A hybrid chalcogenide-on-silicon platform for nonlinear photonics

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ABSTRACT

We demonstrate a highly nonlinear hybrid waveguide platform based on infiltration of As$_2$S$_3$ chalcogenide glass into silicon slot waveguides. The nonlinear properties of the hybrid waveguides have been precisely quantified via a bidirectional top-hat D-scan method, enabling a direct comparison between properties measured using different device geometries. We experimentally report hybrid As$_2$S$_3$-Si slot waveguides with a two-photon absorption (TPA) figure of merit exceeding 2 at near infrared wavelengths. These waveguides allow for nonlinear phase shifts greater than π with minimal overall losses. These results pave the way for efficient and robust ultrafast all-optical devices and circuits in large-scale silicon photonics technology.

Keywords: nonlinear optics, chalcogenide glass, silicon photonics, waveguides.

1. INTRODUCTION

There has been a strong interest in silicon photonics in the last years due to its compatibility with the CMOS technology and its relatively low cost [1]. However, as a nonlinear optical signal processing platform silicon is disadvantaged by high nonlinear losses due to two photon absorption (TPA) at telecom wavelengths [2]. To overcome this limitation, TPA-free alternative platforms such as silicon nitride and high index silica (Hydex) have been explored [3]. But the nonlinear parameter ($\gamma_{eff}$) in these platforms is very low compared to silicon. Another route is the heterogeneous integration of SOI waveguides with a low nonlinear loss material such as a nonlinear polymer. In particular, slot geometries have been proposed where light is confined within a gap between semiconductor rails therefore taking advantage of the high permittivity contrast between Si and the lower index material filling the slot [4].

Here, we demonstrate experimentally complete filling of nano-slots in silicon waveguides with As$_2$S$_3$ glass using a simple thermal reflow process. We also validate enhancement of third order nonlinearities and nonlinear figure of merit in these hybrid slot waveguides using a bidirectional D-Scan measurement method [5], showing the possibility of engineering effective nonlinearities in complex hybrid photonic circuits. Besides, we show experimentally that it is possible to have different effective non-linearities by changing the slot sizes. Our results illustrate the potential for the development of dispersion engineered slotted structures for efficient ultra-fast all-optical nonlinear photonics in chip-scale platforms.

2. SIMULATION RESULTS

To investigate the impact of hybrid waveguide design on the nonlinear parameters, we calculated and plot in Fig. 1 the confinement factor in the As$_2$S$_3$ cladding (left axis) and the inverse of the effective mode area (right axis), which is proportional to the effective third order nonlinear susceptibility ($\gamma_{eff}$) as defined in Ref. [6]. These simulations serve as a guideline for investigating realistic slot width values for nonlinear applications.

![Fig. 1. Simulated modal confinement factor (left axis) and inverse of the effective mode area (right axis) of hybrid As$_2$S$_3$-Si slot waveguides as a function of slot width. Insets: TE- polarized modal profile.](image-url)
3. SAMPLE FABRICATION

The devices were fabricated on SOI wafers (Soitec) with a 220 nm-thick silicon layer over 2 μm of buried SiO₂. Device structures (slots) were defined in ZEP-520A resist (Zeon Chemical Co.) by 80 kV e-beam lithography Nanobeam NB-4 system. The writing fields were set to 50 × 50 μm² for a beam current of 0.5 nA and a beam step size of 2 nm. The resist patterns were then transferred to the Si layer by an inductively coupled plasma (ICP) reactive ion etching process using SF₆ and C₂F₄ gases. Following this, thin films of As₂S₃ were prepared using single-source thermal evaporation. The film deposition was performed using a custom-designed system (PVD Products, Inc.) following previously established protocols [7]. The devices were then annealed for 1 min at 250°C in an inert gas atmosphere. The annealing step reduced viscosity of As₂S₃ at elevated temperatures to facilitate the viscous flow of the glass. Since As₂S₃ wets Si waveguide surfaces, the glass could spontaneously fill the slots completely without leaving voids or other loss-inducing defects [8]. Fig. 2 (a) shows a SEM injection coupler 3 μm wide separated by 3 μm etched silicon in both sides covered with 1 μm As₂S₃ layer. Fig. 2 (b) is a slot waveguide, with squared silicon rails of 220 nm, fully covered with the chalcogenide material, the slot width of 70 nm is the smaller than the one used in this study, demonstrating the ability to fill larger slot widths.

4. EXPERIMENTAL SET-UP

For the experimental characterization of the nonlinear effective susceptibilities, we have used a bidirectional top-hat D-Scan technique [5]. This allowed the measurement of the coupling coefficients, as well as the direct quantification of the sign and magnitude of the real and imaginary third order nonlinear susceptibilities. More details about the technique and the used set-up, shown in Fig. 3, will be presented during the conference.

![Experimental set-up](image)

Fig. 3. Experimental set-up where femtosecond pulses of an Er-doped amplifier fiber laser are sent into a grating-based pulse shaper prior to their injection into the sample by means of a microscope objective [9].

5. RESULTS AND DISCUSSION

We present in Fig. 4 (a) the magnitude of the effective third order nonlinear susceptibilities in the hybrid structures. For larger slots, the real γ is smaller but the imaginary part decreases faster as the confinement in the slot regions is larger. Ending up in a larger TPA figure of merit. After performing the different scan measurements on the different hybrid waveguides, we demonstrated this trend experimentally (Fig 4 (b)). Compared to silicon (gray bar), the hybrid slot waveguides exhibit a fourfold improvement in terms of the FOMTPA. More importantly, the observed trends show that FOMTPA of all the slot waveguides measured are larger than unity (violet-colored-dashed line in Fig. 4 (b)). These devices thus meet a critical criterion for efficient nonlinear integrated photonics. Specifically, the power required to reach a π phase shift for the fabricated device with a 160 nm slot width and a 0.73 mm effective length is on the order of 45 W, the power levels already used in the past with the same chalcogenide glass composition[10]. Moreover, the slot waveguide configuration further enables precise tailoring of the dispersion characteristics and enhancement of light–matter interactions with slow light.
Fig. 4. (a) Real and imaginary susceptibilities as a function of the slot width. Inset: Confinement factor inside the slot. (b) Simulation and experimental TPA figure of merit for the three different characterized waveguides. The milestone of FOM_{TPA}=1 is highlighted [11].

TABLE 1. DIFFERENT EXPERIMENTALLY STUDIED PARAMETERS IN HYBRID SLOT WAVEGUIDES.

<table>
<thead>
<tr>
<th>Slot size [nm]</th>
<th>Prop. L_{eff} [mm]</th>
<th>L_{slot} [mm]</th>
<th>Re(\gamma_{slot}) [W^{-1} m^{-1}]</th>
<th>FOM_{TPA}^\text{pg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>–</td>
<td>–</td>
<td>159 ± 16</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>110 ± 10</td>
<td>1.65</td>
<td>1.37</td>
<td>120 ± 20</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>140 ± 10</td>
<td>0.45</td>
<td>0.42</td>
<td>105 ± 18</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td>160 ± 10</td>
<td>0.85</td>
<td>0.73</td>
<td>95 ± 15</td>
<td>2.1 ± 0.7</td>
</tr>
</tbody>
</table>

*Slot width=0 nm is given as a reference and corresponds to a single mode strip waveguide covered with chalcogenide.

6. CONCLUSION

In conclusion, we demonstrated the improvement of non-linear properties in hybrid silicon slot waveguides filled with As_{2}S_{3} chalcogenide glass. We have shown that the slot width is a critical design parameter that governs the linear propagation losses, the confinement factor in the slot region, and the figure of merit FOM_{TPA}. We further conclude that larger slot widths are beneficial as they combine lower linear propagation losses and a larger FOM_{TPA}, although they require longer structures as the effective area is larger. Our result opens new opportunities for engineering effective nonlinearities in integrated photonic devices and is useful for realizing novel nonlinear functionalities such as stimulated Brillouin scattering (SBS) [12] and the Kerr effect induced spectral broadening in a silicon-based platform.

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REFERENCES