Bright on-chip mid-IR supercontinuum generation to 7.7 μ m in silicon germanium-on-silicon platform

Milan Sinobad^{1, 2,*}, Alberto Della Torre¹, Barry Luther-Davies³, Pan Ma³, Stephen Madden³, David J. Moss⁴, Arnan Mitchell², Regis Orobtcchouk¹, Salim Boutami⁵, Jean-Michel Hartmann⁵, Jean-Marc Fedeli⁵, Christelle Monat¹, Christian Grillet¹

¹ Université de Lyon, Institut des Nanotechnologies de Lyon (INL), 69131 Ecully, France

² CUDOS and School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

³ CUDOS, Laser Physics Centre, Australian National University, Canberra, ACT 0100, Australia

⁴ Centre for Microphotonics, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

⁵ CEA-Leti, MINATEC Campus, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France

Author e-mail address: milan.sinobad@student.rmit.edu.au

Abstract: We report mid-IR supercontinuum generation, from 2.9 to 7.7 μ m, in a CMOS compatible silicon-germanium waveguide. This 1.3 octave bright supercontinuum has been achieved in a low loss dispersion engineered air-clad Si_{0.6}Ge_{0.4}/Si waveguide.

OCIS codes: (320.6629) Supercontinuum generation; (190.4390) Nonlinear optics, Integrated optics; (140.3070) Infrared and far-infrared lasers.

1. Introduction

The generation in a CMOS compatible platform of a spectrally bright supercontinuum covering the mid-wavelength infrared band (MWIR – at 3 – 8 μ m) is a technological challenge that is promising to have a strong impact on molecular detection, as most chemical and biological compounds exhibit strong and unique absorption features in this spectral region [1]. The miniaturization of broadband octave-spanning sources (SCG) in the mid-IR has been already demonstrated on a chalcogenide chip [2]. Yet, these materials do not allow exploiting the advantages of the CMOS fabrication technologies in terms of reliability, mass manufacturing and cost. On the other hand, a mid-IR supercontinuum generation in group IV materials based platforms remains challenging. Although supercontinuum generation has been demonstrated in CMOS compatible platforms like silicon nitride-on-insulator [3, 4], silicon-on-insulator [5, 6], silicon-germanium-on-insulator [7] and silicon-on sapphire [8], these sources are limited to 3.5 μ m and 6 μ m, due to the absorption in the silica and sapphire substrates, respectively. By taking advantage of the wider transparency window of the silicon substrate, the recently proposed silicon germanium-on-silicon platform is promising to overcome these limitations [9-11], potentially extending the spectral region of integrated sources at least up to 8 μ m [12].

2. Waveguide design and experiments

We just reported the generation of an octave spanning supercontinuum from 3 to 8.5 μ m in TE polarization in a silicon germanium-on-silicon waveguide [11]. Here, we demonstrate the generation of 1.3 octave spanning supercontinuum in the MWIR from 2.9 to 7.7 μ m in TM polarization, with a useful on-chip average power greater than 7mW by pumping dispersion engineered silicon germanium-on-silicon waveguide [9, 10]. Our waveguide consists of a 4.2 μ m thick and 4.5 μ m wide Si_{0.6}Ge_{0.4} ridge with a top air cladding that seats on a silicon substrate (see inset Fig. 1a). The air clad design with a large SiGe cross-section (effective area of $\sim 10.5\mu\text{m}^2$) results in low anomalous dispersion across a large bandwidth (see figure 1a), a cut-off wavelength of 8.2 μ m, a strong mode confinement in the waveguide core material (>98 % at 4.15 μ m) and a reduction of the contribution from surface roughness to the propagation loss.

Waveguide propagation losses were measured to be between 0.3 and 0.4dB/cm in the 4 – 5 μ m wavelength range with the minimum value being 0.32dB/cm at 5 μ m.

Supercontinuum was then achieved by pumping the waveguide with ~ 200 fs pulses delivered from a mid-infrared MIROPA-fs optical parametric amplifier at a repetition rate of 63MHz. Using a 7cm long waveguide pumped at 4.15 μ m close to the first zero-dispersion wavelength, we obtained the spectra shown in Fig. 1b for average coupled powers increasing from ~ 1 mW to 21mW. At 21.1mW coupled average power (~ 3 kW coupled peak power), we measured a supercontinuum spanning 1.3 octaves, from 2.9 to 7.7 μ m at the -30 dB level was achieved. Besides, the output spectrum is relatively smooth with a large -10dB bandwidth from 3.0 – 7.4 μ m.

Figure 1 a) Calculated group velocity dispersion (GVD) and confinement of the mode field in the waveguide core (dashed lines), black arrow indicate pump wavelength, blue arrow indicates the cut-off wavelength, schematic of an air clad SiGe waveguide as an insert, b) Output spectra measured at different average coupled power. Coupled average power is calculated assuming 4.5dB coupling loss.

3. Conclusion

In summary, we report supercontinuum generation in TM polarization from a silicon germanium-on-silicon platform covering almost the whole mid-wavelength infrared, where most molecules in atmosphere have relevant fingerprints. The generated on-chip supercontinuum MWIR power and bandwidth exceed that produced so far by other Si-based platforms that are intrinsically limited by the silica or sapphire substrate absorption. This establishes silicon germanium-on-silicon as a promising platform for integrated nonlinear photonics in MWIR, with the potential to extend the operating range beyond 8 μm .

Acknowledgments: Agence Nationale de la Recherche (ANR) MIRSiCOMB (ANR-17-CE24-0028), H2020 EU framework, Marie Skłodowska Curie Action MSCA grant (PCIGA-2013-631543), European ERC grant GRAPHICS (648546); The Australian Research Council (ARC), Discovery Projects Program (DP150104327). We acknowledge the support of the International Associated Laboratory in Photonics between France and Australia (LIA ALPhFA), CM acknowledges the support of the Institut Universitaire de France.

4. References

- [1] L. Zhang, A. M. Agarwal, L. C. Kimmerling, and J. Michel, "Nonlinear group IV photonics based on silicon and germanium: from near-infrared to mid-infrared," *Nanophotonics*, vol. 3, pp. 247-268, 2014.
- [2] Y. Yu, X. Gai, P. Ma, K. Vu, Z. Yang, R. Wang, *et al.*, "Experimental demonstration of linearly polarized 2-10 μm supercontinuum generation in a chalcogenide rib waveguide," *Opt Lett*, vol. 41, pp. 958-61, Mar 01 2016.
- [3] J. M. Chavez Boggio, D. Bodenmüller, T. Fremberg, R. Haynes, M. M. Roth, R. Eisermann, *et al.*, "Dispersion engineered silicon nitride waveguides by geometrical and refractive-index optimization," *JOSA B*, vol. 31, pp. 2846-2857, 2014.
- [4] A. R. Johnson, A. S. Mayer, A. Klenner, K. Luke, E. S. Lamb, M. R. Lamont, *et al.*, "Octave-spanning coherent supercontinuum generation in a silicon nitride waveguide," *Opt Lett*, vol. 40, pp. 5117-20, Nov 01 2015.
- [5] B. Kuyken, X. Liu, R. M. Osgood, Jr., R. Baets, G. Roelkens, and W. M. Green, "Mid-infrared to telecom-band supercontinuum generation in highly nonlinear silicon-on-insulator wire waveguides," *Opt Express*, vol. 19, pp. 20172-81, Oct 10 2011.
- [6] R. K. W. Lau, M. R. E. Lamont, A. G. Griffith, Y. Okawachi, M. Lipson, and A. L. Gaeta, "Octave-spanning mid-infrared supercontinuum generation in silicon nanowaveguides," *Optics letters*, vol. 39, pp. 4518-4521, 2014.
- [7] M. A. Ettabib, L. Xu, A. Bogris, A. Kapsalis, M. Belal, E. Lorent, *et al.*, "Broadband telecom to mid-infrared supercontinuum generation in a dispersion-engineered silicon germanium waveguide," *Optics letters*, vol. 40, pp. 4118-4121, 2015.
- [8] N. Singh, D. D. Hudson, Y. Yu, C. Grillet, S. D. Jackson, A. Casas-Bedoya, *et al.*, "Midinfrared supercontinuum generation from 2 to 6 μm in a silicon nanowire," *Optica*, vol. 2, pp. 797-802, 2015.
- [9] L. Carletti, P. Ma, Y. Yu, B. Luther-Davies, D. Hudson, C. Monat, *et al.*, "Nonlinear optical response of low loss silicon germanium waveguides in the mid-infrared," *Opt Express*, vol. 23, pp. 8261-71, Apr 06 2015.
- [10] L. Carletti, M. Sinobad, P. Ma, Y. Yu, D. Allieux, R. Orobtchouk, *et al.*, "Mid-infrared nonlinear optical response of Si-Ge waveguides with ultra-short optical pulses," *Opt Express*, vol. 23, pp. 32202-14, Dec 14 2015.
- [11] M. Sinobad, C. Monat, B. Luther-Davis, P. Ma, S. Madden, D. J. Moss, *et al.*, "Mid-infrared octave spanning supercontinuum generation to 8.5 μm in silicon-germanium waveguides," *Optica*, vol. 5, 2018.
- [12] J. M. Ramirez, V. Vakarín, C. Gilles, J. Frigerio, A. Ballabio, P. Chaisakul, *et al.*, "Low-loss Ge-rich Si_{0.2}Ge_{0.8} waveguides for mid-infrared photonics," *Opt Lett*, vol. 42, pp. 105-108, Jan 01 2017.