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Silicon-based photonic integrated circuits for the mid-infrared

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Abstract

Silicon-based photonic integrated circuits (PICs) operating in the mid-infrared wavelength range are presented. Firstly, it is shown that the operation of the SOI-based waveguide circuits can be pushed beyond the telecom window till a wavelength of 4 µm. Ge-on-Si based PICs are demonstrated for operation beyond 4 µm wavelength. Low-loss waveguides and integrated spectrometers are reported for both the waveguide platforms. We also present our results on efficient thermo-optic phase shifters for germanium waveguide circuits.

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Keywords: Photonic Integrated Circuits; Dielectric Waveguides; Arrayed Waveguide Gratings; Planar Concave Gratings, Thermo-Optic phase shifters

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1. Introduction

Silicon-on-Insulator (SOI) is an attractive waveguide platform for the realization of various optical functionalities in the telecom wavelength range. It has become attractive because of the possibility of mass-manufacturing of the photonic integrated circuits (PICs) in standard CMOS pilot lines which produce electronic integrated circuits (ICs). There have been various demonstrations of low-loss waveguides and several integrated components such as wavelength filters, spectrometers, modulators, and detectors at telecom wavelengths. SOI PICs have also been integrated with other materials/devices such as III-V based lasers via bonding techniques, which increases the functionality of the platform even further.

Apart from applications in the field of optical communication, SOI PICs are also being used for refractive index sensing applications in the near-infrared (NIR) wavelength range [1]. For spectroscopic sensing applications it is known that most gas and liquid molecules have orders of magnitude higher absorption in the mid-infrared (mid-IR) wavelength range as compared to the NIR wavelength range as can be seen in Fig. 1. This leads to the thought that the realization of PICs in the mid-IR wavelength range could enable integrated (and therefore compact and robust) spectroscopic systems. Fabrication of the PICs in a CMOS/MEMS production line is desired in order to keep the production cost to minimum. Therefore, we investigate silicon-based waveguide platforms to realize optical functionalities in the mid-IR wavelength range.

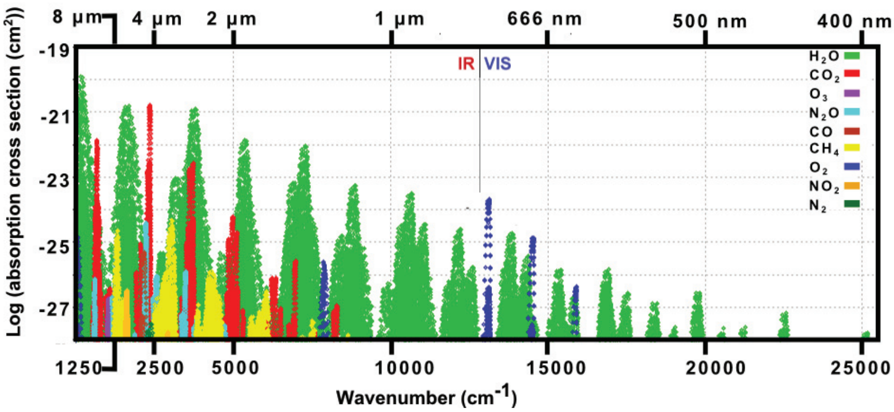
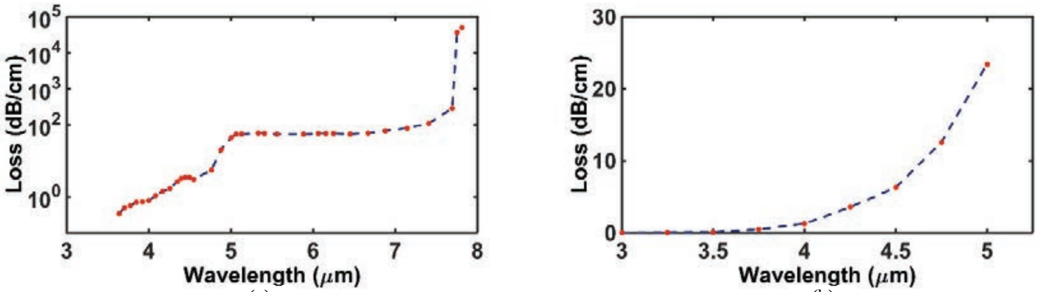


Fig.1. Absorption cross section of atmospheric gases (in logarithmic scale) as a function of wavelength [2]

2. Silicon-based waveguide circuits for the mid-infrared

For the telecom wavelength range, the standard SOI waveguide platform uses 220 nm thick waveguides on a 2 μm buried oxide (BOX) layer. However as one increases the wavelength of operation, the height of the silicon layer becomes insufficient to guide light and additionally one suffers from the higher substrate leakage loss. We have therefore used a 400 nm thick silicon layer on a 2 μm BOX for realizing PICs in the mid-IR wavelength range. This 400 nm thick silicon is either realized by depositing and patterning a poly-silicon layer on top of a crystalline 220 nm thick silicon or one can use an SOI wafer with a 400 nm thick crystalline silicon device layer.

The upper limit on the wavelength of operation of the SOI waveguide circuits is imposed by the absorption of light by the buried oxide layer. As can be seen in Fig. 2(a), the absorption of the buried oxide increases drastically beyond 4 μm wavelength. Another issue which hinders the use of SOI waveguides in the mid-IR wavelength range is the leakage loss to the silicon substrate as seen in Fig. 2(b).



(a) (b)

Fig. 2 (a). Absorption loss of buried oxide in a SOI wafer [3] and (b) simulated leakage loss of the TE polarized mode confined in a 400 nm high Si waveguide, as a function of wavelength. Simulations were done for single mode waveguides at each wavelength.

Therefore, it can be concluded that standard SOI based waveguide circuits can't be used for wavelengths beyond 4 µm and another waveguide platform needs to be explored. There are several candidates in literature however one needs to keep in mind CMOS/MEMS compatibility for cost reduction as well as a wide wavelength window of operation because the absorption peaks of various molecules cover a broad wavelength range. We chose Ge-on-Si as the waveguide platform because not only it can be fabricated in CMOS/MEMS foundries but it potentially also allows for a wider window of operation from 1.7 µm till 14 µm. The germanium layer is grown on a 200 mm <100> silicon wafer and is then annealed to reduce the threading dislocations at the silicon-germanium interface. Then the waveguides are patterned in the germanium layer by using a metal (Ti/Cr) mask defined by i-line contact lift off and CF_4:O_2 etching chemistry in a RIE system. Recently, we have also developed an etching recipe based on a CF_4:SF_6:H_2 plasma which allows defining germanium waveguides with a photoresist mask. This fabrication flow offers a better control on the waveguide dimensions as compared to the previous one. Fig. 3 shows a SEM image of a waveguide fabricated using the alternate fabrication flow.

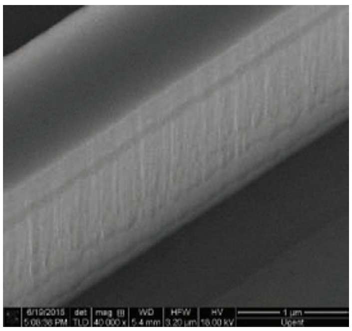


Fig. 3. SEM image of the side wall of a germanium waveguide fabricated using photoresist mask and etched using CF_4:SF_6:H_2 plasma

3. Low-loss waveguides

3.1. SOI Waveguides

The SOI waveguides were measured in the 3.7 µm wavelength range for both 220 nm crystalline+ 160 nm poly silicon waveguides and for 400 nm thick crystalline silicon waveguides. The waveguide losses for fully etched crystalline+poly silicon waveguides were found to be in the range of 3-4 dB/cm for TE polarized light [4] in a 1.2 µm wide waveguide. The waveguide losses of the partially etched 400 nm crystalline waveguides were found to be in the range of 2 dB/cm for TE polarized light as shown in Fig. 4(a) along with the waveguide cross section in Fig. 4(b). The lower losses can be explained by the fact that in a crystalline+poly silicon waveguide, there are scattering losses at the grain boundaries in poly-silicon, while the completely crystalline waveguide doesn't suffer from such scattering.

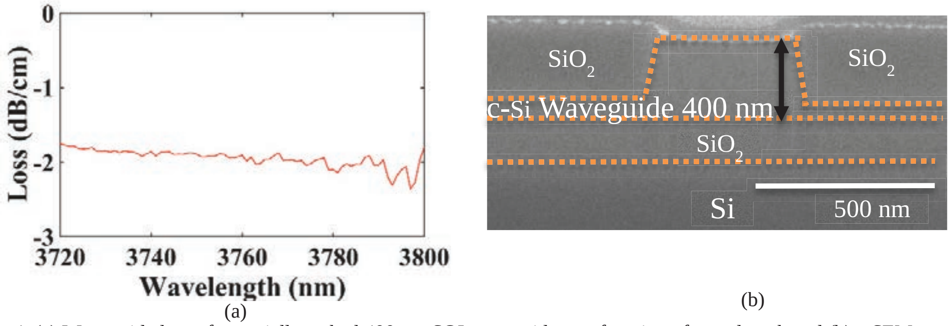


Fig. 4. (a) Waveguide loss of a partially etched 400 nm SOI waveguide as a function of wavelength and (b) a SEM cross section of a waveguide.

3.2. Ge-on-Si waveguides

Both fully and partially etched Ge-on-Si waveguides were measured in the 5.3 µm wavelength range and the losses were found to be in the range of 3-4 dB/cm for both TE and TM polarization as can be seen in Fig. 5 [5,6]. The losses of the waveguides fabricated by using photoresist mask were found to be similar. The origin of these losses can be primarily attributed to the defective silicon-germanium interface. Fig. 6 is showing the defects revealed in the germanium layer using etching in a CrO_3:HF solution and it's evident that the number of defects increase as one approaches the interface. Another source of waveguide loss is the side wall roughness. By reducing the overlap of the mode with the defective interface and by reducing the side wall roughness, one can lower the waveguide losses as shown in [7] where waveguides losses as low as 0.6 dB/cm at 3.8 µm were demonstrated by using a partially etched 3 µm thick germanium layer.

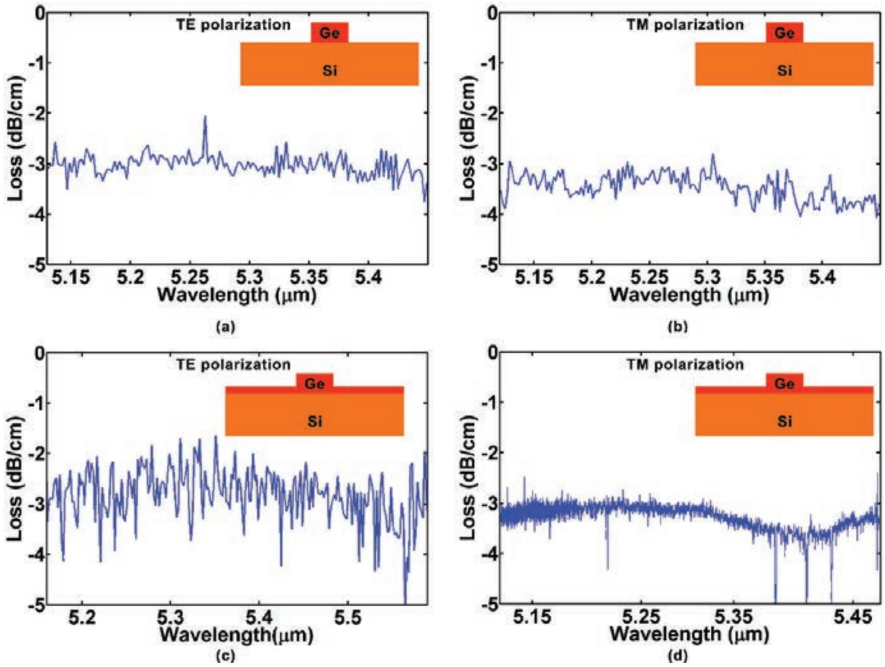


Fig. 5. Waveguide loss measured using cut back method for (a) fully etched waveguide for TE polarization, (b) fully etched waveguide for TM polarization, (c) partially etched waveguide for TE polarization and (d) partially etched waveguide for TM polarization, as a function of wavelength.

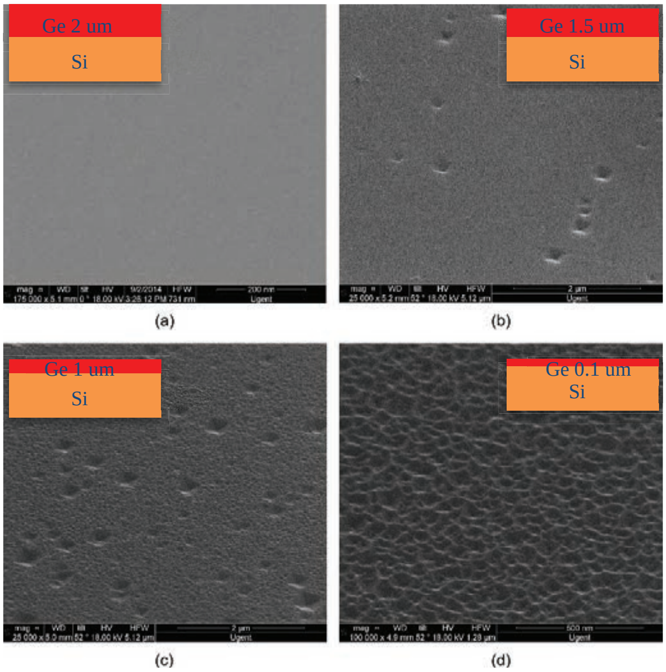


Fig. 6. Defects revealed in a 2 µm Ge film after etching in a CrO_3:HF solution. The film was dry etched in RIE for (a) 0 minutes, (b) 5 minutes, (c) 10 minutes and (d) 14 minutes.

4. Integrated Spectrometers for the mid-IR wavelength range

Wavelength filters are used in sensing applications in many configurations. One can either use the device as a wavelength demultiplexer or one can use it to combine different wavelengths together. In literature, two types of integrated spectrometers namely arrayed waveguide gratings (AWG) and planar concave gratings (PCG) are described. Both of them perform similar functions but have a different working principle. While an AWG is a transmitting device containing an array of waveguides which introduces a different phase delay for different wavelengths and hence causes separation of wavelengths, a PCG is a reflective device where wavelength selection and separation is done using gratings. Depending on the required free spectral range (FSR) and the number of channels, one can choose the appropriate device [8].

4.1. SOI spectrometers

AWGs and PCGs on the crystalline+poly SOI waveguide platform for the 3.8 µm range were designed and they showed low insertion loss (1.5 dB) and good cross talk levels (22 dB) [4] for TE polarized light. However it was found that as the resolution of the AWG is decreased, the cross talk level starts to increase as shown in Fig. 7. This happens because of the added phase noise for the high resolution (and therefore larger size) AWGs. In comparison, it was found that for the 400 nm crystalline SOI waveguide platform, the AWGs didn't suffer from the phase noise issues as shown in Fig. 8 which shows a 7 channel AWG in the 2.3 µm wavelength range with a resolution of 5 nm (300 GHz) and 1.4 nm (80 GHz).

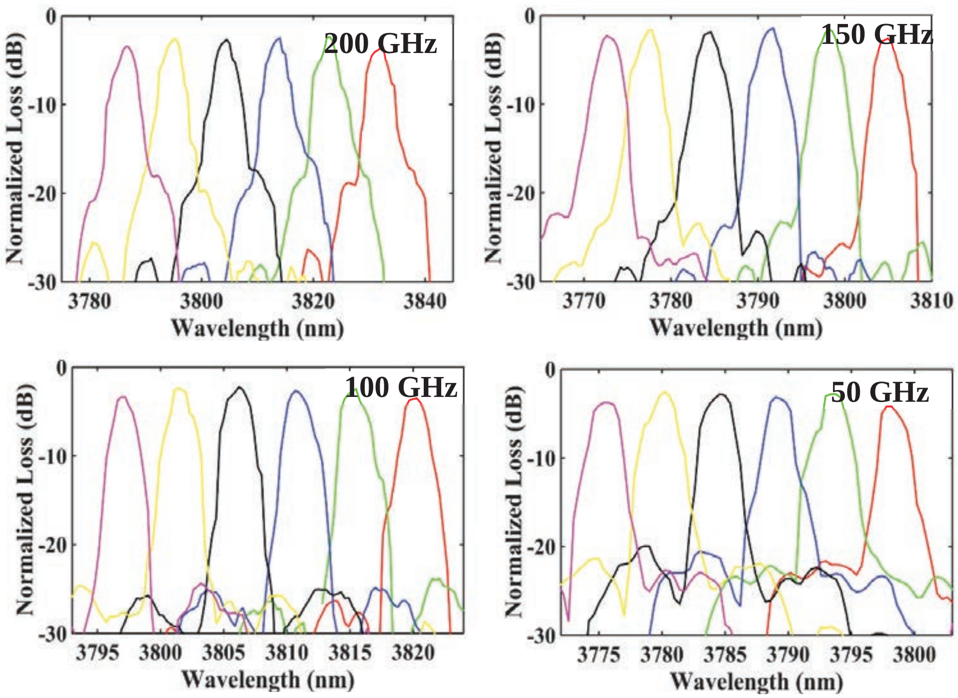
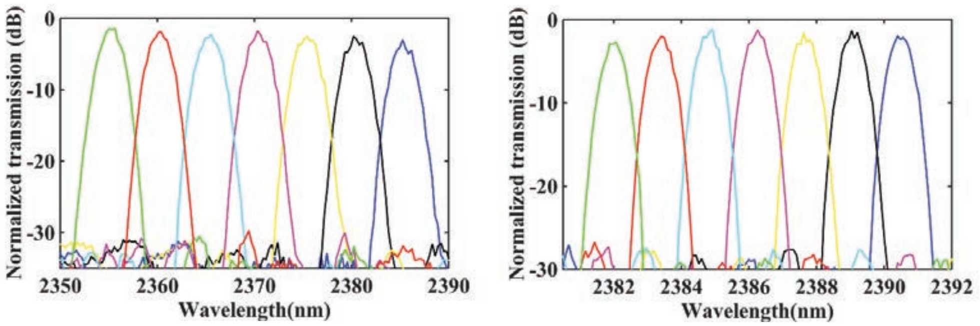


Fig. 7. Normalized transmission spectra of a six channel AWG fabricated in crystalline+poly silicon for different resolution. The cross talk level of the AWG degrades as the resolution in increased.



(a) (b)

Fig. 8. Normalized transmission spectra of a 7 channel AWG fabricated in 400 nm crystalline silicon for (a) 5 nm (300 GHz) channel spacing and (b) 1.4 nm (80 GHz) channel spacing. The cross talk levels stay below 20 dB for both the AWGs

4.2. Ge-on-Si spectrometers

For the Ge-on-Si waveguide platform, AWGs and PCGs were measured for both TE and TM polarized light and they showed low cross talk levels [5,9]. The insertion loss was found to be higher as compared to SOI spectrometers, as seen in Fig. 9. However it must be noted that these devices were fabricated with contact lithography which reduces the minimal feature size. For AWGs, the main source of insertion loss is the amount of light not coupled to the waveguide array and for PCGs, the main reason is the low reflection from the gratings. Both these issues can be addressed by using standard CMOS tools which allow narrower features to be defined.

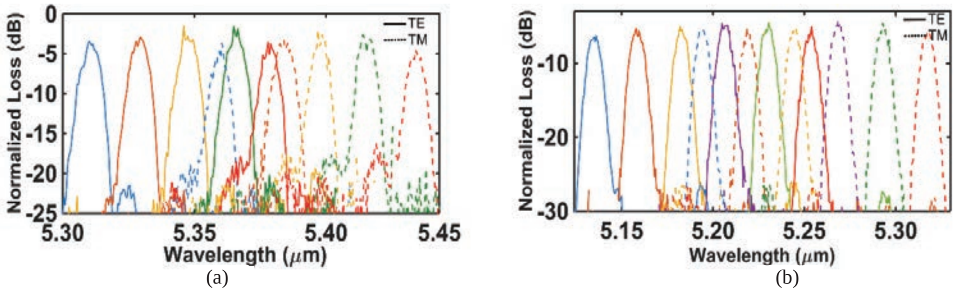


Fig. 9. Normalized transmission spectra of (a) 5 x 200 GHz Ge-on-Si AWG and (b) 6 channel PCG with 25 nm channel spacing. TE polarized spectrum is denoted by a solid line and TM polarized by a dashed line.

5. Thermo-optic phase shifter

Tuning of waveguide circuits is often needed to e.g. provide tunable feedback to a laser. One way of achieving fast tuning in waveguide circuits is by using free carriers introduced via doping. However these free carriers introduce additional losses which are higher at longer wavelengths. Another way of achieving tuning is to use the strong thermo-optic coefficient of silicon and germanium. For the SOI waveguide platform highly efficient thermo-optic phase shifters have been realized [10]. For Ge-on-Si realizing an efficient phase shifter is not straight forward as the generated heat is sunk in the thermally conducting silicon substrate. One requires 700 mW of power to achieve a 2π phase shift. This can be lowered to 80 mW by introducing an air path in the silicon substrate which is formed using FIB [11]. Another elegant way of solving this problem is to introduce an insulator such as SiO_2 in the substrate as shown in Fig. 10 (a). We fabricated Ge-on-SOI phase shifters and found that the required tuning power is 105 mW which can be lowered to 16 mW if the underneath oxide is removed as seen in Fig. 10(b) using wet etching as seen in Fig. 10(c). The increase in required tuning power beyond 280 µm free-standing heater length is attributed to a collapse of the heater to the substrate leading again to good heat sinking to the substrate.

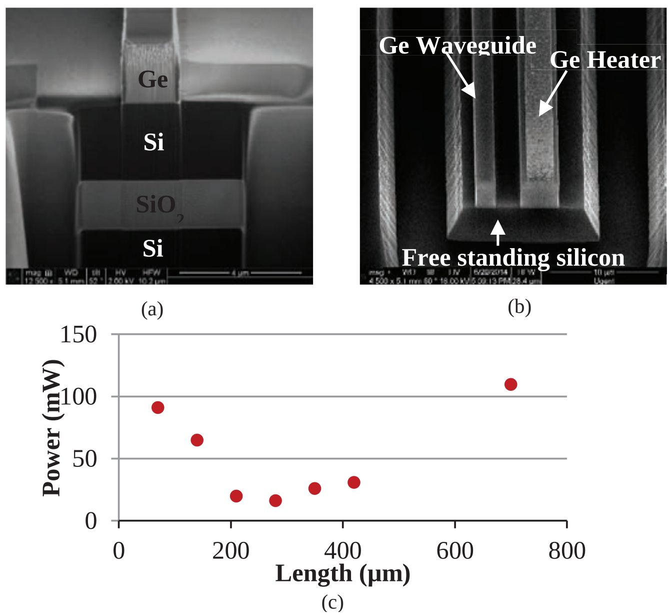
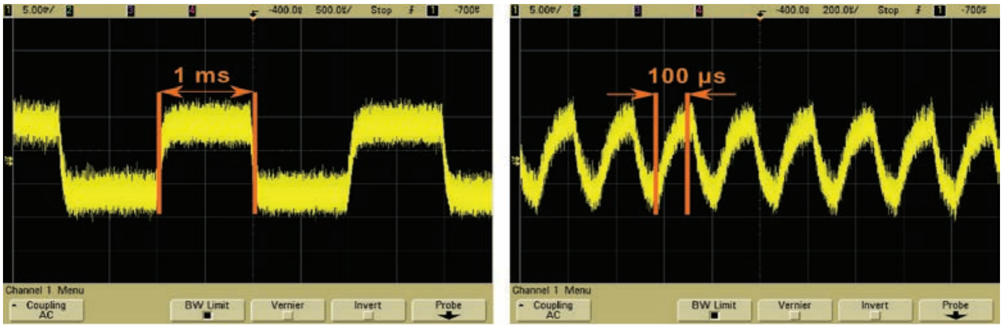


Fig. 10. SEM cross section of a Ge-on-SOI waveguide (a) without undercut and (b) with undercut and with a side heater. (c) Tuning power as a function of heater length

The waveguide losses for Ge-on-SOI waveguides were found to be in the range of 7-8 dB/cm in the 5 µm wavelength range. This is attributed to the higher number of defects present in the Ge film grown on SOI substrate as compared to that grown on Si substrate. We suspect that non-optimal annealing temperature could be the reason behind this. The AC response of the phase shifters was measured by using a pulsed current source. As seen in Fig. 11, the phase shifter can follow a slow current pulse of 1 ms but starts to lag behind when the current pulse width is decreased to 100 µs. The modulation bandwidth of the phase shifter was estimated to be ~16 KHz from these measurements.



(a) (b)

Fig. 11. AC response of a thermo-optic phase shifter when (a) 1 ms current pulse is applied and (b) 100 µs current pulse is applied. The modulation bandwidth of the phase shifters is determined to be ~16 KHz.

6. Conclusions

In conclusion, we have demonstrated low loss waveguides and high performance waveguide circuits based on SOI and Ge-on-Si for the mid-infrared wavelength range. Also, tunability of the germanium based waveguide circuits is demonstrated using thermo-optic phase shifters and the tuning efficiency is improved ~40 times by isolating the phase shifter. Future plans would include integration of these waveguide circuits with active devices such as quantum cascade lasers and interband cascade lasers to realize a compact and rugged mid-IR tunable source.

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