Suspended Mid-infrared Guided-wave Phase Shifters in an InP-based Platform

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Abstract: We fabricate suspended waveguide thermo-optic phase shifters on an InGaAs/InP platform for 3.6 µm to 5.2 µm wavelengths. Utilizing suspended waveguides, 2π phase tuning power ($P_{2\pi}$) drops below 100 mW via a simple fabrication process.

With the development of optical communication technology and light detection and ranging (LIDAR), optical phased arrays (OPAs) have become promising candidates for performance enhancements because of their non-mechanical beam-steering mechanism. Additionally, optical communication technology and OPAs operating in the mid-infrared range exhibit longer detecting distances and superior security, attributed to the lower background solar noise within the atmospheric transmission window of 3-5 µm [1]. Thus, it is crucial to develop high power-efficiency phase shifters that operate in the mid-infrared spectral region for both mid-infrared OPAs and optical communication systems. In this paper, we propose suspended waveguide thermo-optic phase shifters which demonstrate high phase-tuning efficiency in an InGaAs/InP waveguiding platform. Moreover, the proposed mid-infrared phase shifters are also compatible with the monolithic integration of mid-infrared quantum cascade lasers (QCLs) and OPAs, supporting the achievement of a fully integrated mid-infrared LIDAR in the coming future.

The thermo-optic effect, describing the phenomenon that the refractive index variation is induced by the temperature change of waveguides, has been widely used in near-infrared modulators [2]. This phenomenon is mathematically described by the following equation:

$$\Delta\varphi = \frac{2\pi L}{\lambda}\frac{dn}{dT}\Delta T \qquad (1)$$

where φ is the phase change, L is the length of heater interacting region, λ is the wavelength, dn/dT is the thermos-optic coefficient, and ΔT is the temperature variation. However, when it comes to mid-infrared region, the longer the operating wavelength, the larger the waveguide volume, which leads to a substantial decrease in the tuning efficiency, with a scaling factor of $1/\lambda^3$ roughly [3]. Thus, the optimization of thermal confinement within the core, directly proportional to ΔT, becomes imperative for enhancing the tuning efficiency of mid-infrared phase shifters. In Figure 1, it is evident that the thermal confinement of the waveguide with oblique trenches is noticeably superior when subjected to the same power from the metal heater. Moreover, thermal confinement improves further when the waveguide is entirely undercut and suspended, as observed in the following experimental findings.

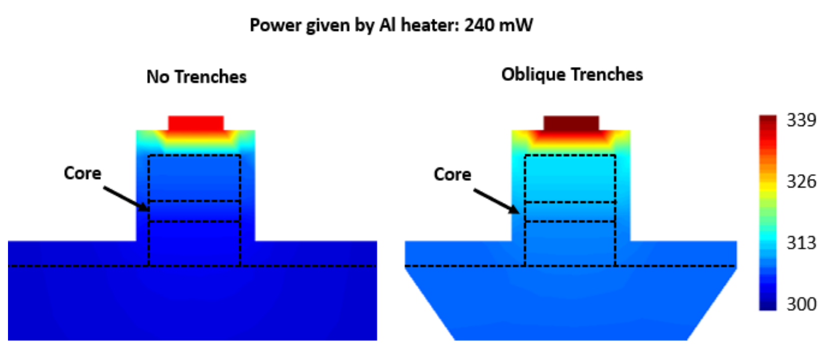

Fig. 1: With the identical power, the ΔT_{core} is approximately ~ 7K for configuration (a) without trenches, and ~ 12K (b) with oblique trenches.

In this study, the proposed waveguide consists of an 850-nm-thick InGaAs core layer (with refractive index n ~ 3.38), cladded by InP (n ~ 3.09) in a 3300-nm-tall ridge structure, as shown in Fig. 2(a). The top and bottom cladding layers have thicknesses of 1450 nm and 1000 nm, respectively, and the waveguide width is 3.3 µm. (A secondary 150-nm-thick InGaAs layer resides in the upper cladding, serving as an etch stop for certain processes.)

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The proposed phase shifter consists of a metal strip heater atop the waveguide as a resistive heating element. As illustrated in figure 2(a), a 260-nm-thick aluminum heater is evaporated onto the waveguide. Consequently, two arrays of trenches running along each side of the heater-lined waveguide are introduced, as illustrated in Figure 2(c). Besides, as depicted in figures 2(a) and 2(b), the implementation of a wet-etching process using a 4% volume bromine-methanol solution results in the formation of reverse-mesa-shaped trenches, which is attributed to the preferential etching characteristics of the (110) plane of InP. It is noteworthy that the thermal phase shifters are totally undercut by left and right trenches, so the thermal suspended thermo-optic phase shifters with great thermal confinement are fabricated in a simple way.

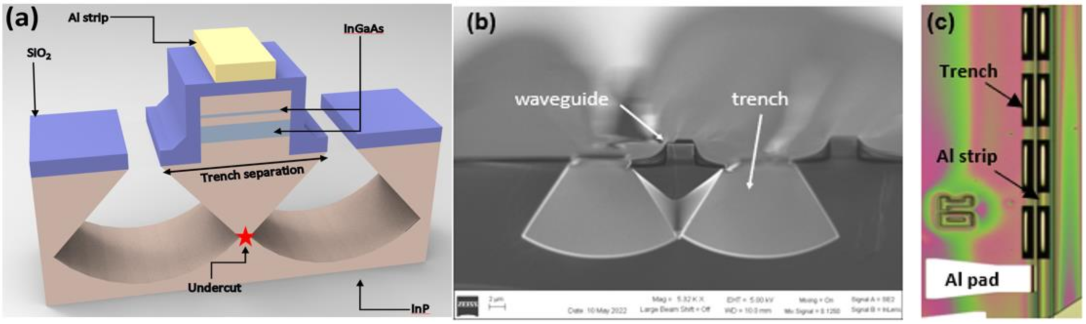

Fig. 2: (a) Schematic of the suspended thermo-optic phase shifters, (b) SEM image of cross-section through waveguide and trenches, and (c) zoomed section of MZI structure.

The phase shifter is evaluated through use of a Mach-Zehnder interferometer. The phase shifter structure, with heating element and trenches, is incorporated into one arm of the interferometer, the other arm remaining as a simple waveguide. Through biasing the phase shifter and monitoring the light out of the MZI, the phase shifting performance is evaluated.

As indicated by Figure 3, a significant reduction in power at 2π phase shift ($P_{2\pi}$) is noticeable with a trench separation distance of 12 µm. The suggested suspended waveguide phase shifters have the capacity to lower $P_{2\pi}$ to less than 100 mW. Therefore, these phase shifters show great potential for future mid-infrared InP photonic integrated circuits in optical communications and LIDAR applications.

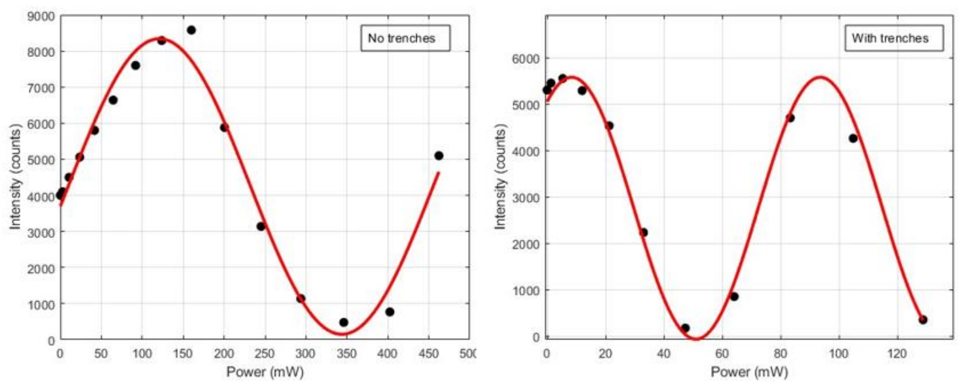

Fig. 3: Representative data plots for two MZI tests. Both devices use 3.3 µm wide waveguides, 1000 µm long in the phase shifter region. (Left) device without trenches, and (right) device with trench separation distance = 12 µm.

In conclusion, this study has successfully demonstrated mid-infrared phase shifters with low $P_{2\pi}$ values. Comparable achievements have been reported in mid-infrared phase shifters manufactured on a germanium-silicon platform, with $P_{2\pi}$ below 100 mW, as shown by M. Prost *et al*. [4]. However, the fabrication of deep-etch trenches down to 200 µm may be complicated or impractical in conjunction with typical substrate thinning processes. Thus, the proposed suspended phase shifters via a simple bromine-methanol wet-etch not only show a comparable $P_{2\pi}$ value but are also compatible with standard InP processing techniques.

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