



EUROPEAN CONFERENCE ON INTEGRATED OPTICS

Mid-infrared integrated photonics in silicon and germanium

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Mid-infrared (MIR) silicon and germanium photonic devices and systems could be useful in a range of applications [1]. Silicon and germanium are transparent in the MIR, have large refractive indices and are dominant materials in microelectronics. Germanium is particularly interesting photonic material that has larger transparency range, refractive index, optical modulation, non-linear effects and carrier mobility compared to silicon. As such, both Si and Ge devices can be very compact (Fig. 1).

We have demonstrated a range of MIR devices and integrated circuits in Si, such as low loss passive devices, large bandwidth detectors, on-chip Fourier-transform spectrometers, and optical modulators [2-7]. For waveguides longer than 4 μm , a suspended Si platform can be used [8,9].

Recently, we have focused our work on the Ge-on-Si platform and have demonstrated low loss waveguides and other passive devices [10], couplers [11], cascaded ring resonators [12] fast all-optical modulation [13,14], modulators and sensors [15]. We have reached wavelengths up to $\sim 9 \mu\text{m}$ and our future work will address the extension of the spectral range for Ge-based platforms and further reduction of the loss.

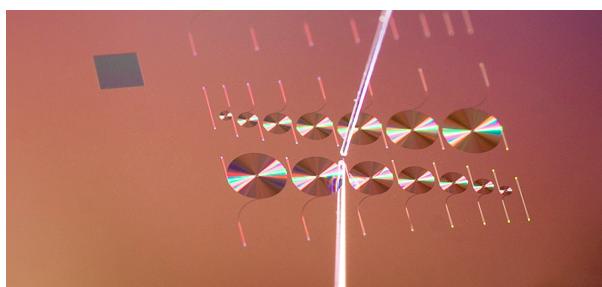


Fig. 1. Mid-infrared light coupling from an optical fibre to long spiral waveguides (up to 40cm in length)

References

- [1] R. Soref, "Mid-infrared photonics in silicon and germanium," *Nat Photon*, vol. 4, pp. 495-497, 2010.
- [2] M. Nedeljkovic, A. Z. Khokhar, Y. Hu, X. Chen, J. Soler Penades, S. Stankovic, D. J. Thomson, F. Y. Gardes, H. M. H. Chong, G. T. Reed, and G. Z. Mashanovich, "Silicon photonic devices and platforms for the mid-infrared" *Opt. Mat. Express*, vol. 3, pp. 1205-1214, 2013.
- [3] J. Soler Penades, A. Z. Khokhar, M. Nedeljkovic, and G. Z. Mashanovich, "Low loss mid-infrared SOI slot waveguides," *IEEE Photon. Technol. Lett.*, vol. 27, pp. 1197-1199, 2015.
- [4] G. Z. Mashanovich, F. Y. Gardes, D. J. Thomson, Y. Hu, K. Li, M. Nedeljkovic, J. Soler Penades, A. Z. Khokhar, C. J. Mitchell, S. Stankovic, R. Topley, S. A. Reynolds, Y. Wang, B. Troia, V. M. N. Passaro, C. G. Littlejohns, T. Dominguez Bucio, P. R. Wilson, and G. T. Reed, "Silicon photonic waveguides and devices for near- and mid-IR applications," *J. Sel. Top. Quantum Electron.*, vol. 21, 8200112, 2015.
- [5] B. Troia, A. Z. Khokhar, M. Nedeljkovic, J. Soler Penades, V. M. N. Passaro, and G. Z. Mashanovich, "Cascade-coupled racetrack resonators based on the Vernier effect in mid-infrared," *Opt. Express*, vol. 22, pp. 23990-24003, 2014.
- [6] M. Nedeljkovic, S. Stanković, C. Mitchell, A. Z. Khokhar, S. Reynolds, D. J. Thomson, F. Y. Gardes, C. Littlejohns, G. T. Reed, and G. Z. Mashanovich, "Mid-infrared thermo-optic modulators in SOI," *IEEE Photon. Technol. Lett.*, vol. 26, pp. 1352-1355, 2014.
- [7] Y. Hu, T. Li, D. J. Thomson, X. Chen, J. Soler Penades, A. Z. Khokhar, C. J. Mitchell, G. T. Reed, and G. Z. Mashanovich, "Wavelength division (de)multiplexing in mid-infrared wavelength range using interleaved angled multimode interferometer on the silicon-on-insulator platform," *Opt. Lett.*, vol. 39, pp. 1406-1409, 2014.
- [8] J. Soler Penades, A. Ortega-Moñux, M. Nedeljkovic, J. G. Wangüemert-Pérez, R. Halir, A.Z. Khokhar, C. Alonso-Ramos, Z. Qu, I. Molina-Fernández, P. Cheben and G. Z. Mashanovich, "Suspended silicon mid-infrared waveguide devices with subwavelength grating metamaterial cladding," *Optics Express*, vol. 24, pp. 22908-22916, 2016.
- [9] J. Soler Penades, C. Alonso-Ramos, A. Z. Khokhar, M. Nedeljkovic, L. A. Boodhoo, A. Ortega-Monux, I. Molina-Fernandez, P. Cheben, and G. Z. Mashanovich, "Suspended SOI waveguide with sub-wavelength grating cladding for mid-infrared," *Opt. Lett.*, vol. 39, pp. 5661-5664, 2014.
- [10] M. Nedeljkovic, J. Soler Penades, C. J. Mitchell, T. Dominquez Bucio, A. Z. Khokhar, C. Littlejohns, F. Y. Gardes, and G. Z. Mashanovich, "Surface grating coupled low loss Ge-on-Si rib waveguides and multimode interferometers," *IEEE Photon. Technol. Lett.*, vol. 27, pp. 1040-1043, 2015.
- [11] C. Alonso-Ramos, M. Nedeljkovic, D. Benedikovic, J. Soler Penadés, C. Littlejohns, D. Pérez-Galacho, L. Vivien, P. Cheben, and G. Z. Mashanovich, "Germanium-on-silicon mid-infrared grating couplers with low-reflectivity inverse taper excitation," *Opt. Lett.*, vol. 41, pp. 4324-4327, 2016.
- [12] B. Troia, J. Soler Penades, A. K. Khokhar, M. Nedeljkovic, C. Alonso-Ramos, V. M. N. Passaro, and G. Z. Mashanovich, "Germanium-on-silicon Vernier-effect photonic microcavities for the mid-infrared," *Opt. Lett.*, vol. 41, pp. 610-613, 2016.
- [13] L. Shen, N. Healy, C. J. Mitchell, J. Soler Penades, M. Nedeljkovic, G. Z. Mashanovich, and A. C. Peacock, "Mid-infrared all-optical modulation in low loss germanium-on-silicon waveguides," *Opt. Lett.*, vol. 40, pp. 268-271, 2015.
- [14] L. Shen, N. Healy, C. J. Mitchell, J. Solar Penades, M. Nedeljkovic, G. Z. Mashanovich, and A. C. Peacock, "Two-photon absorption and all-optical modulation in germanium-on-silicon waveguides for the mid-infrared," *Opt. Lett.*, vol. 40, pp. 2213-2216, 2015.
- [15] G. Z. Mashanovich, C. J. Mitchell, A. Z. Khokhar, C. G. Littlejohns, J. Soler Penades, W. Cao, Z. Qu, L. Shen, N. Healy, A. C. Peacock, F. Y. Gardes, V. Mittal, G. Senthil Murugan, J. S. Wilkinson and M. Nedeljkovic, "Germanium mid-infrared photonic devices," *J. Lightwave Technol.* (in press)