Brillouin Integrated Photonics

Presented by:

OSA Optoelectronics Technical Group

The OSA Optoelectronics (PO) Technical Group Welcomes You!

OSA Optoelectronics Technical Group

Technical Group Leadership 2018

Chair
Winnie Ye
Carleton University, Canada

Vice Chair
Daniele Melati
National Research Council Canada, Canada

Optoelectronics
Technical Group

Technical Group at a Glance

- Focus
  - This group's interests are in the field of semiconductor lasers, amplifiers, LEDs and super luminescent diodes.
  - Over 4,500 members within OSA
- Mission
  - To benefit *YOU*
  - Webinars, e-Presence, publications, technical events, business events, outreach
  - Interested in presenting your research? Have ideas for TG events? Contact winnie.ye@carleton.ca
- Find us here
  - Website: www.osa.org/OptoelectronicsTG
  - LinkedIn: www.linkedin.com/groups/8297718/

OSA Optoelectronics Technical Group

Today's Webinar

Brillouin Integrated Photonics

Prof. Benjamin J. Eggleton

University of Sydney, Australia

Benjamin Eggleton is the Director of The University of Sydney Nano Institute. He also currently serves as co-Director of the NSW Smart Sensing Network (NSSN). Eggleton was the founding Director of the Institute of Photonics and Optical Science at the University of Sydney and served as Director from 2009-2018. He was previously an ARC Laureate Fellow and an ARC Federation Fellow twice and was founding Director of the ARC Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems from 2003-2017. Eggleton obtained the Bachelor's degree in Science in 1992 and Ph.D. degree in Physics from the University of Sydney in 1996. Eggleton is the author or coauthor of more than 480 journal publications, including Nature Photonics, Nature Physics, Nature Communications, Physical Review Letters and Optica and over 200 invited presentations. Eggleton is a Fellow of the Australian Academy of Science, the Australian Academy of Technology and Engineering, The Optical Society and IEEE.

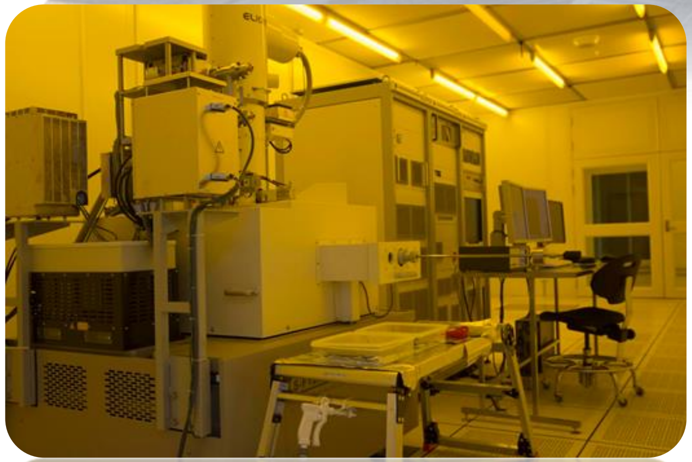
Integrated Brillouin Photonics

Benjamin Eggleton FAA, FTSE, FIEEE, FOSA
Director, The University of Sydney Nano Institute
Co-Director NSW Smart Sensing Network (NSSN)
Editor-in-Chief APL Photonics

School of Physics, University of Sydney

Sydney Nano Institute (a multidisciplinary initiative)

We aim to discover and harness new science at the nanoscale
Programs include: nanorobotics, nanomedicine, neural interface, quantum matter, nanocatalyst, nanomaterials and nanophotonics



Noise Free Laboratories
Temperature and humidity control
Isolation from all sources of mechanical vibration and electromagnetic

Cleanroom
The SNH clean room contain ISO Class 5 and Class 7 spaces (**30 particles < 5μm in 1 m^3**)

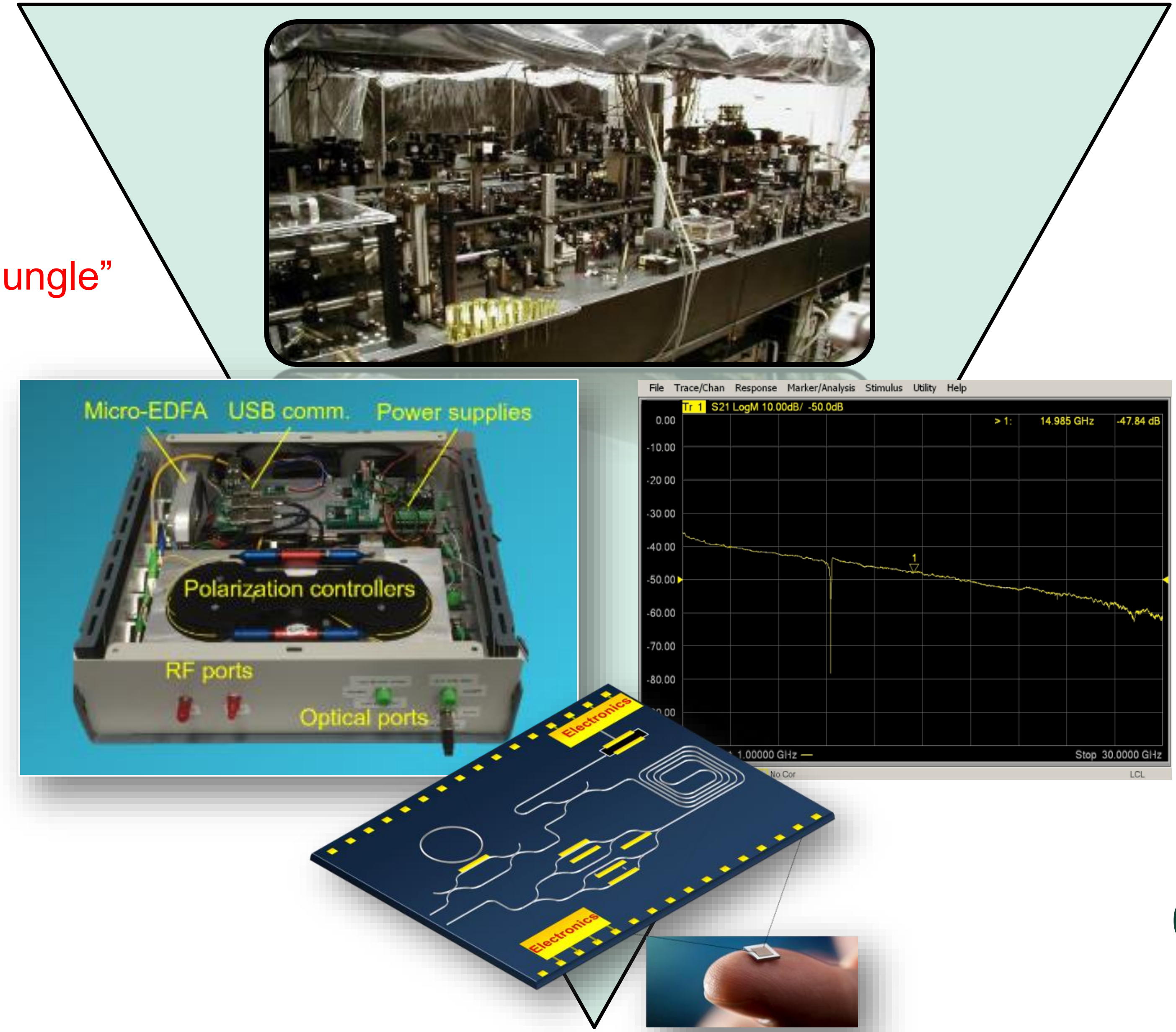
Major tools
i-line stepper (365nm)
Mask writer
electron beam
Thin film deposition
ICP-RIE Etching
Packaging and prototyping

Photonic Integration: Bandwidth, size, weight, power, stability, latency..

Laboratory setup

Traditional bulk “optical jungle”

Size: 3m^2



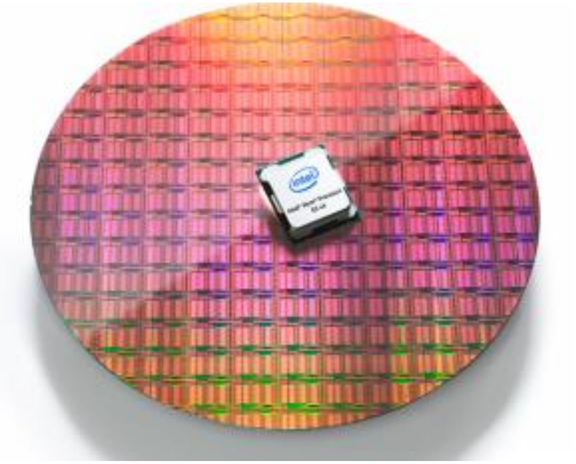
Research prototype

Size: 0.2 m^2

Photonic chip

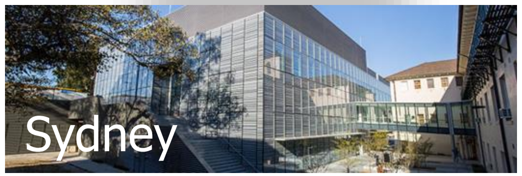
Size: 0.0001 m^2

Integrated silicon → photonics



7.2 billion of transistors (Commercially available)
30 billion transistors (largest up to date)
Based on the 14nm core architecture

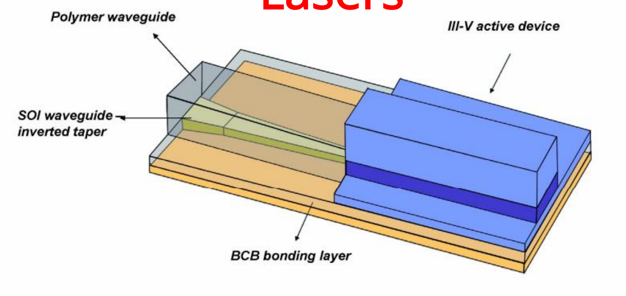
http://techfrag.com/2016/04/01/intel-launches-14nm-broadwell-ep-family-fastest-22-core-chip-servers/



Enhancing data centers

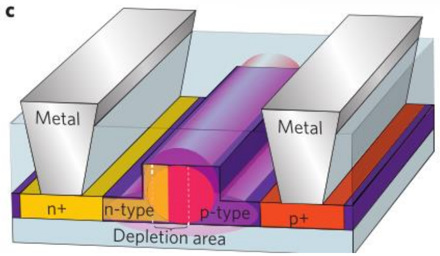
Intel PSM4 silicon photonics module
100 gigabits/s ->2 Km

Lasers



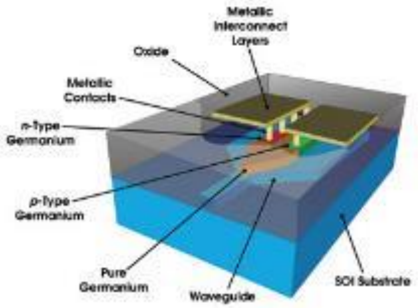
G. Roelkens, *et al.*.
Opt. Expr 14, 8154–8159 (2006).

Modulators



- G. T. Reed *et al. Nat. Phot.* 4, 518-526 (2010).
- David J. T. *IEEE PTL* 24, 234-236 (2012)

Photodetectors

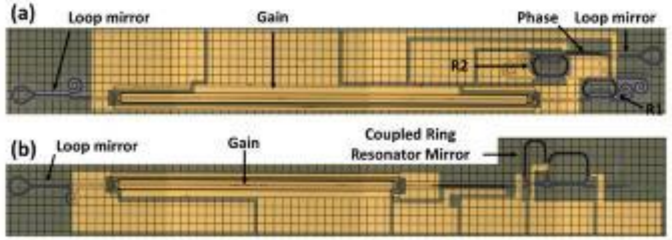


J. Michel, et al..
Nat. Phot. 4, 527-534 (2010).

Integrated Microwave Photonics (IMWP)

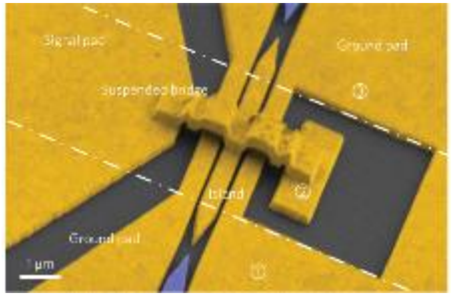
Manipulate RF signals using compact photonic circuits

- **Generation and Modulation**



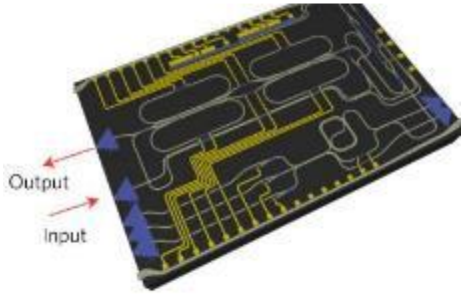
Hulme et al., Opt. Express **25** (2017)

Cheng Wang, Nature **562** (2018)

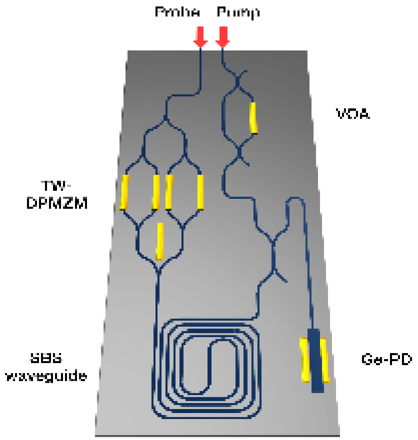


C. Haffner, Nature Photon. **9** (2015)

- **Signal Filtering**

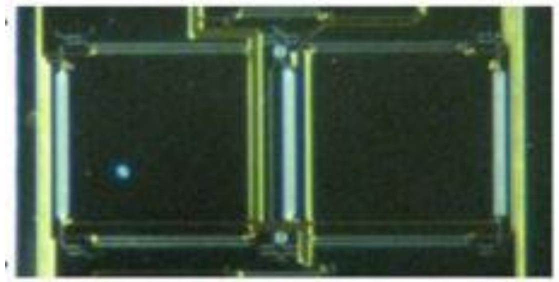


Fandino et al., Nat. Photon.**11** (2016)

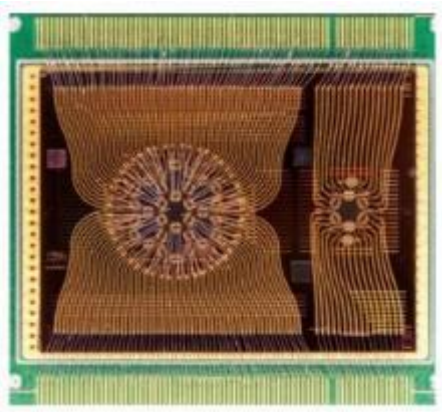


Marpaung et al., Optica **2** (2015)

- **Programmable processing**



Zhuang et al., Optica. **2** (2016)



Pérez et al., Nature Comm. **8** (2017)

The integration circuit revolution

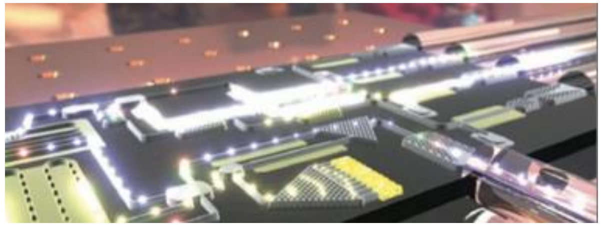
Yesterday

- *Microelectronic* integration
- Delivered unprecedented computational power

Electronics
1980 -

Today

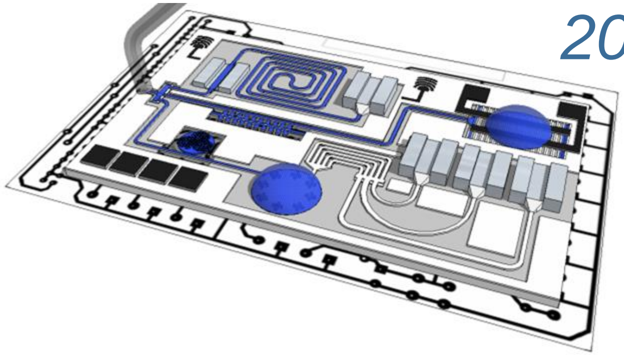
- *Optoelectronic* integration
- Revolutionising communications, data processing, lighting…



Photonics
2010 -

The Future

- *Phonon* physics *(hyper sound)* integrated on chips
- Phonons bridge optical and microwaves (microwave photonics)



Phononics
(Sound)
2020 -

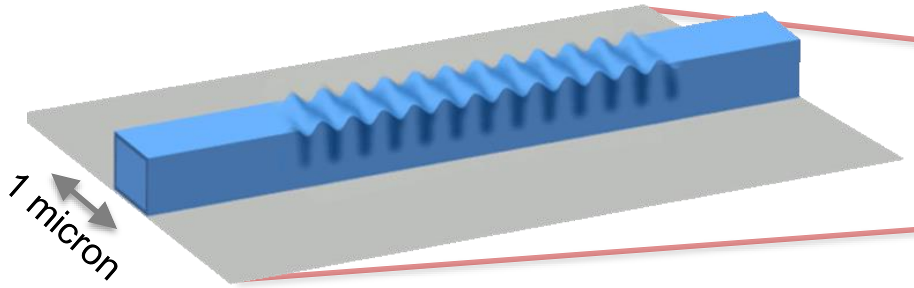
Phononics (acoustics) bridge microwaves and optical waves

Phonon – the elemental unit of mechanical vibration

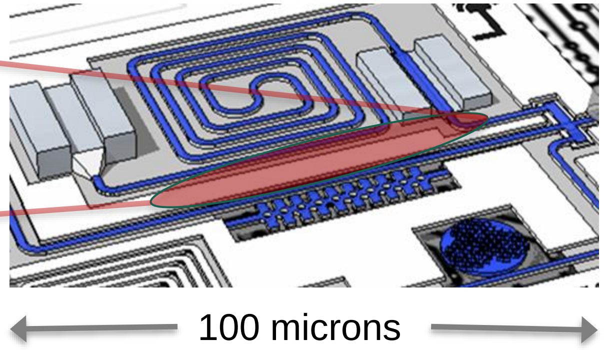
- The *sound wave* analog to the *photon* of light
- Hypersonic sound waves – GHz phonons (phonon wavelength ~ optical wavelength)

Discover new ways to control and harness hypersonic waves – *Phonons* – at the nanoscale in symphony with light and electrons.

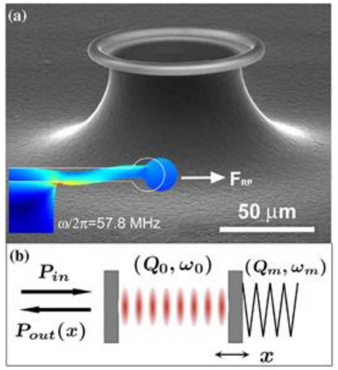
Creating nanowires for sound



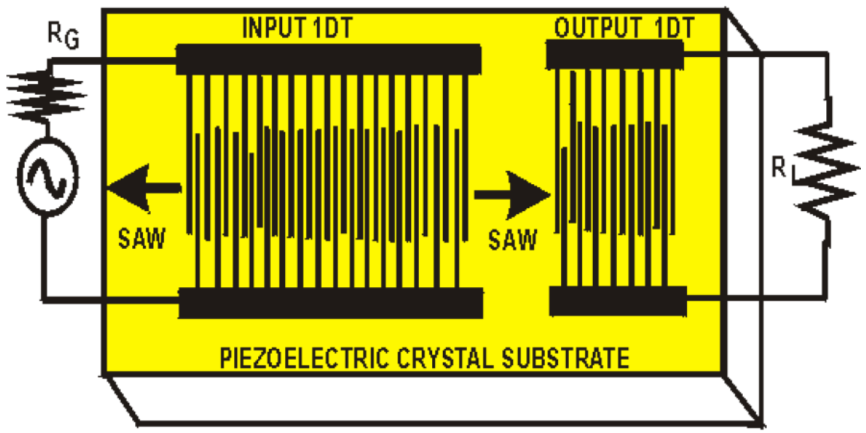
Integrating sound with optoelectronic circuits



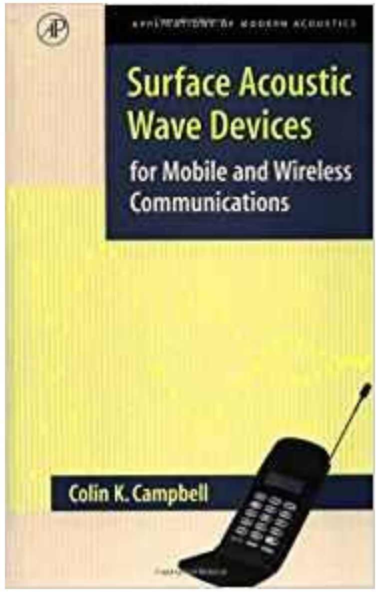
Micron-scale motion



Familiar example of acoustic waves in technology: Surface Acoustic Waves (SAW) filters



RF → acoustic waves via transducer (IDT)



- ✓ Compact
- ✓ High resolution
- × Low frequency (1-2 GHz)
- × Not tunable

Phonons couple to the world

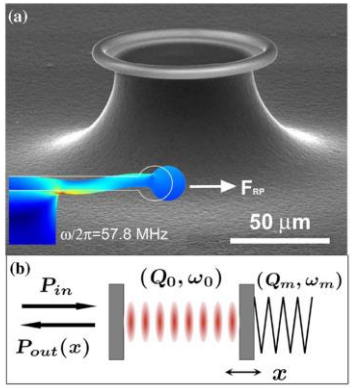
Human-scale vibrations

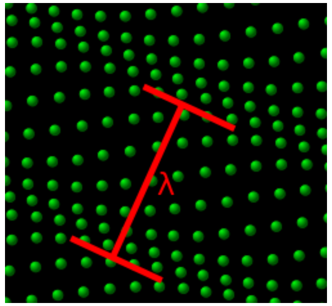
Micron-scale motion

Collective motion of atoms

Vibrations of molecules

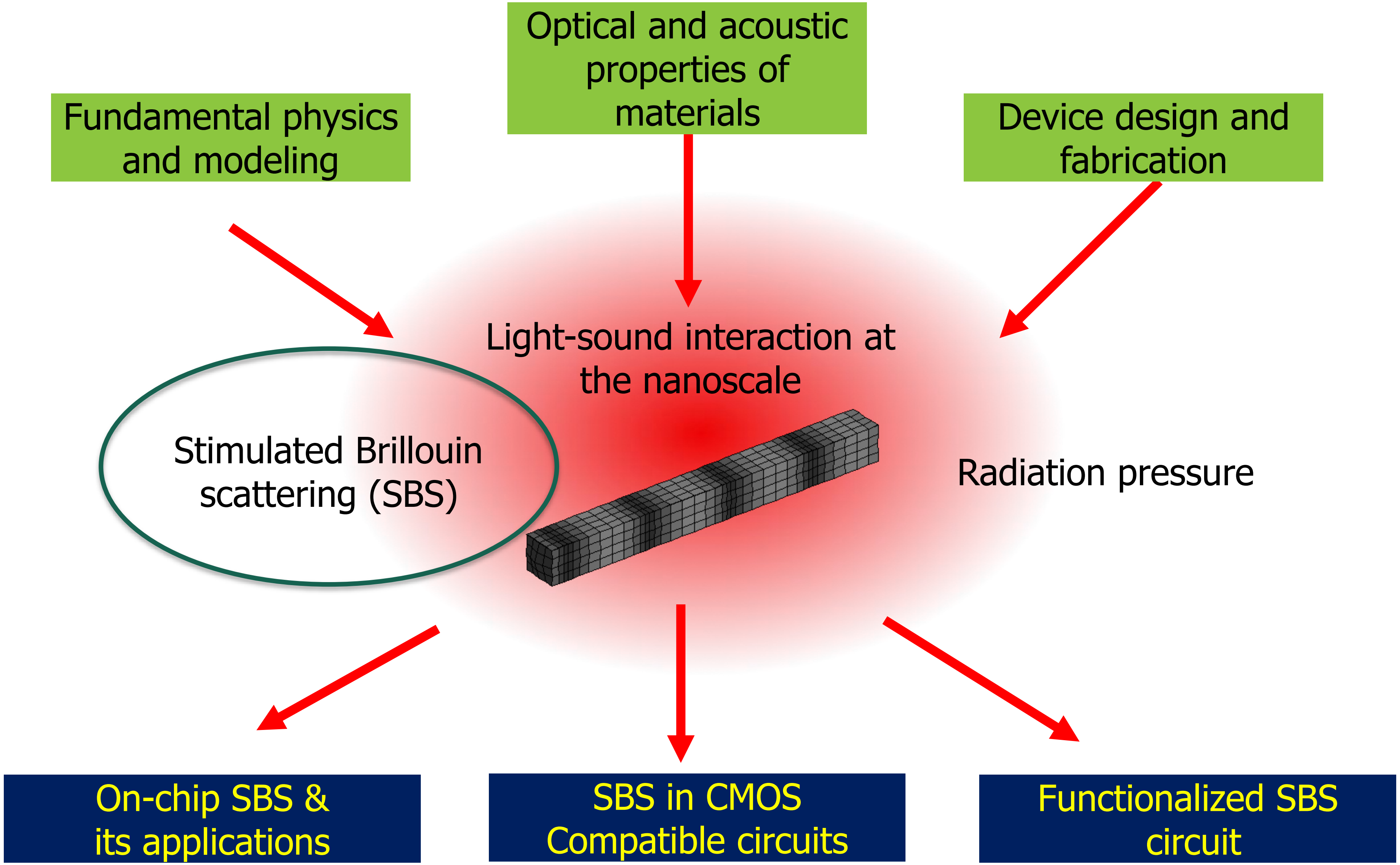
Big





nanoscale

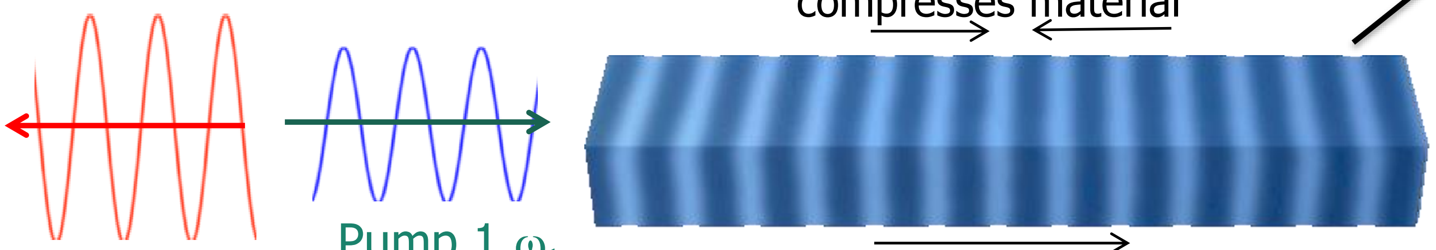
What we are doing?



** CMOS: Complementary Metal-Oxide-Semiconductor – Cheap because it's made of silicon*

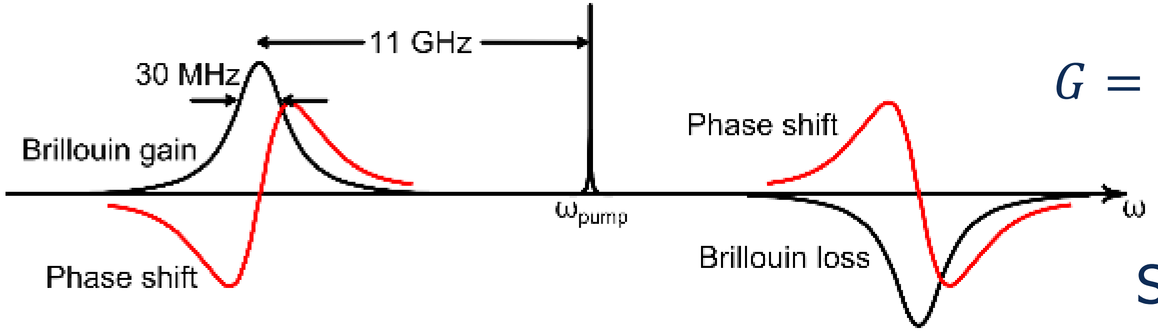
Basic principle of SBS

<u>SBS</u>: nonlinear interaction of a pump wave ω_p with an acoustic wave Ω generating a backscattered Stokes wave $\omega_s = \omega_p - \Omega$



SBS has a narrowband frequency response that is dependent on the pump power

SBS gain: e^G



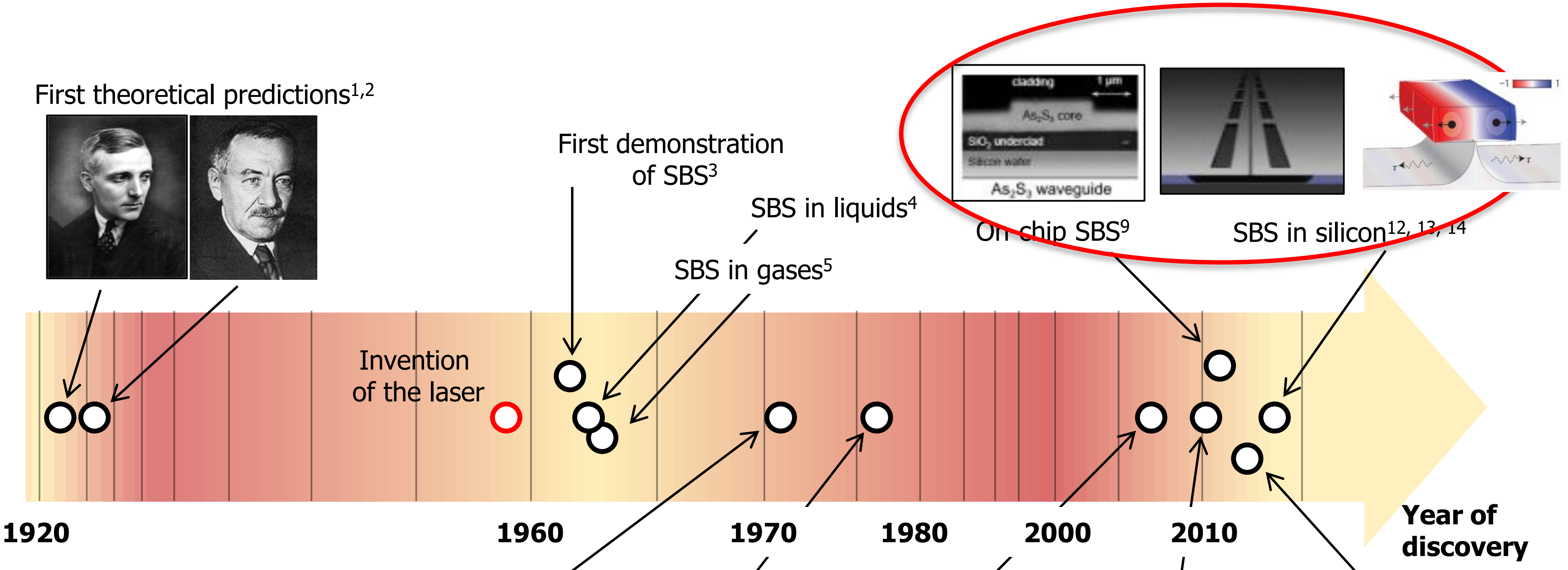
$$G = \frac{g_0 L_{eff}}{A_{ao}} P_{pump}$$

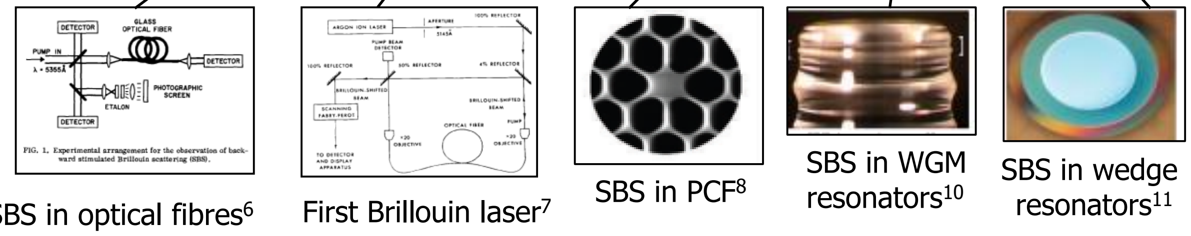
SBS loss: e^{-G}

Phonon lifetime (τ) ~ 9 ns
Gain linewidth = $1/(\pi\tau)$ ~ 35 MHz

1. Robert Boyd, "Nonlinear optics," 3rd Ed. USA: Academic Press, 2008
2. Benjamin Eggleton, et al., "Inducing and harnessing stimulated Brillouin scattering in photonic integrated circuits," Adv. Opt. and Photon. 5 (2013)

SBS historical perspective





1. Brillouin, *Annals of Physics* 17, 88, (1922)
2. Mandelstahm, *Rus. J. Phys. Chem* (1926)
3. Maiman, *Nature* 187 (1960)
4. Chiao *et al. Phys. Rev. Lett.* 12, 592 (1964).
5. Brewer *et al. Phys. Rev. Lett.* 13, 334 (1964).
6. Hagenlocker *et al. Appl. Phys. Lett.* 7, 236 (1965)
7. Ippen *et al. Appl. Phys. Lett.* 21, 539 (1972)
8. Dainese *et al. Nature Physics* 2, 388 (2006)
9. Pant *et al.* Opt. Exp. 19, 8285 (2011)
10. Lee *et al.* Nat. Photon. 6, 369 (2012)
11. Grudinin *et al. Phys. Rev. Lett.* 102, (2009)
12. Shin *et al. Nature Comm.* 4, (2013).
13. Van Laer, *Nature Photonics* (2014)
14. Casas-Bedoya *et al.*, *Optics Letters* (2015)

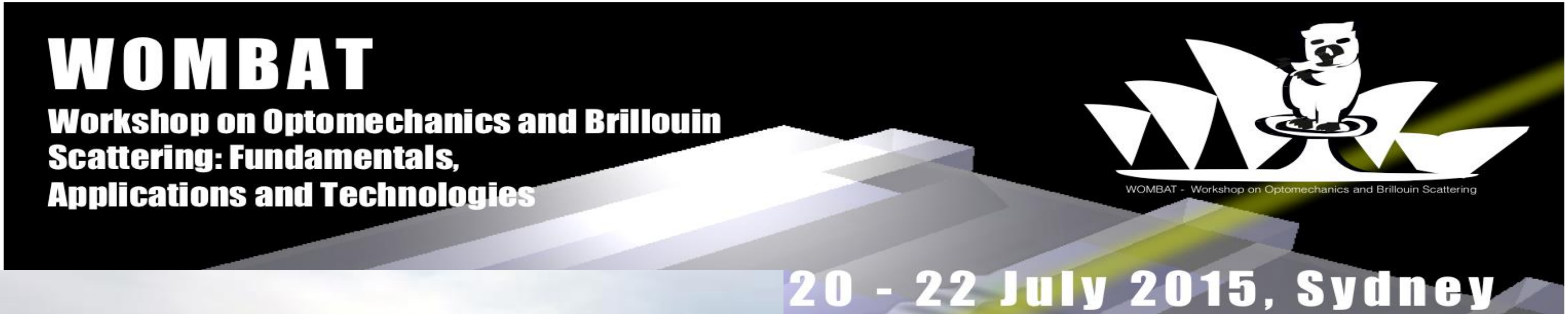
SBS on chip-scale devices

High-Q resonators

Waveguides with large Brillouin gain

B. J. Eggleton, C. G. Poulton, and R. Pant, "Inducing and harnessing stimulated Brillouin scattering in photonic integrated circuits," Adv. Opt. Photonics 5, 131 (2013).

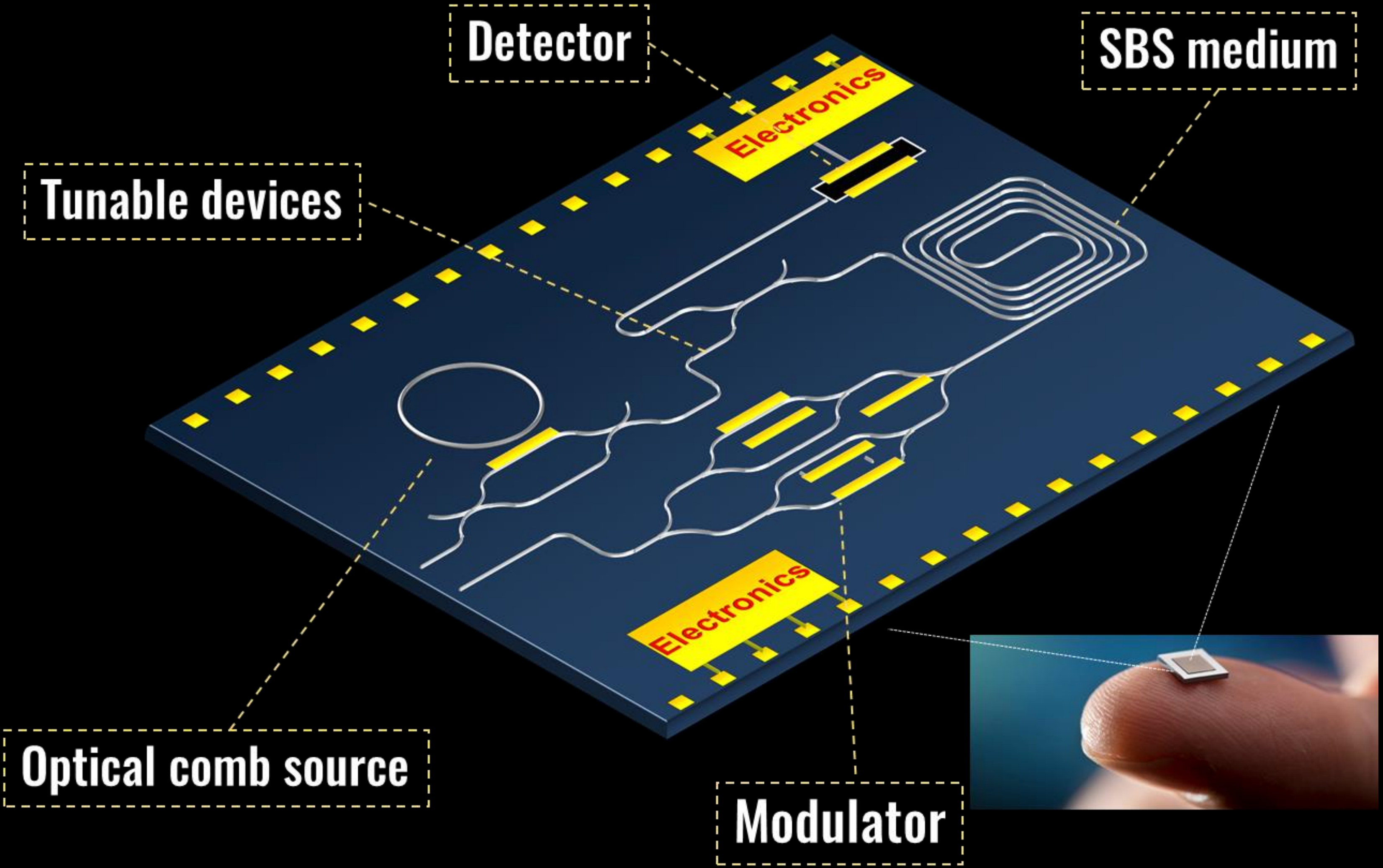
M. Merklein *et al.*, "Stimulated Brillouin Scattering in Photonic Integrated Circuits: Novel Applications and Devices," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 22, no. 2, pp. 336-346, 2016.


WOMBAT
Workshop on Optomechanics and Brillouin Scattering: Fundamentals, Applications and Technologies
WOMBAT - Workshop on Optomechanics and Brillouin Scattering
20 - 22 July 2015, Sydney


WOMBAT
Workshop on Optomechanics and Brillouin Scattering: Fundamentals, Applications and Technologies
3 - 5 JULY 2017
BESANÇON, FRANCE


THE 3rd WORKSHOP ON:
OptoMechanics and Brillouin Scattering:
Fundamentals, Applications and Technologies (WOMBAT)
March 26-28 2019,
Tel-Aviv, Israel

Vision: Integrated Brillouin Processor



SBS on chip

On-chip SBS is challenging because the waveguides are very short.

The gain is

$$G = \frac{g_0 P_p L_{\text{eff}}}{A_{\text{eff}}}$$

g_0 = Brillouin gain coefficient
P_p = Pump power
L_{eff} = Waveguide length
A_{eff} = optical mode area

$$g_0 = \frac{16\pi^3 n^8 p_{12}^2}{c\lambda_p^3 \rho \Omega \Gamma_B}\eta$$

How to get enough gain in a chip scale device?

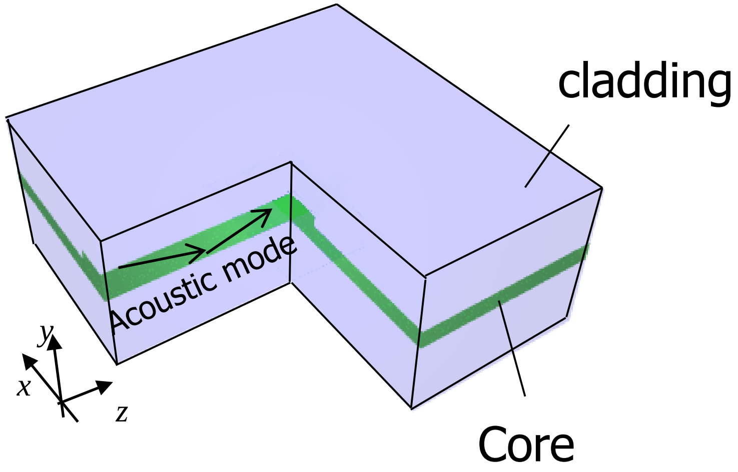
1) Material with high refractive index

2) Small mode area

3) Low loss optical waveguides

4) Good opto-acoustic overlap

Guiding/confinement of acoustic mode → Determined by acoustic velocity in materials



Pant et al., Opt. Express **19** (2011)

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

THE UNIVERSITY OF SYDNEY

SBS in chalcogenide waveguide

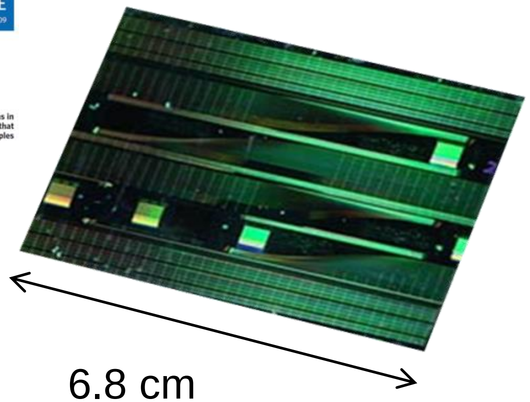
nature photonics REVIEW ARTICLE

PUBLISHED ONLINE: XX MARCH 2011 | DOI: 10.1038/NPHOTON.2011.309

Chalcogenide photonics

Benjamin J. Eggleton, Barry Luther-Davies and Kathleen Richardson

The unique and striking material properties of chalcogenide glasses have been studied for decades, providing applications in the electronics industry, imaging and more recently in photonics. This Review summarizes progress in photonic devices that exploit the unique optical properties of chalcogenide glasses for a range of important applications, focusing on recent examples in mid-infrared sensing, integrated optics and ultrahigh-bandwidth signal processing.



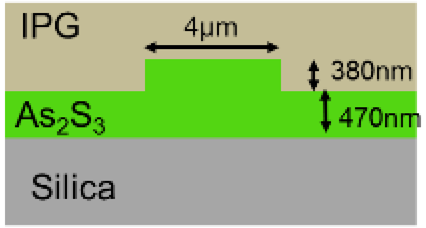
Chalcogenide waveguide:

- High index material As_2S_3 (n~2.45, $g_0 \sim n^8$)
- Small mode area (A_{eff} ~ 2.3 μm²)
- Low propagation loss (~0.2 dB/cm)
- Large overlap of acoustic and optical modes

Eggleton et al., Nature Photonics, (2011)

≈ 500 times higher Brillouin gain than silica SMF

~2.3 μm²

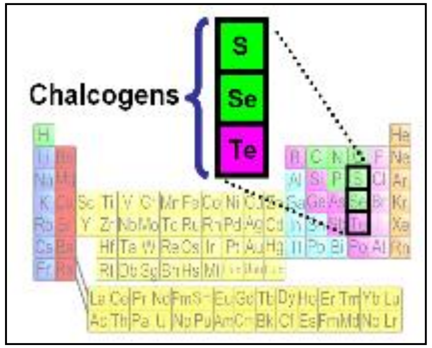


Photonic chip

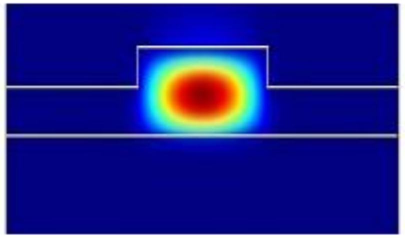
v_{IPG} ~ 1500 m/s

v_{chalc} ~ 2600 m/s

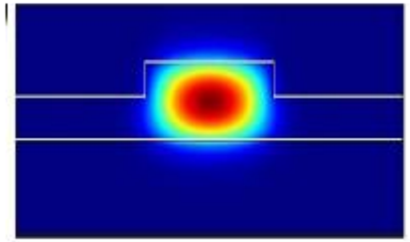
v_{silica} ~ 6000 m/s



~90%



Optical mode



Acoustic mode

Benjamin Eggleton, et al., “Inducing and harnessing stimulated Brillouin scattering in photonic integrated circuits,” Adv. Opt. and Photon. 5 (2013)

Silica ~ 6km/s

As_2S_3 ~ 3km/s

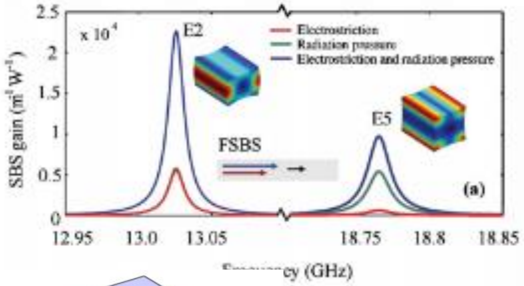
First demonstration of on-chip SBS: R. Pant et al. Optics Express **19,** 8285-8290 (2011)

SBS in silicon?

PHYSICAL REVIEW X 2, 011008 (2012)

Giant Enhancement of Stimulated Brillouin Scattering in the Subwavelength Limit

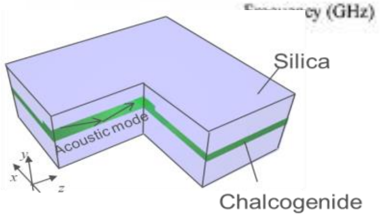
Peter T. Rakich,[1,*] Charles Reinke,[1] Ryan Camacho,[1] Paul Davids,[1] and Zheng Wang[2,3]
[1]Sandia National Laboratories, P.O. Box 5800 Albuquerque, New Mexico 87185-1082, USA
[2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
[3]Department of Electrical and Computer Engineering, Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758 USA
(Received 22 August 2011; published 30 January 2012)



Acoustic confinement and stimulated Brillouin scattering in integrated optical waveguides

Christopher G. Poulton, Ravi Pant, and Benjamin J. Eggleton

Vol. 30, No. 10 / October 2013 / J. Opt. Soc. Am. B

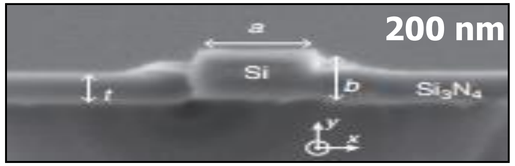


ARTICLE

Received 6 Sep 2012 | Accepted 29 Apr 2013 | Published 6 Jun 2013 OPEN

Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides

Heedeuk Shin[1], Wenjun Qiu[2], Robert Jarecki[1], Jonathan A. Cox[1], Roy H. Olsson III[1], Andrew Starbuck[1], Zheng Wang[3] & Peter T. Rakich[4]



nature photonics ARTICLES
PUBLISHED ONLINE: 16 FEBRUARY 2015 | DOI: 10.1038/NPHOTON.2015.11

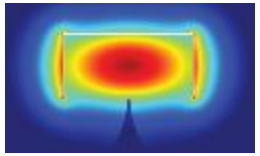
Interaction between light and highly confined hypersound in a silicon photonic nanowire

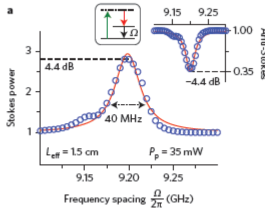
Raphaël Van Laer[1,2*], Bart Kuyken[1,2], Dries Van Thourhout[1,2] and Roel Baets[1,2]

4154 Vol. 40, No. 17 / September 1 2015 / Optics Letters Letter
Optics Letters

Tunable narrowband microwave photonic filter created by stimulated Brillouin scattering from a silicon nanowire

Alvaro Casas-Bedoya,* Blair Morrison, Mattia Pagani, David Marpaung, and Benjamin J. Eggleton

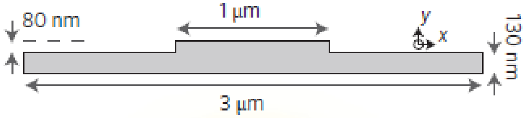




nature photonics LETTERS
PUBLISHED ONLINE: 13 JUNE 2016 | DOI: 10.1038/NPHOTON.2016.112

Large Brillouin amplification in silicon

Eric A. Kittlaus[1†], Heedeuk Shin[1,2†] and Peter T. Rakich[1*]

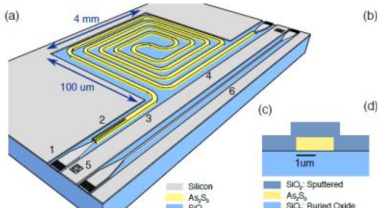


5dB Brillouin amplification (5mW)

Optica – 2017

Compact Brillouin devices through hybrid integration on silicon

Blair Morrison[1,2,*], Alvaro Casas-Bedoya[1,2], Guanghui Ren[3], Khu Vu[4], Yang Liu[1,2], Atiyeh Zarifi[1,2], Thach G. Nguyen[3], Duk-Yong Choi[4], David Marpaung[1,2], Stephen J. Madden[4], Arnan Mitchell[3], and Benjamin J. Eggleton[1,2]



Max gain 22.5 dB

SBS in silicon?

nature photonics | ARTICLES

Interaction between light and highly confined hypersound in a silicon photonic nanowire

Raphaël Van Laer, Bart Kuyken, Dries Van Thourhout and Roel Baets

4154 Vol. 40, No. 17 / September 1 2015 / Optics Letters | Letter

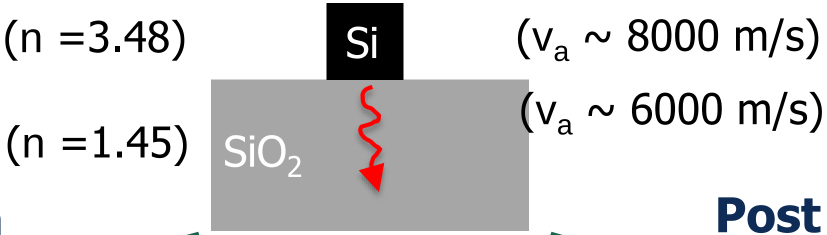
Optics Letters

Tunable narrowband microwave photonic filter created by stimulated Brillouin scattering from a silicon nanowire

Alvaro Casas-Bedoya,* Blair Morrison, Mattia Pagani, David Marpaung, and Benjamin J. Eggleton

How to get SBS in Silicon?

SOI waveguide



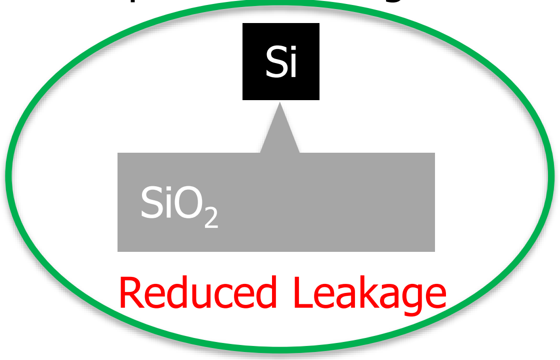
Hybrid Integration

Slot Waveguide

Phonon Trapped

Post Processing

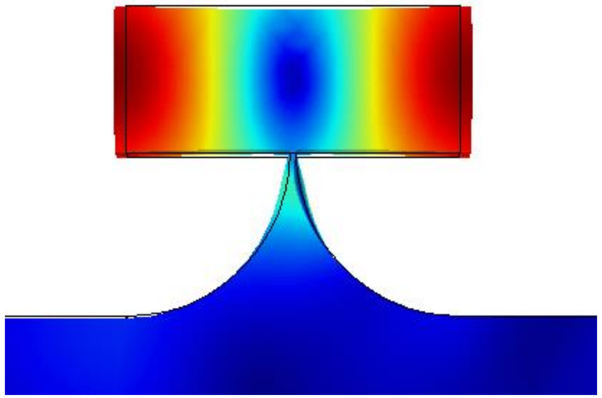
Suspended Waveguide



Reduced Leakage

- HF Acid removes silica
- Minimal change to loss
- Forward SBS

Acoustic Mode



Acoustic confinement and stimulated Brillouin scattering in integrated optical waveguides

Christopher G. Poulton,[1,2,3,*] Ravi Pant,[2,3] and Benjamin J. Eggleton[2,3]

JOSA B (2013)

nature photonics | LETTERS

PUBLISHED ONLINE: 13 JUNE 2016 | DOI: 10.1038/NPHOTON.2016.112

Large Brillouin amplification in silicon

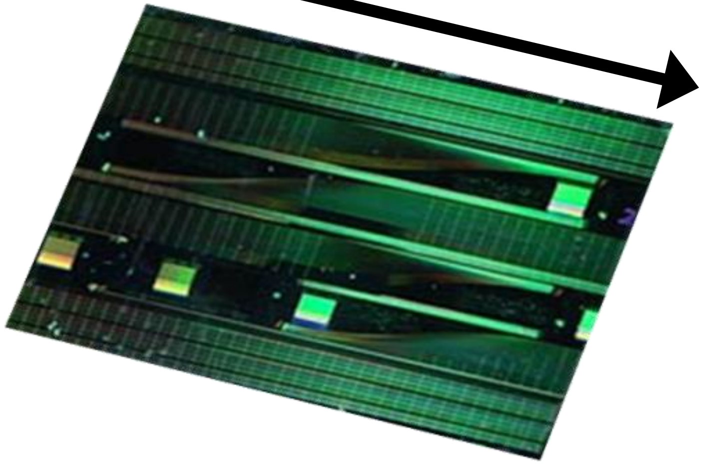
Eric A. Kittlaus[†], Heedeuk Shin[1,2†] and Peter T. Rakich[†*]

Plus two-photon absorption – limits SBS gain to about 5-6dB

SBS Chip History

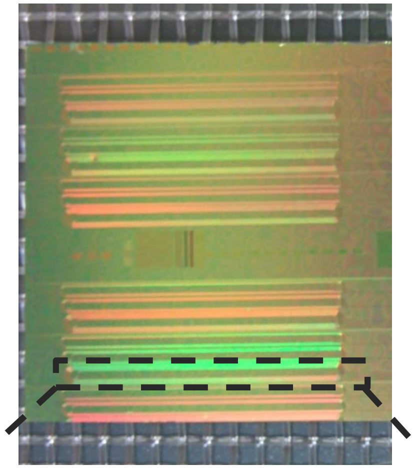
2011	2014	**Today**

7 cm



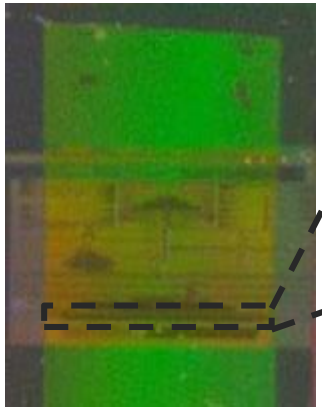
Straight Waveguide
~15dB gain

2 cm



Spiral up to 24 cm
Area ~10 mm^2
~50 dB gain

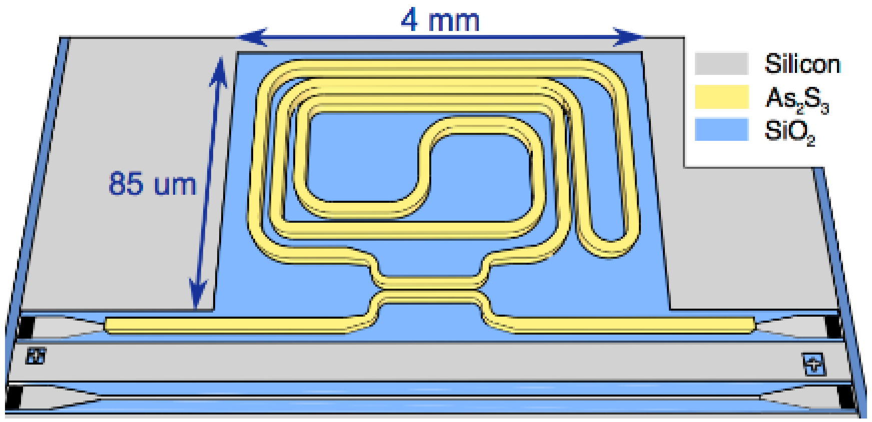
0.6 cm



Hybrid Integration

Spiral up to 6 cm
Area < **0.5 mm^2**

Resonator



Pant et al., OE **19** 8285 2011

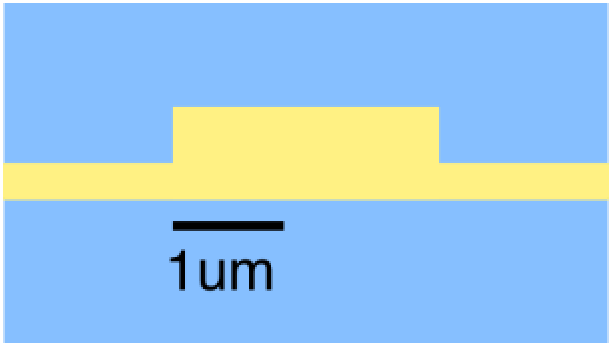
Choudhary et al., JLT **33** 846 2017

Morrison et al., Optica, 4 (2017)

THE UNIVERSITY OF SYDNEY

Brillouin Scattering in Integrated Waveguides

As_2S_3

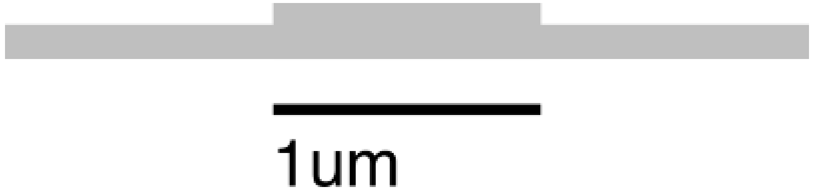


Soft → Embedded

>50dB amplification[1]

No Active optical components

Silicon



Stiff → Suspended

Up to 7 dB amplification[2]

Nonlinear losses

Mature library components

Hybrid Integration

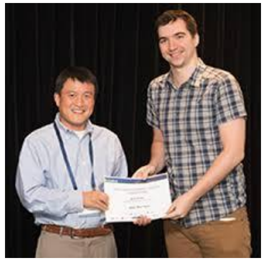
1. Choudhary, JLT **33** 846 2017

2. Kittlaus, Nat. Phot. **10** 463 2016

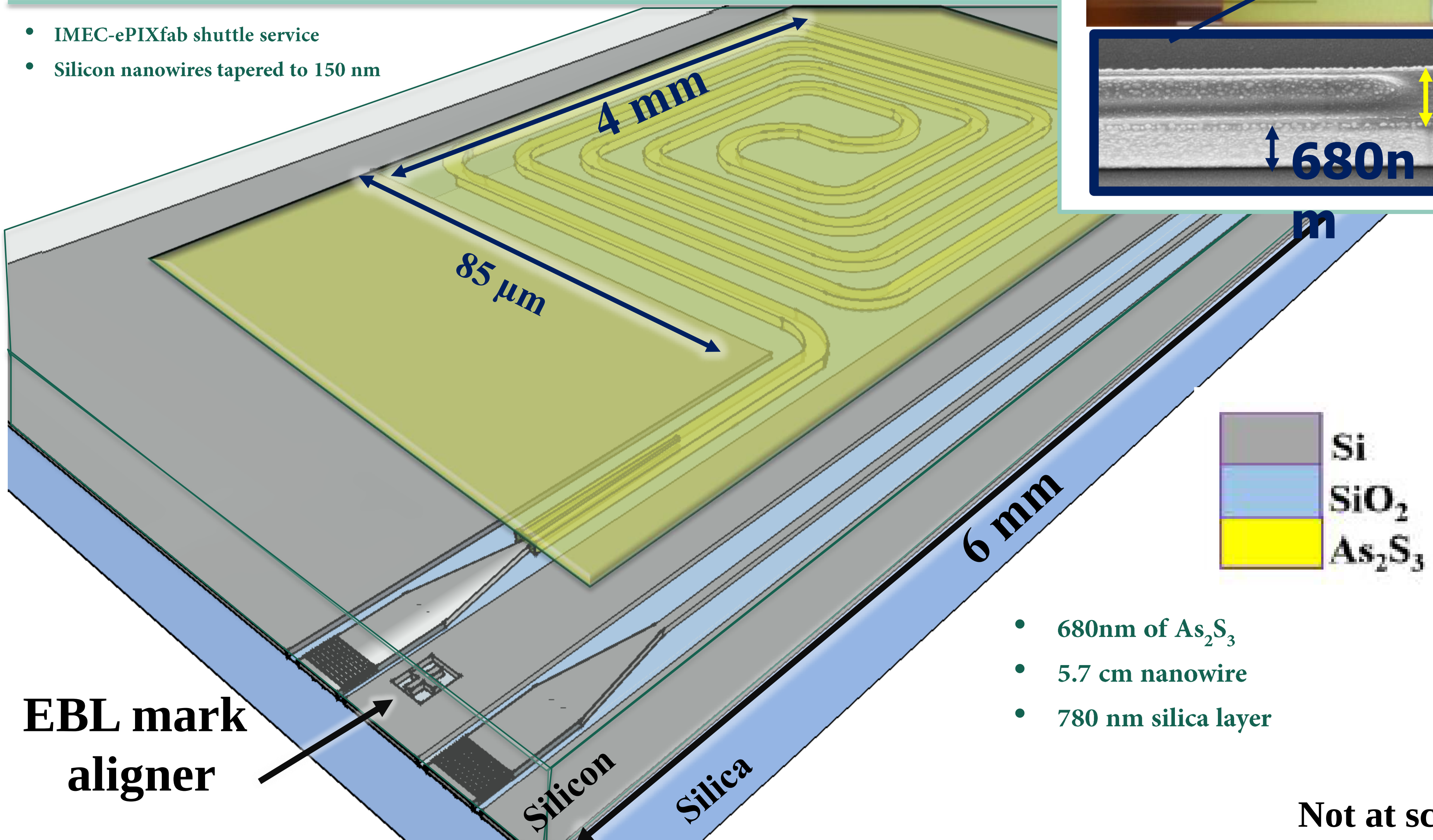

Research Article Vol. 4, No. 8 / August 2017 / Optica 847
optica

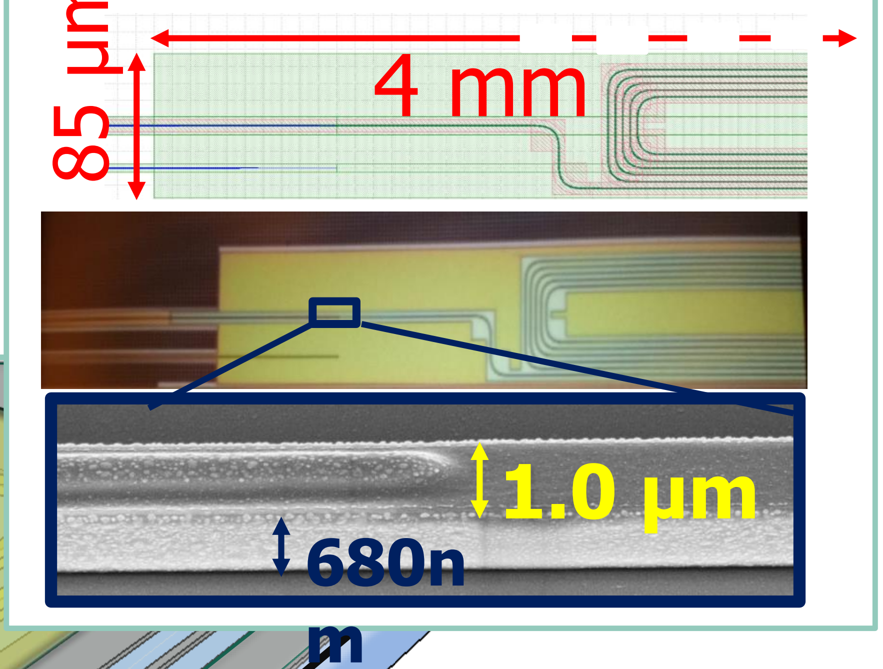
Compact Brillouin devices through hybrid integration on silicon

Blair Morrison,[1,2,*] Alvaro Casas-Bedoya,[1,2] Guanghui Ren,[3] Khu Vu,[4] Yang Liu,[1,2] Atiyeh Zarifi,[1,2] Thach G. Nguyen,[3] Duk-Yong Choi,[4] David Marpaung,[1,2] Stephen J. Madden,[4] Arnan Mitchell,[3] and Benjamin J. Eggleton[1,2]



- IMEC-ePIXfab shuttle service
- Silicon nanowires tapered to 150 nm

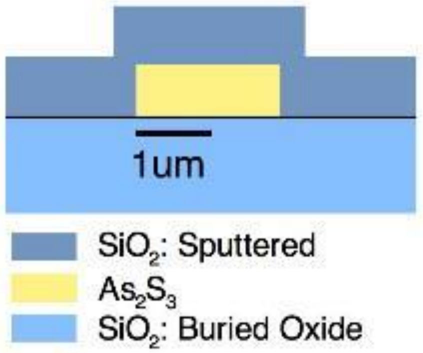


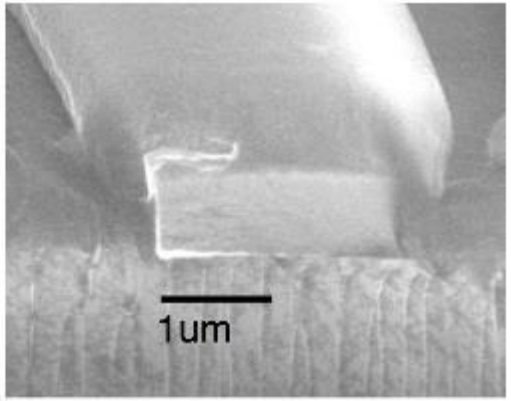


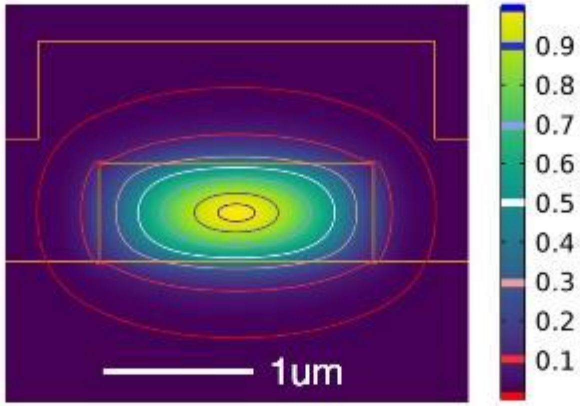
- 680nm of As_2S_3
- 5.7 cm nanowire
- 780 nm silica layer

Not at scale

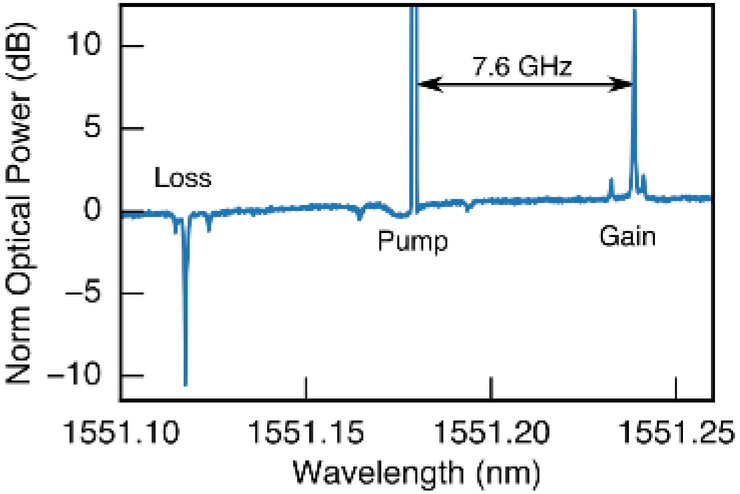
SBS in Hybrid Platform



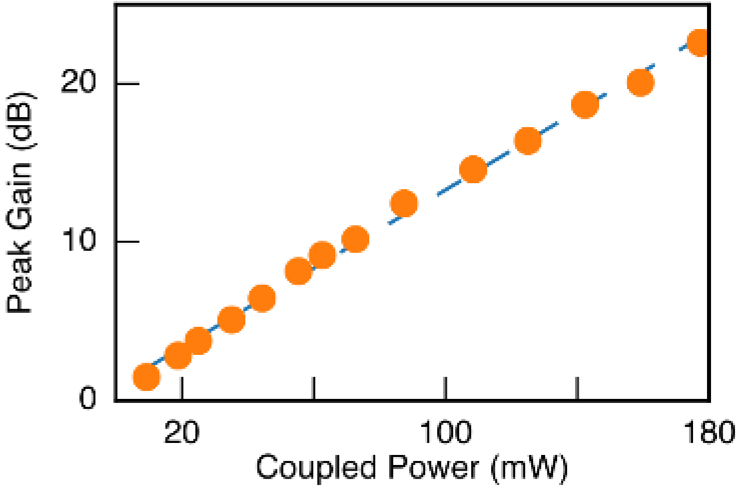




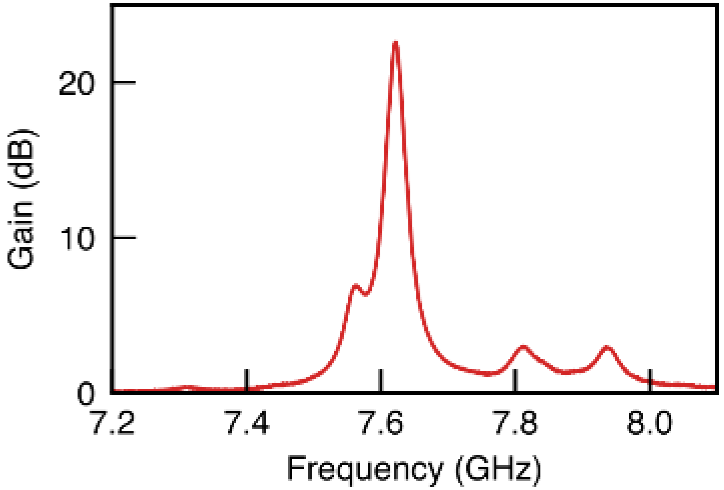
1.9 x 0.68 um
0.7 dB/cm loss
5.7 cm long spiral
0.4 mm² footprint



Shift ~7.6 GHz



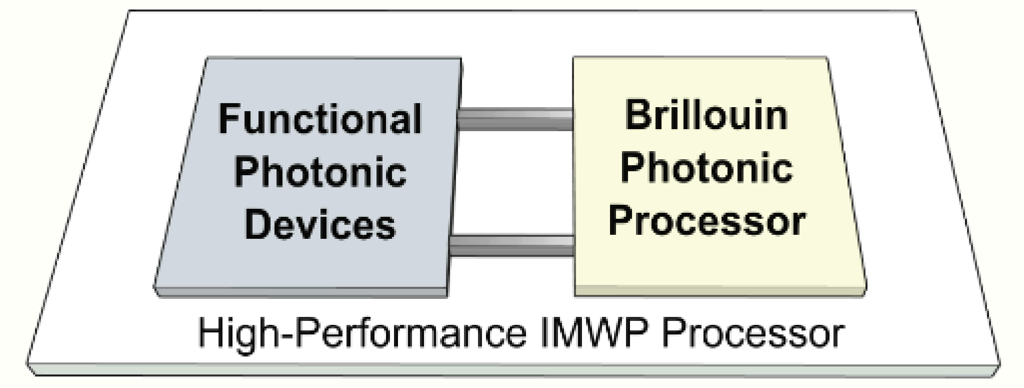
G_{SBS}= 750 /m/W

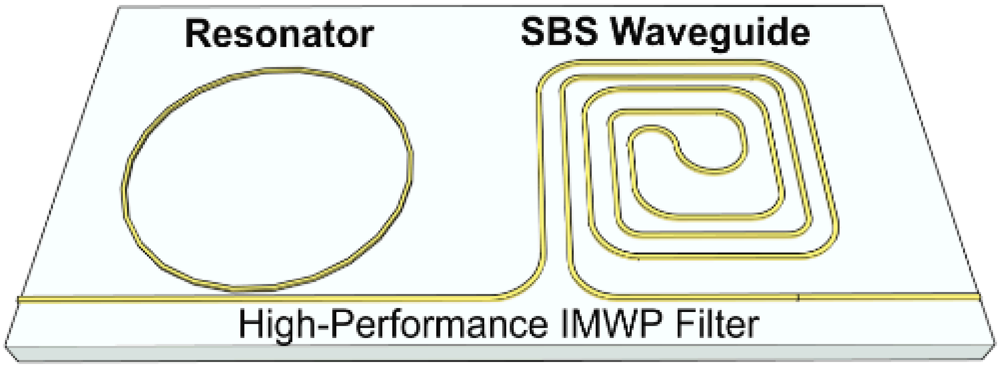


Max gain 22.5 dB

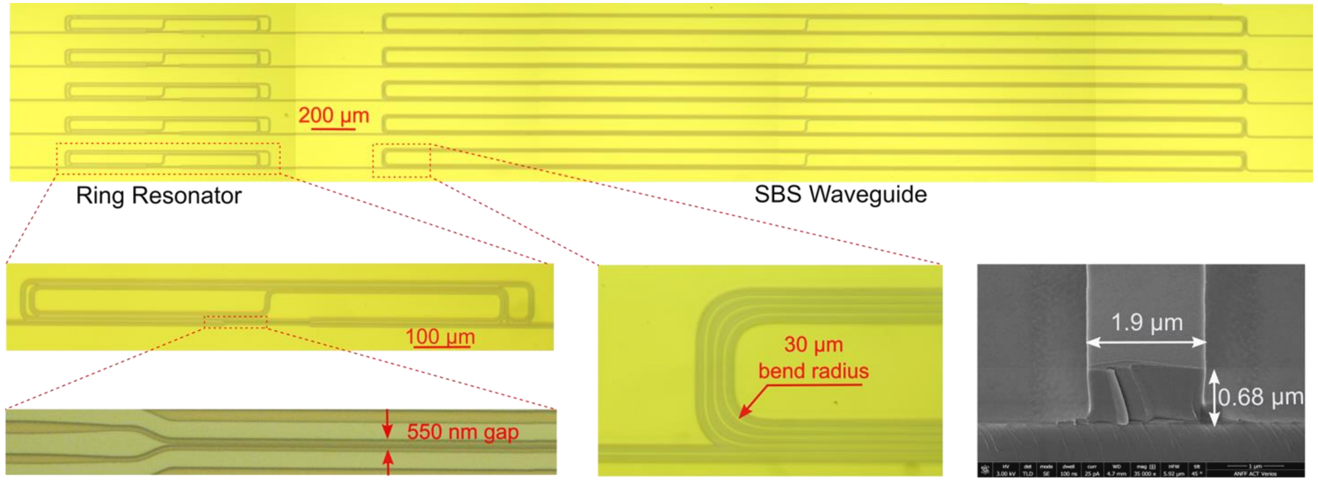
> 20x improvement in amplification over pure Si device

Pairing on-chip linear and nonlinear optics (Yang Liu et al. MWP Conference)



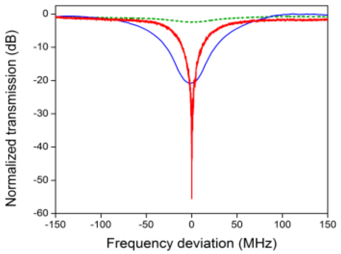


- **'Linear'** device library offers ring resonator, coupler, splitter…
- **'Nonlinear'** devices bring advances in signal amplification, filtering, generation…
- **Combination** unleashes the full potentials.
- **On-chip** circuit means more functions, less interconnection losses and compactness.



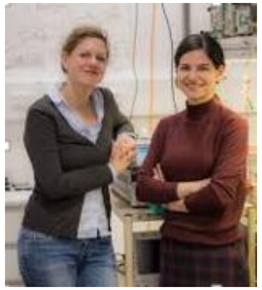
Brillouin Integrated Photonics

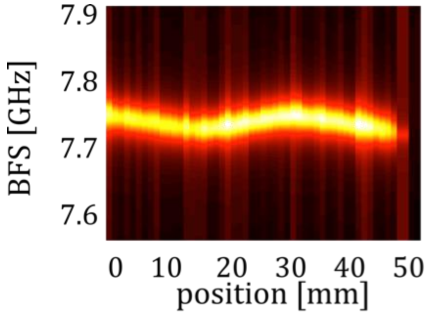
Microwave filter / phase shifter / sources



Byrnes et al., Optics Express, 20 (2012)
Morrison et al., Optics Comm, 313 (2014)
Pagani et al., Optics Letters (2014)
Marpaung et al., Optica 2 (2015)
Casas Bedoya et al., Optics Letters 40 (2015)
Merklein et al., Optics Letters 41, 4633 (2016)

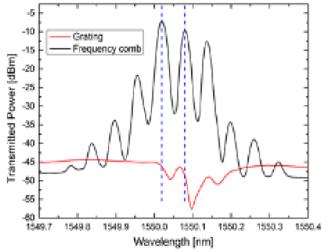
Brillouin sensing



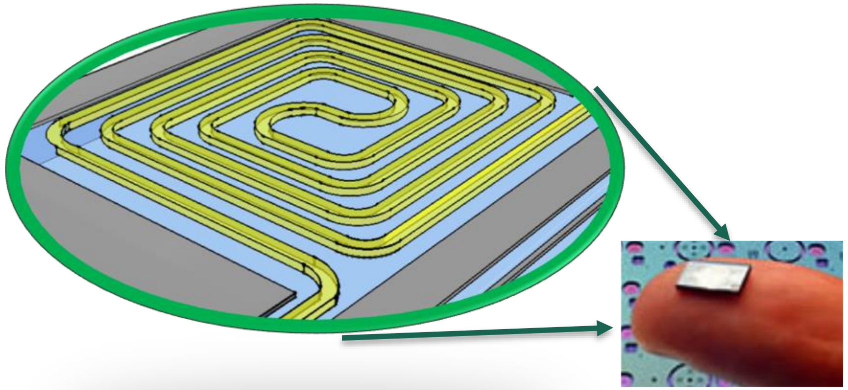


Zarifi, Stiller et al., APL Photonics (2018)

SBS frequency comb



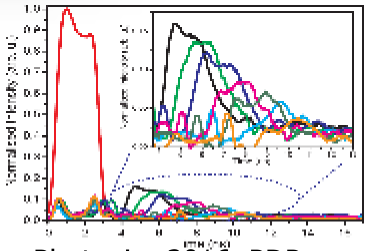
Büttner et al., Scientific Reports 4 (2014)
Büttner et al., Optica, 1(5), 311 (2014)
Merklein et al., Nature Communications 6:6396 (2015)



Carrier recovery in coherent optical communications

Giacoumidis et al. Optica 5, (2018)

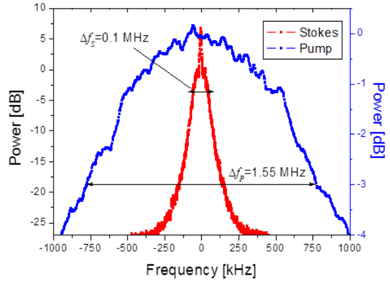
Light storage



Stiller et al., Nonlinear Photonics 2016, PDP
Merklein et al., Nat. Comm. (2017).
Stiller *et al.*, Optics Letters (2018)

On-chip SBS laser

Kabakova et al., Optics Letters 38 (2013)

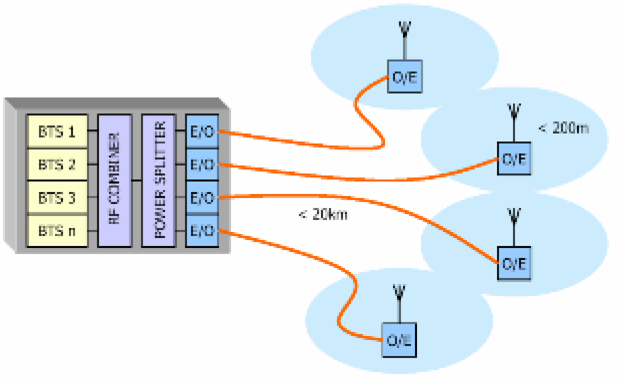


Morrison et al., Optica 4 (2017)

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

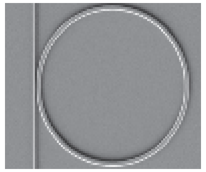
Signal transport

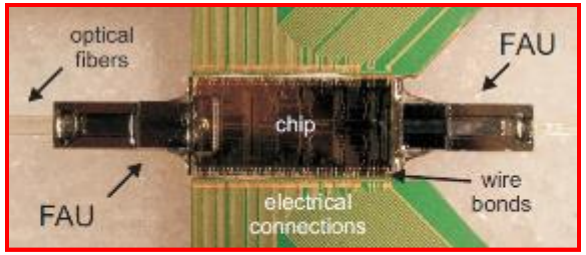
- **Radio over fiber**
- **Antenna remoting**



Signal processing

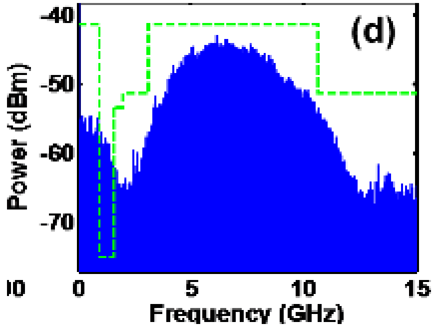
- **Filtering**
- **Phase shifter, beamforming**





Signal generation

- **Ultra-wideband (UWB)**
- **Low phase noise synthesizer**

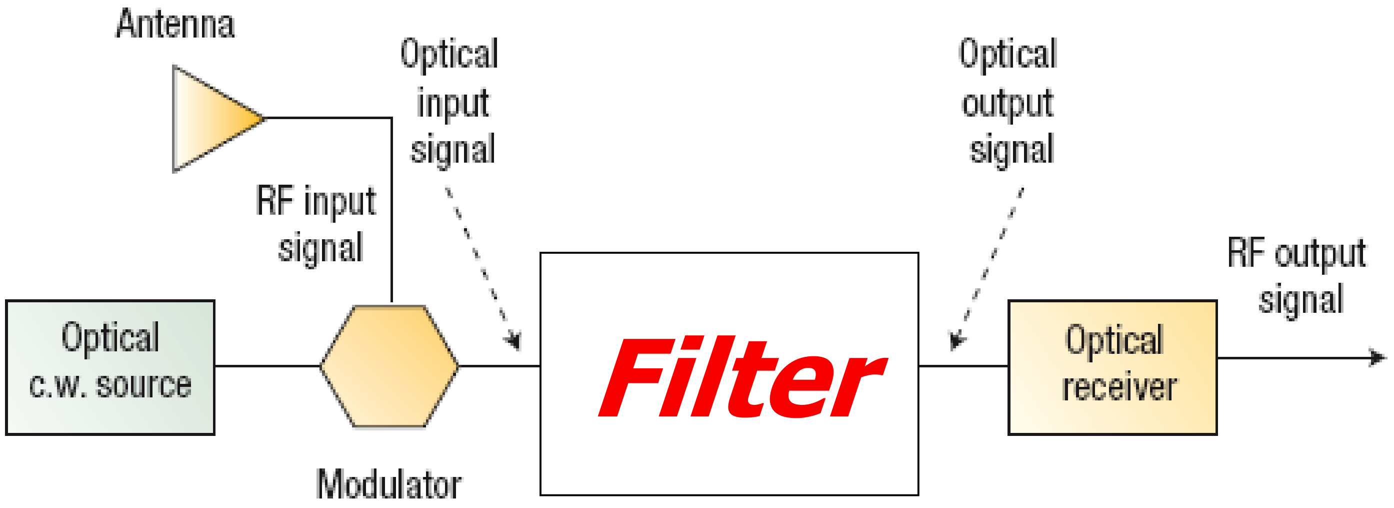


Advantage

- Wide bandwidth
- Low loss
- EMI immunity
- Reconfigurable

Microwave photonics provides bandwidth

Microwave signal processing uses photonics to overcome limitations of RF Electronics [1]



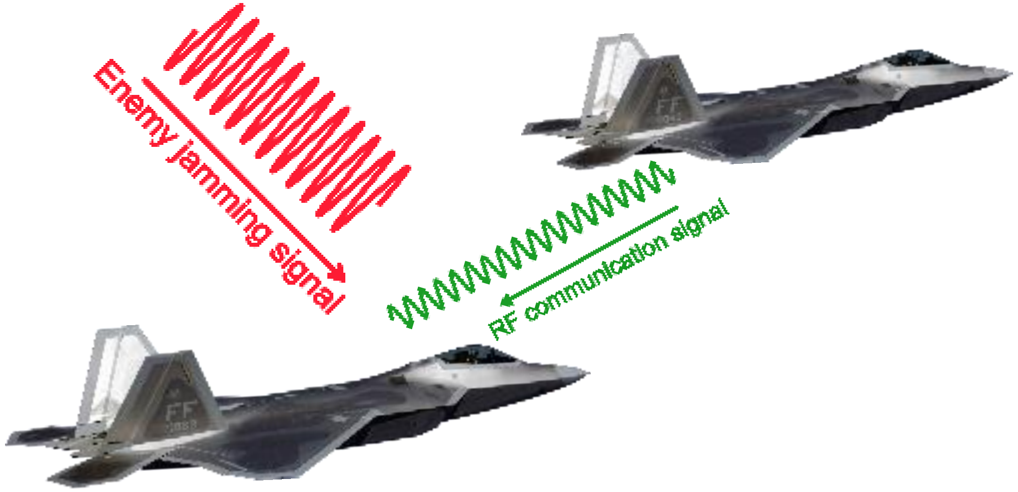
Why a Microwave ***Photonics***?

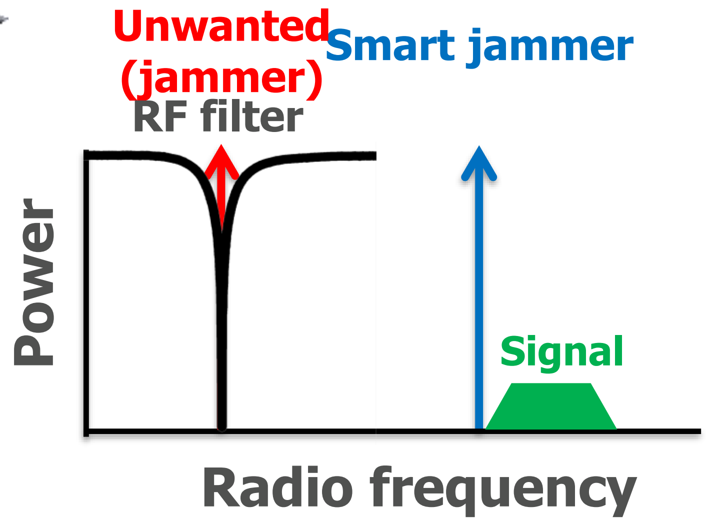
- Tunability over broad range of frequencies (>10s of GHz)
- Electrical isolation
- Immunity to EMI

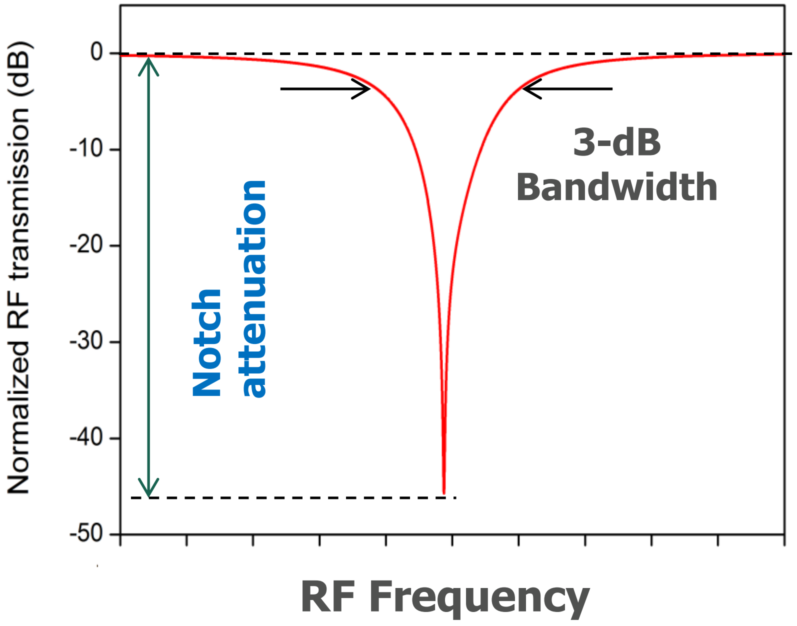
[1] J. Capmany & D. Novak, "Microwave Photonics Combines Two Worlds", *Nature Photonics* **1**, 319 - 330 (2007)

[2] D. Marpaung and B. J. Eggleton, "Nonlinear integrated microwave photonics," Journal of Lightwave Technology (2014)

Microwave notch filters







Desired properties

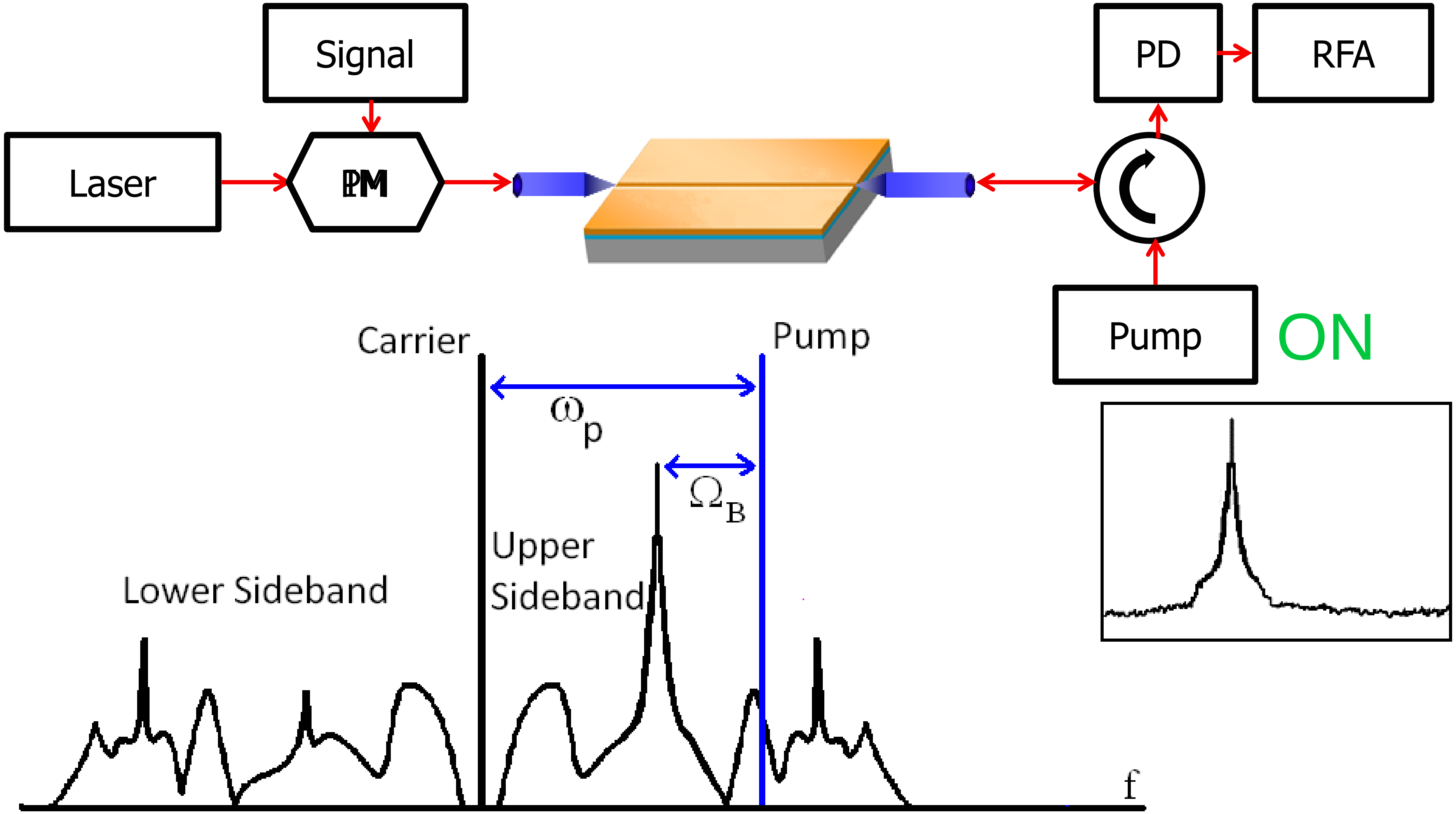
- High peak attenuation (>50 dB)
- High Q (FWHM << 1 GHz)
- Large frequency tuning (tens GHz)
- Reconfigurable response
- Small footprint
- Bandwidth reconfigurability

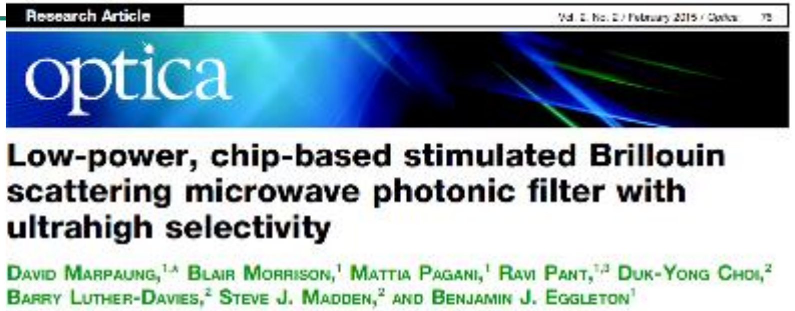
Photonic chip based tunable and reconfigurable narrowband microwave photonic filter using stimulated Brillouin scattering

Adam Byrnes,[1] Ravi Pant,[1] Enbang Li,[1] Duk-Yong Choi,[2] Christopher G. Poulton,[3] Shanhui Fan,[1,4] Steve Madden,[2] Barry Luther-Davies,[2] and Benjamin J. Eggleton[1,*]

13 August 2012 / Vol. 20, No. 17 / OPTICS EXPRESS 18845

Principle of Operation

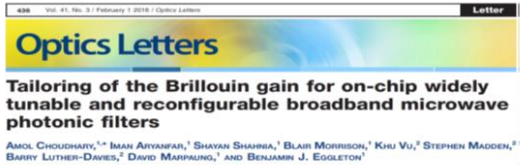



Research Article

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]

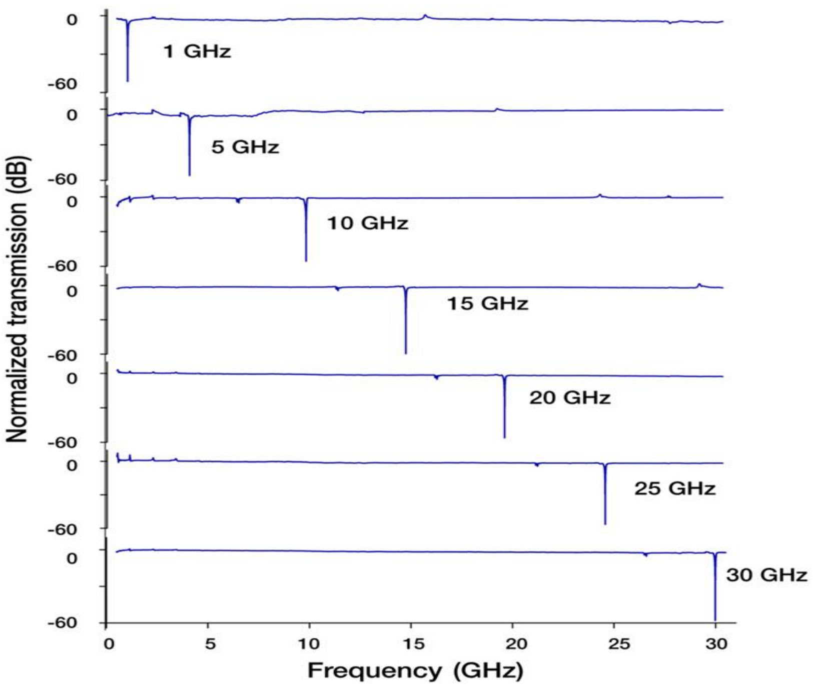

Letter

Optics Letters

Tailoring of the Brillouin gain for on-chip widely tunable and reconfigurable broadband microwave photonic filters

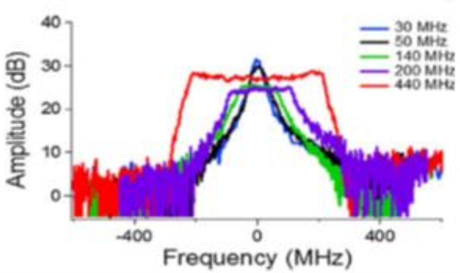

High-resolution, on-chip RF photonic signal processor using Brillouin gain shaping and RF interference

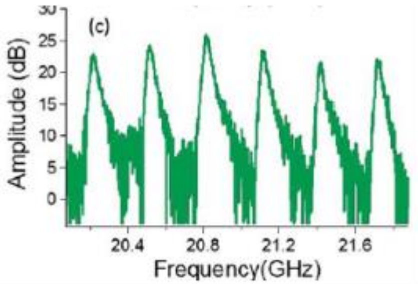
SCIENTIFIC REPORTS | 7: 5932 | DOI:10.1038/s41598-017-06270-4



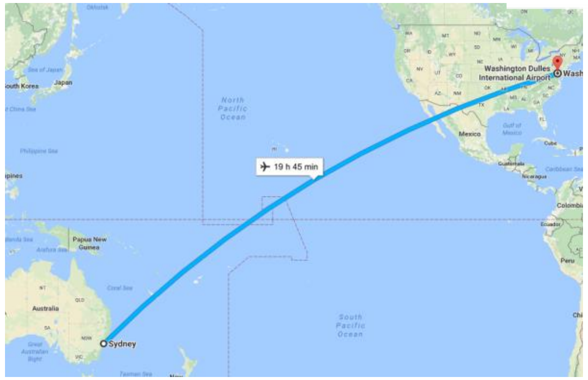
Performance highlight

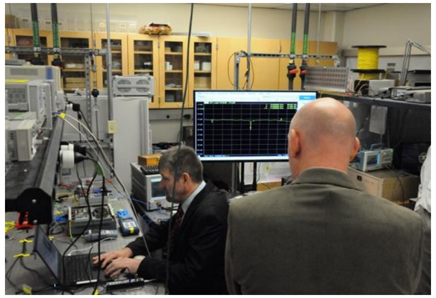
- Ultra-high suppression
- 100x lower energy consumption
- 15x wider tuning vs. electronic RF filter
- Highest Q at 30 GHz for on chip filter
- Reconfigurable bandpass & multiple bandpass filters



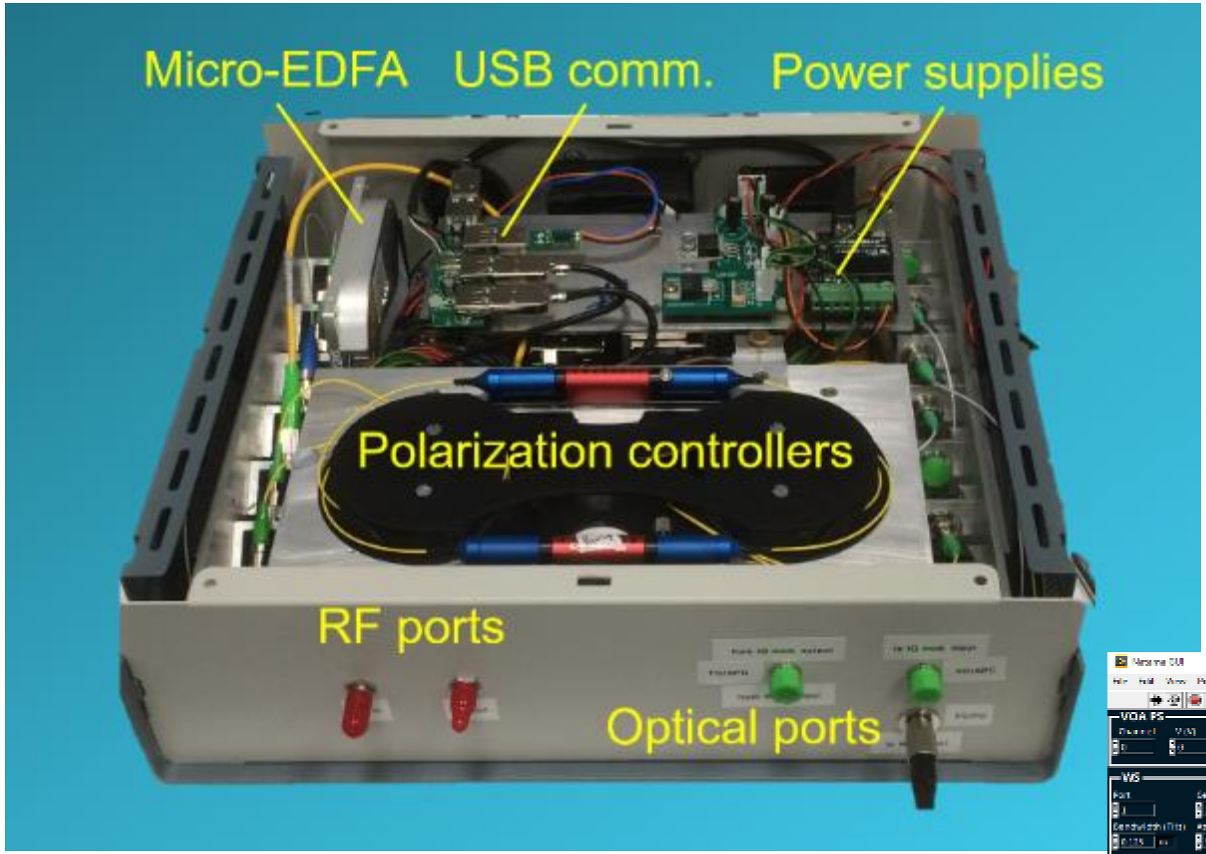


Prototype



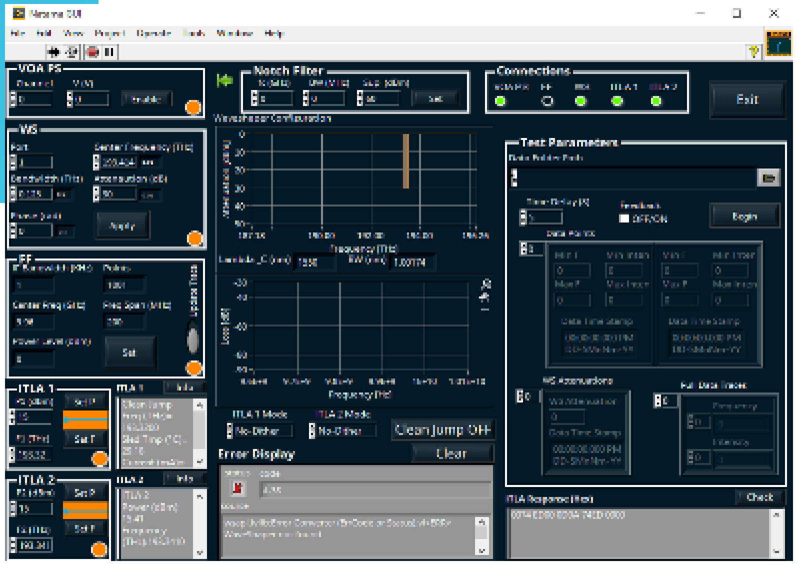


Second generation prototype



Dimension of 28cm x 30cm x 10cm.

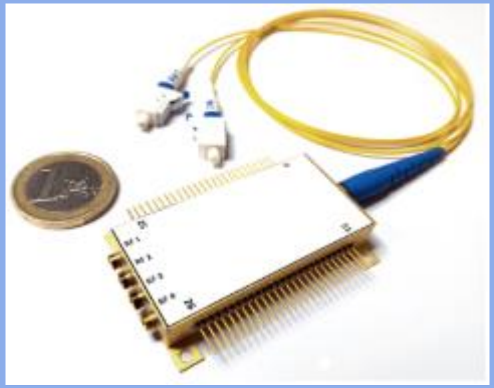
Software user interface



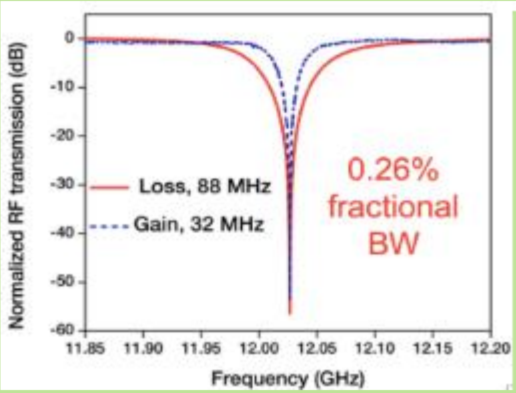
The Vision: three pillars that underpin MWP

Microwave Photonics

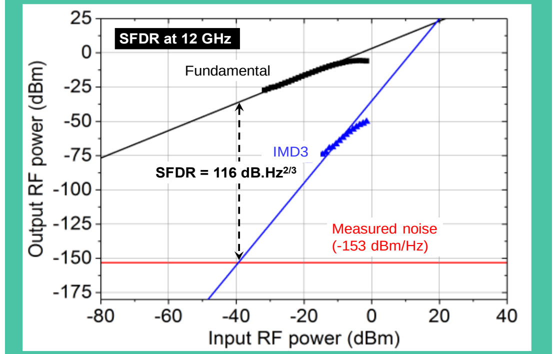
Integration



Functionality



Performance



D. Marpaung et al., Optica (2015)

J. Fandiño et al., Nature Photonics (2016)

Y. Liu et al., Optics Letters (2017)

IEEE Journal of Quantum Electronics (2018)

Chip-Based Brillouin Processing for Phase Control of RF Signals

Yang Liu, Amol Choudhary, David Marpaung, and Benjamin J. Eggleton, *Fellow, IEEE*

IEEE Journal of Selected Topics in Quantum Electronics (2018)

On-chip Brillouin filtering of RF and Optical Signals

Amol Choudhary, Yang Liu, David Marpaung, and Benjamin J. Eggleton

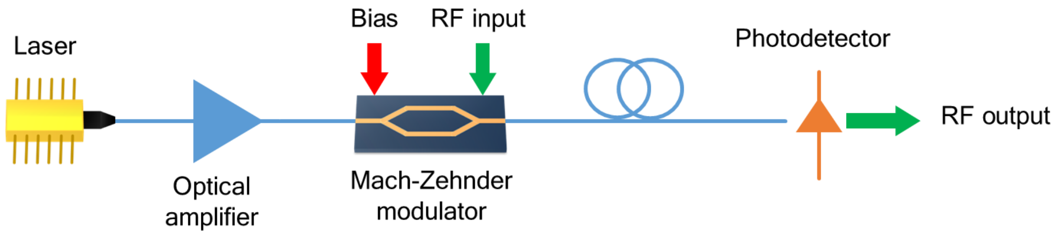
Journal of Lightwave Tehnology (2018)

Link Performance Optimization of Chip-based Si_3N_4 Microwave Photonic Filters

Yang Liu, David Marpaung, *Member, OSA*, Amol Choudhary, *Member, OSA*, Jason Hotten, and Benjamin J. Eggleton, *Fellow, IEEE*

Performance gap hinders IMWP's real-world applications

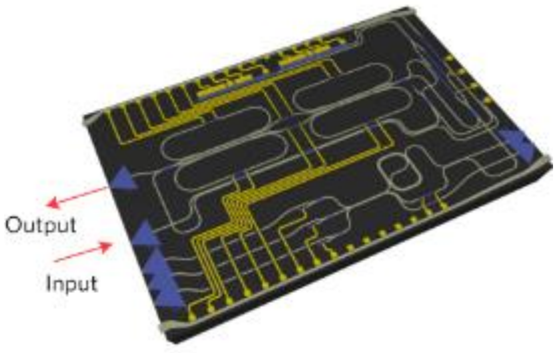
MWP link only



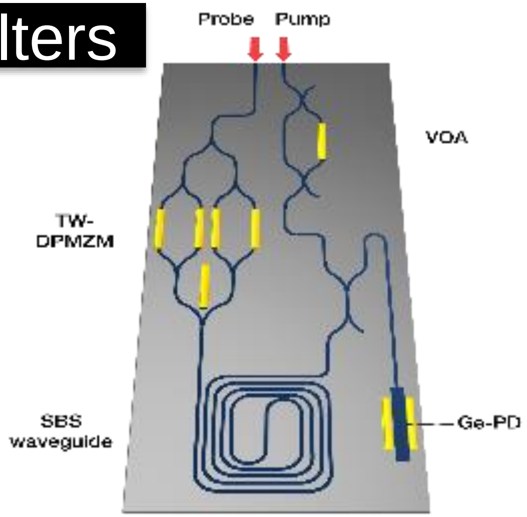
	Link gain (dB)	NF (dB)	SFDR ($dB.Hz^{2/3}$)
MWP link only	> 0	< 10	> 120

V. Urick et al., Fundamentals of Microwave Photonics, Wiley (2015)
V. Urick et al., JLT, **27** (2009)
A. Karim et al., IEEE PTL, **19** (2007)

State-of-the-art IMWP filters



Fandino et al., Nat. Photon.**11** (2016)



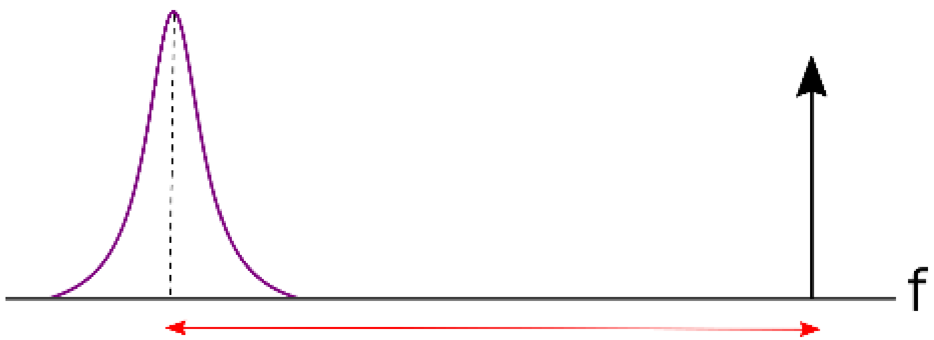
Marpaung et al., Optica **2** (2015)

Why?

- Photonic circuits and processing add losses
- Link performance optimization techniques need to be explored.

Achieving high-performance requires efficient SBS gain: SBS for monitoring micro-scale waveguides

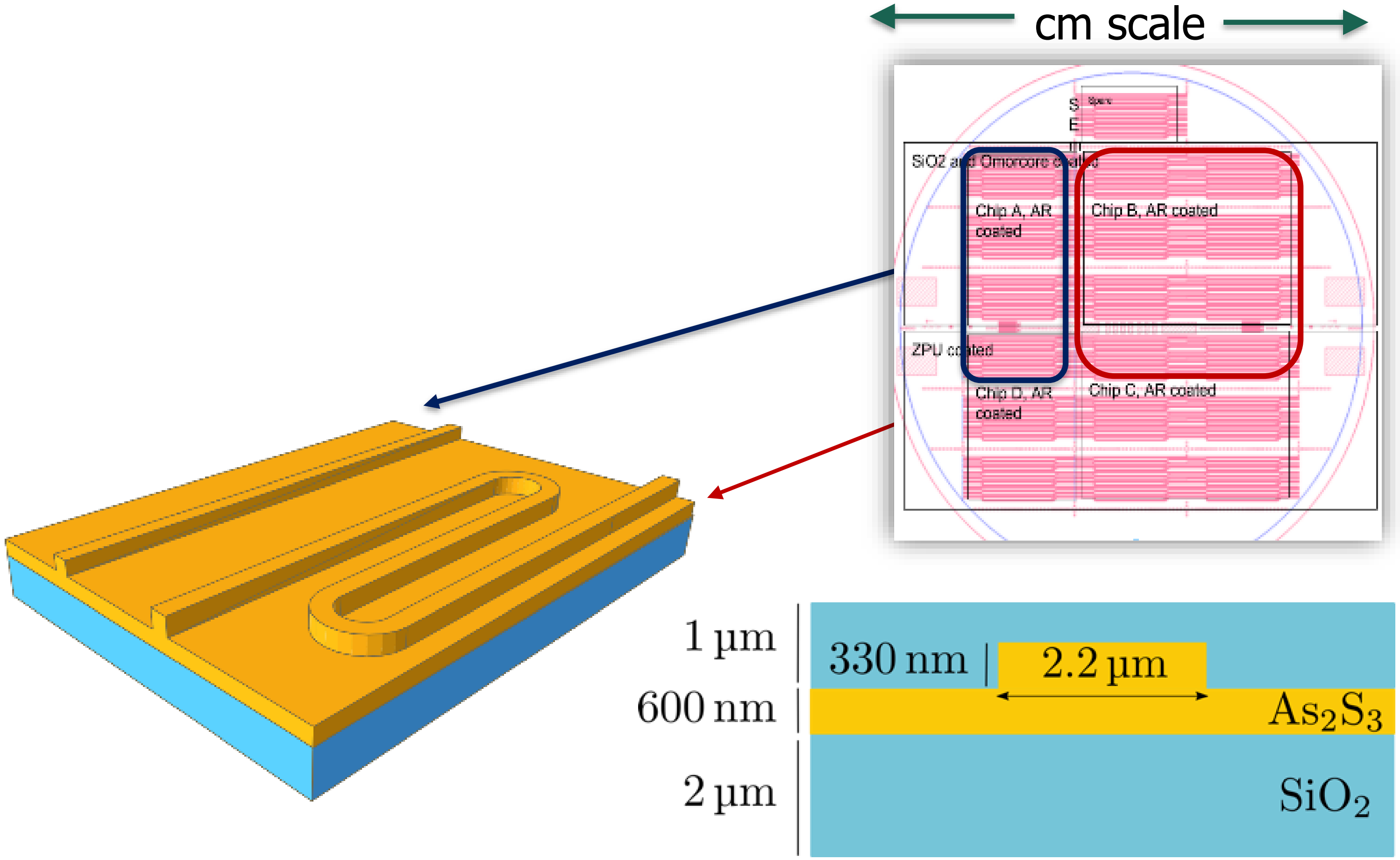
Distributed SBS measurement with high spatial resolution is required to confirm the consistency and high SBS gain in photonic waveguides.



BFS (Ω)

$$\Omega = \frac{2 n_{eff} v_a}{\lambda}$$

Brillouin optical correlation domain analysis



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Highly localized distributed Brillouin scattering response in a photonic integrated circuit

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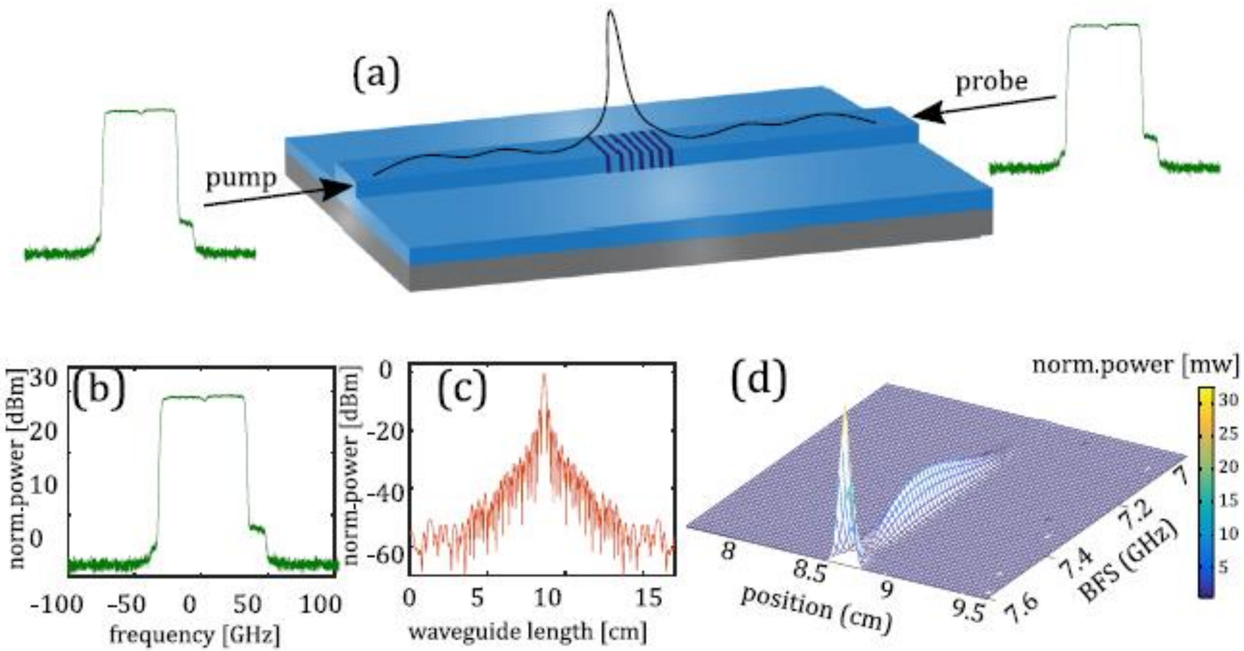

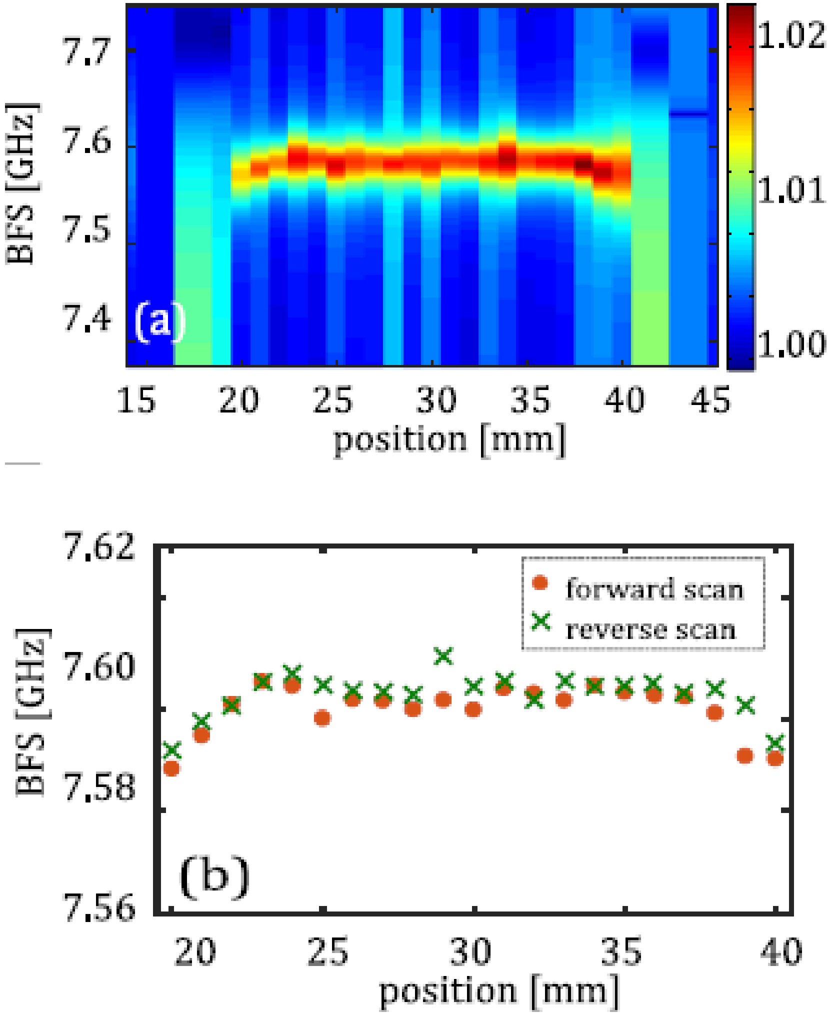

Team and collaborators

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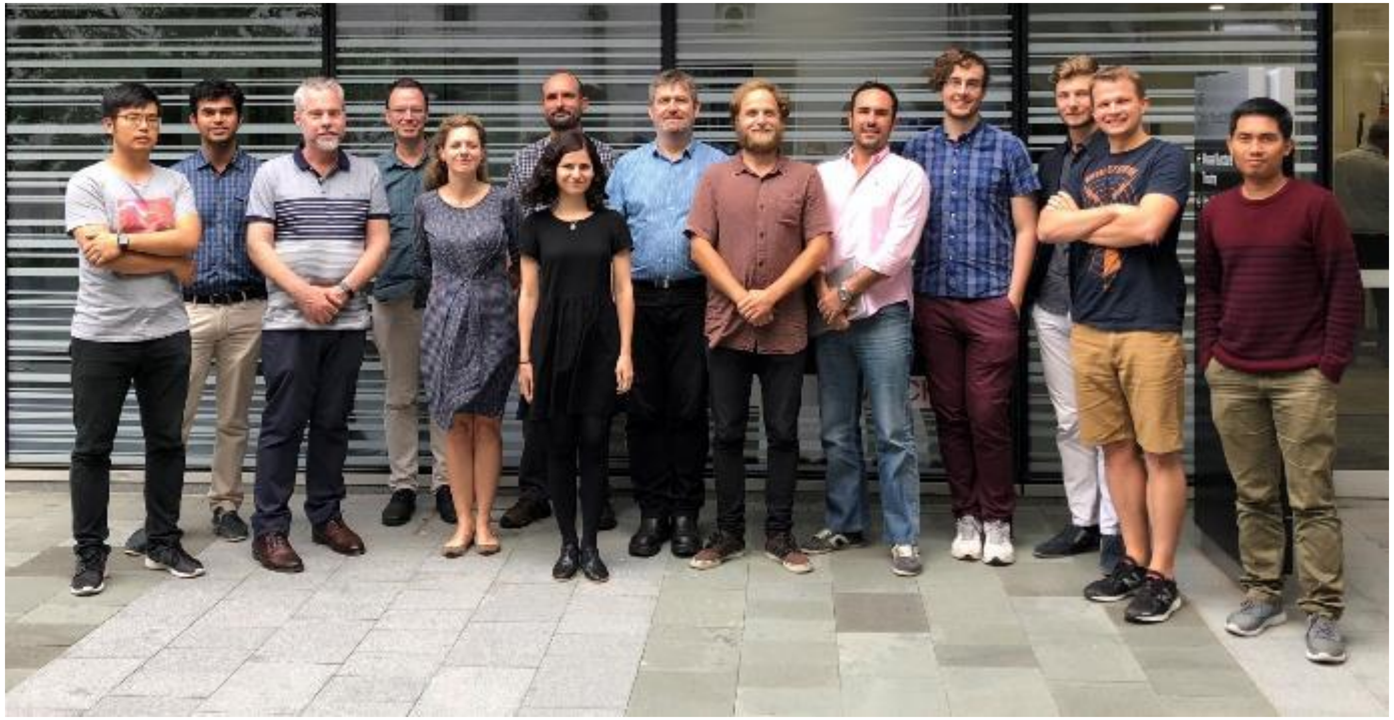

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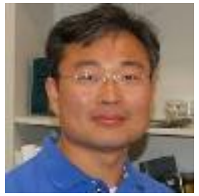


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