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# Mid-Infrared Integrated Silicon-Germanium Ring Resonator with High Q-Factor

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We report the realization of a silicon-germanium on silicon ring resonator with high Q-factor at mid-infrared wavelengths. The fabricated ring exhibits a loaded Q-factor of 236,000 at the operating wavelength of  $4.18 \mu\text{m}$ . Considering the combined waveguide propagation losses and bending losses, which are measured to be below 0.2 dB/cm, even higher Q-factors could be achieved on this platform. Furthermore, our dispersion engineering of the waveguides should make these microrings suitable for nonlinear optical applications. These results pave the way for sensing applications and nonlinear optics in the mid-infrared.

## I. INTRODUCTION

The mid-infrared (MIR) wavelength range (between 3 and  $15 \mu\text{m}$ ) is attractive for sensing applications, as many molecules have strong fundamental absorption lines in this spectral region. Applications that benefit from this spectral range include environmental monitoring, defense & security, health care and industrial process monitoring.<sup>1</sup> However, so far the high cost and large size of MIR devices have slowed down the widespread use of this promising technology. Leveraging progress in group-IV photonic integrated circuits<sup>2</sup> and efforts made to integrate MIR components on chips with reduced cost, power consumption and size, should enable the large scale deployment of MIR technologies.

High quality factor ring (and racetrack) resonators are expected to play a crucial role in on-chip integrated sensing schemes. Firstly, they could be used to generate optical frequency combs<sup>3</sup>, and thus broadband MIR light sources for sensing devices, or they could serve as the basis for dual comb spectroscopy.<sup>4</sup> Secondly, rings can also be directly used to enhance the interaction between light and the analyte molecules surrounding the ring.<sup>5</sup> Whether it be via detecting some changes in the resonance wavelength or linewidth, most of the sensing schemes exploiting microring resonators require a high quality factor (Q-factor) to improve the sensitivity and detection limit of the sensor.<sup>6,7</sup>

High Q-factors in ring resonators have already been demonstrated in the SWIR (Short Wavelength InfraRed range, below  $3.5 \mu\text{m}$ ) in the silicon on insulator (SOI)<sup>8</sup> and the silicon nitride on insulator (SiNOI)<sup>9</sup> platforms with intrinsic Q-factors reaching respectively  $1.1 \times 10^6$  at  $3.8 \mu\text{m}$  and  $10^6$  at  $2.6 \mu\text{m}$ ,

and even in the MIR in silicon on sapphire (SOS)<sup>10</sup> reaching a loaded Q of 151,000 at  $4.4 \mu\text{m}$ . While the SOI, SiNOI and SOS platforms are very interesting for SWIR and low MIR wavelengths, they suffer from high intrinsic losses due to absorption caused by the lower cladding material beyond  $\sim 3.5 \mu\text{m}$  and  $\sim 6.5 \mu\text{m}$ , respectively.<sup>1</sup> Approaches using suspended Si rings<sup>11</sup> and III-V photonics<sup>12</sup> have not yet managed to solve this issue either. Material platforms that have low optical losses across a broad range of the MIR spectrum are thus desired to leverage the full potential of this technology.

In this context, silicon germanium (SiGe) and germanium (Ge) are promising materials, thanks to their CMOS compatibility and transparency window that extends up to  $15 \mu\text{m}$ .<sup>1,13,14</sup> Low-loss SiGe waveguides operating in the MIR have been demonstrated<sup>14,15</sup> and their nonlinear properties were used for supercontinuum generation up to  $8.5 \mu\text{m}$  in SiGe and  $13 \mu\text{m}$  in graded-index SiGe.<sup>16–18</sup> In pure Ge waveguides, supercontinuum generation was achieved up to  $6 \mu\text{m}$ .<sup>19</sup> So far, however, only a few SiGe and Ge ring resonator demonstrations have been reported in the MIR, with moderate loaded Q-factors between 1700 and 20,000 (see Table I for details).<sup>20–23</sup> Very recently, high-Q resonators on Ge have been reported with an intrinsic Q = 250,000 at  $7.8 \mu\text{m}$  wavelength.<sup>24</sup> However, this was achieved using Ge disks on glass pillars, hence hindering the prospects for a full integration within a circuit, as desired for applications.

Here, we report the experimental demonstration of a high Q SiGe ring resonator with a loaded Q-factor of 236,000 at  $4.18 \mu\text{m}$  wavelength. Additionally, our measurements on serpentine waveguides show that bending losses become “negligible” beyond  $250 \mu\text{m}$  radius, indicating that intrinsic Q-factors of microrings on this platform could be as high as 1,170,000. Such high Q resonators achieved in a platform that has a very large transparency window (potentially up to  $15 \mu\text{m}$ ) should allow us to leverage the full potential of the MIR for applica-

<sup>a)</sup>R. Armand and M. Perestjuk contributed equally to this work

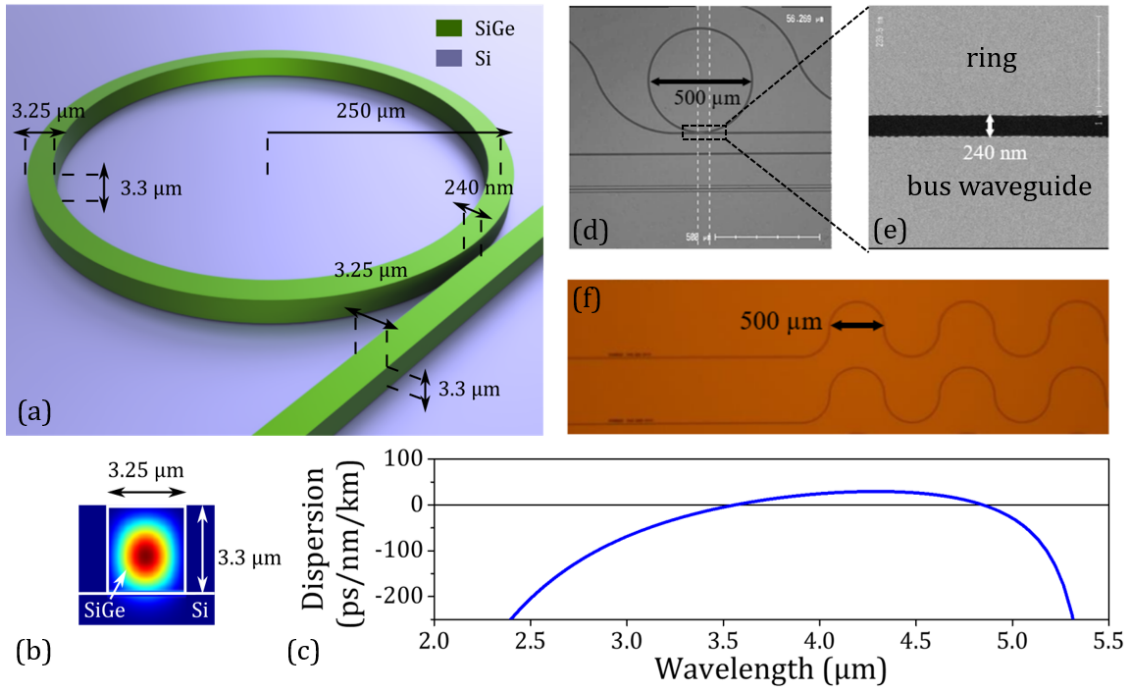


FIG. 1. (a) Ring resonator with dimensions, evanescently coupled to a bus waveguide on the SiGe platform. Air-cladded waveguides of  $\text{Si}_{0.6}\text{Ge}_{0.4}$  ( $n = 3.57$  at  $\lambda = 4.18 \mu\text{m}$ ) on a Si substrate ( $n = 3.42$ ) are used. (b) Mode profile of TE0. (c) Dispersion parameter  $D$  as a function of wavelength  $\lambda$  for the chosen waveguide dimensions (single mode). A broad region of anomalous dispersion ( $D > 0$ ) from  $\lambda = 3.5 \mu\text{m}$  to  $4.8 \mu\text{m}$  is obtained. (d) SEM picture of the fabricated ring. (e) SEM picture of the gap between ring and bus waveguide. (f) Optical microscope picture of fabricated serpentine waveguides for determining bending losses.

tions such as sensing and optical frequency comb generation.

## II. RING RESONATOR DESIGN AND FABRICATION

Our platform consists of an air-cladded  $\text{Si}_{0.6}\text{Ge}_{0.4}$  core waveguide on a Si substrate (Fig.1a). Our intended wavelength of operation is  $4.18 \mu\text{m}$ . Besides the relevance for sensing applications around this wavelength, for example for carbon dioxide<sup>25</sup>, this spectral band was shown to be a sweet spot in terms of SiGe nonlinear properties.<sup>17</sup> To determine the optical properties at this wavelength, especially the refractive indices, ellipsometry measurements were performed. The refractive index of the transparent SiGe layer at  $4.18 \mu\text{m}$  was  $n = 3.57$  and for the Si substrate  $n = 3.42$ . Utilizing these values, we used the finite difference eigenmode (FDE) solver of Lumerical<sup>26</sup> to analyze the modal behavior and calculate the dispersion of the waveguides (including the material dispersion  $n(\lambda)$ ). An example for a mode profile (electric field intensity) of the fundamental mode in transverse-electric (TE) polarization is shown in Fig.1b.

As our long-term objective is the demonstration of MIR micro combs, single mode operation and anomalous dispersion of the waveguides, close to zero dispersion, is preferable<sup>27,28</sup>, ideally in a small cross-section waveguide to boost nonlinear effects. Cross-section waveguide dimensions of  $w = 3.25 \mu\text{m}$  and  $h = 3.3 \mu\text{m}$  lead to the group velocity dispersion profile ( $D$  as a function of wavelength) for the TE0 mode plotted in

Fig.1c, with a broad anomalous regime between  $3.5 \mu\text{m}$  and  $4.8 \mu\text{m}$  wavelength, and single mode operation.

The ring radius was targeted to be as small as possible to reduce both the device footprint and, eventually, the threshold powers for nonlinear processes, while still being large enough not to be significantly impacted by bending losses. An  $R = 250 \mu\text{m}$  value was obtained, corresponding to a free spectral range (FSR) of 53 GHz. Bending losses are expected to be below 0.05 dB/cm from mode solver simulations. A straight bus waveguide was designed to side couple light to the ring resonator (see Fig.1a) with a coupling gap of 240 nm, the smallest gap achievable by deep-UV lithography. We probed our resonators using free-space butt-coupling to the bus waveguide and due to our sufficiently large mode diameter, mode adaptors on the end-facets were not necessary. A summary of all design parameters is provided in Fig.1a.

The ring resonators were fabricated on a 200 mm CMOS pilot line at CEA-Leti. The  $3.3 \mu\text{m}$  thick  $\text{Si}_{0.6}\text{Ge}_{0.4}$  layer was grown by epitaxy on a Si substrate. The choice of a 40% Ge concentration resulted in an alloy with a wide transparency window, high nonlinearity and low propagation loss because of a limited number of misfit dislocations. Deep ultraviolet lithography was then used to pattern the waveguides followed by deep reactive ion etching. More details on the fabrication can be found in the supplementary information of Ref.16. Additionally, the etching process was optimized for fabricating the small  $0.24 \mu\text{m}$  gap. This was needed to meet the difficulties in fabricating large aspect ratio structures<sup>29</sup>, in this

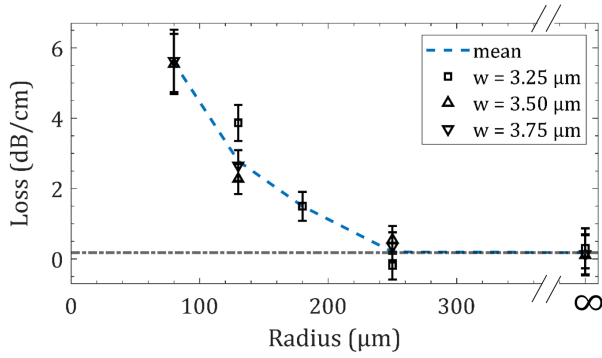


FIG. 2. Loss measurement in TE polarization for SiGe waveguides as a function of bending radius at  $3.9 \mu\text{m}$  wavelength. The total loss includes bending loss and propagation loss. For radii larger than  $250 \mu\text{m}$  there is no additional bending loss: indicated by the black dashed line, the loss in the bends then becomes equal to the propagation loss measured for a straight waveguide, i.e. with  $R = \infty$ . The measurement is shown for different waveguide widths. As no clear trend for a dependence on the width was observed in this case, the blue dashed line shows the mean across the three widths.

case  $3.3 \mu\text{m} / 0.24 \mu\text{m} \approx 14$ . Beside the rings, some serpentine waveguides (waveguides with a large number of subsequent bends) were also fabricated to determine bending losses (Fig.1f). Scanning electron microscope (SEM) pictures of a fabricated ring are shown in Fig.1d and Fig.1e. As shown in Fig.1d, the gap was reliably obtained.

### III. LOSS AND RESONANCE MEASUREMENT

Before characterizing the ring resonator, the bending loss was measured to estimate the achievable intrinsic quality factor and to validate the choice of bending radius. To characterize the losses, we used a tunable optical parametric amplifier (OPA) pulsed laser source (MIROPA-fs, Hotlight Systems) with 5 mW input power, set at  $3.9 \mu\text{m}$ . The power was chosen low enough to stay in the linear loss regime and not be influenced by the three and four photon absorption present in SiGe at this wavelength.<sup>17</sup> The bending loss was determined by measuring the transmission in TE polarization through waveguides with a large number of subsequent bends (serpentine waveguides) and different bending radii (68-212 bends depending on the radius, adding around 1 cm of length) and comparing this to a 2.2 cm long straight reference waveguide. The total loss (propagation + bending loss) measured on the serpentine waveguides for increasing bend radii is shown in Fig.2 for a waveguide width of  $3.25 \mu\text{m}$ . We repeated this study for slightly larger waveguide widths ( $3.50 \mu\text{m}$  and  $3.75 \mu\text{m}$ ), but did not observe any clear effect on the bending loss, showing that the mode was well confined for these waveguide widths. For  $R = 250 \mu\text{m}$ , the loss is around 0.2 dB/cm. In fact, for this radius the loss contribution caused by the bends becomes negligible as the propagation loss for serpentine waveguides with  $R = 250 \mu\text{m}$  and the straight waveguide ( $R = \infty$ ) are indistinguishable within the measurement accu-

racy, which is consistent with our simulated bending loss estimation. These measurements are also in line with our previous demonstration of low propagation loss in the range of 0.1-0.4 dB/cm in straight SiGe waveguides for similar waveguide dimensions and wavelengths.<sup>30</sup> The loss  $\alpha$  and the intrinsic Q-factor  $Q_{in}$  are related through  $Q_{in} = (10/\ln 10) \cdot (2\pi n/\alpha\lambda)$ . Using this, the measured loss of 0.2 dB/cm indicates that an intrinsic Q-factor  $Q_{in} = 1,170,000$  should be achievable for the ring resonator.

Next, we characterized the ring resonators and measured their Q-factor. Fig.3a shows the measurement setup. The ring resonance characterization was performed using a narrowlinewidth continuous wave Adtech distributed feedback quantum cascade laser (QCL) with a small tuning range around  $4.18 \mu\text{m}$ . The out-coupled light was recorded by either a PbSe photodetector or a Thorlabs Fourier transform infrared (FTIR) optical spectrum analyzer. The emission wavelength of the QCL was wavelength modulated between 4177.27 nm and 4177.89 nm by applying a periodic triangular current modulation, which, as a side effect, also resulted in a power modulation of roughly  $\pm 50\%$ . The time-average optical pump power was set at around 20 mW (measured directly before the input coupling lens), which is well below the onset of nonlinear losses as  $4.18 \mu\text{m}$  is beyond the three photon absorption cutoff and four photon absorption is negligible.<sup>17</sup>

Fig.3b shows one period of the triangular wavelength modulation recorded by the FTIR. The triangular power modulation was subtracted (raw data shown in supplementary Fig.1). Over the whole wavelength range, there are pronounced Fabry-Perot resonances with a FSR of around 17 pm. These are caused by reflections at the chip end-facets that are 2.2 cm apart. Superimposed on these fringes, the ring resonance can be clearly distinguished: it manifests as an additional dip occurring twice, during the wavelength ramp up and ramp down, respectively. Fig.3c shows the ring resonance after applying a Fourier filtering to filter out the Fabry-Perot fringes. Some low-amplitude oscillations are visible as remainders of the Fabry-Perot resonances. No significant difference is observed between blue and red detuning, indicating that there are no thermal effects.

It can be seen that the resonance exhibits a Fano line shape that was fitted with the Fano line shape function:<sup>31</sup>

$$\sigma(E) = \Delta^2 \frac{(q + \Omega)^2}{1 + \Omega^2} \quad (1)$$

where  $E = hc/\lambda$  is the energy,  $\sigma(E)$  the spectrum,  $q = \cot(\delta)$  the Fano parameter,  $\delta$  the phase shift between the coupled states,  $\Delta = 4 \sin^2(\delta)$  and  $\Omega = 2(E - E_0)/\Gamma$ , where  $\Gamma$  is the resonance width and  $E_0$  is the resonance energy. Taking  $E_0$ ,  $\Gamma$  and  $\delta$  as free parameters, the measurement of Fig.3c was well fitted with this equation (red line) using the following values:  $\Gamma = 18.7 \text{ pm}$ ,  $\delta = 0.37\pi$ ,  $q = 0.64$ ,  $\Delta = 1.7$ . The value for  $\Gamma$  corresponds to a loaded Q-factor of  $236,000 \pm 25,000$ , where the uncertainty was estimated through averaging over 10 measurements of the same resonance. The physical origin of this Fano shape requires further investigation. The  $q$  value indicates a mixed state between a Fano shape ( $q = 1$ ) and a quasi-Lorentz shape ( $q = 0$ ).

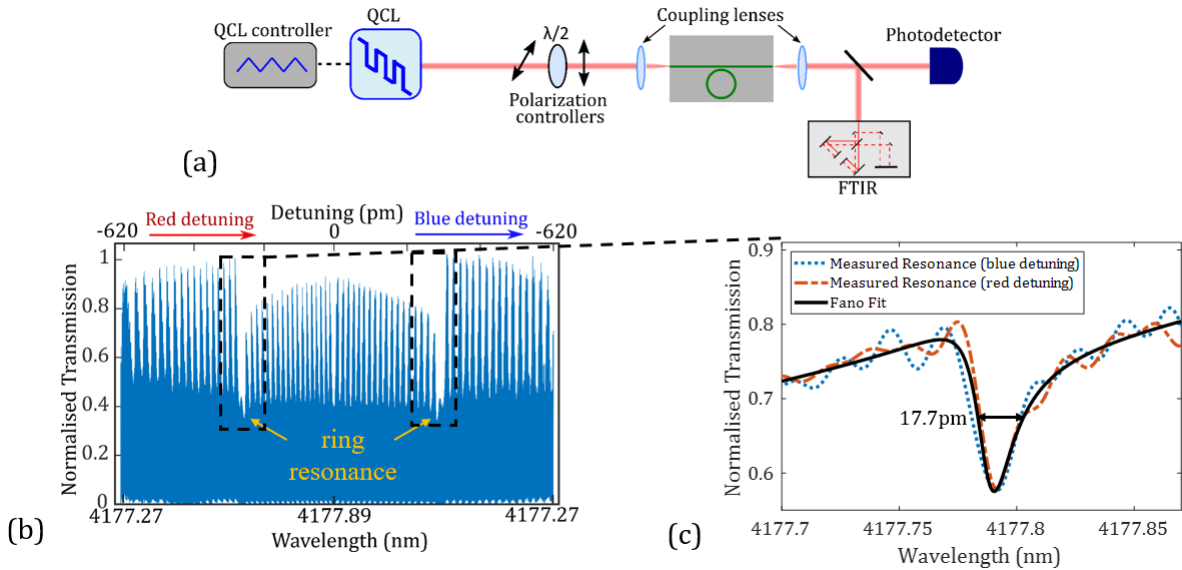


FIG. 3. (a) Experimental setup for Q-factor measurement. The light source is a quantum cascade laser (QCL) tunable around a wavelength of  $4.18 \mu\text{m}$ . A controller is used to apply a current modulation to modulate the wavelength. Polarizers and waveplates are used for polarization and input power control. MIR coupling lenses are used to butt couple the light in and out the waveguide. The output is recorded either by a photodetector or an FTIR. (b) Measurement of the ring resonance by FTIR. Wavelength scan with the QCL through the resonance (ramp up and ramp down). The ring resonance at one specific wavelength can be clearly distinguished from the Fabry-Perot resonances, which occur due to waveguide facets at input and output coupling. (c) Zoom-in on the ring resonance. A Fourier-filtering is applied to remove Fabry-Perot resonances. Due to the Fano shape of the resonance, a Fano function is fitted to it, resulting in a width of  $17.7 \text{ pm}$  corresponding to  $Q = 236,000$ .

It can also be seen from Fig.3b measurements that the resonance does not reach the noise floor and instead we have a transmission around 50% at resonance. This means that we are not at critical coupling ( $Q_{in} = Q_{ext}$ , where  $Q_{ext}$  is the external or coupling quality factor), and that the intrinsic quality factor of the ring ( $Q_{in}$ ) is actually larger than the measured loaded Q-factor ( $1/Q_{loaded} = 1/Q_{in} + 1/Q_{ext}$ ). A detailed discussion on the coupling regime can be found in Sec. II of the supplementary material.

This result represents a Q-factor improvement by more than one order of magnitude among Ge-based integrated microcavities, as can be seen from Table I. Our rings could thus be readily used for a range of sensing applications. This result is still a factor 3.4 smaller than the current record in the MIR across all integrated platforms, held by SOI with a loaded Q around  $800,000^8$  (derived value from data provided in reference). However, the measured loss is almost identical so the difference in Q-factor is likely because we are further away from critical coupling. Moreover, our demonstration was obtained at slightly longer wavelength ( $4.18 \mu\text{m}$  against  $3.8 \mu\text{m}$  in Ref.8). Most importantly, our Ge-based microresonators should also work deeper into the MIR, as the SiGe core waveguide is transparent up to  $15 \mu\text{m}$  while record-holding SOI cavities have increasing losses for wavelengths beyond  $3.5 \mu\text{m}$ . Our operation at  $4.18 \mu\text{m}$  wavelength was indeed only limited here by the wavelength of our laser and these results should be thus easily extendable to longer wavelengths. According to our propagation loss measurements on this platform<sup>30</sup>, we know that reducing the losses by another

factor of 2 should be possible for the exact same material platform by optimizing the ring design (for example by choosing a lower loss wider waveguide and compensating for the decrease in coupling by Pulley or racetrack coupling schemes). This was also confirmed with our bending loss measurements, with possibly intrinsic Q-factors of  $10^6$  in a future fabrication run.

#### IV. CONCLUSION

To conclude, we have reported a SiGe ring resonator operating around  $4.18 \mu\text{m}$ , with a loaded Q-factor of 236,000. This is the highest Q-factor achieved on this material platform and among the highest achieved around this wavelength range on a CMOS-compatible platform in general. Considering the demonstrated potential of the SiGe material platform, these rings should exhibit similarly high Q-factors at longer wavelengths, deeper in the MIR. Measured losses in bent waveguides as low as  $0.2 \text{ dB/cm}$  for  $250 \mu\text{m}$  bend radii show that even higher Q-factors should be achievable on this material platform. These results set the basis for various sensing applications in the MIR spectral range. We also target further improvements of the Q-factor to be able to achieve threshold powers low enough for experimentally demonstrating nonlinear processes. This would be another milestone at these wavelengths.

TABLE I. Experimentally demonstrated loaded Q-factors of integrated ring and racetrack resonators on Ge-based group IV photonics platforms in the MIR.

Ref.	Platform	Integrated	Wavelength ( $\mu\text{m}$ )	Perimeter (mm)	Q-factor
20	Ge-on-Si	yes	3.8	0.44	1,700
21	graded-index SiGe	yes	7.7 - 8.6	1.97	3,200
22	Ge-on-Si	yes	8.1 - 11.0	3.54	10,000
23	Ge-on-SOI	yes	5.3	0.66	20,000
24	Ge	no	7.8	1.41	224,000
This work	SiGe-on-Si	yes	4.18	1.57	236,000

## SUPPLEMENTARY MATERIAL

See the supplementary material for the raw FTIR scan and the discussion on the coupling regime.

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- <sup>1</sup>R. Soref, "Mid-infrared photonics in silicon and germanium," *Nature photonics* **4**, 495–497 (2010).
- <sup>2</sup>D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Viro, J.-M. Fédéli, J.-M. Hartmann, J. H. Schmid, D.-X. Xu, F. Boeuf, P. O'Brien, G. Z. Mashanovich, and M. Nedeljkovic, "Roadmap on silicon photonics," *Journal of Optics* **18** (2016).
- <sup>3</sup>A. G. Griffith, R. K. Lau, J. Cardenas, Y. Okawachi, A. Mohanty, R. Fain, Y. H. Lee, M. Yu, C. T. Phare, C. B. Poitras, A. L. Gaeta, and M. Lipson, "Silicon-chip mid-infrared frequency comb generation," *Nat Commun* **6**, 6299 (2015).
- <sup>4</sup>M. Yu, Y. Okawachi, A. G. Griffith, N. Picque, M. Lipson, and A. L. Gaeta, "Silicon-chip-based mid-infrared dual-comb spectroscopy," *Nat Commun* **9**, 1869 (2018).
- <sup>5</sup>P. Ma, D. Y. Choi, Y. Yu, Z. Yang, K. Vu, T. Nguyen, A. Mitchell, B. Luther-Davies, and S. Madden, "High q factor chalcogenide ring resonators for cavity-enhanced mir spectroscopic sensing," *Opt Express* **23**, 19969–79 (2015).
- <sup>6</sup>Y. Sun and X. Fan, "Optical ring resonators for biochemical and chemical sensing," *Anal Bioanal Chem* **399**, 205–11 (2011).
- <sup>7</sup>C. J. Smith, R. Shankar, M. Laderer, M. B. Frish, M. Loncar, and M. G. Allen, "Sensing nitrous oxide with qcl-coupled silicon-on-sapphire ring resonators," *Opt Express* **23**, 5491–9 (2015).
- <sup>8</sup>S. A. Miller, M. Yu, X. Ji, A. G. Griffith, J. Cardenas, A. L. Gaeta, and M. Lipson, "Low-loss silicon platform for broadband mid-infrared photonics," *Optica* **4** (2017).
- <sup>9</sup>K. Luke, Y. Okawachi, M. R. Lamont, A. L. Gaeta, and M. Lipson, "Broadband mid-infrared frequency comb generation in a si(3)n(4) microresonator," *Opt Lett* **40**, 4823–6 (2015).
- <sup>10</sup>R. Shankar, I. Bulu, and M. Loncar, "Integrated high-quality factor silicon-on-sapphire ring resonators for the mid-infrared," *Applied Physics Letters* **102**, 051108 (2013).
- <sup>11</sup>Y. Zou, S. Chakravarty, C.-J. Chung, X. Xu, and R. T. Chen, "Mid-infrared silicon photonic waveguides and devices [invited]," *Photonics Research* **6** (2018).
- <sup>12</sup>J. Haas, P. Artmann, and B. Mizaikoff, "Mid-infrared gaas/algaas micro-ring resonators characterized via thermal tuning," *RSC Adv* **9**, 8594–8599 (2019).
- <sup>13</sup>L. Zhang, A. M. Agarwal, L. C. Kimerling, and J. Michel, "Nonlinear group iv photonics based on silicon and germanium: from near-infrared to mid-infrared," *Nanophotonics* **3**, 247–268 (2014).
- <sup>14</sup>J. M. Ramirez, Q. Liu, V. Vakarín, J. Frigerio, A. Ballabio, X. Le Roux, D. Bouville, L. Vivien, G. Isella, and D. Marris-Morini, "Graded size waveguides with broadband low-loss propagation in the mid infrared," *Optics Express* **26** (2018).
- <sup>15</sup>L. Carletti, P. Ma, Y. Yu, B. Luther-Davies, D. Hudson, C. Monat, R. Orobtcouk, S. Madden, D. J. Moss, M. Brun, S. Ortiz, P. Labeye, S. Nicoletti, and C. Grillet, "Nonlinear optical response of low loss silicon germanium waveguides in the mid-infrared," *Opt Express* **23**, 8261–71 (2015).
- <sup>16</sup>M. Sinobad, C. Monat, B. Luther-davies, P. Ma, S. Madden, D. J. Moss, A. Mitchell, D. Allieux, R. Orobtcouk, S. Boutami, J.-M. Hartmann, J.-M. Fedeli, and C. Grillet, "Mid-infrared octave spanning supercontinuum generation to 85  $\mu\text{m}$  in silicon-germanium waveguides," *Optica* **5** (2018).
- <sup>17</sup>M. Sinobad, A. DellaTorre, R. Armand, B. Luther-Davies, P. Ma, S. Madden, A. Mitchell, D. J. Moss, J. M. Hartmann, J. M. Fedeli, C. Monat, and C. Grillet, "Mid-infrared supercontinuum generation in silicon-germanium all-normal dispersion waveguides," *Opt Lett* **45**, 5008–5011 (2020).
- <sup>18</sup>M. Montesinos-Ballester, C. Lafforgue, J. Frigerio, A. Ballabio, V. Vakarín, Q. Liu, J. M. Ramirez, X. L. Roux, D. Bouville, A. Barzaghi, C. Alonso-Ramos, L. Vivien, G. Isella, and D. Marris-Morini, "On-chip mid-infrared supercontinuum generation from 3 to 13  $\mu\text{m}$  wavelength," *ACS Photonics* **7**, 3423–3429 (2020).
- <sup>19</sup>A. Della Torre, M. Sinobad, R. Armand, B. Luther-Davies, P. Ma, S. Madden, A. Mitchell, D. J. Moss, J.-M. Hartmann, V. Reboud, J.-M. Fedeli, C. Monat, and C. Grillet, "Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide," *APL Photonics* **6** (2021).
- <sup>20</sup>B. Troia, J. S. Penades, A. Z. Khokhar, M. Nedeljkovic, C. Alonso-Ramos, V. M. Passaro, and G. Z. Mashanovich, "Germanium-on-silicon vernier-effect photonic microcavities for the mid-infrared," *Opt Lett* **41**, 610–3 (2016).
- <sup>21</sup>J. M. Ramirez, Q. Liu, V. Vakarín, X. Le Roux, J. Frigerio, A. Ballabio, C. Alonso-Ramos, E. T. Simola, L. Vivien, G. Isella, and D. Marris-Morini, "Broadband integrated racetrack ring resonators for long-wave infrared photonics," *Opt Lett* **44**, 407–410 (2019).
- <sup>22</sup>D. A. Kozak, N. F. Tyndall, M. W. Pruessner, W. S. Rabinovich, and T. H. Stievater, "Germanium-on-silicon waveguides for long-wave integrated photonics: ring resonance and thermo-optics," *Opt Express* **29**, 15443–15451 (2021).
- <sup>23</sup>S. Radosavljevic, N. T. Beneitez, A. Katumba, M. Muneeb, M. Vanslebrouck, B. Kuyken, and G. Roelkens, "Mid-infrared vernier racetrack resonator tunable filter implemented on a germanium on soi waveguide platform [invited]," *Optical Materials Express* **8** (2018).
- <sup>24</sup>D. Ren, C. Dong, S. J. Addamane, and D. Burghoff, "High-quality microresonators in the longwave infrared based on native germanium," *Nat Commun* **13**, 5727 (2022).
- <sup>25</sup>F. Ottonello-Briano, C. Errando-Herranz, H. Rödjegård, H. Martin, H. Sohlström, and K. B. Gylfason, "Carbon dioxide absorption spec-

- troscopy with a mid-infrared silicon photonic waveguide,” *Optics Letters* **45** (2019).
- <sup>26</sup>“Ansys lumerical,” <https://www.lumerical.com>.
- <sup>27</sup>C. Godey, I. V. Balakireva, A. Coillet, and Y. K. Chembo, “Stability analysis of the spatiotemporal lugiato-lefever model for kerr optical frequency combs in the anomalous and normal dispersion regimes,” *Physical Review A* **89** (2014).
- <sup>28</sup>J. S. Levy, A. Gondarenko, M. A. Foster, A. C. Turner-Foster, A. L. Gaeta, and M. Lipson, “Cmos-compatible multiple-wavelength oscillator for on-chip optical interconnects,” *Nature Photonics* **4**, 37–40 (2009).
- <sup>29</sup>I. W. Rangelow, “Critical tasks in high aspect ratio silicon dry etching for microelectromechanical systems,” *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* **21**, 1550–1562 (2003).
- <sup>30</sup>A. D. Torre, R. Armand, M. Sinobad, K. F. Fiaboe, B. Luther-Davies, S. Madden, A. Mitchell, T. Nguyen, D. J. Moss, J.-M. Hartmann, V. Reboud, J.-M. Fedeli, C. Monat, and C. Grillet, “Mid-infrared supercontinuum generation in a varying dispersion waveguide for multi-species gas spectroscopy,” *IEEE Journal of Selected Topics in Quantum Electronics* , 1–10 (2022).
- <sup>31</sup>M. F. Limonov, M. V. Rybin, A. N. Poddubny, and Y. S. Kivshar, “Fano resonances in photonics,” *Nature Photonics* **11**, 543–554 (2017).