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Ge-rich graded-index $Si_{1-x}Ge_x$ racetrack resonators for long-wave infrared photonics

J. M. Ramirez[a,b], V. Vakarin[a], Q. Liu[a], J. Frigerio[c], A. Ballabio[c], X. Le Roux[a], G. Isella[c], C. Alonso-Ramos[a], M. Montesinos[a], L. Vivien[a] and D. Marris-Morini[a]
[a]Centre de Nanosciences et de Nanotechnologies, Université Paris Sud, CNRS, Université Paris Saclay, 91405 Orsay, France; [b]Now at III-V Lab, a joint lab from Nokia Bell Labs, Thales and CEA, 1 avenue Augustin Fresnel, 91767 Palaiseau Cedex ; [c]L-NESS, Dipartimento di Fisica, Politecnico di Milano, Polo di Como, Via Anzani 42, 22100 Como, Italy

ABSTRACT

Mid-infrared racetrack resonators are demonstrated working at 8µm wavelength. The devices are based on a graded SiGe platform providing low propagation loss on a large wavelength range in the mid-IR. Different resonators designs have been fabricated, with varying gap distances in the directional coupler. Q factors of more than 3000 have been experimentally demonstrated. These results pave the way towards compact mid-IR sensors or efficient active devices.

Keywords: Photonic integrated circuits, resonator, mid-infrared, silicon photonics

1. INTRODUCTION

The mid-IR wavelength range covering from 2 µm to 20 µm has raised as a promising 'sweet spot' to develop advanced silicon photonic systems [1-4] owing to its several interesting features, including: i) The low material dispersion present on Si-based materials in the mid-IR wavelength range, which eases the design of dispersion-engineered photonic integrated circuits with broadband flat dispersion windows; ii) the absence of two-photon absorption losses, which are known to be detrimental for certain applications, notably for components requiring high-power management; iii) the mid-IR wavelength range allocates a large number of 'molecular fingerprints' associated with vibrational modes of many substances and molecules relevant for the human being, thus being of interest for the implementation of ultra-sensitive optical sensors with potentially parts-per-billion floor detection [5]. Moreover, the mid-IR spectrum also provides two atmospheric transparency windows placed at 3-5 µm and 8-13 µm respectively that can be leveraged to implement novel free-space optical communication systems when combined with high power quantum cascade lasers [6]. To successfully implement such interesting functionalities, a material platform compatible with the CMOS processing while having a large transparency window is required. In this regard, Ge stands as one of the most promising materials as it fulfils both conditions. With a transparency window that spans from the near infrared up to a wavelength of $\lambda = 15$ µm, Ge provides a unique opportunity to exploit the long-wave infrared range [7]. An interesting family of the Ge-based platform is the one that uses an epitaxial SiGe graded buffer directly grown on Si, as they offer fine control of the optical properties by tuning the graded Ge profile in the growth direction to form the waveguide core. Moreover, this strategy enables a gradual accommodation of the lattice mismatch between Si and Ge, providing a low-defect density alloy with low propagation losses [8]. Various demonstrations of mid-IR photonic components based on graded SiGe waveguides have been reported, including ultra-broadband Mach Zehnder interferometers [9] and integrated Fourier-transform spectrometers [10]. Furthermore the ability of this platform to sense small concentrations of methane gas has been discussed [11] while non-linear properties of Ge rich SiGe alloys have been studied as a function of Ge concentration [12], opening the path to the design of efficient devices based on NL effects such as supercontinuum generation though self-phase modulation [13].

In this context, integrated resonators appear as important building blocks to be developed, as they can be used (i) to develop compact sensors by an increased interaction length between the propagating mode and the analyte, (ii) as an interferometric structure for next development of optical modulators, (iii) as a nonlinear device, to provide a strong-light matter interaction with the nonlinear material. Although ring resonators have been largely developed using Silicon-On-Insulator waveguides in the near-IR wavelength range [14], their extension towards mid-IR wavelengths using graded

SiGe waveguides is not straightforward. Indeed a reduced mode confinement could prevent from compact bends and thus limiting achievable Free Spectral Ranges (FSR).

In this paper we report on the main design rules and the device characterization showing that by carefully designing the coupler and ring resonator we have been able to demonstrate for the first time an integrated mid-IR racetrack ring resonator working at 8 µm wavelength, with a maximum loaded quality factor (Q) of 3200. This result paves the way towards efficient non-linear devices and compact sensors in the long-wave infrared (LWIR).

2. DESIGN OF THE GE-RICH GRADED-INDEX SI$_{1-X}$GE$_X$ RACETRACK RESONATORS

2.1 Ge-rich SiGe racetrack resonator design and fabrication.

The Ge-rich SiGe waveguides are based on the epilayer reported in Fig 1(a). The 6-µm thick graded SiGe waveguide core is grown on a standard Si substrate using Low Energy Plasma Enhanced Chemical Vapor Deposition (LEPECVD). This approach allows an efficient reduction of the number of threading dislocations (TDD) by gradual accommodation of the Si-Ge lattice mismatch in the layer stack. In addition the linear refractive index increases (as shown in Fig. 1(b)) due to the gradual increase of the Ge content in SiGe alloy, allowing the confinement of light at the top of the graded SiGe layer. Rib waveguides can then been defined by etching the SiGe graded layer as shown in Fig 1(a). Directional couplers and racetrack resonators have been designed using numerical simulations as illustrated in Fig 1.c. After optimization, the coupler length has been fixed to 200 µm while gap distances varying from 0.6 to 1.2 µm have been selected. The ring radius R in the racetrack is fixed to 250 µm to avoid bending losses.

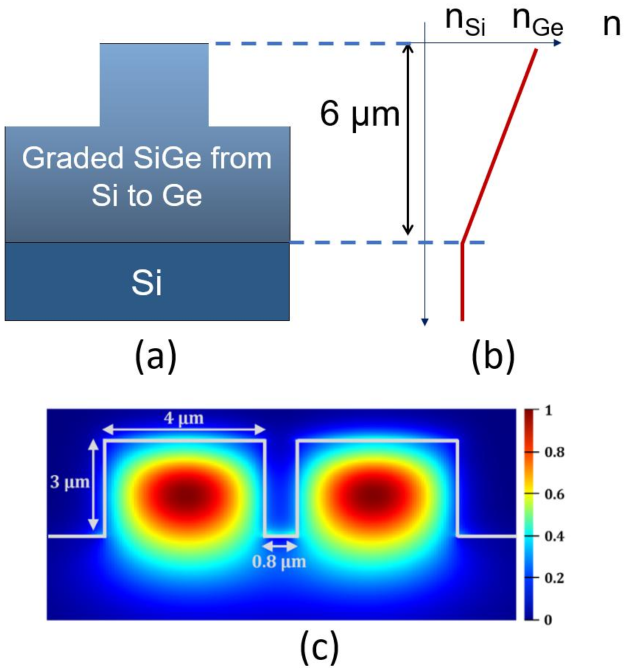

Figure 1. Cut-view of the Ge-rich SiGe waveguides (a): epilayer grown by LEPECVD in standard Si substrate. (b) : refractive index profile along the growth direction ; (c) example of super-mode calculation in the directional coupler.

The racetrack ring resonators were fabricated using e-beam lithography and ICP etching. A scanning electron microscopy (SEM) image of the racetrack resonator is shown in Fig 2(a). After fabrication, waveguide facets were diced for butt-coupling using a free-space experimental set-up.

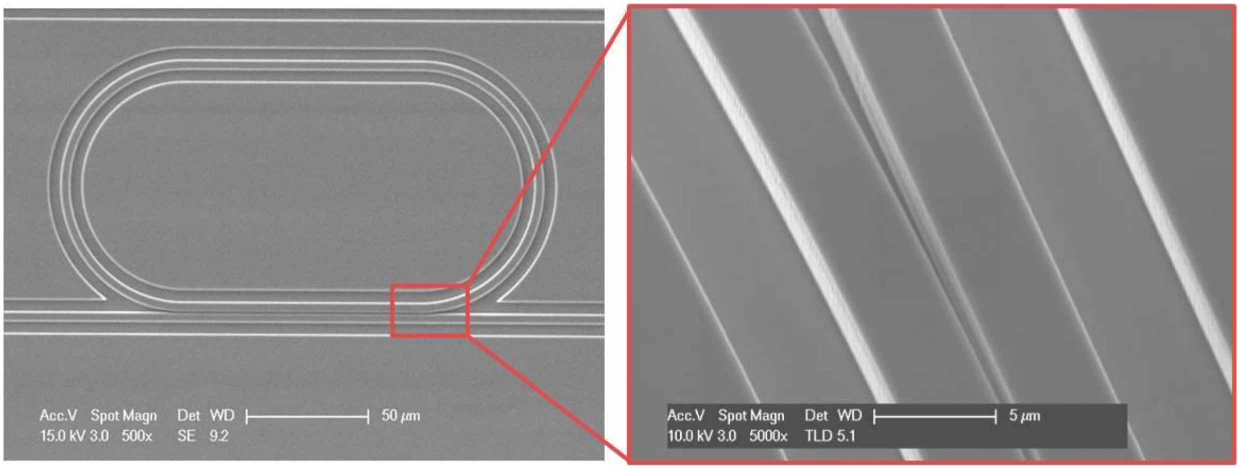

Figure 2: Top view SEM image of a single racetrack resonator with the access bus waveguide. The figure at the right-hand side shows a zoomed-in area of the coupling region.

2.2 Characterization set-up.

Measurements were performed using an ad-hoc free-space mid-IR setup, placed inside an isolation box and equipped with a dry air filling system, to reduce the impact of the atmospheric absorption (Fig. 3(b)). Transmission measurements were performed using a mid-IR tunable external cavity quantum cascade laser (MIRCAT) from $\lambda = 7.5$ µm (1333.3 cm^{-1}) to 8.6 µm (1162.8 cm^{-1}), operating in pulsed regime (duty cycle of 5 % and repetition rate of 100 kHz), with a linewidth specified to be below 1 cm^{-1}. Input/output chip butt-coupling was carried out by means of aspheric ZnSe lenses. The collected signal was sent to either an MCT detector or a mid-IR camera (see Fig 3. (a)).

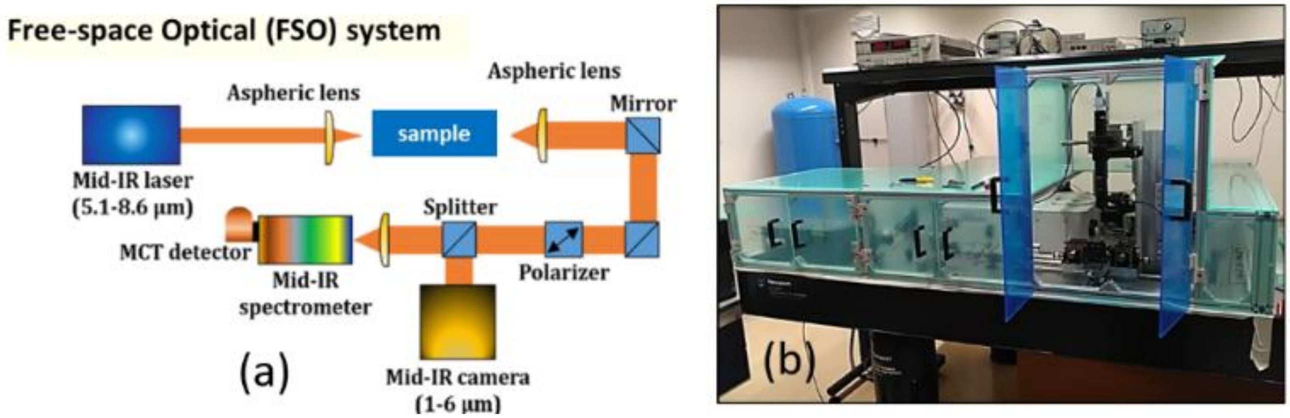

Figure 3: (a) Schematic view of the experimental set-up used for the mid-IR characterization: (b) Picture of the experimental set-up.

2.3 Experimental results

Figure 4 summarizes the normalized quasi-TM transmission of the racetrack ring resonators for the different gap distances. Resonances are clearly observed in all the reported results. As expected, the critical coupling condition shifts towards larger wavelength (lower wavenumber) when the gap distance is increased, corresponding to a decrease of the intensity coupling in the directional coupler. From the measurements, a linearly increasing FSR with wavelength can be deduced for the different racetrack resonators, as expected. This trend is reported in Fig 5. A good correlation between measured FSR and calculation confirms the single mode operation of the devices. Interestingly, a maximum loaded quality factor of Q ≈ 3200 is obtained in the different configurations.

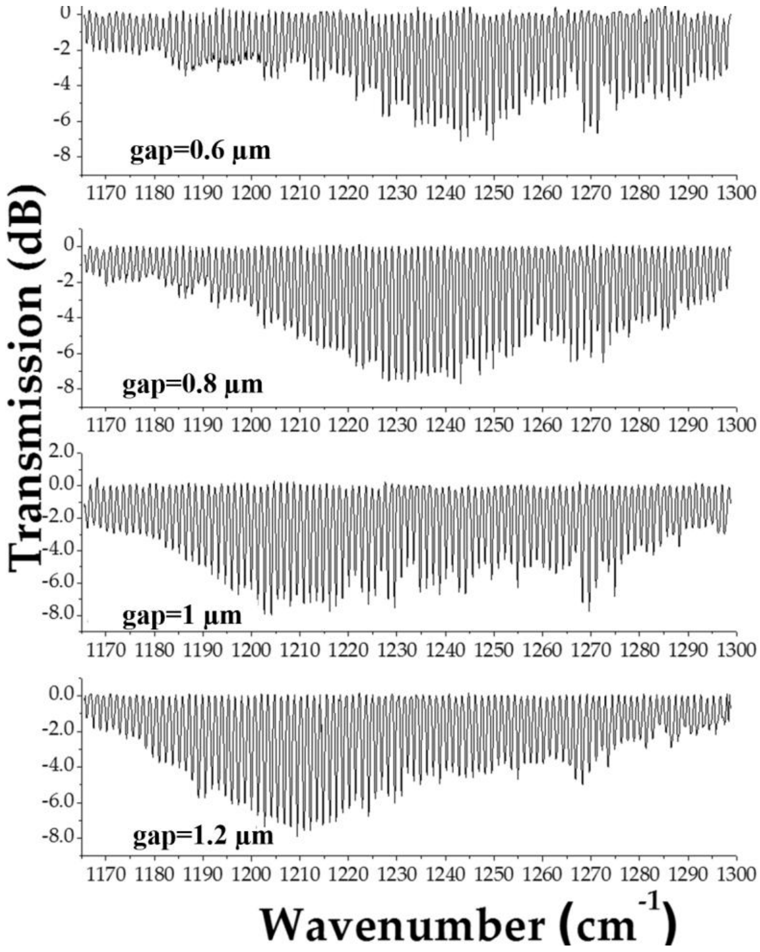

Figure 4: . Experimental transmission spectra of racetrack ring resonators operating in quasi-TM polarization, for different values of the gap within the directional coupler, from 0.6 to 1.2 µm. The shift of the critical coupling condition related to a decrease of the intensity coupled in the racetrack when the gap is increased is clearly seen.

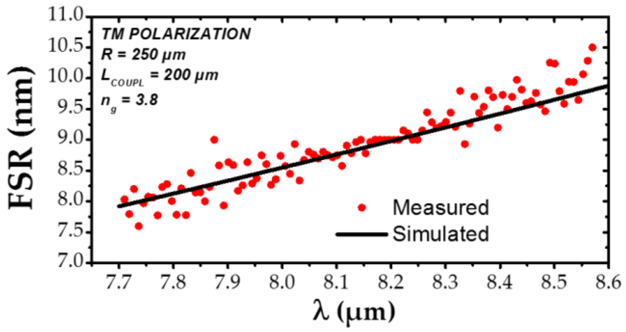

Figure 5: Free Spectral Range extracted from the measurement and compared with theoretical value. A good correlation is obtained indicating the single mode operation of the racetrack ring resonators.

3. CONCLUSION

In conclusion, this paper reports the first demonstration of mid-IR racetrack resonators working around 8 μm wavelength. The resonant structures are based on a 6 μm-thick graded SiGe platform. A maximum Q-factor of 3200 is demonstrated. This work paves the way towards the implementation of resonant structures for multi-target molecular spectroscopic sensors or for the development of non-linear devices in integrated photonic platforms.

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