Nonlinear Integrated Microwave Photonics

Presented by:

OSA Nonlinear Optics Technical Group

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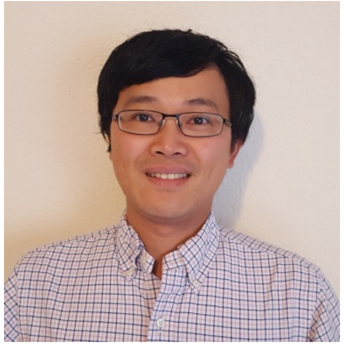

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OSA Nonlinear Optics Technical Group

Technical Group at a Glance

- Focus
  - "Physics of nonlinear optical materials, processes, devices, & applications"
  - **3800** members (**largest** in OIS, 3rd largest in OSA)
- Mission
  - To benefit ***YOU***
  - Webinars, e-Presence, publications, technical events, business events, outreach
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  - LinkedIn: www.linkedin.com/groups/8302249

Today's Webinar

Nonlinear Integrated Microwave Photonics

A/Prof. David Marpaung
Laser Physics and Nonlinear Optics Group
University of Twente, Enschede, Netherlands
d.a.i.marpaung@utwente.nl

Speaker's Short Bio:
David received his Ph.D in electrical engineering from the University of Twente, Netherlands. He then did post-docs at the University of Twente, and the University of Sydney as an Australian Research Council DECRA Fellow. He is now an Associate Professor (Vidi Laureate) at the Laser Physics and Nonlinear Optics group, University of Twente.

Nonlinear Integrated Microwave Photonics

David Marpaung

University of Twente,
the Netherlands

LPNO
Laser Physics and Nonlinear Optics

MESA+
INSTITUTE FOR NANOTECHNOLOGY

UNIVERSITY OF TWENTE.

The wireless revolution

Source: NBC News

- 10 billion internet devices in 2016
- Exponential growth in wireless data consumption

THE BANDWIDTH BOTTLENECK

Researchers are scrambling to repair and expand data pipes worldwide — and to keep the information revolution from grinding to a halt.

BY JEFF HECHT

J. Hecht, Nature **536**, 2016

Outline

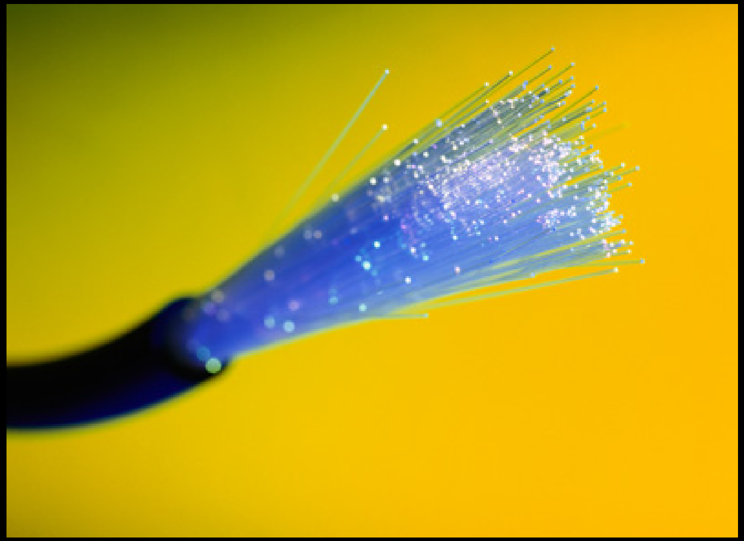
- Fundamentals of microwave photonics
- Nonlinear integrated microwave photonics
- Recent advances
- Challenges and roadmap

Microwave photonics

Microwave photonics (MWP): manipulation of RF signals using photonic techniques/components

Capmany and Novak, Nat. Photon **1** (2007)
Seeds and Williams, J. Lightwave Technol.**24** (2006)
Yao, J. Lightwave Technol. **27** (2009)
Marpaung et al., Laser Photon. Rev. **7** (2013)

vs.



- Heavy (copper, 567 kg/km)
- High loss(190 dB/km @ 6 GHz)
- Rigid and large cross section

- Lightweight
- Low loss(0.25 dB/km)
- Very flexible

Microwave photonics

MWP applied in the generation, distribution, processing, measurement of RF signals

Arbitrary waveform generator

Reconfigurable processor

True time delay

Integrator and differentiator

Antenna remoting

Optical beamforming

Radio over fiber

Phase shifter

RF spectrum analyzer

Optoelectronic oscillator

Instantaneous frequency measurement

Tunable filtering

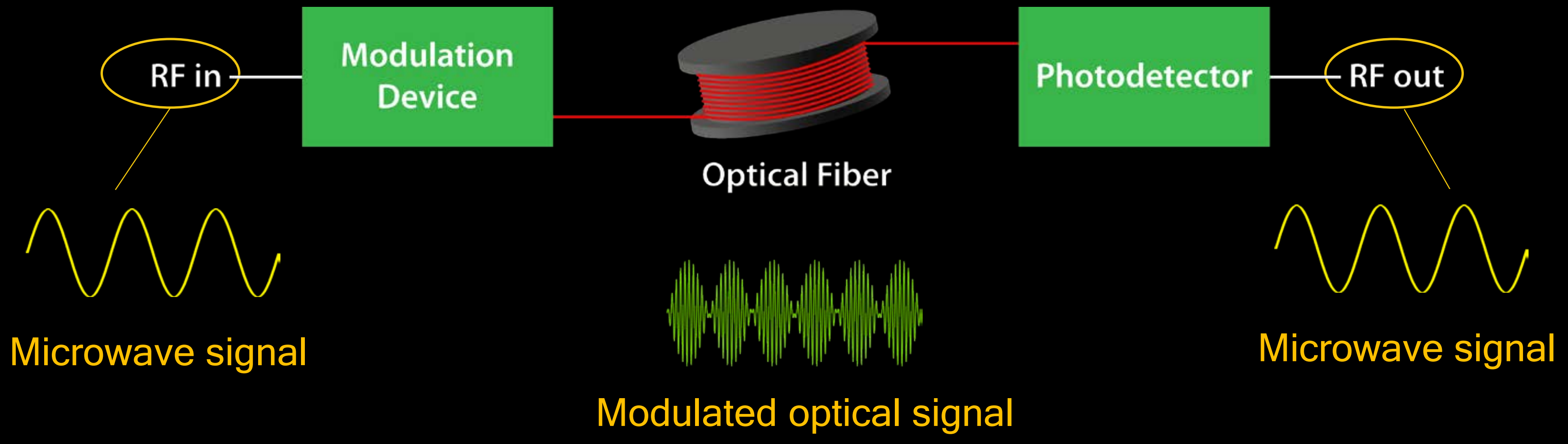
Next generation wireless

Satellite communication

Defense

Microwave photonics

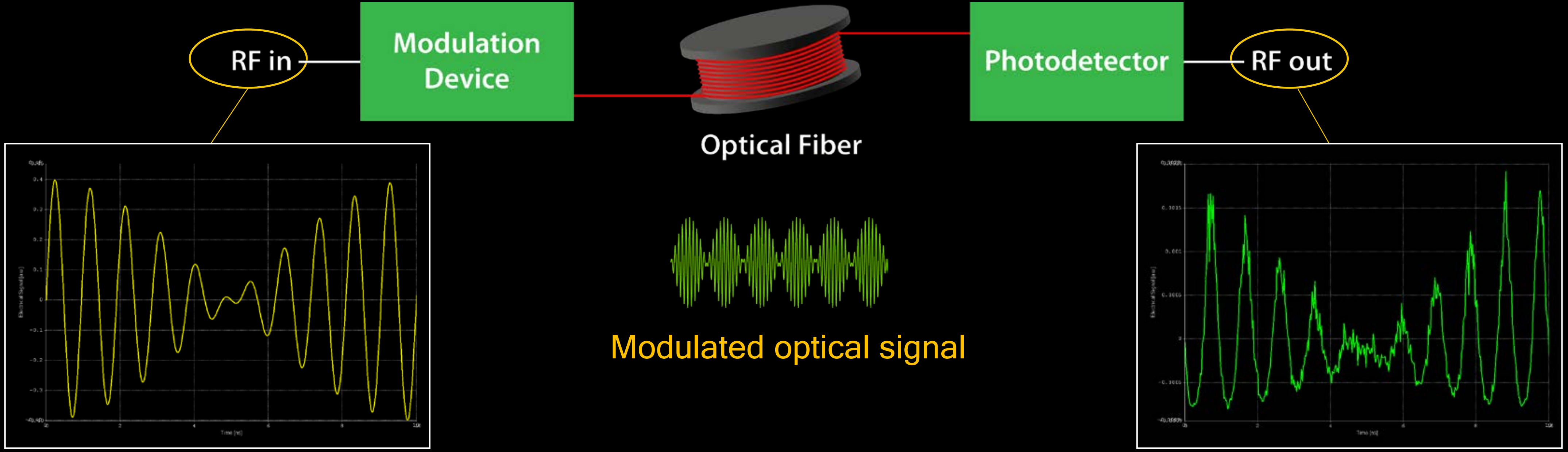
Microwave photonic link



- Modulation device: CW laser+ external modulator or directly modulated laser
- Modulation: phase, intensity, complex

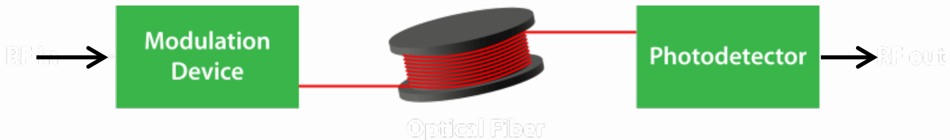
Microwave photonics

Microwave photonic link

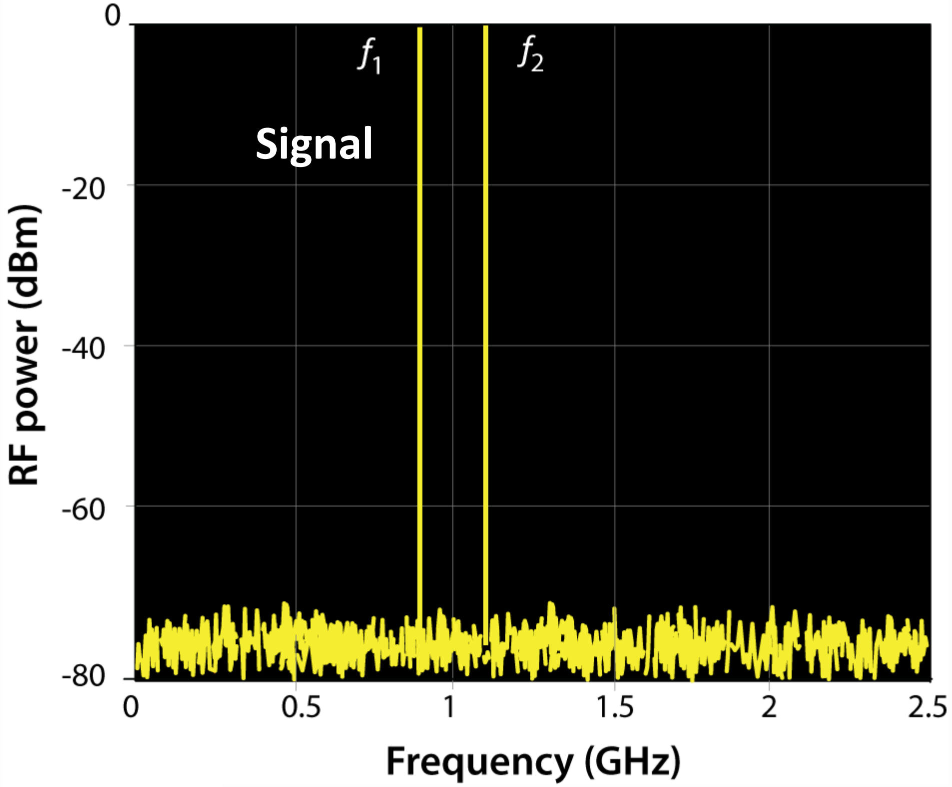


- Source of signal degradation: E/O and O/E losses, noise, and nonlinear distortion
- Noise source: laser relative intensity noise, shot noise, thermal noise

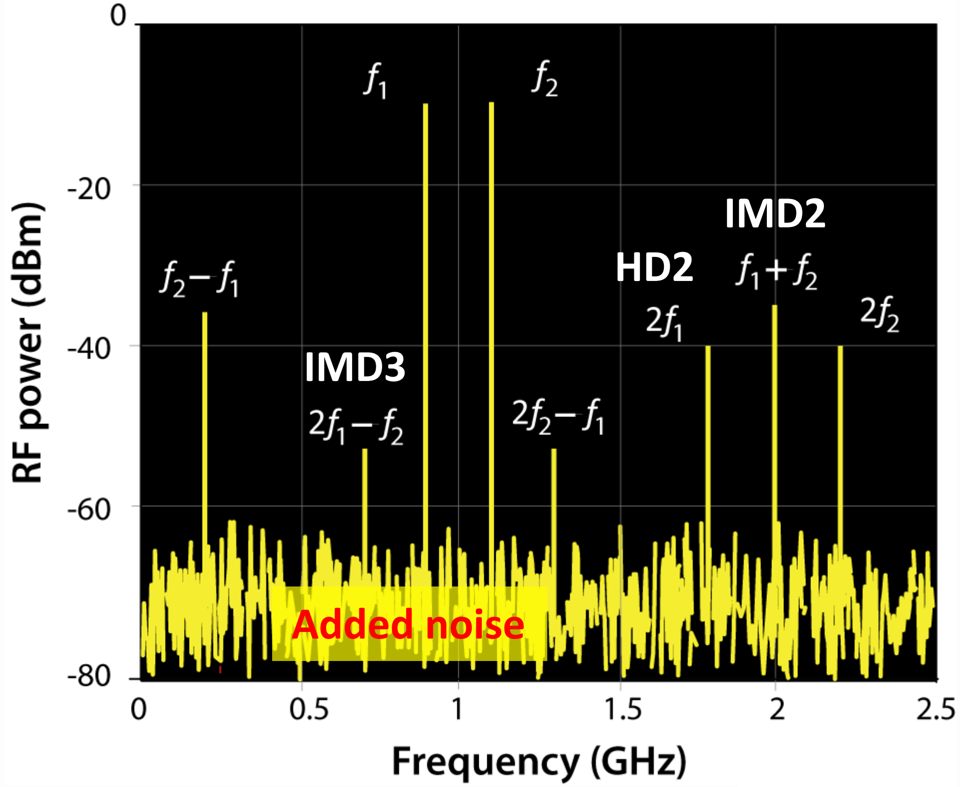
Two-tone test



Input spectrum

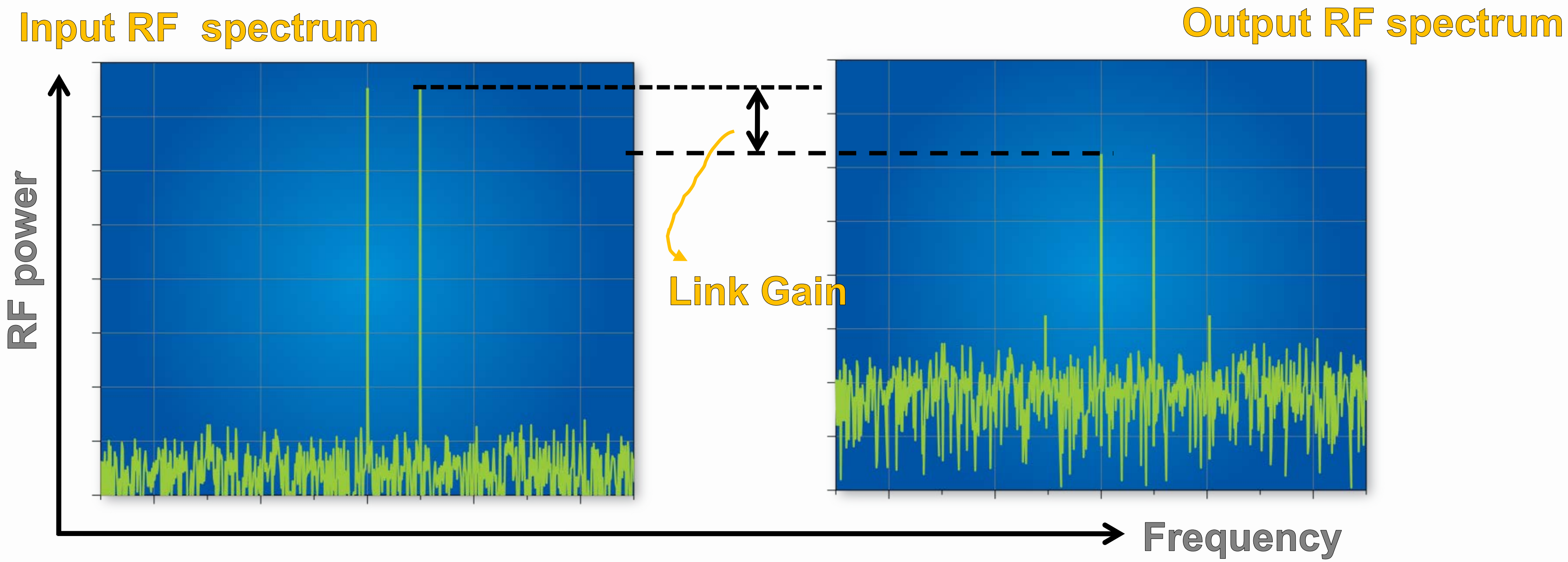


Output spectrum



IMD: Intermodulation distortion
HD: Harmonic distortion

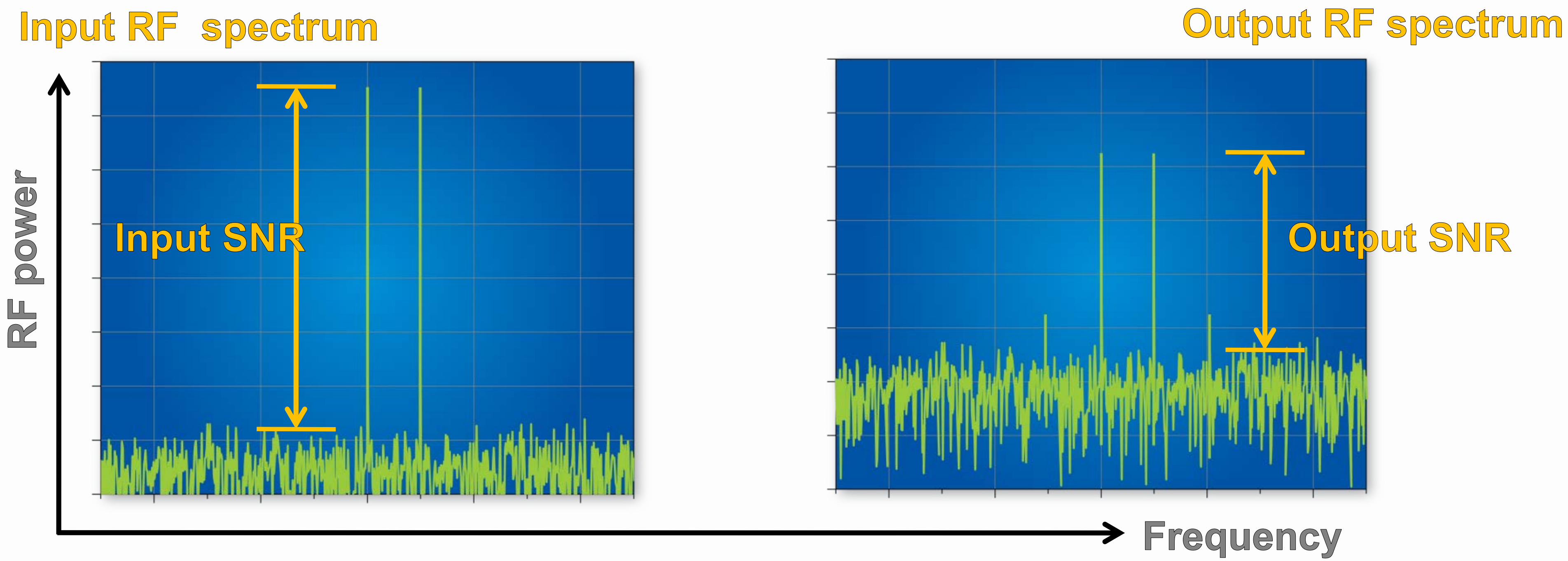
Link gain



Link Gain (dB) = Output signal power(dBm) – Input signal power (dBm)

- Mostly < 1 (loss) → "bad" design: -40 dB; state of the art > 20 dB
- Depends on efficiency of E/O and O/E conversions
- Square dependence on optical loss → effect of loss is severe

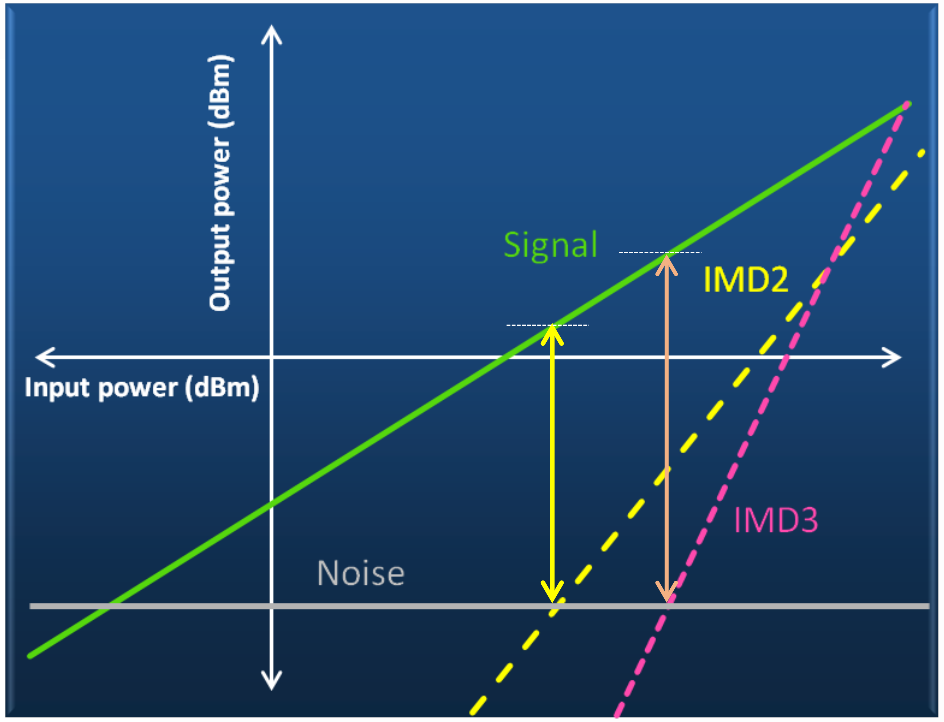
Noise figure

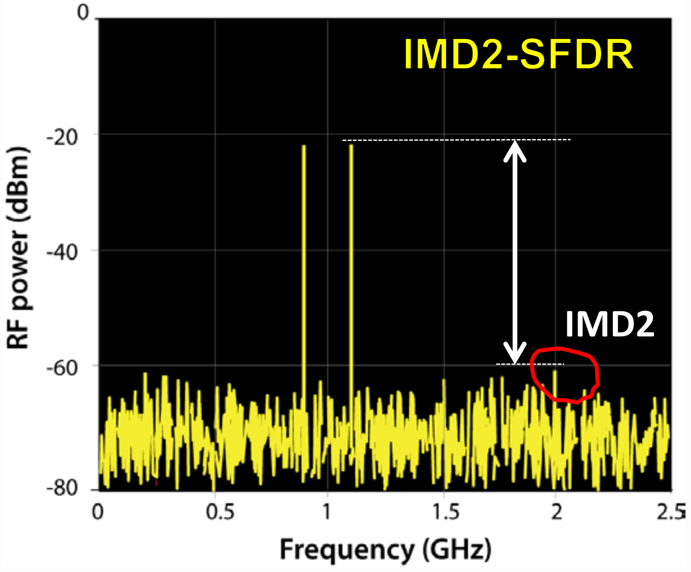


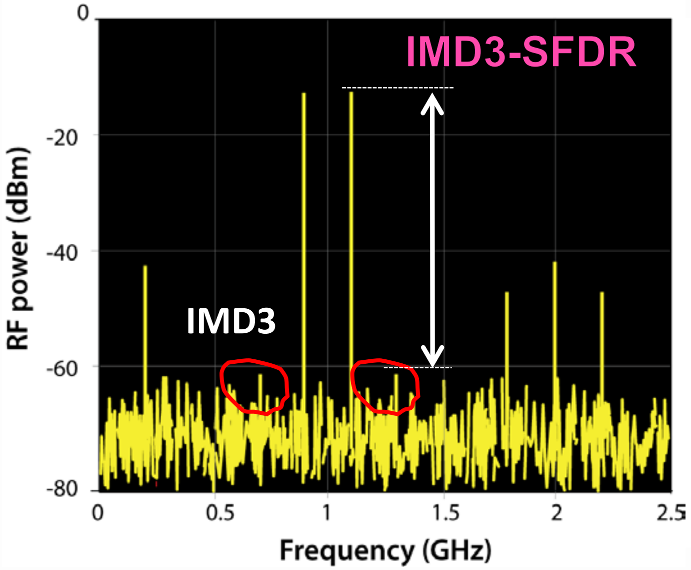
Noise figure (dB) = Input SNR (dB) – Output SNR (dB)

- "Bad" design: > 50 dB; state of the art < 10 dB
- Depends on link gain and link noise $NF\,(\mathrm{dB}) = P_{noise}\,(\mathrm{dBm/Hz}) - G\,(\mathrm{dB}) + 174$
- Depends on many parameters: optical power, RIN, bias point etc.

Spurious-free dynamic range (SFDR)







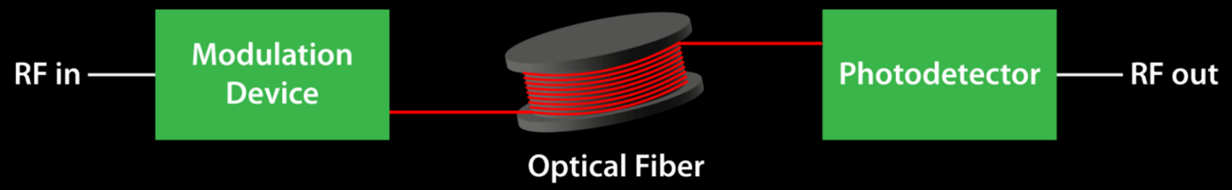
SFDR : SNR @ IMD power = noise power

= The strongest signal that can be filtered out without distortion

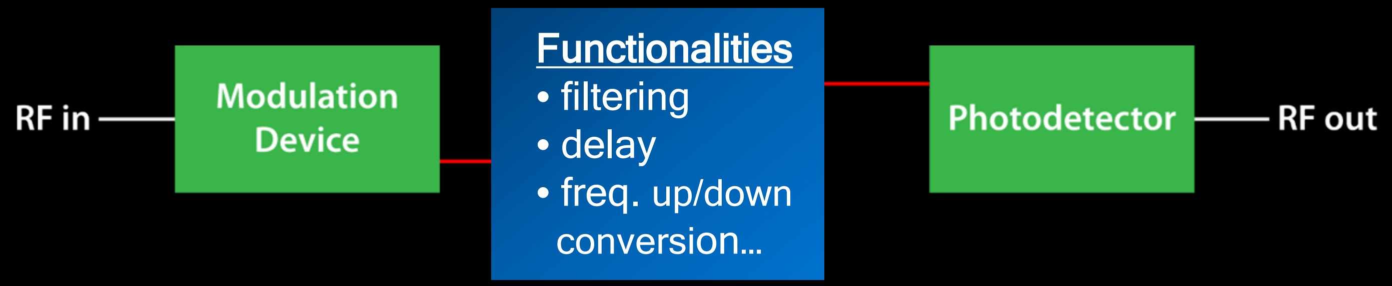
Important figure of merit (!)

Integrated microwave photonics

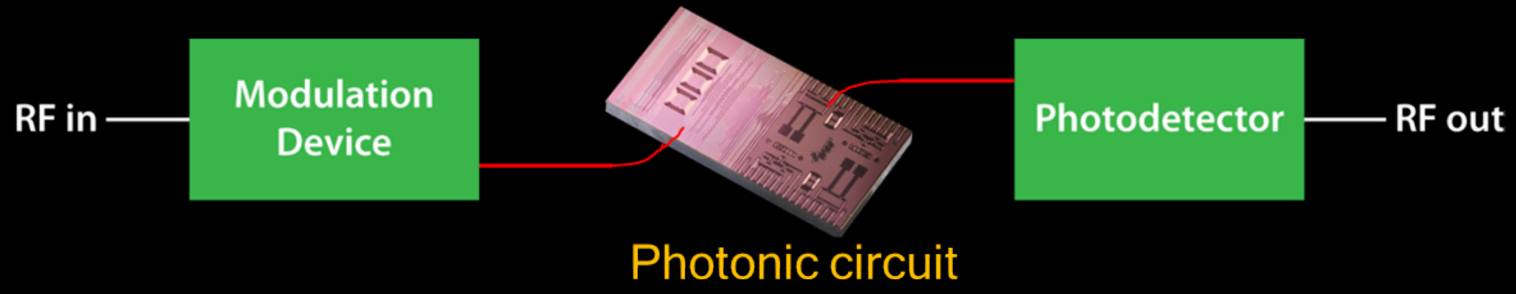
MWP link: low loss signal transport/distribution



MWP system: wideband, reconfigurable RF signal processing



Integrated MWP: PICs for advantage in size, weight and power



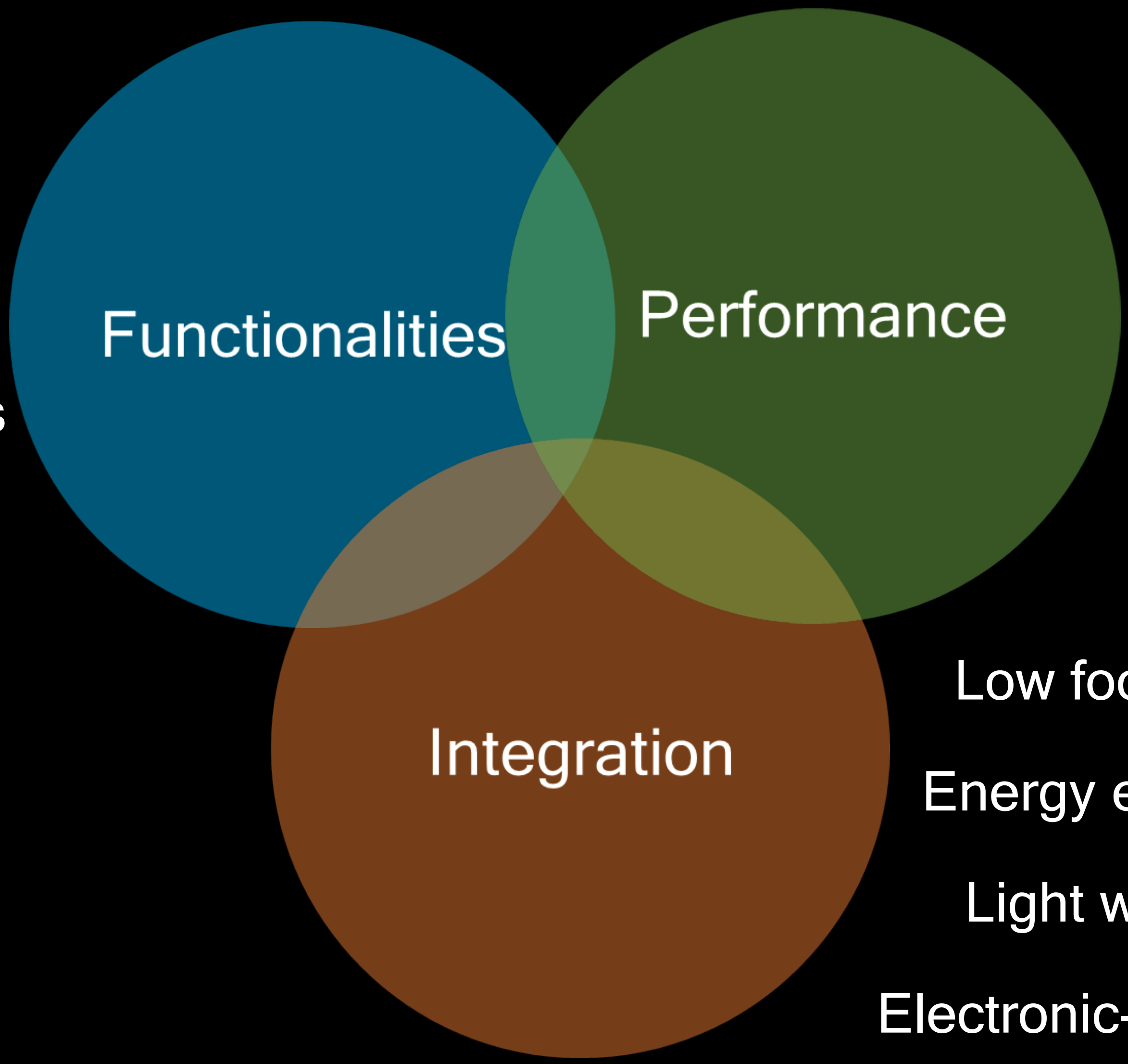
Three pillars of integrated MWP

Fast beamsteering

Low noise oscillator

Agile filters

Wideband converters



High link gain

Low noise figure

High dynamic range

Wide bandwidth

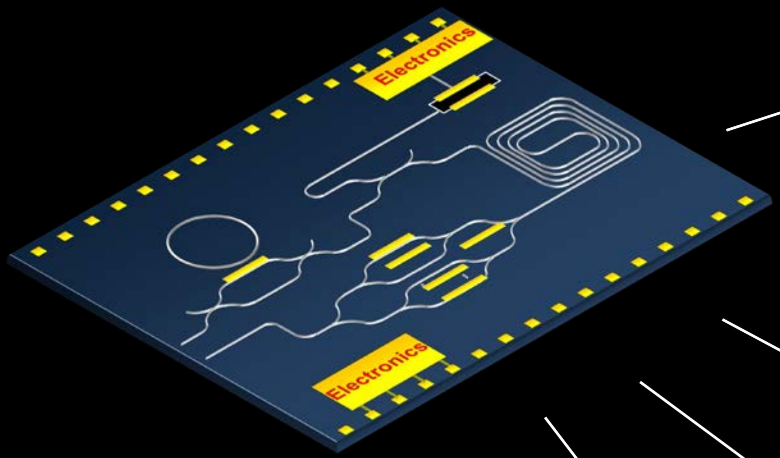
Low footprint

Energy efficient

Light weight

Electronic-photonic

Why beyond silicon: stringent requirements



Low loss ✗

High power handling ✗

Compact ✓

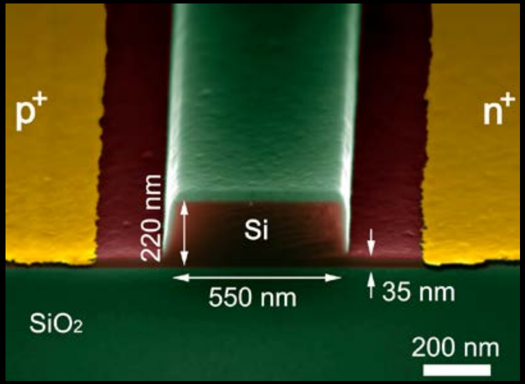
Lasers ✗

Linear modulation & detection ✗

CMOS compatible ✓

Optical nonlinearities ✓

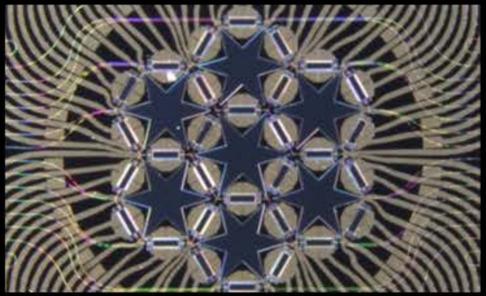
Standard silicon



- Loss ~ 1-3 dB/cm
- Tens of micron bend radius
- Carrier depletion modulator
- Nonlinear loss for high intensity (TPA and FCA)

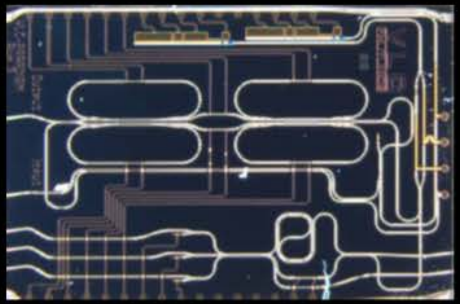
Material platforms

Silicon



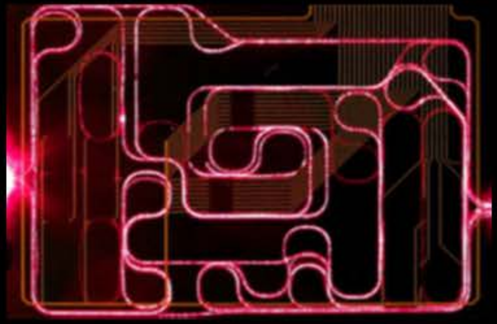
Universal signal processor
(UPV, Nat. Comm. 2017)

Indium phosphide



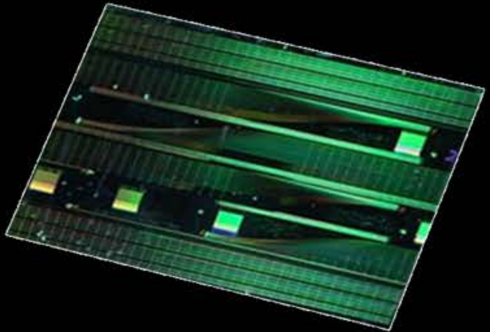
All integrated filter
(UPV, Nat. Photon. 2017)

Silicon nitride



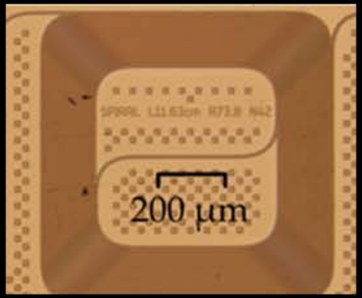
Channelizer, processor
(LioniX, JSTQE 2018)

Chalcogenide



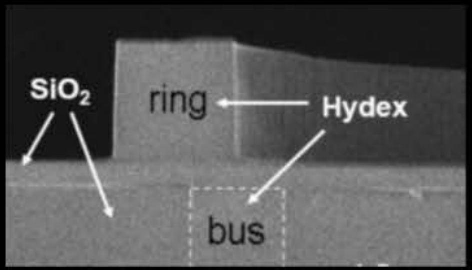
SBS tunable filter
(Sydney, Optica 2015)

Thick SOI



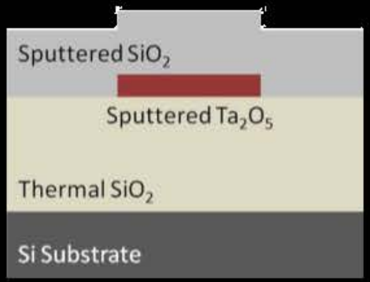
Instantaneous frequency measurement
(Sydney, Optica 2016)

Hydex

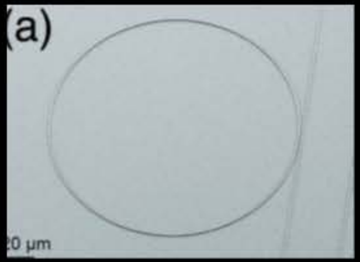


Comb-based RF photonics
(Swinburne, JSTQE 2018)

Emerging materials



Ta_2O_5 (UCSB, Optica 2017)

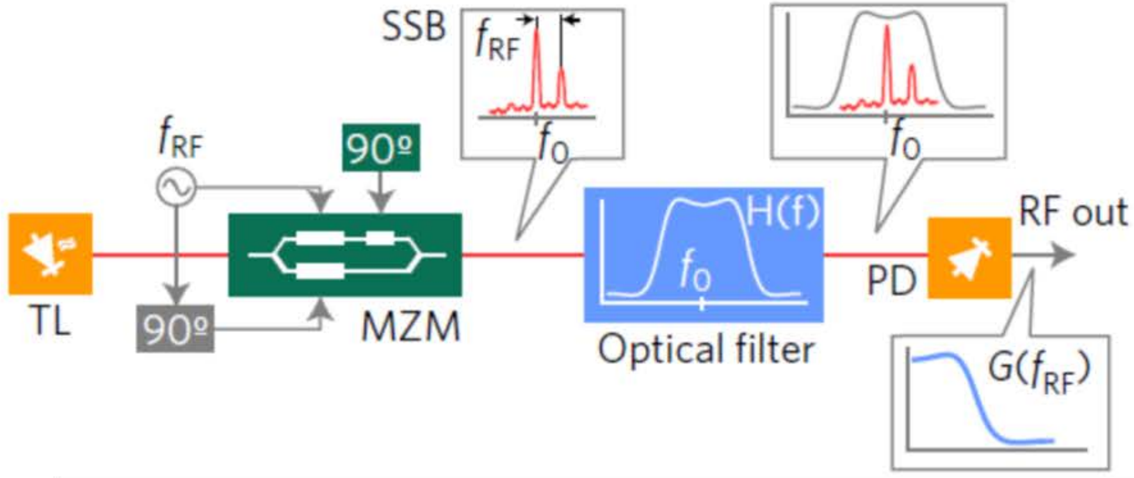


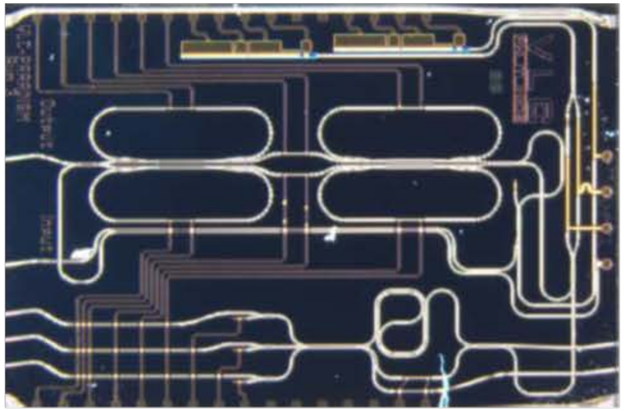
LNOI (Harvard, Optica 2017)

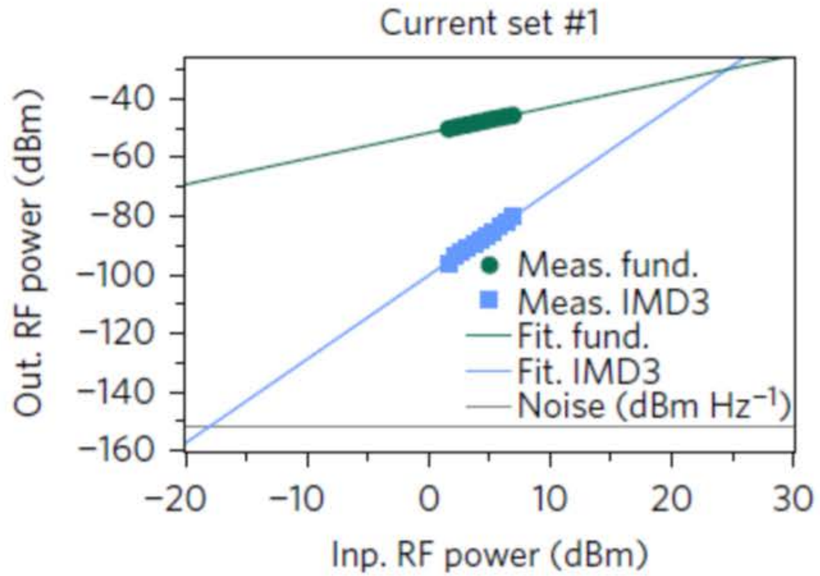
ARTICLES
PUBLISHED ONLINE: 5 DECEMBER 2016 | DOI: 10.1038/NPHOTON.2016.233
nature photonics

A monolithic integrated photonic microwave filter

Javier S. Fandiño[1], Pascual Muñoz[1,2], David Doménech[2] and José Capmany[1]*







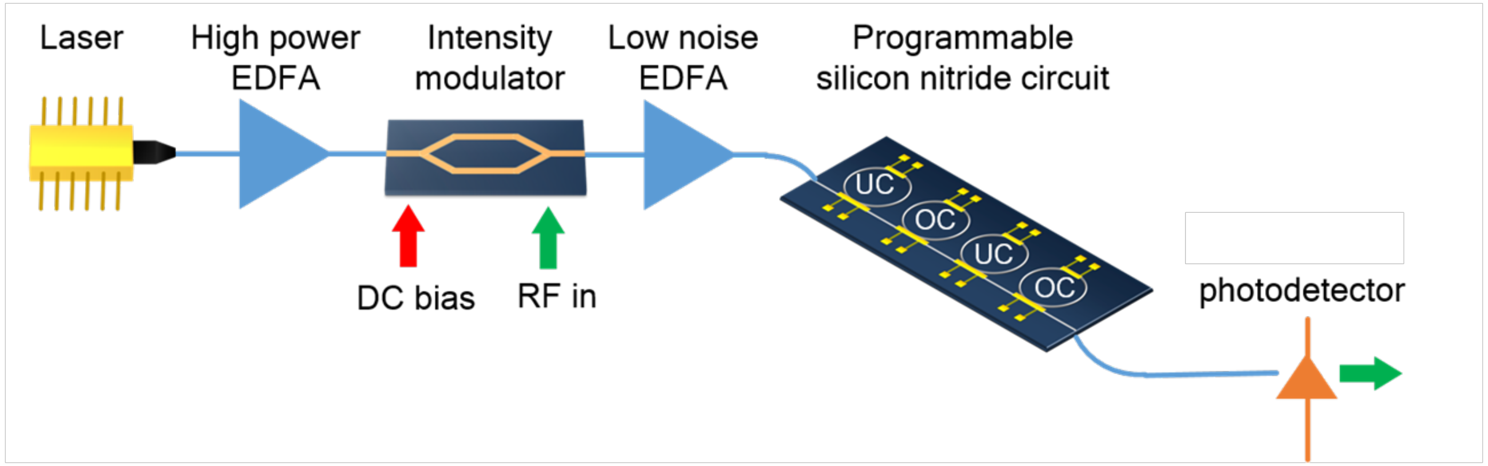
- Platform: indium phosphide
- 100% integration (laser, modulator, rings, PD)
- But relatively low performance

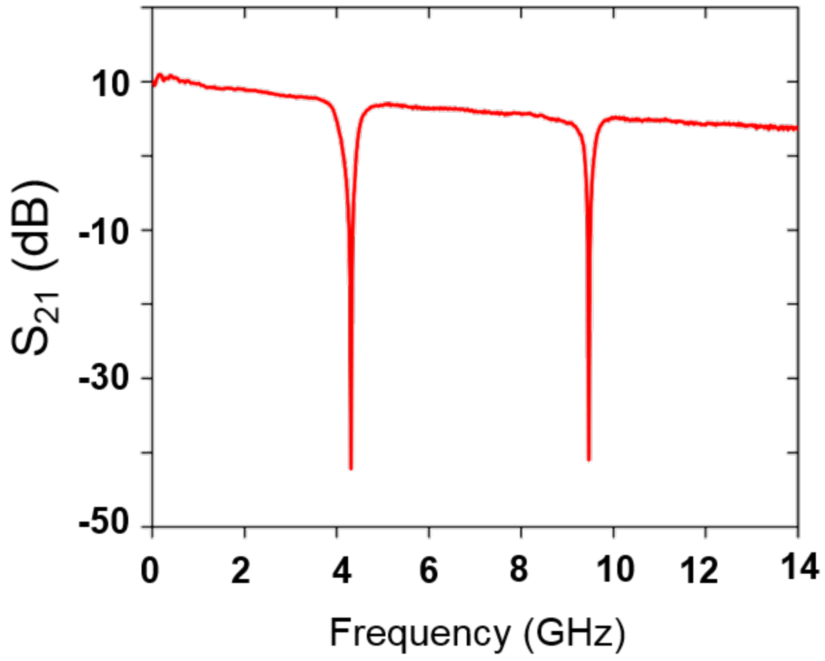
Letter
Vol. 42, No. 22 / November 15 2017 / *Optics Letters* 4631

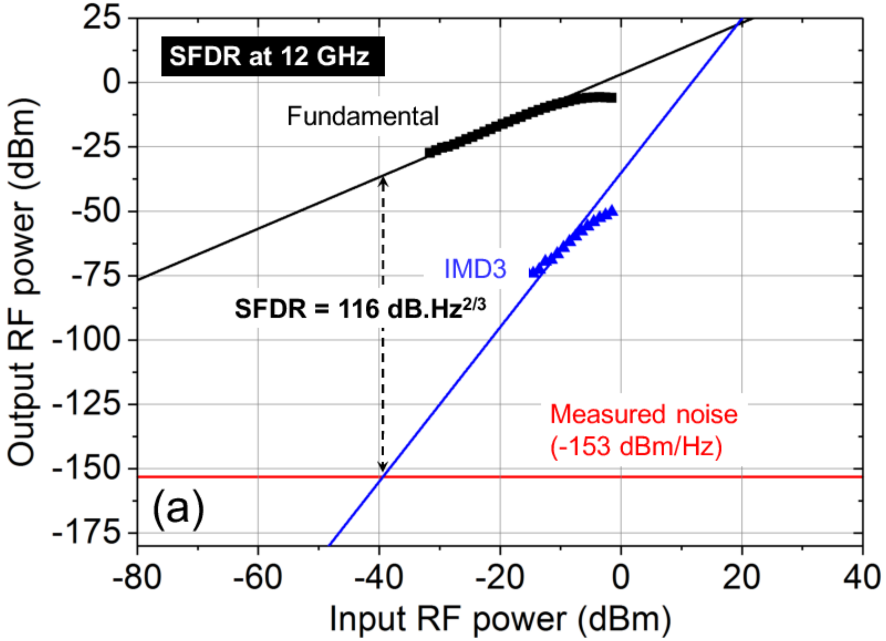
Optics Letters

All-optimized integrated RF photonic notch filter

Yang Liu,[1,2] Jason Hotten,[1,2] Amol Choudhary,[1,2] Benjamin J. Eggleton,[1,2] and David Marpaung[1,2,*]







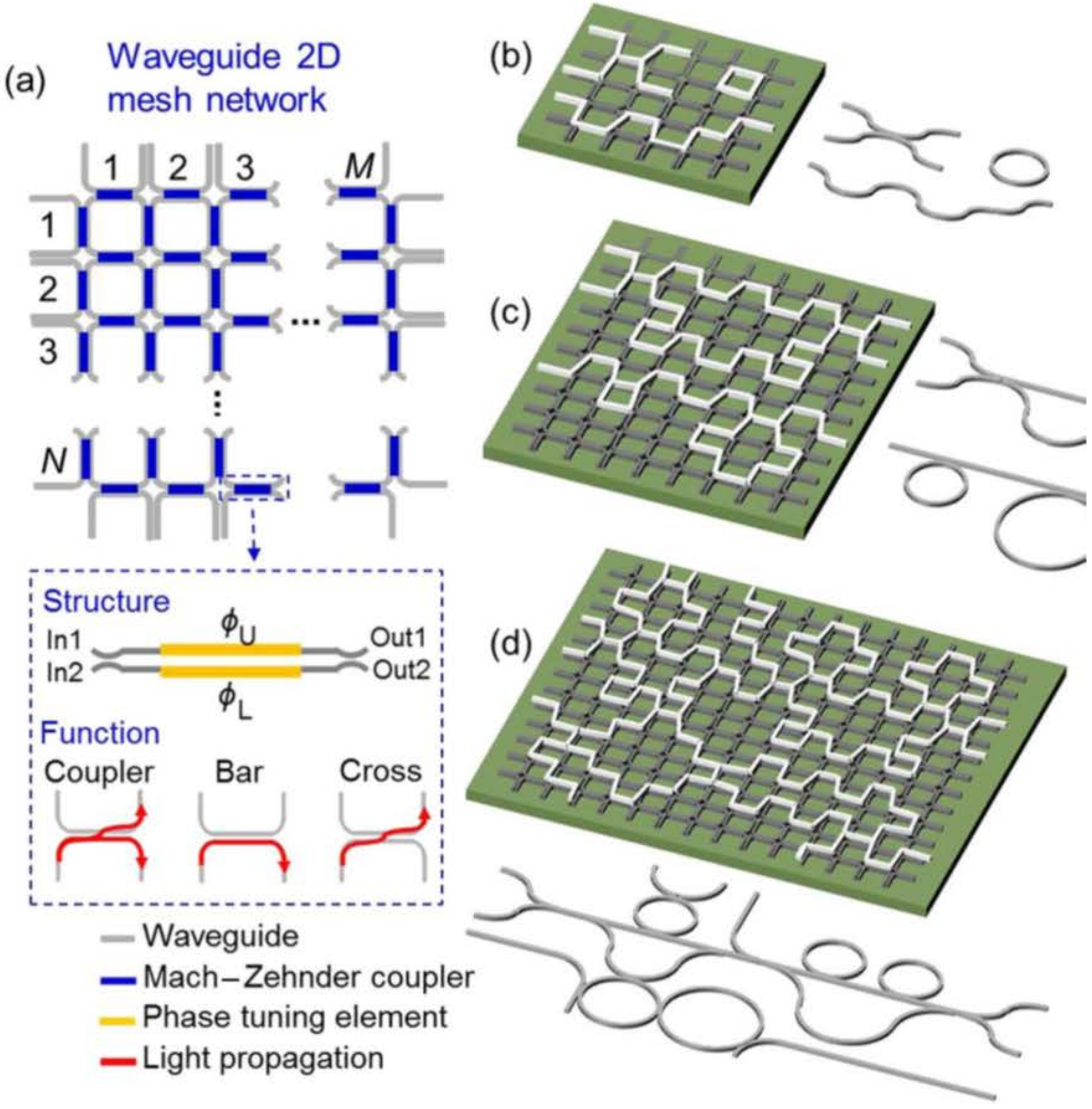
- For the first time, advanced filtering and high performance are achieved simultaneously
- The filter exhibits record-low noise figure (15.6 dB) and high dynamic range (116 dB.Hz), amplification in the passband (8 dB) and ultrahigh stopband rejection (55 dB)

Research Article Vol. 2, No. 10 / October 2015 / Optica 854

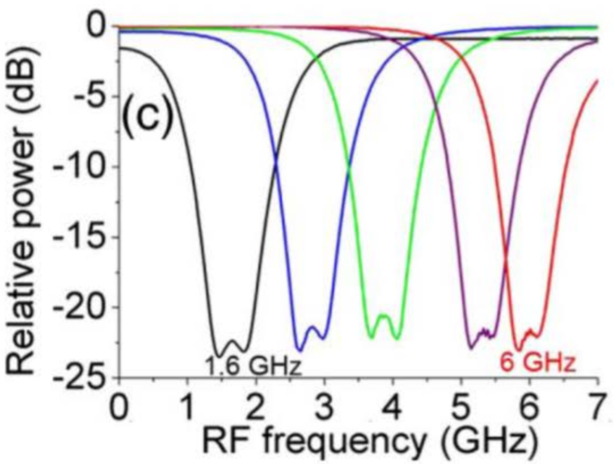
optica

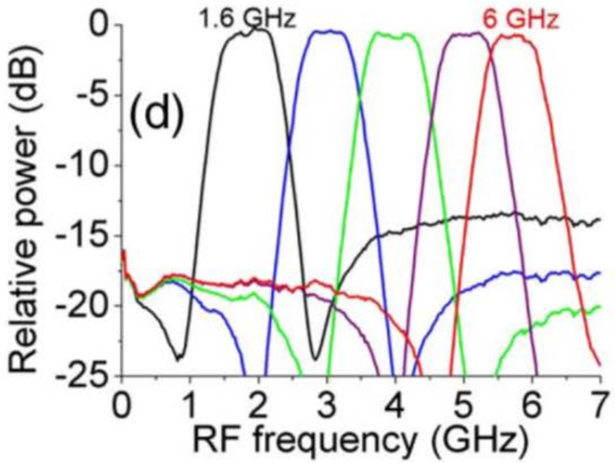
Programmable photonic signal processor chip for radiofrequency applications

Leimeng Zhuang,[1,*] Chris G. H. Roeloffzen,[2] Marcel Hoekman,[3] Klaus-J. Boller,[4] and Arthur J. Lowery[1,5]



- Platform: silicon nitride
- Key component: Mach-Zehnder interferometers
- Reconfigurable processor
- Loss 0.1 dB/cm





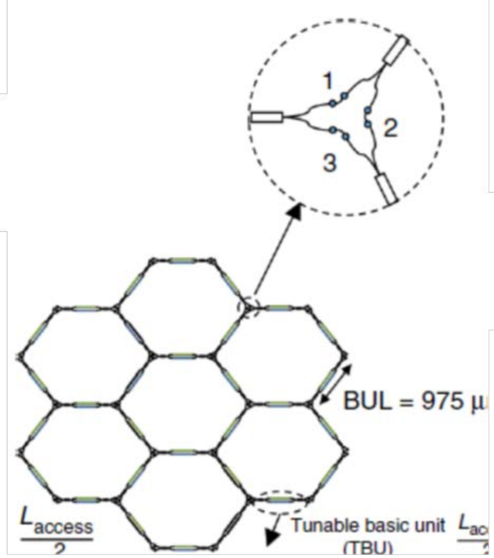
nature COMMUNICATIONS

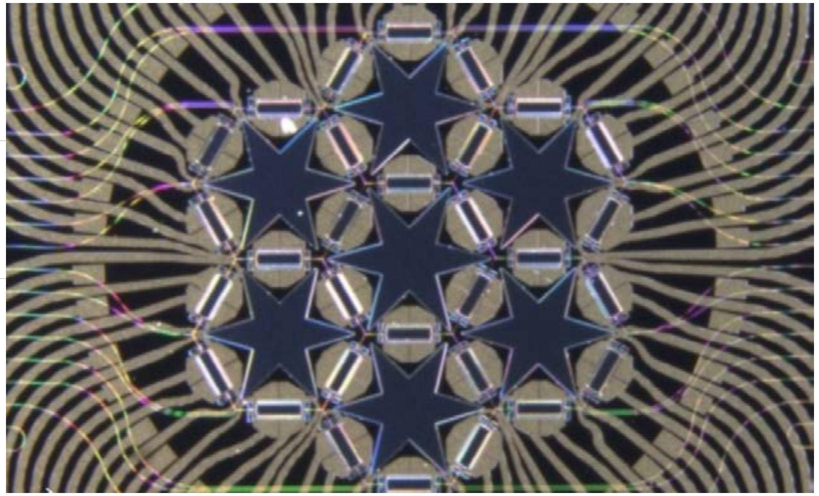
ARTICLE

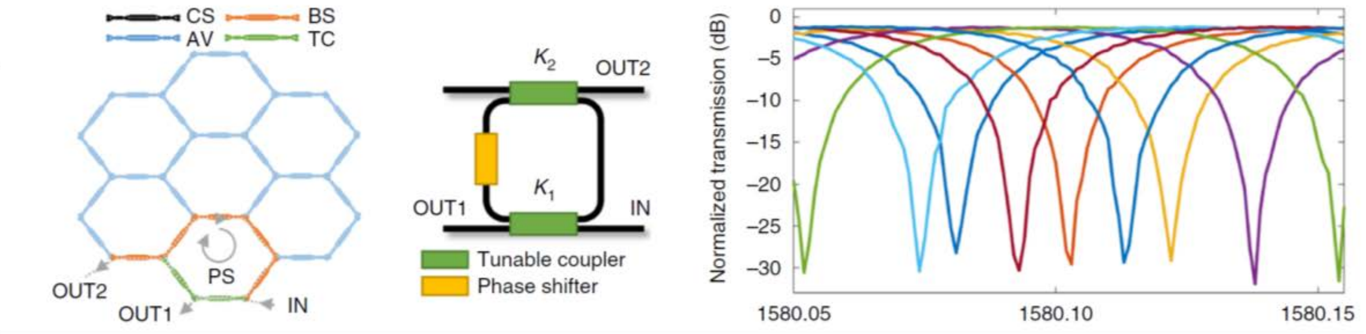
DOI: 10.1038/s41467-017-00714-1 OPEN

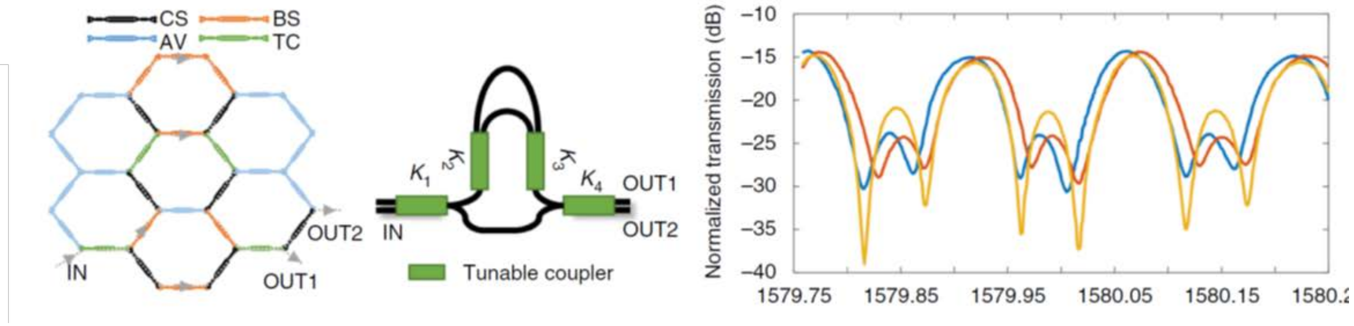
Multipurpose silicon photonics signal processor core

Daniel Pérez[1], Ivana Gasulla[1], Lee Crudgington[2], David J. Thomson[2], Ali Z. Khokhar[2], Ke Li[2], W
Goran Z. Mashanovich[2,3] & José Capmany[1]









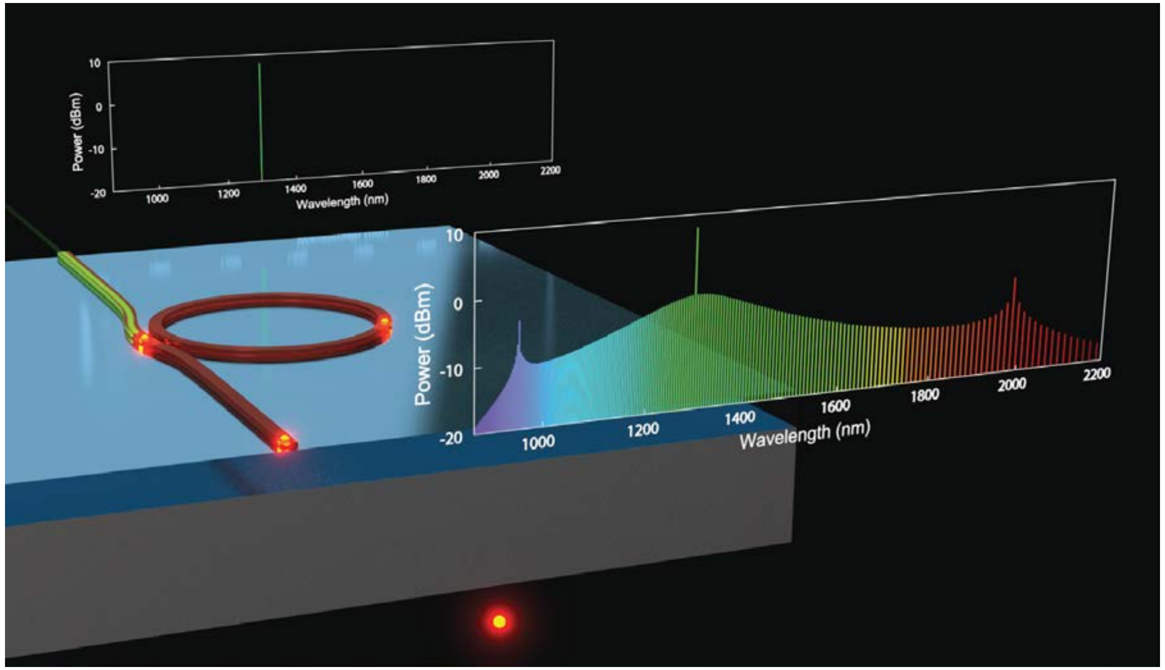
- Platform: silicon
- Hexagonal waveguide mesh
- Can exhibit more than 20 functionalities
- Application beyond MWP, including quantum photonics

Why nonlinear integrated MWP

Nonlinear optics leads to generation of new optical frequencies

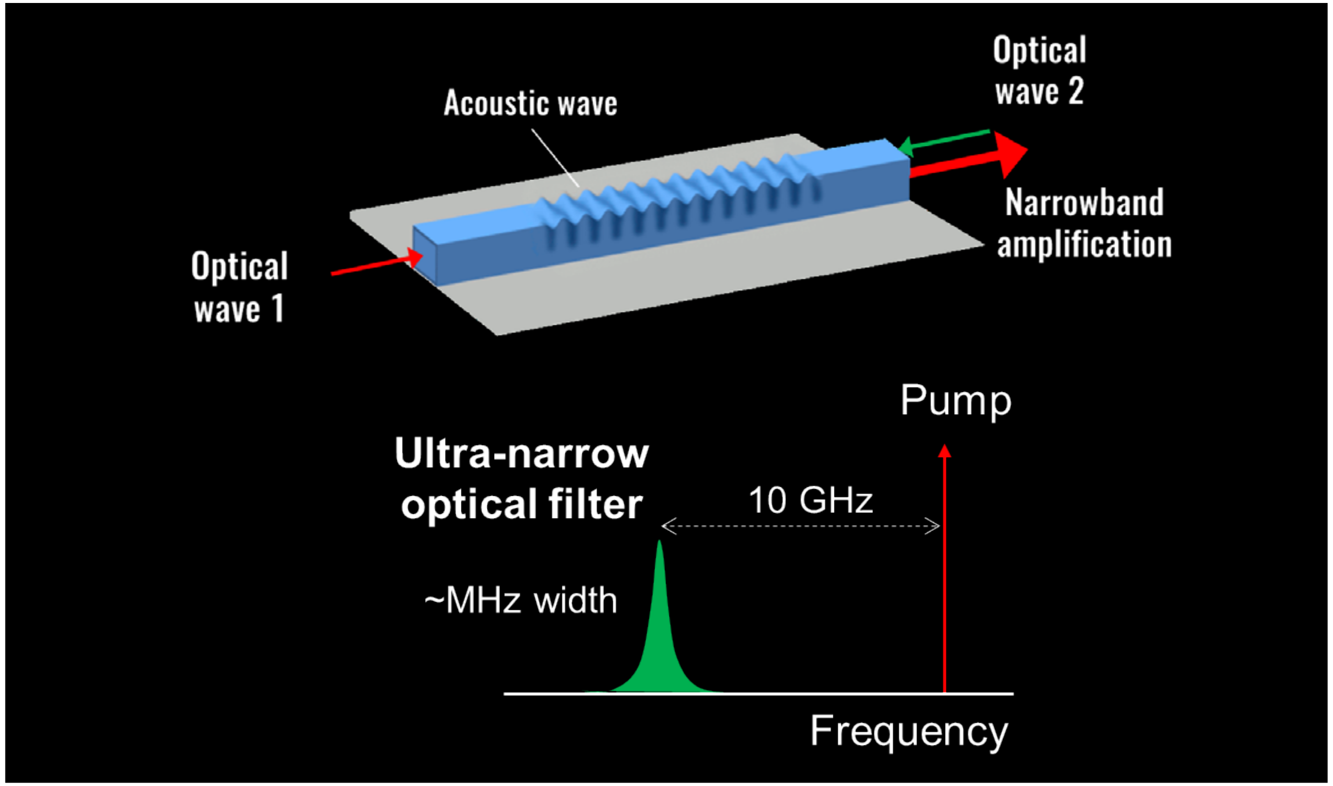
Can be used for unique MWP signal processing, for example:

Multiwavelength optical source



T Kippenberg et al, Science (2018)

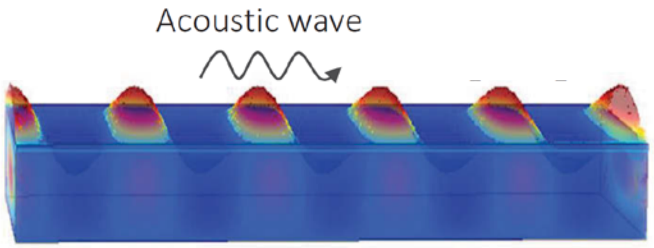
Ultra-high resolution filtering

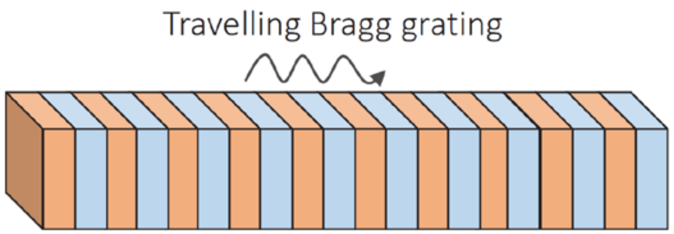


Acousto-optic interactions

Photo-elastic effect: acoustic wave (“sound”) influences light

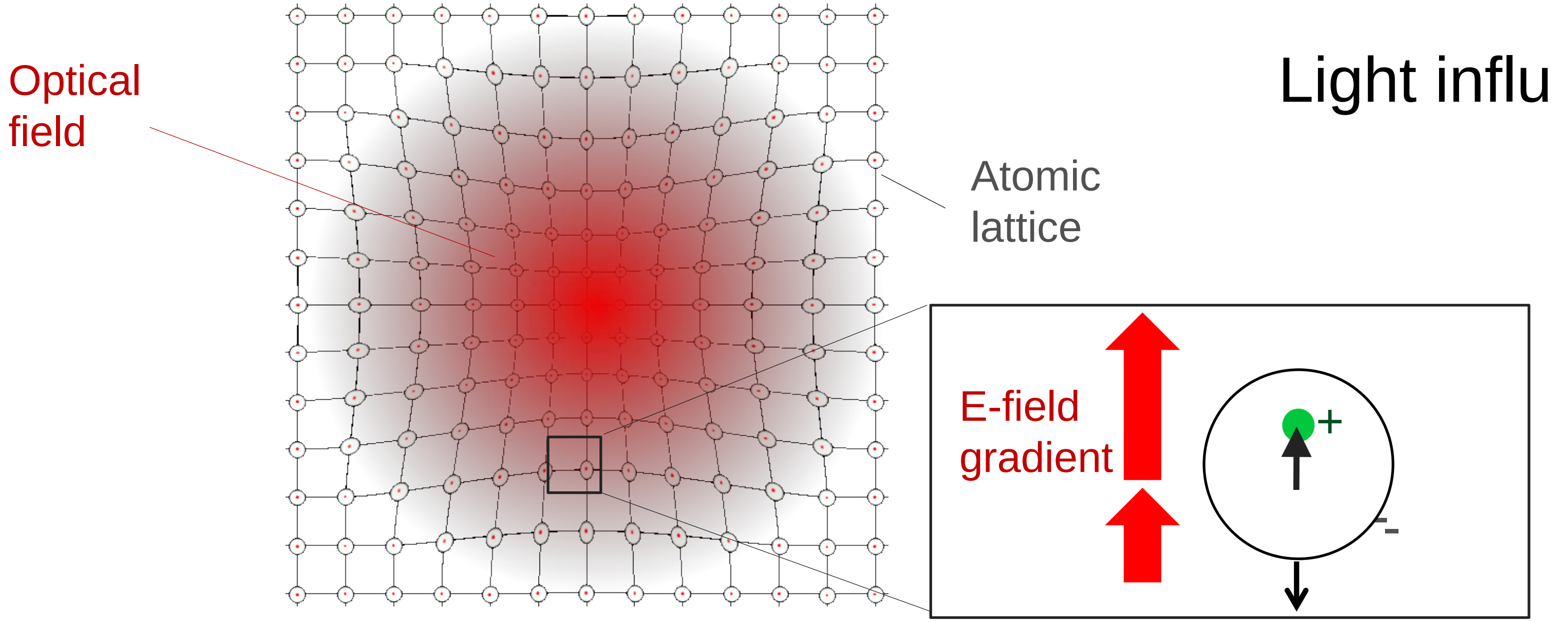
Stress variation induces refractive index change





S. Minarzy, PhD thesis, UTS, 2018

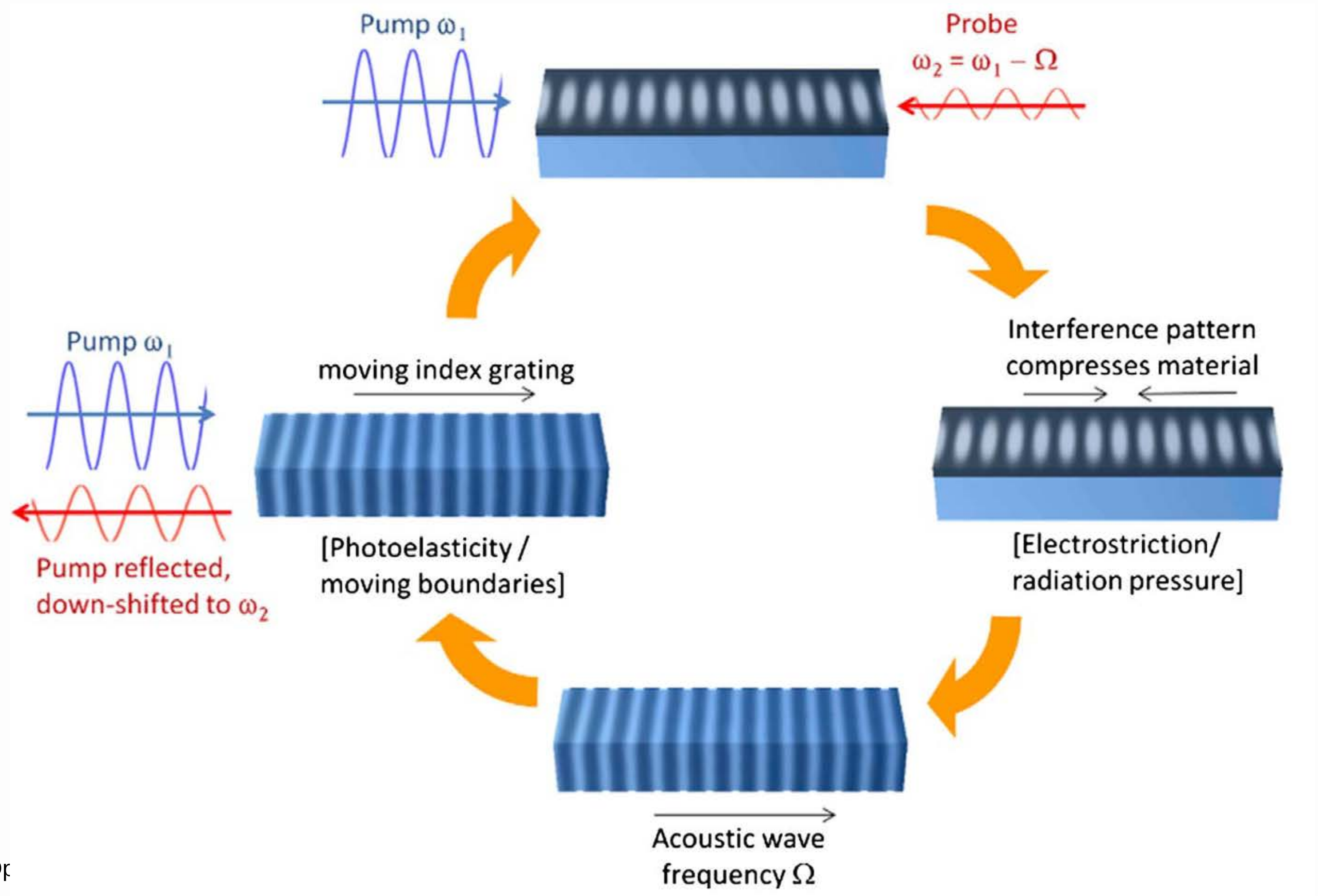
Electrostriction: electric field (“light”) induces displacement/material compression



Light influences sound

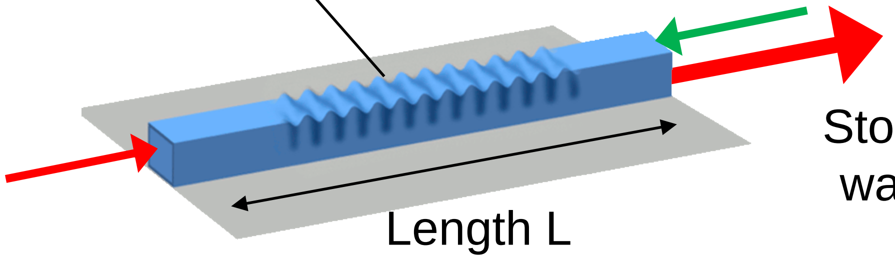
Animation by Prof. Chris Poulton (UTS)

Stimulated Brillouin scattering



Eggleton et al,. Adv. Op

Strength of SBS: Brillouin gain coefficient



Brillouin peak gain [m/W]

Opto-acoustic overlap

$$G = \frac{g_0}{A_{\mathrm{eff}}} \eta P_{\mathrm{p}} L_{\mathrm{eff}}$$

SBS gain

Brillouin gain coefficient (G_B) [$m^{-1}W^{-1}$]

Elasto-optic coefficient

$$g_0 = \frac{16\pi^3 n^8 (p_{12})^2}{c\lambda^3 \rho \Omega \Gamma_{\mathrm{B}}}$$

Recipe for high gain in short (chip) devices :

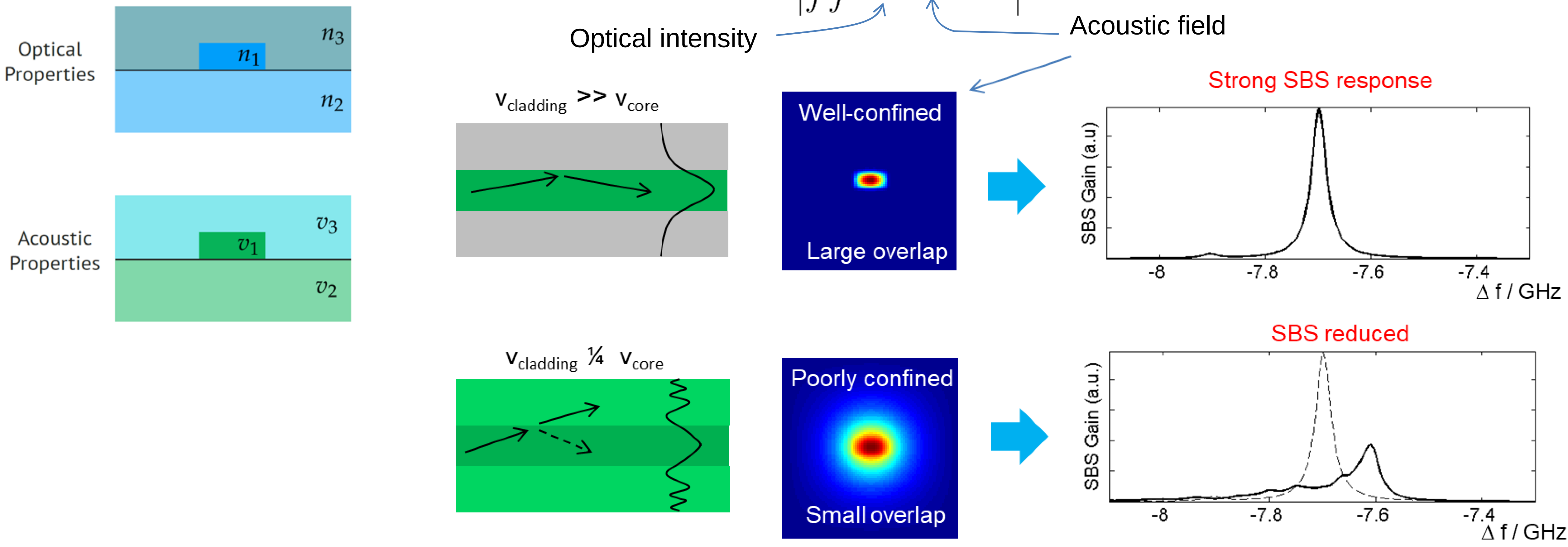
1) High index material
2) High elasto-optic coefficient
3) Small mode area
4) Low loss, long interaction length
5) High opto-acoustic overlap

Eggleton et al,. Adv. Opt. Photon **5** (2013)

Role of overlap and mode confinement

- Large overlap requires confinement of optical and acoustic modes
- Acoustic confinement is determined by acoustic impedance (velocity) of materials

$$g_0 \sim \left| \iint ||\mathbf{E}||^2 \rho^* \mathrm{d}x\mathrm{d}y \right|^2$$



Poulton et al. JOSA B **30** (2013)

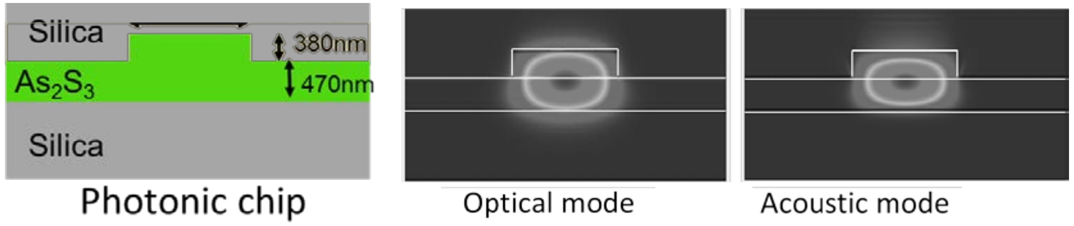
Example of on-chip Brillouin device: chalcogenide

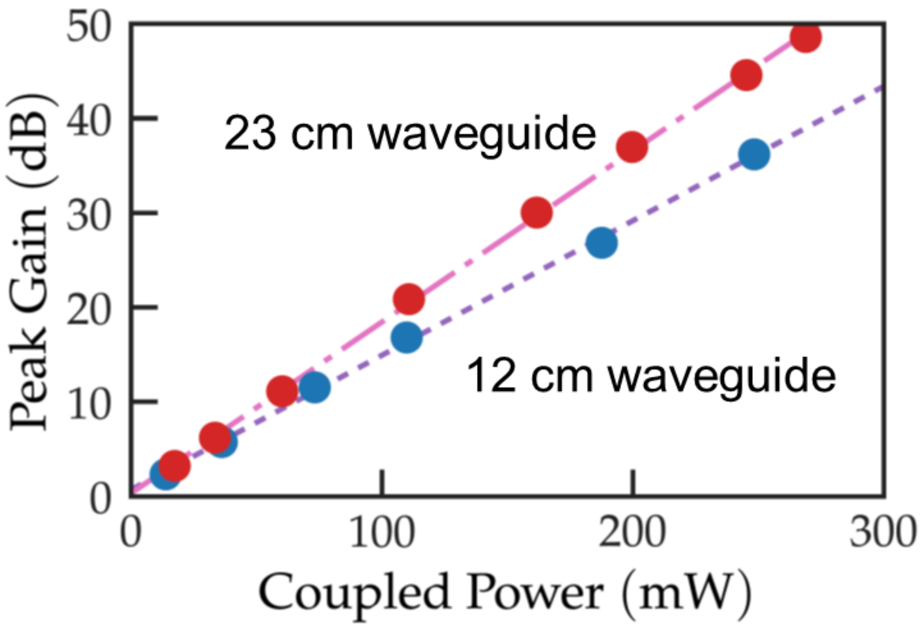
- High index material As_2S_3 (n~2.45)
- Small mode area (A_{eff} ~ 2.3 μm^2)
- Low propagation loss (~0.2 dB/cm)
- Low nonlinear loss
- Large elasto-optic coefficient
- Large overlap of acoustic and optical modes

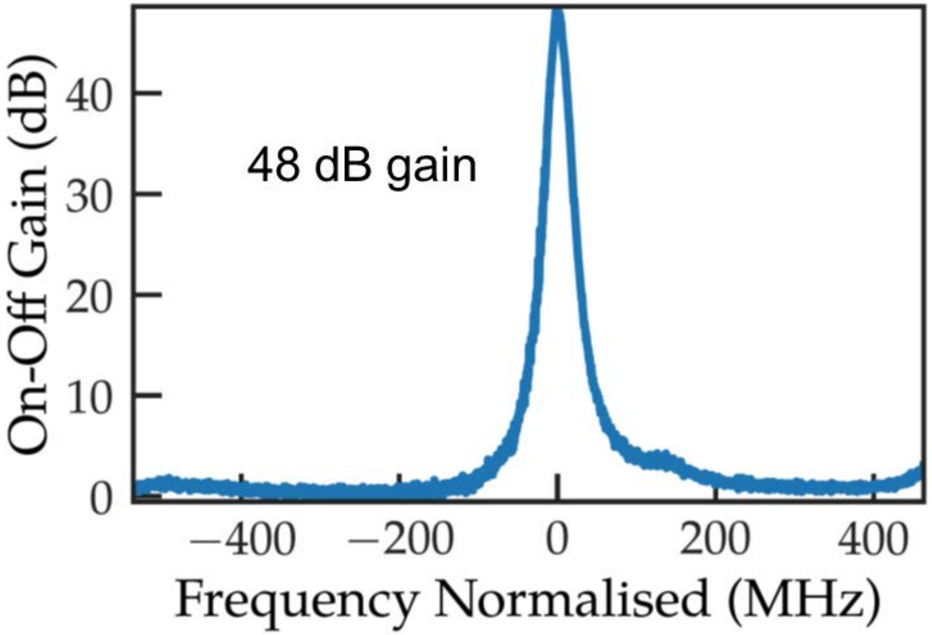
v_{silica} ~ 6000 m/s

v_{chalc} ~ 2600 m/s

v_{silica} ~ 6000 m/s





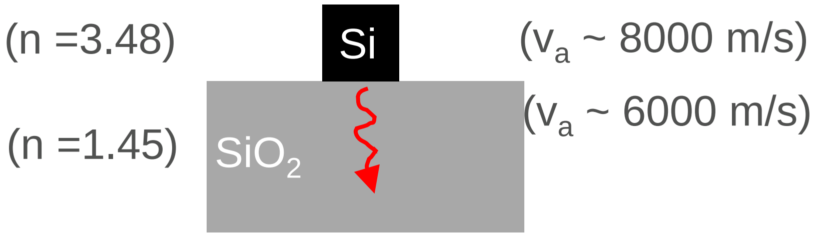


B. Morrison, PhD thesis (2018)

Silicon Brillouin device

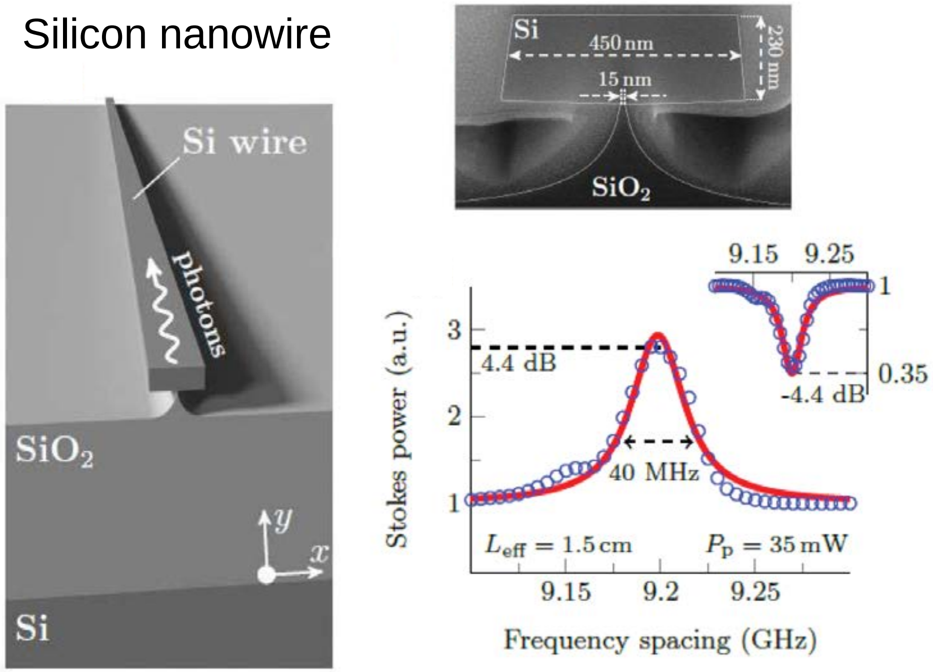
- High index and small mode area
- Relatively high propagation loss (1-2 dB/cm)
- Nonlinear loss (Two-photon and free-carrier absorption)
- Small elasto-optic coefficient (200x lower than ChG)
- Acoustic leakage (small overlap)

SOI waveguide



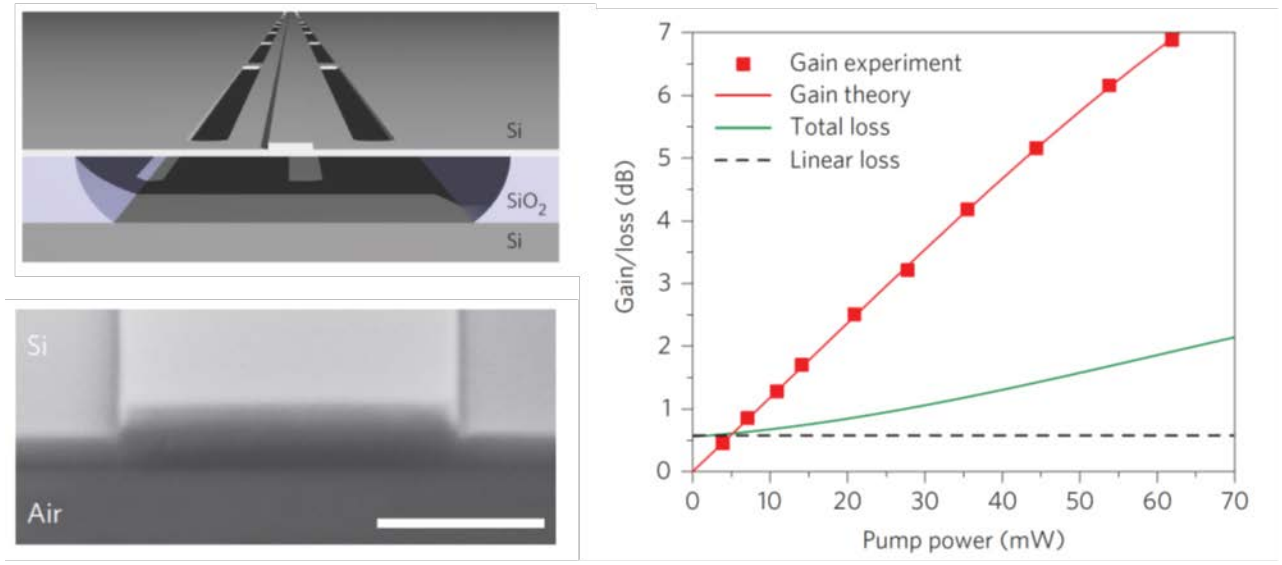
Phonon leakage

Silicon nanowire



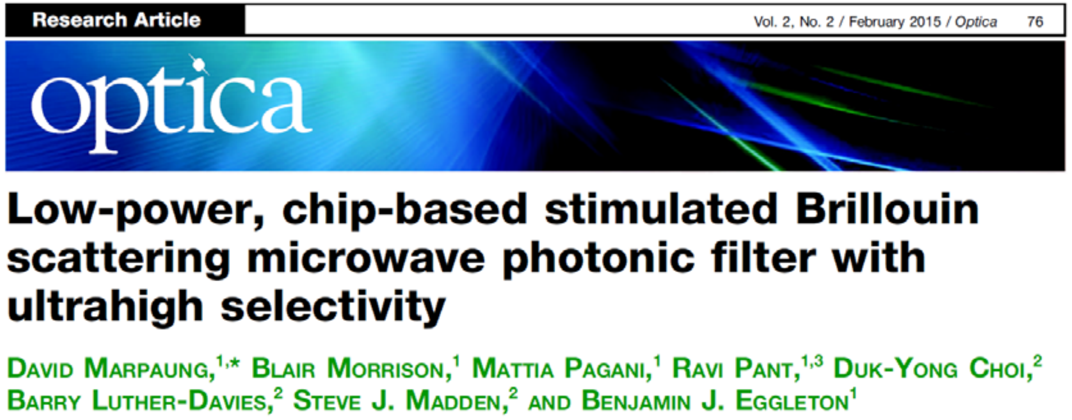
R. Van Laer et al., Nat. Photon. (2015)

Silicon rib-waveguide



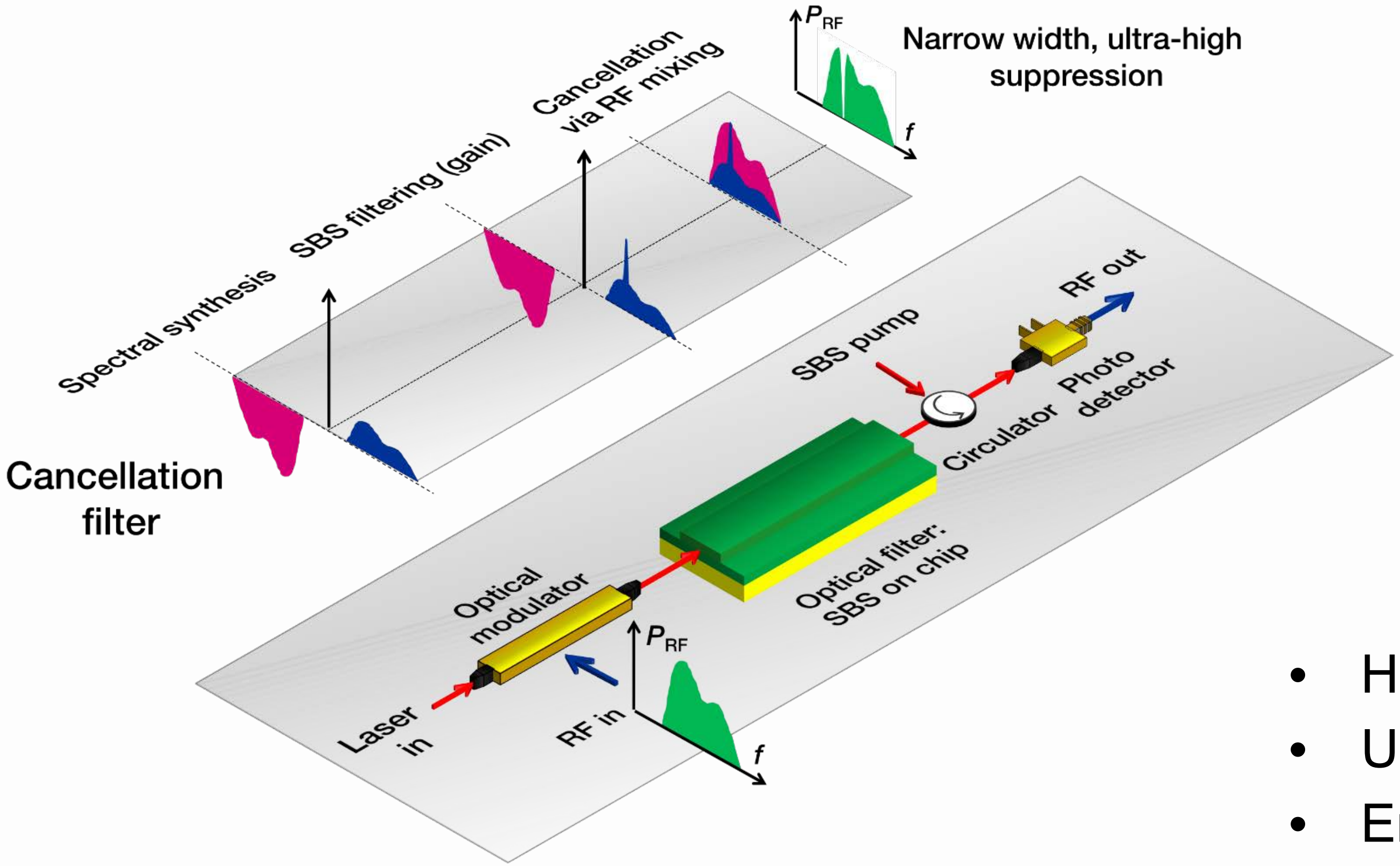
E. Kittlaus et al., Nat. Photon. (2016)

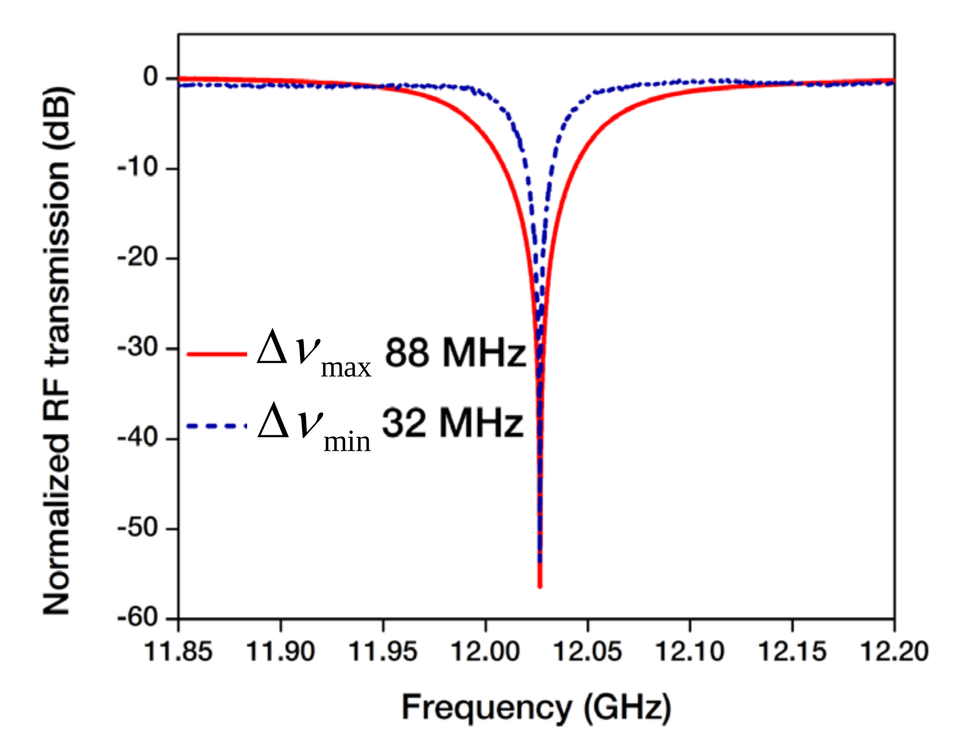
Tunable notch filter


Research Article
Vol. 2, No. 2 / February 2015 / Optica 76
optica

Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity

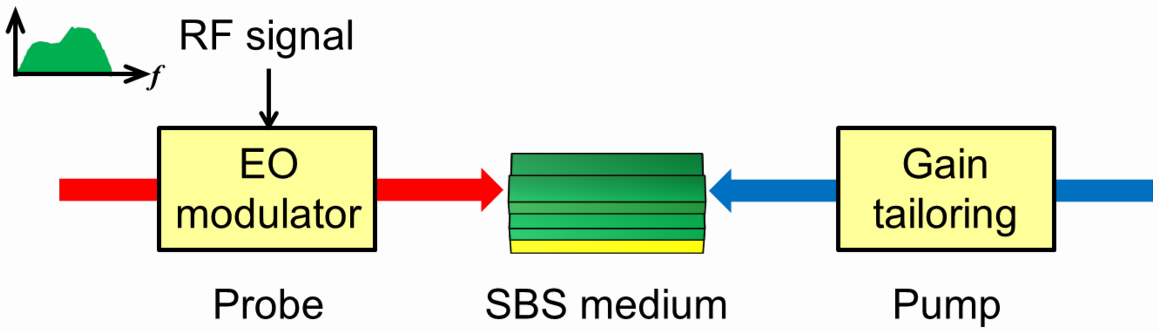
David Marpaung,[1,*] Blair Morrison,[1] Mattia Pagani,[1] Ravi Pant,[1,3] Duk-Yong Choi,[2] Barry Luther-Davies,[2] Steve J. Madden,[2] and Benjamin J. Eggleton[1]

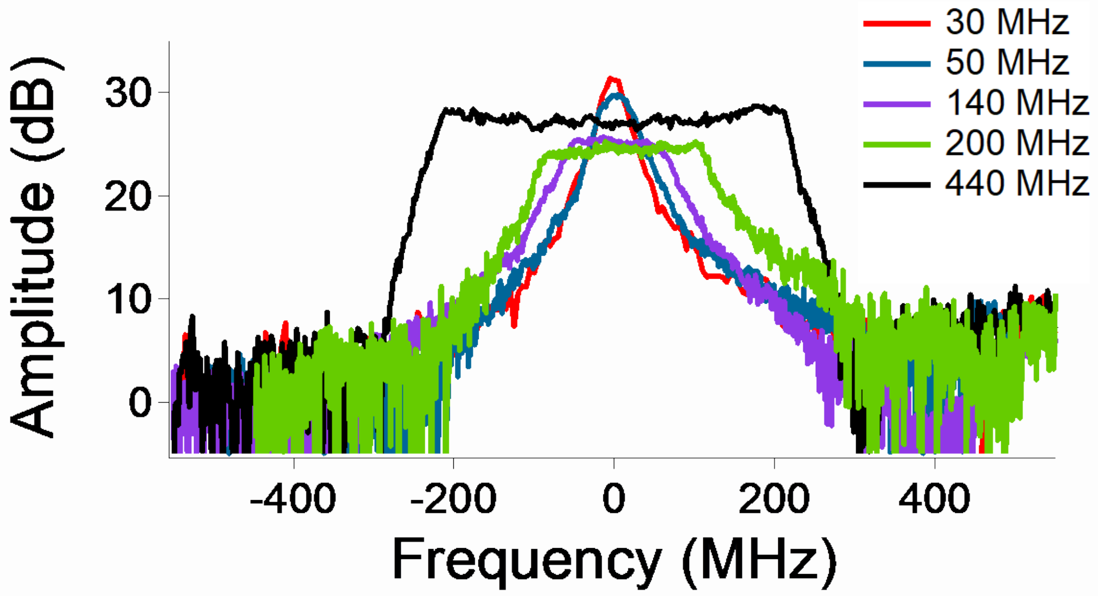


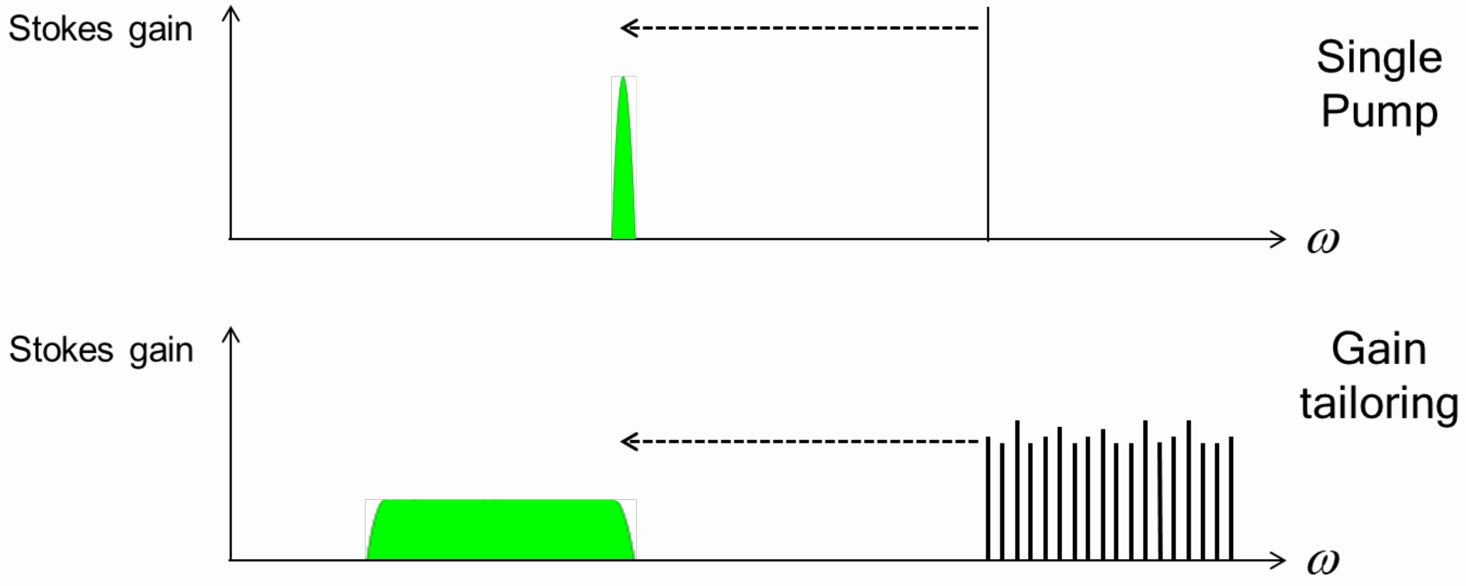


- High Q RF filter
- Ultra-high suppression
- Energy efficiency (low gain)
- Tens of GHz tuning range

Pump tailoring







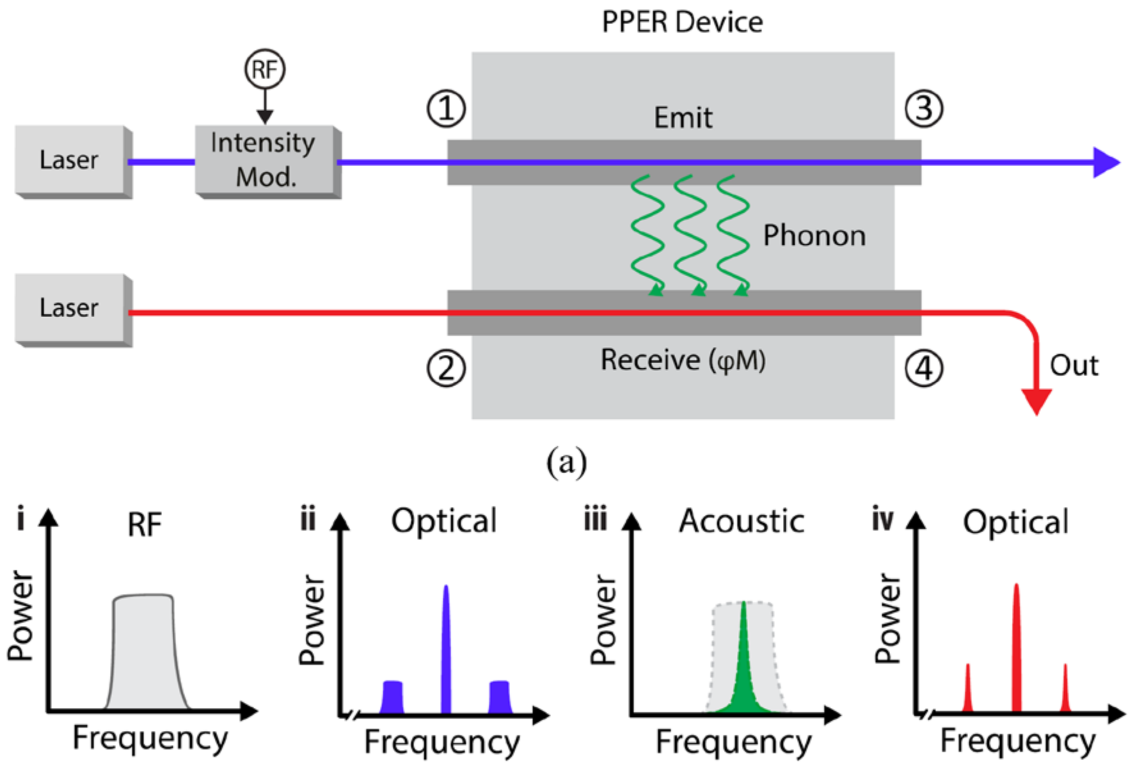
- Tunable bandwidth bandpass filter (30 MHz-440 MHz)
- Low passband ripple (< 1.9 dB)
- 25 dB selectivity
- Achieved from approx. 44 dB equivalent gain

Choudhary et al., Opt. Letters **41** (2015)

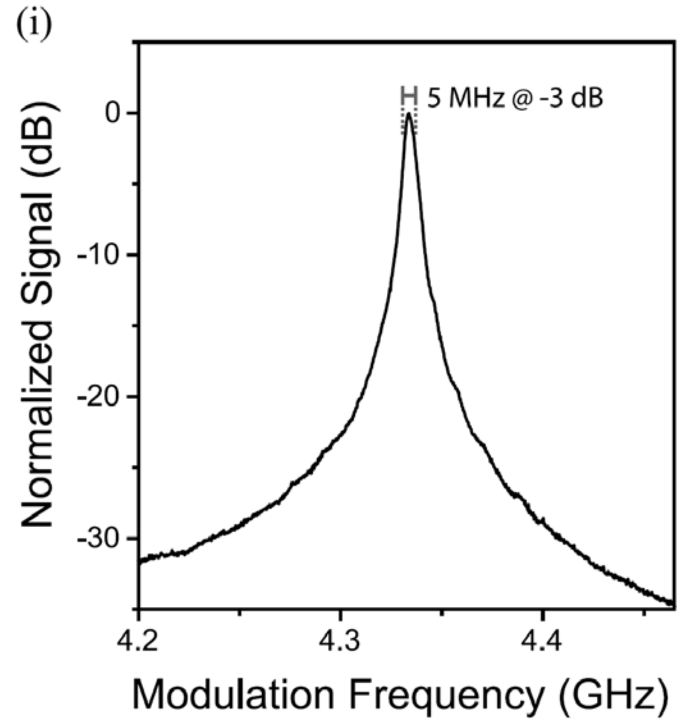
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 36, NO. 13, JULY 1, 2018

RF-Photonic Filters via On-Chip Photonic–Phononic Emit–Receive Operations

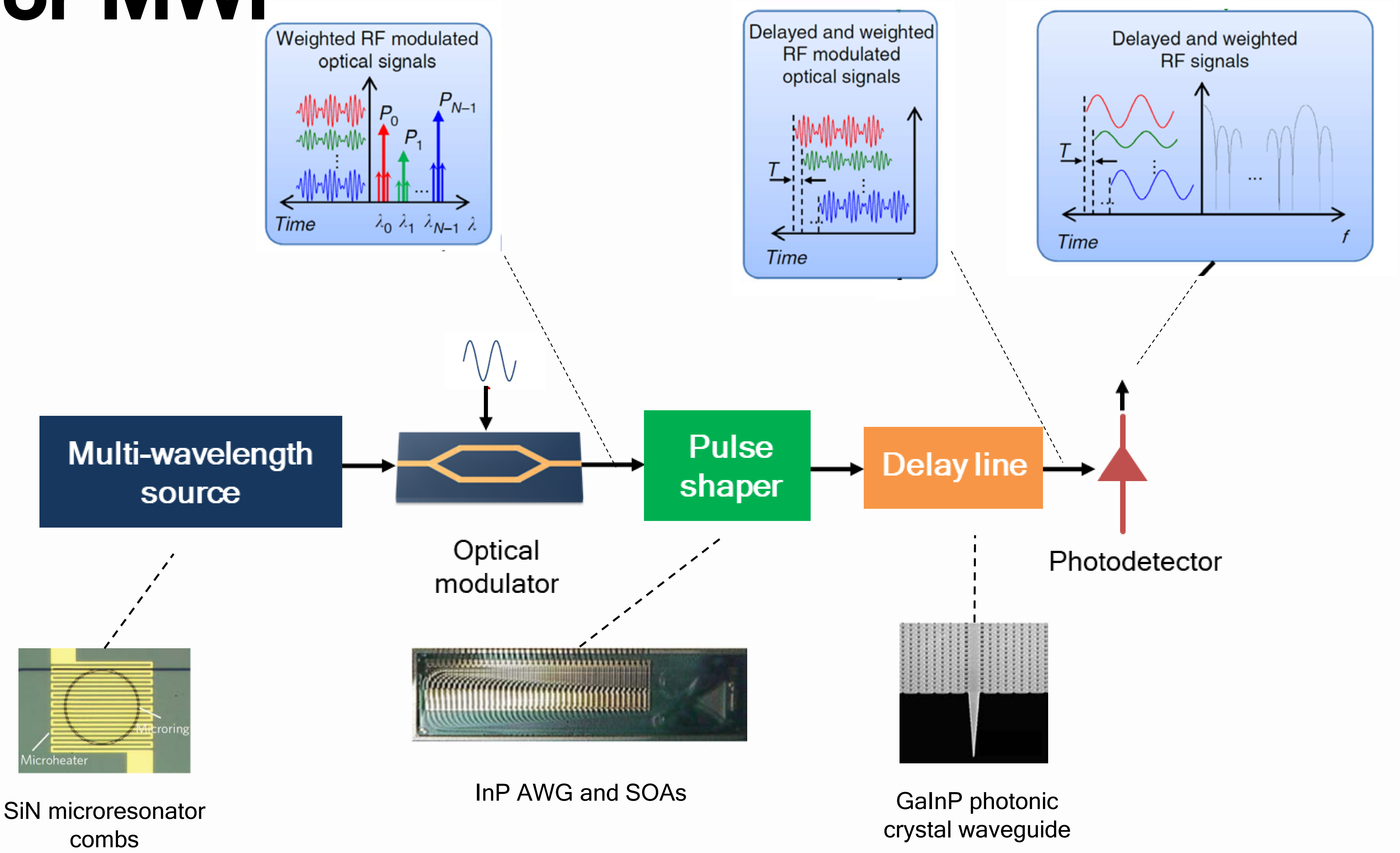
Eric A. Kittlaus, *Student Member, IEEE*, Prashanta Kharel, Nils T. Otterstrom, Zheng Wang, *Member, IEEE*, and Peter T. Rakich



(b)

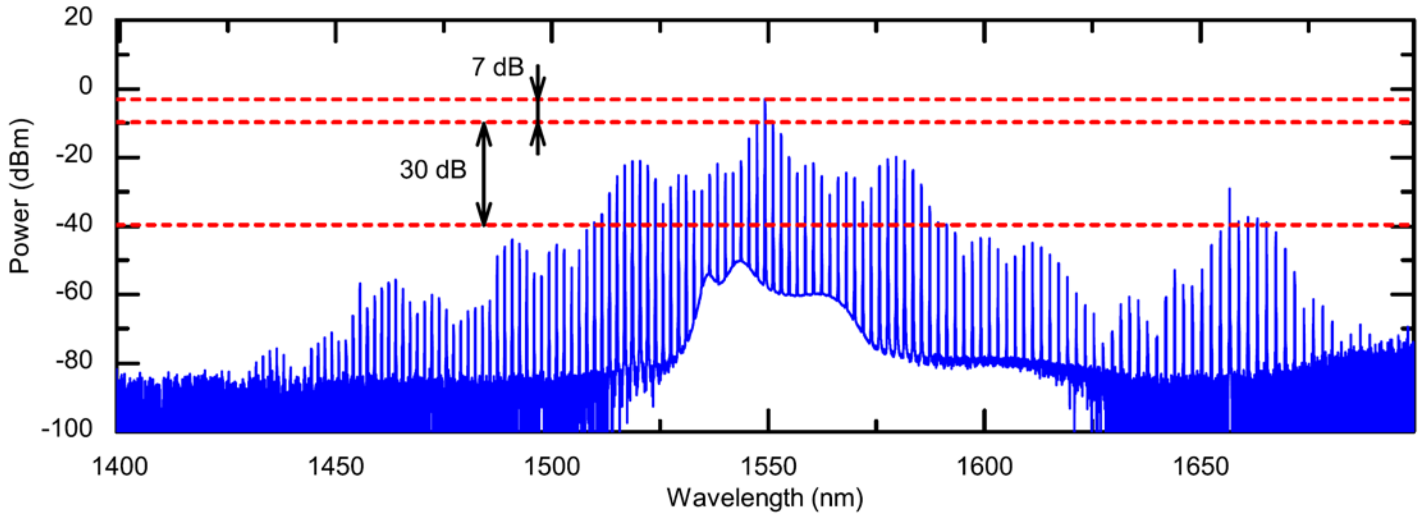


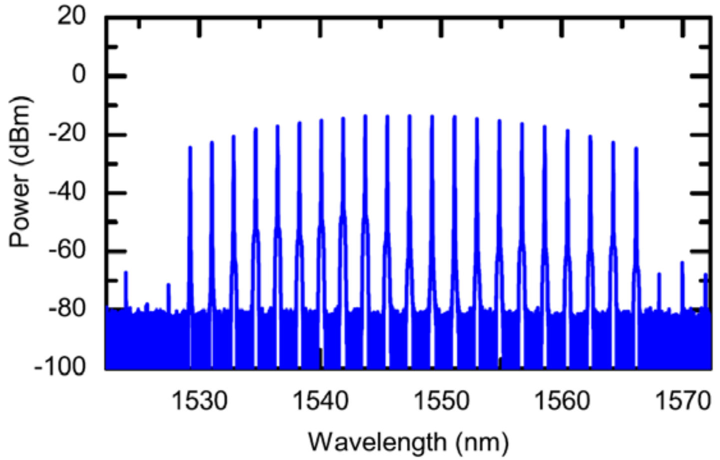
Frequency Combs for MWP filter

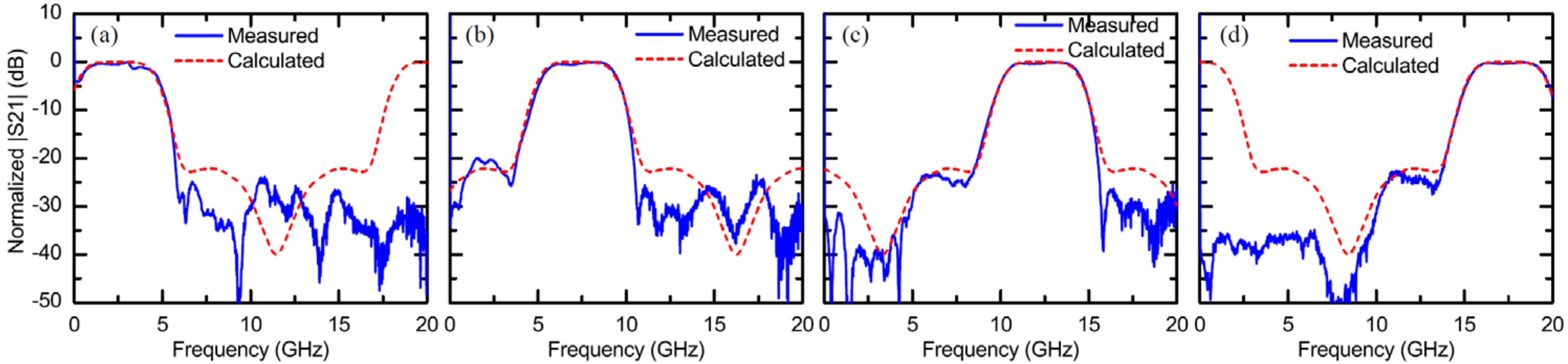


Programmable Single-Bandpass Photonic RF Filter Based on Kerr Comb from a Microring

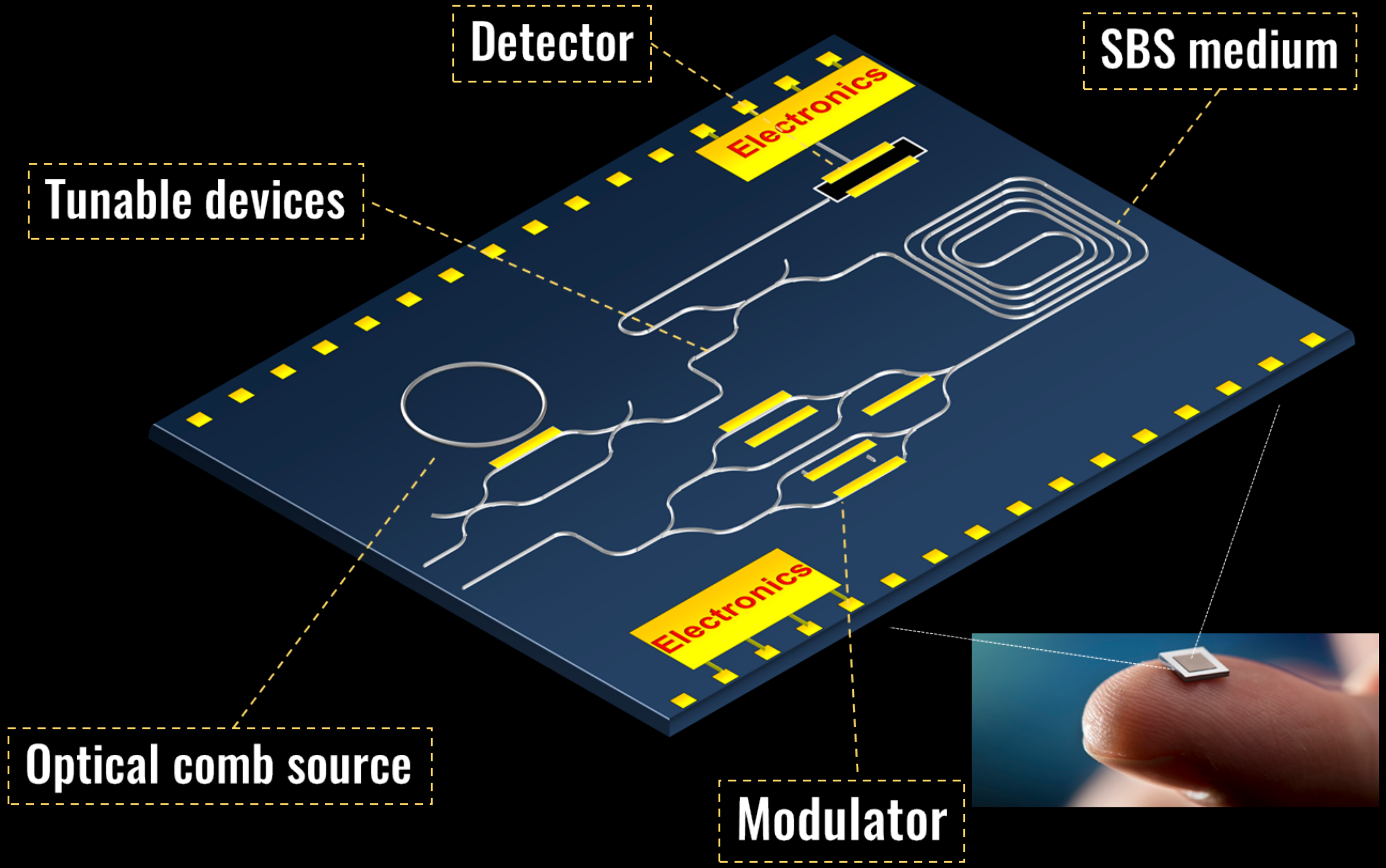
Xiaoxiao Xue, Yi Xuan, Hyoung-Jun Kim, Jian Wang, Daniel E. Leaird, Minghao Qi, and Andrew M. Weiner





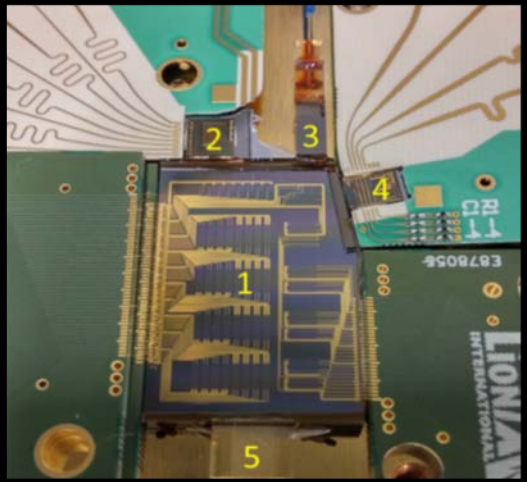


Vision: Integrated Brillouin Processor



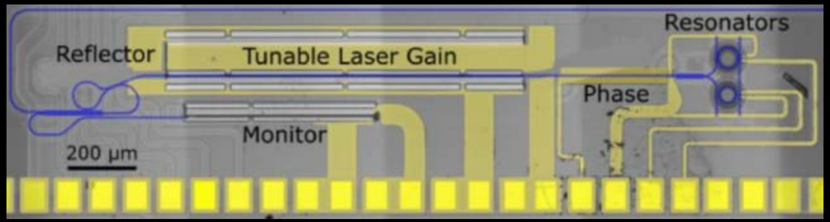
The way forward: hybrid/heterogeneous integration

III/V-Si_3N_4 hybrid integration



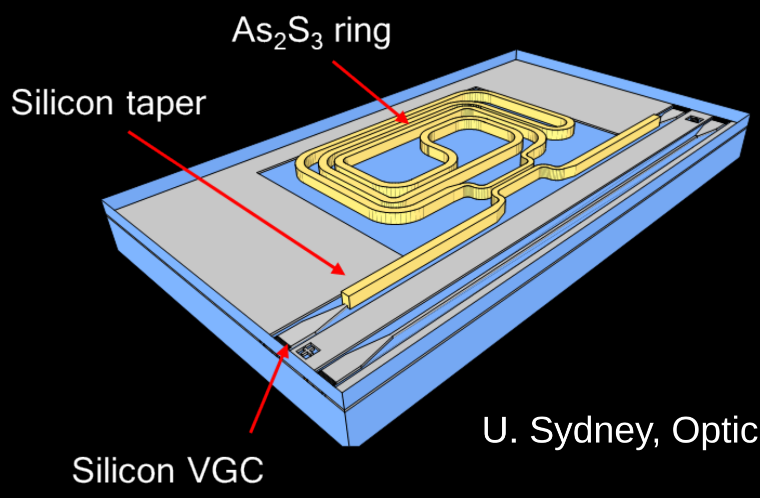
U. Twente/LioniX, JSTQE 2018

III/V-Si heterogeneous integration



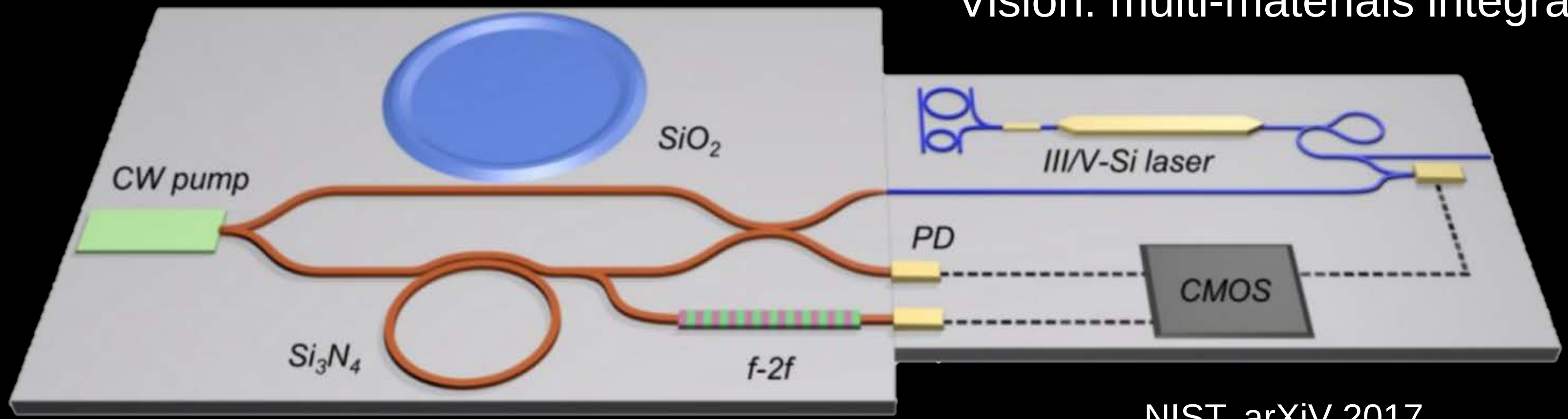
UCSB, JLT 2016

Hybrid silicon-chalcogenide



U. Sydney, Optica 2017

Vision: multi-materials integration for best performance

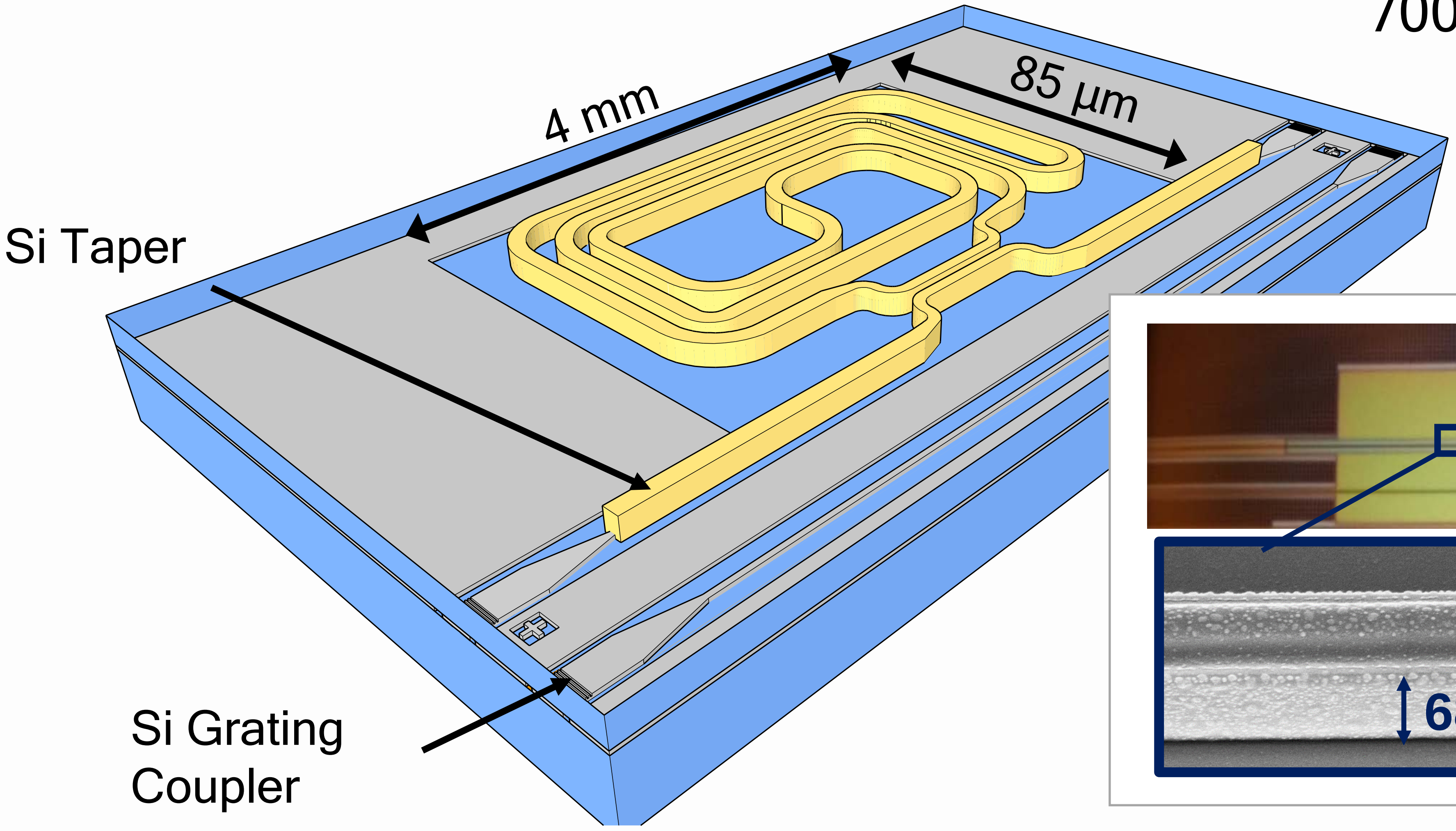


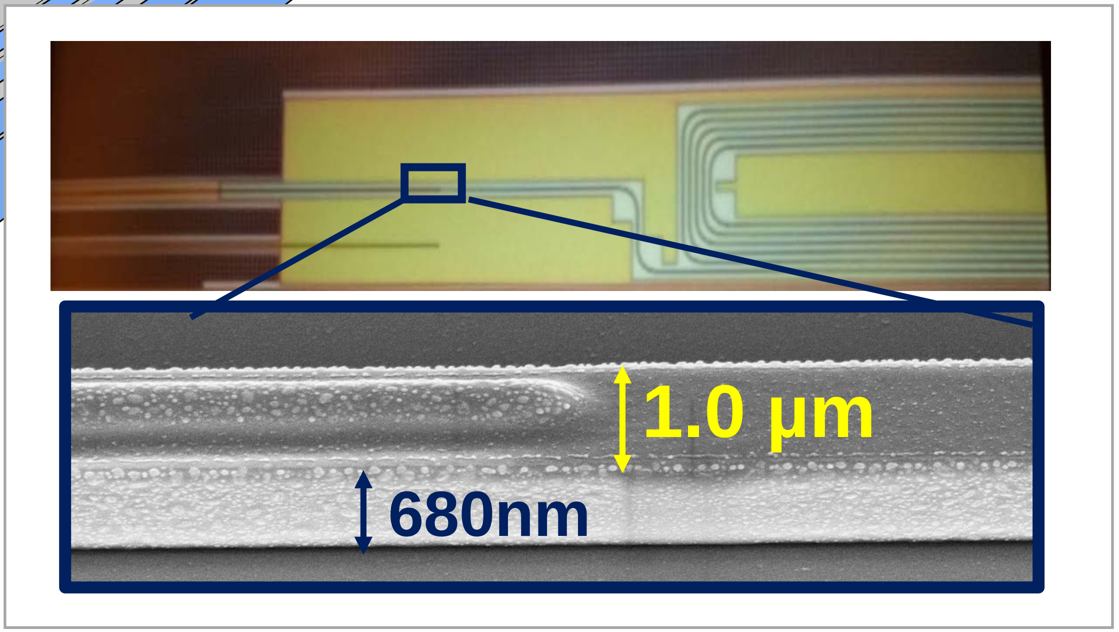
NIST, arXiV 2017

New direction: hybrid integration

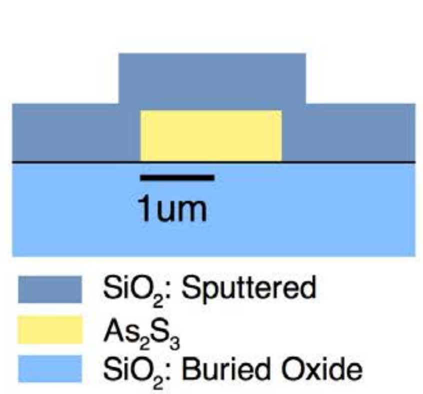
IMEC Silicon, ePIXfab shuttle service

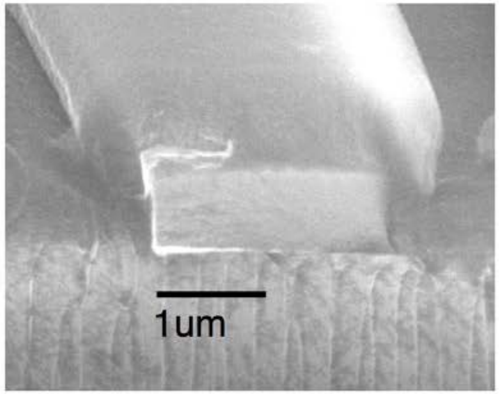
Deposit 680nm As_2S_3
Lithography and Etching
700nm SiO_2 Cladding

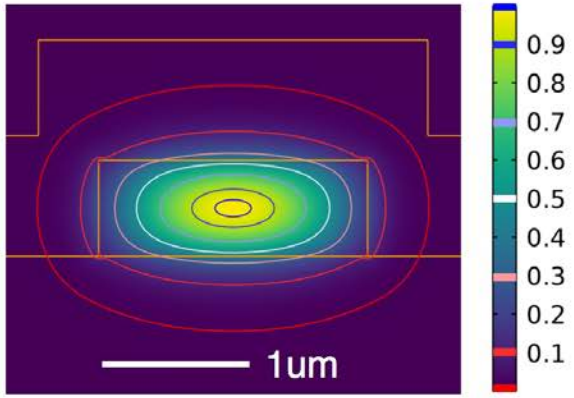


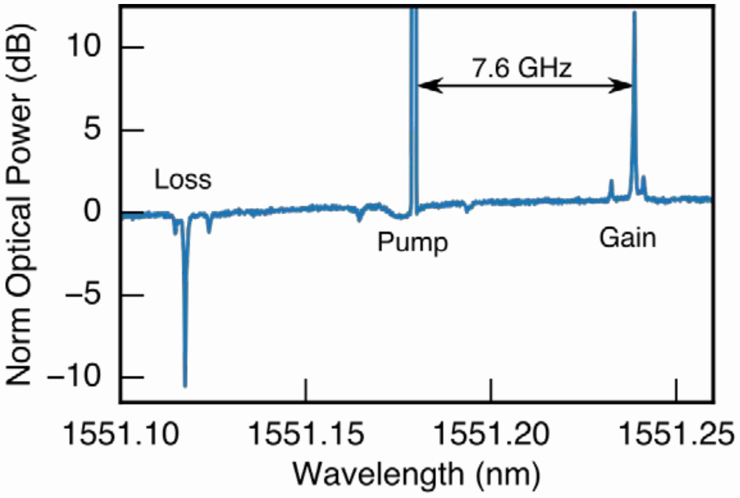


New direction: hybrid integration

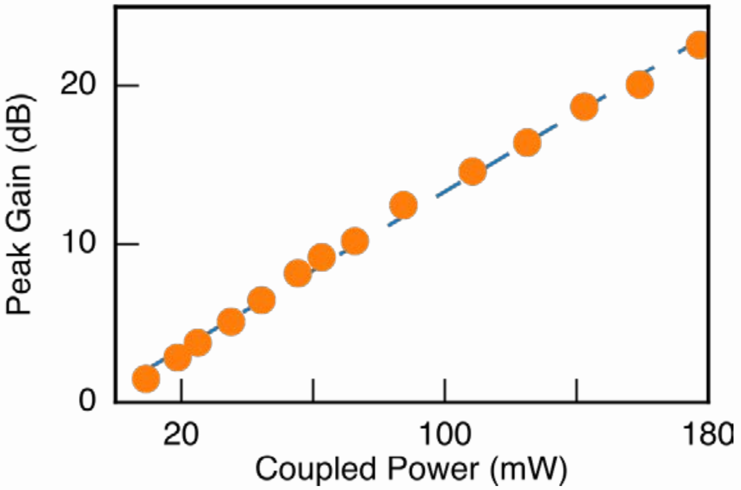




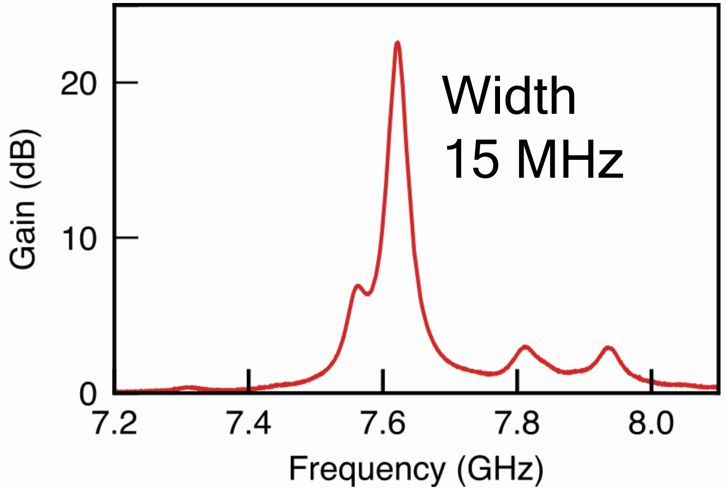




Shift ~7.6 GHz



Net Gain = 18.5 dB



Max gain 22.5 dB

> 20x improvement in amplification over purely silicon device

B. Morrison et al., Optica 4(8), 847-854 (2017)

Conclusions

- Microwave photonics is promising, but requires high performance
- Nonlinear optics bring new dimension to microwave photonics
- Light sound interactions via Brillouin scattering useful for high spectral resolution processing
- Frequency combs can be versatile light sources for MWP
- Hybrid integration opens the path to all-integrated nonlinear MWP processor

Thanks

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- Yang Liu
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UTS

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RMIT

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- Thach Nguyen

ANU

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