and melting point, offering

enhanced stability for the heaters.<sup>?</sup> This stability is beneficial for devices that require consistent performance over time. Additionally, tungsten heaters can be electrically interconnected with copper wires, taking advantage of copper's lower resistivity to ensure that the majority of heat is dissipated in the tungsten heater. This configuration maximizes the thermal efficiency of the device.

A study by Masood et al.<sup>?</sup> demonstrated the effectiveness of tungsten heaters in a silicon waveguide, fabricated using a CMOS-like layer stack without further optimization. The devices exhibited power consumption levels around 22 mW and switching times approximately 40  $\mu$ s. The optical loss was reported to be less than 1 dB, with excellent electrical stability observed over 750 switching cycles.

Thermal crosstalk is a critical consideration in densely packed PICs, where the proximity of devices can lead to undesirable interference due to heat diffusion. Depending on the TOPS configuration, the minimum thermal crosstalk between devices can range between less than 10  $\mu$ m to 50  $\mu$ m.<sup>?,?</sup> Although utilizing longer heaters can decrease the temperature difference required to achieve a phase shift of  $\pi$  as indicated by Eq. (2), this approach also expands the device's footprint and potentially increases optical loss. Thus, achieving an optimal balance among device specifications necessitates careful consideration and judicious optimization.

A strategy to mitigate parasitic thermal phase shifts involves the implementation of deep trenches between the aggressor (source of thermal interference) and victim (affected device) components.<sup>?</sup> This technique effectively isolates devices thermally, minimizing crosstalk without compromising the compactness or performance of the circuit. By employing such structural modifications, PIC designers can enhance device integration density while maintaining control over thermal effects, ensuring that each component functions as intended with minimal interference.

### 3.1.1 Thermal isolation

The thermal isolation of phase shifters, achieved through the implementation of air trenches or by detaching the structure from the substrate via an undercut (illustrated in Figs. 2a and 2b), significantly decreases power consumption. This reduction is due to air's thermal conductivity being nearly two orders of magnitude lower than that of SiO<sub>2</sub> (approximately 0.025 W m<sup>-1</sup> K<sup>-1</sup>), thereby concentrating and elevating the temperature within the silicon waveguide as depicted in Fig. 2c. However, it is important to note that this approach leads to an increase in switching time [as indicated by Eqs. (5) and (6)]. Despite this drawback, such thermal optimization strategies are particularly beneficial for deploying multiple phase shifters within applications where moderate total power consumption is prioritized over rapid switching speeds.

A straightforward method for achieving thermal isolation involves deep etching on both sides of the waveguide, preserving the conventional heater-waveguide layout. Following this approach, devices have demonstrated power consumption and switching speeds around 10 mW and 10 μs, respectively.<sup>2</sup> Moreover, submilliwatt power consumption (0.54 mW) has been reported for waveguides released from the substrate.<sup>2</sup> These free-standing phase shifters, supported by two SiO<sub>2</sub> struts across a 320-μm-long released waveguide, exhibit mechanical stability. However, this configuration results in extended switching times, increasing from 39 μs in the attached version to 141 μs upon release. Recent studies have reported similar outcomes for released switching structures,<sup>2,2,2</sup> underscoring the trade-offs between power efficiency, switching speed, and structural design in the development of TOPS.

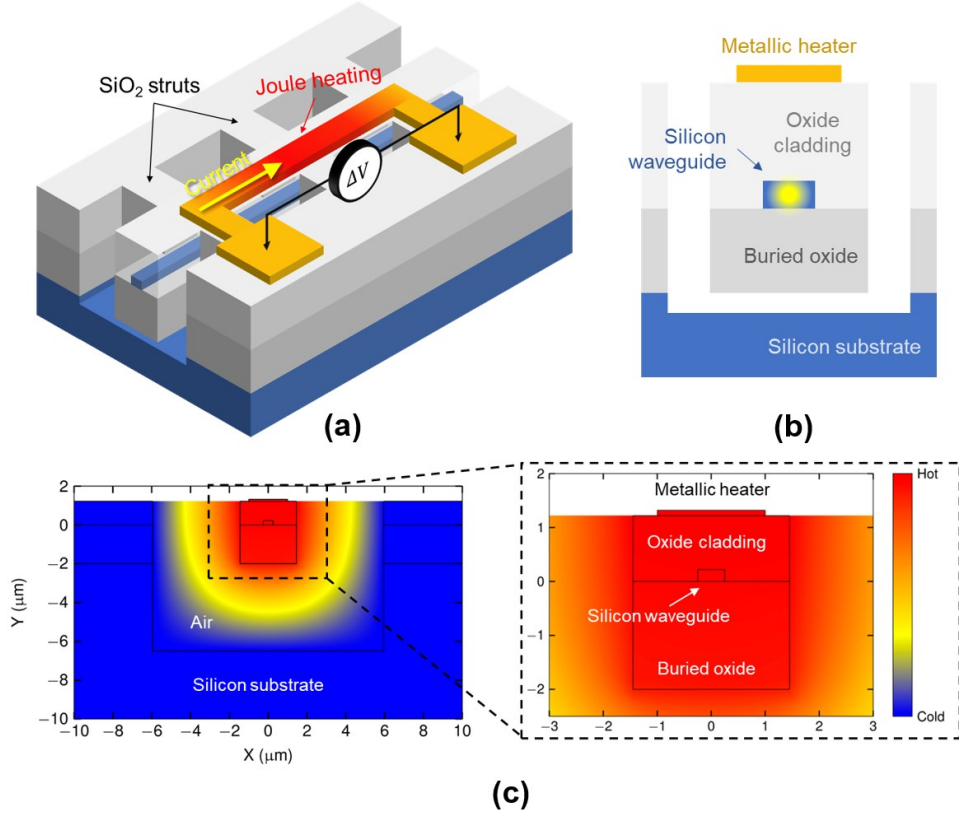


Fig 2: (a) Illustration of a TOPS using a metallic heater on top of the waveguide with thermal isolation by etching the top cladding and buried oxide. (b) Cross-section of the free-standing TOPS. (c) Simulated temperature distribution of the free-standing TOPS. The considered TOPS comprises a  $500 \text{ nm} \times 220 \text{ nm}$  Si waveguide with a  $2 \text{ }\mu\text{m} \times 100 \text{ nm}$  Ti heater on top. The gap between the waveguide and the heater is  $1 \text{ }\mu\text{m}$ . The temperature distribution in the cross-section was obtained by solving the conductive heat equation using COMSOL Multiphysics simulation tool. We considered the thermal constants reported in literature.<sup>?</sup> A non-uniform tetrahedral mesh, with element sizes ranging from  $1 \text{ nm}$  to  $500 \text{ nm}$ , was employed. A conductive heat flux boundary condition with a heat transfer coefficient of  $5 \text{ W}/(\text{m}^2 \text{ K})$  was set on the boundaries in contact with air. The temperature of the remaining boundaries was fixed at  $293.15 \text{ K}$  (cold).

### 3.2 *Transparent heaters*

Transparent heaters, i.e., electrically conductive materials with minimal optical loss in the near-infrared region, provide a strategic avenue to mitigate the trade-off between optical loss, power consumption, and switching speed in TOPS. This approach facilitates placing the heater in close proximity to the silicon waveguide, as illustrated in Figs. 3a and 3b, significantly reducing both the temperature gradient and the diffusion time between the waveguide and the heater. Consequently, this configuration not only improves the efficiency of heat transfer but also enhances the switching time of the phase shifter by shortening the thermal diffusion pathway.

Transparent heaters can be constructed using either 2D materials or transparent conducting oxides (TCOs). 2D materials, such as graphene and carbon nanotubes (CNTs), offer the advantage of low optical loss due to their exceptional optical properties and atomic-scale thickness, while also being electrically conductive. However, fabricating heaters from graphene presents challenges not encountered with traditional metal heaters. Typically, graphene heaters are produced by synthesizing a monolayer through chemical vapor deposition (CVD) and subsequently transferring it onto the photonic chip, followed by precise patterning. It is important to note that the optical and electrical characteristics of graphene heaters are significantly influenced by the quality of the graphene sheet.

In contrast, TCOs such as indium tin oxide (ITO) are widely utilized in various optoelectronic applications, including photovoltaic cells and displays, due to their well-established and mature fabrication techniques, such as sputtering. TCOs combine transparency in the visible to near-infrared range with good electrical conductivity, making them suitable for integration into photonic devices.



Table 2 summarizes the main specifications for experimental thermo-optic phase shifters in silicon that utilize transparent materials for heating.

Table 2: Summary of basic experimental thermo-optic phase shifters using transparent heaters in silicon photonics.

Ref.	Structure / Heater material	Gap (nm)	Loss (dB)	$P_\pi$ (mW)	Switching time ( $\mu\text{m}$ )*	FOM (mW $\mu\text{s}$ )	Length ( $\mu\text{m}$ )
?	MZI / Metal + graphene	0	5 <sup>+</sup>	> 50	20	> 1000	120
?	Microdisk / Graphene	0	< 1	23.5	13	305.5	~ 5
?	MRR / Graphene	240	< 1	11	3.5	38.5	~ 55
?	MZI-PhCW / Graphene	11	1.1	2	< 1	< 2	20
?	PhCC / Graphene	0	2	N/A	1.5	N/A	5
?	MRR / CNTs	0	N/A	14.5	4.5	65.3	~ 315
?	MRR / MoS <sub>2</sub>	30	~ 0.42	7.5	25	187.5	~ 283
?	MZI / ITO	660	~ 0.01	9.7	5.2	50.44	50
?	MZI / IHO	0	~ 0.5	9.6	0.98	9.41	10

\* We consider the limiting switching speed of the switch in the case that the value of the phase shifter is not reported, i.e., the highest value between the rise and fall time constants.

+ Value obtained through numerical simulation.

N/A = Not available; MZI = Mach-Zehnder interferometer; MRR = Microring resonator; PhCW = Photonic crystal waveguide; PhCC = Photonic crystal cavity; CNTs = Carbon nanotubes; MoS<sub>2</sub> = Molybdenum disulfide; ITO = Indium tin oxide; IHO = Hydrogen-doped indium oxide.

Graphene, renowned for its electrical conductivity, also boasts a remarkable thermal conductivity of  $\sim 5000 \text{ W m}^{-1} \text{ K}^{-1}$ .<sup>?</sup> Initial propositions for incorporating graphene into silicon waveguides for thermo-optic tuning aimed to exploit its thermal conductance, envisioning a graphene layer to

bridge the metallic heater and the silicon waveguide for more effective heat transfer.<sup>2</sup> Despite these efforts, experimental outcomes indicated power consumption exceeding 50 mW and a moderate switching speed of 20  $\mu\text{s}$ , failing to surpass the performance of conventional metal-based phase shifters. Additionally, numerical simulations revealed that the graphene layer could induce optical losses around 5 dB, further challenging its practicality for this application.

Subsequent advancements were made by adopting a similar approach and silicon structure as outlined in ref.,<sup>2</sup> where a graphene heater was implemented atop a silicon microdisk, replacing the metallic counterpart.<sup>2</sup> This configuration achieved a power consumption of 23.5 mW and a switching speed of  $\sim 10 \mu\text{s}$ , with the insertion loss attributable to the graphene heater being negligible ( $< 2 \times 10^{-4}$  dB/ $\mu\text{m}$ ). This minimal interaction between the heater and the optical mode of the microdisk resonator contributed to the device's enhanced performance.

A breakthrough was reported with the use of a graphene heater on a silicon waveguide, achieving a record FOM value of less than 40 mW  $\mu\text{s}$  ( $P_\pi = 11$  mW and  $\tau = 3.5 \mu\text{s}$ ).<sup>2</sup> The design included two intermediate layers, HSQ and  $\text{Al}_2\text{O}_3$ , positioned between the silicon waveguide and the graphene heater, with a meticulously optimized gap of 240 nm to maximize performance while minimizing optical loss. It is noteworthy that the reported power consumption was characterized at a wavelength of  $\lambda = 1310$  nm, with potential variations at  $\lambda = 1550$  nm due to differences in optical mode confinement.

Beyond graphene, carbon nanotubes (CNTs) have been proposed as an alternative for crafting transparent heaters, offering the principal advantage of lower absorption in the near-infrared spectrum. Direct integration of CNTs atop silicon waveguides has been explored for thermo-optic tuning purposes.<sup>2</sup> Despite their promising optical properties, a significant limitation of CNTs is their incompatibility with standard CMOS fabrication processes. Moreover, the performance met-

rics reported, including a power consumption of 14.5 mW and a switching speed of 4.5  $\mu$ s, do not exhibit marked improvements over analogous devices based on graphene.

Transition-metal dichalcogenides (TMDs), particularly a single layer of MoS<sub>2</sub> (molybdenum disulfide), have shown better prospects as heater materials when positioned in close proximity (30 nm) to the Si waveguide.<sup>7</sup> This configuration yielded an impressively low power consumption of 7.5 mW in a 283- $\mu$ m-long MoS<sub>2</sub> microheater, alongside a minimal insertion loss of  $\sim$  0.42 dB. However, the relatively slow response time of the phase shifter, around 25  $\mu$ s, can be attributed to the Schottky contact formed between the MoS<sub>2</sub> layer and the Au electrical pads. Future enhancements could potentially be realized by establishing Ohmic contacts with low resistance, optimizing the device's performance further.

The synergy between transparent heaters and the augmentation of light-matter interactions through slow light phenomena offers a pathway to substantial improvements in the power efficiency and speed of TOPS. The slow light effect, facilitated by the elevated group index in photonic crystal waveguides (PhCWs), enhances tuning efficiency dramatically. As a result, switching times under one microsecond and power consumptions as low as 2 mW (yielding a FOM of less than 2 mW  $\mu$ s) have been achieved in ultra-compact phase shifters, measuring merely 20  $\mu$ m in length, based on a PhCW integrated with a graphene heater.<sup>7</sup> The minimal gap of only 11 nm between the heater and the PhCW contributes to this high efficiency, despite the graphene layer inducing an optical loss of 1.1 dB.

Furthermore, ultra-compact device switches can also be realized through the development of a photonic crystal cavity (PhCC).<sup>7</sup> This innovative approach allows for a switching power, defined as the energy required to transition from a low loss state to a high loss state, to be less than 2 mW, coupled with a switching speed of approximately 1.5  $\mu$ s for a device with a footprint of only 5  $\mu$ m.

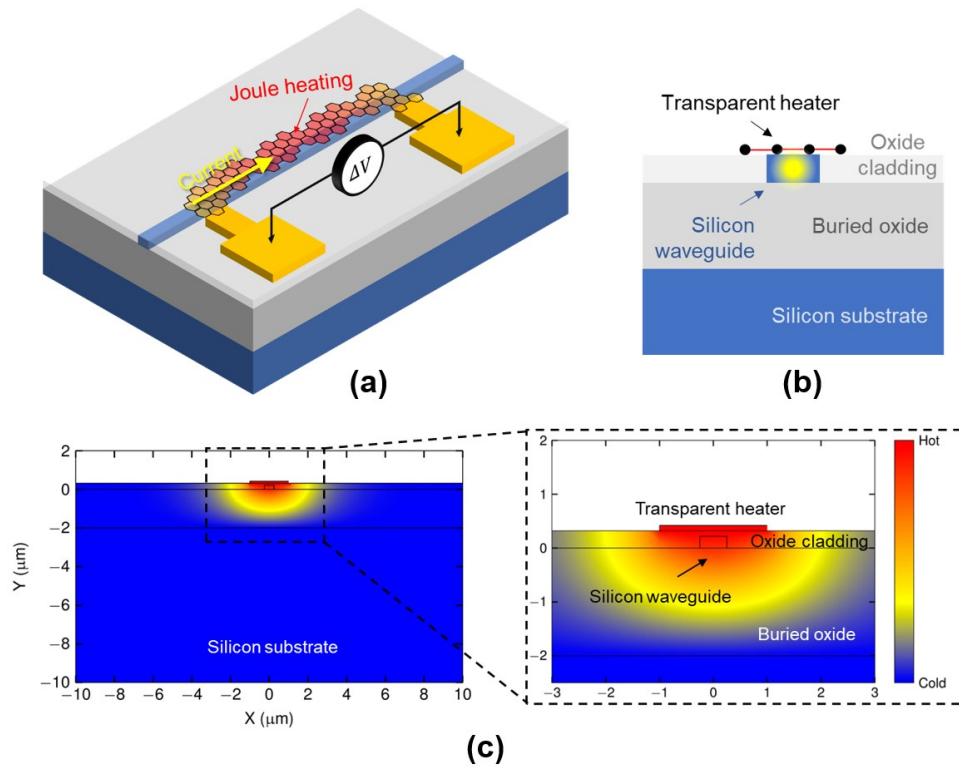


Fig 3: (a) Illustration of a TOPS using a transparent heater directly on top of the waveguide. (b) Cross-section of the TOPS. (c) Simulated temperature distribution of the TOPS using an ITO heater. The considered TOPS comprises a  $500 \text{ nm} \times 220 \text{ nm}$  Si waveguide with a  $2 \mu\text{m} \times 100 \text{ nm}$  ITO heater on top. The gap between the waveguide and the heater is  $100 \text{ nm}$ . The temperature distribution in the cross-section was obtained by solving the conductive heat equation using COMSOL Multiphysics simulation tool. We considered the thermal constants reported in literature.<sup>2</sup> A non-uniform tetrahedral mesh, with element sizes ranging from  $1 \text{ nm}$  to  $500 \text{ nm}$ , was employed. A conductive heat flux boundary condition with a heat transfer coefficient of  $5 \text{ W}/(\text{m}^2 \text{ K})$  was set on the surface. The temperature of the remaining boundaries was fixed at  $293.15 \text{ K}$  (cold).

TCO-based microheaters stand out for their CMOS-compatible manufacturing processes and thermo-optical characteristics. A key advantage of TCOs, such as ITO, resides in their capacity to modulate the concentration of mobile electrons within the near-infrared spectrum. This unique property enables these materials to function akin to metals with minimal loss at the operational wavelengths of devices, thus mitigating the optical losses typically associated with metal-based heaters. As a result, the spacer between the silicon waveguide and the heater can be substantially reduced, enhancing power efficiency and switching speed without incurring the significant optical losses characteristic of thinner metal gaps.<sup>?</sup> Specifically, a compact ITO/Si TOPS, measuring only 50  $\mu\text{m}$  in length, demonstrated a power consumption of 9.7 mW and a switching time of 5.2  $\mu\text{s}$ .

Further advancements were achieved with the introduction of a hydrogen-doped indium oxide (IHO) microheater, implemented directly atop the waveguide.<sup>?</sup> This 10- $\mu\text{m}$ -long IHO heater not only showcased an insertion loss of approximately 0.5 dB but also achieved a sub-microsecond switching speed (0.98  $\mu\text{s}$ ) while consuming 9.6 mW. Consequently, this led to an exceptionally low FOM of 9.41 mW  $\mu\text{s}$ .

### *3.3 Doped silicon*

Doped silicon serves a dual purpose in the topic of TOPS, acting simultaneously as both the heater resistor and the silicon waveguide. The doping process, which can involve n-type or p-type dopants such as arsenic (As), boron (B), or phosphorus (P), introduces free carriers into the silicon, leading to inherent optical losses. This effect creates a fundamental trade-off between the resistivity of the heaters and the optical absorption they introduce. To achieve a balance that minimizes optical losses while ensuring resistance values are compatible with electrical drivers and intended applications, silicon is typically doped to a carrier concentration of approximately  $10^{18} \text{ cm}^{-3}$ . Ad-

ditionally, employing multiple heater resistors in parallel is a common strategy to lower the total resistance, enhancing the device’s compatibility with electrical systems (illustrated in Fig. 4a).

It is important to note that doped silicon heaters exhibit specificity towards the silicon photonic platform and may not be directly transferable to other photonic materials like silicon nitride. Table 3 compiles experimental studies that have utilized doped silicon as the heating element, detailing their main specifications.

Table 3: Summary of basic experimental thermo-optic phase shifters using doped silicon heaters in silicon photonics.

Ref.	Structure	Dopant / Concentration	Current injection	Loss (dB)	$P_\pi$ (mW)	Switching time ( $\mu\text{s}$ )*	FOM (mW $\mu\text{s}$ )	Length ( $\mu\text{m}$ )
?	MZI	p-type (B) / $10^{18} \text{ cm}^{-3}$	Direct	3	6	0.6	3.6	115
?	MRR	n-type (As) / $1.8 \times 10^{18} \text{ cm}^{-3}$	Direct	0.5	12.7	2.4	30.5	$\sim 10$
?	MZI	p-type (B) / $7 \times 10^{17} \text{ cm}^{-3}$	Direct	$\sim 0.2$	$\sim 25$	$\sim 3$	$\sim 75$	61.6
?	MZI	n-type (N/A) / N/A	Parallel heaters	N/A	25	5	125	100
?	MRR	p and n-type (N/A) / $2 \times 10^{18}$ and $4 \times 10^{17} \text{ cm}^{-3}$	Direct with pn junction	N/A	19.5	0.45	7.8	$\sim 125$
?	MRR	n-type (As) / $4 \times 10^{13} \text{ cm}^{-2}$	Direct with pn junction	2.5	14	4	56	3.4
?	MZI	p and n-type (N/A) / N/A	Parallel heater with pn junction	1.6 <sup>+</sup>	20.9	97.5	$\sim 2000$	50
?	MZI	n-type (P) / $10^{20} \text{ cm}^{-3}$	Parallel heaters	$< 0.4$	22.8	2.2	50.2	320
?	MZI	p-type (P) / $10^{18} \text{ cm}^{-3}$	Direct	2	29	2	58	35
?	MZI	p-type (N/A) / $10^{18} \text{ cm}^{-3}$	Direct	0.24	22.6	0.5	11.3	$\sim 15$

\* We consider the limiting switching speed of the switch in the case that the value of the phase shifter is not reported, i.e., the highest value between the rise and fall time constants.

<sup>+</sup> The value corresponds to the entire switching device. The optical loss of the phase shifter is not reported. N/A = Not available; MZI = Mach-Zehnder interferometer; MRR = Microring resonator.

Employing doped silicon wires as heaters presents a viable alternative to traditional metallic heaters. Such resistive elements are typically build by doping the edges of a rib waveguide, maintaining a distance of less than 1  $\mu\text{m}$  from the core to mitigate excessive optical loss, while the

central region of the waveguide remains undoped. Consequently, the electrical current flows parallel to the waveguide's length. This configuration allows for power consumption levels comparable to those of metallic heaters positioned atop the waveguide ( $\sim 20$  mW) but offers the advantage of faster switching speeds (ranging from 2 to 5  $\mu$ s). The enhanced speed is attributable to the reduced distance over which heat must propagate.<sup>2,2</sup>

On the other hand, doped silicon waveguides can facilitate even more fast switching through direct current injection. This approach enables the heat generation directly within the waveguide itself, as depicted in Fig. 4b, effectively bypassing the limitations associated with heat propagation from external sources. Additionally, this approach offers a slight reduction in power consumption compared to parallel heaters adjacent to the silicon waveguide. Rib waveguides, characterized by heavily doped edges and a lightly doped center, are essential for facilitating electrical current injection into the waveguide, as depicted in Fig. 4c. This doping configuration ensures an optimal overlap between the thermal profile and the optical mode, minimizing the optical loss due to free carriers.

The phase shifter may also be designed as a series of individual resistors in parallel, allowing for customization of the device's resistance and driving voltage/current by adjusting the number of unit cells, independently of its length. Such configurations have achieved insertion losses as low as 0.2 dB, power consumptions around 25 mW, and switching times  $\sim 3$   $\mu$ s.<sup>2</sup> Optimizing the waveguide geometry further reduces power consumption without significantly affecting optical loss or switching speed. Notably, power consumption was minimized to 12.7 mW using a compact Si-doped heater, approximately 10  $\mu$ m in length, integrated directly into the waveguide. An adiabatic bend was employed to minimize optical loss from free carrier absorption and avoid optical mismatch, thereby preventing undesired reflections or the excitation of higher-order modes.<sup>2</sup>

Moreover, leveraging the field pattern distribution in MMI devices facilitates achieving low insertion loss, compact footprints, and fast switching. Electrical connections are strategically placed at positions corresponding to field pattern minima within the MMI. A 35- $\mu\text{m}$ -long device demonstrated power consumption and switching times of 29 mW and 2  $\mu\text{s}$ , respectively, with a moderate insertion loss of 2 dB.<sup>?</sup> Subsequent improvements reduced the insertion loss to below 1 dB by minimizing the number of electrical connections, while the switching speed was enhanced to 500 ns through the incorporation of a thin Al heat sink.<sup>?</sup>

Integrating a pn junction within a silicon waveguide, as illustrated in Fig. 4d, enhances the operational stability of TOPS. The saturated I-V response characteristic of pn junctions serves as a safeguard against thermal runaways by inherently limiting the current flow. Furthermore, the diode-like behavior of the junction facilitates the independent driving of multiple heaters using the same electrical pads.<sup>?</sup> This configuration involves two diode heaters arranged in parallel, with the cathode of one heater connected to the anode of the other and vice versa, allowing for selective heating by simply reversing the voltage polarity. Reported configurations demonstrated power consumption of  $\sim 21$  mW and switching speeds nearing 100  $\mu\text{s}$ .<sup>?</sup> To decrease the overall resistance and, consequently, the required driving voltage, a total of 8 diode heaters were placed in parallel, each 50  $\mu\text{m}$  in length (8  $\mu\text{m}$  p-doped) and 1.2- $\mu\text{m}$  wide, placed 0.75  $\mu\text{m}$  from the waveguide in the same plane.

To address the inherent challenge of non-linear phase shift responses to applied voltage in diode heaters, the authors in ref.<sup>?</sup> innovated a linear response technique through the utilization of pulse-width modulation (PWM). By fixing the PWM signal amplitude above the diode heater's threshold voltage and modulating the signal's duty cycle, power delivery was linearized and controlled effectively. This diode heater configuration has been successfully applied to manage larger



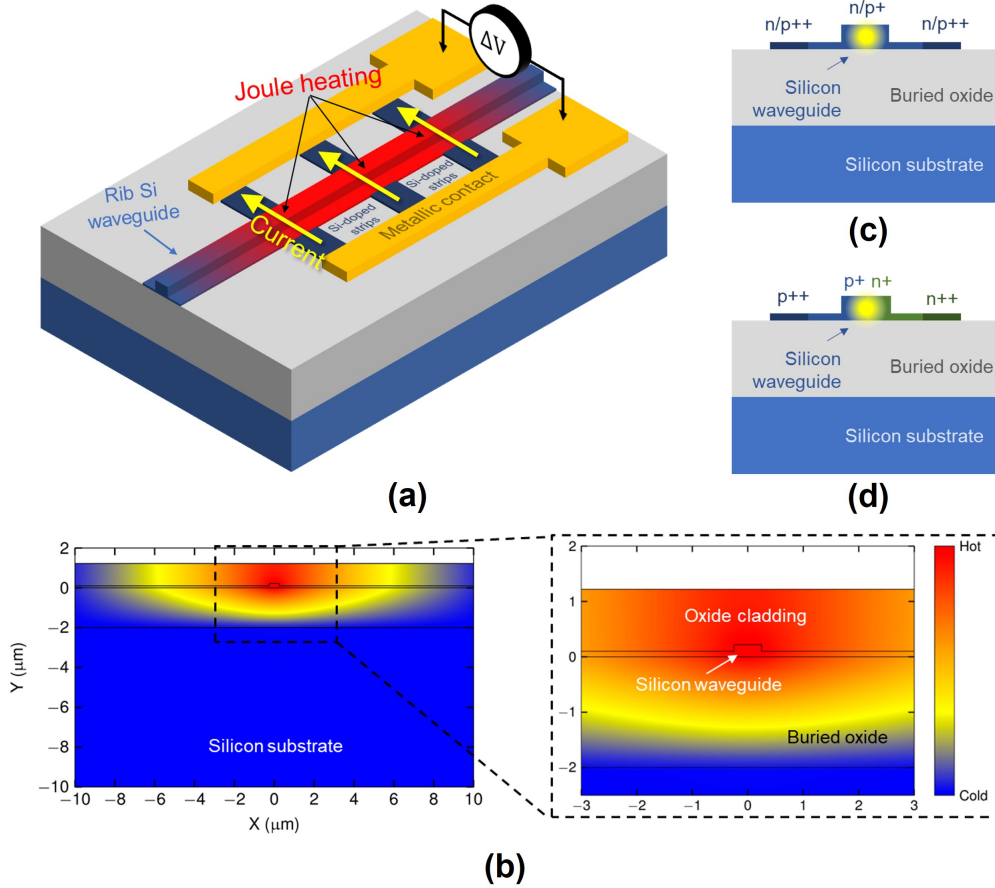


Fig 4: (a) Illustration of a TOPS utilizing a Si-doped heater, where heat generation occurs within the doped silicon waveguide. In this configuration, the waveguide is of the rib type, with several Si-doped heaters arranged in electrical parallel to minimize total resistance. Metallic contacts are linked to the Si waveguide via Si-doped strips. (b) Simulated temperature distribution within the TOPS, consisting of a  $500 \text{ nm} \times 220 \text{ nm}$  Si waveguide atop a 100-nm-thick slab, with  $1 \mu\text{m}$ -thick  $\text{SiO}_2$  cladding. Temperature distribution analysis was performed by solving the conductive heat equation with the COMSOL Multiphysics simulation tool, considering the waveguide core as the heat source, based on thermal constants from literature.<sup>2</sup> A non-uniform tetrahedral mesh, with element sizes ranging from 1 nm to 500 nm, was employed. A conductive heat flux boundary condition, with a heat transfer coefficient of  $5 \text{ W}/(\text{m}^2 \text{ K})$ , was applied on the surface, while the temperature for all other boundaries was fixed at 293.15 K (cold). (c,d) Cross-sectional views of the TOPS featuring (c) direct current injection and (d) a pn junction setup.

silicon photonic circuits, allowing for the digital control of matrix topologies comprising  $N$  rows and  $M$  columns by connecting  $N \times M$  heaters.<sup>2</sup> Employing PWM signals and time-multiplexing across different channels, the system obviates the need for digital-to-analog converters, requiring only  $M + N$  wires for comprehensive circuit control. An experimental demonstration controlling

a  $3 \times 5$  matrix with a  $1 \times 16$  power splitter tree and 15 thermo-optic phase shifters via 8 bond pads showcased this concept's effectiveness.<sup>?</sup>

For further acceleration of switching times, the pn junction can be directly integrated into the silicon waveguide, enhancing speed to the microsecond range<sup>?</sup> or even down to the hundreds of nanoseconds.<sup>?</sup> However, this direct integration method results in a notable increase in the optical loss for the phase shifter, approximately 2 dB.<sup>?</sup>

#### **4 Advanced configurations**

Advanced configurations in TOPS aim to decouple the traditionally correlated lengths of the heater and the light path to enhance energy efficiency. This approach is characterized by extending the light path length while maintaining the heater's length constant, thereby facilitating a greater phase shift for the same level of power consumption. The primary limitation of this strategy, however, lies in the requirement for larger device footprints to significantly reduce power consumption.

##### *4.1 Folded waveguides*

Folded waveguides provide a straightforward method to extend the waveguide path length. By folding the silicon waveguide multiple times beneath the heater, for example, in a spiral configuration (illustrated in Figs. 5a and 5b), significant increases in path length can be achieved. Densmore et al. reported the fabrication of a waveguide spiral comprising a total of 59 folds.<sup>?</sup> To mitigate coupling, the separation between adjacent waveguides was maintained at  $2 \mu\text{m}$ . A meander Cr/Au heater, separated from the photonic spiral by a  $1.5\text{-}\mu\text{m}$ -thick  $\text{SiO}_2$  layer, facilitated a temperature change  $\Delta T_\pi = 0.67 \text{ C}$  across an active length of  $6.3 \text{ mm}$  for the TM polarization, resulting in a power consumption of approximately  $6.5 \text{ mW}$ .<sup>?</sup> When compared to a phase shifter employing a

Table 4: Summary of advanced experimental thermo-optic phase shifters using folded waveguides and metallic heaters in silicon photonics.

Ref.	Structure	Number of folds	Loss (dB)	$P_\pi$ (mW)	Switching time ( $\mu\text{s}$ )*	FOM (mW $\mu\text{s}$ )	Length ( $\mu\text{m}$ )
?	MZI	59	$\sim 6^+$	$\sim 6.5$	$\sim 14$	$\sim 91$	$\sim 13000$
?	MZI	9	$2.9^+$	$4.2^\dagger/0.095^\ddagger$	$65^\dagger/1200^\ddagger$	$237^\dagger/114^\ddagger$	2900
?	MZI	14	1.23	2.56	35	89.6	2300
?	MZI	22	0.9	3	11	33	1876

\* We consider the limiting switching speed of the switch in the case that the value of the phase shifter is not reported, i.e., the highest value between the rise and fall time constants.

+ The value corresponds to the entire switching device. The optical loss of the phase shifter is not reported.

$\dagger$  With air trenches.  $\ddagger$  With undercut.

N/A = Not available; MZI = Mach-Zehnder interferometer.

straight waveguide, the folded configuration demonstrated a fivefold reduction in power consumption (from 36 mW). The switching time was observed to be 14  $\mu\text{s}$ , constrained by the thickness of the  $\text{SiO}_2$  cladding surrounding the waveguide. Employing varying widths between adjacent waveguides can further mitigate phase matching and subsequent coupling.<sup>?</sup> Additionally, releasing the entire phase shifter structure can minimize power consumption to as low as 0.095 mW, albeit at the cost of a prolonged switching time of  $\sim 1$  ms.

Additional optimization in folded TOPS have been achieved through the incorporation of non-circular Clothoid bends and the optimization of the heater's width and position.<sup>?</sup> This design facilitates a more efficient harnessing of generated heat. Peripheral waveguides are utilized to recollect residual heat energy, thereby enhancing the efficiency of the phase shifter without resorting to thermal isolation techniques such as air trenches or undercuts. This approach has demonstrated a power consumption of 2.56 mW and a switching speed of approximately 35  $\mu\text{s}$ . Subsequent

research has yielded even higher performance, with a reported power consumption as low as 3 mW and a fast switching time of 11  $\mu\text{s}$ .<sup>?</sup> Additionally, optical losses in such devices have been minimized to 0.9 dB, achieved by introducing a slight offset at the junction between the bend and straight waveguide segments to mitigate the excitation of higher-order modes.

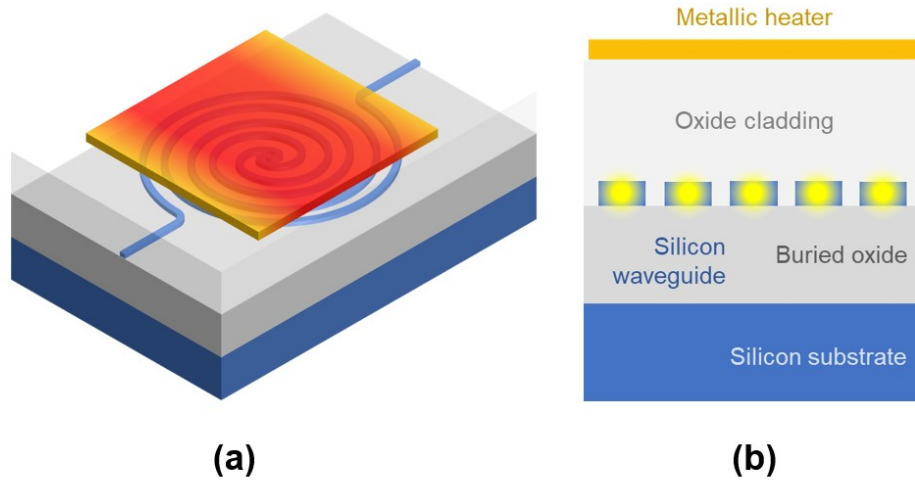


Fig 5: (a) Illustration of a TOPS using folded waveguides based on a Spiral waveguide with a wide heater on top. (b) Cross-section of the folded TOPS. The folded waveguide needs to be designed to avoid cross-coupling between adjacent waveguides.

#### 4.2 Multi-pass waveguides

A recent innovative TOPS configuration relies on a multi-pass photonic architecture, enhancing the effective path length of light through a mode multiplexing approach. This strategy reduces the power consumption of the phase shifter while preserving high switching speed and, more importantly, broadband operation.<sup>?</sup> Indeed, while conventional resonant cavities enhance the effectiveness of phase shifters, this approach comes at the cost of narrowing the optical bandwidth. In contrast, the multi-pass strategy utilizes spatial mode multiplexing to circulate light multiple times through the phase shifter, with each pass converting the light to a higher-order orthogonal spatial

mode. This method increases the effective path length without the need for a resonant cavity. It operates on the premise that the effective refractive indices of higher-order modes exhibit greater sensitivity to temperature changes due to their stronger dispersion. Thus, by integrating a thermo-optic phase shifter into this multi-pass structure, light accumulates significant phase shifts from all passes.

The working principle is illustrated in Fig. 6: light is launched into the multi-pass structure in the  $TE_0$  mode. As detailed in,<sup>7</sup> the light is converted to the  $TE_1$  mode upon exiting the multimode waveguide through a mode converter consisting of an adiabatic directional coupler. The  $TE_1$  mode then circulates within the multimode waveguide in the opposite direction. Subsequently, light exits the multimode waveguide to be converted into the  $TE_2$  mode and is sent back to the multimode waveguide in the forward direction, and the process continues. Ultimately, the fundamental  $TE_0$  mode is outputted from the structure.

This design was experimentally realized with a 360- $\mu\text{m}$ -long Pt heater placed atop the multimode waveguide and separated by an intermediate 1- $\mu\text{m}$ -thick  $\text{SiO}_2$  layer. The device exhibited a switching time of 6.5  $\mu\text{s}$ . Interestingly, the number of passes does not influence the device's switching time but does affect power consumption and optical loss. The effective path length and consequently, the optical loss increases with the number of passes due to the greater number of adiabatic couplers involved. For a 3-pass phase shifter, the power consumption and insertion loss were measured at 4.6 mW and 1.2 dB, respectively. Increasing the passes to 7 resulted in reduced power consumption, down to 1.7 mW, albeit with an elevated loss of almost 5 dB.

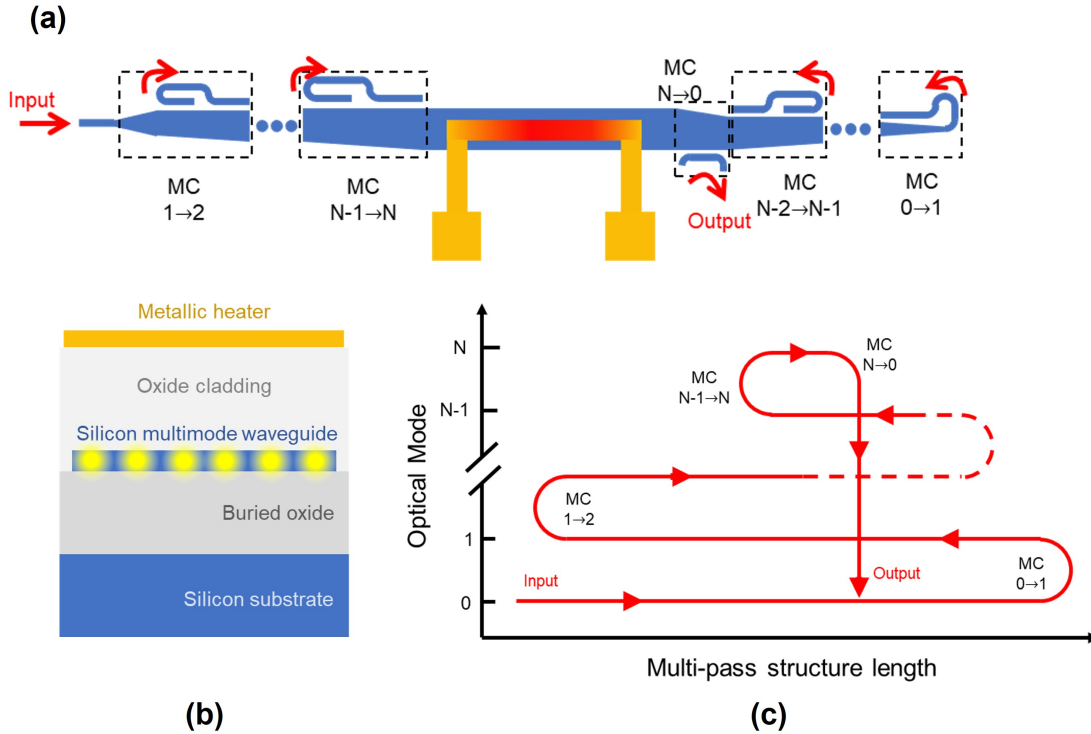


Fig 6: (a) Illustration of a TOPS utilizing a multimode waveguide where light is recycled  $N$  times through a multi-pass structure, demonstrating how power consumption decreases as the number of passes increases. (b) Cross-section of the TOPS within the multimode waveguide. (c) Depiction of optical mode conversion as a function of the multi-pass structure's length. Light enters the structure in the fundamental mode and, after  $N$  passes, is converted to the  $N$ th-order mode before being output from the structure and reverted to the fundamental mode.

## 5 Other phase shifter mechanisms and technologies

In addition to leveraging the silicon thermo-optic effect, various mechanisms and technologies have been proposed to address the inherent limitations of TOPS, including energy consumption, switching speed, and device footprint. Table 5 provides a comprehensive summary of both established and emerging electro-optical phase shifter technologies within the realm of silicon photonics.

### 5.1 Silicon plasma-dispersion effect

The plasma-dispersion effect in silicon offers a well-established approach for implementing phase shifters. The underlying physical phenomenon is inherently rapid (on the order of hundreds of

Table 5: Comparison of mainstream and emerging electro-optic technologies for implementing phase shifters in silicon photonics.

Technology	Insertion loss	Static power consumption	Switching time	Footprint	Manufacturability
Si TOPS	Ultra low ( $< 1$ dB)	Very high ( $> \text{mW}$ )	Very slow ( $> \mu\text{s}$ )	Large ( $> 100 \mu\text{m}$ )	Excellent
Si PDE	High ( $> 1$ dB)	Moderate ( $> \mu\text{W}$ )	Very fast ( $< \text{ns}$ )	Very large ( $\sim \text{mm}$ )	Excellent
MEMS	Low ( $\sim 1$ dB)	Ultra low ( $\sim \text{nW}$ )	Slow ( $\sim \mu\text{s}$ )	Compact ( $\sim 100 \mu\text{m}$ )	Good
Plasmonics	Very high ( $> 5$ dB)	Ultra low ( $\sim \text{nW}$ )	Ultra fast ( $\sim \text{ps}$ )	Ultra compact ( $\sim \mu\text{m}$ )	Limited
Ferroelectrics	Ultra low ( $< 1$ dB)	Ultra low ( $\sim \text{nW}$ )	Ultra fast ( $\sim \text{ps}$ )	Very large ( $\sim \text{mm}$ )	Limited
Phase-change materials	Low ( $\sim 1$ dB)	Zero	Slow ( $\sim \mu\text{s}$ )	Ultra compact ( $\sim \mu\text{m}$ )	Limited

TOPS = Thermo-optic phase shifter; PDE = Plasma-dispersion effect.

picoseconds) and can be realized through n-/p-doping of the silicon waveguide, utilizing the same fabrication processes available in microelectronic CMOS foundries.<sup>2,2</sup> Additionally, the power consumption associated with such phase shifters is moderately low, typically in the microwatts range. However, these devices face two primary limitations. Firstly, the plasma-dispersion effect alters both the real and imaginary components of the silicon refractive index,<sup>2</sup> leading to relatively high optical losses ( $> 1$  dB) in these phase shifters. Secondly, the refractive index change induced is minimal (on the order of  $10^{-5}$ ), necessitating large device footprints (on the scale of millimeters) to achieve significant phase shifts.<sup>2,2,2,2,2</sup>

To mitigate the issue of large footprints, resonant structures such as MRRs have been explored. However, these solutions introduce their own set of challenges, including high sensitivity to external thermal fluctuations and a limited operational bandwidth.<sup>2,2,2,2,2</sup>

## 5.2 Silicon MEMS

Over recent decades, silicon microelectromechanical systems (MEMS) technology has achieved maturity, offering promising avenues for mechanical devices in photonics. MEMS-based phase

shifters are known for their low optical loss ( $\sim 1$  dB), high energy efficiency, and compact footprints.<sup>2,2,2,2,2,2</sup> These mechanical devices function by altering the modal cross-section of a suspended silicon waveguide through geometrical adjustments, facilitated by a MEM actuator. The application of a voltage bias between the movable shuttle and a fixed, anchored electrode generates an attractive force within the actuator. This force diminishes the gap between the sets of teeth, causing displacement of the free-hanging shuttle. Consequently, a phase shift is achieved due to changes in the effective refractive index of the guided mode, resulting from this geometrical tuning. The induced optical losses are minimal, primarily originating from optical mismatches caused by structural transitions.

The primary challenges associated with MEMS-based phase shifters include their switching speed (ranging from  $\sim 0.1$  to 1 MHz), the relatively high driving voltage (exceeding 20 V), and the complexity of fabrication. Although MEMS technology is compatible with microelectronic industry manufacturing standards, the fabrication processes involved are intricate.

### 5.3 Plasmonics

The synergistic combination of nonlinear polymers with the high optical confinement afforded by plasmonics presents a promising avenue for the development of highly energy-efficient, ultrafast, and ultra-compact phase shifters.<sup>2,2,2,2</sup> Nonetheless, a significant challenge of this approach is the very high optical loss, typically exceeding 5-10 dB, which stands as a principal limitation. Additionally, the reliance on non-CMOS-compatible metals such as gold hinders the mass production of plasmonic devices. The long-term reliability and stability of the organic polymers used also necessitate further investigation.<sup>2</sup>

To address these challenges, TCOs emerge as promising candidates for new low-loss and



CMOS-compatible plasmonic devices.<sup>2,2,2</sup> Notably, the significant free-carrier dispersion effect of indium tin oxide (ITO) has been exploited to realize sub-wavelength-long phase shifters capable of sub-nanosecond switching speeds. This is achieved by electrostatically tuning the ITO carrier concentration close to, but not within, the high-loss epsilon-near-zero (ENZ) plasmonic region.<sup>2</sup> Despite these advancements, further optimization is required, as the insertion loss associated with these devices remains substantial ( $> 5$  dB).

#### 5.4 *Ferroelectrics*

Ferroelectric materials are recognized for their capacity to enable high-performance electro-optic devices by harnessing the Pockels effect. Unlike silicon, which lacks the Pockels effect due to its material symmetry, ferroelectrics offer ultra-fast operational speeds (on the order of picoseconds) without contributing to optical loss. In recent years, various platforms have been proposed to utilize these distinctive properties for the development of ferroelectric-based phase shifters, ensuring compatibility with silicon photonic devices. Predominantly, these efforts have centered around lithium niobate (LN), a material with a longstanding history in commercial fiber-based electro-optic modulators.<sup>2,2</sup> Innovations in phase-shifting devices have led to the demonstration of both ultra-low loss, ultra-fast standalone LN thin films,<sup>2</sup> and hybrid LN/Si phase shifters,<sup>2</sup> noted for their high energy efficiency (less than pJ).

Alternatively, barium titanate (BTO) has emerged as a ferroelectric material with a Pockels coefficient significantly higher than that of LN (923 vs.  $\sim 30$  pm/V),<sup>2,2</sup> paving the way for experimental demonstrations of BTO/Si phase-based devices.<sup>2,2,2,2,2</sup> Recent advancements include the development of a multilevel non-volatile phase shifter based on BTO/Si.<sup>2</sup> The direct growth of BTO on silicon highlights its potential for monolithic integration with electronic circuits and mass

manufacturing within silicon photonic platforms. Furthermore, wafer-scale production has also been showcased in standalone LN on insulator<sup>2</sup> and LN on silicon nitride through heterogeneous integration.<sup>2</sup>

### 5.5 Phase-change materials

Phase-change materials (PCMs) are distinguished by their dramatic optical refractive index change, facilitating the development of photonic devices with ultra-compact footprints spanning only a few micrometers. The predominant PCMs utilized in photonics are chalcogenides,<sup>2</sup> capable of non-volatile transitions between amorphous and crystalline states. This attribute may significantly decrease power consumption, as no static power is needed to maintain the material state.<sup>2</sup> State switching is typically achieved by locally heating the PCM through photothermal excitation with optical pulses or Joule heating via microheaters,<sup>2</sup> leading to comparatively slower switching times (on the order of microseconds). Among various chalcogenide compounds,  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  (GST) has been extensively used.<sup>2</sup> However, GST high optical absorption in both material states positions it as an ideal candidate for absorption-based devices like optical memories,<sup>2,2</sup> but limits its use in phase-based devices. Conversely, alloys such as  $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$  (GSST),  $\text{Sb}_2\text{S}_3$ , and  $\text{Sb}_2\text{Se}_3$  show minimal or negligible optical absorption at telecom wavelengths.<sup>2,2,2,2,2,2,2,2,2</sup> In this regard,  $\text{Sb}_2\text{Se}_3/\text{Si}$  phase shifters have achieved an insertion loss of merely 0.36 dB with phase modulation up to  $0.09 \pi/\mu\text{m}$ .<sup>2</sup>

Yet, the long-term reliability and endurance of PCMs in photonics remain challenging, attributed to material property degradation after numerous switching cycles.<sup>2</sup> Reversible switching operation up to only  $10^4$  cycles has been recently demonstrated in a  $\text{Sb}_2\text{Se}_3/\text{Si}$  phase-shifter device.<sup>2</sup> Thus, the application of PCMs in phase-shifters might be confined to scenarios not demand-

ing extensive cycling over time.

## **6 Conclusions and prospects**

In this review, a comprehensive overview of the current landscape of PIC technology based on TOPS. It has examined the most relevant heater technologies and advanced waveguide-heater configurations, highlighting the prevalent use of metallic heaters as the standard in silicon photonics due to their compatibility with CMOS foundry processes. Despite their widespread adoption, metallic heaters are criticized for their high power consumption and slow response times. An alternative strategy, involving the release of the silicon waveguide, has been shown to significantly reduce power consumption, albeit at the cost of device speed.

The exploration of transparent materials, such as graphene and TCOs, offers promising avenues for enhancing performance by enabling closer placement of the heater to the waveguide. Nevertheless, the literature on these innovative approaches remains limited, underscoring a need for further investigation, particularly regarding their practical application and integration into the silicon photonic foundry fabrication processes.

Doping the silicon waveguide emerges as a preferable option for phase shifters requiring swift operation and minimal power consumption, as it facilitates internal heat generation within the waveguide. However, this method introduces optical losses due to free carriers. Additionally, its application is confined to silicon waveguides, precluding its adoption in other photonic platforms, such as silicon nitride.

Addressing these open questions and challenges is crucial for advancing the field of TOPS in PICs. Future efforts should aim at demonstrating the practical applications of these technologies

and exploring their integration into standard fabrication processes, thereby paving the way for more efficient, faster, and versatile photonic devices.

Advanced waveguide-heater configurations present a promising avenue to augment the capabilities of conventional TOPS schemes. While existing implementations predominantly utilize metal heaters, the exploration of alternative materials, such as those based on transparent heaters, holds the potential to further capitalize on the advantages offered by these configurations. Notably, advanced approaches, including folded waveguides and light recycling, aim at minimizing power consumption without adversely affecting switching speed and optical bandwidth. This contrasts with strategies involving released waveguides, where power efficiency improvements often come at the cost of reduced operational speed.

A critical challenge associated with these advanced configurations is the inverse relationship between power consumption reduction and the TOPS footprint. In scenarios demanding high device density, such as in the deployment of deep neural networks, the increased footprint could impose significant constraints. Consequently, there is a pressing need for novel strategies that concurrently optimize speed, power efficiency, and device compactness. Such developments would not only overcome existing limitations but also enable broader application of TOPS in densely packed PICs.

This review also has explored various alternative mechanisms and technologies for phase shifters, each presenting unique advantages, limitations, and potential application scopes. The silicon plasma dispersion effect offers significantly faster operation speeds (lower than nanoseconds) while retaining fabrication compatibility with CMOS foundries. However, this approach incurs moderate insertion losses ( $> 1$  dB) and necessitates millimeter-scale footprints due to free carrier effects and the inherently weak modulation mechanism.

Hybrid ferroelectric-silicon photonics platforms, utilizing materials such as LN or BTO, propose an avenue for ultra-low loss ( $< 1$  dB) phase shifters capable of ultra-fast speeds (on the order of picoseconds). Despite these advantages, their millimeter-long footprints may limit their applicability in densely integrated systems.

MEMS-based phase shifters emerge as a compact alternative ( $\sim 100$   $\mu\text{m}$ ), featuring low optical losses and ultra-low power consumption (in the nanowatt range). Their operation, predicated on the mechanical displacement of released silicon waveguides via an external electric field, leverages CMOS-compatible fabrication processes. Nonetheless, the slow operational speeds (on the order of microseconds) and the necessity for high voltages, which are incompatible with standard CMOS voltages, pose significant drawbacks.

Plasmonic phase shifters have demonstrated potential for energy-efficient and ultra-fast operation within ultra-compact footprints. The primary challenge for plasmonics lies in their very high optical losses ( $> 5$  dB), constraining scalability and suitability for certain applications, such as quantum optics.

PCMs stand out for applications requiring ultra-compact devices or benefiting from non-volatile phase tuning, offering the advantage of zero static energy consumption. Yet, the principal challenge for PCMs is ensuring long-term stable operation across numerous switching cycles, a critical requirement for many applications.

In summary, silicon's relatively high thermo-optic coefficient, alongside the potential for negligible insertion losses, positions thermal tuning as the most versatile and widely applicable approach in the vast array of integrated photonic applications, spanning fields from computing and quantum technologies to artificial intelligence. The choice of TOPS optimization strategy and configuration will inevitably be guided by the specific requirements of each application, considering

the inherent trade-offs among power consumption, speed, and ease of fabrication. Consequently, additional research efforts are crucial for overcoming these challenges. Emerging technologies that offer alternative methods for implementing integrated phase shifters within the silicon photonics platform present a promising avenue for superseding traditional TOPS. However, the determination of which technology will ultimately be embraced by existing CMOS foundries remains an open question, underscoring the dynamic and evolving nature of this field.

### *Disclosures*

The authors declare no conflicts of interest.

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### *Code, Data, and Materials Availability*

Data sharing is not applicable to this article, as no new data were created or analyzed.

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