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# Silicon-Germanium Integrated Ring Resonator with High Q-factor in the Mid-Infrared

Marko Perestjuk<sup>1,2,4</sup>, Rémi Armand<sup>1</sup>, Alberto Della Torre<sup>1</sup>, Milan Sinobad<sup>1</sup>, Arnan Mitchell<sup>2</sup>, Andreas Boes<sup>2</sup>, Jean-Michel Hartmann<sup>3</sup>, Jean-Marc Fedeli<sup>3</sup>, Vincent Reboud<sup>3</sup>, Christelle Monat<sup>1</sup>, and Christian Grillet<sup>1</sup>

<sup>1</sup>Université de Lyon, Institut des Nanotechnologies de Lyon (INL, UMR-CNRS 5270), Ecole Centrale de Lyon, 69130 Ecully, France

<sup>2</sup>School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

<sup>3</sup>Université Grenoble Alpes, CEA-Leti, 38054 Grenoble Cedex 9, France

<sup>4</sup>email: marko.perestjuk@ec-lyon.fr

**Abstract:** We demonstrate a high-Q ring resonators in the mid-infrared in a silicon-germanium chip-based platform. The achieved a loaded Q-factor of 90,000 for the side-coupled ring around 4.18 $\mu$ m operating wavelength.

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## 1. Introduction

Many molecules have strong fundamental absorption lines in the mid-infrared (MIR) wavelength range (between 3 and 13  $\mu$ m) resulting in a large potential for sensing applications at these wavelengths [1]. However, a real breakthrough of MIR technologies has been prevented by a high cost and bulky components so far. The integration of MIR components on-chip would provide a decisive step towards large scale applications.

Ring and racetrack resonators are expected to play a crucial role in on-chip integrated sensing schemes. As was first demonstrated in the near-IR, they can be used to generate frequency combs [2], and could thus provide a broadband MIR light source, a key element of sensing devices that can operate in a wide spectral range. Resonators with a high Q-factor can also enhance the interaction between light and molecules [3]. Several ring resonators have been demonstrated in the MIR, some of which have also been used for frequency comb generation [3-6]. High Q-factors have been achieved predominantly on silicon-on-insulator (SOI, [7]) and silicon-on-sapphire (SOS, [8]) platforms, which, however, have high losses beyond  $\sim 3.5$   $\mu$ m and  $\sim 6.5$   $\mu$ m, respectively [1]. This has also prevented the generation of frequency combs beyond 4  $\mu$ m. For example, in a state-of-the-art demonstration in [4] a span of 2.4-4.3  $\mu$ m was achieved, while the power at long wavelengths was quite low due to absorption. High-Q ring resonators in the MIR have been realized also with chalcogenide glass [9], although the material photosensitivity could translate in a low temporal device stability. Moreover, group IV materials are preferable instead for cost-effective large scale fabrication.

Specifically silicon-germanium (SiGe) and germanium (Ge) are promising materials, thanks to their CMOS compatibility and transparency window up to 15  $\mu$ m [1]. Low-loss SiGe waveguides operating in the MIR have been already demonstrated and their nonlinear properties were exploited for supercontinuum generation [10]. The same applies for Ge [11]. So far, however, only a few SiGe and Ge ring resonator demonstrations have been reported in the MIR, with a moderate Q-factors of 1,672 [12], 3,200 [13] and 20,000 [14]. Here, we report a SiGe ring resonator coupled to a bus waveguide, with loaded Q-factor of 90,000 at 4.18  $\mu$ m.

## 2. Fabrication and Ring Resonance Measurement

Our platform consists of an air-cladded 3.3  $\mu$ m thick and 3.25  $\mu$ m wide Si<sub>0.6</sub>Ge<sub>0.4</sub> core waveguide on a silicon substrate (Fig. 1a). These dimensions were chosen for the waveguide to have anomalous dispersion around 4  $\mu$ m wavelength to allow for frequency comb generation in the future, as well as ensuring a single-mode waveguide. The resonators were fabricated on a 200 mm CMOS pilot line at CEA-Leti using deep ultraviolet photolithography and deep reactive

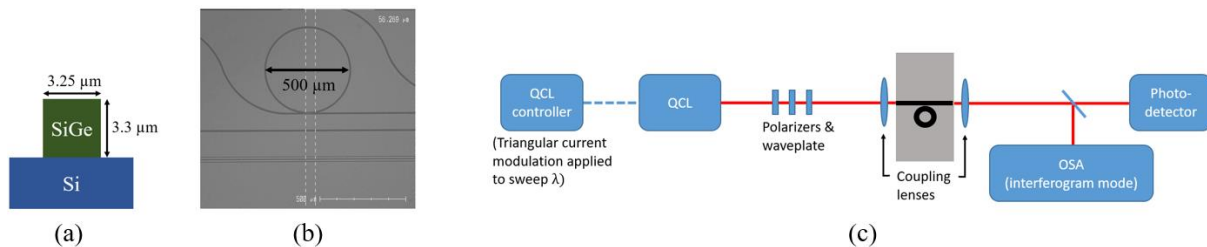


Fig. 1. SiGe platform used for the ring resonator. (b) SEM picture of the ring resonator. (c) Measurement Setup.

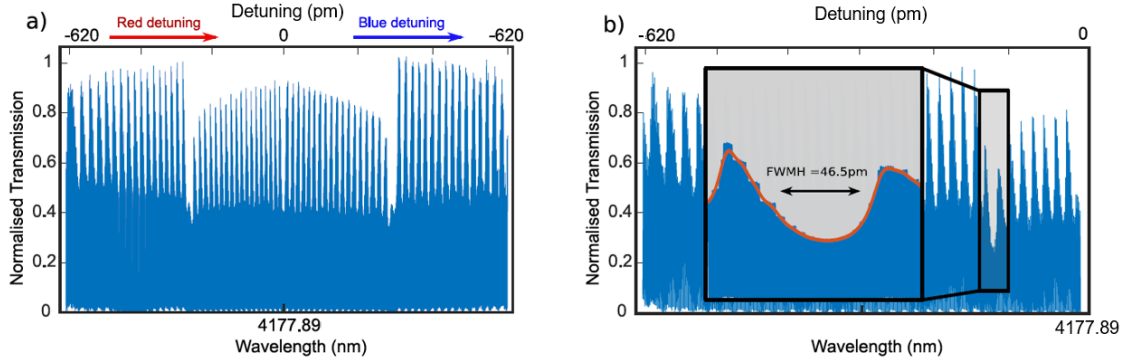


Fig. 2. (a) Wavelength scan (ramp up and ramp down) of the ring resonance with a cw QCL. The ring resonance at one specific wavelength can be clearly distinguished from the Fabry-Perot resonances, which occur due to the waveguide facet at input and output coupling. (b) Zoom-in on the ring resonance.

ion etching. A ring radius of  $R = 250 \mu\text{m}$  (Fig. 1b) was chosen to target a free spectral range (FSR) of 53 GHz. The coupling gap between ring and bus waveguide is 250 nm.

Fig. 1c shows a scheme of our measurement setup. The ring resonance characterization was done using an Adtech 4.18  $\mu\text{m}$  distributed feedback quantum cascade laser (QCL) providing cw light. The out-coupled light was recorded by a Thorlabs Fourier transform optical spectrum analyzer (OSA). We did not utilize the spectral mode of the OSA but rather used it as a photodetector through the interferometry between the two delay beams to have less noise than with a normal photodetector. The emission wavelength of the QCL was modulated between 4177.27 nm and 4177.89 nm by applying a periodic triangular current modulation. The optical pump power was 20 mW (measured directly before the input coupling lens).

Fig. 2a shows one period of the modulation recorded by the interferogram mode of the OSA. Over the whole wavelength range there are pronounced Fabry-Perot resonances, which result from the cavity formed by the two end-facets of the access bus waveguide. Nonetheless, the ring resonance can be clearly distinguished on this plot: it manifests as an additional dip occurring twice, during the wavelength ramp up and the ramp down, respectively. Fig 2b shows a zoom-in of the ring resonance. From this resonance we could retrieve a total (loaded) quality factor of  $Q = 90,000$ . We did not determine yet if we are at critical coupling. In any case, for the intrinsic quality factor a value much higher than  $10^5$  is expected.

#### 4. Conclusion

In conclusion, we have reported a SiGe ring resonator operating around 4.18  $\mu\text{m}$ , with a loaded Q-factor of 90,000. The operation at 4.18  $\mu\text{m}$  was only limited by the availability of the QCL while SiGe allows for much longer wavelengths, so we expect to be able to demonstrate similar Q-factors deeper into the MIR. The high Q-factor sets the basis for on-chip frequency combs generation in the MIR on a CMOS compatible platform.

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