Ultra broadband mid-infrared Ge-on-Si polarization rotator

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The design and modelling of an ultra broadband Ge-on-Si waveguide polarization rotator is presented. The polarization rotator demonstrates high extinction ratio (≥ 18.5 dB) and low insertion loss (≤ 1 dB) over the full operating range of 8 to 11 µm wavelength.

Keywords—Mid-infrared, sensors, Ge-on-Si waveguides

I. INTRODUCTION

There is substantial interest in developing integrated photonic circuits for molecular sensing in the mid-infrared with potential applications in health-care, security and environmental monitoring [1-2]. The 8 to 14 µm atmospheric transmission window is particularly interesting as it is located within the 'fingerprint region' due to the ability to uniquely identify analytes from their optical absorption spectra [3]. The Ge-on-Si waveguide platform has long been proposed as the ideal candidate for this window since Ge is optically transparent up to ~ 15 µm. We recently demonstrated Ge-on-Si waveguides operating up to 11 µm wavelength with low propagation losses (~ 1 dB/cm) [4]. A single chip photonic sensor will require the integration of a source and detector with the passive Ge waveguides [5]. The most obvious candidate for the source is a quantum cascade laser (QCL). One drawback of a QCL is the inherent vertical polarization emitted that will only couple to TM waveguide modes. It has previously been shown that the TE fundamental mode provides lower propagation losses ≥ 9 µm wavelength for Ge-on-Si waveguides due to the reduced modal overlap with the Si substrate [4]. We present the design and modeling of an ultra-broadband Ge-on-Si waveguide polarization rotator operating between 8-11 µm wavelength that provides low insertion loss (≤ 1 dB) and high extinction ratio (≥ 18.5 dB) without requiring any additional fabrication steps.

II. GE-ON-SI MODE HYBRIDIZATION

The polarization rotator design is based on 2 µm thick Ge-on-Si waveguides with a partial 1 µm etch to form a rib structure [4]. Due to the asymmetry of the rib waveguide and large Δn of Ge-on-Si the supported modes are very birefringent (see Fig. 1 (top)). It is known from similar waveguide structures (SOI) that such conditions can lead to mode hybridization at specific waveguide widths [6]. A finite difference eigenmode solver (Lumerical) was used to model the effective index of the guided modes. Mode hybridization occurs at the width where there is a cross-over in effective index of the TM0 and TE1 modes (see Fig. 1 (Top)). The hybridization can be confirmed by calculating the TE polarization fraction of the modes. The TM0 and TE1 modes become fully hybridized when the TE fraction is 50 % and thus both modes are indistinguishable. What is particularly interesting is that for hybridization to occur between 8 to 11 µm wavelength only requires the width of the waveguide to change by ~ 0.5 µm (see Fig. 1 (Bottom)).

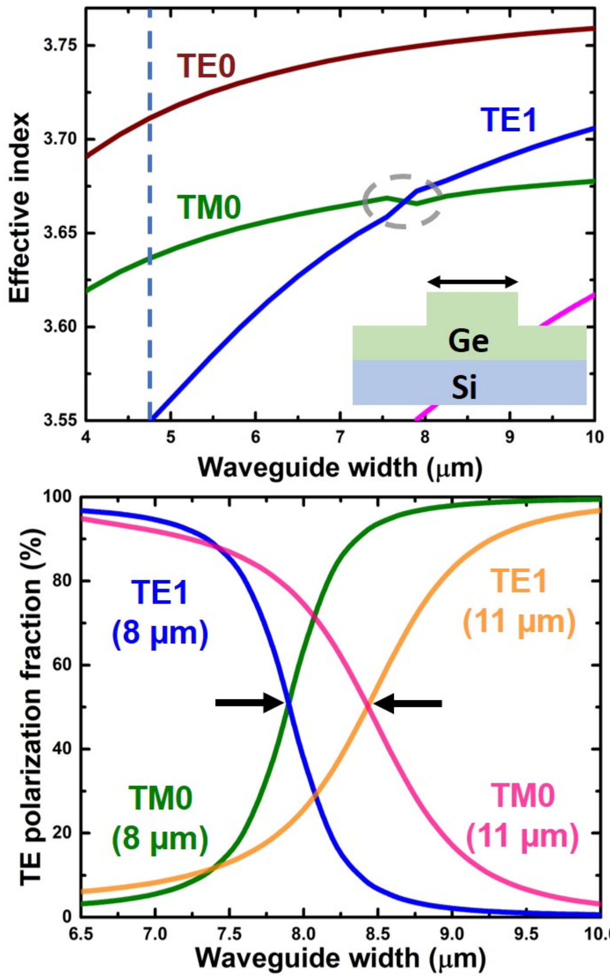

Fig. 1 (Top). The modelled effective index versus width for a Ge-on-Si rib waveguide with a 1 µm partial etch at 8 µm wavelength. (Below) The TE polarization fraction of the TM0 and TE1 mode versus width at 8 and 11 µm wavelength.

III. BROADBAND POLARIZATION ROTATOR

Since mode hybridization arises within the rib waveguide a simple approach can be taken based on mode evolution within an adiabatic taper to couple between the TM0 and TE1 modes. This approach tends to be more robust to fabrication tolerances and easier to implement compared to other rotator-based waveguide designs [6]. Importantly it also allows the polarization rotator to be patterned at the same stage as the waveguides and does not require any additional fabrication. An eigenmode expansion solver was used to model the TM0 to TE1 conversion efficiency for a change in linear taper length. Fig. 2 demonstrates that broadband mode conversion (≥ 99 %) for 8-11 µm wavelength can be achieved with a 2 mm long taper. It should be noted that this taper length could be reduced by at least an order of magnitude at the expense of operational bandwidth.

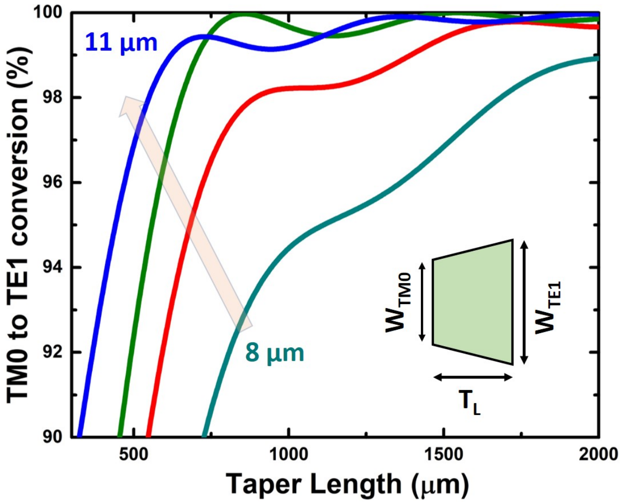

Fig. 2. The modeled TM0 to TE1 mode conversion efficiency for a Ge-on-Si rib waveguide that is linearly tapered from a waveguide width of 7.9 to 8.7 µm at different wavelengths (8, 9, 10 and 11µm).

IV. TE1 TO TE0 MODE CONVERTER

To convert from TE1 to TE0 the standard approach normally employed is based on using an asymmetric directional coupler to phase match between the two modes. Directional couplers, however, are inherently narrow-band and fabrication sensitive structures. To allow broadband conversion over the 8-11 µm wavelength range the TE1 to TE0 mode converters proposed by D.Chen et al were utilized [7]. This approach is based on using an asymmetric taper structure so that it provides the anti-phase components of the TE1 mode different effective path lengths so that both components become in-phase and a TE0 mode is generated at the output. This was designed by first optimizing for a structure that contained two asymmetric tapers, which subsequently then provided optimization parameter bounds for a more complex six asymmetric taper design. Optimization was performed using 2.5D FDTD and a particle swarm algorithm with the figure of merit the power overlap with the TE0 mode at the output. The overall polarization rotator design is thus the linear taper (TM0 to TE1) followed by an asymmetric taper structure (TE1 to TE0). Fig. 3 shows the modelled total insertion loss and extinction ratio for the full polarization rotation structure. The insertion loss is dominated by the TE1 to TE0 mode converter, which was optimized for the center wavelength of 9.5 µm. Therefore, at the extremes of the wavelength range it shows ~ 1 dB of insertion loss. The extinction ratio is dominated by the TM0 to TE1 conversion. A high extinction ratio (≥ 18.5 dB) is provided across the full wavelength range with it peaking at ~ 33 dB at 11 µm wavelength.

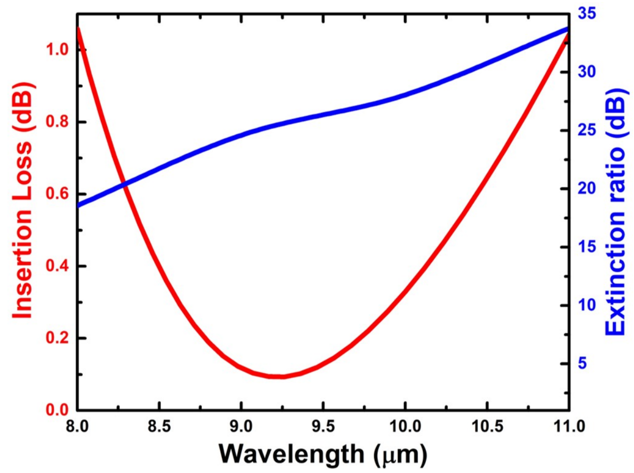

Fig. 3. The modelled insertion loss (left axis) and the extinction ratio (right axis) versus wavelength for the Ge-on-Si rib waveguide polarization rotator.

V. CONCLUSION

An ultra-broadband Ge-on-Si rib waveguide polarization rotator has been designed and modelled operating from 8 to 11 µm wavelength. The design based on symmetric and asymmetric tapers mode converts from TM0 to TE1 to finally TE0. This novel design demonstrates ≥ 18.5 dB extinction ratio and ≤ 1 dB insertion loss across the full range without requiring any additional fabrication steps.

VI. REFERENCES

[1] R. Soref, "Mid-infrared photonics in silicon and germanium" Nat. Photon. vol. 4, no. 8, pp. 495 - 497, 2010.
[2] L. Baldassarre et al. "Midinfrared plasmon-enhanced spectroscopy with Ge antennas on Si substrates" Nano Lett. vol. 15, no. 11, 2015.
[3] D.J. Paul et al. "n-Ge on Si for mid-infrared plasmonic sensors" 2017 IEEE Photonics Society Topical Meeting, pp. 125-126, 2017.
[4] K. Gallacher et al., "Low loss Ge-on-Si waveguides operating in the 8 – 14 µm atmospheric transmission window" Opt. Exp. vol. 26, no. 20, pp. 25667 - 25675, 2018.
[5] M.P. Fischer et al. "Plasmonic mid-infrared third harmonic generation in Ge nanoantennas" Light: Sci. & Appl. vol. 7, no. 1, 106, 2018.
[6] D. Dai, "Advanced Passive Silicon Photonic Devices With Asymmetric Waveguide Structures," in Proceedings of the IEEE, vol. 106, no. 12, pp. 2117-2143, 2018.
[7] Daigao Chen, Xi Xiao, Lei Wang, Yu Yu, Wen Liu, and Qi Yang, "Low-loss and fabrication tolerant silicon mode-order converters based on novel compact tapers," Opt. Express 23, 11152-11159 (2015).