Microwave Photonics

Radio Frequency (RF) engineering with LASERS!

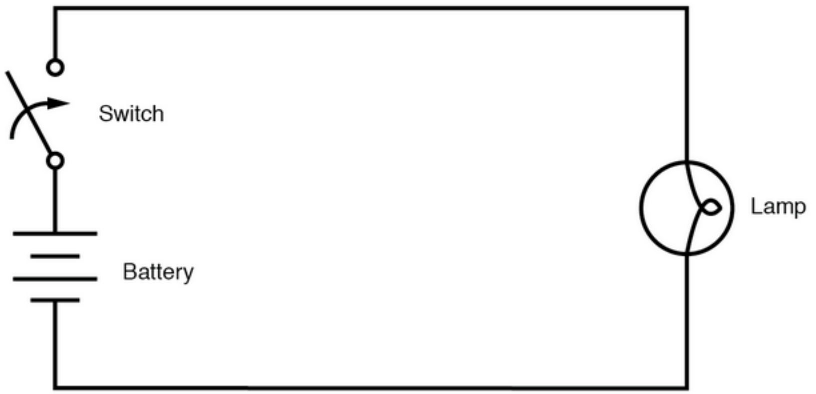
Outline

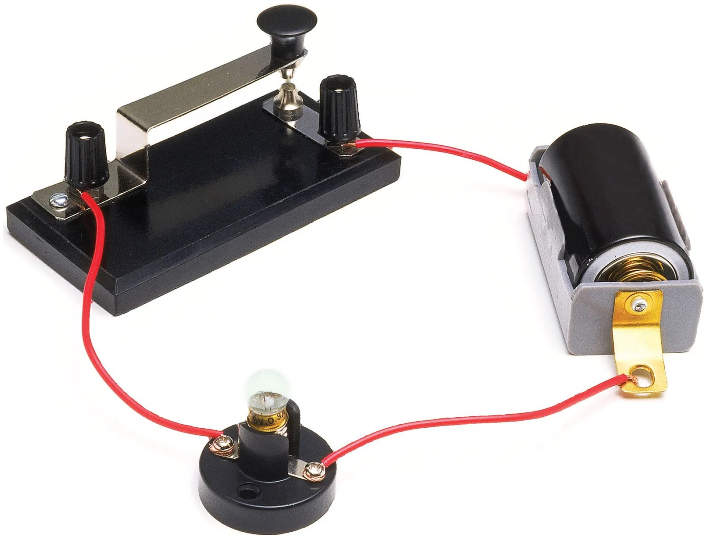
- Microwave electronics
- Photonics
  - Integrated photonics
- Introduction to microwave photonics (MWP)
- Photonic signal processing
  - Linear optics
  - Nonlinear optics
- MWP applications
- SBS phase shifter
- Conclusion

Lumped element model

- Perfectly conducting wires
- Wire length doesn’t really matter
- More or less instantaneous

Useful for low frequencies





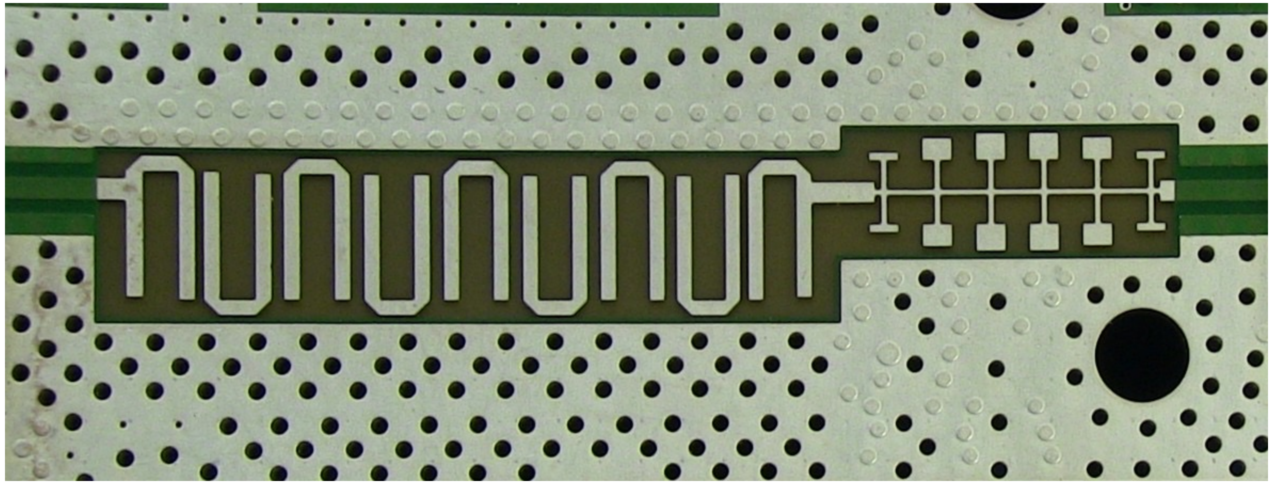
britannica.com, www.allaboutcircuits.com

Transmission lines:

- Voltages treated as waves
- Impedances need to be considered
- Wanted/unwanted Coupling

Necessary for high frequencies

Microstrip filter



Wikipedia.com

Radio frequency applications

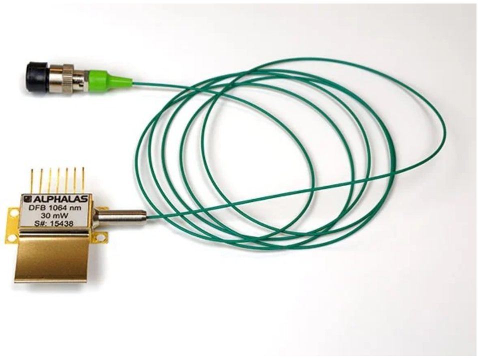
Applications:

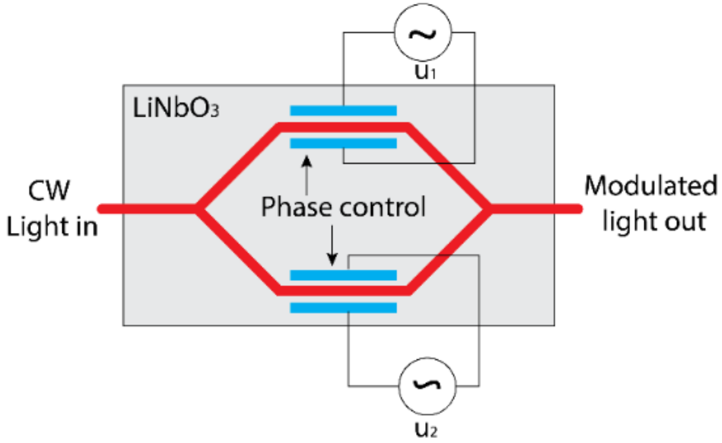
- Communications
- Sensing (RADAR ect)
- Medical imaging
- Radio telescopes
- Many others

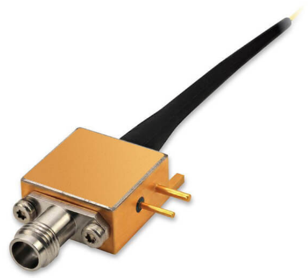
www.skatelescope.org, TP link, R. C. Hansen, *Phased Array Antennas*. New York, USA: John Wiley & Sons, Inc., 1998.

Photonics:

- Light instead of electrons
- Photonic components
  - Laser
  - Modulator
  - photodetector
- Photonic signal processing approaches





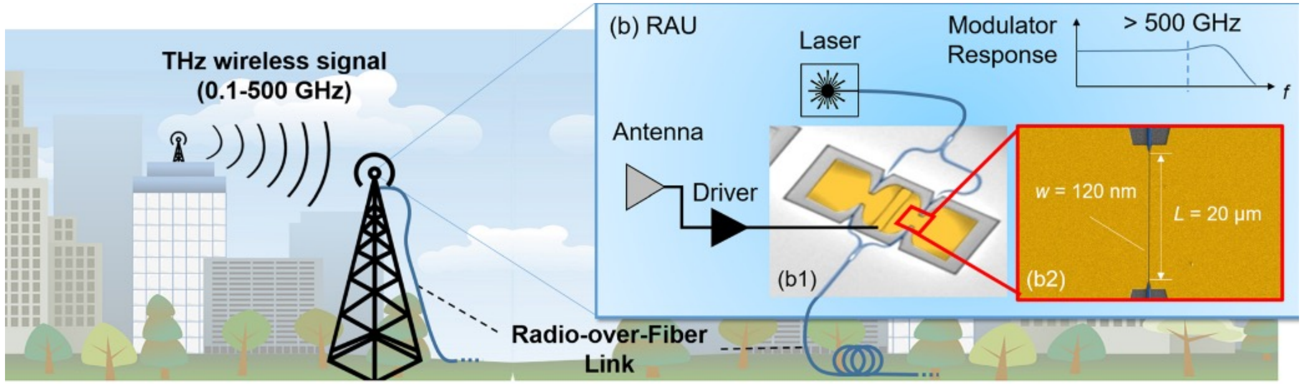


www.alphalas.com, T. Huszaník, et al., in *Jour. of Com. Soft. Sys.*, vol. 14, no. 4, pp. 367-375, Dec.2018, ii-vi.com

* In some instances

Advantages:

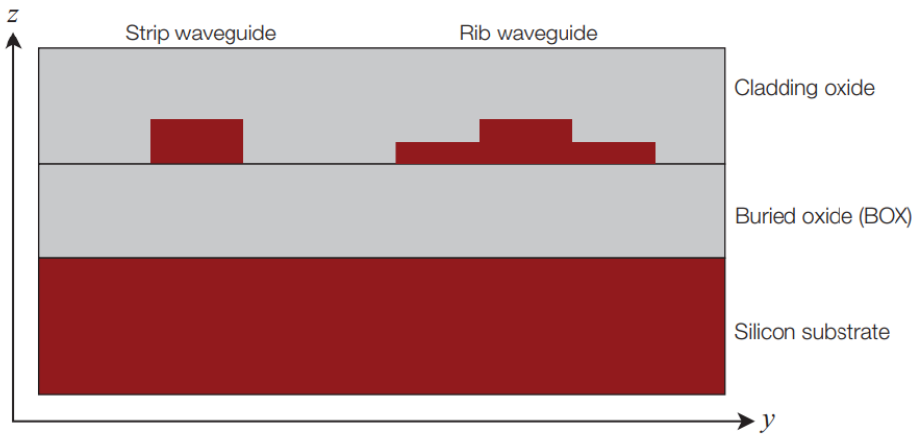
- Ultra-broadband operation (100’s of GHz)
- Extremely flat spectral operation
- Capable of operating at high frequencies
- Resistant to RFI and EMI*
- Compatibility with optical fibre (0.2dB/km)
    - Antenna remoting
- High dynamic range (upwards of 100dB/Hz$^{2/3}$)



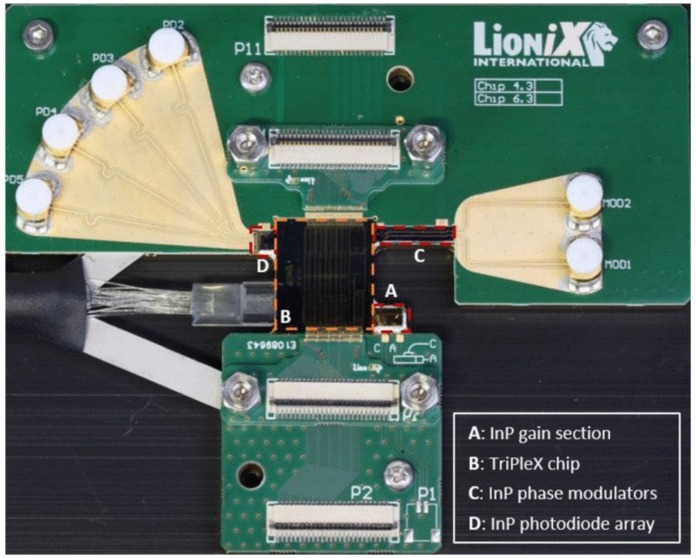
https://fibertronics.com, Maurizio Burla et al., "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics", APL Photonics 4, 056106 (2019)

Integrated Photonics:
- Integrate entire platform onto a chip
- Integrated components
- Smaller formfactor
- Stable
- CMOS compatible
- Scalable
- Hybrid integration
- Allows for complex functionality

On-chip waveguide

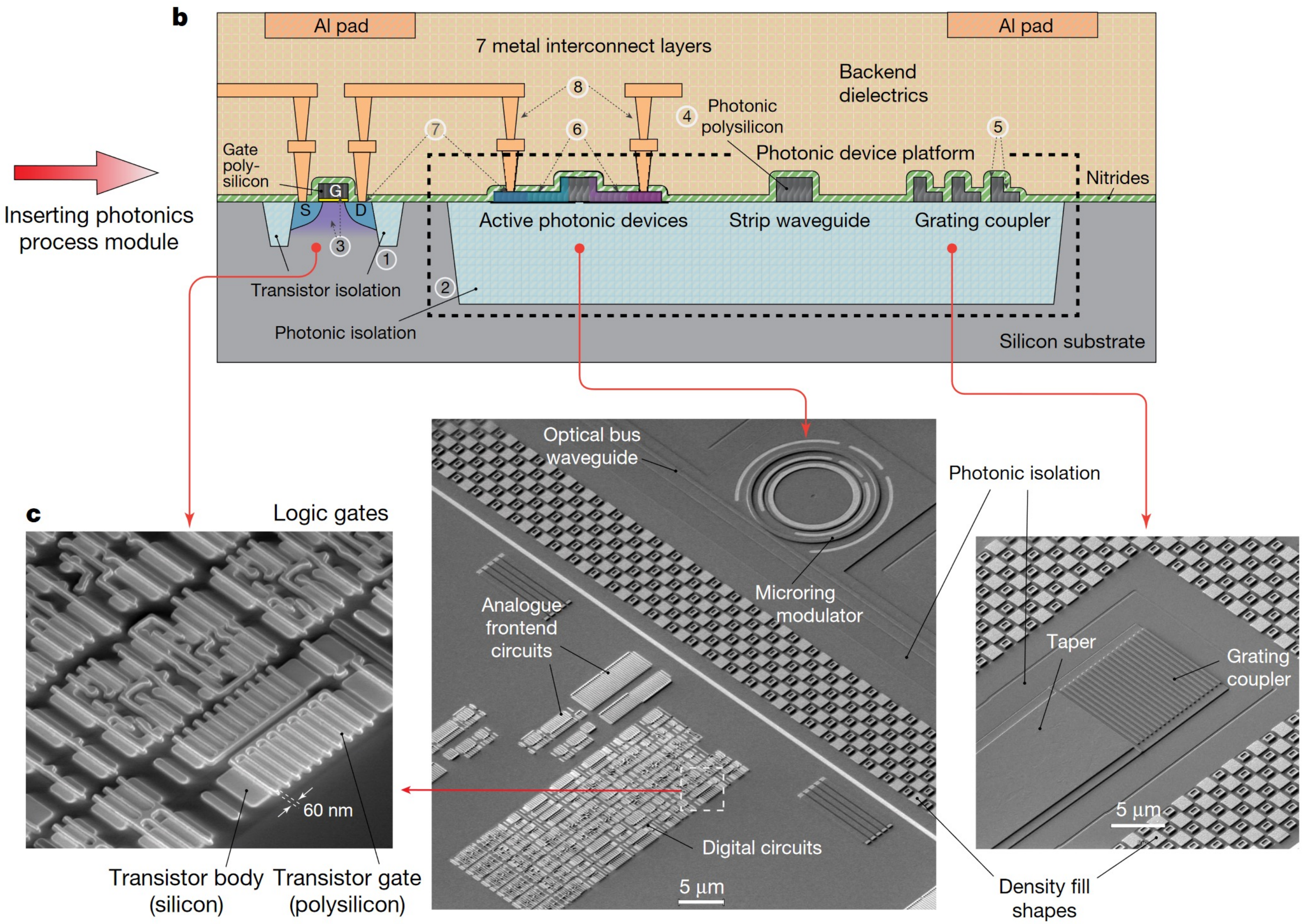


SiN + InP fully integrated chip



Lukas Chrostowski. Silicon photonics design. Cambridge University Press, Cambridge, England, 2015 - 2015. C. Tsokos *et al.*, in *Jour. of Light. Tech.*, vol. 39, no. 18, pp. 5845-5854, Sept.15, 2021

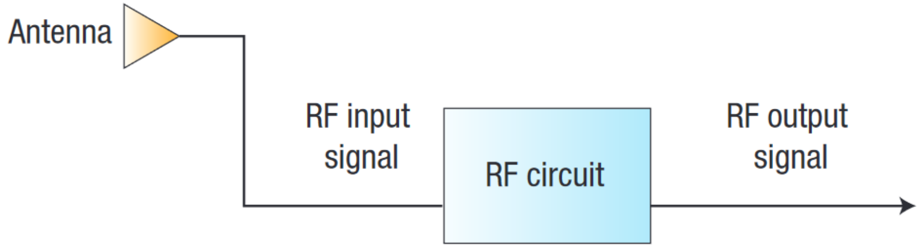
Integrated photonics



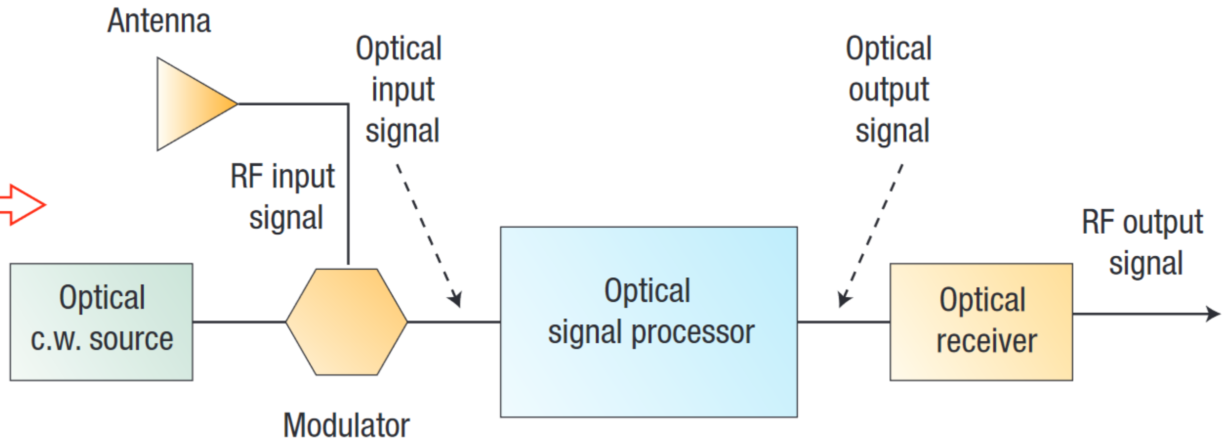
Atabaki, A.H., Moazeni, S., Pavanello, F. *et al.* Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip. *Nature* **556,** 349–354 (2018)

Microwave photonics

Traditional RF electronics



Microwave photonic

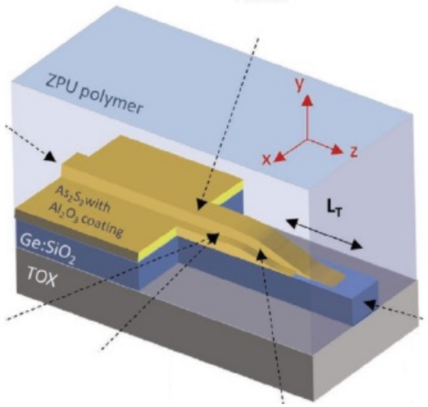


Capmany, J., Novak, D. Microwave photonics combines two worlds. *Nature Photon* **1,** 319–330 (2007).

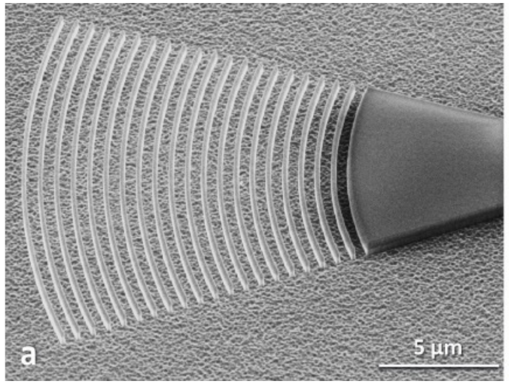
Linear:
- Ring resonator
- Couplers
- Gratings
- Many more

Non-linear
- Pockels effect
- Kerr effect
- Stimulated Brillouin scattering
- Many more

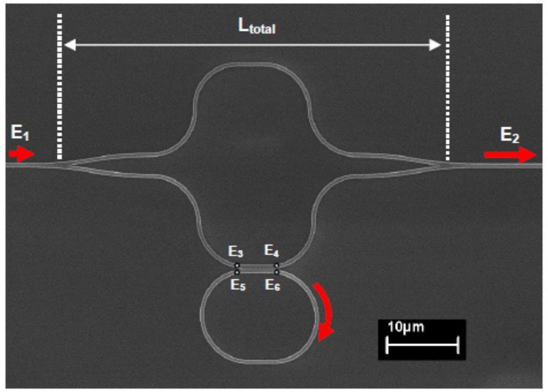
Taper



Grating Coupler



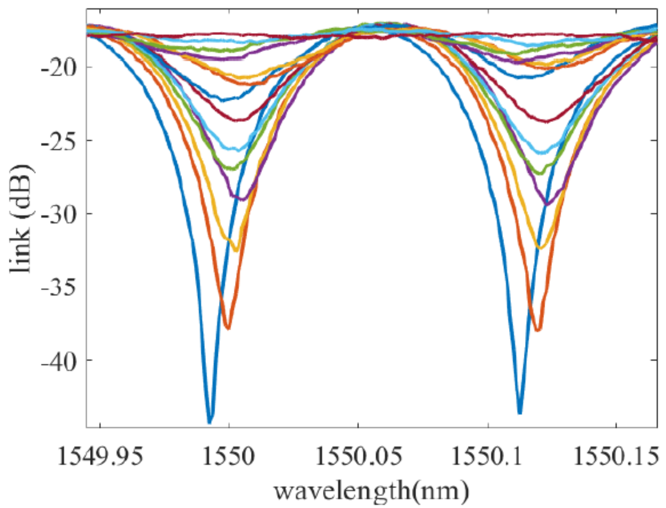
Mach Zehnder interferometer
with ring resonator



Rath, P.et al. *J. Nanotechnol.* **2013,** *4,* 300–305, Choon Kong Lai et al. Advanced functional materials, Fengnian Xia et al. Opt. Express **14**, 3872-3886 (2006)

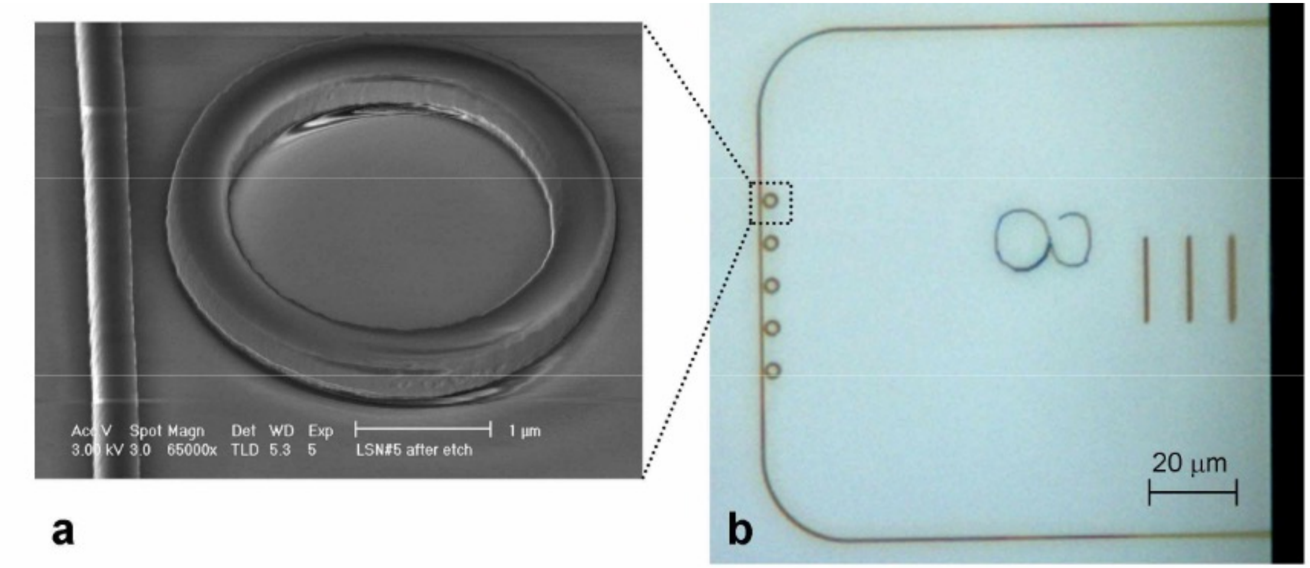
Ring resonator

- Waveguide loop
- Only wavelength multiples of the ring resonate
- Manipulate phase and amplitude



Scanning electron microscope (SEM) image

Optical microscope image

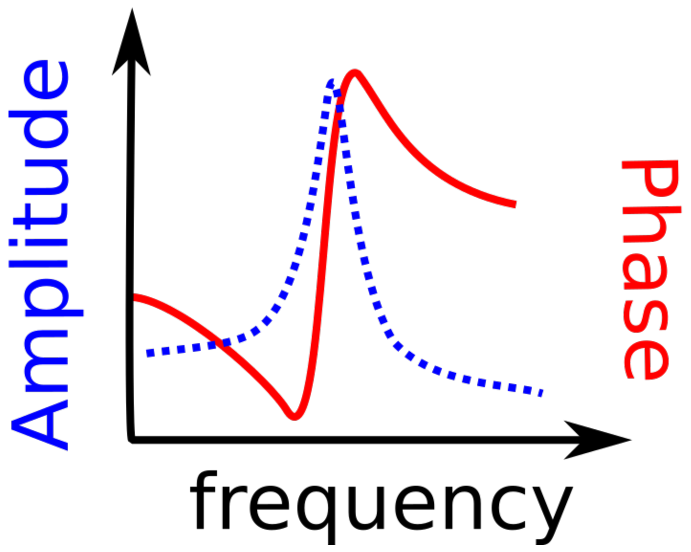


Qianfan Xu, David Fattal, and Raymond G. Beausoleil, "Silicon microring resonators with 1.5-µm radius," Opt. Express **16**, 4309-4315 (2008)

Stimulated Brillouin scattering

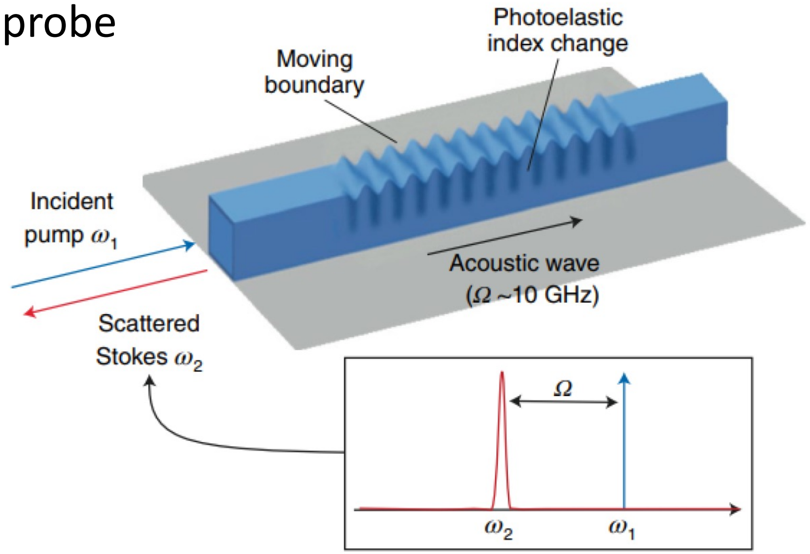
- Optically induced photon-phonon interaction
- High resolution (~30MHz)
- Gain based phase shifts
- Continuously tuneable
- Large operating range
- Can be broadband with additional pumps
- Can induce loss
- Can be integrated on a chip

Phase and amplitude response

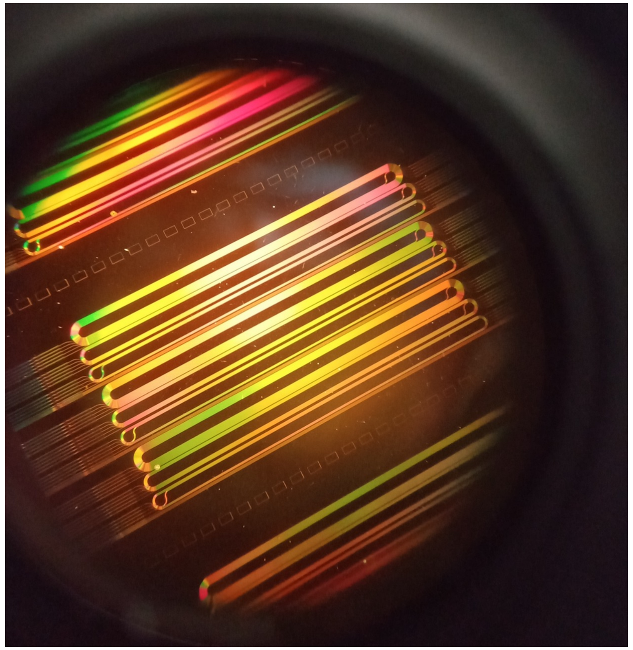


Stimulated Brillouin scattering:

- Pump (blue) wave interacts with counter propagating Stokes wave
- The electrics field overlap and generate moving standing wave
- The waveguide gets locally stretched and compressed due to electrostriction
- Higher density areas have a higher index (photoelasticity)
- Leads to moving grating
- Moving grating coherently amplifies the probe
- Chalcogenide is good for SBS



Chalcogenide waveguide (As_2S_3 on silica)

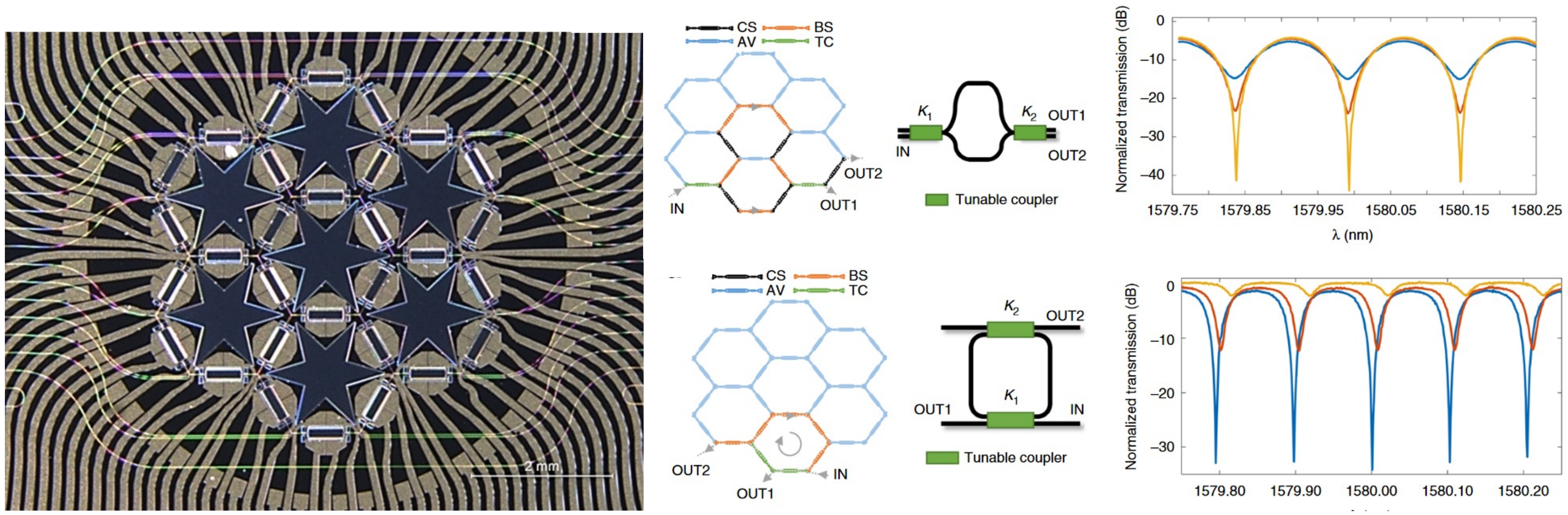


Benjamin J Eggleton et al. Nature photonics, 13 (10):664–677, 2019. ISSN 1749-4885.

Microwave photonic devices:

- Optoelectronic oscillators (OEOs)
- Filters
- Mixers
- Beam formers
- Sensors
- Amplifiers
- RADAR
- Spectral shaping
- And more

Reconfigurable general purpose processor



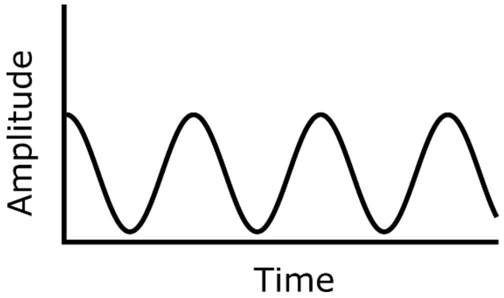
Pérez, D. *et al.* Multipurpose silicon photonics signal processor core. *Nat Commun* **8,** 636 (2017)

Integrated photonics devices using stimulated Brillouin scattering and interferometry:

- Phase shifters
  - Silicon (forward SBS)
  - Chalcogenide (backwards SBS)
  - Fibre (backwards SBS)
- True time delays
- Image rejection mixer

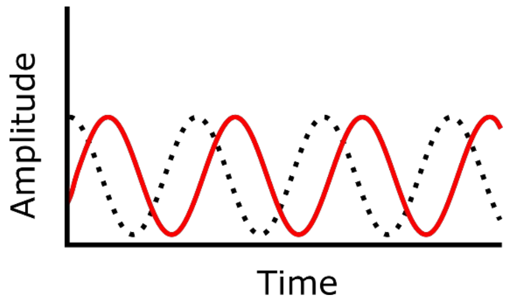
Phase shifter

Input



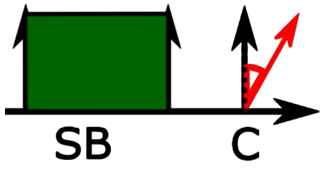
Phase shifter

Output

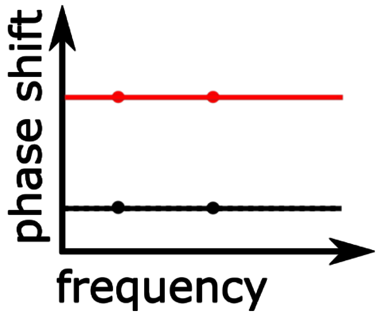


Phase shifter

Optical

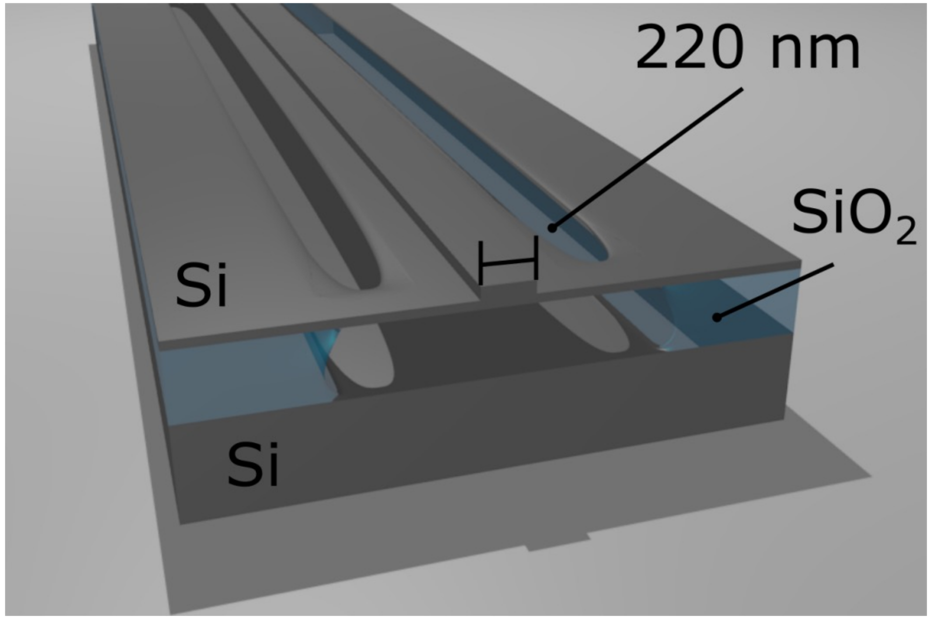


Electrical



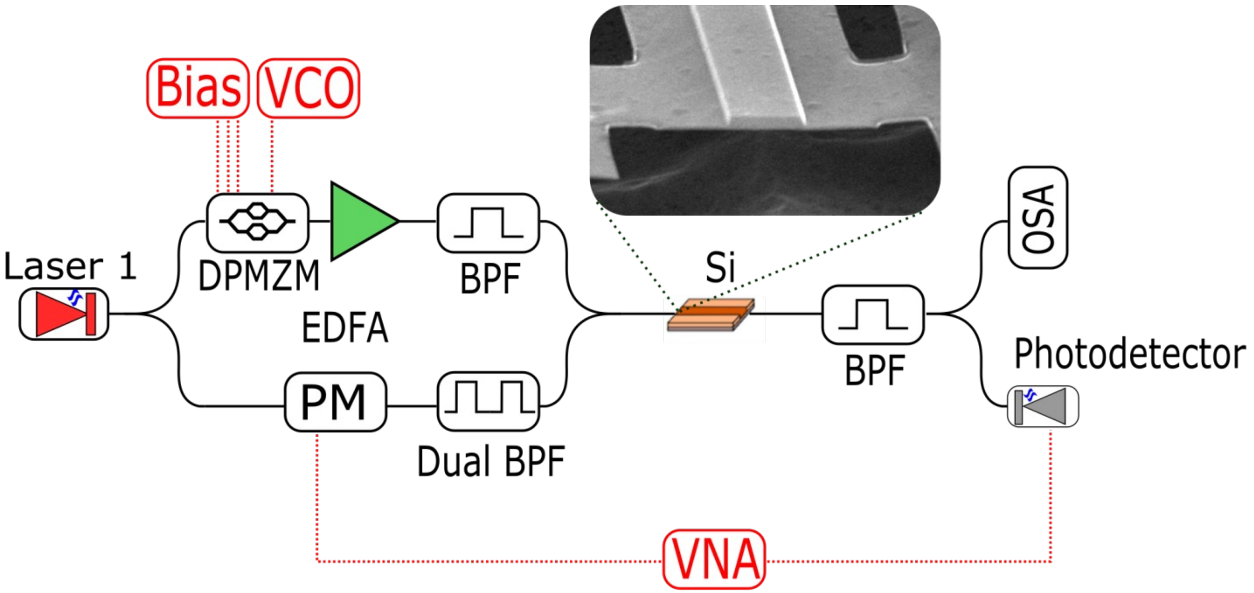
SBS gain medium

- Suspended silicon waveguide
- Forward SBS, pump co-propagates with the Stokes
- Guides both optical and acoustic modes
- CMOS compatible
- Only able to achieve ~ +- 7 degrees phase tunability
- Needs enhancement for 360^0 phase tunability



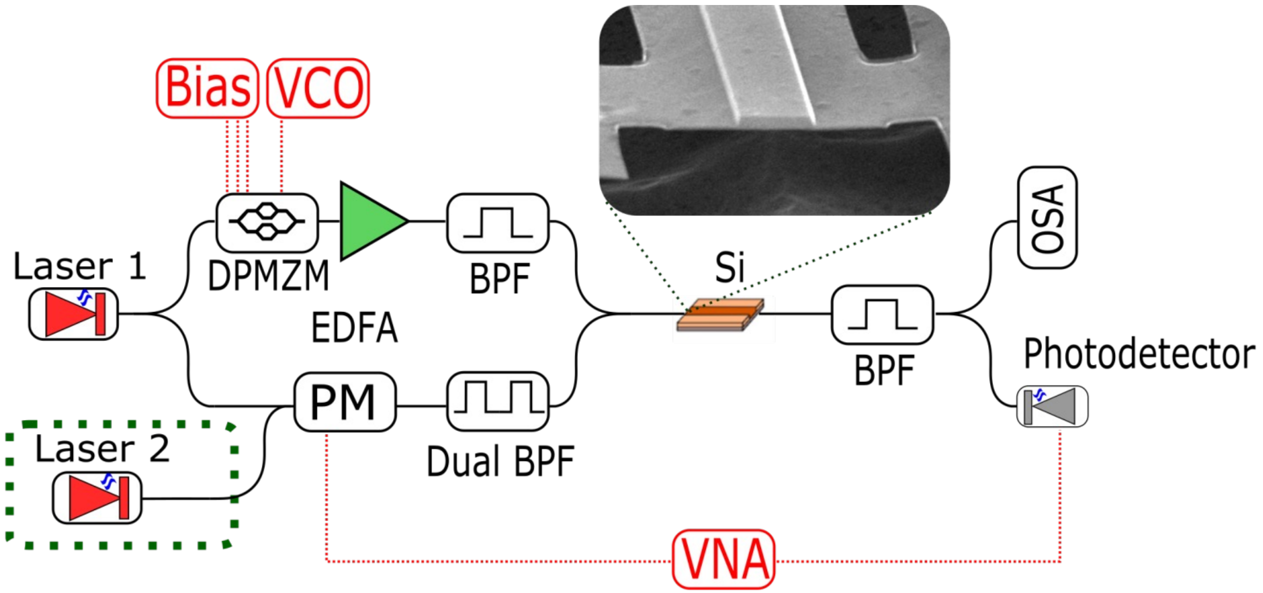
Eric A. Kittlaus et al. *Nature Photonics* volume 10, pages 463–467 (2016)

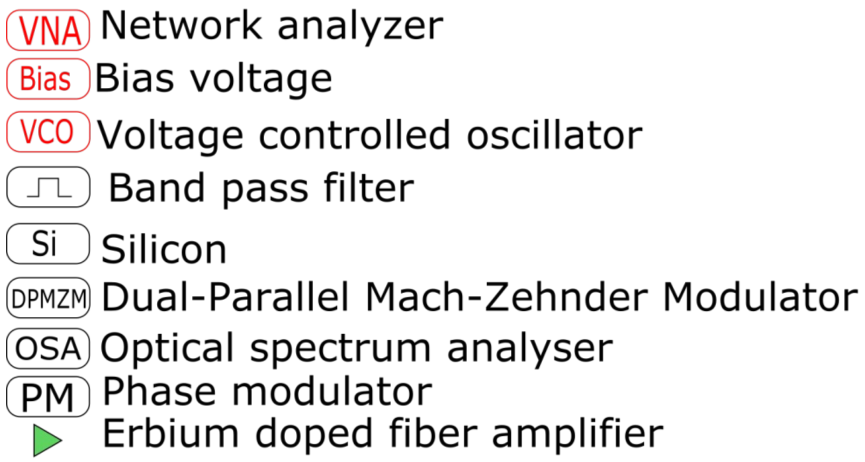
Experimental setup



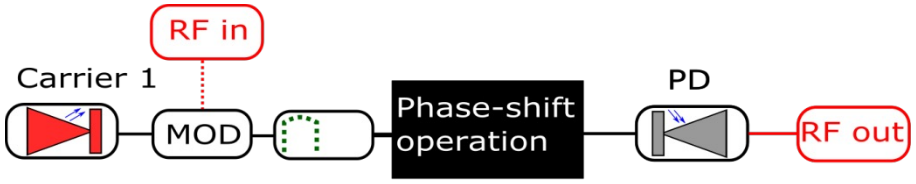
VNA Network analyzer
Bias Bias voltage
VCO Voltage controlled oscillator
Band pass filter
Si Silicon
DPMZM Dual-Parallel Mach-Zehnder Modulator
OSA Optical spectrum analyser
PM Phase modulator
Erbium doped fiber amplifier

Experimental setup

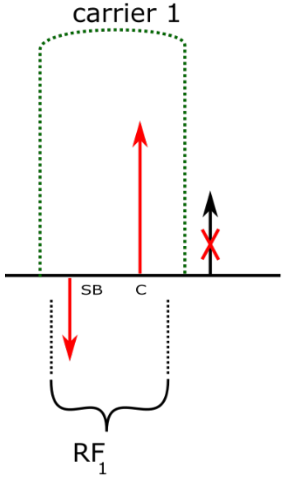




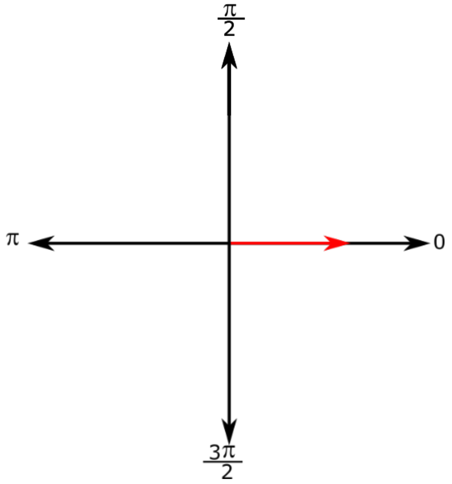
Principle of amplification



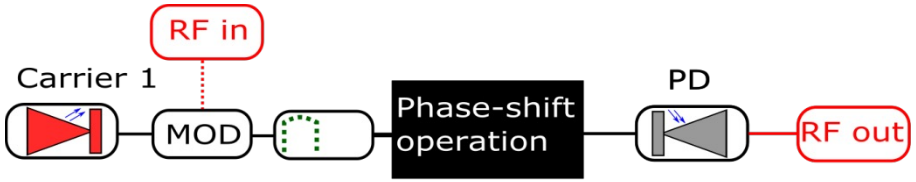
Optical

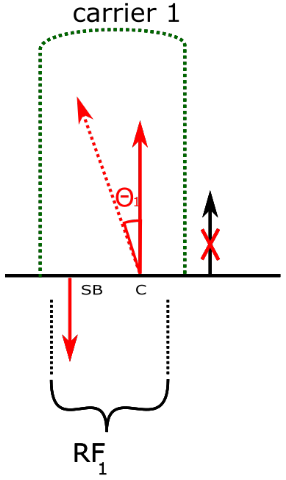


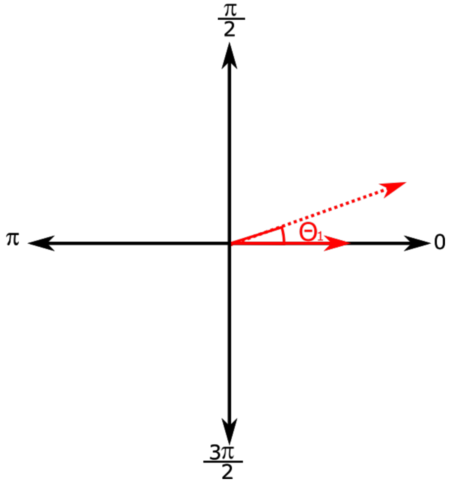
Electrical



Principle of amplification







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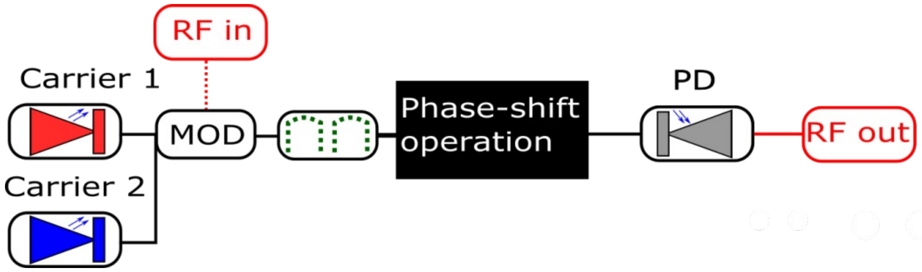
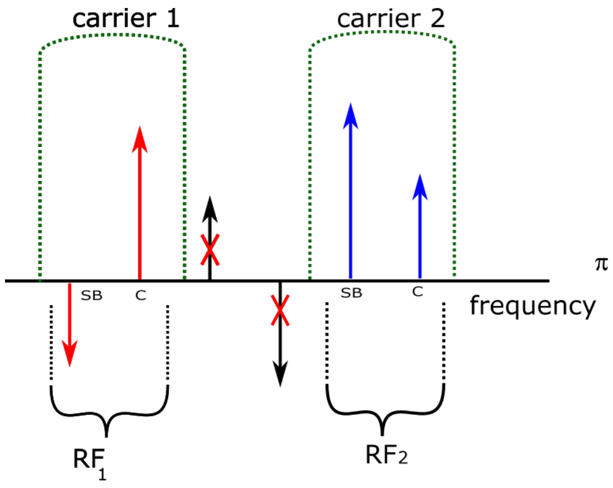
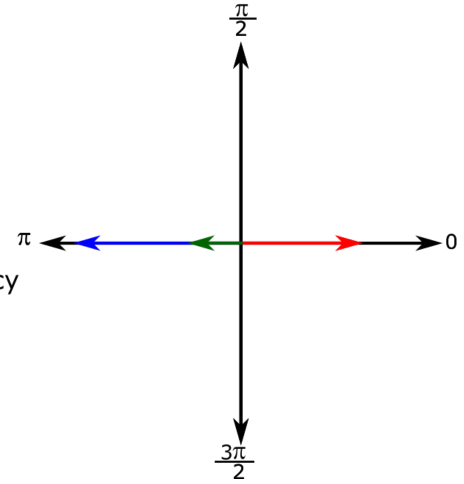


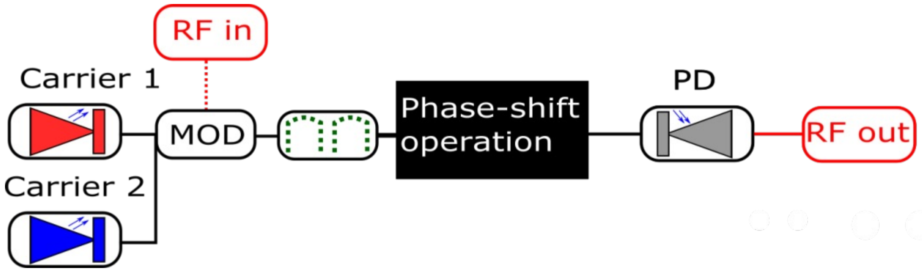
Optical

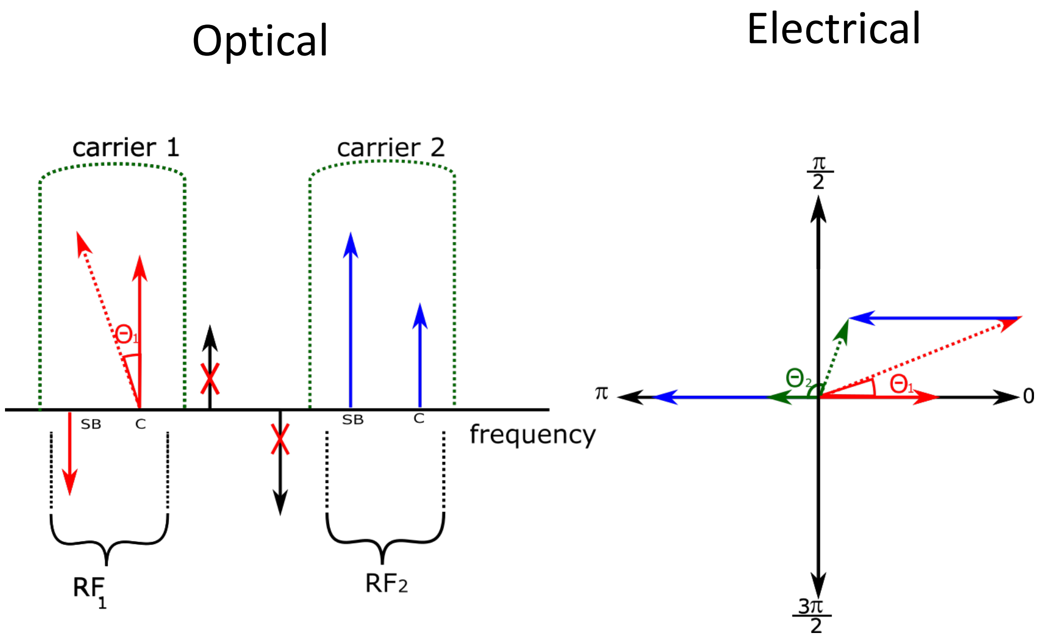
Electrical



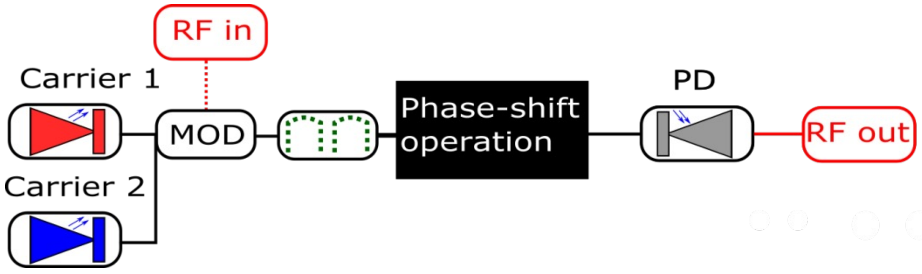


Principle of amplification





Principle of amplification



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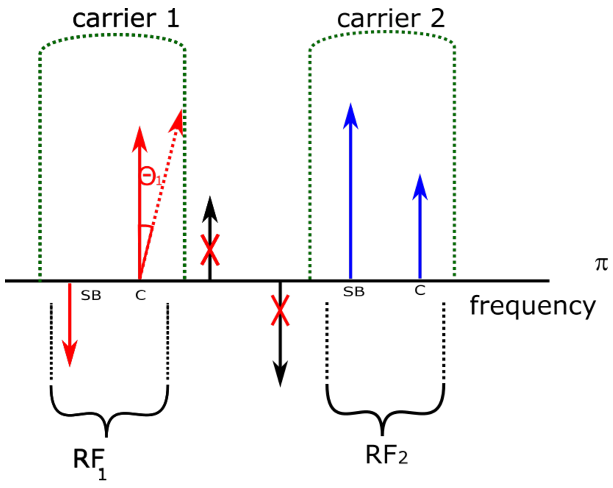
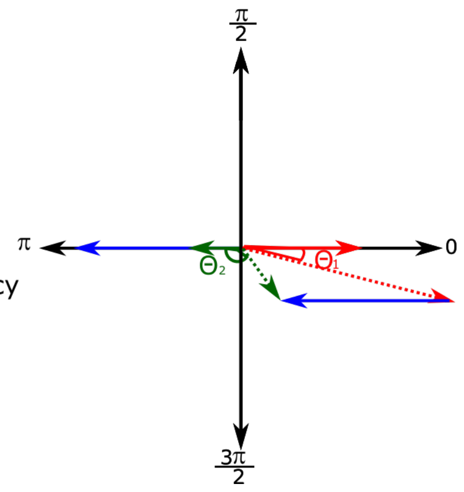
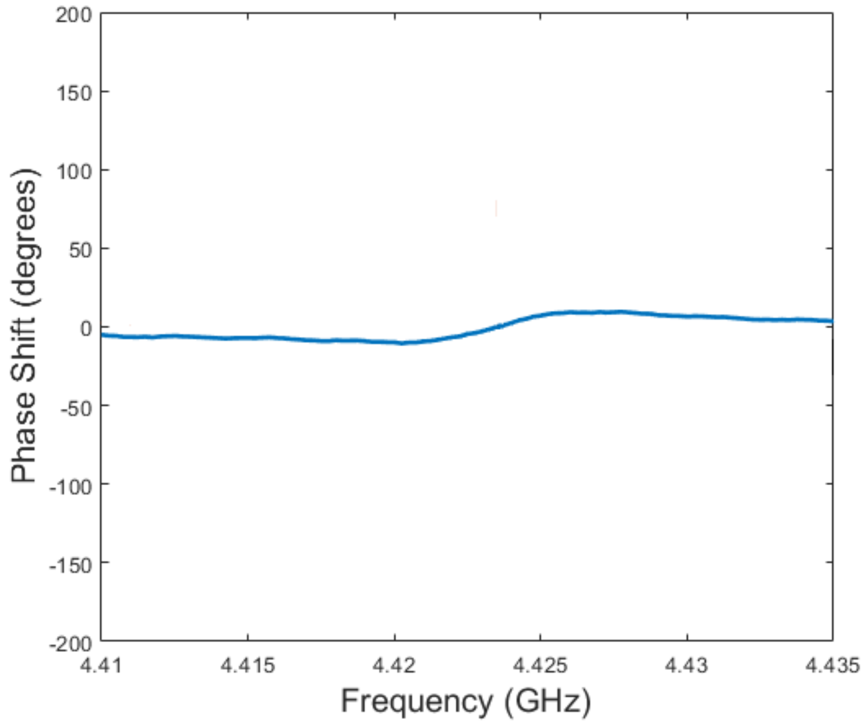


Electrical



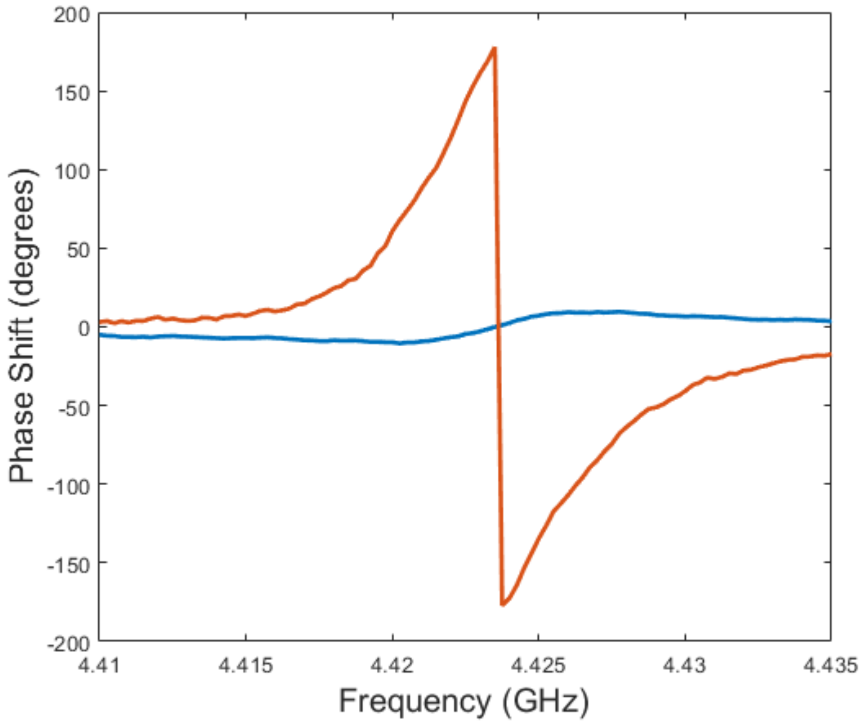
Experimental results

Without enhancement



Experimental results

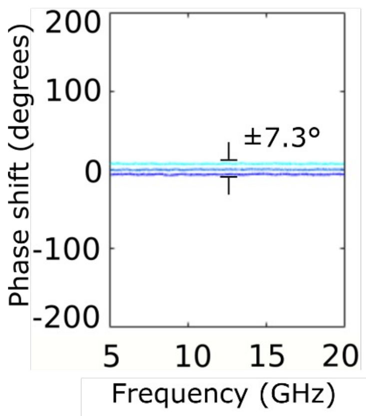
With enhancement



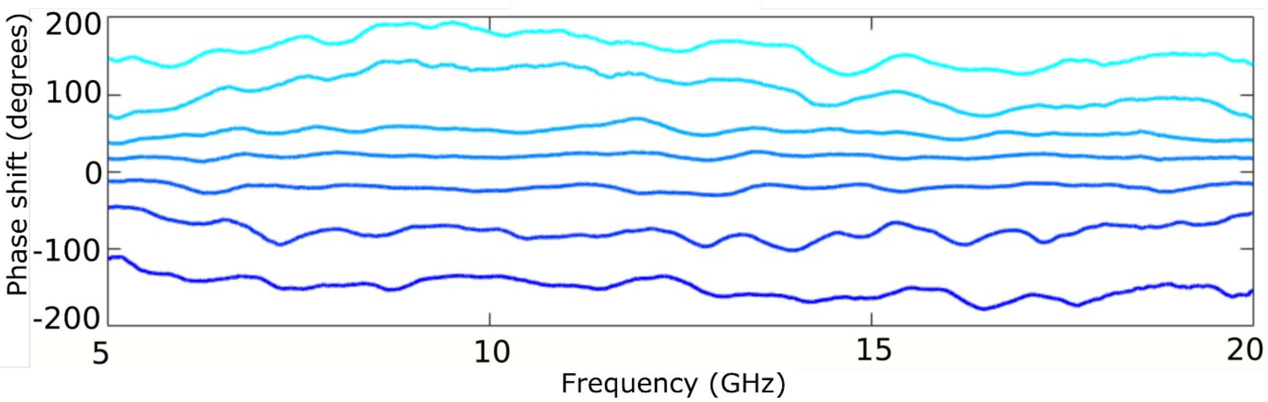
Broadband results:

- 5 – 20GHz bandwidth
- Enhancement factor of 25
- 18 dBm on-chip pump power
- 1.6dB of Brillouin gain

Without enhancement



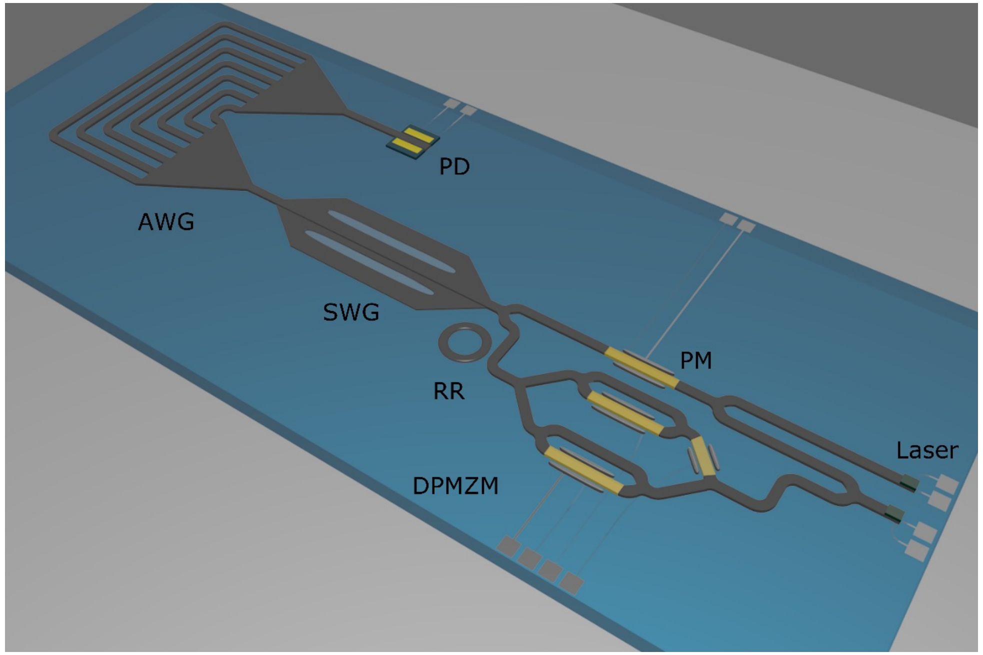
With enhancement



Conclusion:

- First optically controllable 360^0 phase shift in silicon
- 15 GHz bandwidth
- CMOS compatible

Impression of fully integrated system



Conclusion:

- MWP is a promising technological platform
- Complements current silicon electronics
- Unprecedented flexibility and reconfigurability

Limiting factors:

- Noise performance is the largest current bottleneck
- Work is required on combining complementary materials

Impression of fully integrated system