High Performance Integrated Microwave Photonic Systems

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

- Capmany and Novak, Nat. Photon 1 (2007)
- 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

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

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

Navy ships with antennas operating at 50 MHz- 50 GHz
A closer look at the RF front-ends

Phased-array antenna

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

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
Microwave photonic link

- Laser
- Optical modulator
- Optical fiber
- Two-port RF component
- Photo-detector
- RF in
- RF out
- Link “gain” (usually loss)

Record: 20 dB (NRL)

Noise Figure = \[ \frac{\text{SNR in}}{\text{SNR out}} > 1 \]

Measure of SNR degradation
Record: 7-9 dB (NRL, PSI)

Optical spectrum
- Optical carrier
- Lower sideband
- Upper sideband
- 193 THz
- 1 GHz
Microwave photonic signal processing

- Laser
- Optical modulator
- Antenna
- Photodetector
- RF Signal processing
- Suppress Interfering Signal(s)
- Adjust Amplitude and/or Phase and/or Delay
- "Channelize"
- Down-convert to Baseband
- Sample + Digitize
- To Receivers

7
Microwave photonic signal processing

Antenna

Suppress Interfering Signal(s)
Adjust Amplitude and/or Phase and/or Delay
“Channelize”
Down-convert to Baseband
Sample + Digitize

Optical filter
Optical delay
Optical channelizer
Optical mixer

LO

A/D

Optical A/D
to Receiver

Chip! → Integrated MWP

Optical processing
Photo-detector
RF out

Laser

Optical modulator

Microwave photonic signal processing
Material platforms

- Low loss: \( \times \)
- High power handling: \( \times \)
- Compact: \( \checkmark \)
- Lasers: \( \times \)
- Linear modulation & detection: \( \times \)

Optical nonlinearities: \( \checkmark \)
CMOS compatible: \( \checkmark \)

Standard silicon

- Loss \( \sim 1-3 \text{ dB/cm} \)
- 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)

Hydrex
- Comb-based RF photonics
  (Swinburne, JSTQE 2018)

Emerging materials
- Ta$_2$O$_5$ (UCSB, Optica 2017)
- LNOI (Harvard, Optica 2017)
Three pillars of integrated MWP

Functionalities:
- Fast beamsteering
- Low noise oscillator
- Agile filters
- Wideband converters

Performance:
- High link gain
- Low noise figure
- High dynamic range
- Wide bandwidth

Integration:
- Low footprint
- Energy efficient
- Light weight
- Electronic-photonic
Optical power vs. RF power

- $P_{\text{opt}}$: optical power
- $I_{\text{det}}$: detected photocurrent
- $r_{\text{PD}}$: photodetector responsivity
- $P_{\text{RF}}$: RF power
- $R_L$: Load resistance (50 ohm)

$L$: Optical loss

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

![Diagram showing the noise modeled as current sources with labels for $i_{th,s}(t)$, $i_{rin}(t)$, $i_{shot}(t)$, $i_{th,d}(t)$, $i_N(t)$, $P_O$, $R_{Match}$, and $R_L$.]

![Graph showing noise power vs. detected photocurrent with labels for total link noise, shot noise, thermal noise (-174 dBm/Hz), and RIN (-160 dB/Hz).]
Spurious-free dynamic range (SFDR)

**Input power (dBm)**

**Output power (dBm)**

**Fundamental**

**IMD3**

**SFDR**

**Noise (1 Hz)**

**RF power**

**Frequency**

**RF spectrum**

**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


Filtering


Signal measurement

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

Phased-array antenna

Beam direction

Wavefront

Antenna elements

Beam former

Delay = T

Delay = T

Delay = 2T

Combiner

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

## Components for integrated optical beamformer

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

### Modulators
- InP modulators (30 GHz, 3V Vπi)
- InP detectors (40 GHz, 0.8 A/W)

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

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### Diagrams
- [InP laser](image1)
- [InP detectors](image2)
- [4 delay lines - 6 rings each](image3)
- [1 to 4 splitter](image4)
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
- Multi-band and multi-beam operation
- Operation the millimeter-wave (27 GHz)
- Noise figure 7 dB
- Power consumption: 100 W
- SFDR 100 dB Hz$^{2/3}$
Microwave photonic filters

Radar

**Target**

**Clutter/interferer**

Strong interferers saturate receiver
(should be removed)

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

J. Capmany et al, JLT, 24, 201, 2006
Optical filter-based MWP filter

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


Loss ~ 1.4 dB/m
Low biasing + cancellation filter

Gain enhancement

Noise figure reduction
High performance MWP filter

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)
• 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

Simultaneous-cascaded functionalities

- 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

- 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}
Simultaneous notch filtering with true time delay

- 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

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

Field Programmable Gate Array (FPGA)

Applications:
- Quantum computing
- Microwave photonics
- Neuromorphic computing
- ......
Stimulated Brillouin scattering filter

Further references:
- Eggleton et al., Brillouin Integrated Photonics, Nat. Photon. 13 (2019)
Comb-based MWP filter

Microcomb-driven silicon photonic systems

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[Diagram and graphs showing frequency and power data]
Integration of high-performance modulator

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

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

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