Photonic Integrated Circuits for Microwave Photonics

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Outline

- Introduction to Microwave Photonics (MWP)
- SiP-based MWP systems
  - Photonic generation of microwave waveforms
  - Photonic processing of microwave signals
  - A fully SiP integrated MWP filter
- InP-based signal processing
  - A fully reconfigurable photonic signal processor
  - A fully InP integrated MWP filter
- SiN-based MWP systems
  - True time delay beamforming
  - Reconfigurable signal processor
- Conclusion
Three materials systems:
1) Indium Phosphide (InP)
2) Silicon Nitride (Si3N4)
3) Silicon Photonics (SiP)

1) InP:
- Able to monolithically integrate both active and passive photonic components
- High loss, and large size
- Difficulty to integrate with electronics
Materials systems

2) $\text{Si}_3\text{N}_4$:
• Very low loss, <0.2 dB/cm
• No active components such as light sources, modulators, amplifiers and photodetectors can be supported, thus full monolithic integration is hard to achieve

3) SiP:
• A technology that allows optical devices to be made economically using the standard and well-developed CMOS fabrication process
• Most of the optical components, both passive and active, can be fabricate
• The key advantages include much smaller footprint, low loss, and simple fabrication process
• No optical amplification and light generation
Microwave Photonics (RF Photonics) is a field that studies the generation, processing, control, and transmission of microwave signals by means of photonics for applications such as wireless communications, radar, sensing, imaging, and instrumentation.
What is Microwave Photonics (MWP)?

MWP

- CW lasers
- Pulsed lasers
- Modulators
- Photodetectors
- Optical amplifiers
- High Q resonators
- Gratings
- Nonlinear fibers
- MWP
- Large TBWP delay line
- High-speed sampling
- Photonic ADCs
- Wideband front end
- Local oscillators
- True time delay beamforming
- Tunable filters
- Channelizer
- Antenna remoting
- Radio over fiber
- Signal processors
Applications of Microwave Photonics

surface radars with large antennas

The Atacama Large Millimeter Antenna (ALMA) Array
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  - In-P signal processing
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    - A fully InP integrated MWP filter
- **SiN-based MWP systems**
  - True time delay beamforming
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Chirped microwave pulse can be compressed by matched filtering, widely employed in Radar systems.
Photonic microwave waveform generation based on spectral shaping and frequency-to-time mapping

Ultra-short optical pulse

\[ y(t) \propto G(\omega) \bigg|_{\omega = \frac{t}{\Phi}} \]
Photonic microwave waveform generation based on spectral shaping and frequency-to-time mapping

**Frequency-to-time mapping**

Wavelength-to-time mapping, namely dispersive Fourier transformation, is a fast and effective way to measure optical spectrum in the time domain.

\[
y(t) = g(t) \ast \exp \left( j \frac{t^2}{2 \Phi} \right) = \int_{-\infty}^{\infty} g(\tau) \times \exp \left[ j \frac{(t-\tau)^2}{2 \Phi} \right] d\tau
\]

\[
= \exp \left( j \frac{t^2}{2 \Phi} \right) \times \int_{-\infty}^{\infty} g(\tau) \times \exp \left( j \frac{\tau^2}{2 \Phi} \right) \times \exp \left[ -j \left( \frac{t}{\Phi} \right) \tau \right] d\tau
\]

\[
\approx \exp \left( j \frac{t^2}{2 \Phi} \right) \times \int_{-\infty}^{\infty} g(\tau) \times \exp \left[ -j \left( \frac{t}{\Phi} \right) \tau \right] d\tau
\]

\[
= \exp \left( j \frac{t^2}{2 \Phi} \right) \times G(\omega) \bigg|_{\omega = \frac{t}{\Phi}} \approx G(\omega) \bigg|_{\omega = \frac{t}{\Phi}}
\]
On-chip spectral shaper incorporating multi-microring resonators

Perspective view of the proposed on-chip spectral shaper. (Inset: (left) Wire wave guide structure and (right) the simulated fundamental transverse electric (TE) mode profile of the wire waveguide at 1550 nm.

On-chip spectral shaper incorporating multi-microring resonators

Schematic layout of the designed on-chip spectral shaper.

(a) Measured spectral response of an on-chip spectral shaper consisting of four cascaded MRRs. (b) Measured spectral response of an on-chip spectral shaper consisting of five cascaded MRRs.
On-chip spectral shaper incorporating multi-microring resonators

Experimental results

The generated chirped microwave waveforms and the spectrogram illustrating the time distribution of the microwave frequency components.

Bandwidth: 15.5 GHz
Chirp rate: 17.2 GHz/ns

Bandwidth: 8.5 GHz
Chirp rate: 12.2 GHz/ns
On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings
On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings

Perspective view of the proposed on-chip silicon-based optical spectral shaper. (Inset: (Left) Wire waveguide and (Right) Rib waveguide)

On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings

\[ \lambda_B = 2n_{\text{eff}} \Lambda \]

Perspective view of the proposed LC-WBG. (Inset: Simulated fundamental TE mode profile of the rib waveguide with the rib width of 500 nm (left) and 650 nm (right)).

The grating is realized by introducing periodic sidewall corrugations on the slab. By keeping the grating period uniform and linearly increasing the width of the rib along the grating, a linear chirp is produced since the effective refractive index is linearly increasing as the rib width increases in a definite range.

Measured spectral and group delay responses of the LC-WBG with the rib width increasing from 500 nm to (a) 550 nm, (b) 600 nm and (c) 650 nm along the gratings.
Experimental Results

Measured spectral response of an on-chip spectral shaper when the length of the offset waveguide is (left) zero and (right) the length of the LC-WBG.

Experimental Results

Experimental result: (a) the generated LCMW; (b) experimental spectrogram curve and numerical instantaneous frequency of the generated LCMW, and (c) compressed pulse by autocorrelation when the length of the offset waveguide equates to zero.

Experimental result: (a) the generated LCMW; (b) experimental spectrogram curve and numerical instantaneous frequency of the generated LCMW, and (c) compressed pulse by autocorrelation when the length of the offset waveguide equates to the length of LC-WBG.
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A \textit{nth} order temporal differentiator: 
\[ y(t) = \frac{d^n x(t)}{dt^n} \]

The transfer function:

\[ H(\omega) = [j(\omega - \omega_0)]^n = \begin{cases} 
  e^{jn\left(\frac{\pi}{2}\right)} |\omega - \omega_0|^n, & \omega > \omega_0 \\
  e^{jn\left(-\frac{\pi}{2}\right)} |\omega - \omega_0|^n, & \omega < \omega_0 
\end{cases} \]

Magnitude and phase response of a differentiator.

Applications: phase to intensity conversion in an optical phase-modulated system.
Photonic microwave temporal differentiator using an integrated phase-shifted Bragg grating

Configuration of the phase-shifted Bragg grating (PSBG) in an silicon-on-insulator ridge waveguide.

(a) Schematic layout. (b) Image of the fabricated device. (c) Image of the grating couplers and the strip waveguides. (d) Image of the taper waveguides for the transition between the strip waveguides and ridge waveguides.

Experimental Results

(Left) Measured reflection and transmission spectral responses of the fabricated PSBG on a ridge waveguide with a designed corrugation width of 125 nm. (Right) Zoom-in view of the reflection notch and its phase response.

(Left) An input Gaussian pulse with an FWHM of 25 ps, and (Right) the temporally differentiated pulses by simulation and experiment.
Independently tunable *multichannel* fractional-order temporal differentiator

Applications: phase modulation to intensity modulation conversion in a WDM optical phase-modulated system.

Measured spectral response of the five-channel fractional-order temporal differentiator; Inset: measured phase response of the five-channel fractional-order temporal differentiator.

Experimental Results

Experimental Results - differentiated output pulses

Experimental results. (a) The measured Gaussian pulse from AWG (the blue solid line) and the simulated Gaussian pulse (the red dotted line); and measured differentiated output pulses from the photonic fractional differentiator at the (b) 1st, (c) 2nd, (d) 3rd, (e) 4th, and (f) 5th channel.
Experimental results for differentiation order tuning: (a) Measured phase response of the second channel with the power of the pumping light increased, and the measured differentiated output pulses from the differentiator at the fifth channel with the pumping power at (b) 0 dBm, (c) 21.7 dBm, (d) 25 dBm, (e) 28.7 dBm, and (f) 31 dBm.
Experimental Results - independent tunability

Experimental results for independent tunability. Measured differentiated output pulses from the differentiator at the second and the fifth channels with the pumping light wavelength at (a) 1537.498 nm corresponding to a resonant wavelength of the fifth channel, and (b) 1535.920 nm corresponding to a resonant wavelength of the second channel.
Silicon-based on-chip electrically tunable sidewall Bragg grating Fabry–Perot filter

Weifeng Zhang, Nasrin Ehteshami, Weilin Liu, and Jianping Yao*
Silicon-based on-chip electrically tunable sidewall Bragg grating Fabry–Perot filter

![Graph showing reflection and transmission spectra](image)

Fig. 2. Measured reflection and transmission spectra of the TBG-FPF with a zero bias voltage applied.

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the PN junction is reverse biased. (d) Wavelength shift when the bias voltage is increasing.
Amoeba waveguide Bragg grating

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Figure 1. Perspective view. An ultrafast and fully reconfigurable amoeba waveguide Bragg grating in an SOI platform.
Figure 2. The schematics of the designed amoeba grating. (a) Perspective view of an amoeba grating on a silicon chip; (b) cross-sectional view of the rib waveguide of the amoeba grating; (c) top-view of an amoeba grating; (d) image of the fabricated grating; zoom-in view of (e) the input grating coupler and compact Y-branch, (f) the FP cavity section and (g) the transmission and reflection grating couplers.
Figure 3 Measured reflection and transmission spectrums.
(a) Reflection and transmission spectrum of the fabricated grating in the static state;
(b) notch wavelength shift when the bias voltages applied to the left and right sub-gratings vary synchronously;
(c) extinction ratio tuning while the notch wavelength is kept unchanged;
(d) reflection and transmission spectrums when the grating is reconfigured to be a uniform grating;
(e) wavelength tuning of the uniform grating;
(f) reflection and transmission spectrums when the device is reconfigured to be a uniform grating by increasing the cavity loss;
(g) reflection and transmission spectrums when the device is reconfigured to be two independent uniform sub-gratings; and
(h) reflection and transmission spectrums when the device is reconfigured to be a chirped grating.
A Silicon Photonic Integrated Frequency-Tunable Microwave Photonic Bandpass Filter

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Frequency-tunable photonic microwave filter — Principle

- **Central frequency of the PMF** \(\leftrightarrow\) the wavelength of the TLS;
- **Tuning range** \(\leftrightarrow\) the reflection band of the PS-FBG;
- **The 3-dB bandwidth of the PMF** \(\leftrightarrow\) the transmission bandwidth of the PS-FBG

Fig. 3 Optical spectrums of the modulated optical signal using the on-chip high-speed PM when the microwave signal applied to the PM has a frequency of (a) 7, (b) 16 and (c) 25 GHz.
Fig. 7 Experimental result: (a) frequency response of the filter with a center frequency of 13 GHz; (b) optical spectrum of the modulated optical signal when the microwave signal frequency is 13 GHz; (c) measured frequency responses of the filter with the center frequency tuned from 7 to 25 GHz.
Frequency response of the filter (in blue) with a center frequency of 6 GHz and measured frequency response (in red) when no optical signal is coupled into the chip (to show the EMI).

Measurements of the fundamental signal power and that of the IMD3. Given a noise floor of -140 dBm/Hz, the measured spurious-free dynamic range (SFDR) of the filter are $92.4 \text{ dB} \cdot \text{Hz}^{2/3}$. 
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A fully reconfigurable photonic integrated signal processor

Weilin Liu, Ming Li, Robert S. Guzzon, Erik J. Norberg, John S. Parker, Mingzhi Lu, Larry A. Coldren and Jianping Yao

The signal processor can be reconfigured to operate as a

• Temporal integrator
• Temporal differentiator
• Hilbert transformer
• Microwave generator
Temporal Integrator

Data storage

Bit counting

Optical memory

Optical computing

(Linear Differential Equation)

\[
\frac{dy(t)}{dt} + ky(t) = x(t)
\]

Photonic implementation of a temporal integrator

Mathematically, a temporal integrator can be implemented using a linear filtering device with a transfer function given by

\[ H(\omega) = \frac{1}{j(\omega - \omega_0)} \]

A photonic temporal integrator can be implemented using a fiber Bragg grating (FBG) or a microring resonator.

Reflection Spectra

Apodized uniform FBG

Micro-ring resonator

FSR
Temporal Differentiator

\[ H(\omega) = \left[ j(\omega - \omega_0) \right]^n = \begin{cases} e^{jn\frac{\pi}{2}} |\omega - \omega_0|^n & \omega > \omega_0 \\ e^{-jn\frac{\pi}{2}} |\omega - \omega_0|^n & \omega < \omega_0 \end{cases} \]

where \( n \) is the order of differentiation, and \( n \) can be a fractional order. When \( n=1 \), it is the first order differentiation.

\[ y(t) = \frac{d^n x(t)}{dt^n} \]
Temporal Differentiator

UWB pulse generation for wireless access

Tunable Image Enhancement

Implementation of a Photonic Temporal Differentiator

Practically, a temporal differentiator can be implemented using an optical interferometer, such as a Michelson interferometer, a Mach-Zehnder interferometer (MZI).

![Michelson Interferometer Diagram](image)

- **Michelson Interferometer**
  - Laser
  - Beam Splitter (BS)
  - Mirror 1 (M1)
  - Mirror 2 (M2)
  - Screen
  - Path: (1) + (2)

![MZI Diagram](image)

- **MZI**
  - Magnitude
  - Phase
  - FSR
Hilbert Transformer

\[
H^{(1)}(\omega) = \begin{cases} 
    j\frac{\pi}{2} & \omega > 0 \\
    e^{j\frac{\pi}{2}} & \omega = 0 \\
    e^{-j\frac{\pi}{2}} & \omega < 0
\end{cases}
\]

where \( \varphi = P\pi / 2 \), and \( P \) indicates the fractional order. When \( P = 1 \), it becomes the conventional Hilbert transform.
Temporal Hilbert Transformer

Single Sideband Modulation

Power fading due to chromatic dispersion

Practically, a Hilbert transformer can be implemented using a linear filtering device with a narrow notch.

A photonic Hilbert transformer can be implemented using a phase shifted fiber Bragg grating (FBG) or a microring resonator.
Reconfigurable Photonic Signal Processor - Configuration

Reconfigurable - The reconfigurability is achieved by tuning the injection currents to the semiconductor optical amplifiers (9 SOAs) and current injection phase modulators (3 PMs) in the design.

Phase Modulator (PM)
Semiconductor Optical Amplifier (SOA)
Tunable Coupler
Multimode Interference Coupler

Photonic Signal Processor - SEM images

Low loss deeply etched waveguide (1.7 cm⁻¹)  
2 × 2 Multi-mode interference (MMI) coupler

Transaction between an active and passive region (PM loss: 1.56 dB at 2π phase shift)  
Tunable MMI Mach-Zehnder interferometer coupler
Photonic Signal Processor – pictures of the chip
400 µm SOA: Large Signal Gain

(a) The measured gain profile of an SOA as a function of the injection current. (peak gain at 240 dB/cm, saturation power 12.8 dBm)

(b) Tunable coupling coefficient of an MMI MZI coupler at different injection current of one PM on one of the two arms.
Photonic Temporal Integrator

Insertion Loss (dB)

Wavelength (nm)

1556.6 1557.4 1558.2

10.9 ns

2.2 2.4

Intensity (n.u.)

0 2 4 6 8 10

Time (ns)

3rd-order

2nd-order

Intensity (n.u.)

0 0.2 0.4 0.6 0.8 1

Time (ns)

7.8 ns

0 π

Intensity (n.u.)

0 0.2 0.4 0.6 0.8 1

Time (ns)
Photonic Temporal Differentiator

![Diagram of a photonic temporal differentiator with SOA and PM components, showing input and output signals.](image)

![Graphs showing intensity and phase changes with Wavelength (nm) and Time (ps) for different transmission coefficients n: 0.785, 0.842, 1, 1.2, and 1.68.](image)
Photonic Hilbert Transformer

\[ x(t) \rightarrow y_n(t) \]

\[ H_n[x(t)] \]

\[ \alpha = 1, \beta = 1 \]
\[ \alpha = 0.5, \beta = 0.5 \]
\[ \alpha = 0.2, \beta = 0.05 \]
Photonic Temporal Hilbert Transformation

- Figure a: Experimental and Simulation results for Fractional Hilbert Transformer.

- Figure b: Insertion Loss vs. Wavelength (nm) for different experimental conditions.

- Figure c: Insertion Loss vs. Wavelength (nm) for simulation with different parameters.

- Figure d: Phase vs. Wavelength (nm) for simulation.

- Figure e: Power vs. wavelength (nm) with different values of \( n \).

- Figure f: Power vs. wavelength (nm) with different values of \( n \).

- Figure g: Power vs. wavelength (nm) with different values of \( n \).

- Figure h: Power vs. wavelength (nm) with different values of \( n \).

- Figure i: Phase vs. Time (ps) with different values of \( \alpha \) and \( \beta \).

- Figure j: Phase vs. Time (ps) with different values of \( \alpha \) and \( \beta \).
Application Examples

Image processing using the signal processor

Waveforms

(a) Square Waveform
(b) Sawtooth Waveform
(c) Triangular Waveform
(d) Trapezoidal Waveform
(e) Stepped Waveform

Normalized Amplitude

Normalized Amplitude

Normalized Amplitude

(a) Square Waveform
(b) Sawtooth Waveform
(c) Triangular Waveform
(d) Trapezoidal Waveform
(e) Stepped Waveform

Normalized Amplitude

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(e) Stepped Waveform

Normalized Amplitude

Normalized Amplitude

Normalized Amplitude

(a) Square Waveform
(b) Sawtooth Waveform
(c) Triangular Waveform
(d) Trapezoidal Waveform
(e) Stepped Waveform

Normalized Amplitude
Single Sideband modulation is important in a radio over fiber (RoF) link to avoid dispersion-induced power penalty.
Photonic Microwave Signal Generator

Lasing wavelength

\( \Delta \lambda \)

\( \lambda_1 \)

\( \lambda_2 \)

Coupler

PD

\( \lambda_1 \)

\( \lambda_2 \)

\( \lambda \)

Time

Amplitude

IPC2017
The signal processor is reconfigured to operate as a microwave generator consisting of two ring lasers.

A changing driving voltage is applied to PM3 in R3 to generate a chirped optical light.

\[
\Delta f = \frac{d\phi}{dt} = At \quad \text{if} \quad \phi(t) = \frac{A}{2} t^2
\]
The optical spectrum measured at the output port of the chip. Two wavelengths with a wavelength spacing of 85 pm.

(a) The driving voltage applied to the PM3 (red) and the generated high frequency microwave waveform (blue); (b) and (c) the zoom-in view of the generated waveform at different locations within a period of the driving voltage.
Within the temporal duration of the 10 µs, the frequency increases from 5 to 17 GHz, corresponding to a TBWP of $1.2 \times 10^5$.

A compressed pulse with a temporal width of 200 ps is achieved from the autocorrelation of the generated waveform. The pulse compression ratio is calculated to be $5 \times 10^4$. 

Spectrogram of the generated LCMW. The color scale represents the normalized amplitude of the instantaneous spectrum.

Calculated auto-correlation between two generated LCMWs. A correlation peak of 250 ps is achieved.
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A monolithic integrated photonic microwave filter

Javier S. Fandiño¹, Pascual Muñoz¹², David Doménech² and José Capmany¹*
A monolithic integrated photonic microwave filter

Javier S. Fandiño¹, Pascual Muñoz¹,², David Doménech² and José Capmany¹*

Image of a fabricated die

Packaged chip
A monolithic integrated photonic microwave filter

RAMZI filter

3 dB coupler
Custom coupler
Phase shifter

Transmission (dB)

FSR

Norm. frequency \((f-f_0)\) (GHz)

On-chip area

Current sources

d.c. pads

TL 1
RF pad 2
RAMZI filter

Output

OSA

MZW
RF pad 3

Bias tees

VNA

Source meters

Current set #1

E/O transmission (dB)

Mod. frequency (GHz)
Measured powers of the fundamental signal and the IMD3 when the filter is tuned at 1.4 GHz

Measured spurious-free dynamic range (SFDR) for these three cases as a function of modulation frequency
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Squint-free beamforming - true time delay (TTD)

Phased Array Antenna System based on phase shifters

Example of beam squint with electrical phase shift technique

\[ \theta = \sin^{-1}\left(\frac{\Delta \phi \lambda}{2\pi d}\right) \]

Phased Array Antenna System based on TTD

Example of beam squint-free pattern with true-time delay

\[ \theta = \sin^{-1}\left(\frac{\tau}{d}\right) \]
Single-Chip Ring Resonator-Based $1 \times 8$ Optical Beam Forming Network in CMOS-Compatible Waveguide Technology

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True time delay beamforming

Fig. 2. Binary tree-based $1 \times 8$ OBFN for transmitter system, consisting of 12 ORRs and seven tunable splitters.
Fig. 5. Measurement results of different outputs of the 1 8 OBFN chip: (a) and (b) show group delay responses of Outputs 2 and 4, respectively; (c) shows the linearly increasing delay at all outputs of the 1 8 OBFN chip.
System integration and radiation pattern measurements of a phased array antenna employing an integrated photonic beamformer for radio astronomy applications

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Maurizio Burla,¹,* Chris G. H. Roeloffzen,¹ Leimeng Zhuang,¹ David Marpaung,¹ Muhammad Rezaul Khan,¹ Peter Maat,² Klaas Dijkstra,² Arne Leinse,³ Marcel Hoekman,³ and René Heideman³
Fig. 10. (Color online) Measured (thick lines) versus simulated (thin solid lines) radiation patterns (E-plane) for three different pointing angles of the main beam: 0 degrees (top), −11.5 degrees (center), and −23.5 degrees (bottom). The measurements are also compared with the patterns that would be obtained in case phase shifters are used (dashed lines). Measurements at four frequencies (left to right: 1000 MHz, 1150 MHz, 1300 MHz, 1500 MHz) show the absence of beam squinting for the main lobe (indicated by the arrows) over the whole frequency range. Note the shift to the right of the leftmost null of radiation and the irregular shape assumed by the main lobe, in several of the measured patterns, as a consequence of parasitic effects in the measurement setup.
Silicon photonics - TTD beamforming

1x2 Silicon Switch → 2x2 Silicon Switch → 2x2 Silicon Switch → ... → 2x2 Silicon Switch → 2x1 Silicon Switch

Bit 1 Silicon Delay Waveguide Path

Bit 2 Silicon Delay Waveguide Path

Bit N Silicon Delay Waveguide Path
Silicon photonics - TTD beamforming

grating coupler  contact  n implant  p implant  waveguide
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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. Lowery1,5

(a) Waveguide 2D mesh network

Structure
In1
In2

\[ \Phi_U \]

Out1
Out2

Function
Coupler
Bar
Cross

Waveguide
Mach–Zehnder coupler
Phase tuning element
Light propagation

Basic circuit components
FIR filter
IIR filter
Programmable photonic signal processor chip for radiofrequency applications

Arbitrary circuit topology
Proof-of-concept demonstration

Silicon Nitride (TriPleX)

Tunable coupler

Tunable phase shifter

TriPleX Si3N4/SiO2 waveguide

Waveguide
- Mach-Zehnder coupler
- Resistor-based heater
Proof-of-concept demonstration

Bar (switch)  Coupler

Notch filter  Hilbert transformer  Bandpass filter  Delay line
ARTICLE

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Multipurpose silicon photonics signal processor core

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Fig. 1 Software-defined general-purpose photonic processor and its waveguide mesh reconfigurable core. 

(a) Architecture of the processor showing the reconfigurable core as its central element and the different possible electrical, optical and control input/output signals (E/O: External modulator. O/E: Optical receiver). 

(b) Schematic of the hexagonal waveguide mesh; a 7 unit cell structure is marked in blue. 

(c) Layout detail of the 7-cell hexagonal waveguide mesh designed and fabricated, including a zoom (lower) of a hexagon side of length 1 basic unit length (BUL) implemented by means of a 3-dB Mach-Zehnder Interferometer (MZI) and a zoom (upper) of an optical interconnection node. TBU, tuneable basic unit
Fig. 2 Fabricated hexagonal waveguide mesh chip. a Design layers (optical, electrical, and thermal) of the 7-cell hexagonal waveguide mesh and the auxiliary test cell. b Fabricated silicon on insulator (SOI) chip of footprint $15 \times 20$ mm. c Zoomed vision of the 7-cell hexagonal waveguide mesh. Scale bar of 2 mm. In the right bottom corner d zoomed image of an optical interconnection node of three tuneable basic units (TBUs). Scale bar of 100 μm. In the right bottom corner e zoomed image of a single hexagonal cell showing the Mach Zehnder Interferometer (MZI). Scale bar of 500 μm. In the right bottom corner, tuning heaters, and star-type thermal isolation trenches. f Printed circuit board with the waveguide mesh chip mounted and wired bonded.
Fig. 3 Experimental results for tuneable unbalanced Mach Zehnder Interferometers and finite impulse response filters. Waveguide mesh connection diagram, circuit layout and measured modulus, and phase transfer function for different values of the coupling constants $K_1$ and $K_2$ in the case of a 4-BUL unbalanced Mach-Zehnder Interferometer (UMZI) filter; b an 8-BUL UMZI filter; c a 4-BUL basic delay 3-tap transversal filter. For each case, the first column shows the 7-cell hexagonal waveguide mesh configuration, where each Mach Zehnder Interferometer (MZI) device is represented by a given color depending on whether it is activated as a cross (black) or bar (orange) switch, a tuneable coupler (green) or not used/available (blue). The second column shows the layout of the implemented structure, while the third and fourth columns show, respectively, the measured modulus and corresponding phase (calibrated by the shortest path) for the synthesized configuration where the input is in the IN port and the output is the OUT1 port. Measured curves are displayed for different values of the coupling constants $K_1$ and $K_2$, which are tuned by changing the injection currents to the heater elements of the input and output MZI devices of the UMZI. Changing these values alters the position of the zero in the UMZI transfer function bringing it closer or farther to the unit circle. The closer the zero is to the unit circle, the deeper are the notches in the transfer function and the higher is the phase shift step in the transfer function is ref. BUL, basic unit length; CS, cross state; BS, bar state; AV, available; TC, tuneable coupler.
Fig. 4 Experimental results for 6-BUL ring resonator infinite impulse response and combined finite impulse response and infinite impulse response filters. Waveguide mesh connection diagram, circuit layout and measured modulus, and phase transfer function for a 6-BUL optical ring resonator (ORR) infinite impulse response (IIR) filter for different values of the coupling constants $K_1$ and $K_2$; b 6-BUL ORR finite impulse response (FIR) + IIR filter for different values of the coupling constants $K_1$ and $K_2$; c 6-BUL ORR IIR filter along a full spectral period for different values of the optical ring resonator round-trip phase shift. BUL, basic unit length; CS, cross state; BS, bar state; AV, available; TC, tuneable coupler.
Conclusion

• MWP has been extensively investigated, but its applications are limited due to large size and high cost of discrete components.

• The use of PICs is a solution to reduce the size and cost.

• The 3 materials systems have their own limitations
  o SiP – no light amplification, no light source
  o InP – large size, high loss, and complexity in fabrication
  o SiN – passive only devices

• Hybrid Integration (SiP + InP) may be needed to produce laser sources and optical amplifiers using III-V materials - a key challenge for wide applications of silicon photonics.
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