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Mid-IR linear optical properties of hybrid Sb₂S₃/SiGe waveguides

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Abstract — Chip-based broadband Mid-IR sources, like a supercontinuum generated in integrated waveguides, are of great interest for applications such as free space communication or gas detection. Different applications may require sources with different characteristics. Reconfigurable sources are thus needed to meet the requirements of a given application. The combination of group IV photonics and phase-change materials like Sb₂S₃ is a promising approach for their realization. Here, we study the impact of Sb₂S₃ deposition on SiGe waveguide linear propagation loss. We experimentally demonstrate that Sb₂S₃ induces relatively low extra loss in the mid-IR, below 1 dB/cm between 3.3 and 3.9 μm wavelength.

Keyword—Mid-infrared, supercontinuum, phase-change materials, antimony trisulfide, integrated photonics

I. INTRODUCTION

Mid-infrared (covering the wavelength range from 3 to 13 μm) spectroscopy finds various applications in technological fields such as environmental monitoring or food quality analysis[1]. Developing a chip-based and CMOS-compatible mid-IR broadband light source is of great interest. An extensively studied approach, combining excellent optical properties and potential scalability, appears to be the use of group-IV photonics. Air-cladded Si_{0.6}Ge_{0.4} waveguide on Si substrate was used to demonstrate supercontinuum generation across more than one octave (from 3 up to 8.5 μm)[2]. Nonetheless, the spectral characteristics of the generated supercontinuum strongly depend (in terms of bandwidth, flatness, and coherence) on the waveguide dispersion profile[3] since supercontinuum generation is driven primarily by soliton fission in the anomalous dispersion regime or by self-phase modulation and optical wave breaking in the normal dispersion regime[4]. Depending on the potential application, one or the other may be more desirable. However, in most of the existing devices, the waveguide dispersion profile is set at the moment of fabrication and cannot be modified *a posteriori*.

An attractive solution for controlling the dispersion characteristics on-demand, and thus for reconfigurable supercontinuum generation, is the use of PCMs, that can be switched thermally, optically, or electronically between amorphous and crystalline phases. The different phases are characterized by different optical properties (such as

complex refractive index, see Fig. 1)[5-6] and thus allow to control the waveguide dispersion. For this purpose, a material exhibiting significant refractive index contrast between the phases and high transparency in the mid-IR band is required. Antimony trisulfide – Sb₂S₃ has proven to be an attractive candidate in the near-IR due to its stable switching endurance and very low losses in the near-IR[7].

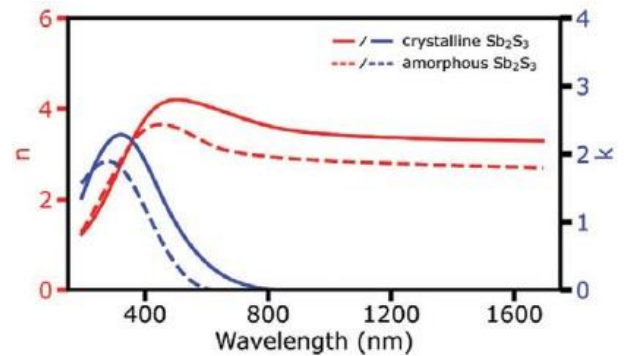


Fig. 1. Complex refractive index of Sb₂S₃ in both amorphous (dashed) and crystalline (solid) phases. Source: [7].

In this paper, we study the suitability in the mid-IR (between 3 and 4 μm) of Sb₂S₃ for reconfigurable SiGe-on-Si waveguides by experimental linear propagation losses measurements in Sb₂S₃-coated SiGe-on-Si waveguides.

II. WAVEGUIDE DESIGN

The main objective of our design is to achieve all-normal dispersion regime for the crystalline Sb₂S₃ phase and a relatively flat anomalous regime, centred around a pump wavelength of 4.0 μm, for the amorphous phase. This will allow us in the future to reconfigure our supercontinuum source by simply switching the phase of Sb₂S₃. To this end, we designed a 3.00 μm × 3.20 μm cross-section SiGe-on-Si waveguide. For the given geometry, the waveguide is single-mode beyond 3.6 μm with a fundamental TE mode. Furthermore, the small waveguide cross-section leads to small mode effective area (6.29 μm² at 4 μm wavelength), which is beneficial for nonlinear applications.

III. DEVICE FABRICATION

The photonic chip was fabricated at CEA-Leti, Grenoble, France using standard epitaxy and lithography processes. First, the SiGe layer was epitaxially grown on top of the Si substrate and encapsulated by 550 nm thick Si layers. The waveguides were then patterned using deep ultraviolet photolithography followed by a deep reactive ion etching process. More details about the fabrication procedure are included in Ref. [2].

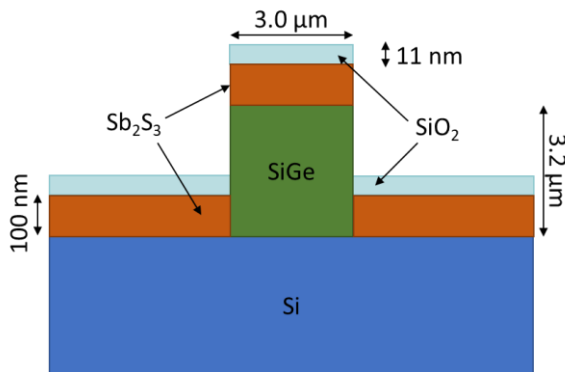


Fig. 2. Schematic view of the fabricated PCM-cladded waveguide.

Afterwards, the chip was processed in the INL clean-room facility. A 100 nm thick amorphous Sb_2S_3 (a- Sb_2S_3) layer was deposited by electron-beam physical vapor deposition preceded by image reversal UV lithography. Eventually, to avoid its degradation, the PCM was covered with a 11 nm SiO_2 capping layer, see Fig. 2.

The crystallisation process (c- Sb_2S_3) was carried out using a hot plate. Temperature was varying from 27°C up to 280°C with a rate of 10°/min and the sample was heated for a total time of 60 min. Change of the phase was subsequently confirmed by ellipsometry measurements.

IV. EXPERIMENTAL RESULTS

For measuring the linear propagation losses, we used a tunable pulsed OPA laser source (MIROPA-fs, Hotlight Systems) with a repetition rate of 63 MHz. The laser wavelength varied from 3.3 to 3.9 μm with ~ 200 fs pulse duration and TE polarization. To evaluate the propagation losses, we measured the transmission on three waveguides with different length (4.2, 6.2, and 8.2 cm) and geometry described in Section II, under relatively low average power (~ 1 mW). At each wavelength, the losses were calculated as the slope of the linear fit to the decimal logarithm of the output voltage signal, measured with a Thorlabs PDA20H-EC photodetector. Measurements were performed for air-, a- Sb_2S_3 - and c- Sb_2S_3 -cladded waveguides. The results are presented in Fig. 3.

The outcomes show that the deposition of a 100 nm amorphous Sb_2S_3 layer brings negligible additional propagation losses compared to the air-clad SiGe waveguide. What is of paramount importance is the fact that its crystallisation introduces less than a dB/cm extra loss, which is still compatible with efficient supercontinuum generation.

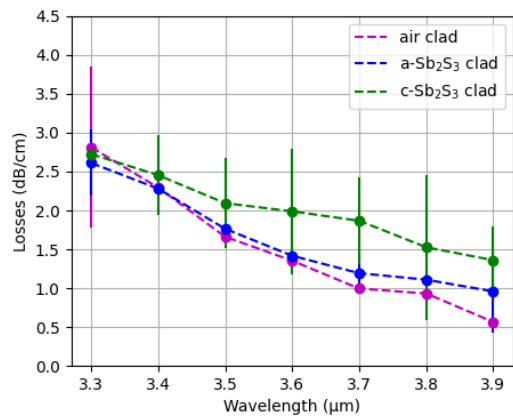


Fig. 3. Measured linear propagation losses in air- and Sb_2S_3 -cladded waveguides.

V. CONCLUSIONS AND PERSPECTIVES

We measured mid-IR linear propagation losses in waveguides with air-clad and Sb_2S_3 -clad in both amorphous and crystalline phases. Our results show that Sb_2S_3 induces negligible loss in the amorphous state and relatively low extra loss in the mid-IR in the crystalline phase ($< \text{dB/cm}$). Our preliminary results show that Sb_2S_3 is a highly promising PCM for reconfigurable mid-IR supercontinuum sources.

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REFERENCES

- [1] T. Hu *et al.*, 'Silicon photonic platforms for mid-infrared applications [Invited]', *Photonics Res.*, vol. 5, no. 5, p. 417, Oct. 2017, doi: 10.1364/PRJ.5.000417.
- [2] M. Sinobad *et al.*, 'Mid-infrared octave spanning supercontinuum generation to 85 μm in silicon-germanium waveguides', *Optica*, vol. 5, no. 4, p. 360, Apr. 2018, doi: 10.1364/OPTICA.5.000360.
- [3] M. Sinobad *et al.*, 'Mid-infrared supercontinuum generation in silicon-germanium all-normal dispersion waveguides', *Opt. Lett.*, vol. 45, no. 18, p. 5008, Sep. 2020, doi: 10.1364/OL.402159.
- [4] M. Sinobad *et al.*, 'Dispersion trimming for mid-infrared supercontinuum generation in a hybrid chalcogenide/silicon-germanium waveguide', *J. Opt. Soc. Am. B*, vol. 36, no. 2, p. A98, Feb. 2019, doi: 10.1364/JOSAB.36.000A98.
- [5] Y. Zhang *et al.*, 'Broadband transparent optical phase change materials for high-performance nonvolatile photonics', *Nat. Commun.*, vol. 10, no. 1, p. 4279, Sep. 2019, doi: 10.1038/s41467-019-12196-4.
- [6] Y. Zhang *et al.*, 'Electrically reconfigurable non-volatile metasurface using low-loss optical phase-change material', *Nat. Nanotechnol.*, vol. 16, no. 6, pp. 661–666, Jun. 2021, doi: 10.1038/s41565-021-00881-9.
- [7] M. Delaney, I. Zeimpekis, D. Lawson, D. W. Hewak, and O. L. Muskens, 'A New Family of Ultralow Loss Reversible Phase-Change Materials for Photonic Integrated Circuits: Sb_2S_3 and Sb_2Se_3 ', *Adv. Funct. Mater.*, vol. 30, no. 36, p. 2002447, Sep. 2020, doi: 10.1002/adfm.202002447.

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KRÓTKIE STRESZCZENIE

Liniowe właściwości optyczne hybrydowych falowodów $\text{Sb}_2\text{S}_3/\text{SiGe}$ w zakresie średniej podczerwieni

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Zintegrowane szerokopasmowe źródła światła na zakres średniej podczerwieni cieszą się dużym zainteresowaniem w zastosowaniach takich jak komunikacja w wolnej przestrzeni lub spektroskopia. Konieczność uzyskania różnych właściwości spektralnych dla różnych aplikacji prowadzi do potrzeby pracy nad przestrajalnym źródłem. Jego realizacja może być osiągnięta dzięki wykorzystaniu półprzewodników grupy IV wraz z materiałami zmiennofazowymi (PCM), takimi jak siarczek antymonu – Sb_2S_3 . W niniejszej pracy zaprojektowano hybrydowy falowód $\text{Sb}_2\text{S}_3/\text{SiGe}$ i eksperymentalnie wykazano wzrost jego tłumienności spowodowany dodatkowym pokryciem na poziomie poniżej 1 dB/cm dla fal z zakresu od 3,3 do 3,9 μm .

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ABSTRACT

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