UNIVERSITY OF TWENTE.

MESA+ INSTITUTE

OPTICA

High Performance Integrated Microwave Photonic Systems

David Marpaung
Nonlinear Nanophotonics
University of Twente

erc

NWO

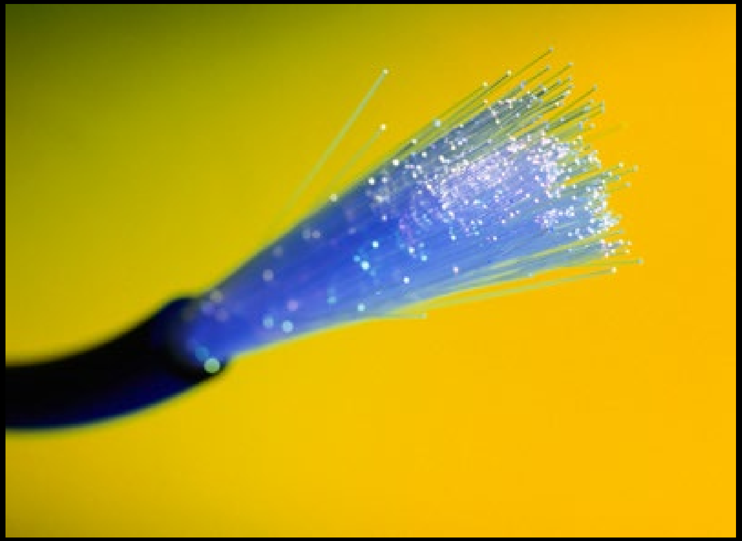
National Growth Fund

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.

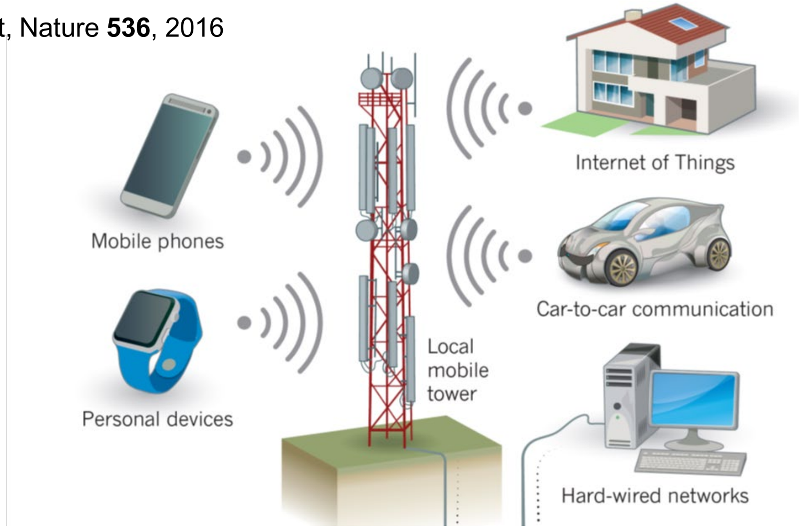


- Heavy (copper, 567 kg/km)
- High loss(190 dB/km @ 6 GHz)
- Rigid and large cross section

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

The need for broadband signal reception and processing

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



Next generation wireless communications with ultra-high frequencies and data rates

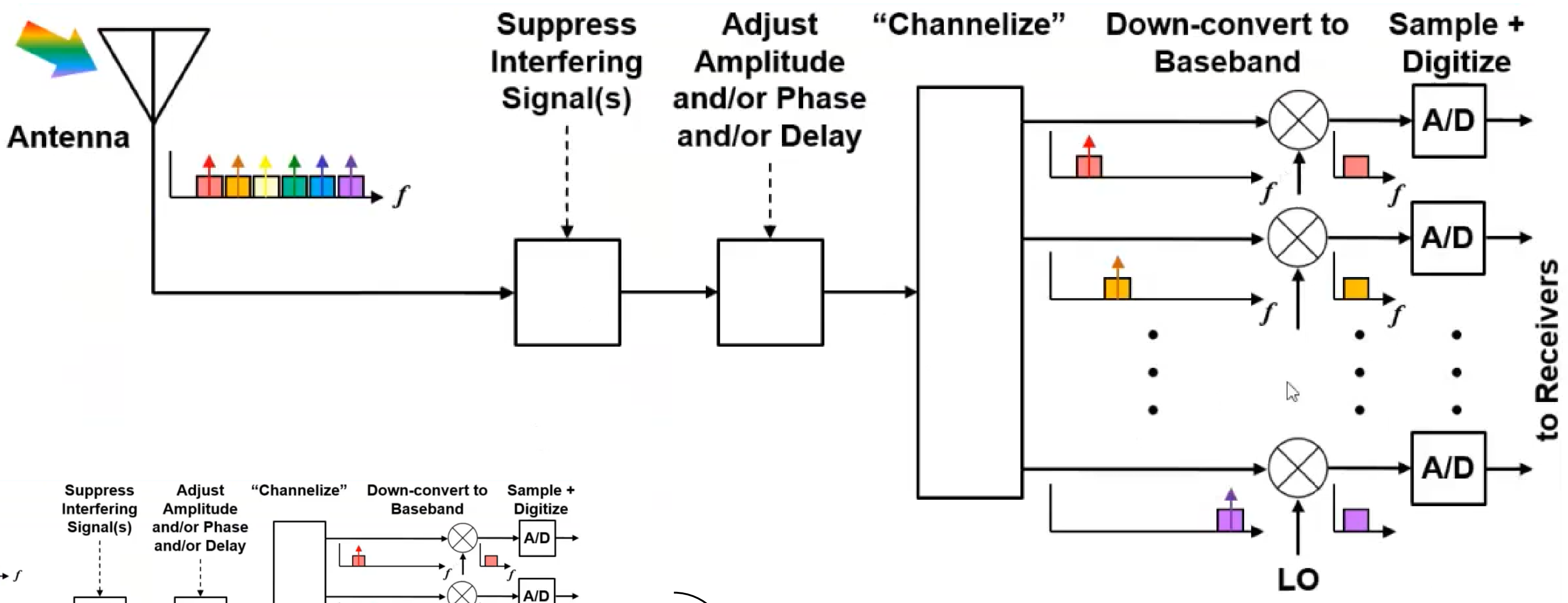
High throughput satellite with multiple beams operating at Ka band (30 GHz)

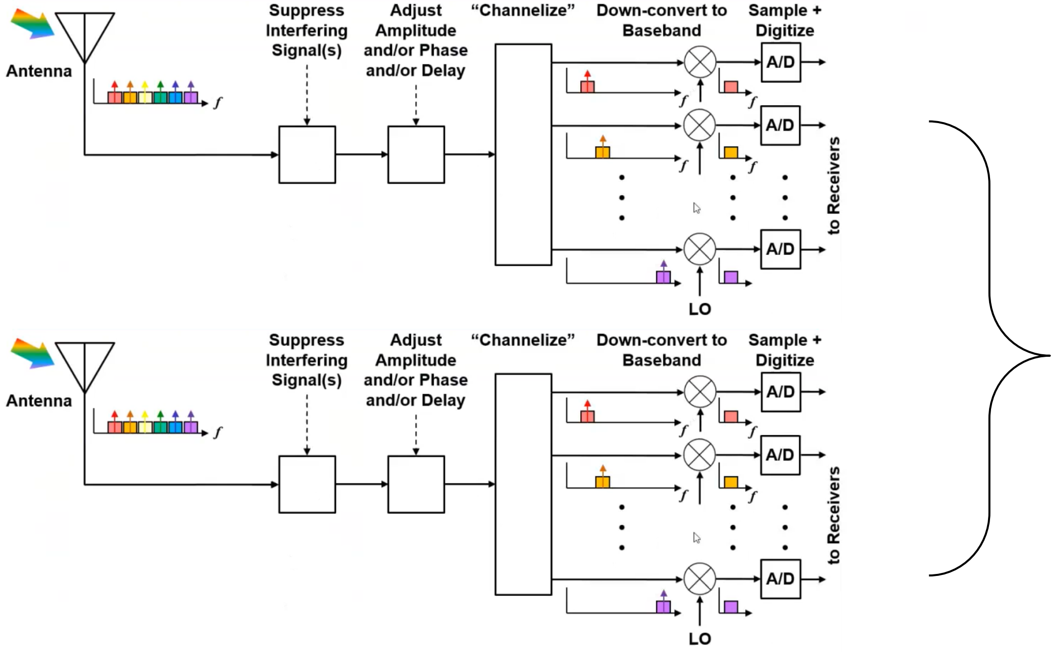
Atacama Large Millimeter-wave Array (66 dishes operating at 30-1,000 GHz)

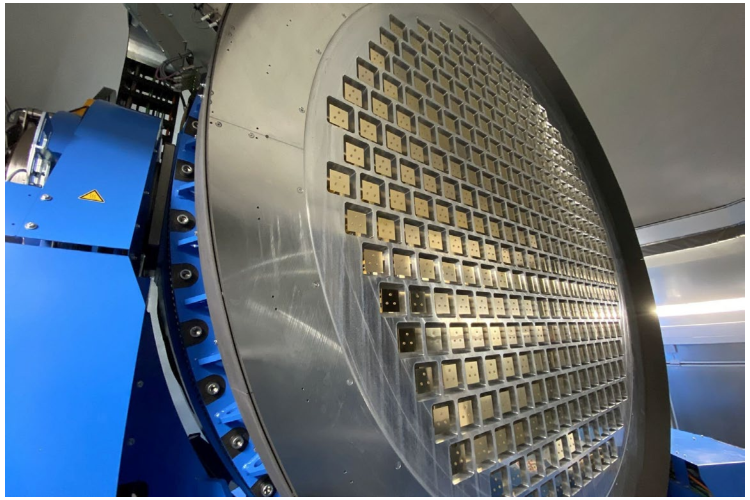
Navy ships with antennas operating at 50 MHz- 50 GHz

A closer look at the RF front-ends

E. Ackerman, Analog Photonic Systems: Features & Techniques to Optimize Performance, IEEE MTT-S Distinguished Lecture



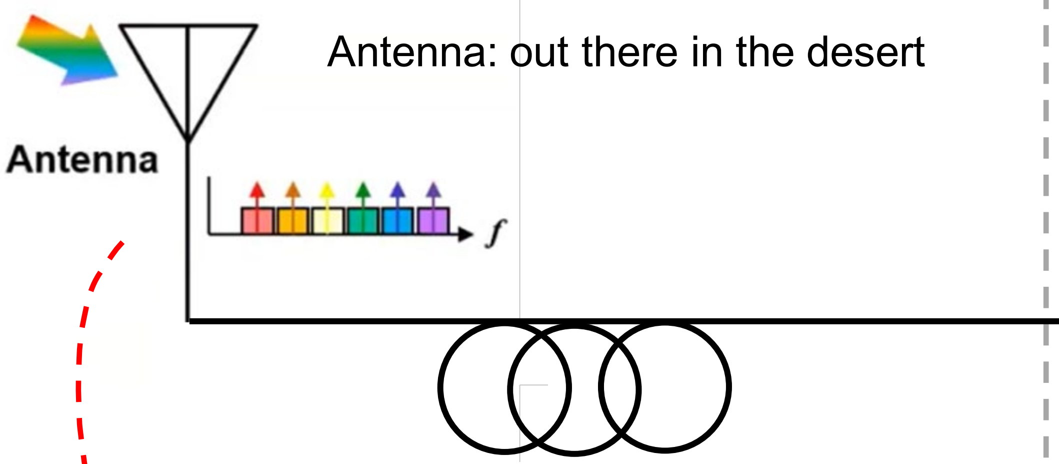




Phased-array antenna

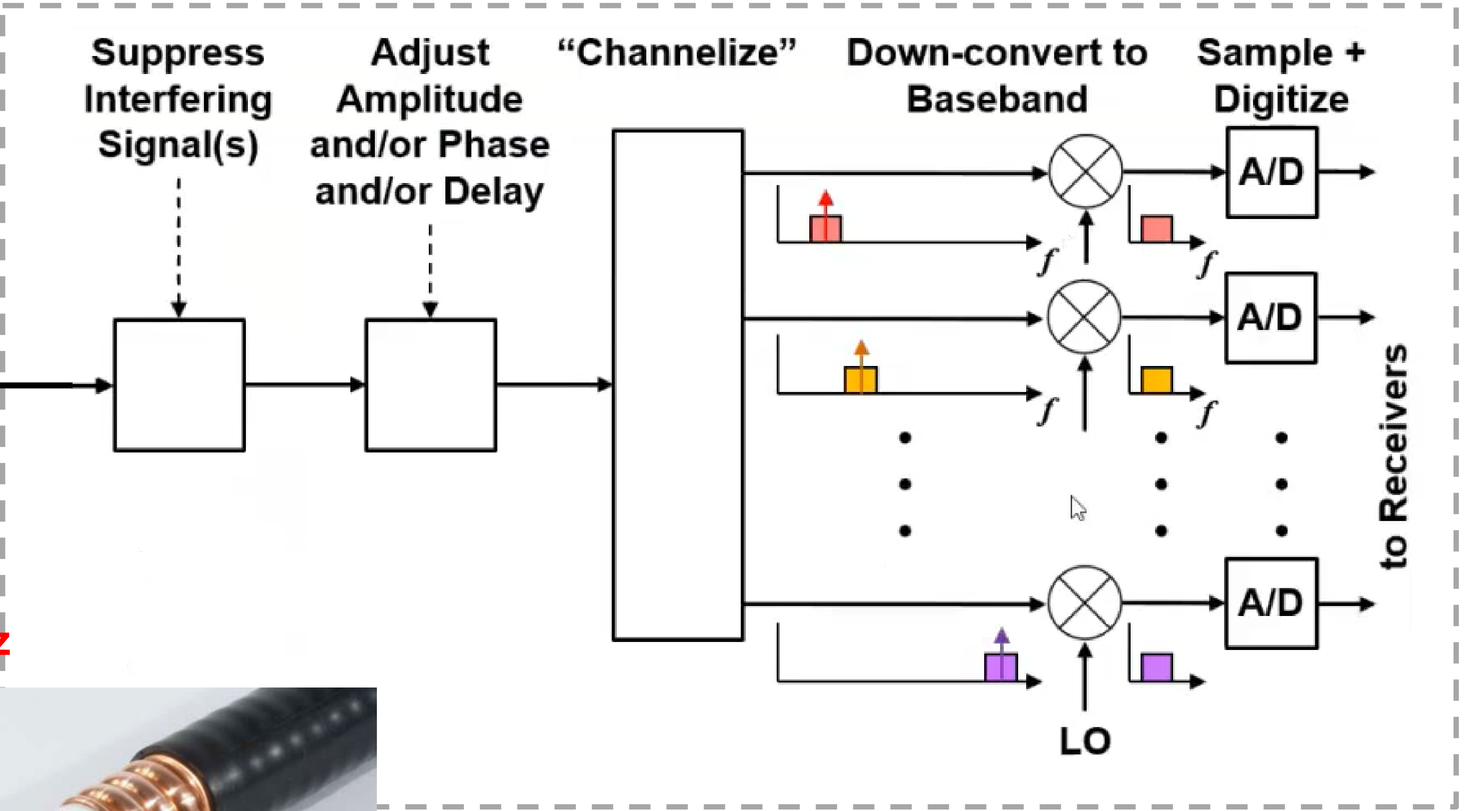
The beginning of microwave photonics: antenna remoting

Antenna: out there in the desert



Need to bridge a few hundred meters

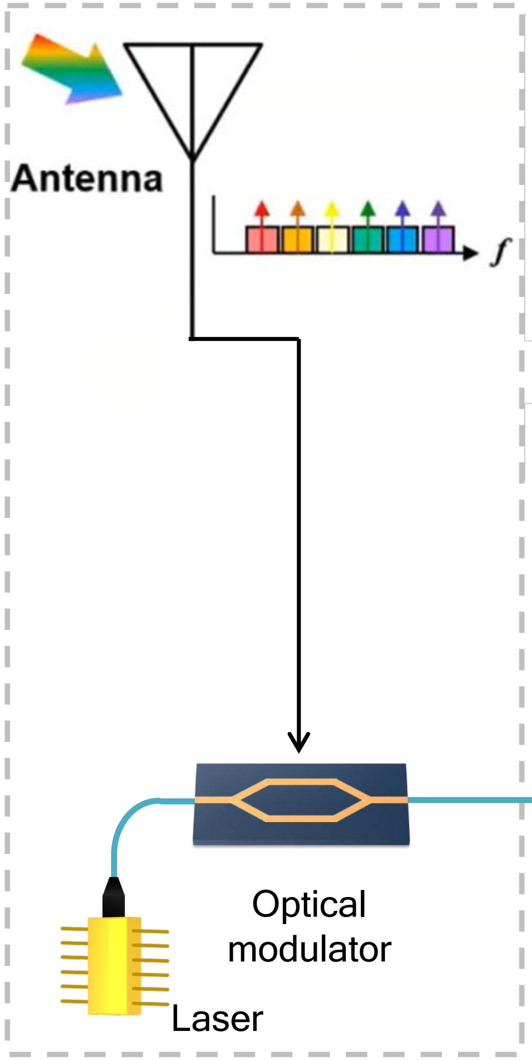
Coax cable loss: **> 25 dB/100m @ 5 GHz**

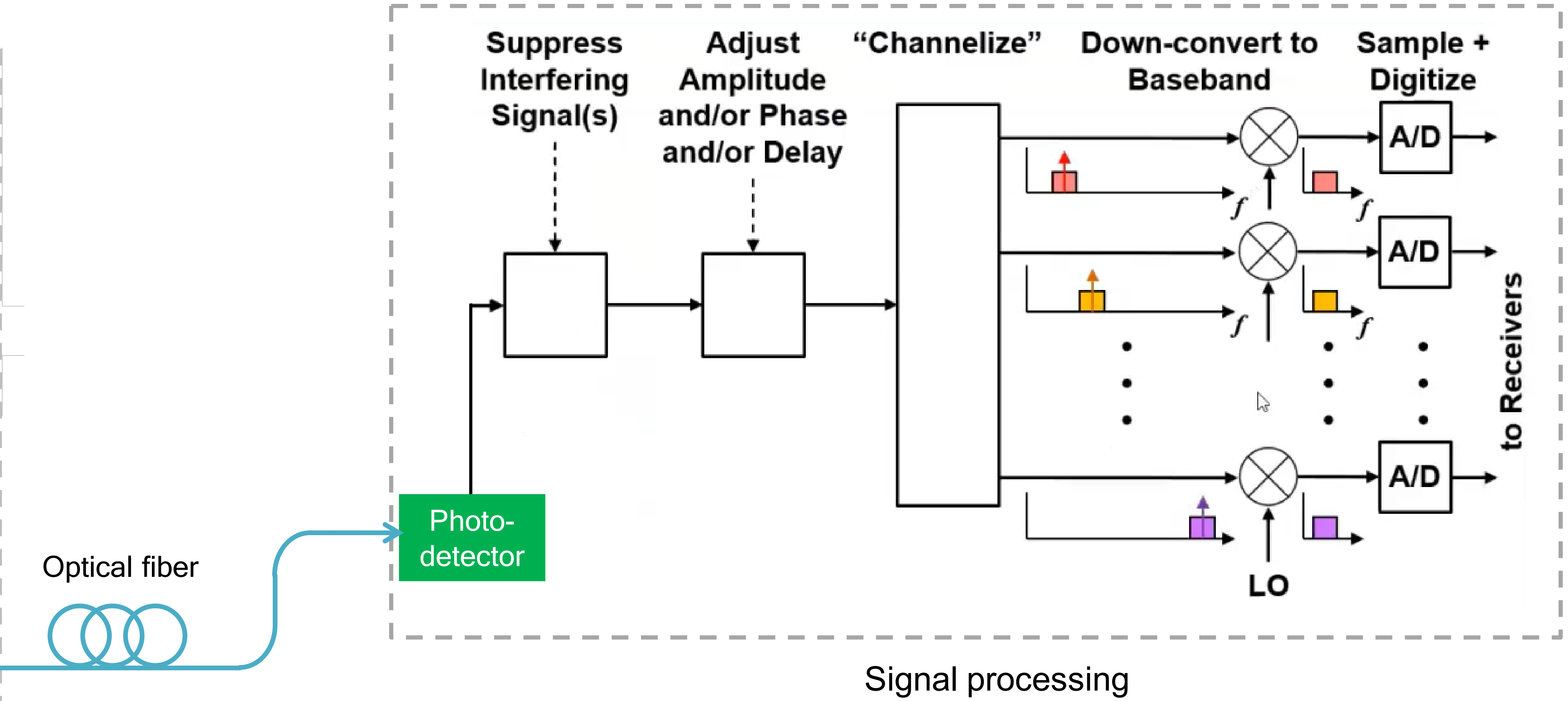


Signal processing: somewhere more hospitable

Adapted from: E. Ackerman, Analog Photonic Systems: Features & Techniques to Optimize Performance, IEEE MTT-S Distinguished Lecture

The beginning of microwave photonics: antenna remoting



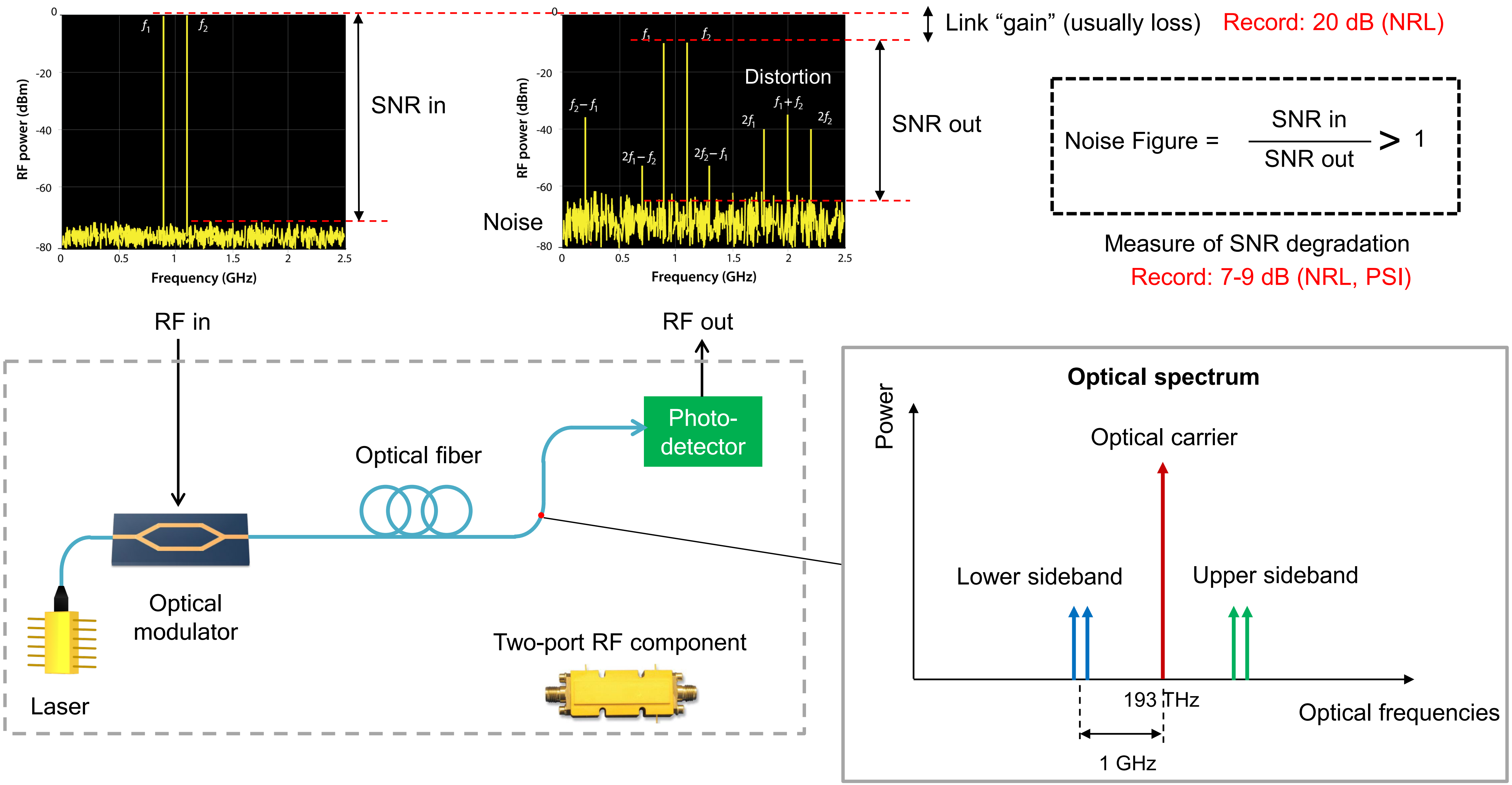


- Low loss (0.2 dB/km), broadband
- Lightweight
- Flexible
- EMI immunity

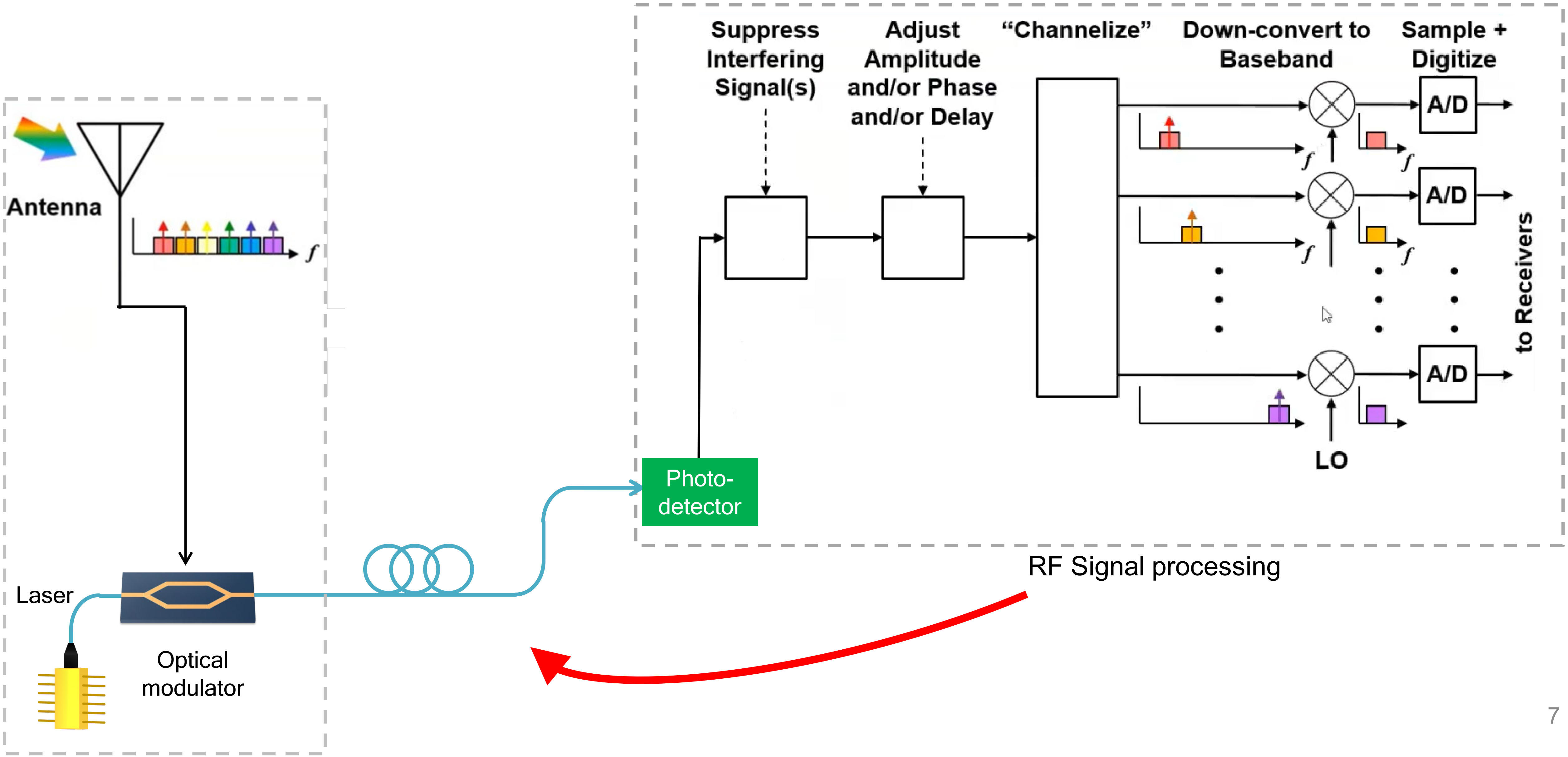
Adapted from: E. Ackerman, Analog Photonic Systems: Features & Techniques to Optimize Performance, IEEE MTT-S Distinguished Lecture

Adapted from: E. Ackerman, Analog Photonic Systems: Features & Techniques to Optimize Performance, IEEE MTT-S Distinguished Lecture

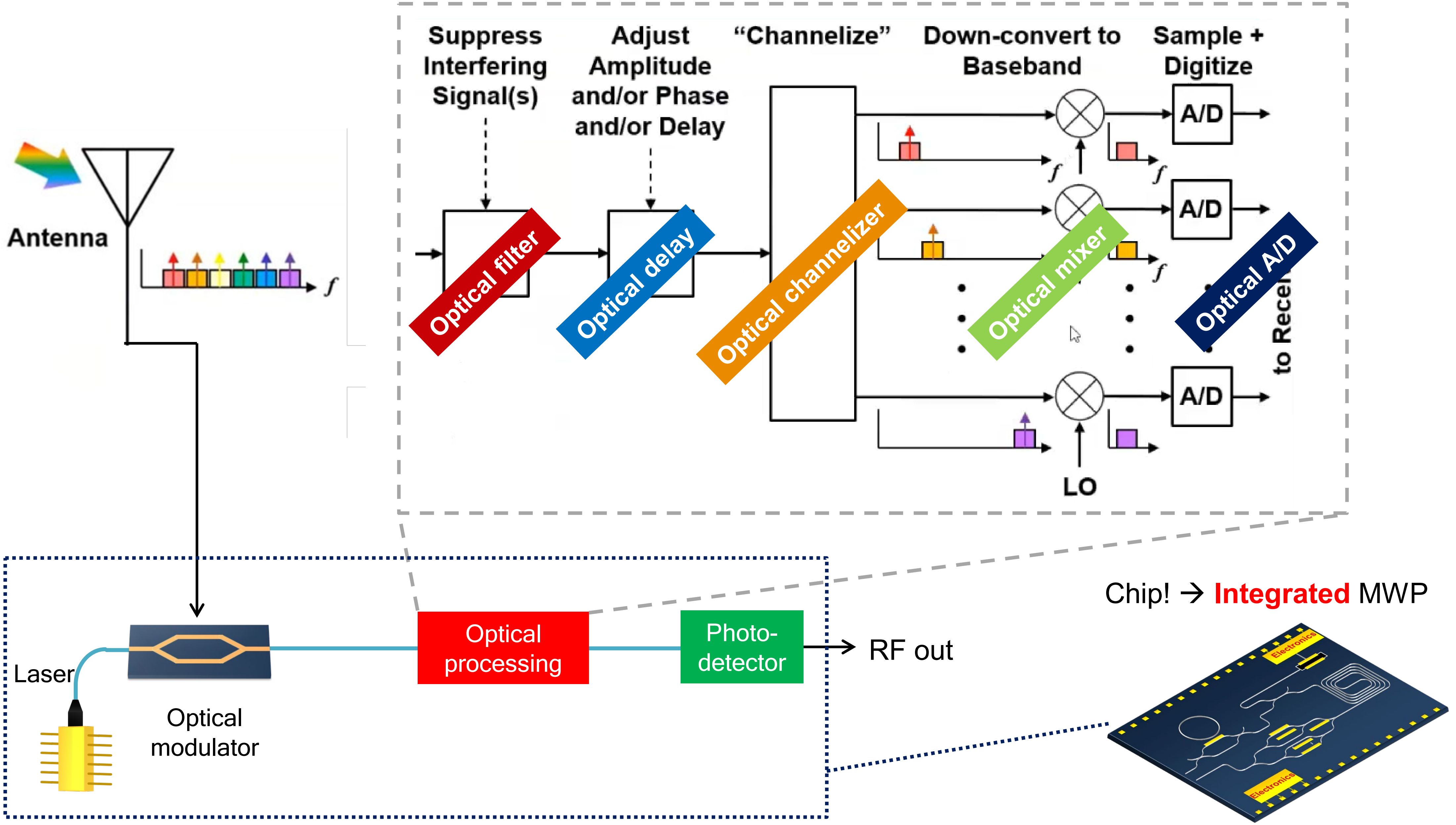
Microwave photonic link



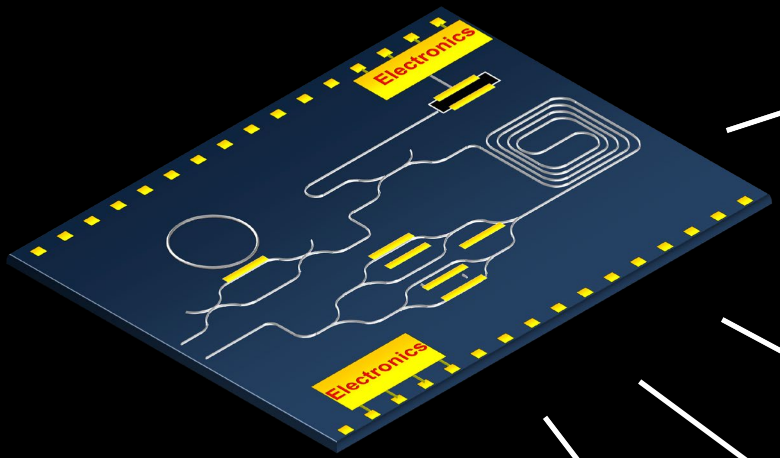
Microwave photonic signal processing



Microwave photonic signal processing



Material platforms



Low loss ✗

High power handling ✗

Compact ✓

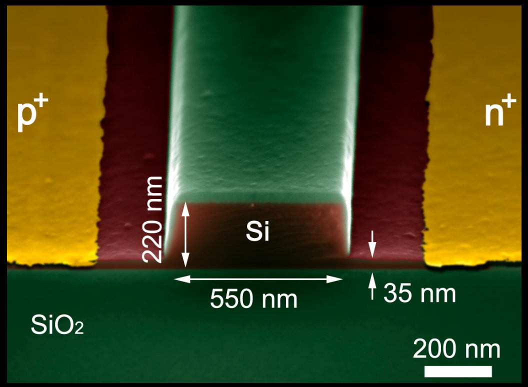
Lasers ✗

Linear modulation & detection ✗

Optical nonlinearities ✓

CMOS compatible ✓

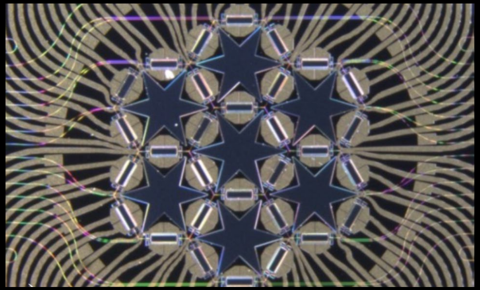
Standard silicon



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

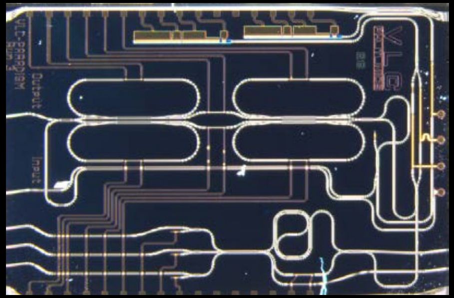
Material platforms

Silicon



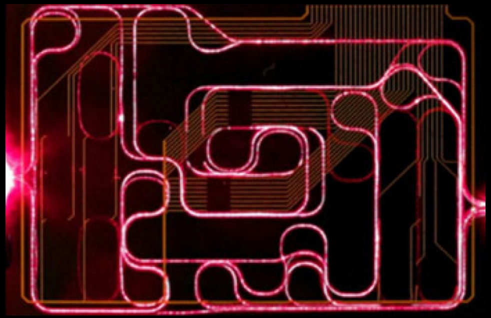
Universal signal processor
(UPV, Nat. Comm. 2017)

Indium phosphide



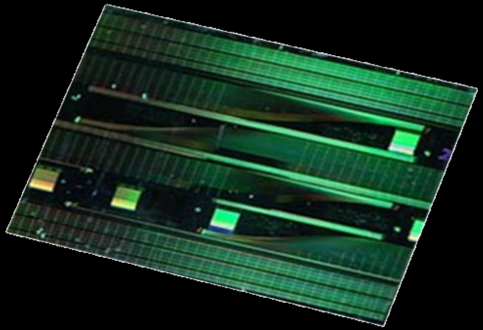
All integrated filter
(UPV, Nat. Photon. 2017)

Silicon nitride



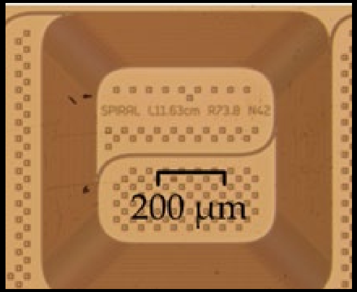
Channelizer, processor
(LioniX, JSTQE 2018)

Chalcogenide



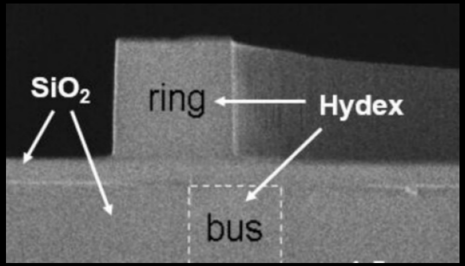
SBS tunable filter
(Sydney, Optica 2015)

Thick SOI



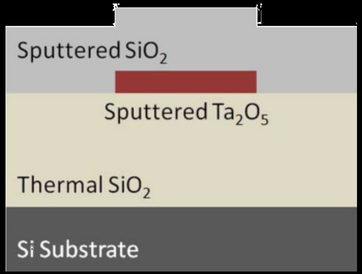
Instantaneous frequency measurement
(Sydney, Optica 2016)

Hydex

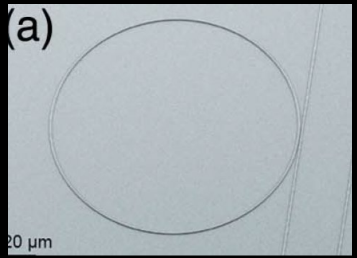


Comb-based RF photonics
(Swinburne, JSTQE 2018)

Emerging materials



Ta_2O_5 (UCSB, Optica 2017)



LNOI (Harvard, Optica 2017)

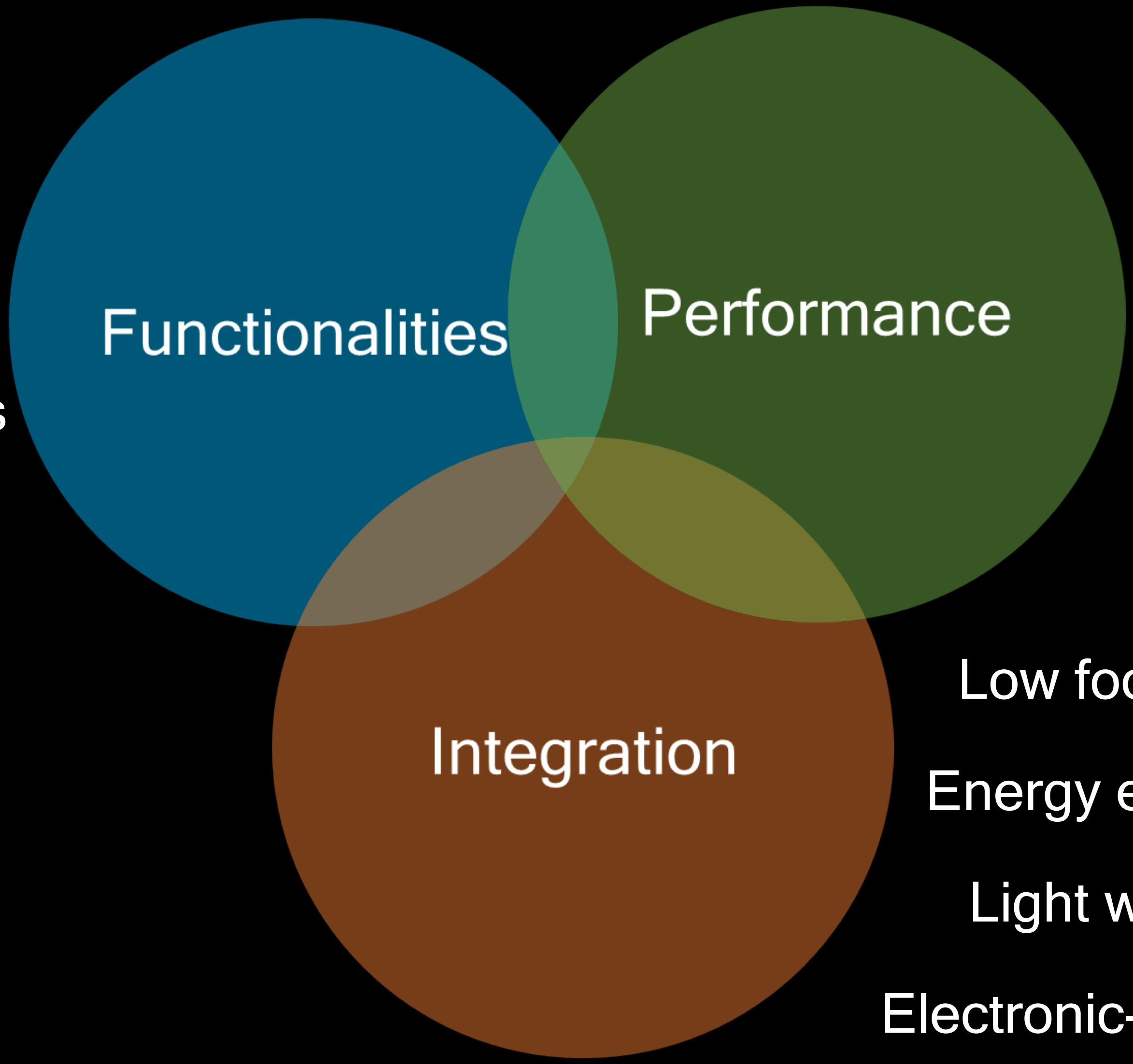
Three pillars of integrated MWP

Fast beamsteering

Low noise oscillator

Agile filters

Wideband converters



High link gain

Low noise figure

High dynamic range

Wide bandwidth

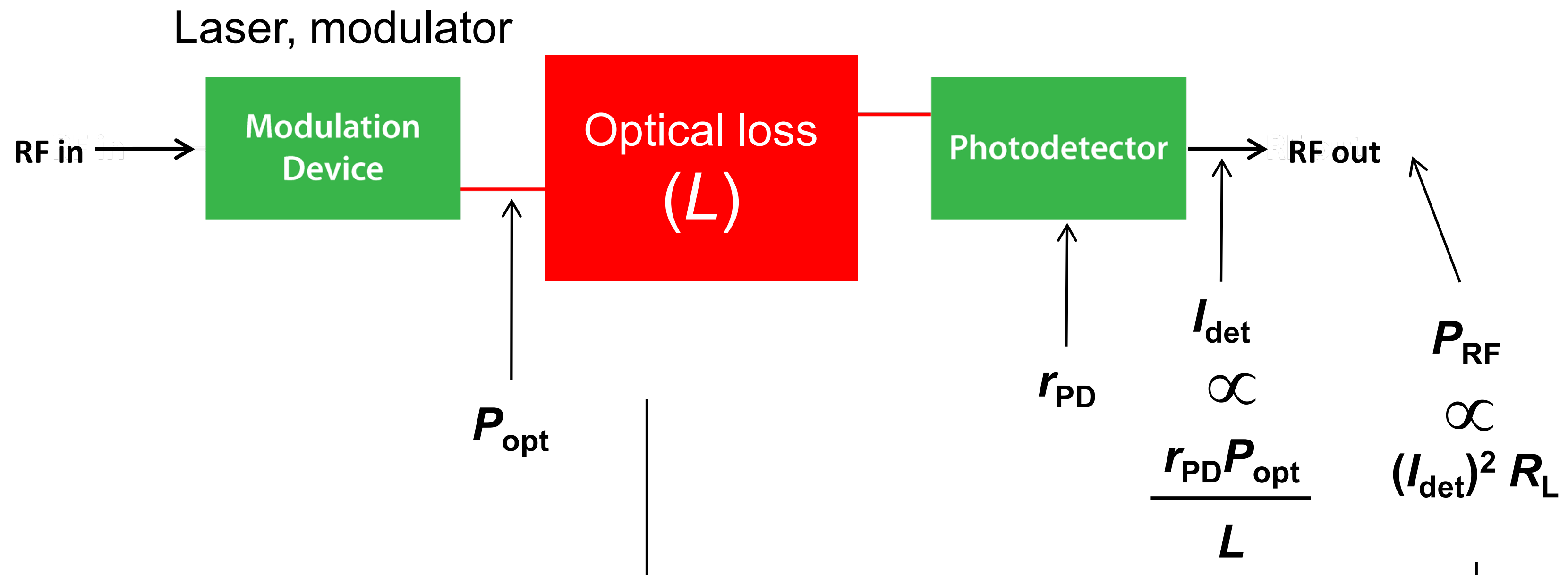
Low footprint

Energy efficient

Light weight

Electronic-photonic

Optical power vs. RF power



P_{opt} : optical power

I_{det} : detected photocurrent

r_{PD} : photodetector responsivity

P_{RF} : RF power

R_L : Load resistance (50 ohm)

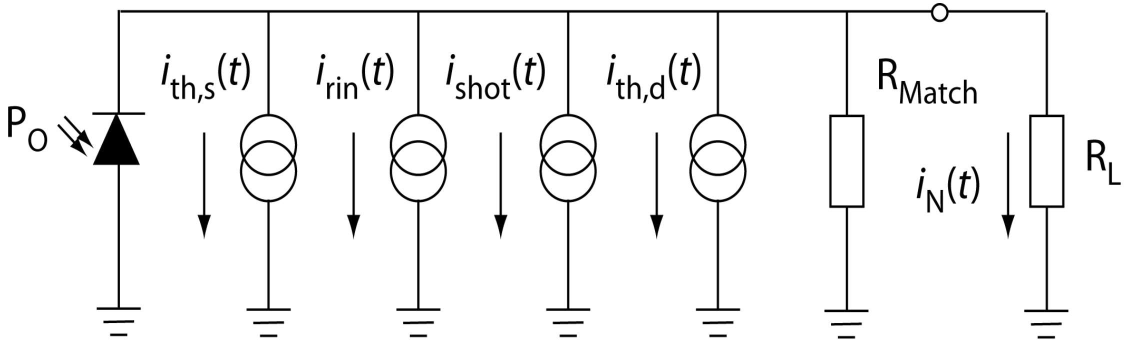
$$P_{RF} \propto \left(\frac{P_{opt}}{L}\right)^2$$

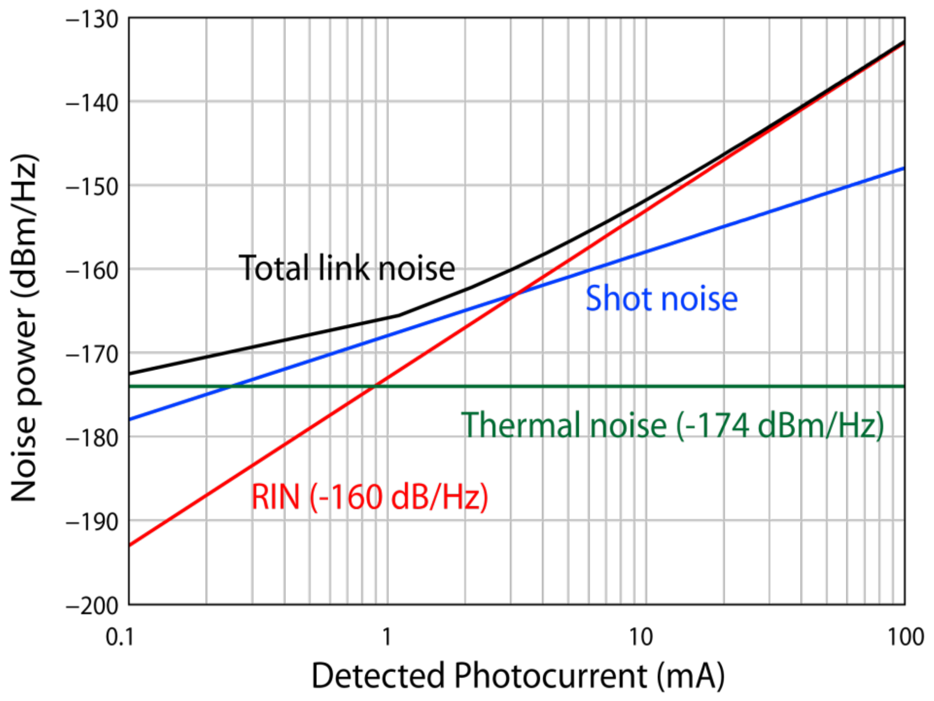
Minimizing optical loss is very important!

Link noise

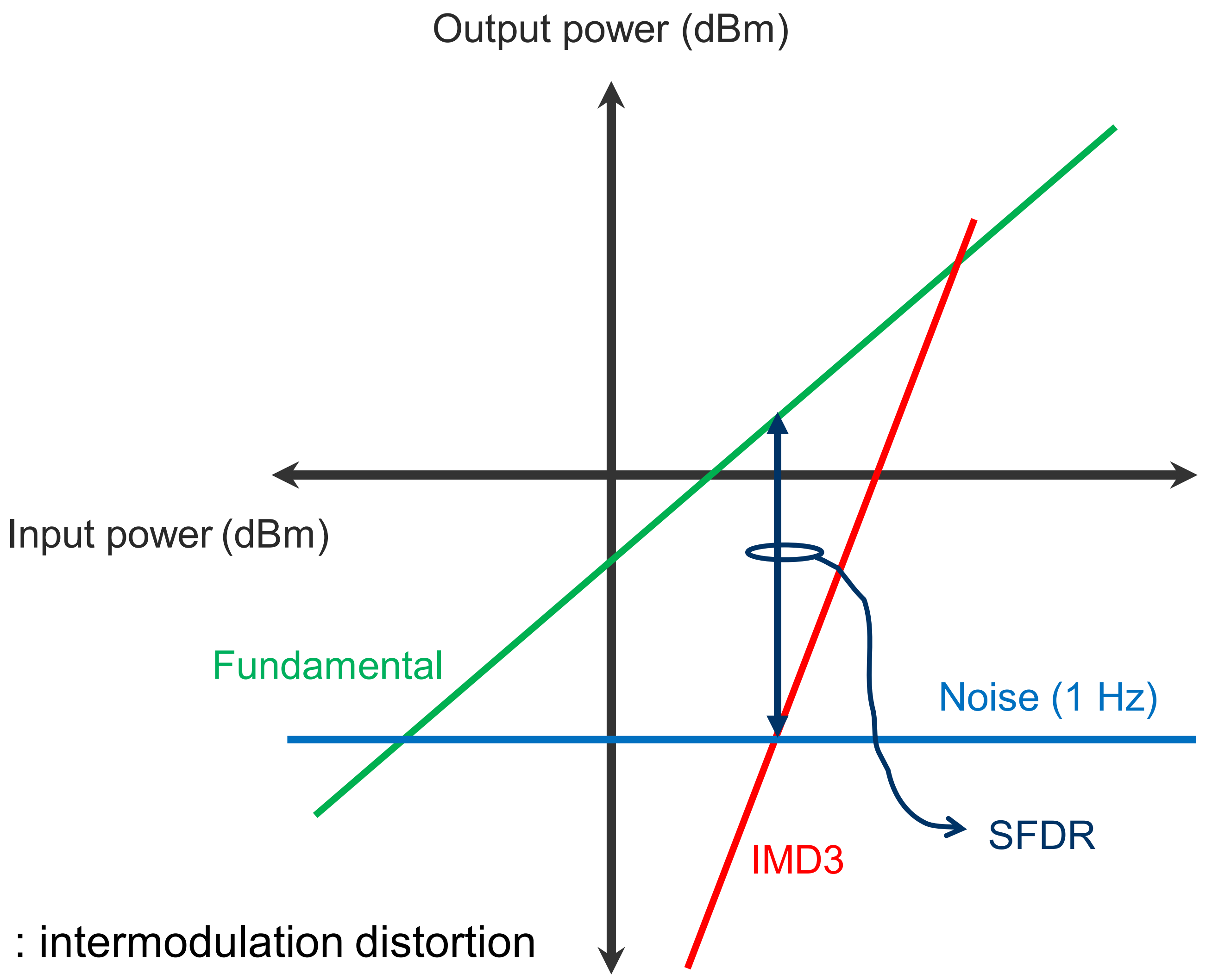
- Thermal noise
- Shot noise → proportional to optical power (P_{opt})
- Relative intensity noise (RIN) → proportional to (P_{opt})^2

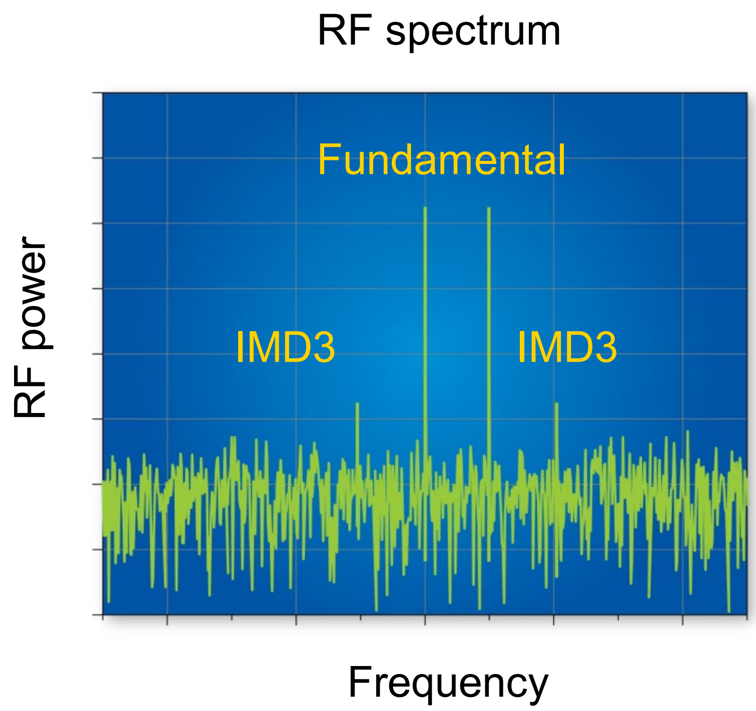
Noise modeled as current sources





Spurious-free dynamic range (SFDR)

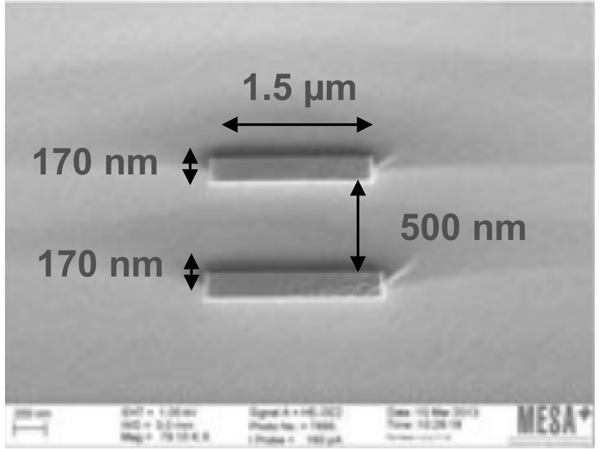




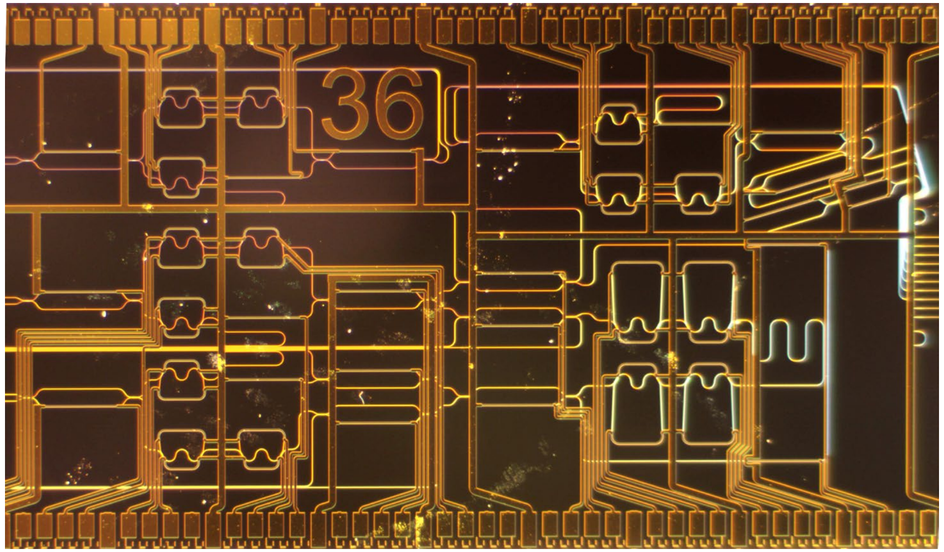
IMD : intermodulation distortion

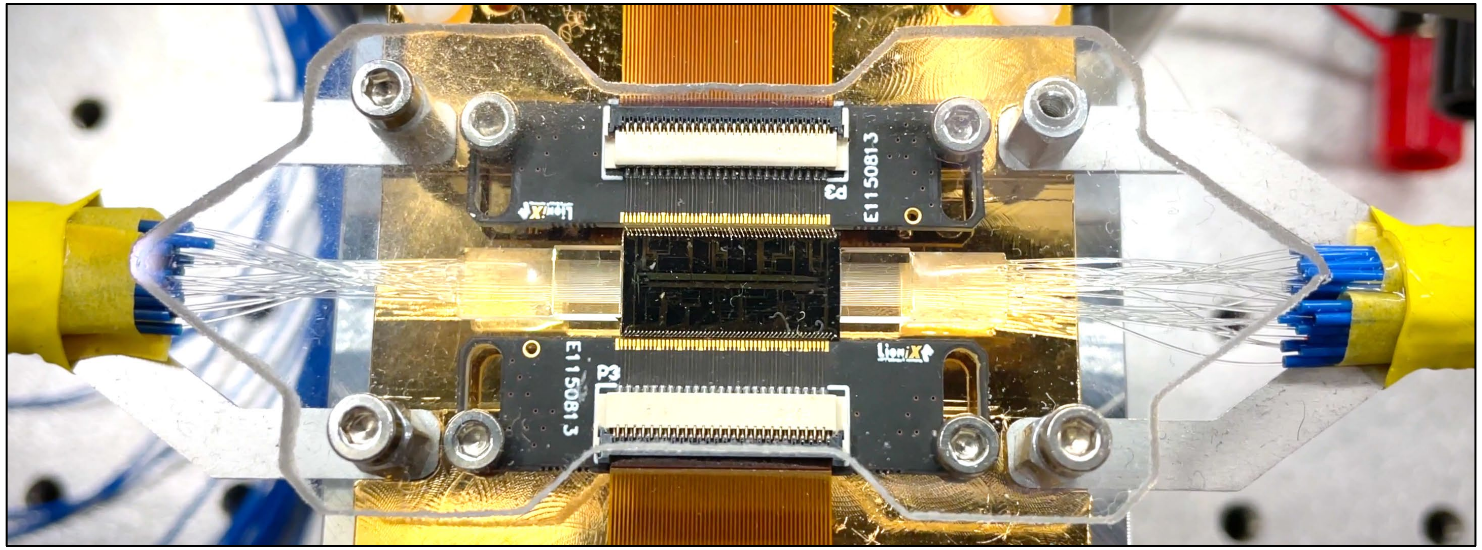
SFDR : spurious-free dynamic range

Material: silicon nitride



- Cross section: ~ 1 µm x 1.5 µm
- Propagation loss: ~ 0.1 dB/cm (ring Q ~ 1 Million)
- Bend radius ~ 75-100 µm
- Coupling loss ~1 dB/facet (spot-size converter to SMF)
- TPA and FCA free
- Thermo –optic tuning, or PZT actuators
- High-complexity circuits, assembly, and packaging

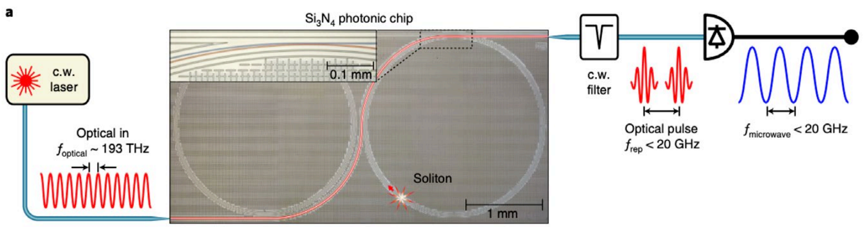




Microwave Photonic functionalities

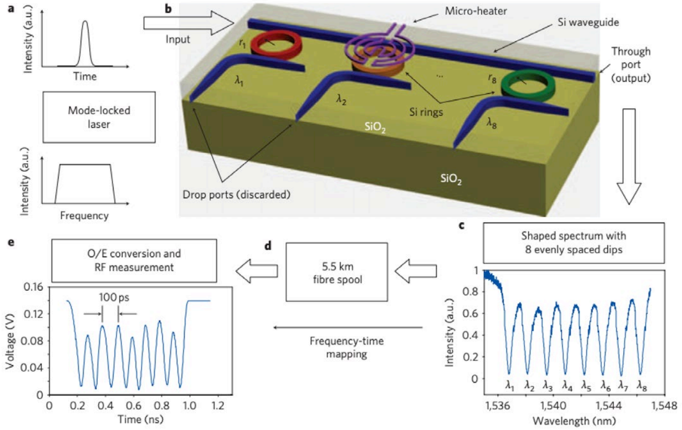
Signal Generation

Microwave tone



J. Liu et al., *Nat. Photon., 2020*

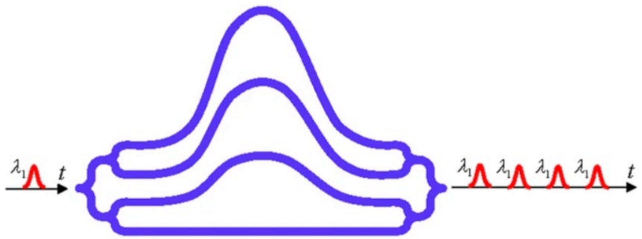
RF waveform



M. Khan et al., *Nat. Photon., 2010*

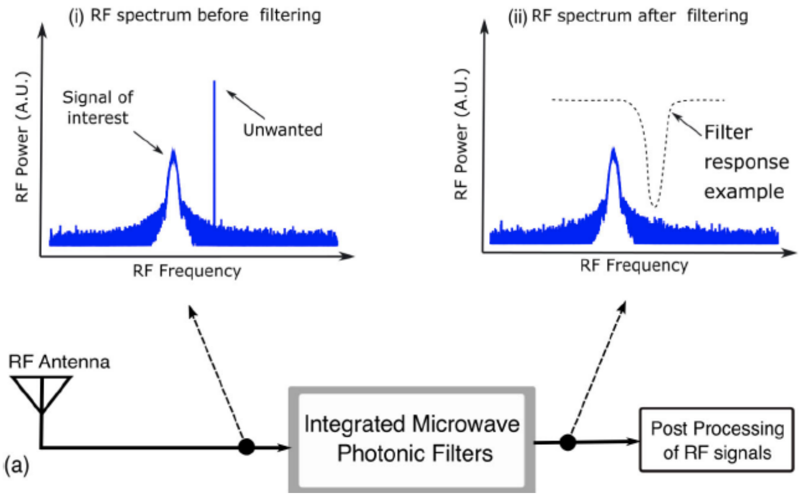
Signal processing

Tunable delay line



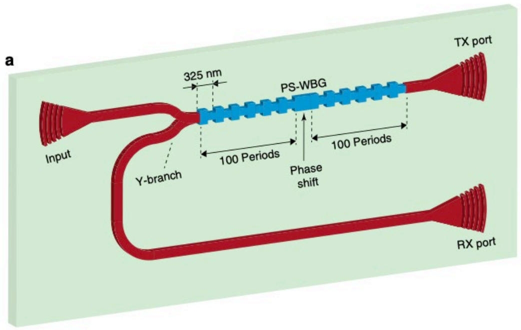
J. Wang et al., *Sci. Rep., 2016*

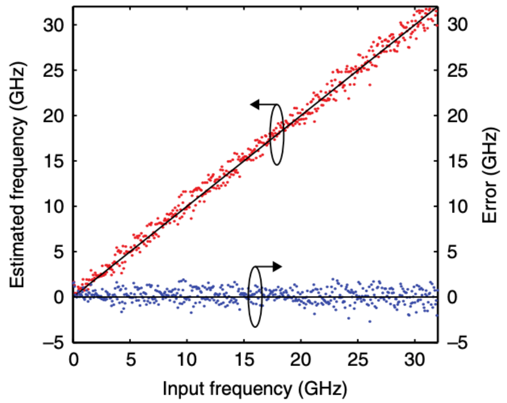
Filtering



Y. Liu et al., *Adv. Opt. Photon., 2020*

Signal measurement

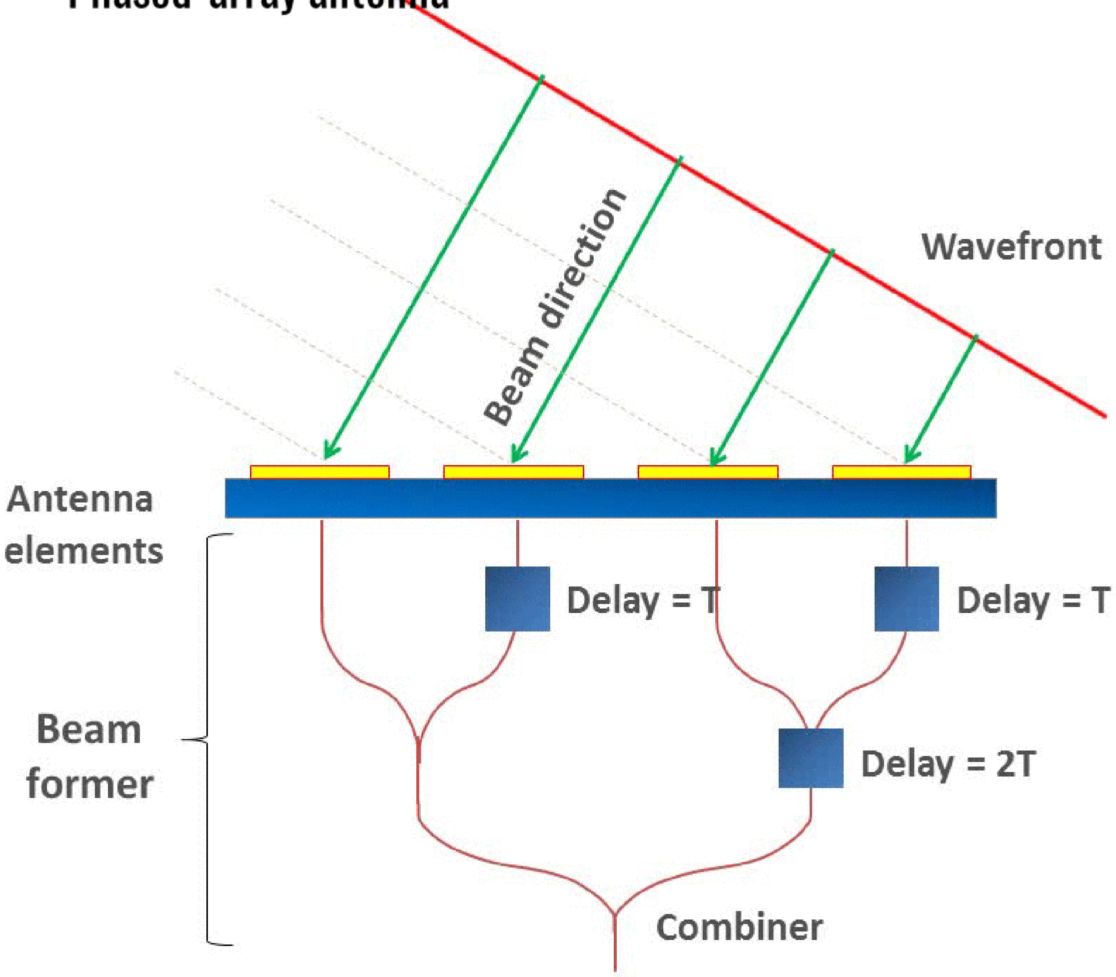




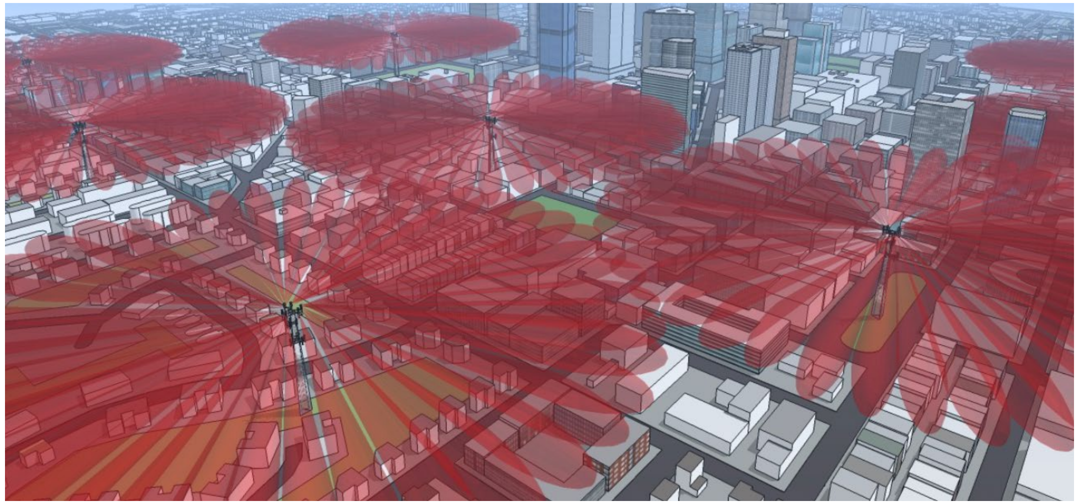
M. Burla et al., *Nat. Comm., 2016*

Beamforming

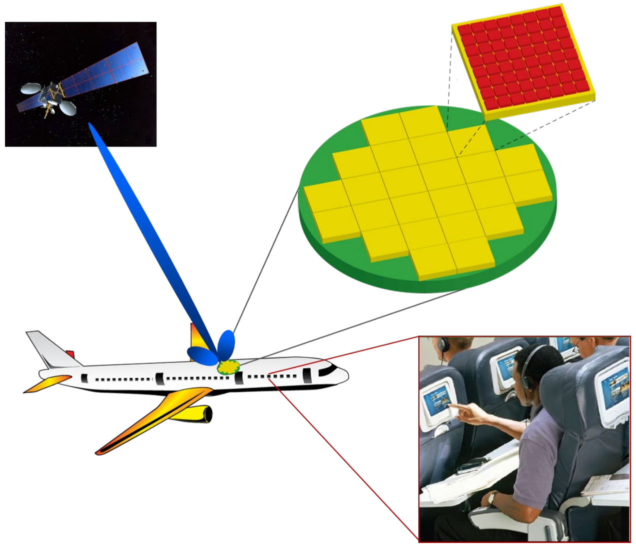
Phased-array antenna



5G/6G wireless



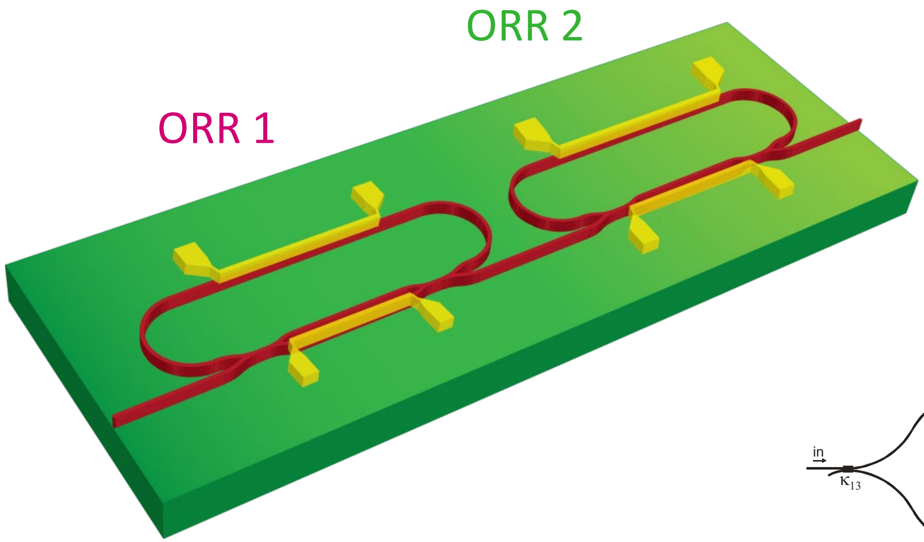
Satellite communications

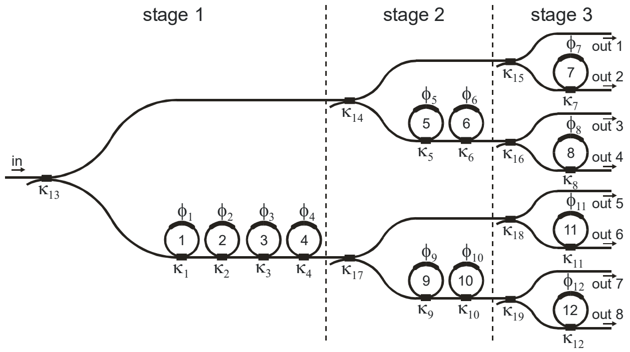


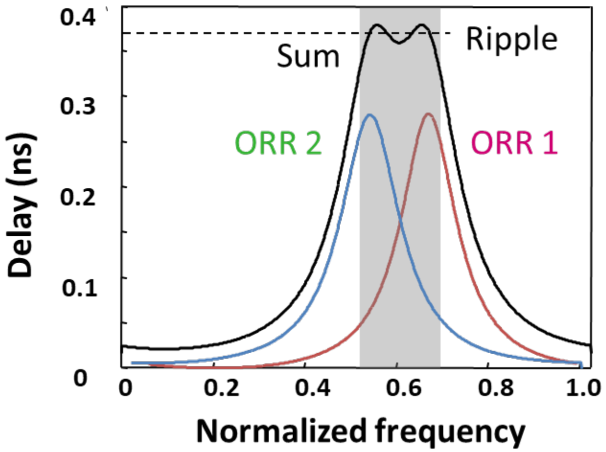
Radio astronomy

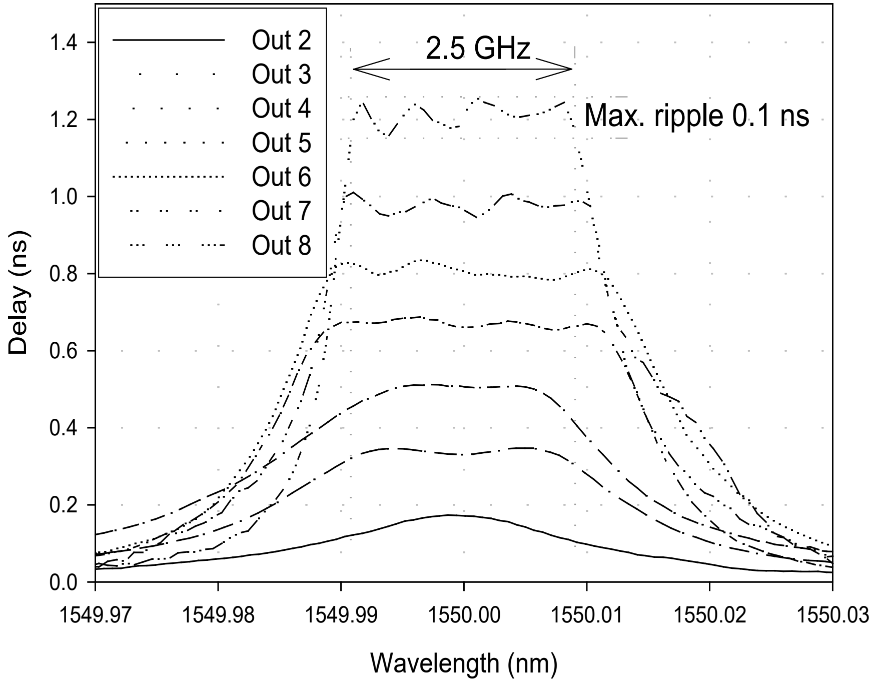
Cascaded ring resonators for broadband delay

- Single ORR provides tunable delay, but it is band limited
- Trade-off between maximum delay and delay bandwidth
- Solution→ cascade more than one ORRs





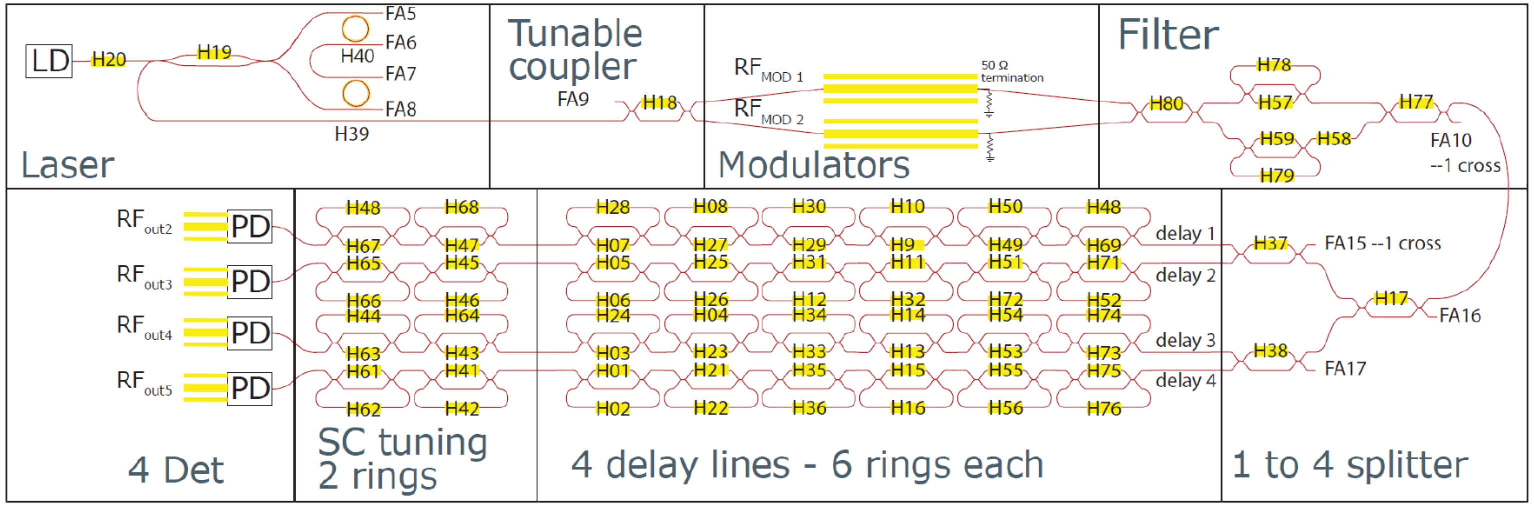


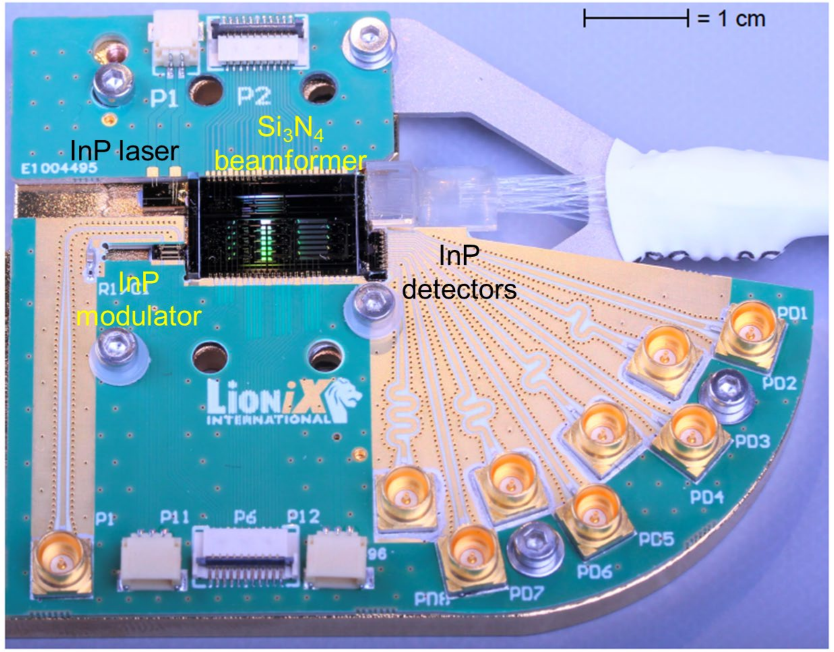


- More ORRs cascaded → more bandwidth but more ripple
- Trade-off between bandwidth , the number of ORR and the delay ripple

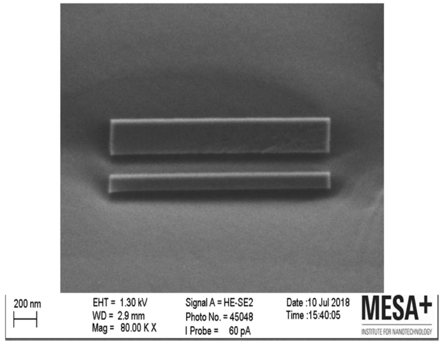
Zhuang et al., *IEEE Photon. Technol. Lett., 19(15)*, 2007.

Components for integrated optical beamformer

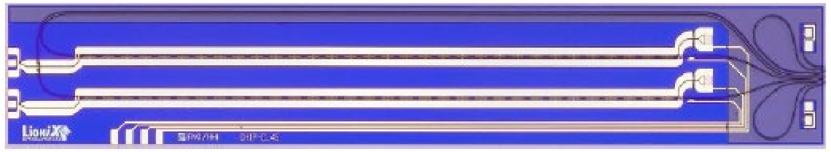




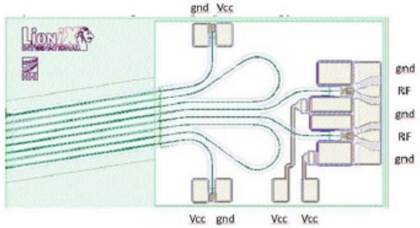
Asymmetric double-stripe (ADS) waveguide (0.1 dB/cm)



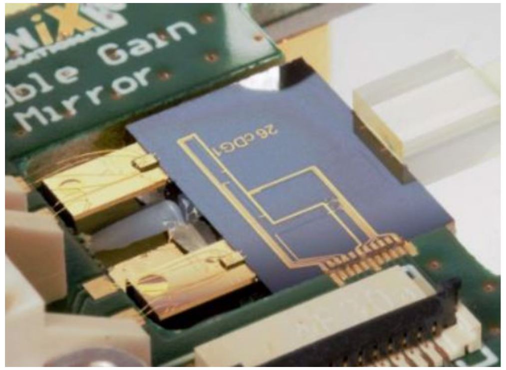
InP modulators (30 GHz, 3V Vpi)



InP detectors (40 GHz, 0.8 A/W)



Dual-gain on-chip laser (100 mW, -170 dB/Hz RIN)



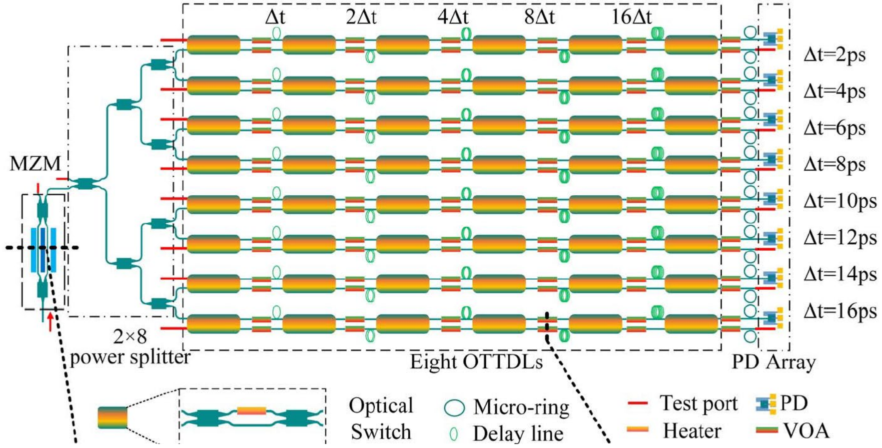
Silicon integrated beamformer

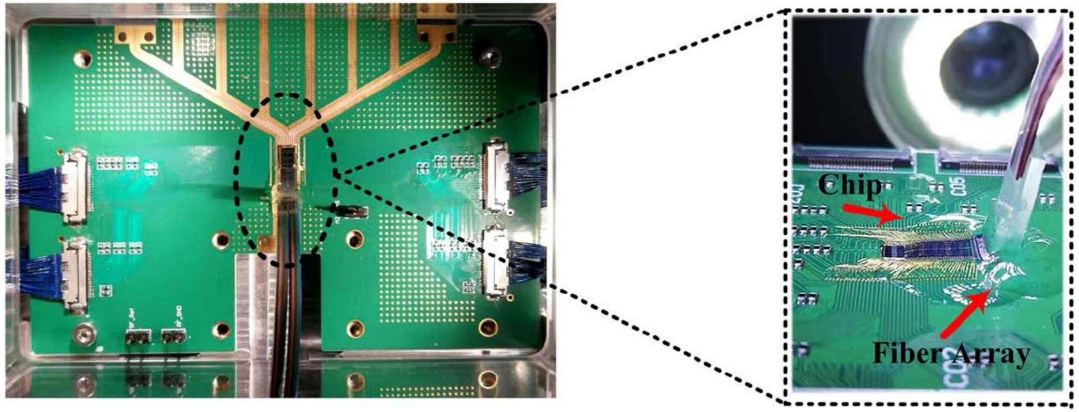
- 8-channel beamformer with integrated MZMs, switched delays, PDs
- 10 GHz instantaneous bandwidth (8-18 GHz)
- Total insertion loss 35 dB
- Noise figure 70 dB

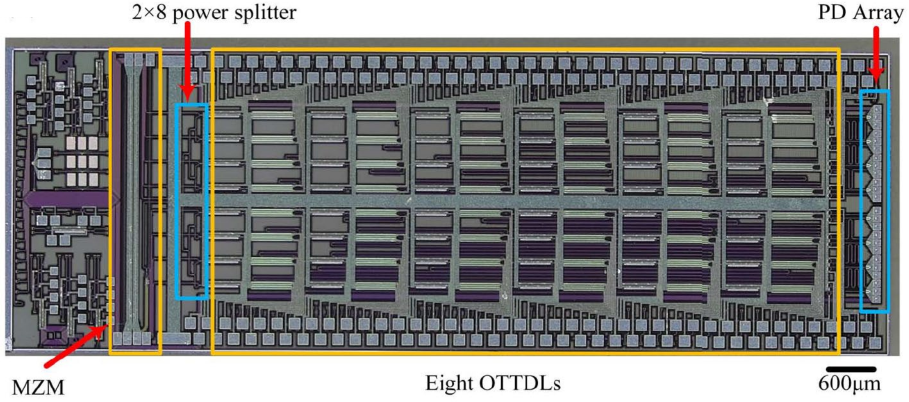
1162 Vol. 7, No. 9 / September 2020 / Optica Research Article
optica

Silicon integrated microwave photonic beamformer

CHEN ZHU, LIANGJUN LU,* WENSHENG SHAN, WEIHAN XU, GANGQIANG ZHOU, LINJIE ZHOU, AND JIANPING CHEN

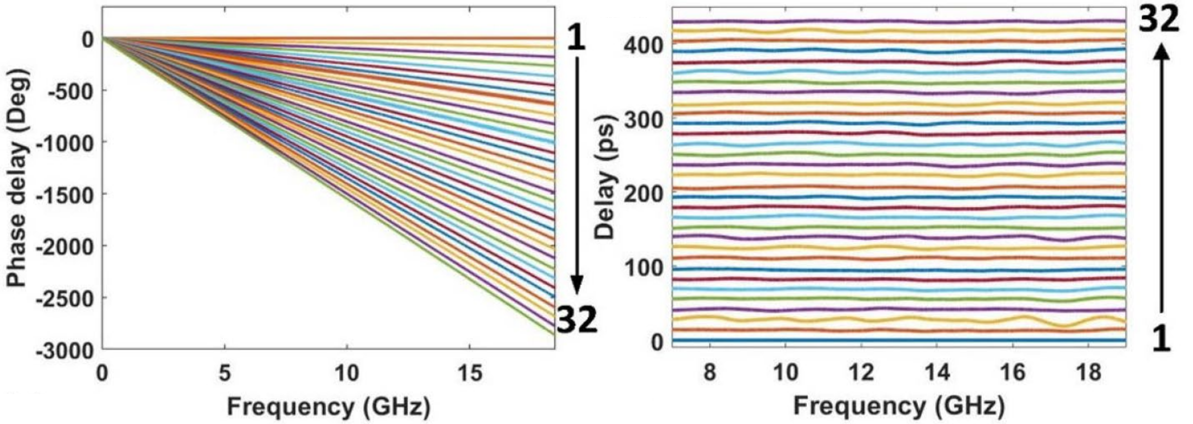






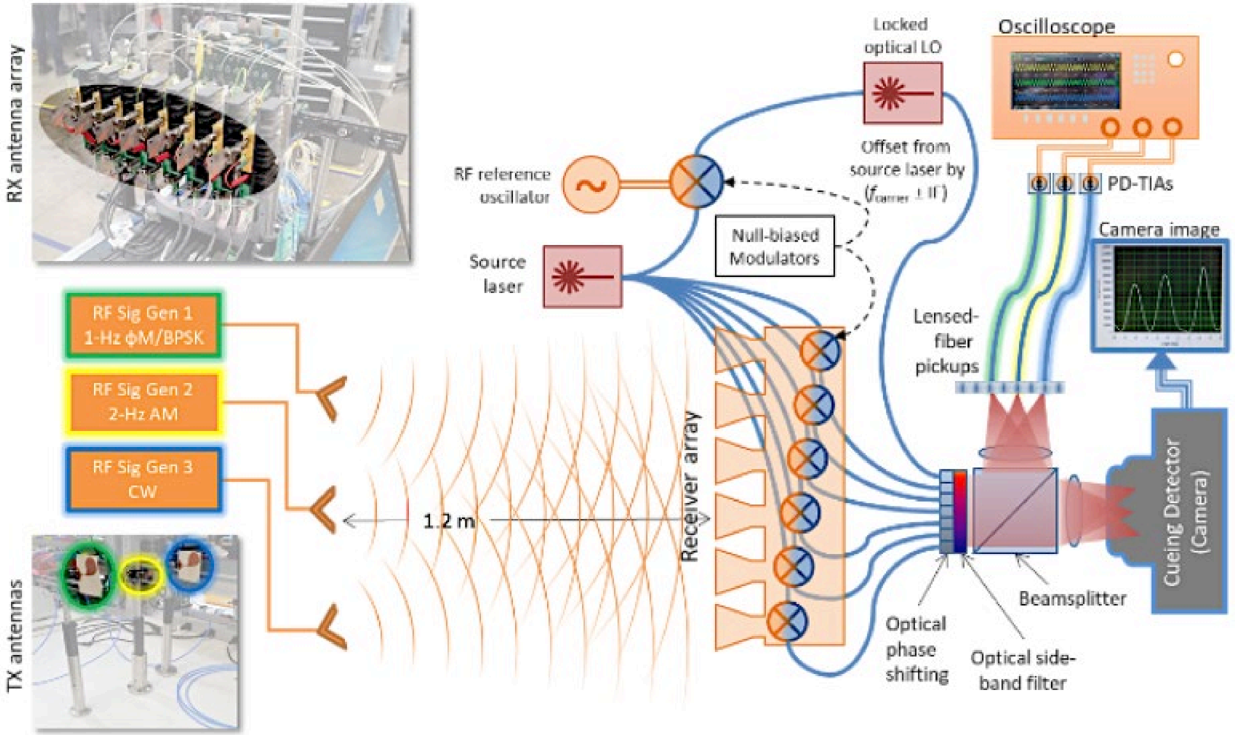
RF phase

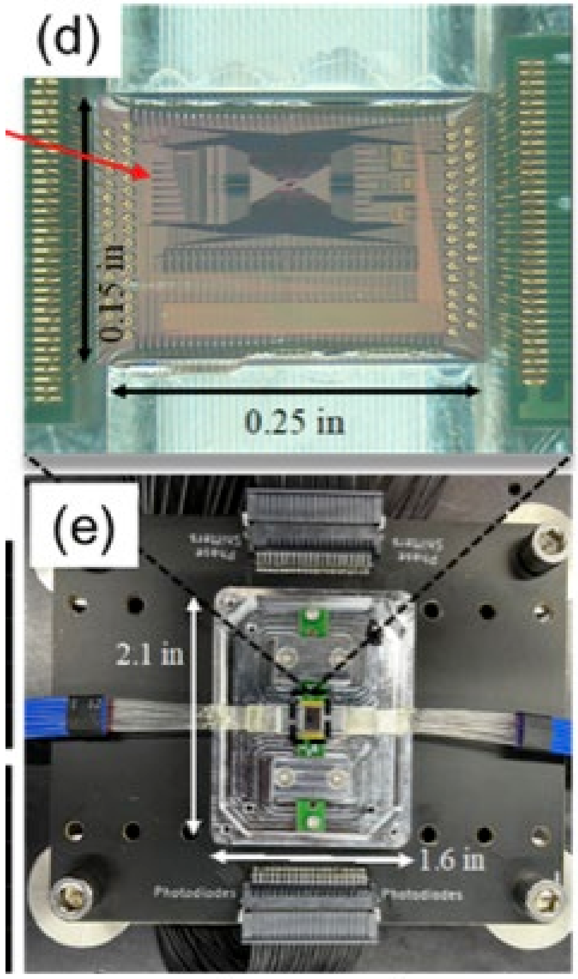
RF group delay



Multibeam phased array antenna

- Multi-band and multi-beam operation
- Operation the millimeter-wave (27 GHz)
- Noise figure 7 dB
- Power consumption: 100 W
- SFDR 100 dB.Hz$^{2/3}$



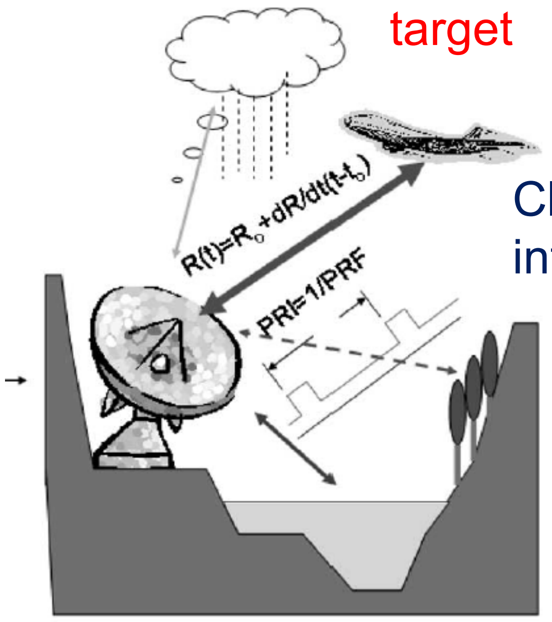


U Delaware, Dennis Prather's group
D. Prather, et al., W4J.4, OFC 2023.

Optically Upconverted, Spatially Coherent Phased-Array-Antenna Feed Networks for Beam-Space MIMO in 5G Cellular Communications,

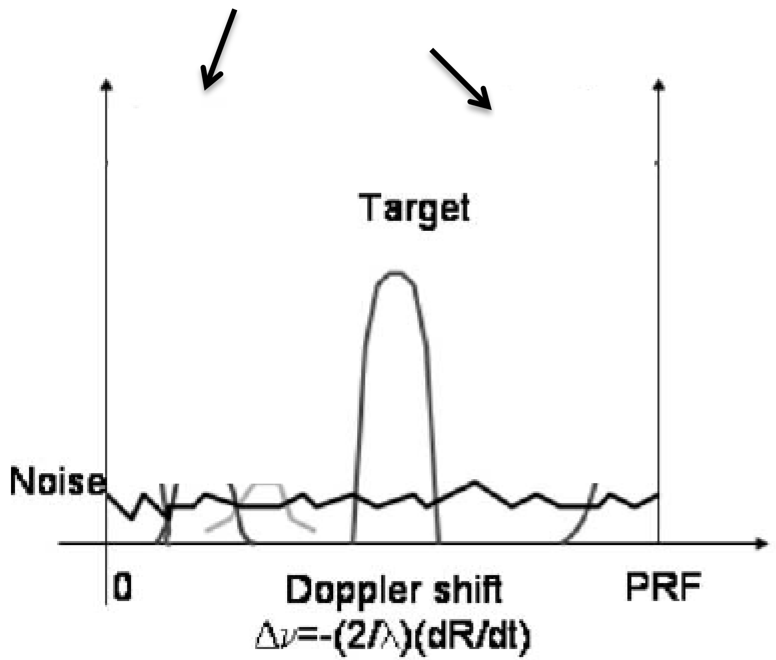
Microwave photonic filters

Radar



J. Capmany et al, JLT, 24, 201, 2006

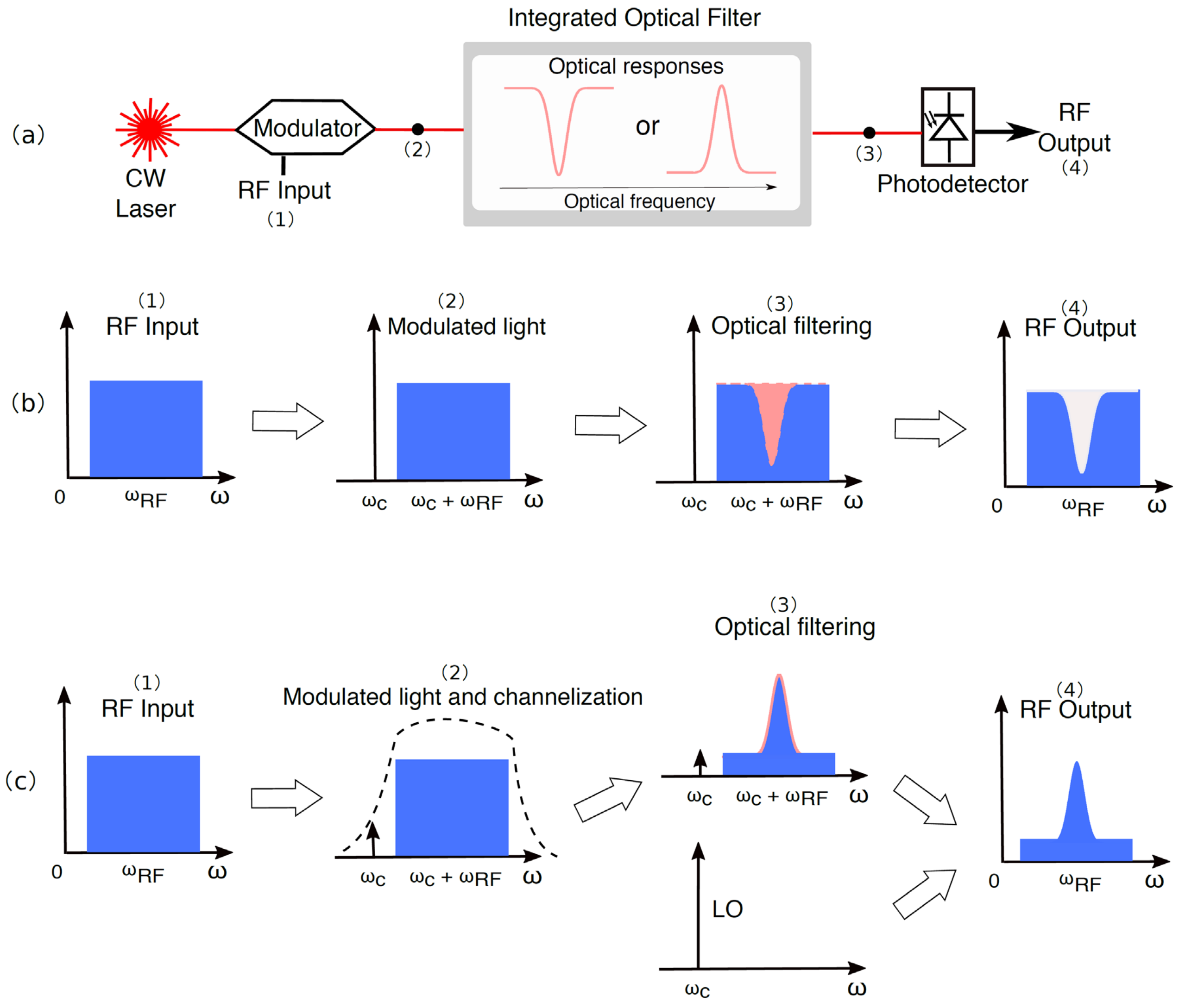
Strong interferers saturate receiver
(should be removed)



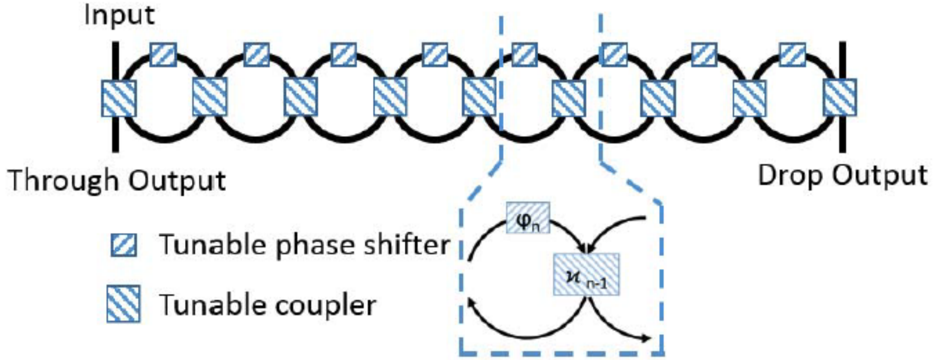
Requires: RF filters with high selectivity, widely tunable frequency, dynamically reconfigurable

Optical filter-based MWP filter

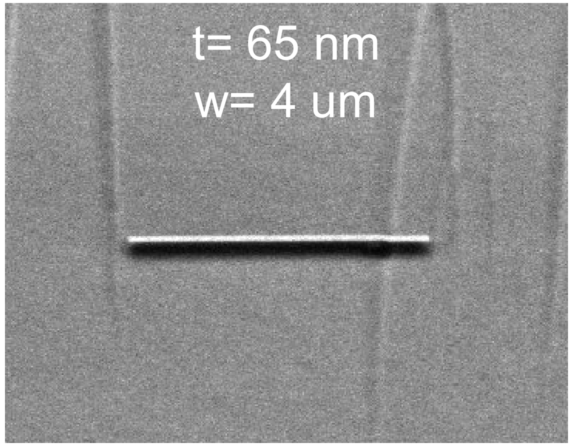
- Simplest way to make a filter: use single sideband modulation

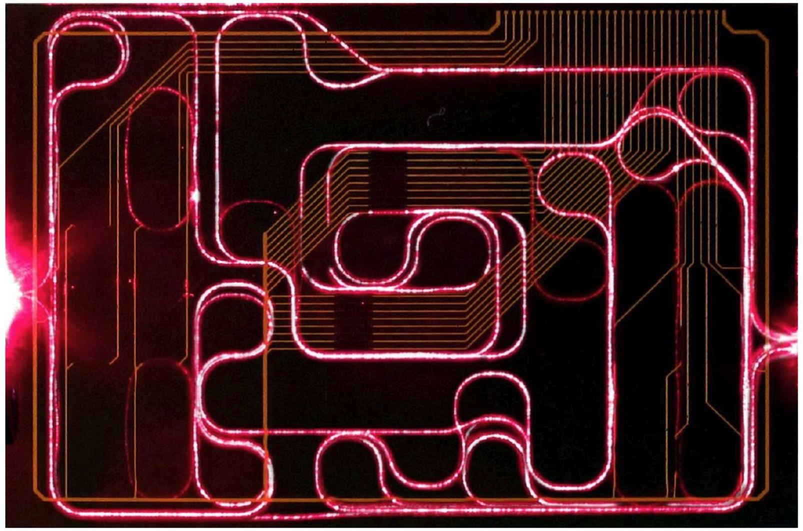


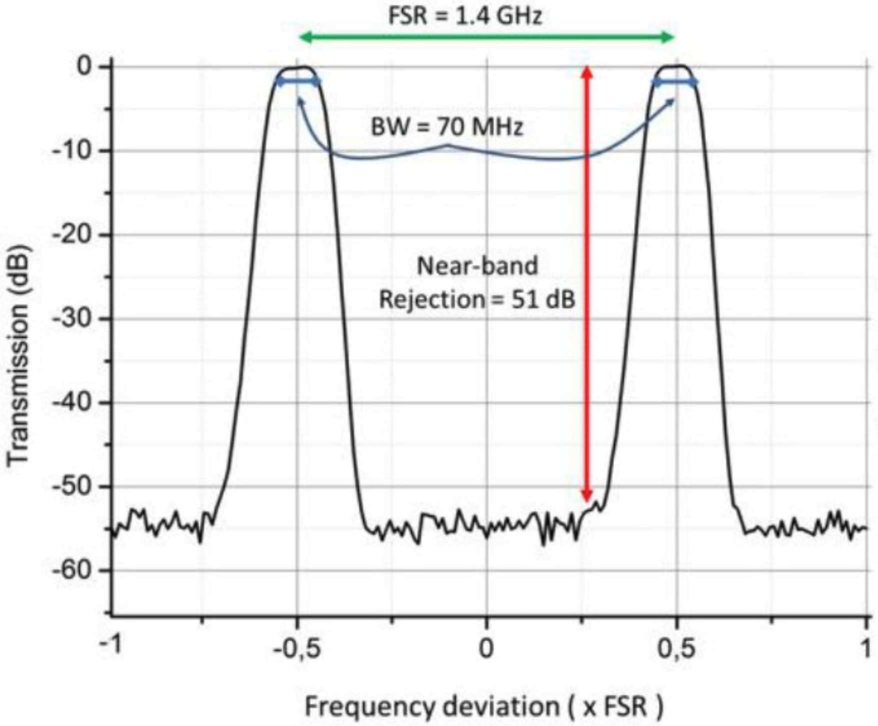
High resolution bandpass filter



Loss ~ 1.4 dB/m



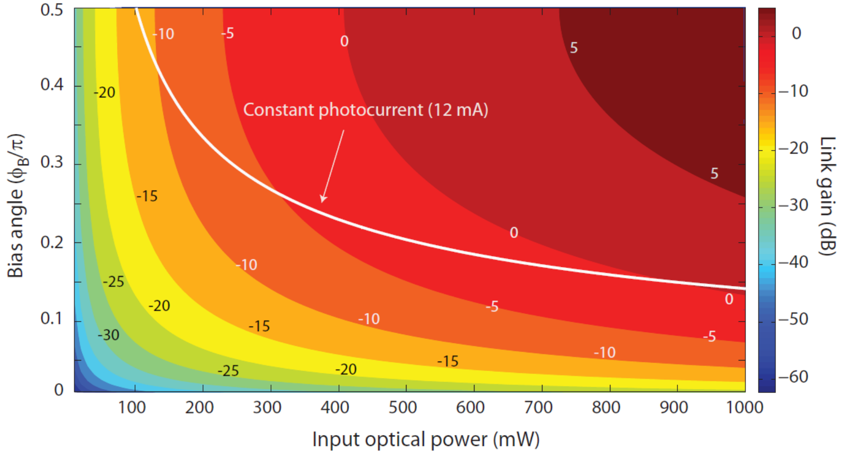




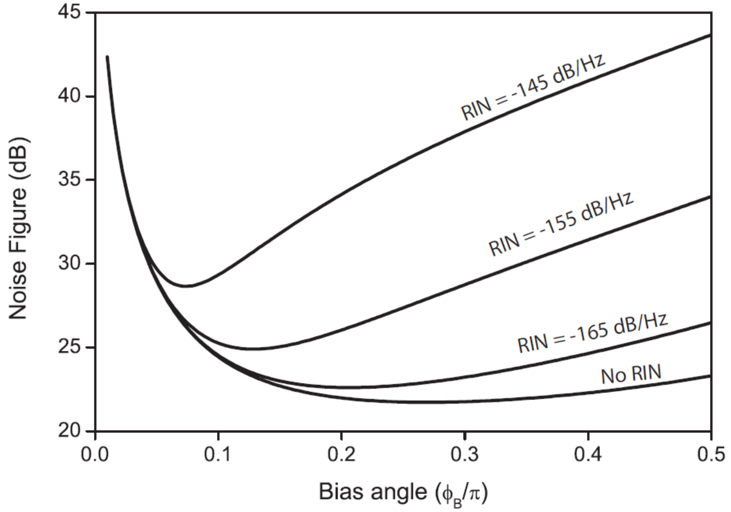
C. Taddei, et al "High-selectivity on-chip optical bandpass filter with sub-100-MHz flat-top and under-2 shape factor," IEEE Photonics Technol. Lett. 31 (2019)

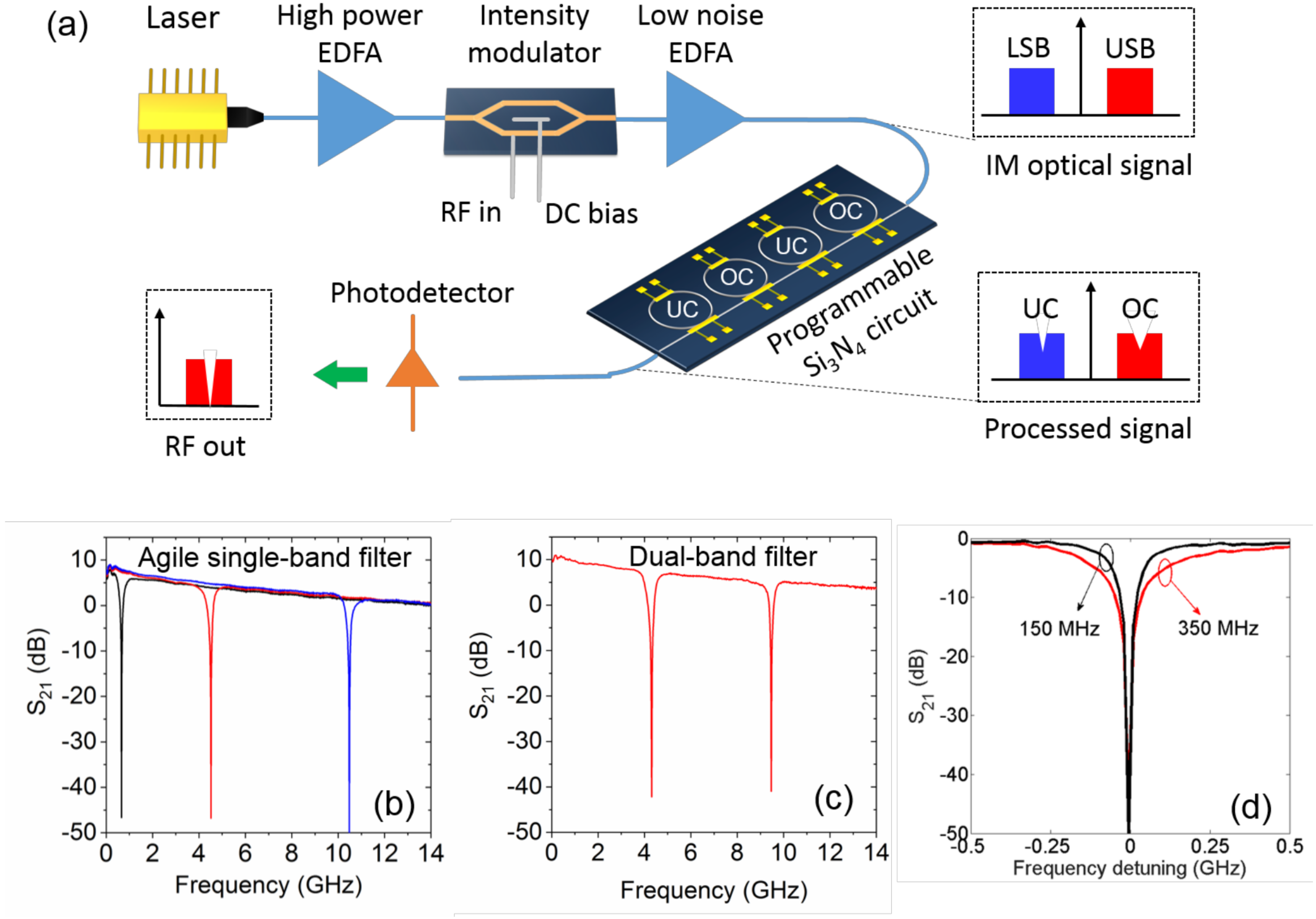
Low biasing + cancellation filter

Gain enhancement



Noise figure reduction





Y.Liu et al.,Optics Letters, *2017*

High performance MWP filter

nature communications

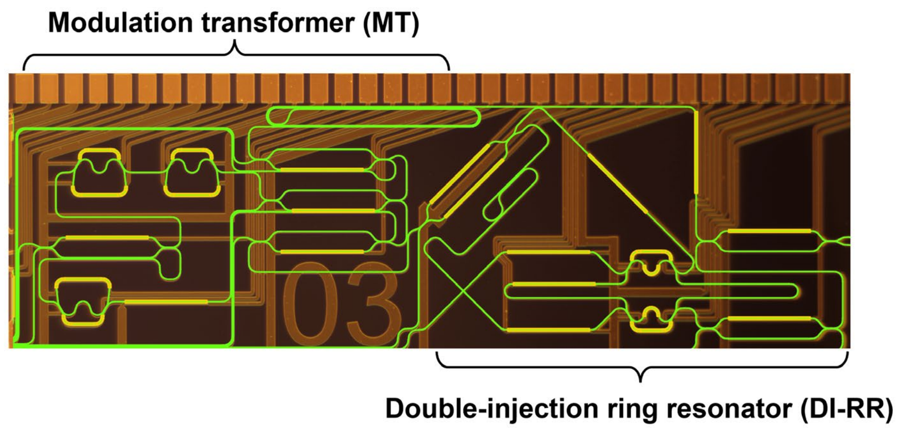
Article https://doi.org/10.1038/s41467-022-35485-x

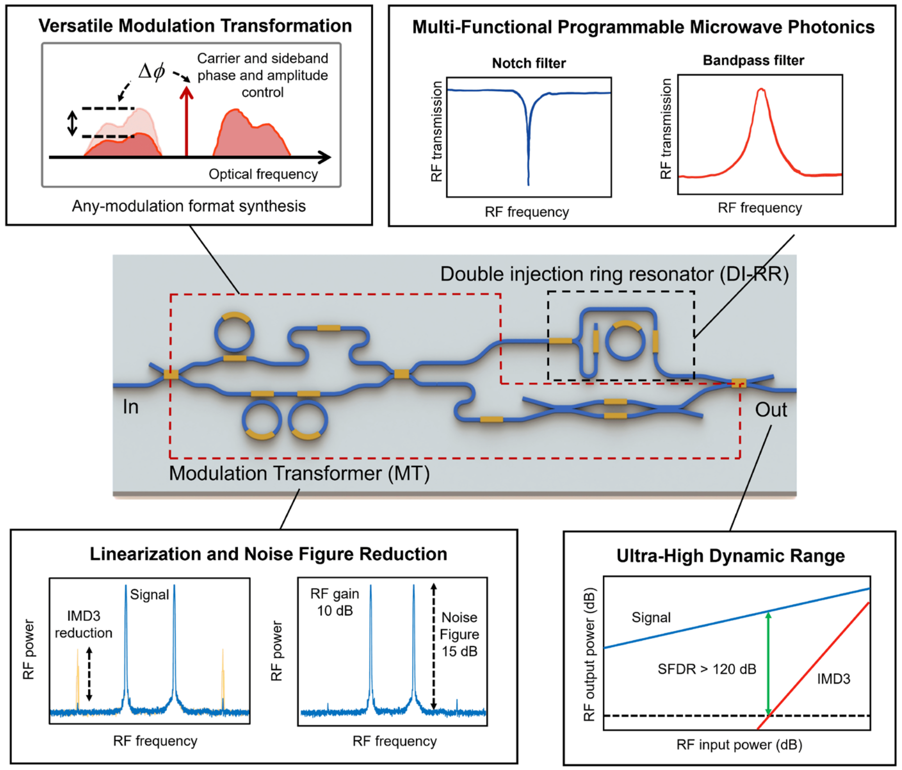
Ultrahigh dynamic range and low noise figure programmable integrated microwave photonic filter

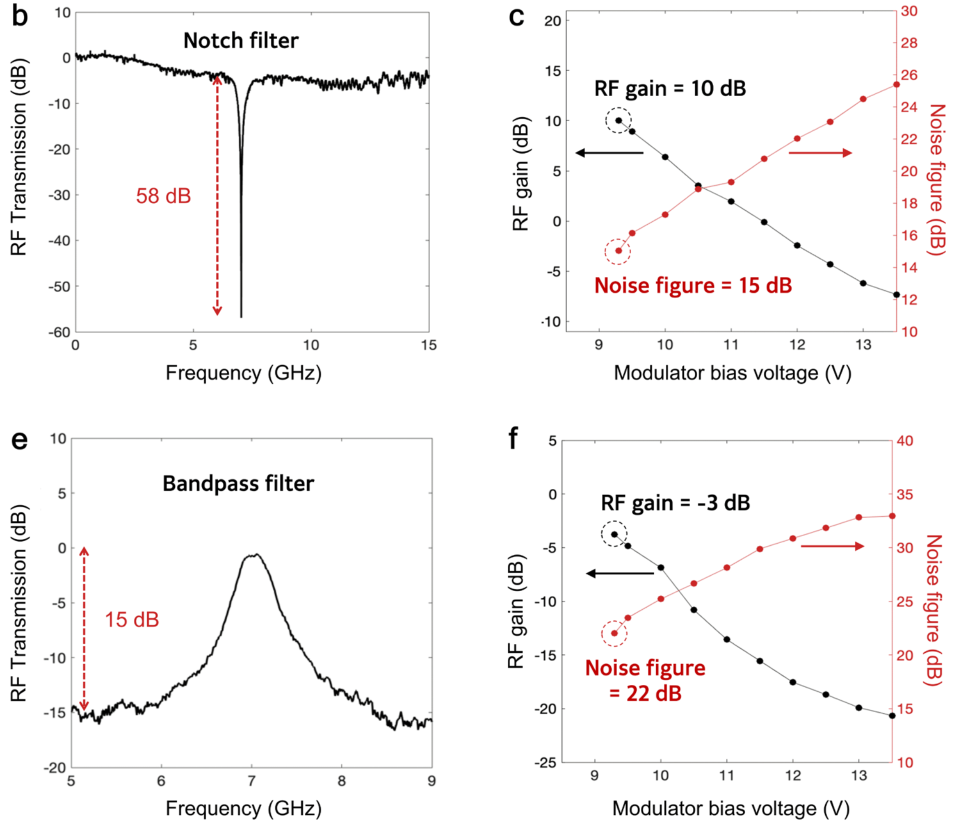
Received: 24 March 2022

Accepted: 1 December 2022

Okky Daulay[1,5], Gaojian Liu[1,2,5], Kaixuan Ye[1], Roel Botter[1], Yvan Klaver[1], Qinggui Tan[2], Hongxi Yu[2], Marcel Hoekman[3], Edwin Klein[3], Chris Roeloffzen[3], Yang Liu[4] & David Marpaung[1]

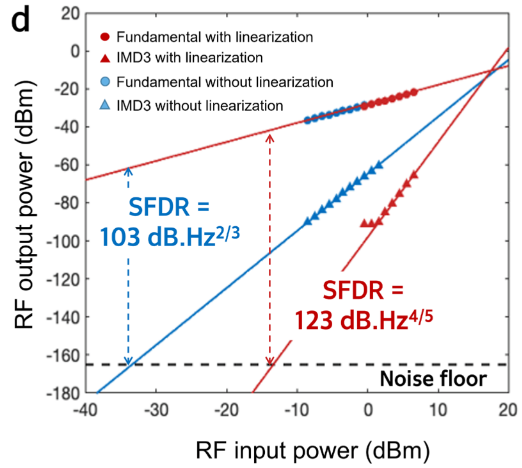




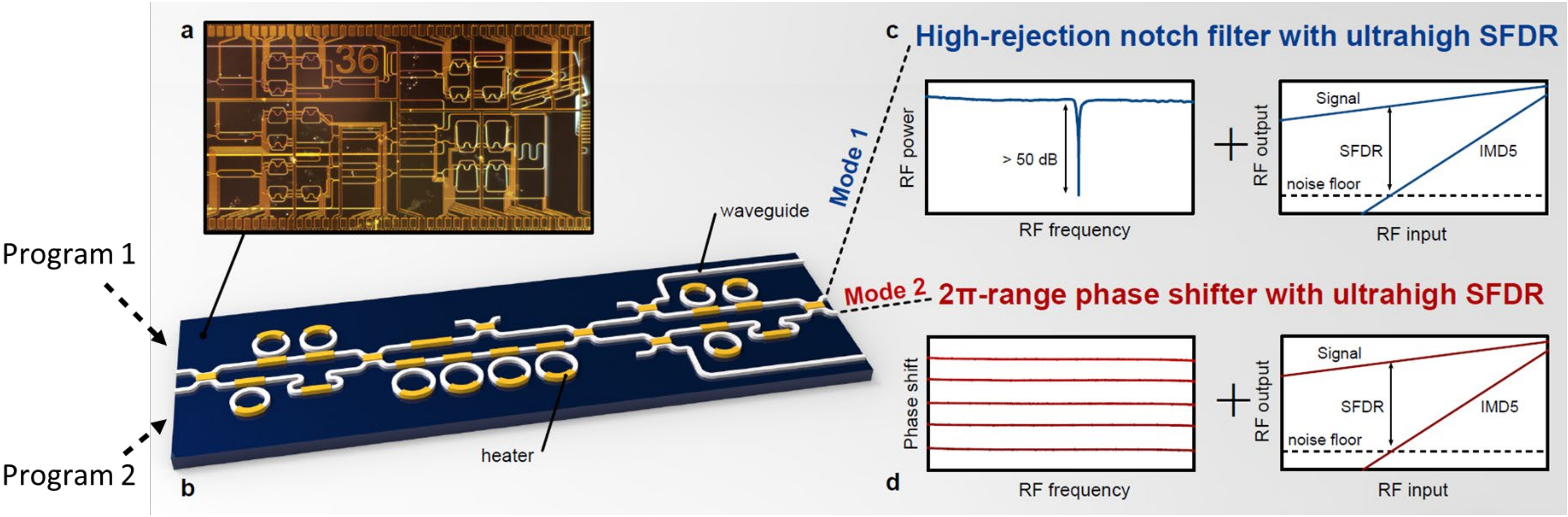


Record values:

- RF Gain **10 dB**
- Noise figure: **15 dB**
- Dynamic Range: **123.6 dB.Hz**
- Programmable with **6 functionalities**



Switchable integrated microwave photonic circuit

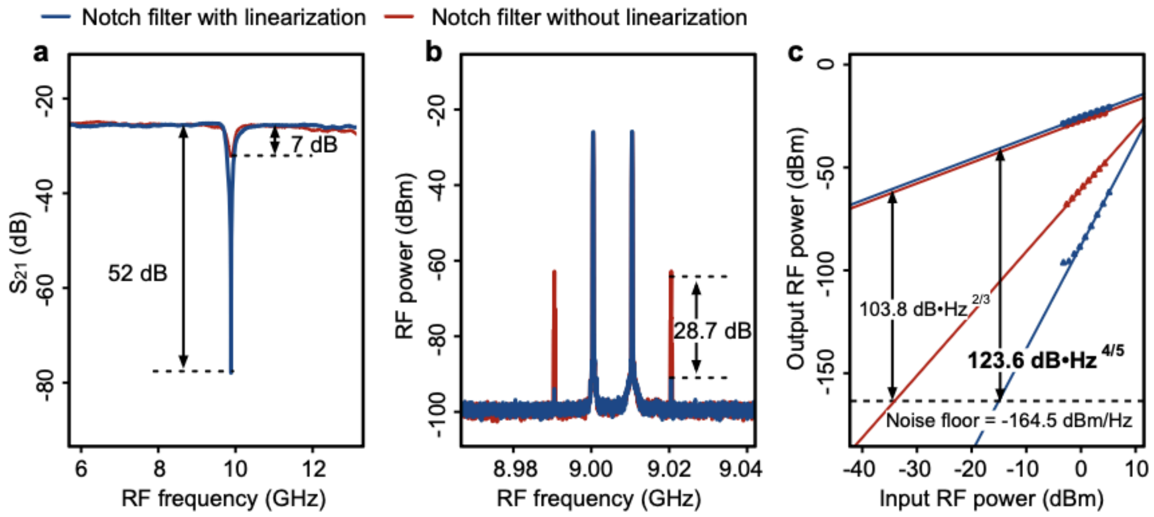


- Multifunction circuit: switchable notch filter and the phase shifter
- High dynamic range for each function

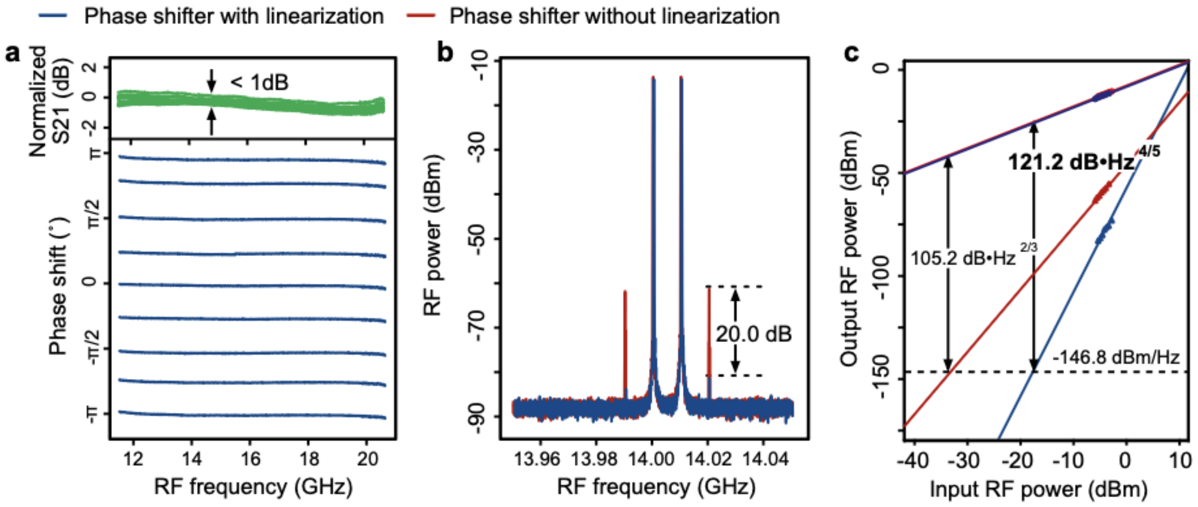
G. Liu, K. Ye, et al, Linearized integrated microwave photonic circuit for filtering and phase shifting, **APL Photonics** (2023)

Linearized notch filter/phase shifter

Linearized notch filter



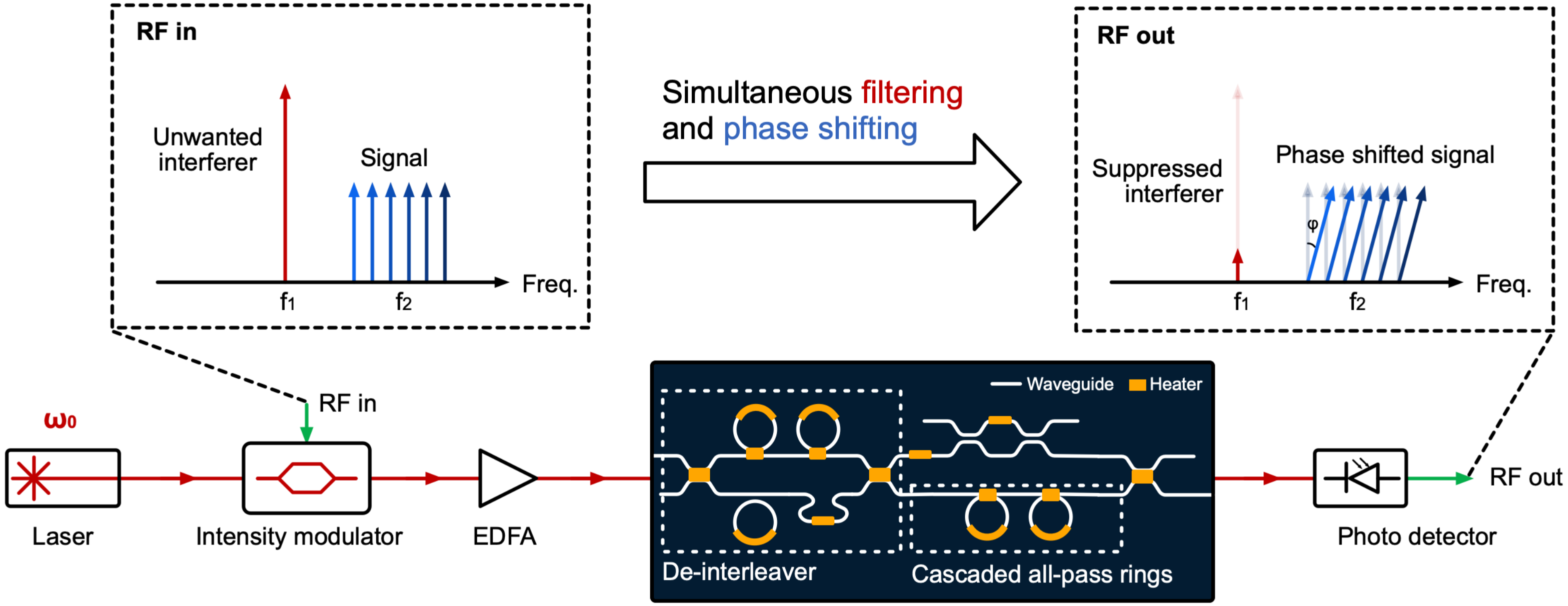
Linearized phase shifter



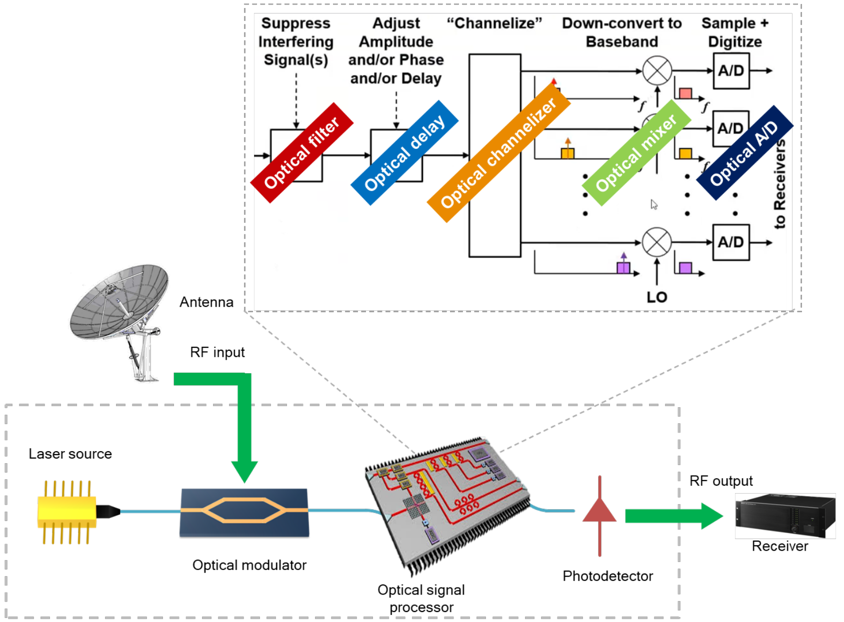
- Over 120 dB·Hz$^{4/5}$ spurious-free dynamic range in both the notch filter and the phase shifter
- High-extinction notch filtering over 6-16 GHz and 2π continuously tunable phase shifting over 12-20 GHz frequencies

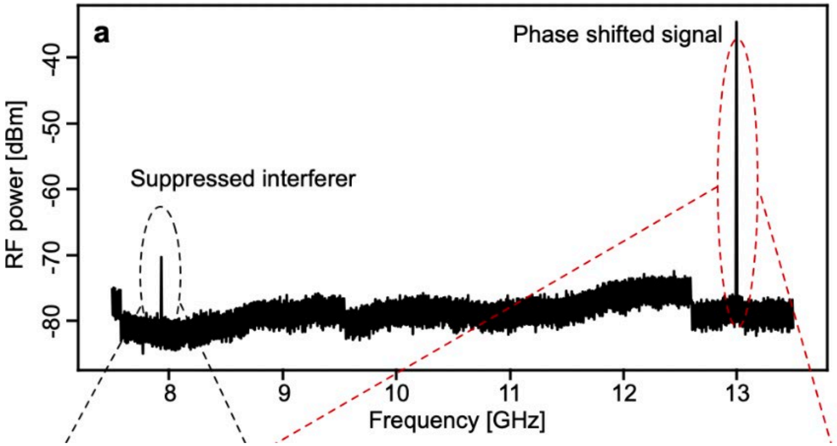
G. Liu, K. Ye, et al, Linearized integrated microwave photonic circuit for filtering and phase shifting, **APL Photonics** (2023)

Simultaneous-cascaded functionalities



Simultaneous multi-function integrated RF photonic front-end





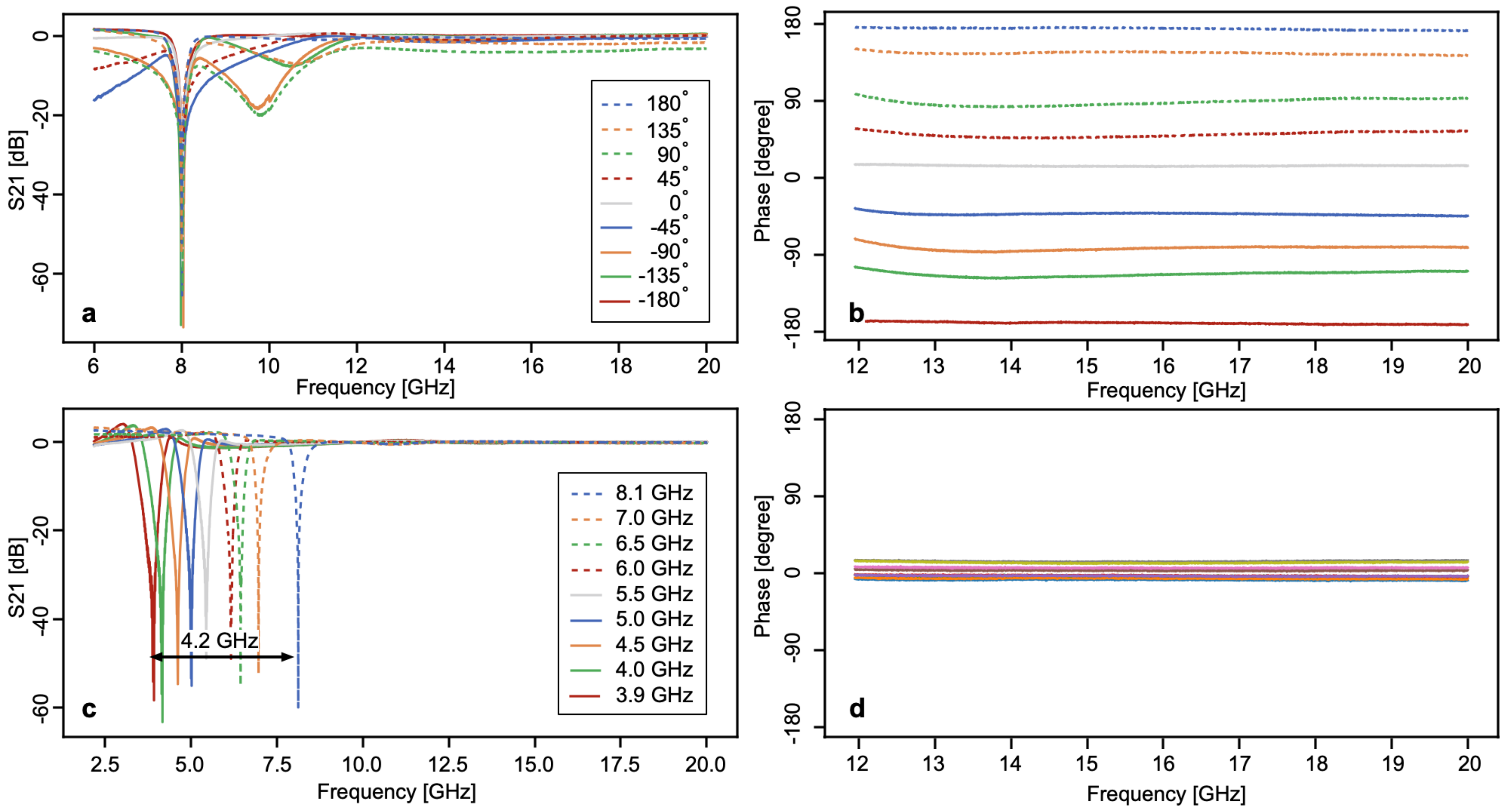
- Two functions performed simultaneously: filter + phase shifter, filter + tunable delay
- Each function has high performance

K. Ye, et al, CLEO 2023

Simultaneous notch filtering with phase shifting

Fixed notch frequency at different phase shifts

Fixed phase shift at different notch frequencies

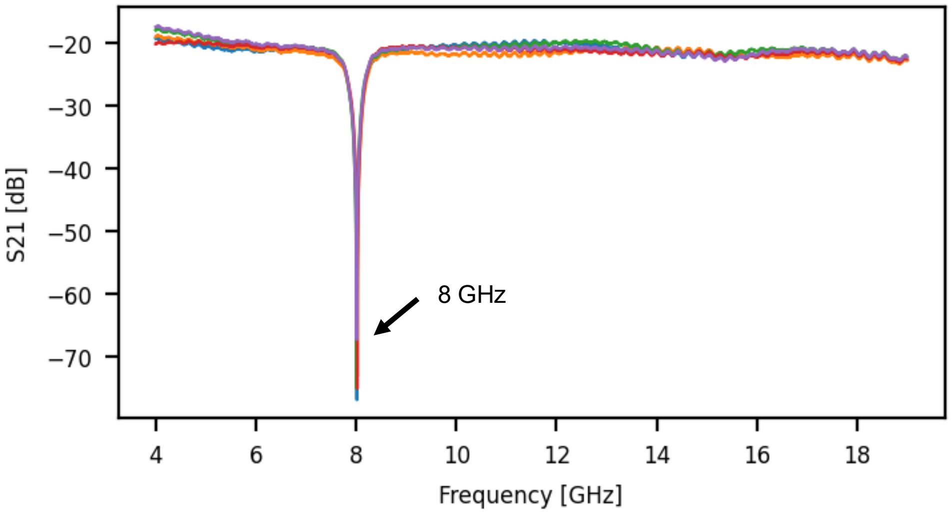


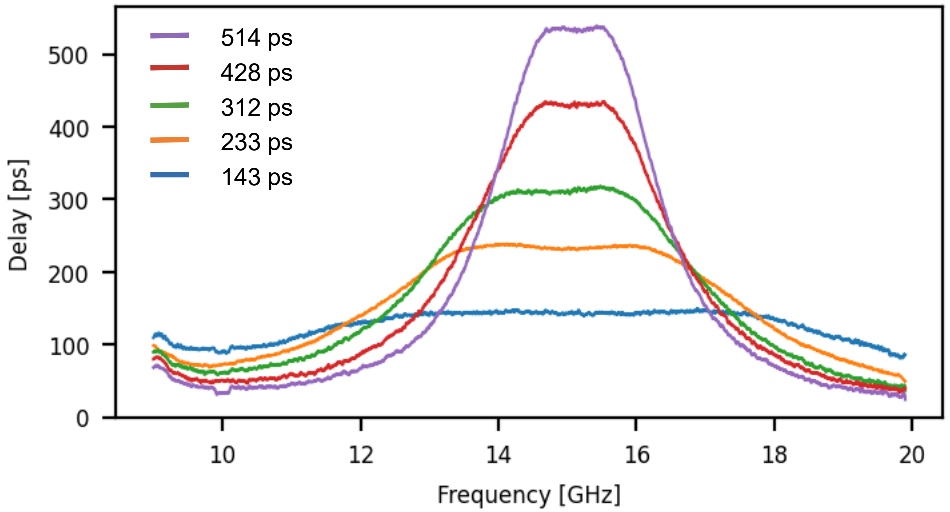
- Larger than 50 dB notch filtering tunable from 3.9 to 8.1 GHz and tunable 2π phase shift from 12 to 20 GHz
- Optimized noise figure of 24 dB and a SFDR of 105 dB·Hz$^{2/3}$

K. Ye, et al, CLEO 2023

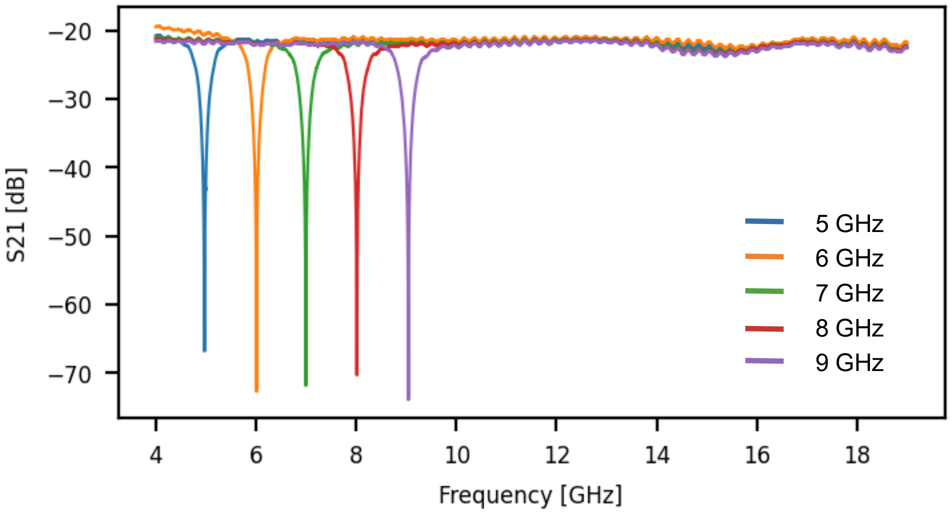
Simultaneous notch filtering with true time delay

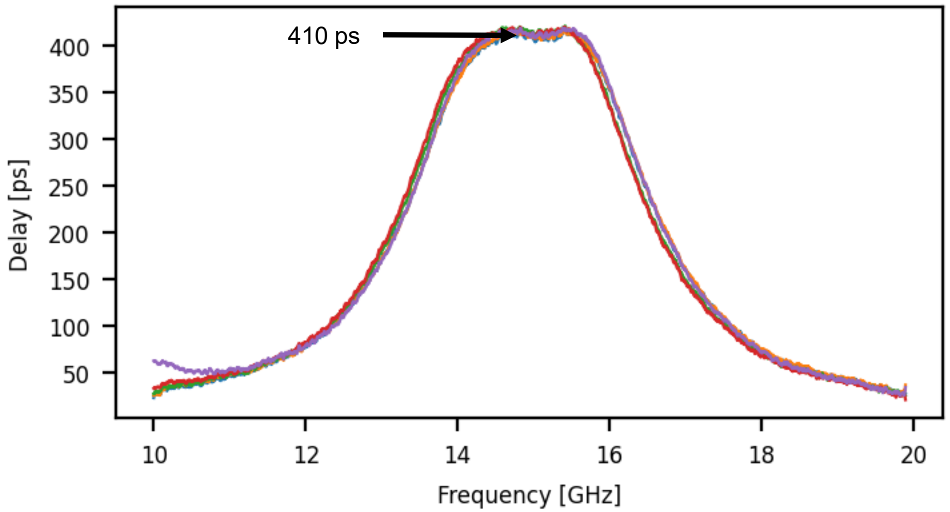
Fixed notch frequency with different time delay





Fixed time delay at different notch frequencies





- 50 dB notch filtering tunable from 5 to 9 GHz and tunable time delay (143 ps to 514 ps) from 14 to 16 GHz

Emerging technologies in integrated MWP

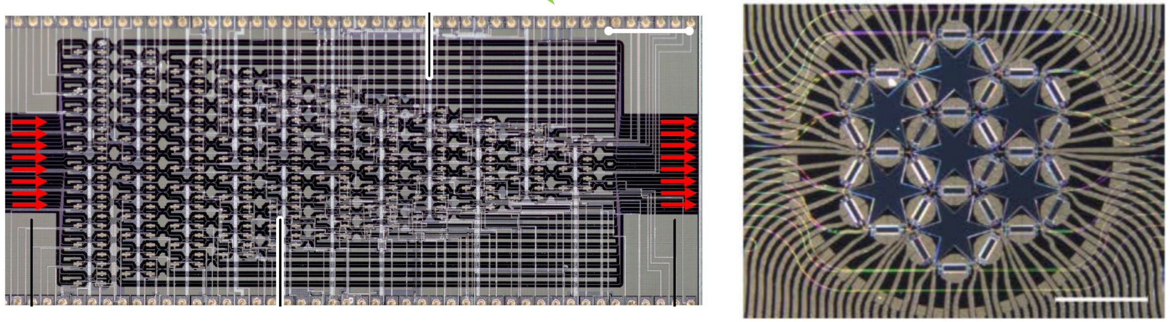
- **Programmable photonics** (meshes, general purpose processor)
- **Enhancing spectral resolution**: ultra-high Q rings, Brillouin optomechanics
- **Frequency combs** for microwave signal generation, frequency conversion, filtering
- High performance **modulators and detectors** (thin-film lithium niobate, plasmonics)
- Low noise (RIN, phase), high power **on-chip lasers**
- **Optical amplifier** on chip (erbium on silicon nitride)
- High level of **integration** (electronic-photonic, passive, laser, modulator, detector)
- **System** experiments (real wireless signals, blind source separation)

Programmable photonics

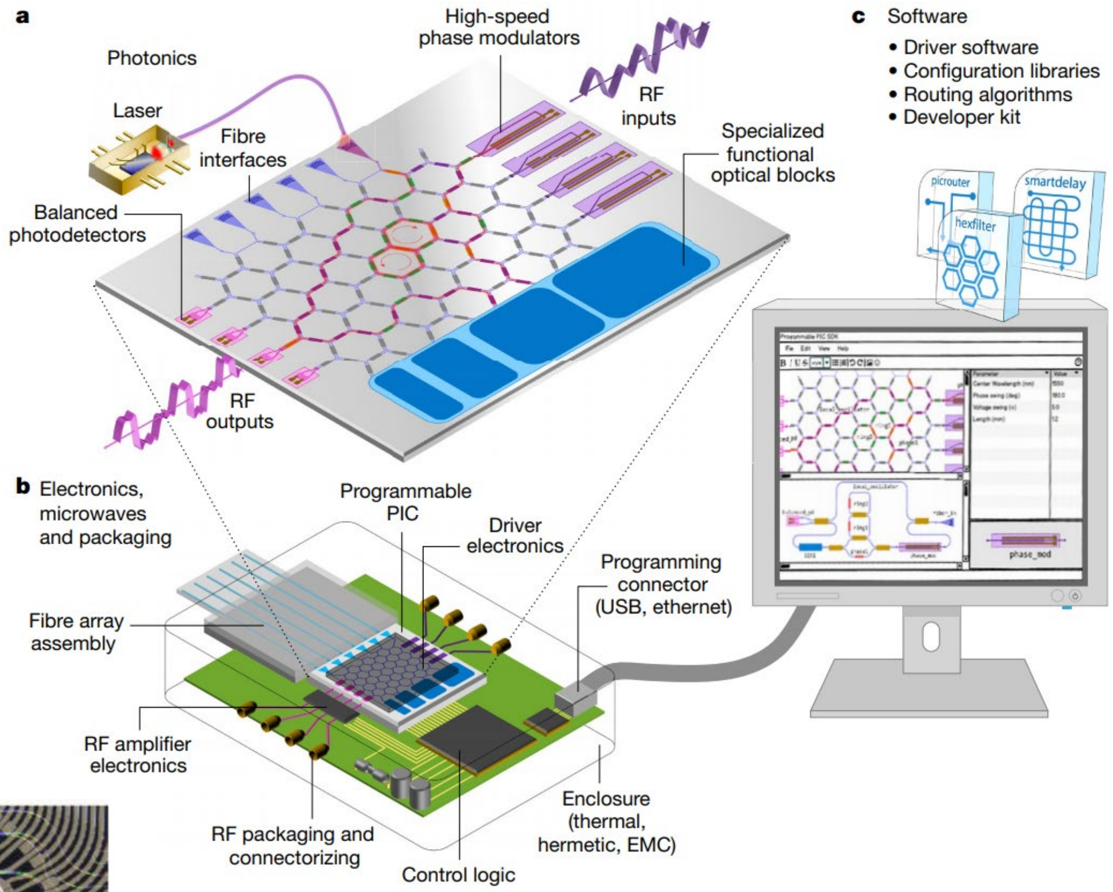
W. Bogaerts et al. Nature (2021)

Photonic Integrated Circuits
that **can be reconfigured**
using **software**
to perform **different functions**.

Field Programmable Gate Array (FPGA



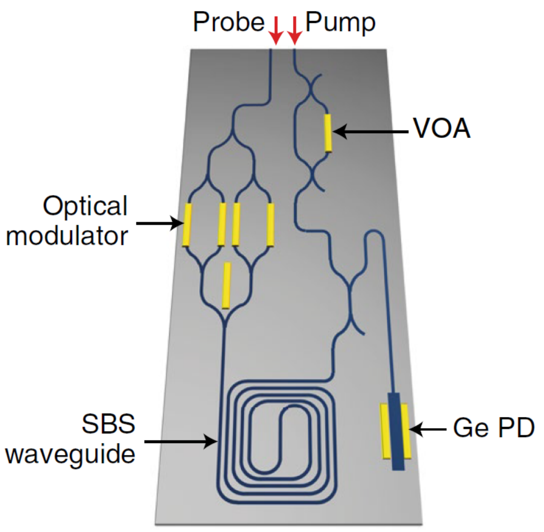
Photonic equivalent of FPGA

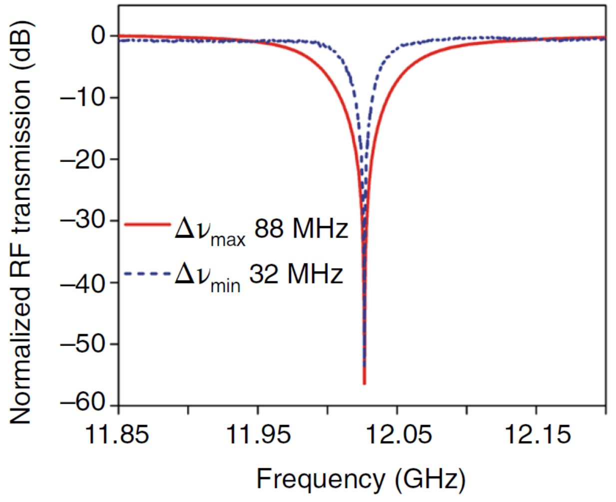


Applications:

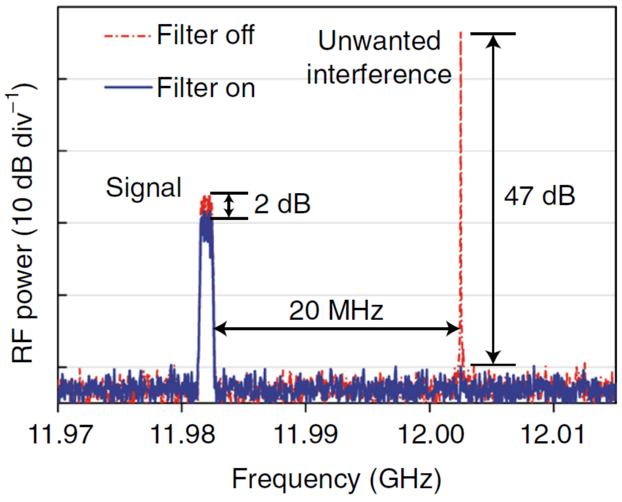
- Quantum computing
- Microwave photonics
- Neuromorphic computing
- ……

Stimulated Brillouin scattering filter

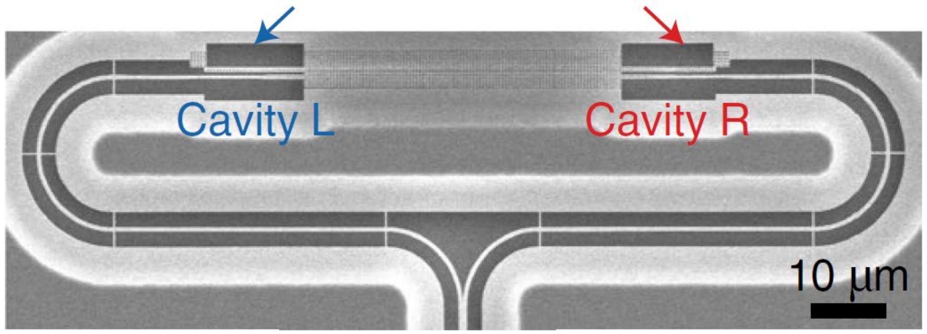


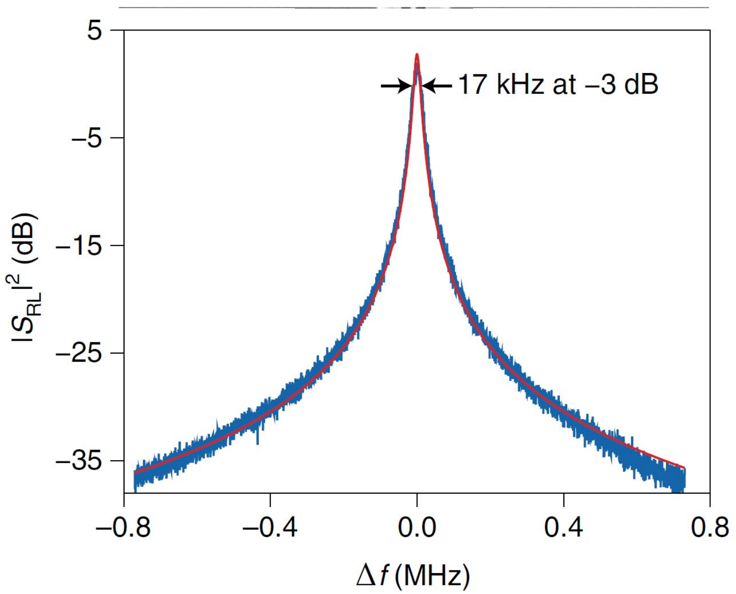


SBS notch filter



Optomechanical crystals





Further references:

- Eggleton et al., *Brillouin Integrated Photonics*, Nat. Photon. **13** (2019)

Comb-based MWP filter

Article

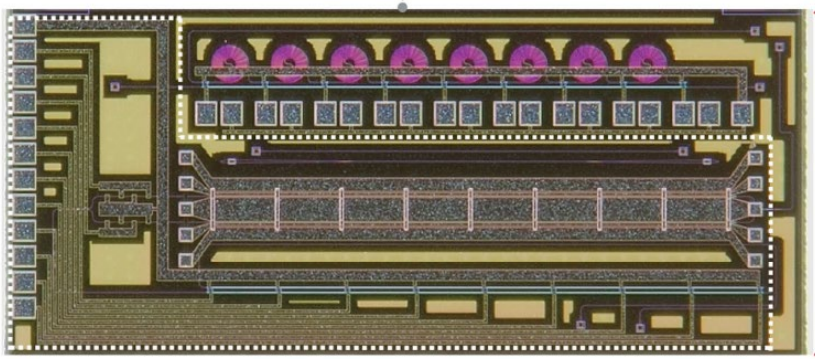
Microcomb-driven silicon photonic systems

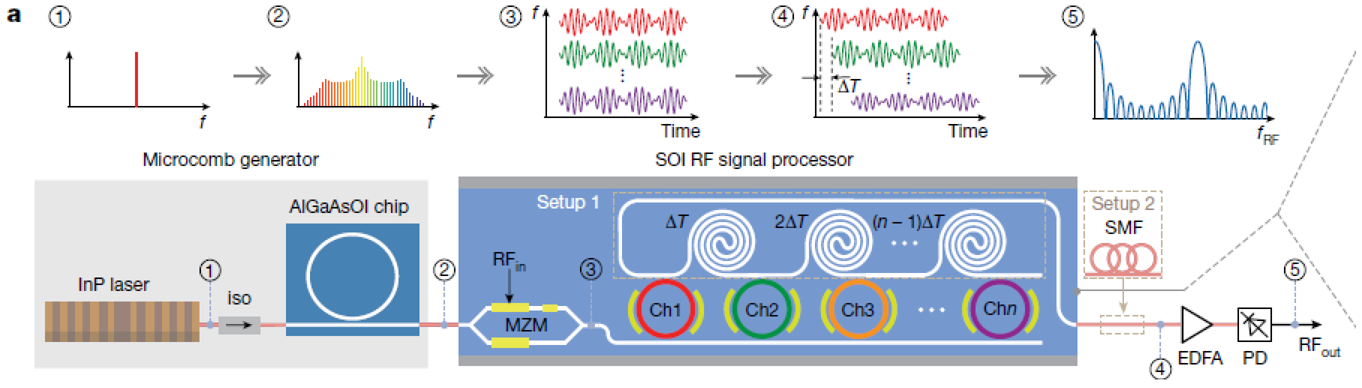
https://doi.org/10.1038/s41586-022-04579-3

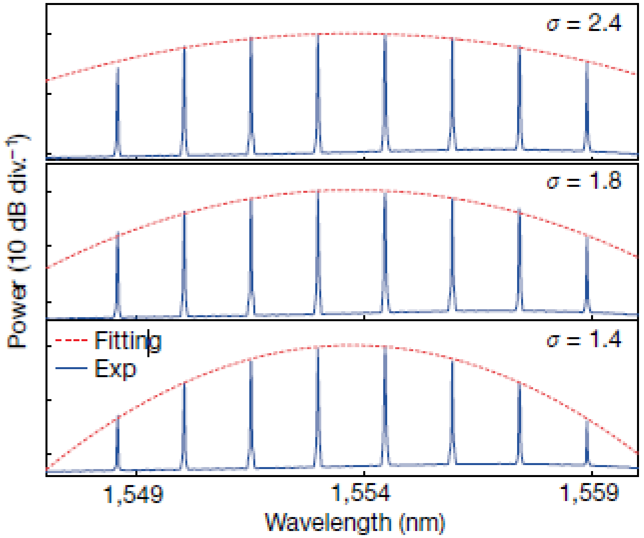
Received: 4 August 2021

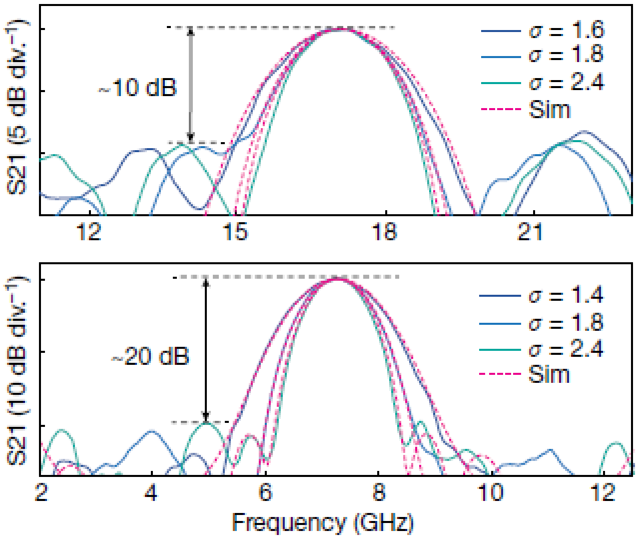
Accepted: 24 February 2022

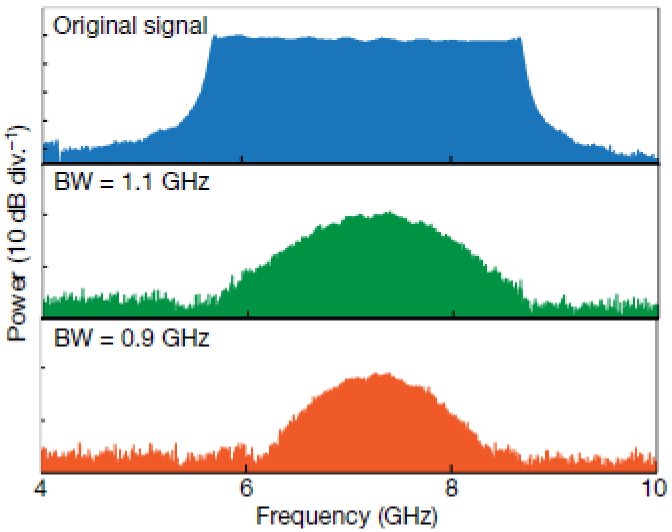
Haowen Shu[1,5], Lin Chang[2,5], Yuansheng Tao[1,5], Bitao Shen[1,5], Weiqiang Xie[2], Ming Jin[1], Andrew Netherton[2], Zihan Tao[1], Xuguang Zhang[1], Ruixuan Chen[1], Bowen Bai[1], Jun Qin[1], Shaohua Yu[1,3], Xingjun Wang[1,3,4] ✉ & John E. Bowers[2] ✉









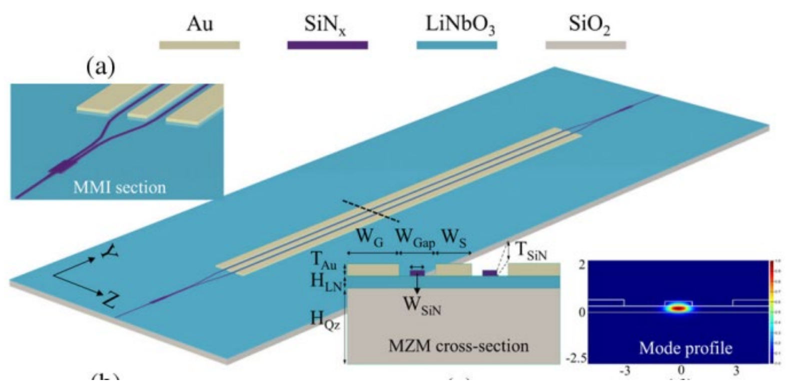


Integration of high-performance modulator

Optics Letters

Subvolt electro-optical modulator on thin-film lithium niobate and silicon nitride hybrid platform

ABU NAIM R. AHMED,[1,*] SEAN NELAN,[1] SHOUYUAN SHI,[1] PENG YAO,[2] ANDREW MERCANTE,[2] AND DENNIS W. PRATHER[1,2]
[1]School of Electrical and Computer Engineering, University of Delaware, Newark, Delaware 19716, USA
[2]Phase Sensitive Innovations, Newark, Delaware 19711, USA

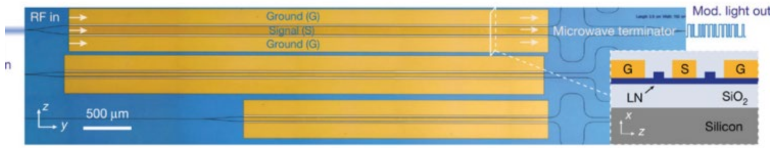


LETTER

https://doi.org/10.1038/s41586-018-0551-y

Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages

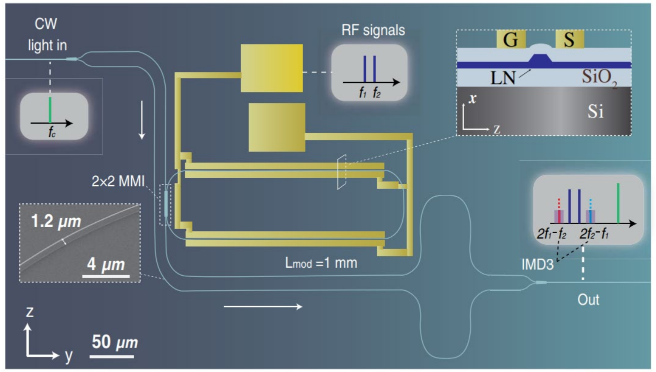
Cheng Wang[1,2,6], Mian Zhang[1,6], Xi Chen[3], Maxime Bertrand[1,4], Amirhassan Shams-Ansari[1,5], Sethumadhavan Chandrasekhar[3], Peter Winzer[3] & Marko Lončar[1]*



PHOTONICS Research

Ultra-high-linearity integrated lithium niobate electro-optic modulators

HANKE FENG,[1,†] KE ZHANG,[1,†] WENZHAO SUN,[1] YANGMING REN,[2,3] YIWEN ZHANG,[1] WENFU ZHANG,[2,3] AND CHENG WANG[1,*]



APL Photonics ARTICLE scitation.org/journal/app

500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics

Maurizio Burla,[1,a)] Claudia Hoessbacher,[1] Wolfgang Heni,[1] Christian Haffner,[1] Yuriy Fedoryshyn,[1] Dominik Werner,[1] Tatsuhiko Watanabe,[1] Hermann Massler,[2] Delwin L. Elder,[3] Larry R. Dalton,[3]