Silicon-Germanium Ring Resonator On-Chip with High Q-factor in the Mid-Infrared

Marko Perestjuk[1,2], Rémi Armand[2], Alberto Della Torre[2], Milan Sinobad[3], Arnan Mitchell[1], Andreas Boes[1,4], Jean-Michel Hartmann[5], Jean-Marc Fedeli[5], Vincent Reboud[5], Alfredo de Rossi[6], Sylvain Cmbrié[6], Christelle Monat[2] and Christian Grillet[2]

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[2]Université de Lyon, Institut des Nanotechnologies de Lyon (INL, UMR-CNRS 5270), Ecole Centrale de Lyon, 69130 Ecully, France
[3]Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany
[4]Institute for Photonics and Advanced Sensing, The University of Adelaide, Adelaide, SA 5005, Australia
[5]CEA-Leti, Université Grenoble Alpes, 38054 Grenoble Cedex 9, France
[6]Thales Research and Technology, Campus Polytechnique, Palaiseau, France

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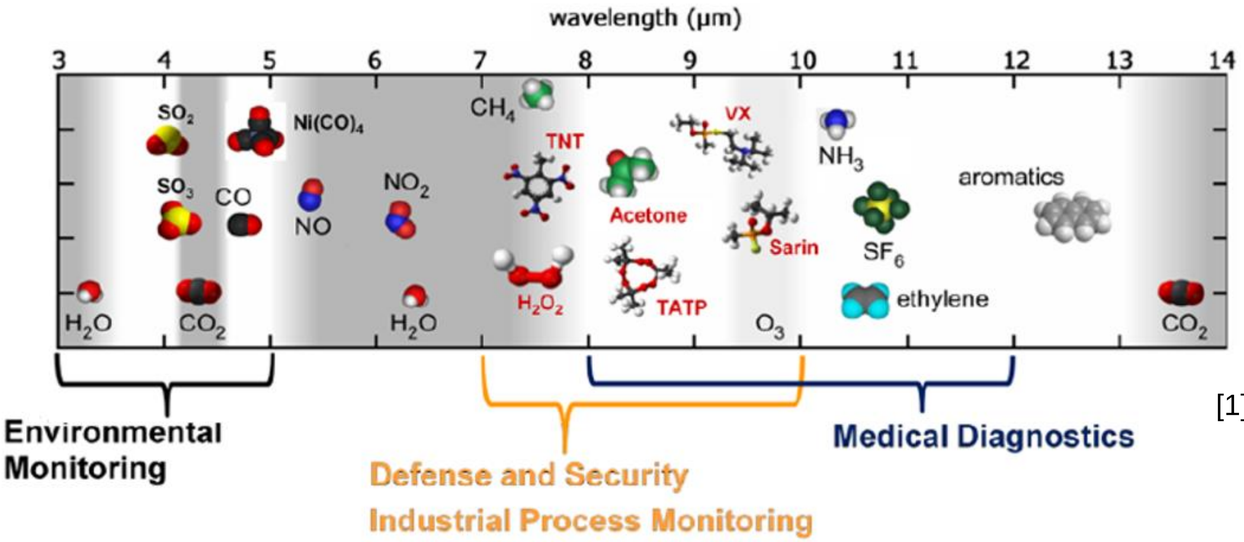
Outline

"Silicon-Germanium Ring Resonator On-Chip with High Q-factor in the Mid-Infrared"

- Introduction
  - Why Mid-Infrared?
  - Why Silicon Germanium?
  - Why High Q ring resonators?
  - State of the art
- Design and fabrication of ring
- Loss and Q-factor measurement
- Simulation of frequency comb generation

- Fundamental absorption lines of many molecules in the MIR
  → high application potential



[1]

[1] D. Caffey et al., Photonics West 2011

Why Mid-Infrared (MIR) Photonics?

- Fundamental absorption lines of many molecules in the MIR
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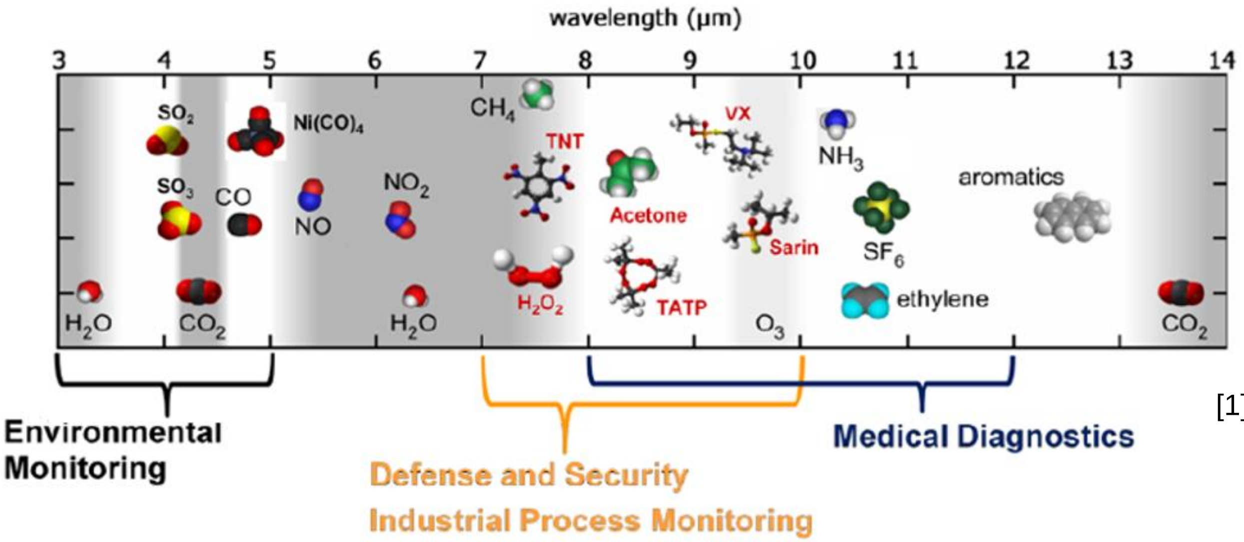
- Lack of compact and low cost devices
- Proposed MIR sensor system



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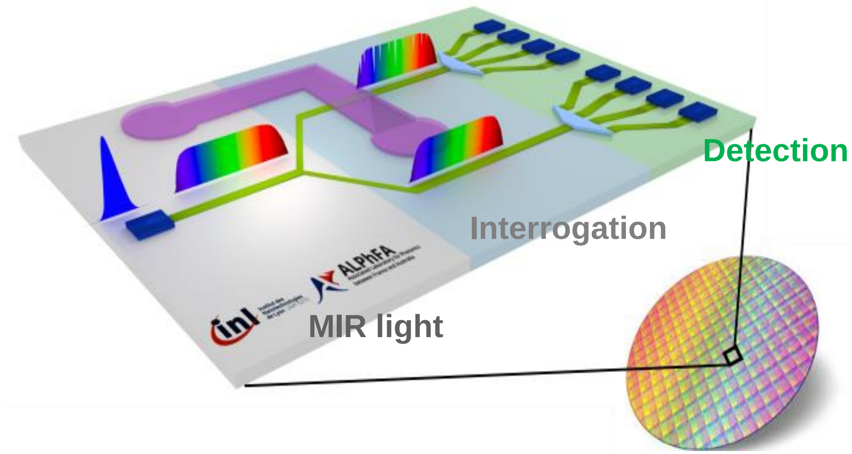

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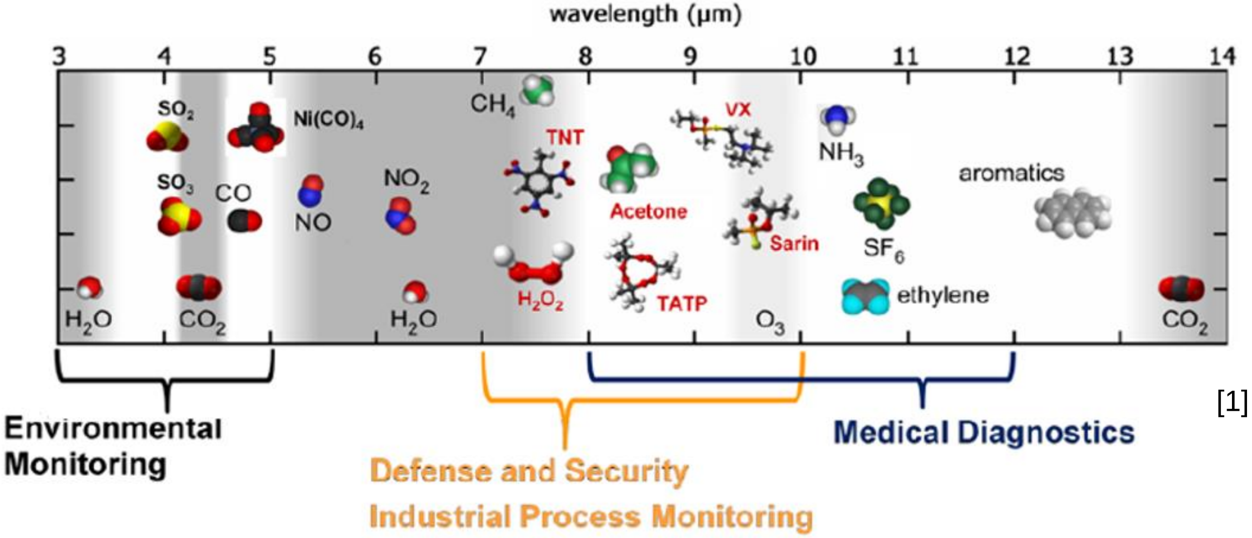
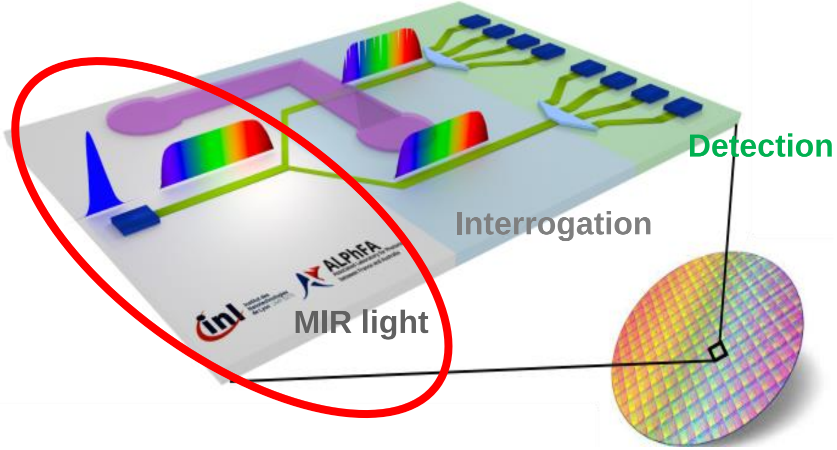


[1]

→



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Through Nonlinear Optics

Wave equation : $\nabla \times \nabla \times E(r,t) + \frac{1}{c^2}\frac{\partial^2 E(r,t)}{\partial t^2} = -\mu_0 \frac{\partial^2 P(r,t)}{\partial t^2}$

$$\boldsymbol{P} = \varepsilon_0\left(\chi^{(1)} \cdot \boldsymbol{E}\right) + \varepsilon_0\left(\chi^{(2)} \cdot \boldsymbol{EE} + \chi^{(3)} \cdot \boldsymbol{EEE} + \cdots\right)$$

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linear →
- Absorption
- Dispersion

nonlinear →
- Four wave mixing
- Self phase modulation
- Cross phase modulation
- Soliton fission
- Raman scattering
- Brillouin scattering
- …

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Broadband and Intense MIR Sources

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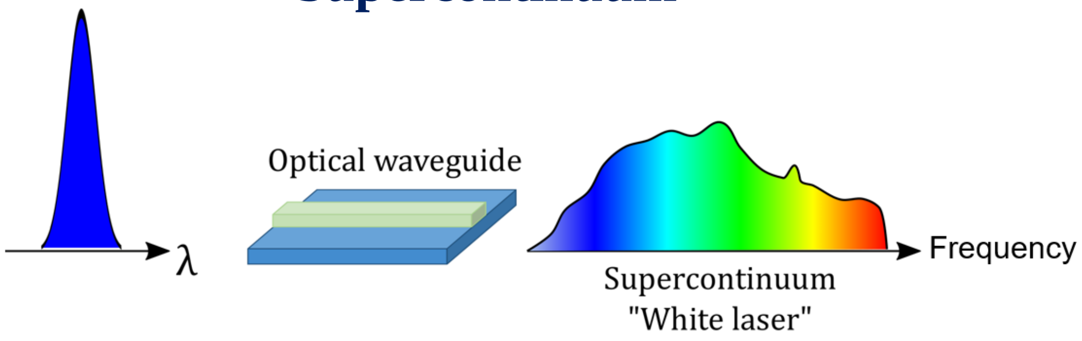
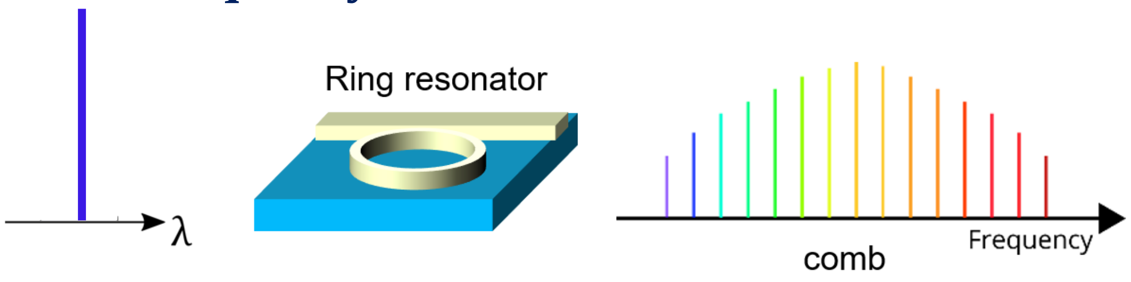
Two options for broadband sources:

Supercontinuum



Frequency Comb



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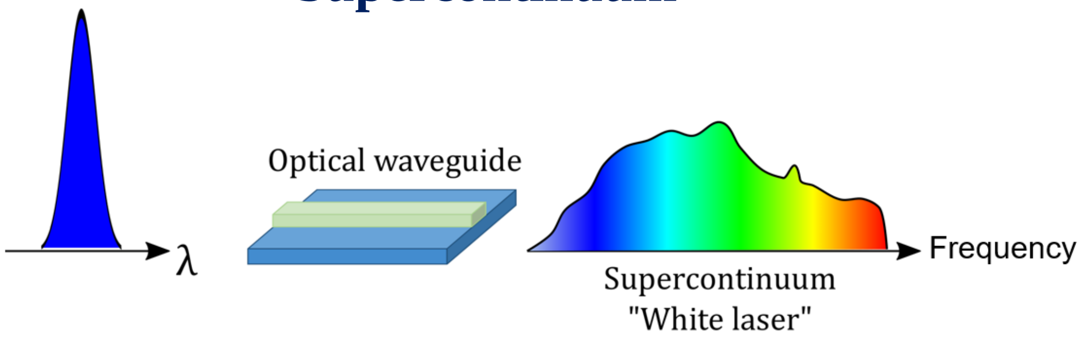

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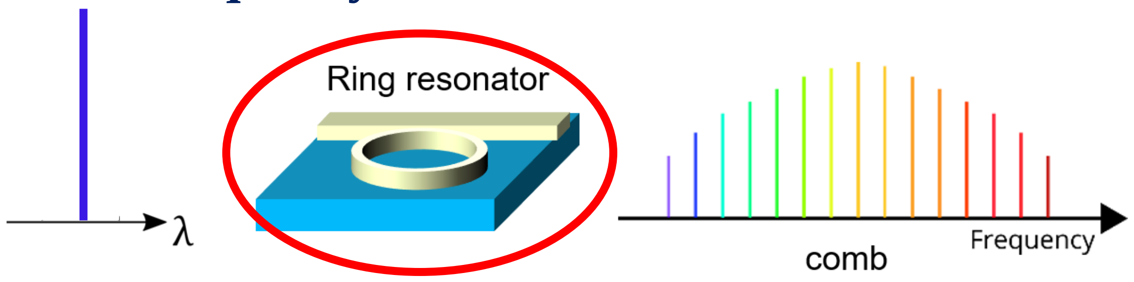
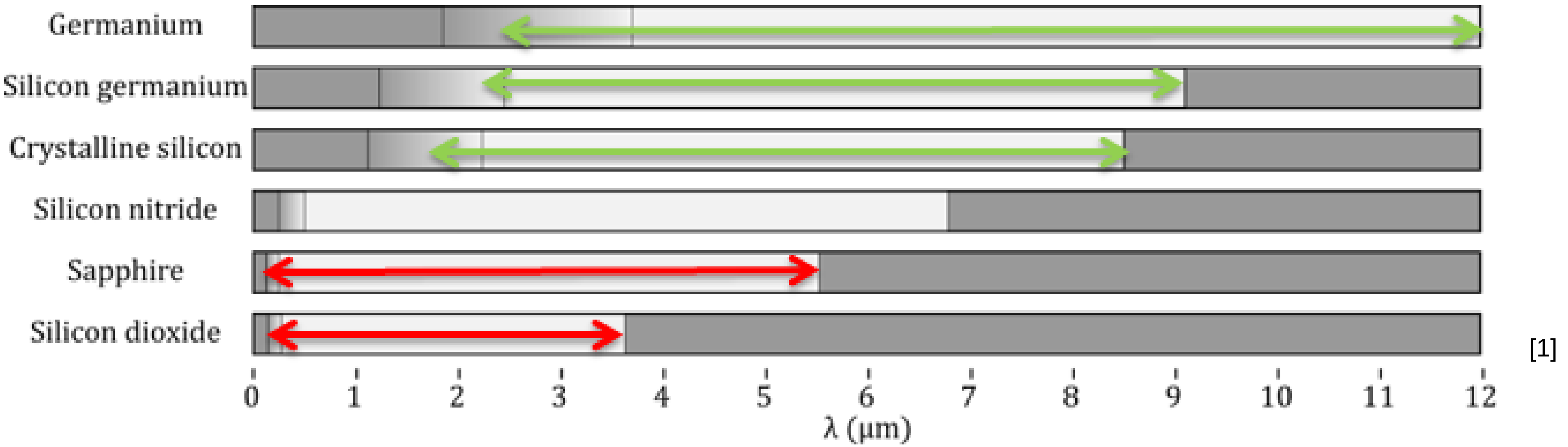


Cavities are a crucial building block

But: many linear applications also possible for sensing

Transparency Window of Group IV Materials



- SOI has strong absorption beyond 3.5µm wavelength due to the silicon dioxide
- SiGe and Ge based waveguides transparent deep into the MIR
- CMOS compatible
- Low loss and nonlinearities demonstrated in SiGe and Ge [2]

[1] adapted from: Soref, Richard, *Mid-infrared photonics in silicon and germanium*, Nature photonics vol. 4, no. 8, pp. 495-497, 2010
[2] L. Carletti, *et al.*, *Nonlinear optical response of low loss silicon germanium waveguides in the mid-infrared*, Opt Express, vol. 23, no. 7, pp. 8261-8271, 2015

MIR Supercontinuum Generation

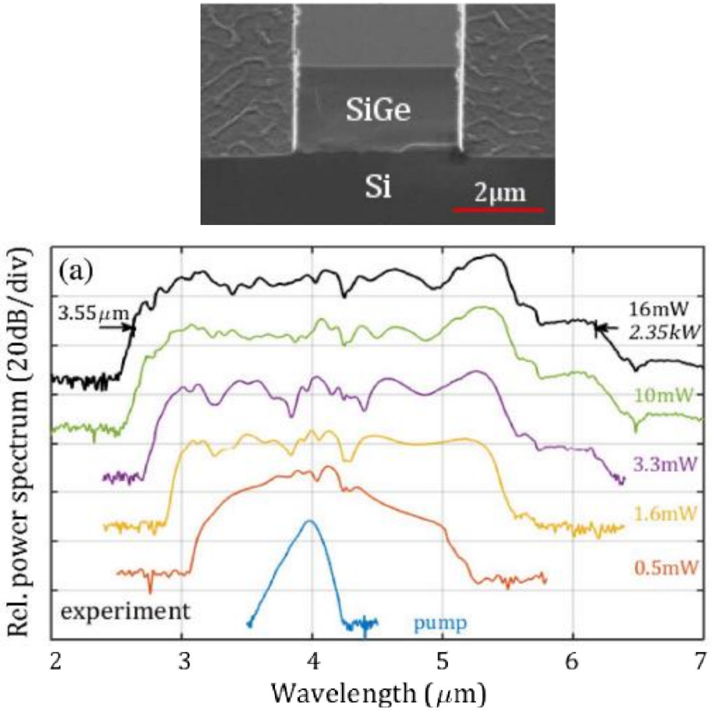
Fast Progress in the Last Years

Research Article Vol. 5, No. 4 / April 2018 / Optica 360

optica

Mid-infrared octave spanning supercontinuum generation to 8.5 μm in silicon-germanium waveguides

Milan Sinobad,[1,2,7] Christelle Monat,[1] Barry Luther-Davies,[3] Pan Ma,[3] Stephen Madden,[3] David J. Moss,[4] Arnan Mitchell,[2] David Allioux,[1] Regis Orobtchouk,[1] Salim Boutami,[5] Jean-Michel Hartmann,[5] Jean-Marc Fedeli,[5] and Christian Grillet[1,6]



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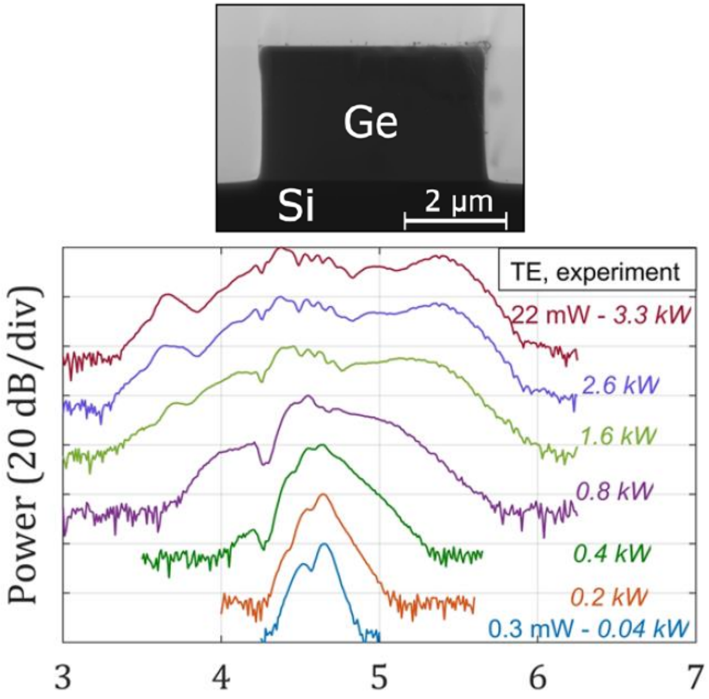
Mid-infrared supercontinuum generation in a low-loss germanium-on-silicon waveguide

Cite as: APL Photon. 6, 016102 (2021); doi: 10.1063/5.0033070
Submitted: 13 October 2020 • Accepted: 13 December 2020 •
Published Online: 4 January 2021

Alberto Della Torre,[1,a)] Milan Sinobad,[1] Remi Armand,[1] Barry Luther-Davies,[2] Pan Ma,[2] Stephen Madden,[2] Arnan Mitchell,[3] David J. Moss,[4] Jean-Michel Hartmann,[5] Vincent Reboud,[5] Jean-Marc Fedeli,[5] Christelle Monat,[1] and Christian Grillet[1]

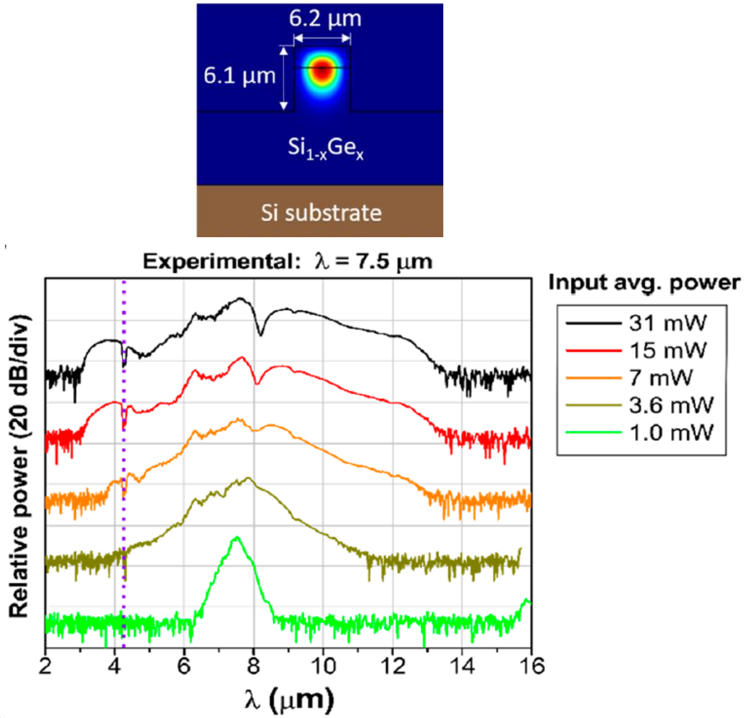


ACS Photonics
pubs.acs.org/journal/apchd5 Article

On-Chip Mid-Infrared Supercontinuum Generation from 3 to 13 μm Wavelength

Miguel Montesinos-Ballester,*,# Christian Lafforgue,# Jacopo Frigerio, Andrea Ballabio, Vladyslav Vakarin, Qiankun Liu, Joan Manel Ramirez, Xavier Le Roux, David Bouville, Andrea Barzaghi, Carlos Alonso-Ramos, Laurent Vivien, Giovanni Isella, and Delphine Marris-Morini

Cite This: ACS Photonics 2020, 7, 3423–3429 Read Online



- Impressive results over the past years
- But: Demonstrations of cavities in the MIR so far lack at least one of the following:
  - Integrability
  - CMOS compatibility
  - High Q-factor
  - Sufficiently long λ

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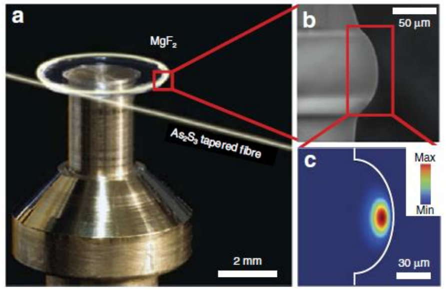
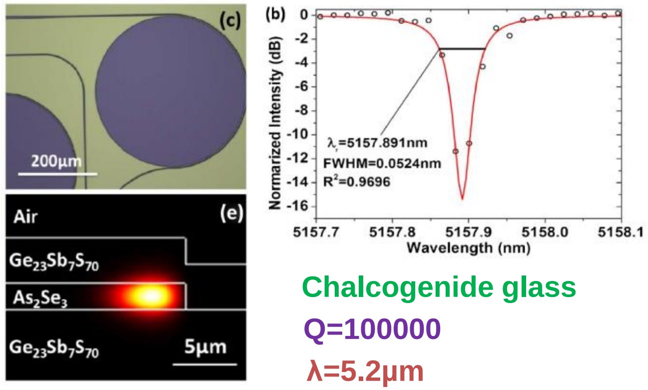


Fluoride crystalls
Q=1.6x10[8]
λ=4.4µm

C. Lecaplain et al., Nat. Commun. 7, 13383 (2016)



Chalcogenide glass
Q=100000
λ=5.2µm

H. Lin et al., Opt. Lett. 38(9), 1470 (2013)

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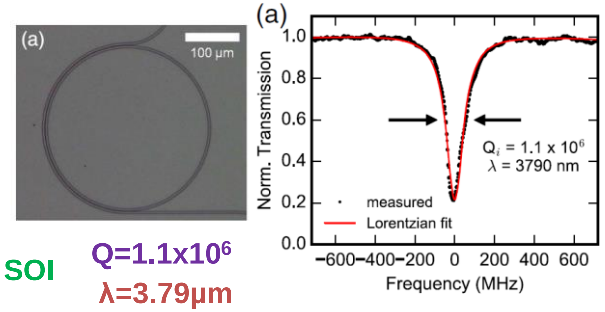
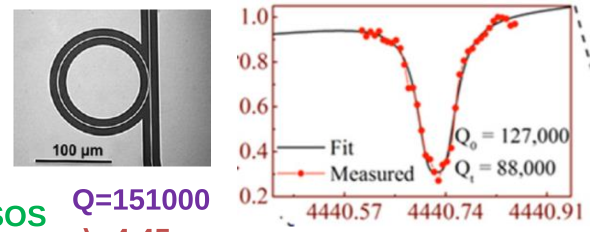


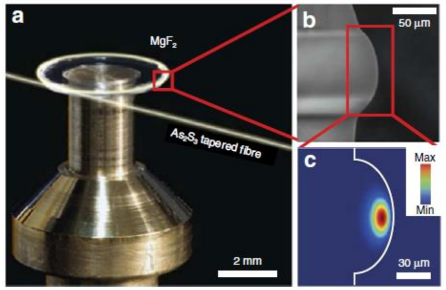
SOI Q=1.1x10^6 λ=3.79µm

S.A. Miller et al., Optica 4(7), 707-712 (2017)



SOS Q=151000 λ=4.45µm

R. Shankar et al., APL 102, 051108 (2013)



Fluoride crystalls Q=1.6x10^8 λ=4.4µm

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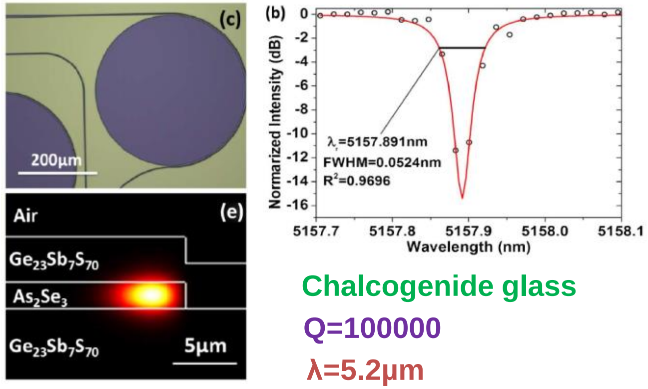

Chalcogenide glass Q=100000 λ=5.2µm

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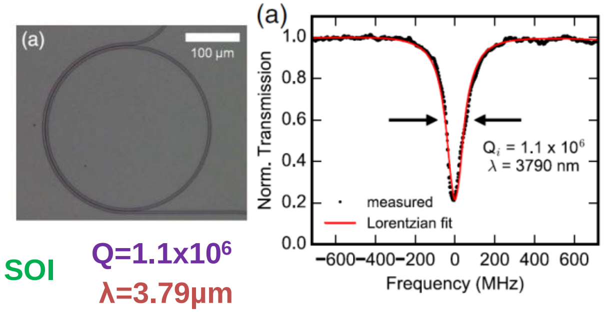

SOI $Q=1.1\times10^6$ $\lambda=3.79\mu m$

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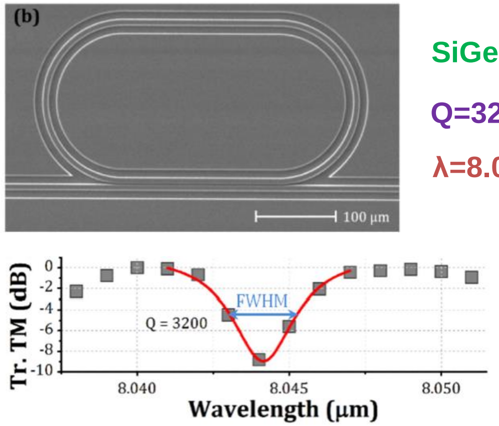
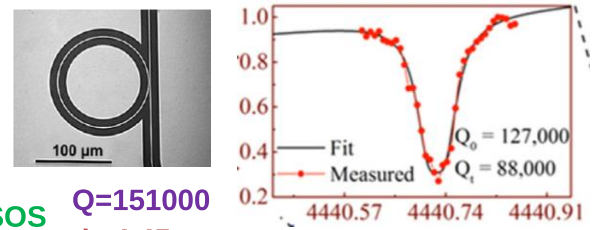


SiGe

Q=3200

$\lambda=8.0\mu m$

J.M. Ramirez et al., Opt. Lett. 44(2), 407-410 (2019)



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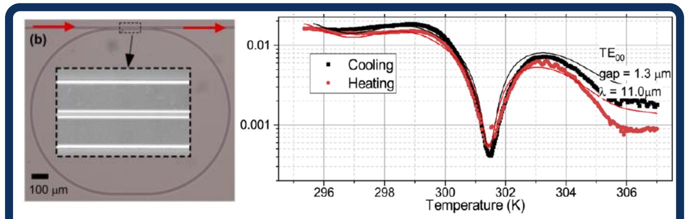
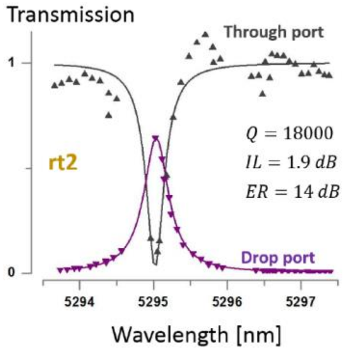


Ge Q=10000 $\lambda=11\mu m$

D.A. Kozak et al., Opt. Exp. 29(10), 15443 (2021)

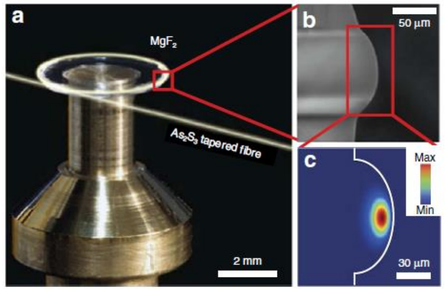


Ge

Q=18000

$\lambda=5.3\mu m$

S. Radosavljevic et al., Opt. Mat. Exp. 8(4), 824 (2018)



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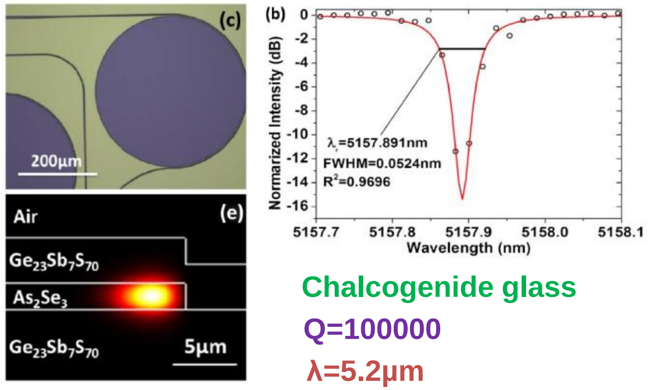

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$\lambda=5.2\mu m$

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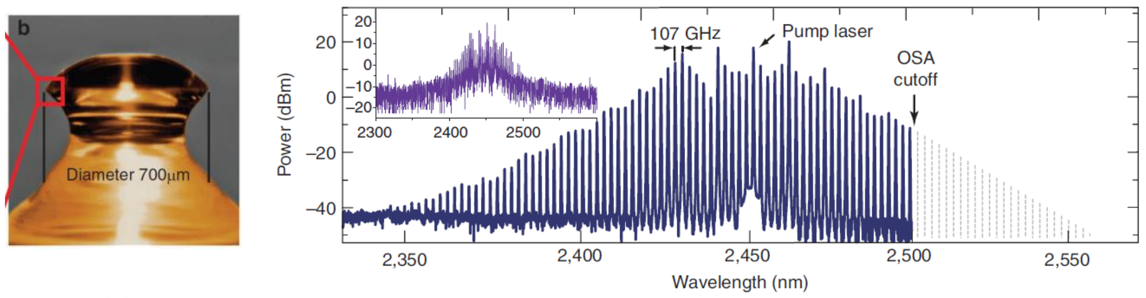
- Demonstrations of combs in the MIR have the same problems as cavities:
  - No integrability
  - No CMOS compatibility
  - Not sufficiently long λ



Fluoride crystalls λ_{max}=2.5µm

C.Y. Wang et al., Nat. Comm. 4:1345 (2013)

Frequency Combs in the MIR

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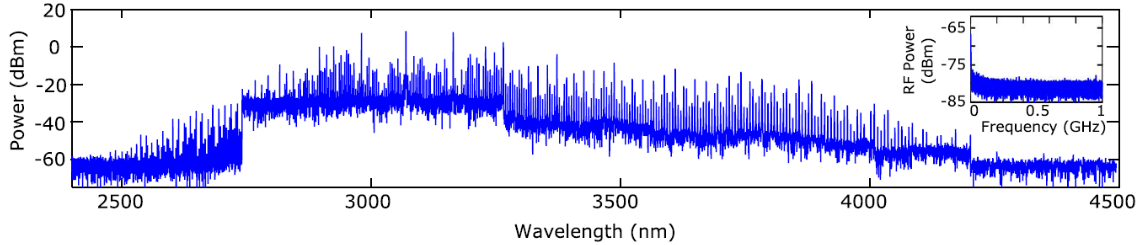
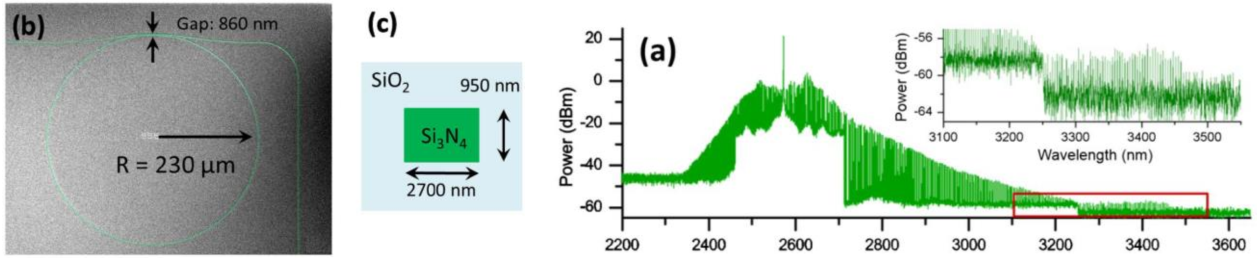


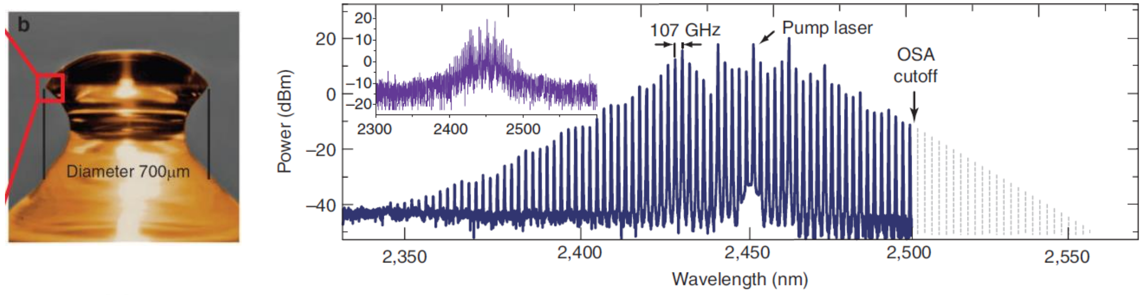
M. Yu et al., Optica 3(8), 854 (2016)

SOI λ_{max}=4.3μm



K. Luke et al., Opt. Lett. 40(21), 4823 (2015)

Si_3N_4 λ_{max}=3.5μm



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Si

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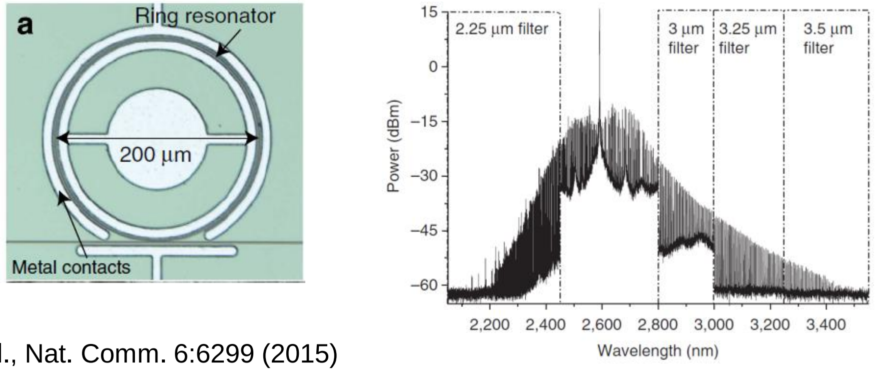
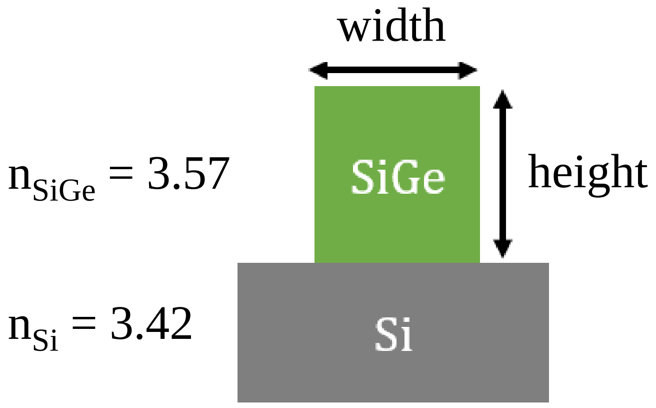
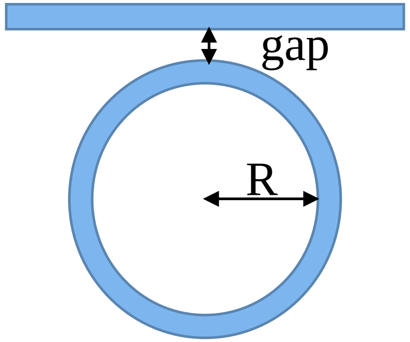


A.G. Griffith et al., Nat. Comm. 6:6299 (2015)

Ring Design - Targets

- Suitable for frequency comb generation
  - Anomalous dispersion required
  - This will determine width/height





- Suitable for frequency comb generation
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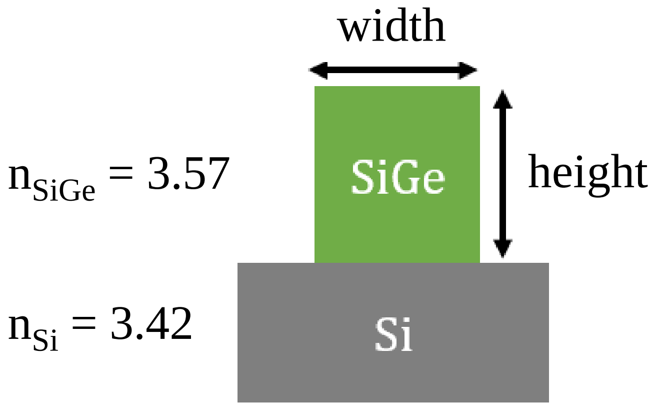
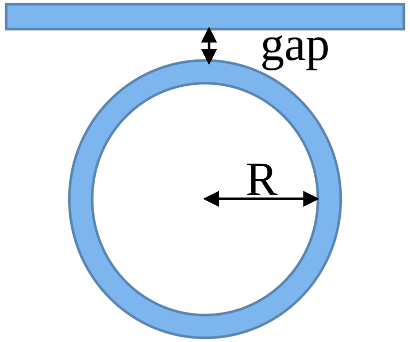
- Have a free spectral range (FSR) useful for sensing applications
  - R = 250µm (FSR of 53GHz)





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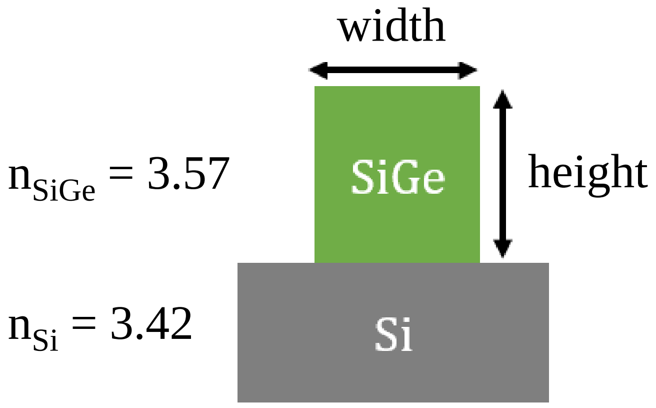
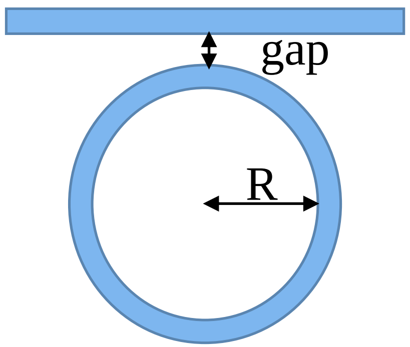
- High Q
  - Reduce bending loss, lower bound for R = 250µm





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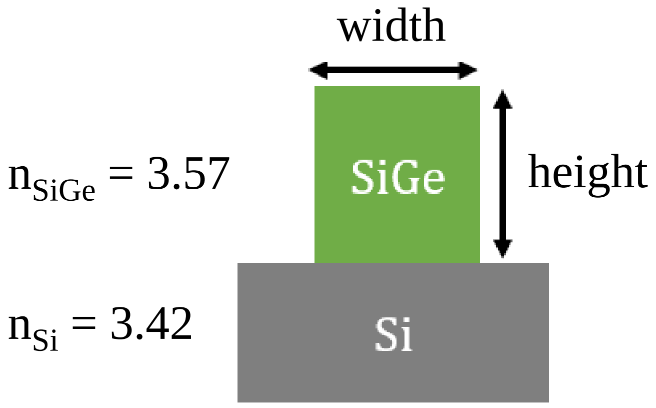
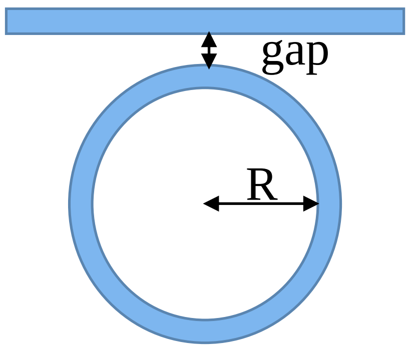
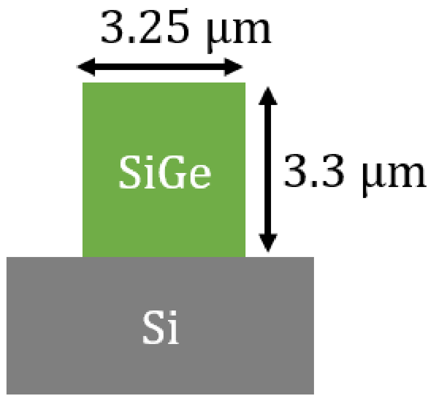
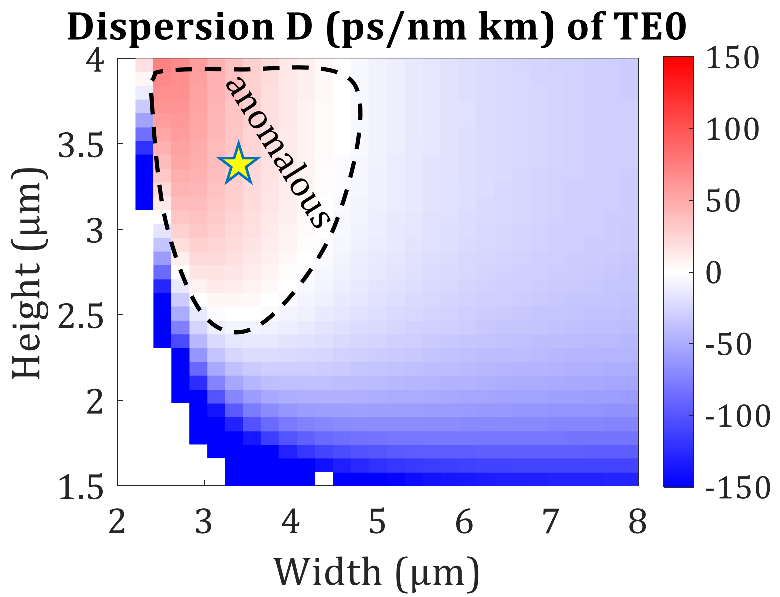
  - Reduce bending loss, lower bound for R = 250µm
- Aiming for critical coupling
  - gap = 250nm (smallest achievable gap in fabrication)

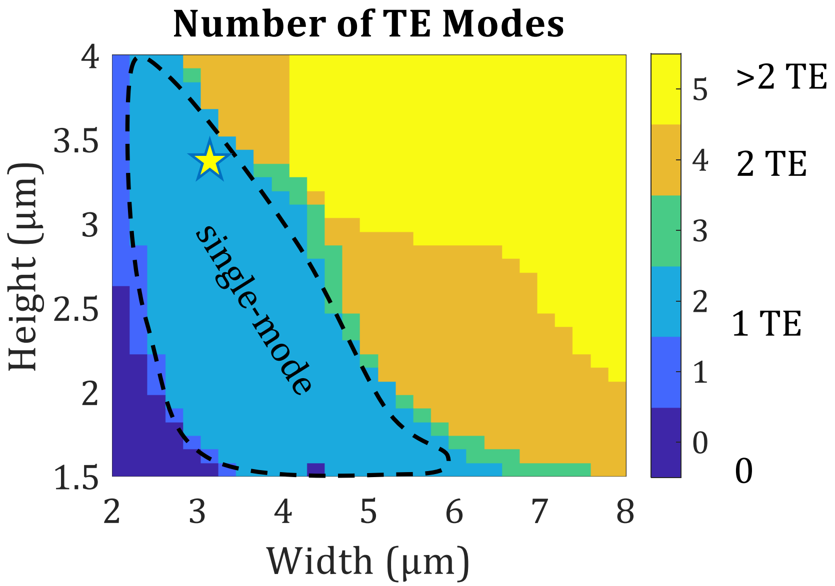




- Operating in TE polarization
- Pump wavelength λ = 4.18µm
- Single-mode
- Sufficiently large region with anomalous dispersion

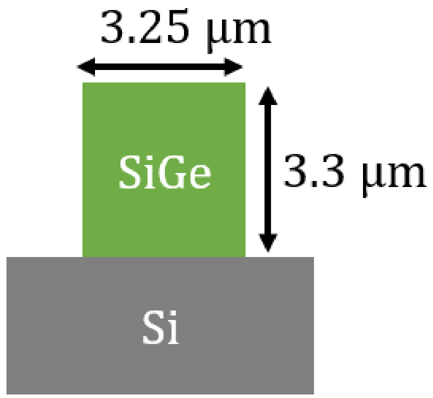


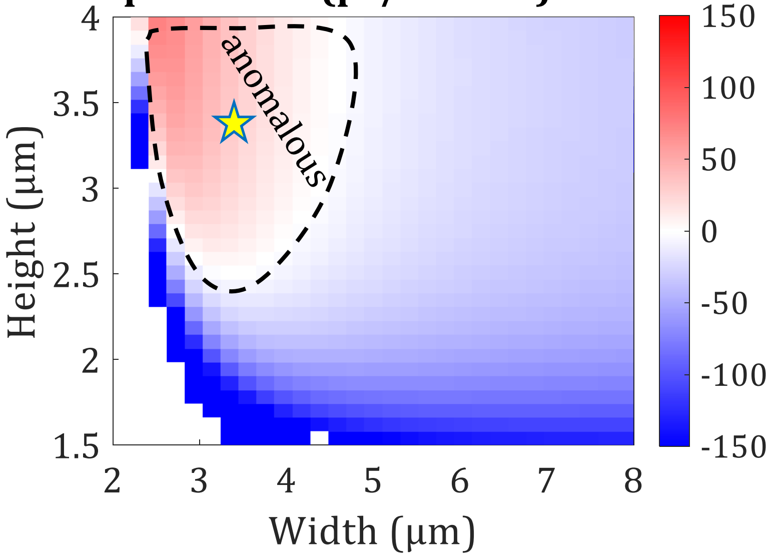


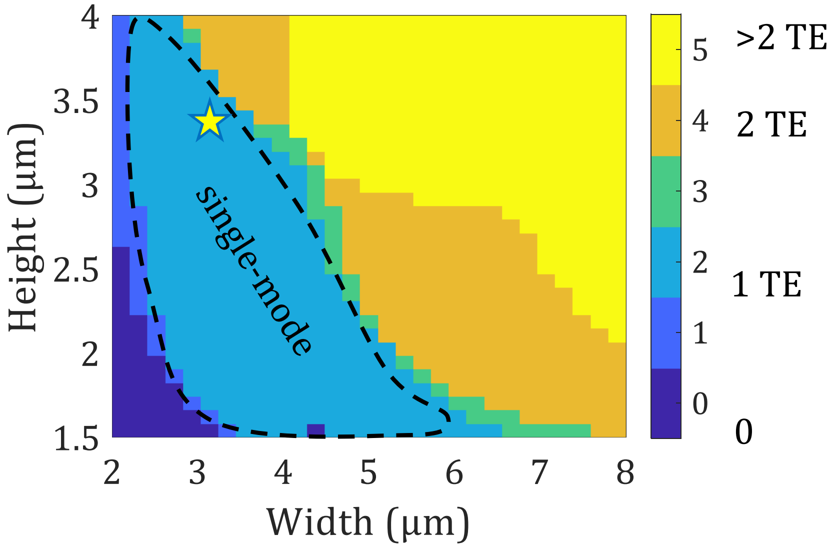


Waveguide Design - Dispersion

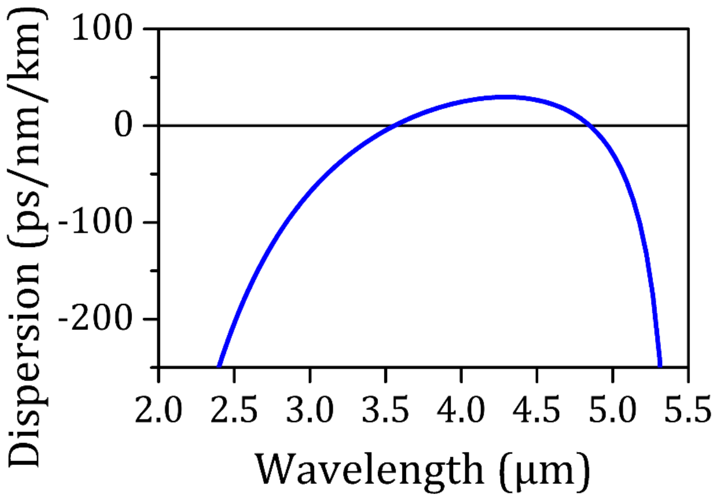
- Operating in TE polarization
- Pump wavelength λ = 4.18µm
- Single-mode
- Sufficiently large region with anomalous dispersion





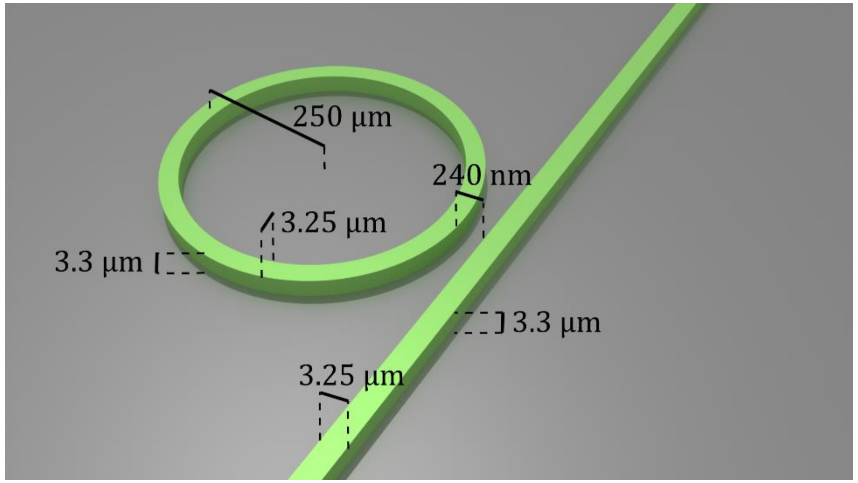


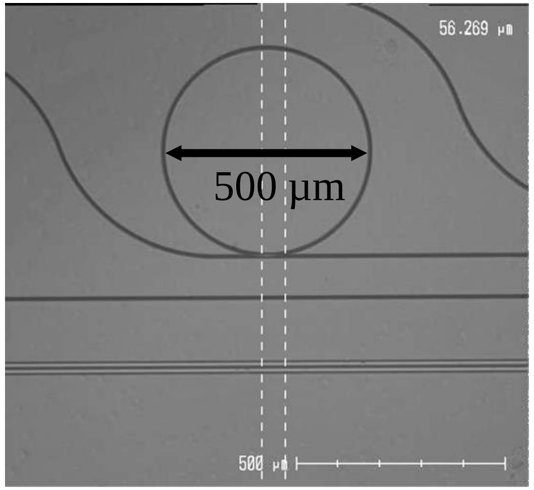
Dispersion for w=3.25µm, h=3.3µm:



Ring Fabrication

- $Si_{0.6}Ge_{0.4}$ waveguide (air-cladded) on Si substrate
- Deep UV photolithography
- 200mm CMOS pilot line at CEA-Leti

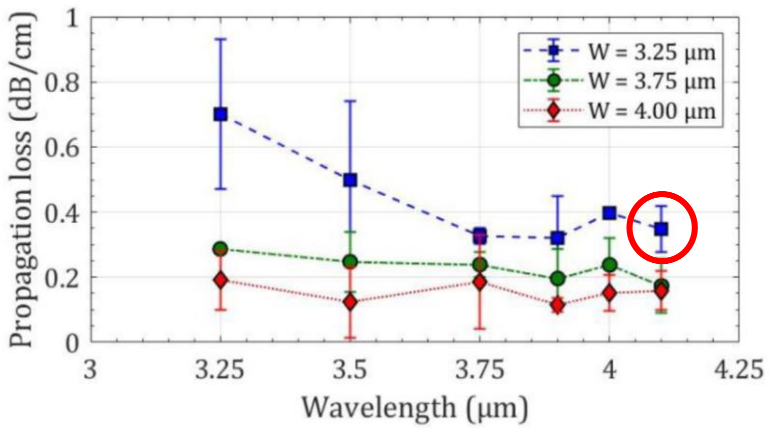




	Radius (µm)	Width (µm)	Gap (nm)
Range of parameters	80, 130, 180, 250	3.25, 3.50, 3.75	250, 500, 750, 1000
Featured value	250	3.25	250

Propagation loss:

- Loss measurement from spirals with different lengths (TE)
- 0.35 dB/cm propagation loss for w = 3.25µm
  - Estimated Q_{int} = 680,000
- Even 0.18 dB/cm for w = 3.75 µm, but difficult to couple



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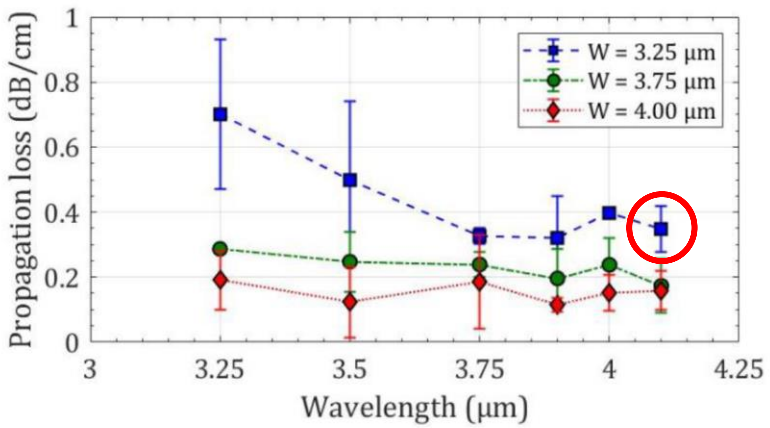
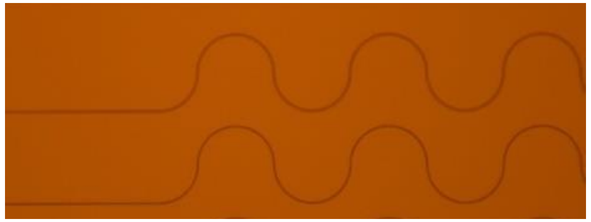
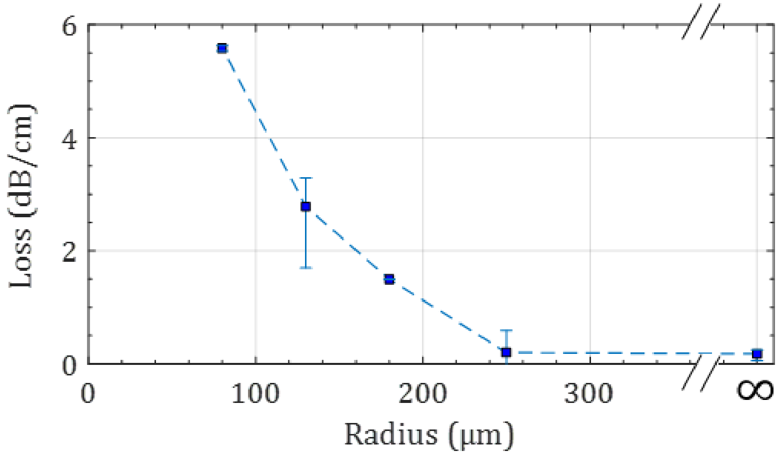


Bending loss:

- Loss measurement from snake waveguides (TE)
- R=250μm shows almost no difference to straight waveguide

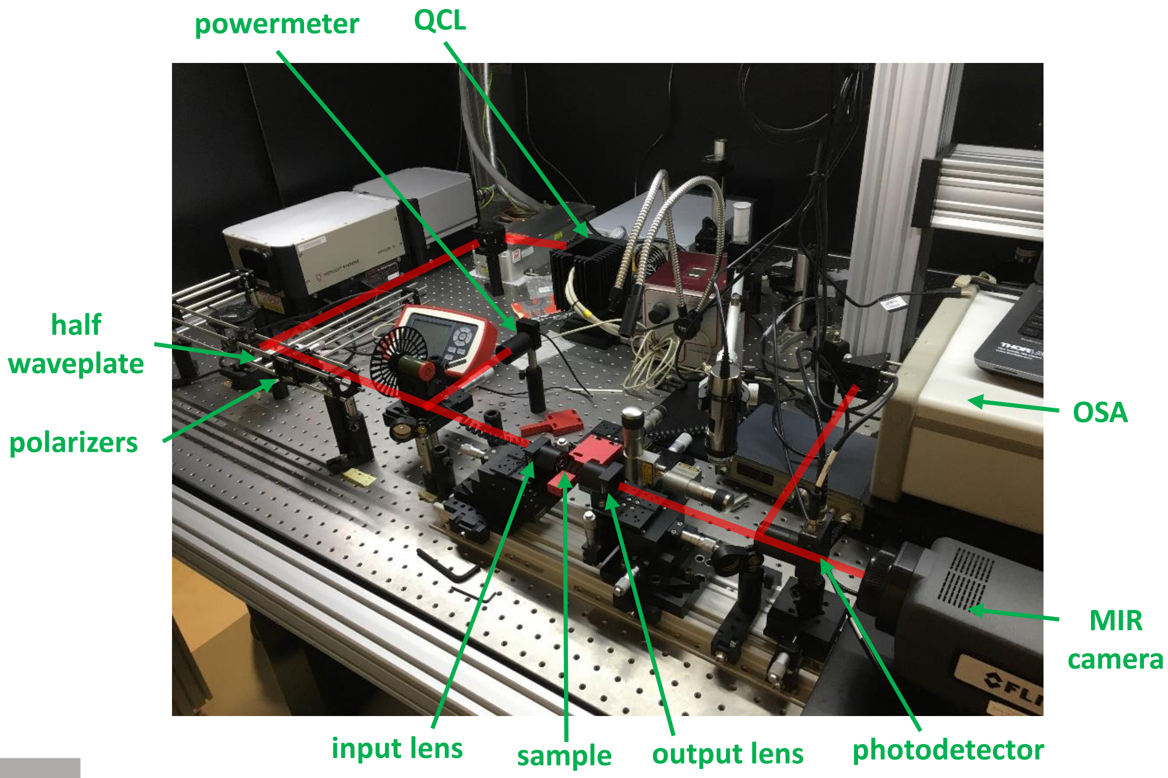


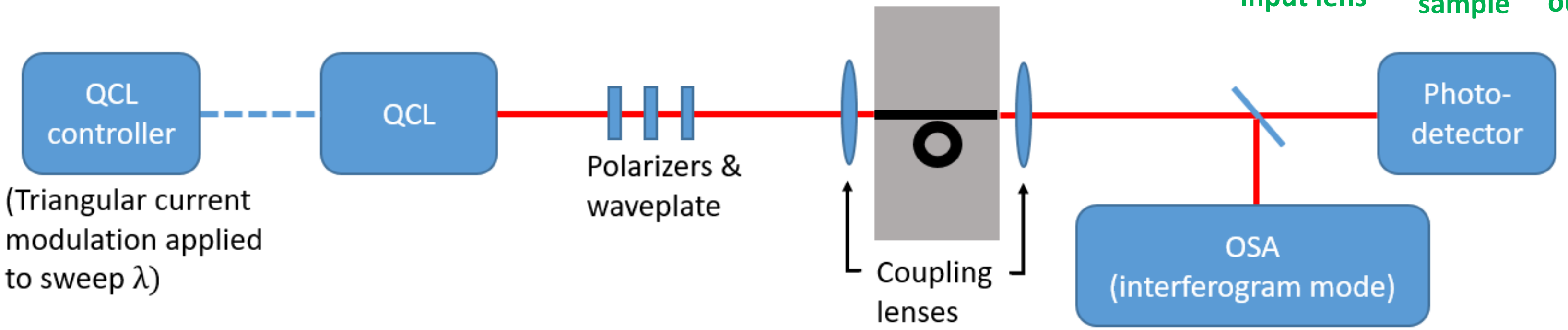


Measurement Setup

Q-factor characterization

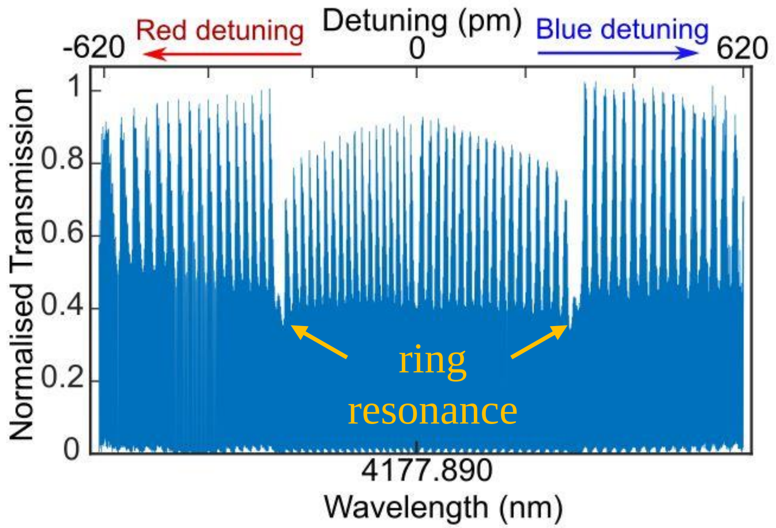
- cw QCL around 4.18µm
- But-coupling to the chip
- Wavelength sweep (4177.58 ± 0.31) nm (periodic, achieved by triangular current modulation)
- Coupled power: 20 mW (side effect: there is also a power modulation)





First High-Q Ring on SiGe in the MIR

- Spectrum shows ring resonance and Fabry-Perot resonances from chip facets



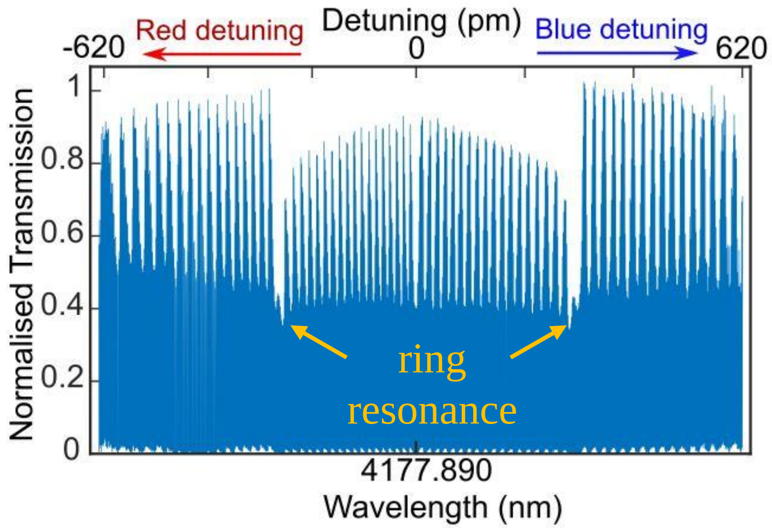
Fabry-Perot cavity from
partially reflecting facets

Q-Factor Measurement

First High-Q Ring on SiGe in the MIR

- Spectrum shows ring resonance and Fabry-Perot resonances from chip facets
- Fourier filtering to remove Fabry-Perot effect
- FWHM = 23pm (corresponds to Q_{tot} = 176,000)

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{coup}} + \frac{1}{Q_{int}}$$



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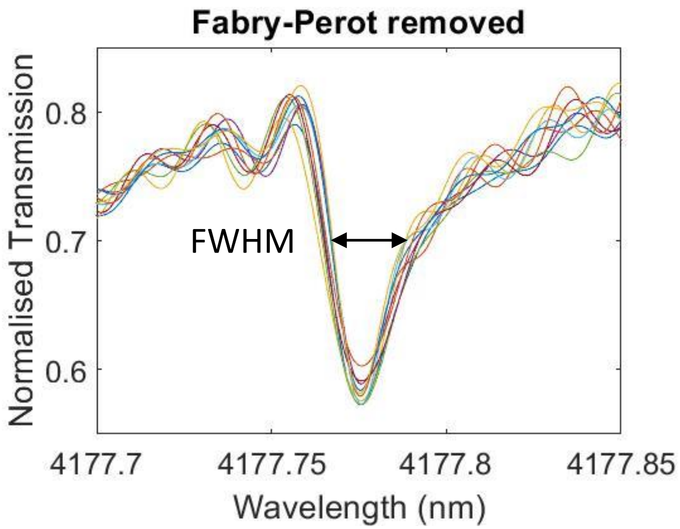
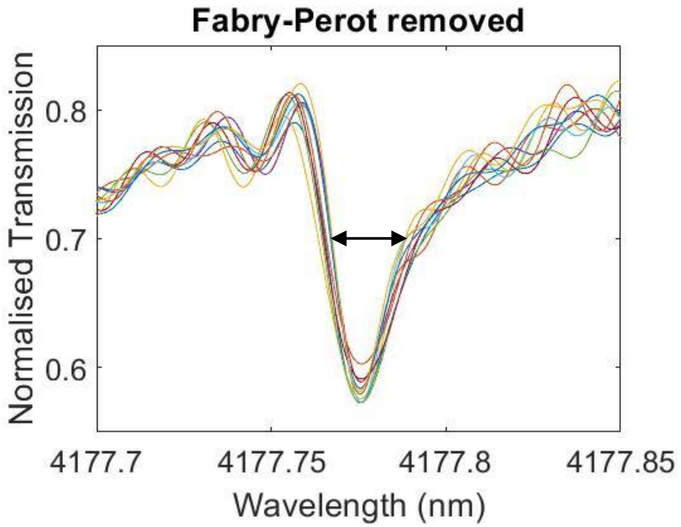


First High-Q Ring on SiGe in the MIR

- Resonance had Fano shape
- Fitting Fano function [1]:

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

σ – spectrum
q = cot(δ) Fano parameter
δ – phase shift between coupled states
$D = 4\sin^2(\delta)$
$\Omega = 2(E-E_0)/\Gamma$
Γ – resonance width
E_0 – resonance energy



[1] M.F. Limonov et al, *Fano resonances in photonics*, Nature photonics vol. 11, pp. 543-554, 2017

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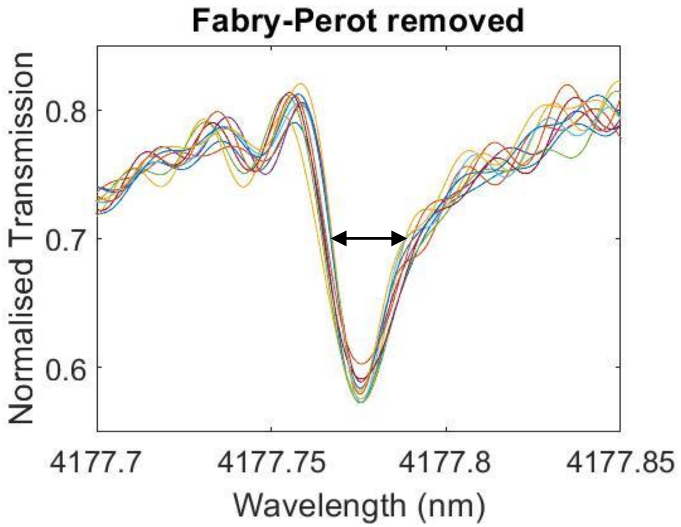
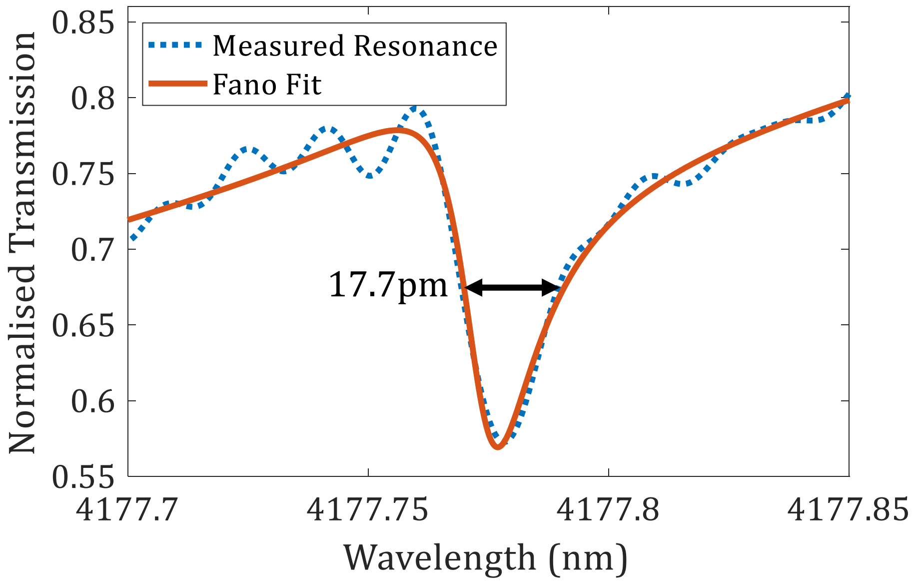
- $\Gamma = 17.7$ pm ($Q_{tot} = 236{,}000$)





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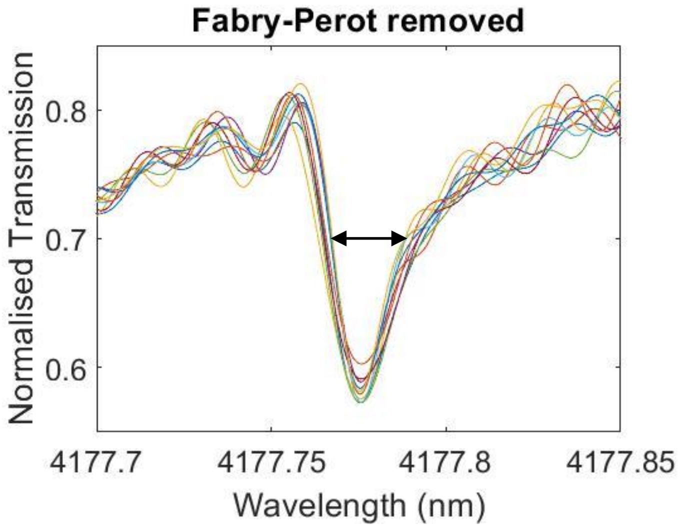
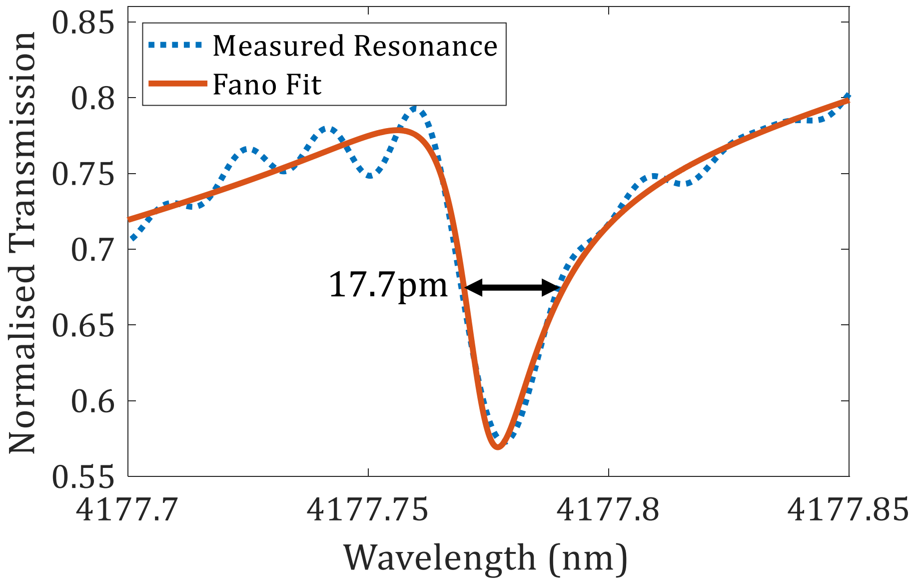
- Γ = 17.7 pm (Q_{tot} = 236,000)
- Nature of Fano resonance not entirely clear





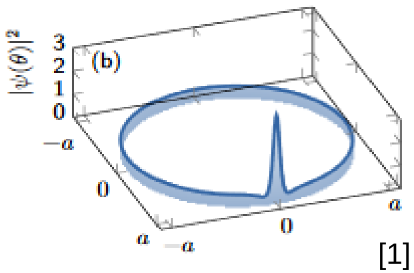
[1] M.F. Limonov et al, *Fano resonances in photonics*, Nature photonics vol. 11, pp. 543-554, 2017

Using our Experimental Q-factor Results for the Rings

Lugiato-Lefever equation

$$\frac{d\psi}{dt} = -(1+i\alpha)\psi + i|\psi|^2\psi - i\frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F$$

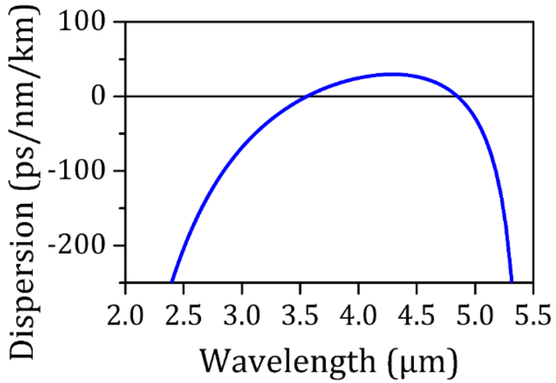
ψ – Intracavity field
F – External pump field intensity
θ – azimuthal angle along circumference
α – frequency detuning
β – dispersion parameter
(Loss is included in α and β)



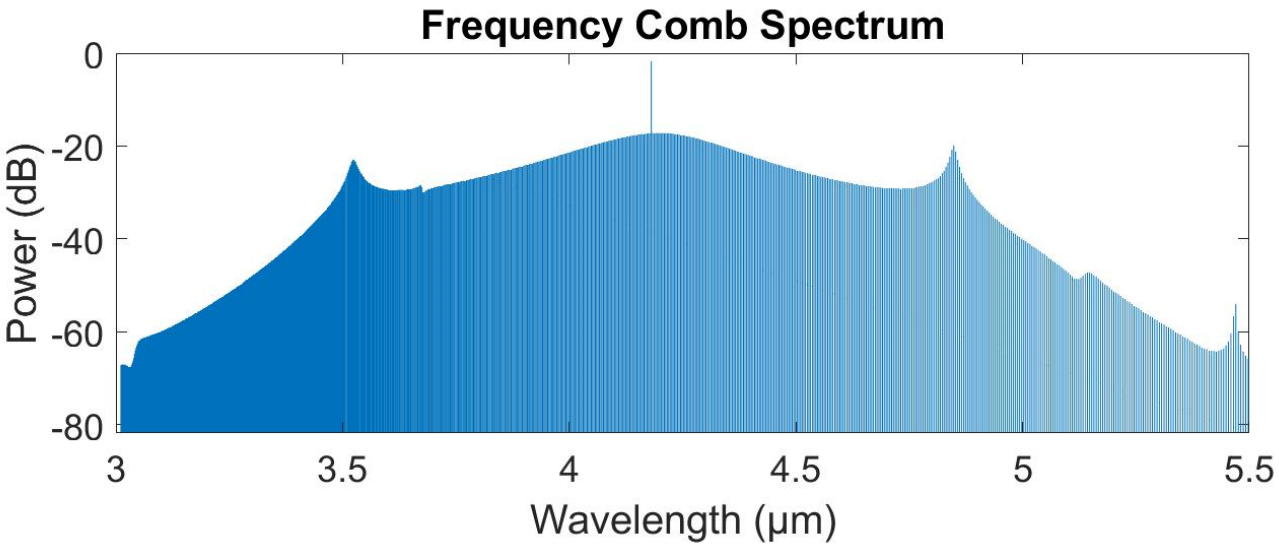
[1]

Simulation taking into account ring parameters:

- R = 250 µm
- Q = 236,000
- Waveguide nonlinear parameter $\gamma = 0.63\ W^{-1}m^{-1}$
- Threshold pump power $P_{th} = 200$ mW
- Waveguide dispersion (simulated):



Soliton state at $P = 1.5\ P_{th}$:



[1] C. Godey et al., Phys. Rev. A 86, 063814 (2014)

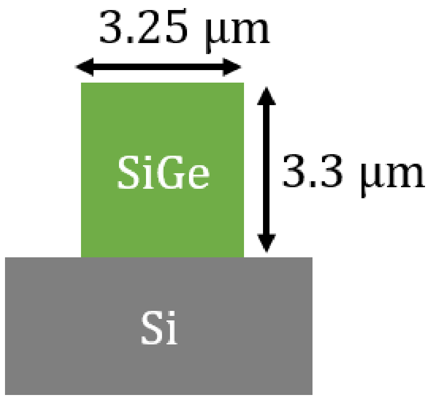
Summary and Future Work

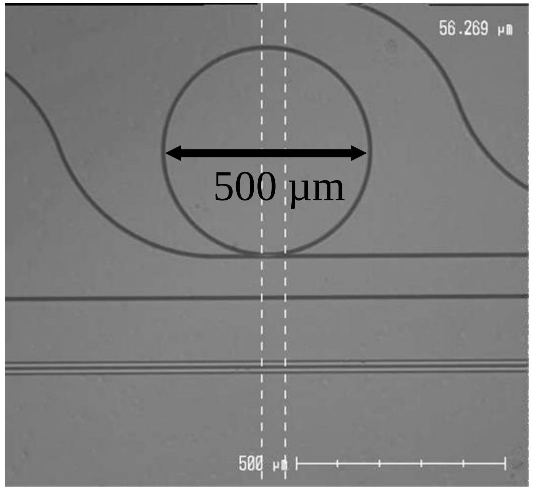
- First demonstration of an integrated high-Q ring resonator on SiGe in the MIR

- Loaded Q_{tot} = 236,000 at λ = 4.18µm (intrinsic Q higher)

- Next batch will start fabrication soon (improved designs)

- Rings show great potential to be used for Kerr frequency comb generation very soon (now already promising for linear sensing applications)





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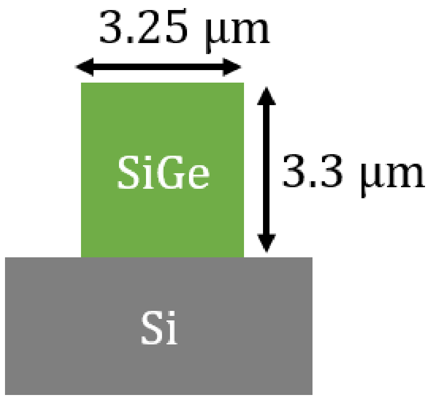
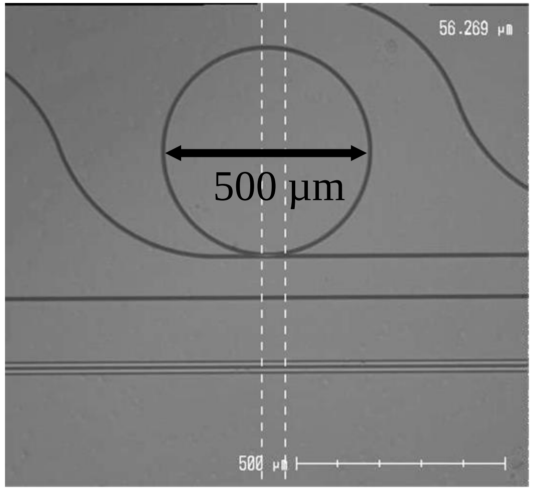
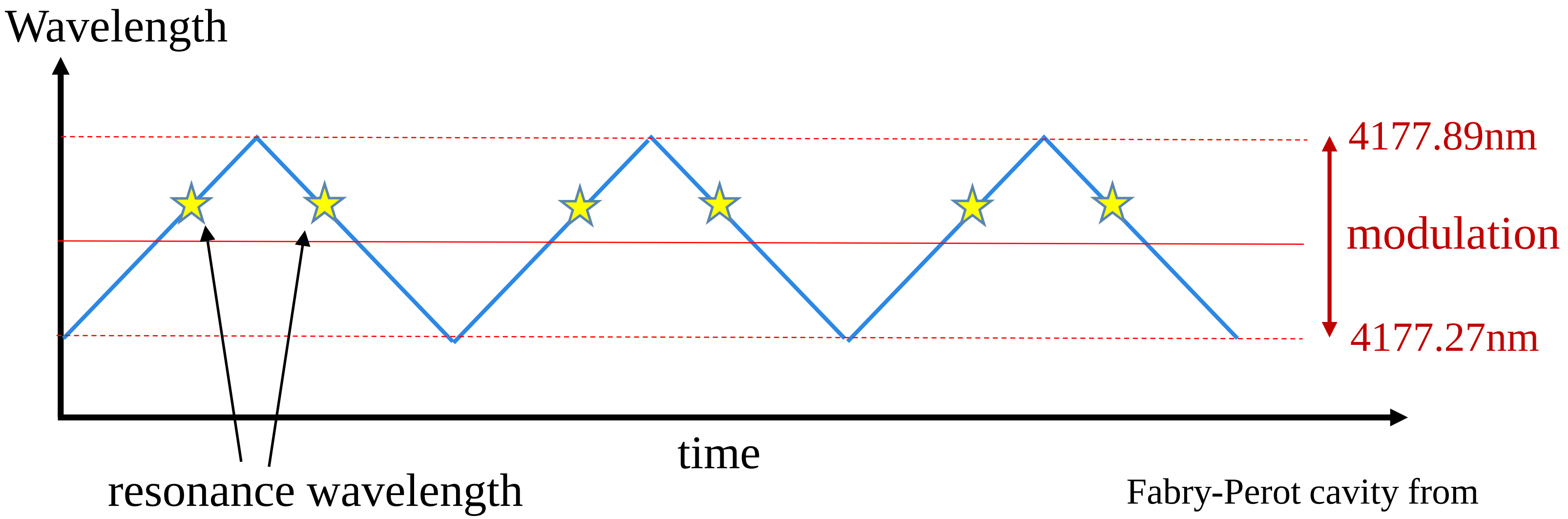


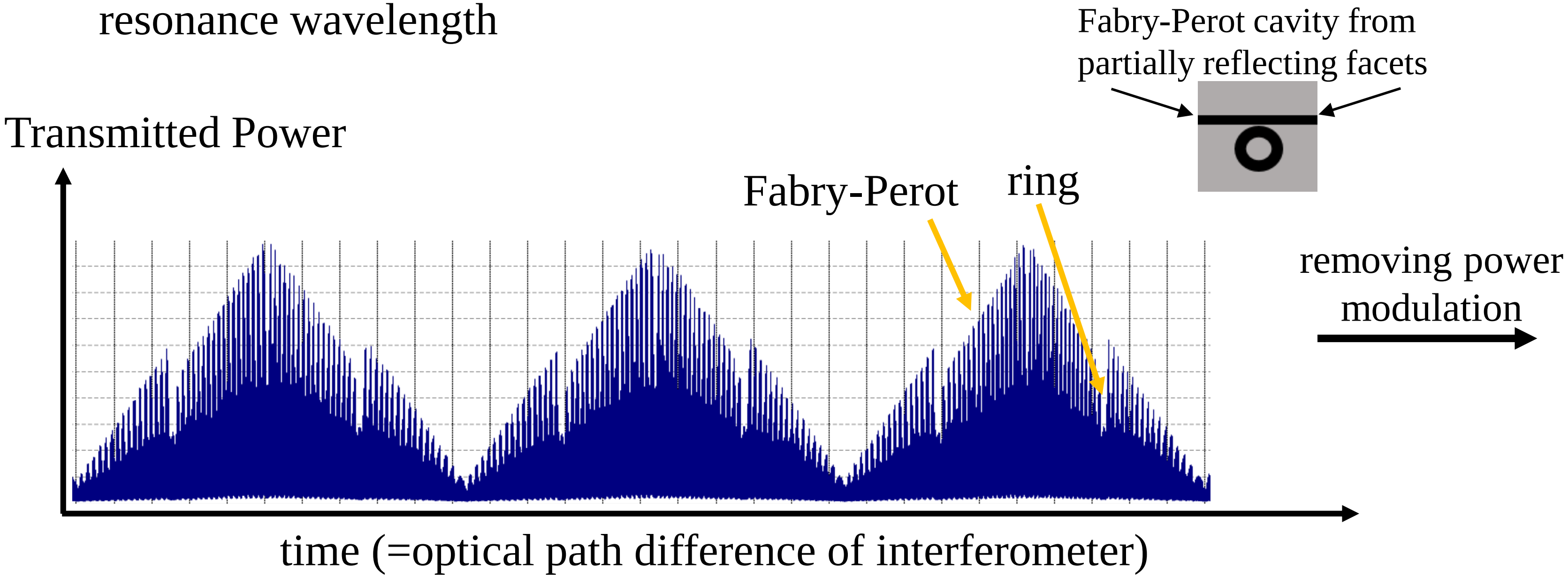


Thank you for your attention! Questions?

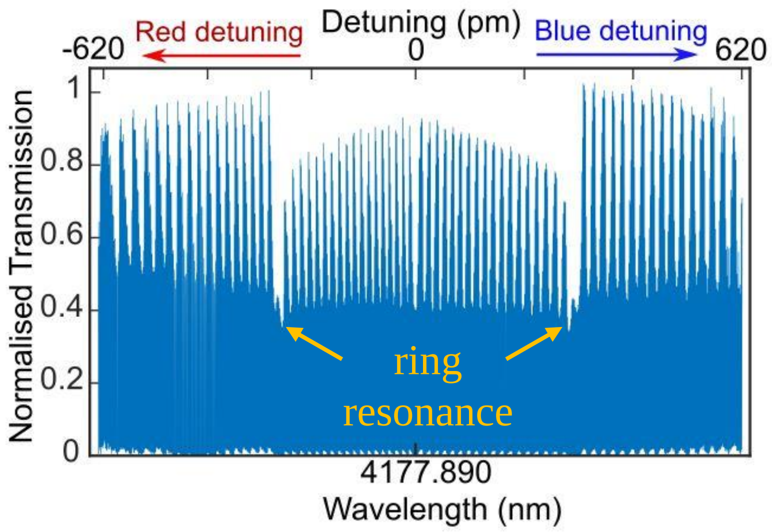
Backup Slides

Q-Factor Measurement Principle





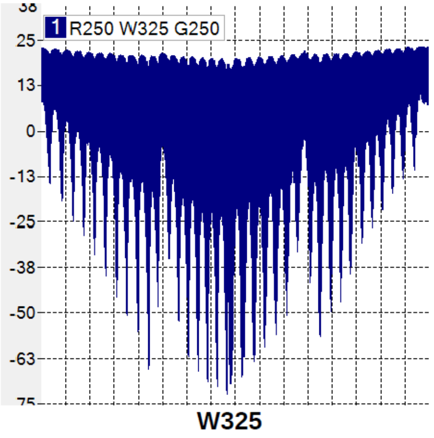
- Spectrum shows ring resonance and Fabry-Perot resonances from chip facets
- Ring resonance can be isolated

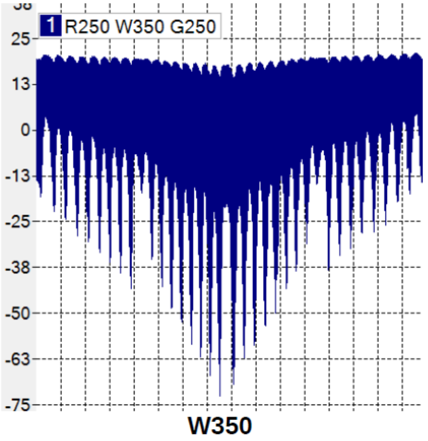


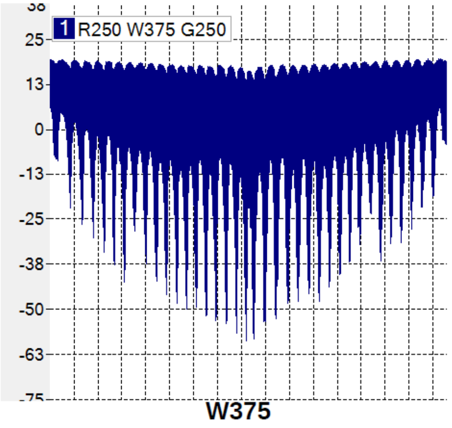
Investigation of Other Parameters

- Investigation of different radii, gaps, widths:
  - Q is decreasing if R goes below 250µm due to increased bending loss
  - Critical coupling likely not reached yet (no resonance observed for gap > 250nm)
  - Resonance depth weakens for increasing w=3.25, 3.50, 3.75µm

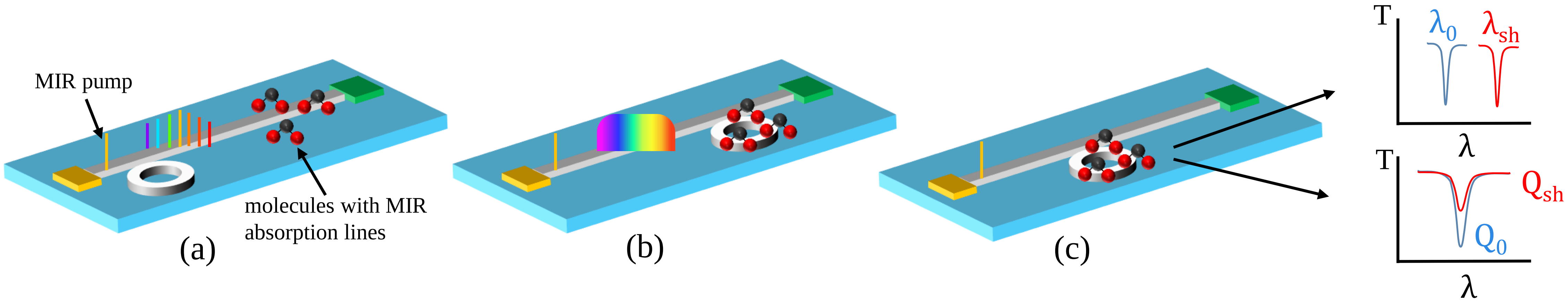
Increasing waveguide width







Many Different Sensing Schemes



Rings for Kerr frequency combs generation

(broadband light source for sensing)

Rings for enhancement of light-molecule interaction (for example with a supercontinuum source)

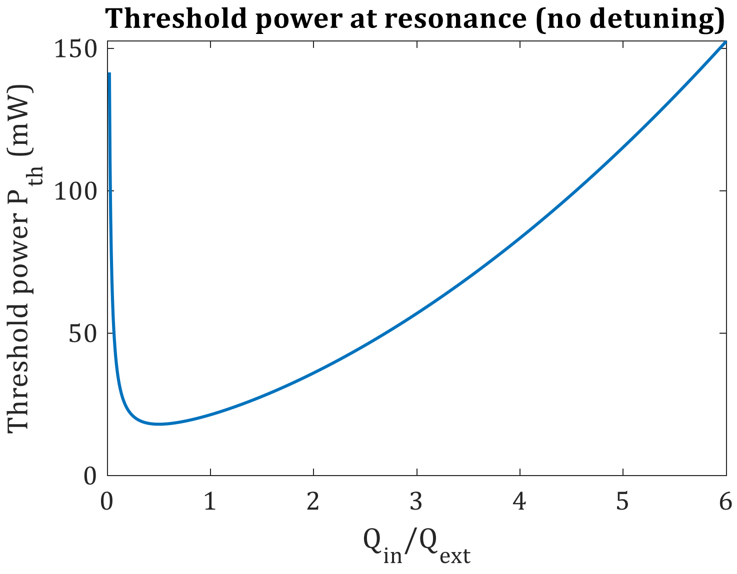
Rings as sensors through
- Shift in resonance wavelength
- Shift of Q-factor

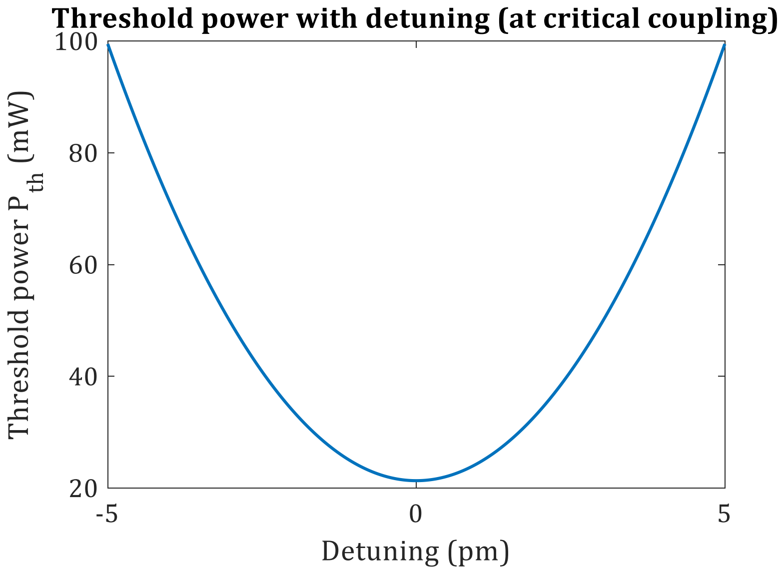
Threshold Power

Calculated for our scenario

$$P_{th}(resonance) = \frac{\pi n_g^2 L A_{eff}}{4\lambda n_2 Q_{in}^2} \frac{(1+K)^3}{K}$$

$$P_{th} = P_{th}(resonance) + \frac{n_g^2 L A_{eff}(\omega - \omega_0)^2}{2 n_2 \omega c}\left(1 + \frac{1}{K}\right)$$ [1]





Used parameters:

- Wavelength λ = 4.18 μm
- Ring radius R = 250 μm
- Q = 236,000
- Q_{in} = 1,600,000
- Group index $n_g = 3.67$
- Mode area $A_{eff} = 6.87\ \mu m^2$
- $n_2 = 4x10^{-14}\ \frac{cm^2}{W}$ (Optica paper)

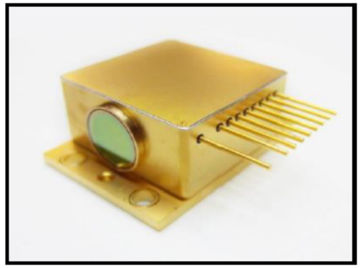
[1] P.-S.Wang et al.,*Sci Rep* 11.1 (2021): 1-10.

QCL

ADTECH PHOTONICS

4.18 µm Distributed Feedback (DFB) QCL

Part No: **HHL-19-64**

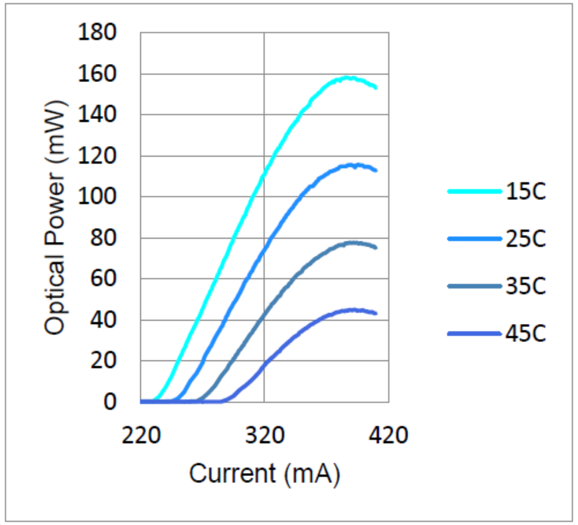


High Heat Load (HHL) Package

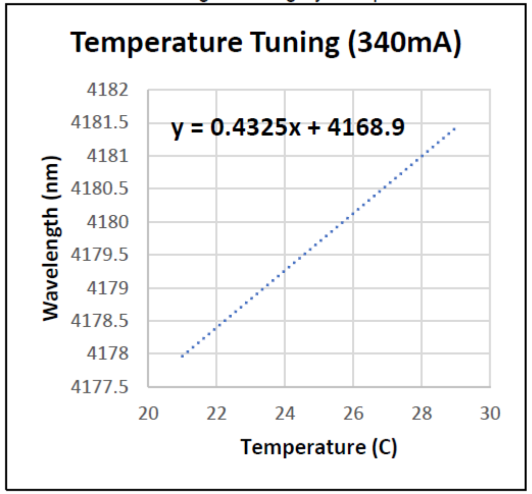
Features

- Pulse or CW operated lasers
- Thermo-electrically cooled. External heat sink still required.
- Sensitive to electrostatic discharge, must have standard ESD precautions during handling
- Package dimensions (approx): 44.5 x 31.8 x 18.4 mm (excluding pins)

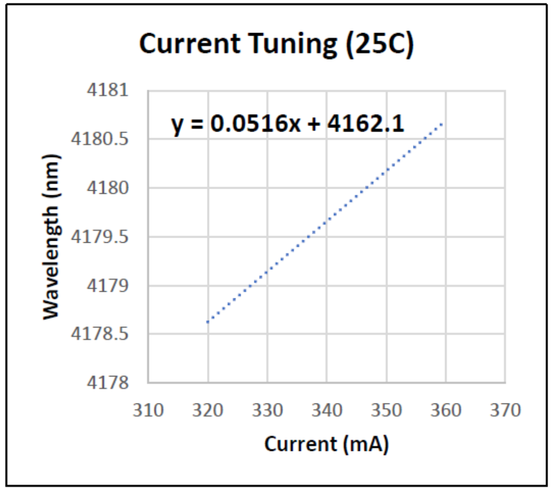
L-I curve under CW



Wavelength Tuning by Temperature

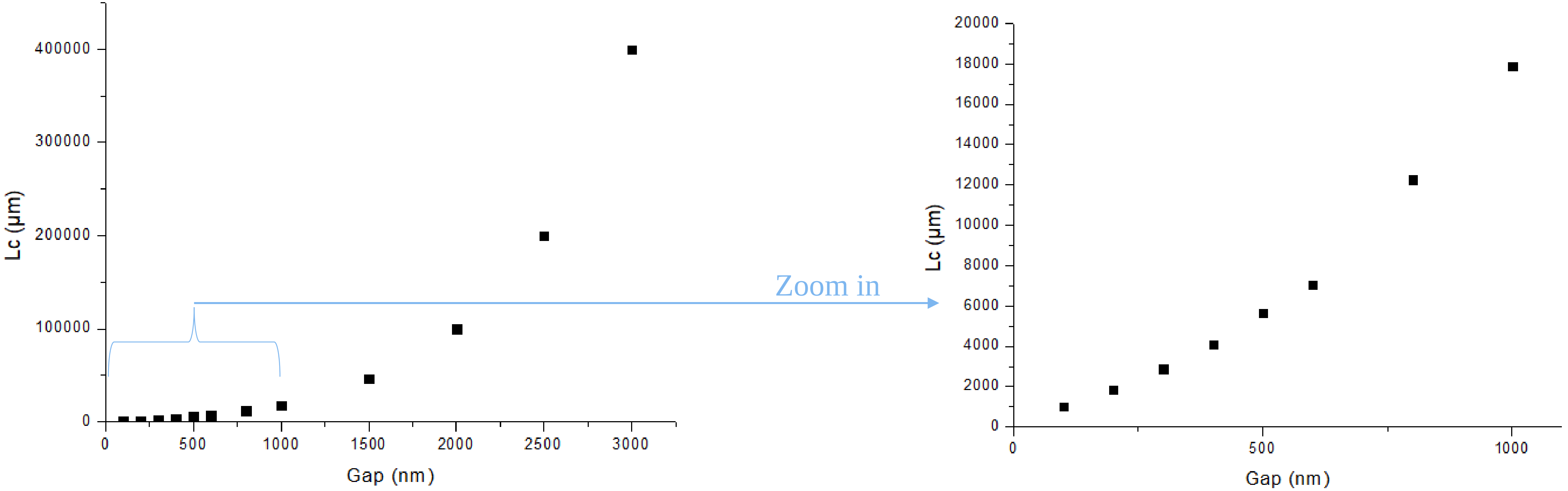


Wavelength Tuning by Current

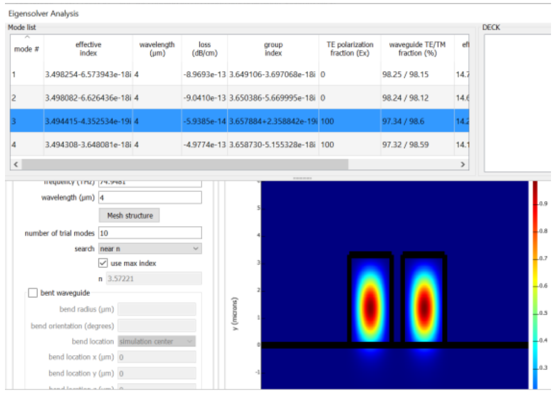


Simulation of Straight Directional Coupler

Dependence on Coupling Gap

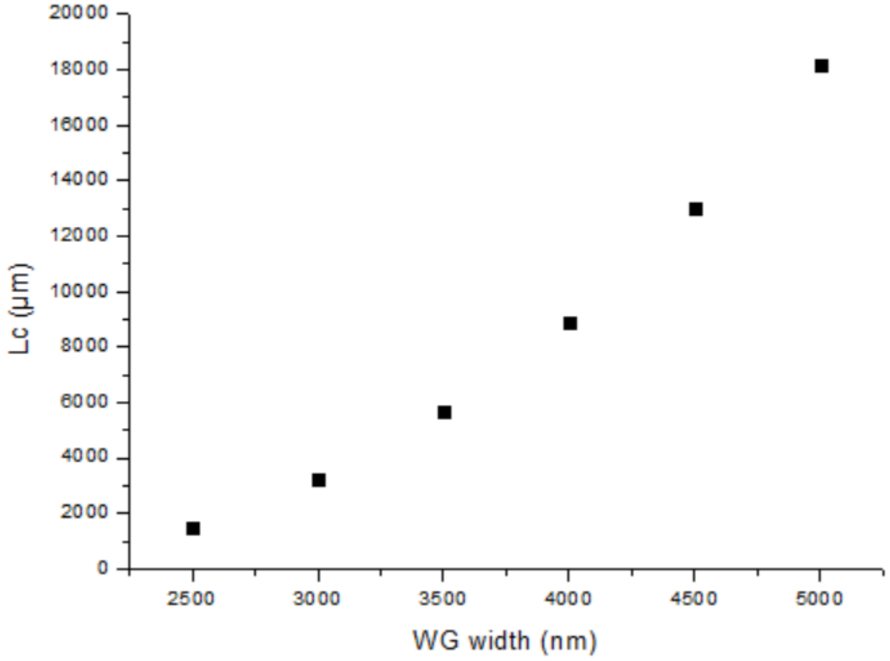


- Example for the following parameters: λ=4µm, width=3.5µm, height 3.3µm, SiGe-on-Si
- Calculation performed in Lumerical
- $L_C = \dfrac{\lambda_0}{2\,\Delta n_{eff}}$ where Δn_{eff} is the difference between the two supermodes



Simulation of Straight Directional Coupler

Dependence on Waveguide Width



Example for the following parameters: λ=4µm, height=3.3µm, gap=500nm, SiGe-on-Si

Calculation performed in Lumerical with the method from the previous slide

Conclusion: As expected intuitively, the coupling strength decreases with increasing waveguide with (the two mode centers are further apart and the evanescent field is weaker)

Comparison of our Coupling with Literature

Some Examples of Coupling Lengths of SiGe and Ge resonators from Literature

Letter Vol. 44, No. 2 / 15 January 2019 / Optics Letters 407

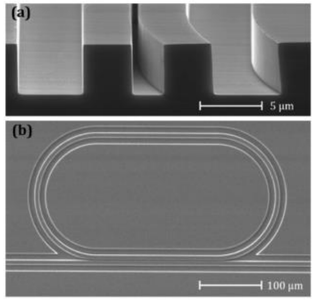
Optics Letters

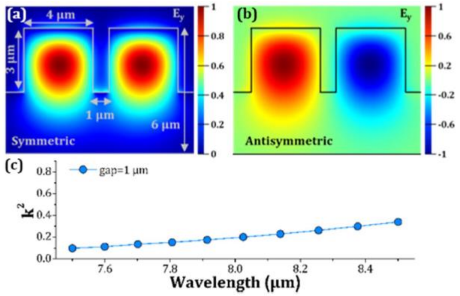
Broadband integrated racetrack ring resonators for long-wave infrared photonics

Joan Manel Ramirez,[1,*] Qiankun Liu,[1,†] Vladyslav Vakarin,[1,†] Xavier Le Roux,[1] Jacopo Frigerio,[2] Andrea Ballabio,[2] Carlos Alonso-Ramos,[1] Enrico Talamas Simola,[2] Laurent Vivien,[1] Giovanni Isella,[2] and Delphine Marris-Morini[1]

[1]Centre de Nanosciences et de Nanotechnologies (C2N), Université Paris Sud, CNRS, Université Paris Saclay, 91405 Orsay, France
[2]L-NESS, Dipartimento di Fisica, Politecnico di Milano, Polo di Como, Via Anzani 42, 22100 Como, Italy
*Corresponding author: joan.ramirez@3-5lab.fr

Long-wave infrared photonics is an exciting research field meant to revolutionize our daily life by means of key advances in several domains including communications, imaging systems, medical care, environmental monitoring, or multispectral chemical sensing, among others. For this purpose, integrated photonics is particularly promising owing to its compactness, mass fabrication, and energy-efficient characteristics. We present in this Letter, for the first time to the best of our knowledge, broadband integrated racetrack ring resonators operating within the crucial molecular fingerprint region. Devices show an operation bandwidth of $\Delta\lambda \approx 900$ nm with a central wavelength of $\lambda \approx 8$ µm, a quality factor of $Q \approx 3200$, and an extinction ratio of ER ≈ 10 dB around the critical coupling condition. These resonant structures establish the basis of a new generation of integrated building blocks for long-wave infrared photonics that opens the route towards miniaturized multi-target molecule detection systems.





$g = 1$ µm

$L = 200$ µm

Ge-rich SiGe

Simulation Lumerical: L_c=1800µm

Research Article Vol. 8, No. 4 | 1 Apr 2018 | OPTICAL MATERIALS EXPRESS 824

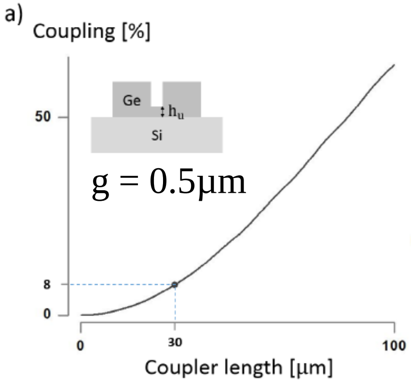
Optical Materials EXPRESS

Mid-infrared Vernier racetrack resonator tunable filter implemented on a germanium on SOI waveguide platform [Invited]

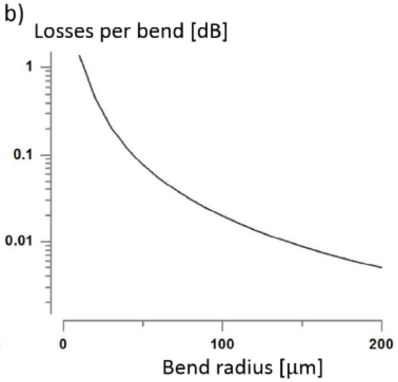
Sanja Radosavljevic,* Nuria Teigell Beneitez, Andrew Katumba, Muhammad Muneeb, Michael Vanslembrouck, Bart Kuyken, and Gunther Roelkens

Photonics Research Group, Ghent University - imec, Technologiepark 15, 9052 Ghent, Belgium
Center for Nano- and Biophotonics, Technologiepark 15, 9052 Ghent, Belgium
sanja.radosavljevic@ugent.be

Abstract: Currently, most widely tunable lasers rely on an external diffraction grating to tune the laser wavelength. In this paper we present the realization of a chip-scale Vernier tunable racetrack resonator filter on the Ge-on-SOI waveguide platform that allows for wide tuning (108 nm free spectral range) in the 5 µm wavelength range without any moving parts. The fabricated racetrack resonators have a loaded Q-factor of 20000, resulting in a side-peak suppression of more than 20 dB, which is more than sufficient for wavelength selection in an external cavity laser.



g = 0.5µm



Simulation Lumerical: L_c=251µm

610 Vol. 41, No. 3 / February 1 2016 / Optics Letters Letter

Optics Letters

Germanium-on-silicon Vernier-effect photonic microcavities for the mid-infrared

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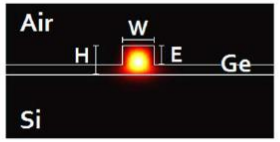
We present Vernier-effect photonic microcavities based on a germanium-on-silicon technology platform, operating around the mid-infrared wavelength of 3.8 µm. Cascaded racetrack resonators have been designed to operate in the second regime of the Vernier effect, and typical Vernier comb-like spectra have been successfully demonstrated with insertion losses of ~5 dB, maximum extinction ratios of ~23 dB, and loaded quality factors higher than 5000. Furthermore, an add–drop racetrack resonator designed for a Vernier device has been characterized, exhibiting average insertion losses of 1 dB, extinction ratios of up to 18 dB, and a quality factor of ~1700.

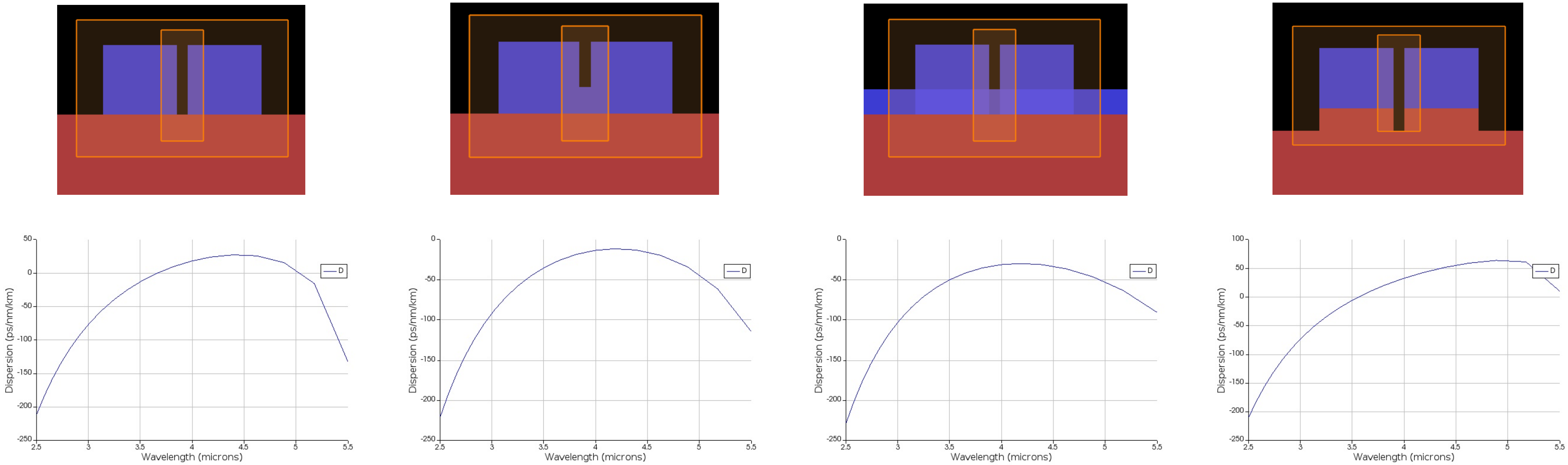


	Vernier #A		Vernier #B	
Parameters	RR #A1	RR #A2	RR #B1	RR #B2
L (µm)	439.60	449.60	1039.30	1079.10
R (µm)	59	59	142	149
L_i (µm)	34.44	39.44	73.54	71.45
g_0 (nm)	450	450	650	650

Simulation Lumerical: $L_{c,TE}$=562µm, $L_{c,TM}$=520µm

Conclusion: The typical coupling lengths in literature for comparable platforms are lower than ours. But this likely comes from some differences, like gap underetching. So this is something we can also try if we want to increase the coupling

Dispersion Comparison for Different Etch



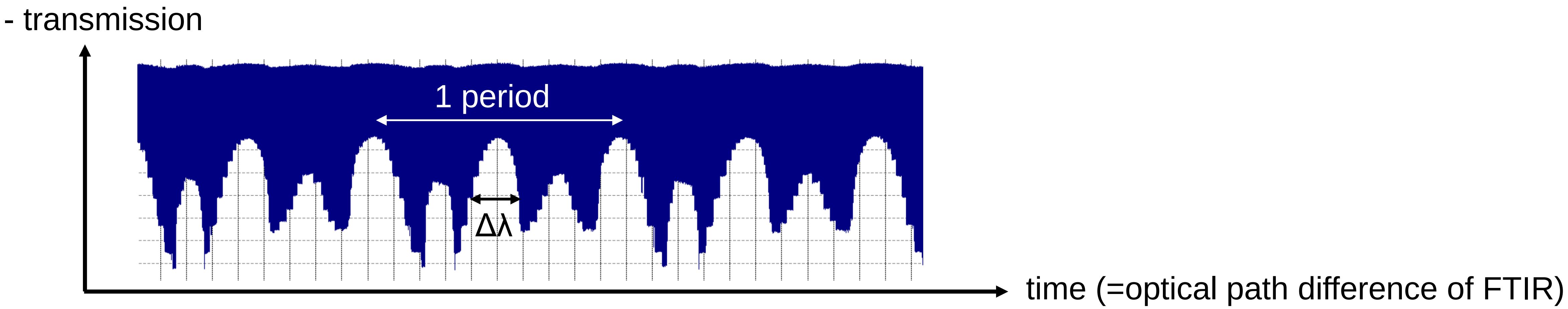
Example for the following parameters: width=3.5µm, gap=500nm, SiGe-on-Si

Calculation performed in Lumerical

Conclusion: Underetching will move us to all-normal dispersion at some point. Overetching has the opposite effect, the anomalous dispersion gets stronger.

Decreasing the modulation

And hence narrowing down the resonance wavelength



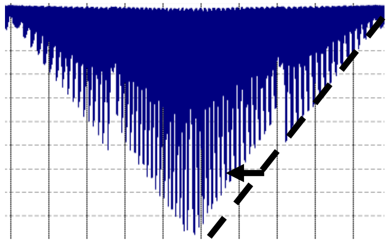
→We know how much one period in time is in terms of wavelength, so we also know the width of the resonances

→We are sure that these are resonances from the chip, because if we heat the chip the resonances move

→Q = 90 000 for this ring

Analytical Treatment of Fano Resonances

To try to understand the jump in our ring resonator measurements



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Sharp asymmetric line shapes in side-coupled waveguide-cavity systems

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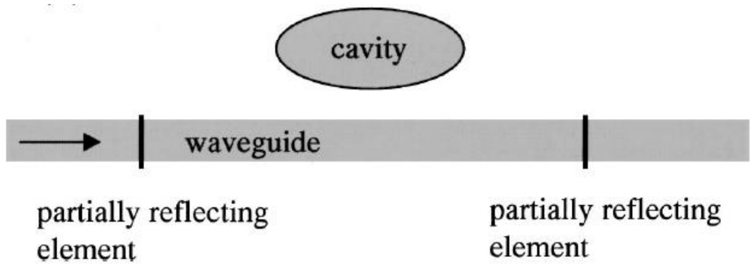
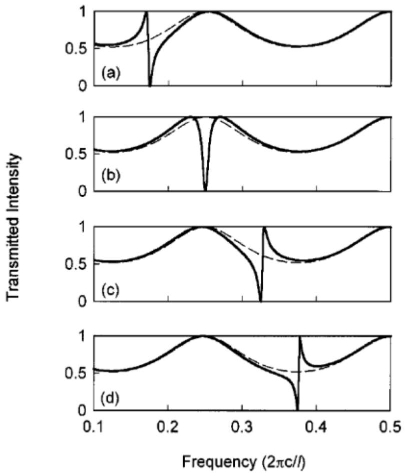
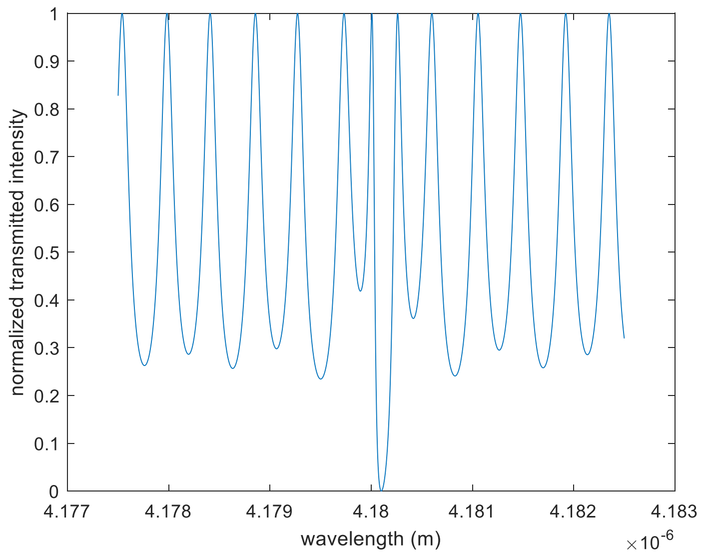
We show that, for an optical microcavity side coupled with a waveguide, sharp, and asymmetric line shapes can be created in the response function by placing two partially reflecting elements into the waveguides. In such a system, the transmission coefficient varies from 0% to 100% in a frequency range narrower than the full width of the resonance itself. We numerically demonstrate this effect by simulating the propagation of electromagnetic waves in a photonic crystal. © 2002 *American Institute of Physics*. [DOI: 10.1063/1.1448174]

$$t_s = \frac{(r^2-1)e^{2i\delta}(\omega-\omega_0)}{-e^{4i\delta}r^2(\omega-\omega_0-i\gamma)-2e^{2i\delta}(i\gamma)r+\omega-\omega_0+i\gamma}$$

t_s – amplitude transmissivity
r – amplitude reflectivity at waveguide facet
δ – $\omega l/c$ phase shift aquired by waveguide mode (l – half length of Fabry-Perot cavity)
ω_0 – resonance frequency
γ – width of resonance







- "The shapes of the resonant features depend critically on the relative positions of the resonant frequency in relation to the background."
- But no parameter combination seems to lead to a jump
- Can maybe still be useful to estimate resonance visibility

Analytical Treatment of Fano Resonances

More general, not in the limit of a narrow ring resonance

Highly sensitive silicon microring sensor with sharp asymmetrical resonance

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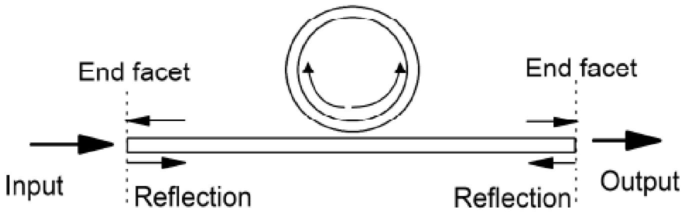
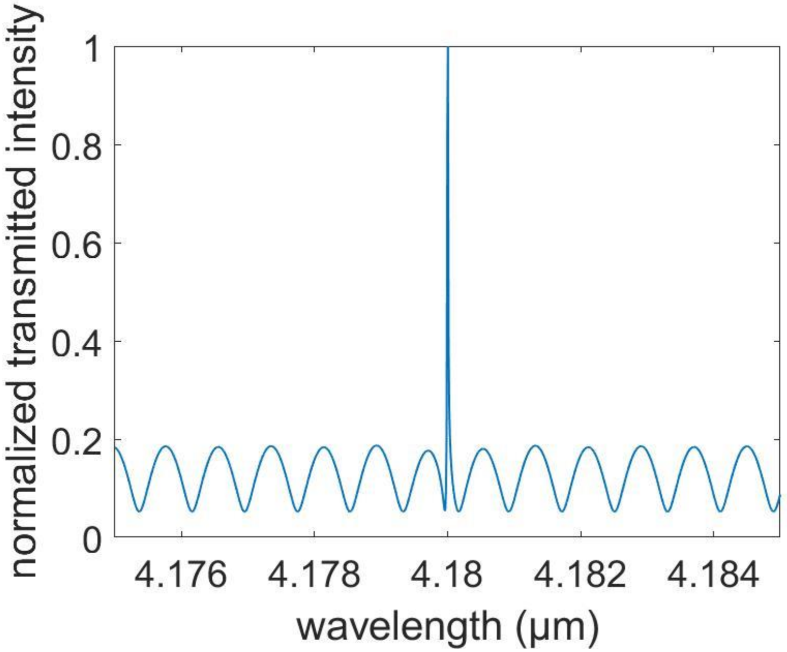


$$T = T_{FP}\begin{bmatrix} e^{i\varphi} & 0 \\ 0 & e^{-i\varphi} \end{bmatrix} T_r \begin{bmatrix} e^{i\varphi} & 0 \\ 0 & e^{-i\varphi} \end{bmatrix} T_{FP},\quad T_r = \begin{bmatrix} 1-\dfrac{iW}{\omega-\omega_0} & \dfrac{-iW}{\omega-\omega_0} \\ \dfrac{iW}{\omega-\omega_0} & 1+\dfrac{iW}{\omega-\omega_0} \end{bmatrix},$$

$$T_{FP} = \frac{1}{i\sqrt{1-r^2}}\begin{bmatrix} -1 & -r \\ r & 1 \end{bmatrix}$$

T – transfer matrix
r – amplitude reflectivity at waveguide facet
$\varphi = \omega l/2c$ phase shift aquired by waveguide mode (l – length of Fabry-Perot cavity)
ω_0 – resonance frequency
W – width of resonance (HWHM)



Does not reproduce the asymmetry either

Determining Nonlinear Parameter

Through supercontinuum generation

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Mid-infrared octave spanning supercontinuum generation to 8.5 μm in silicon-germanium waveguides

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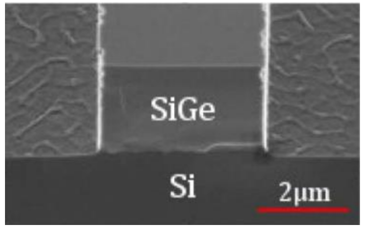
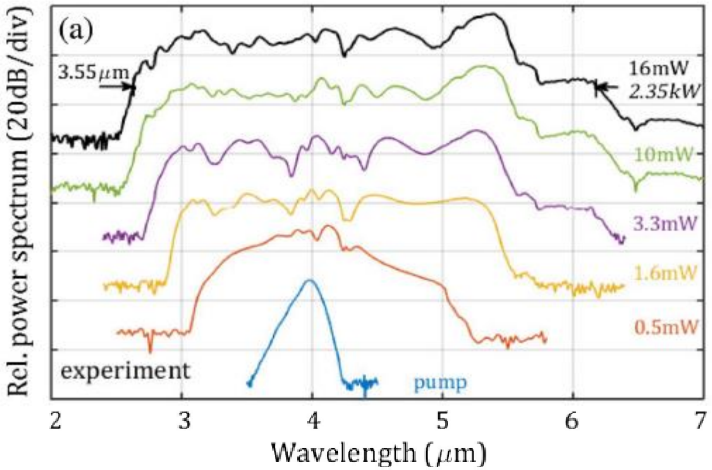




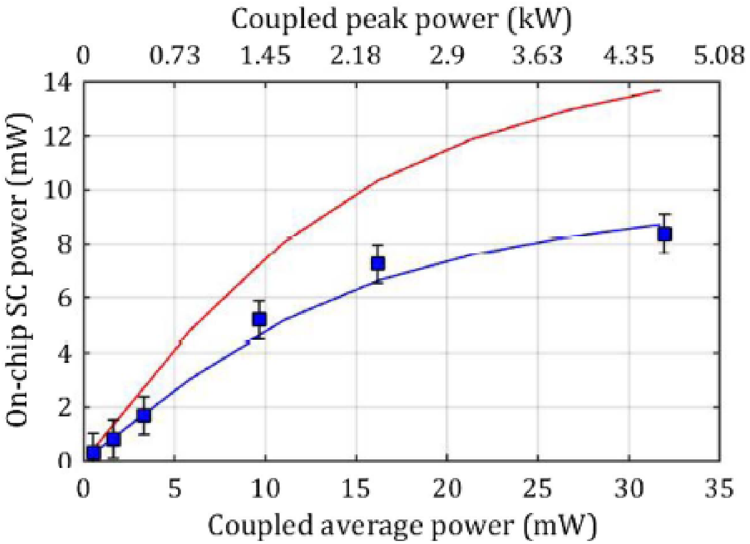


Fig. 5. On-chip SC power versus coupled average power measured for the 7 cm long waveguide (1) in TE at 4.0 μm (blue squares), simulated results for the 7 cm waveguide (blue line) and simulated results for a 2 cm long similar waveguide (red line).

Fit gives $\gamma = 0.63\ W^{-1}m^{-1}$

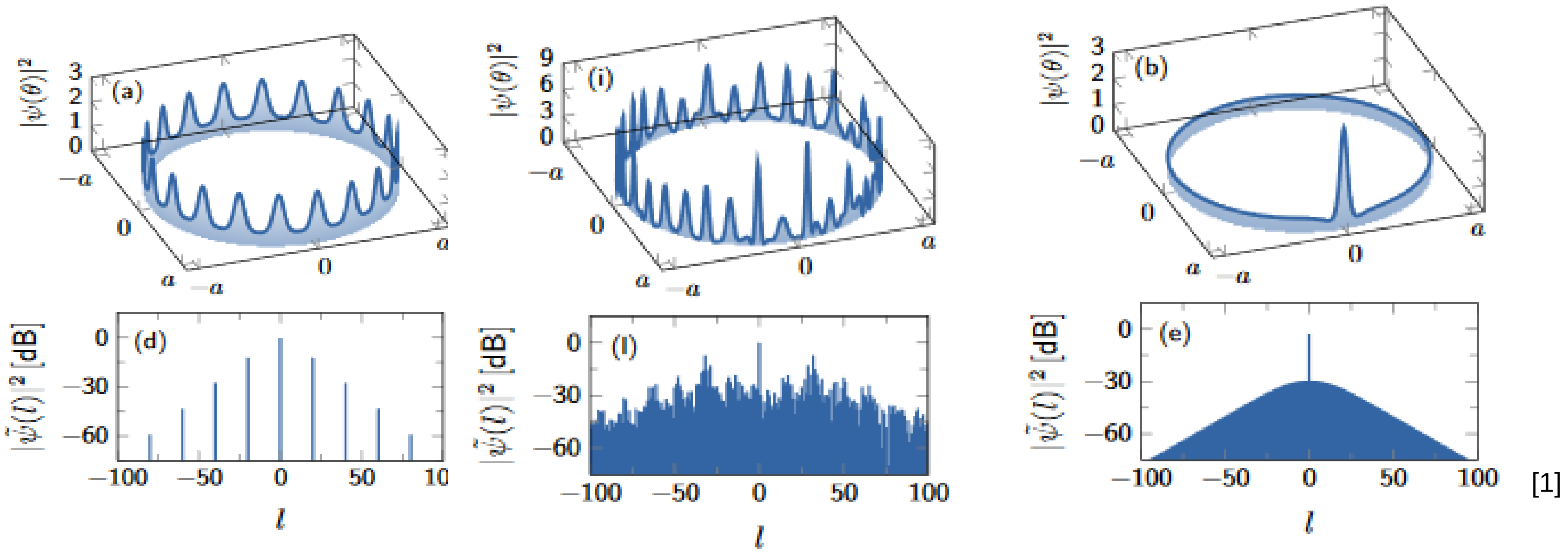
Simulation of Frequency Comb

Lugiato-Lefever equation

$$\frac{d\psi}{dt} = -(1 + i\alpha)\psi + i|\psi|^2\psi - i\frac{\beta}{2}\frac{\partial^2\psi}{\partial\theta^2} + F$$

Cavity field

Spectrum



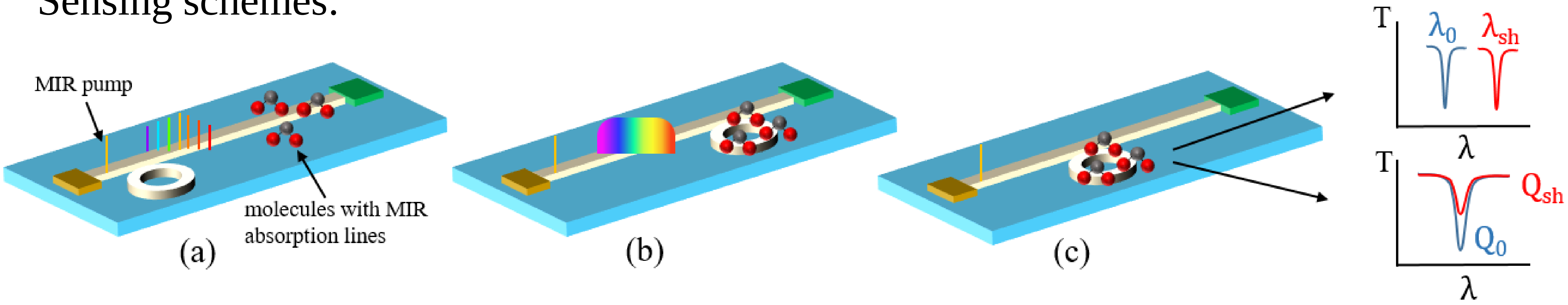
Turing rolls

Chaos

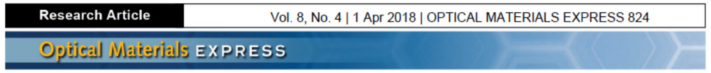
Soliton

[1] C. Godey et al., Phys. Rev. A 86, 063814 (2014)

Sensing schemes:



Rings for filters: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Mid-infrared Vernier racetrack resonator tunable filter implemented on a germanium on SOI waveguide platform [Invited]

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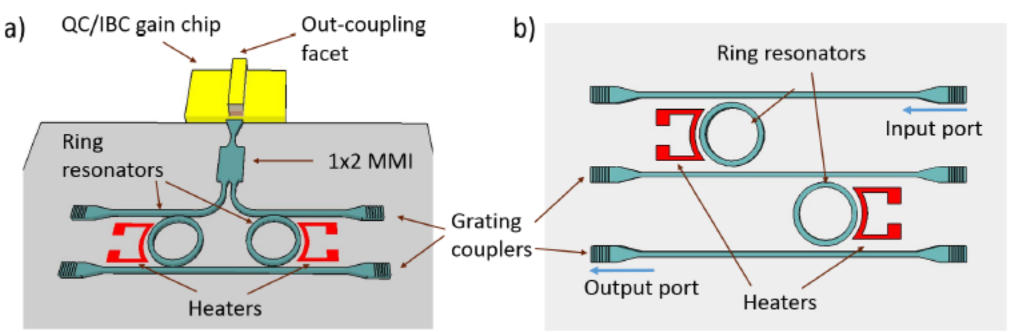

Ring Gap