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# OPTICAL BISTABILITY IN HIGH-Q SILICON-GERMANIUM RING RESONATORS IN THE MID-INFRARED

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## ABSTRACT

We strongly improve the power coupling to high quality factor on-chip silicon germanium ring resonators by fabrication optimization and anti-reflection coatings. This allows us to demonstrate optical bistability on the silicon-germanium-on-silicon platform in the mid-infrared at wavelengths around 4.1  $\mu\text{m}$ .

**KEYWORDS:** *Mid-Infrared, ring resonator, silicon germanium, integrated photonics*

## 1. INTRODUCTION

The mid-infrared (MIR) wavelength range ( $\sim 3 - 13\mu\text{m}$ ) has enormous application potential in the sensing domain as many molecules have strong absorption lines here [1]. However, a real breakthrough of MIR technologies still has been prevented by high cost and bulky components. The integration of MIR components on-chip would provide a decisive step towards wide applications. Broadband, bright and coherent sources are of critical importance for MIR sensing schemes.

Very promising for such sources for integrated photonics are microcombs [2]. There have been demonstrations of integrated microcombs in the MIR [3-5], but the current wavelength record is at  $\sim 4.3\mu\text{m}$  cutoff [5]. Hence, so far the largest portion of the MIR is inaccessible by microcombs. The challenges to realize such devices is to find material platforms with broad transparency windows in the MIR and be able to fabricate cavities with high quality (Q) factor. Silicon germanium (SiGe) is one such promising material platform due to its transparency window up to  $15\mu\text{m}$  and supercontinuum generation up to  $8.5\mu\text{m}$  as another form of a MIR light source has been demonstrated [6]. SiGe resonators are an active research topic [7] and very recently we demonstrated a SiGe ring resonator with a loaded Q of 236,000 at  $4.18\mu\text{m}$  wavelength [8]. This starts to lower threshold powers for nonlinear effects and comb generation to levels reachable by modern equipment. One interesting nonlinear effect is optical bistability [9, 10]. It happens when the power buildup in a cavity is large enough to change the refractive index of the cavity material significantly. This leads to a feedback loop and a “tilt” of the resonance, resulting in a two state system. For one given wavelength there are two resonance states, so the cavity acts as a bistable switch. Besides being a precursor for the use of other nonlinearities, bistability itself has many applications, for example all optical switching [9], and, specifically interesting in the MIR, sensing applications [11].

Here, we first show that improvements in the fabrication of the gap between the ring and the bus waveguide can greatly improve the coupling to the cavity. Second, we demonstrate optical bistability. And last, to further increase the power coupling to microring in the future, we

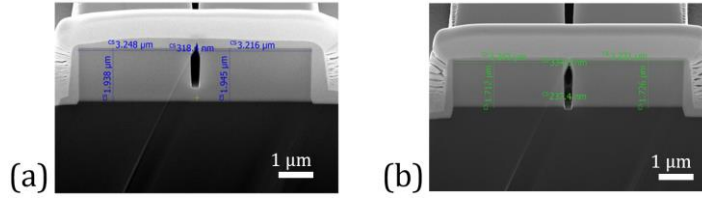


Fig. 1. Gap between ring and bus waveguide before (a) and after (b) optimization.

demonstrate a MIR anti-reflection-coating (ARC) that is compatible with integrated SiGe chips. ARCs are invaluable for improving signal quality and reducing the tight power requirements for comb generation. However, ARCs in the MIR are hard to obtain due to the limited selection of suitable materials with transparency [12, 13].

## 2. RESULTS

The general design and fabrication of the ring resonator is described in [8]. It has a radius of  $250\ \mu\text{m}$  with  $3.25\ \mu\text{m}$  wide and  $3.3\ \mu\text{m}$  high waveguides of SiGe on a Si substrate. The dispersion is designed to be slightly anomalous to be suitable for Kerr comb generation. As was shown in [8], it was a difficulty to achieve critical coupling for SiGe waveguides with tight mode confinement as this required small gaps. As can be seen in Fig. 1a, this can be attributed to difficulties to control the etching of the very narrow gap between the ring and the bus waveguide (here  $250\ \text{nm}$ ). We improved the fabrication and Fig. 1b shows the optimized gap that is fully etched.

To characterize the fabricated rings and show that we have better control of coupling, and hence can load more power in the cavity, we used the setup shown in Fig. 2a. We use a tunable (idler  $\sim 2.4 - 4.5\ \mu\text{m}$ ) continuous wave optical parametric oscillator (OPO) from Excelitas, which is pumped by an amplified near infrared seed laser. Modulating the seed laser gives fine tuning of the OPO output wavelength and hence allows us to scan through the ring resonance. We can either measure the transmission by a photodetector or the in-cavity power by a MIR camera (FLIR). Imaging the ring with the camera (Fig. 2b) shows that we can achieve high loading power. In Fig. 2c we show the resonance by the recorded in-cavity power for increasing input power (as measured before the coupling lens). For increasing power the typical bistability shape appears with a “tilted” resonance. Optical bistability can result from various different sources of nonlinearity, of which the most important ones for SiGe are the thermal nonlinear optical effect, where the high intensities result in a temperature change and hence through the thermo-optic coefficient in a refractive index

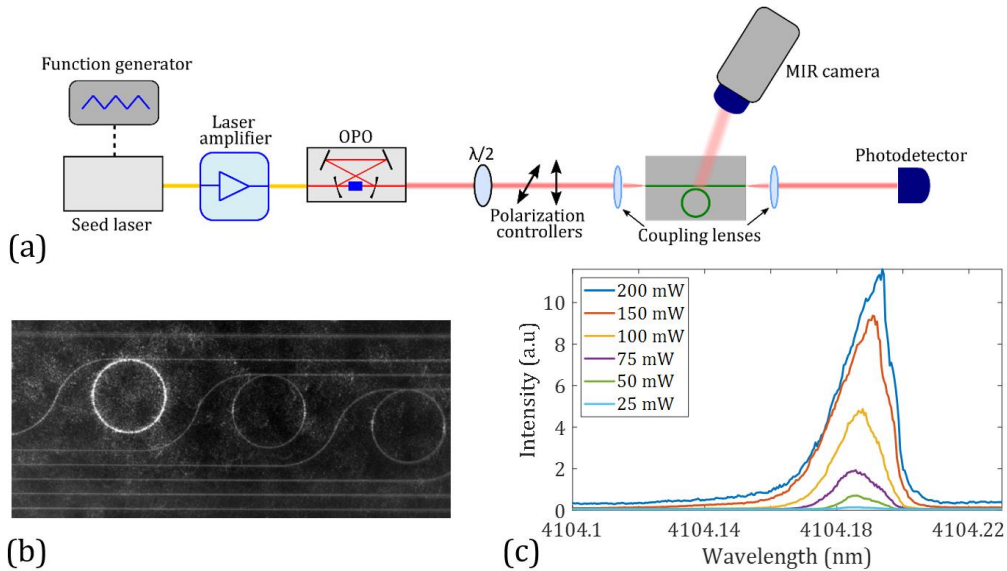


Fig. 2. (a) Measurement setup. (b) Image of MIR camera showing loaded ring. (c) Ring resonances (in-cavity power recorded by MIR camera) showing bistability behavior for increasing power.

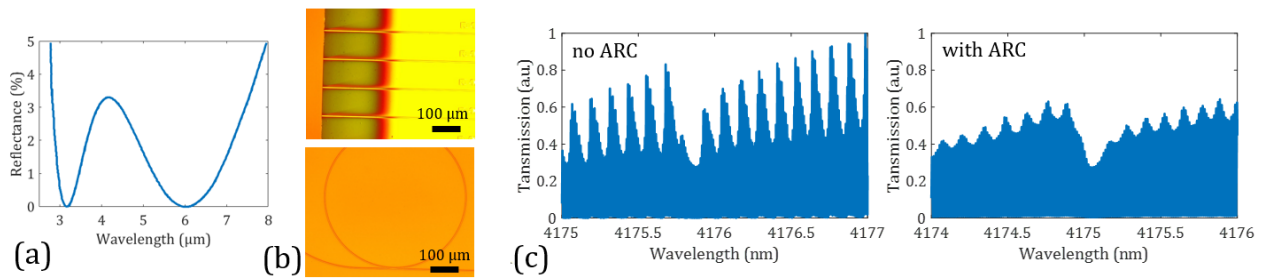


Fig. 3. (a) Reflectance of the designed ARC. (b) Optical microscope pictures of - Top: the chip edge (top view) showing a visible ARC penetration to the top facet. Bottom: the ring resonator. (c) Measured ring resonance on chip with and without ARC.

change, and the Kerr nonlinearity, where the  $\chi_3$  of SiGe leads to a direct dependence of the refractive index on optical intensity. In the future we envision to analyze the contribution of them to the observed bistability, which can be done by fast modulation of the input as the thermal and Kerr nonlinearities have different time scales [10].

Another challenge in [8] was resolving the resonance due to the presence of Fabry-Perot fringes caused by the cavity formed by the chip end-facets. This issue can be mitigated by an ARC, which simultaneously increases the power coupling to the chip. We developed a two-layer ARC using a 464 nm layer of ZnS and a 715 nm layer of YF<sub>3</sub>. The simulated reflectance of the ARC is shown in Fig. 3a. It is deposited on both chip facets using e-beam deposition using a Bühler/Leybold Optics SYRUSpro 710 with an in-situ optical monitoring at 950 nm (Bühler OMS 5000) in order to minimize thickness errors. Fig. 3b shows a picture of the edge of the chip, the ARC residue is visible on the top facet. No residue is visible on the ring. The ARC increased the through-coupled power by around 50%. Fig. 3c shows the ring resonance before and after the ARC deposition (using a lower Q to show the effect of the ARC more clearly). While without the ARC the resonance just manifests itself by one missing Fabry-Perot fringe, with the ARC its shape can be clearly resolved.

### 3. CONCLUSION

In conclusion, we have demonstrated optical bistability in the MIR in SiGe ring resonators, enabled by fabrication improvements for the SiGe platform and hence better power coupling to the ring. Furthermore, we have developed an efficient ARC in the MIR, which can increase the on-chip power even more in upcoming experiments. Bistability is moving us another step closer to MIR integrated frequency combs, but can already enable important sensing applications by itself.

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