uOttawa

L'Université canadienne
Canada's university

Fully reconfigurable waveguide Bragg gratings for programmable photonic signal processing

Jianping Yao and Weifeng Zhang

Microwave Photonics Research Laboratory
School of Electrical Engineering and Computer Science
University of Ottawa

OFC2019

March 3-7, 2019, San Diego

Outline

- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry–Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg gratings for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg gratings for multichannel signal processing
- Conclusion

Material systems

Three material systems:

1) Indium Phosphide (InP)
2) Silicon Nitride (Si_3N_4)
3) Silicon on Insulator (SOI)

1) InP:

- Able to monolithically integrate both active and passive photonic components
- High loss, and large size
- Difficulty to integrate with electronics

Material systems

2) Si_3N_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

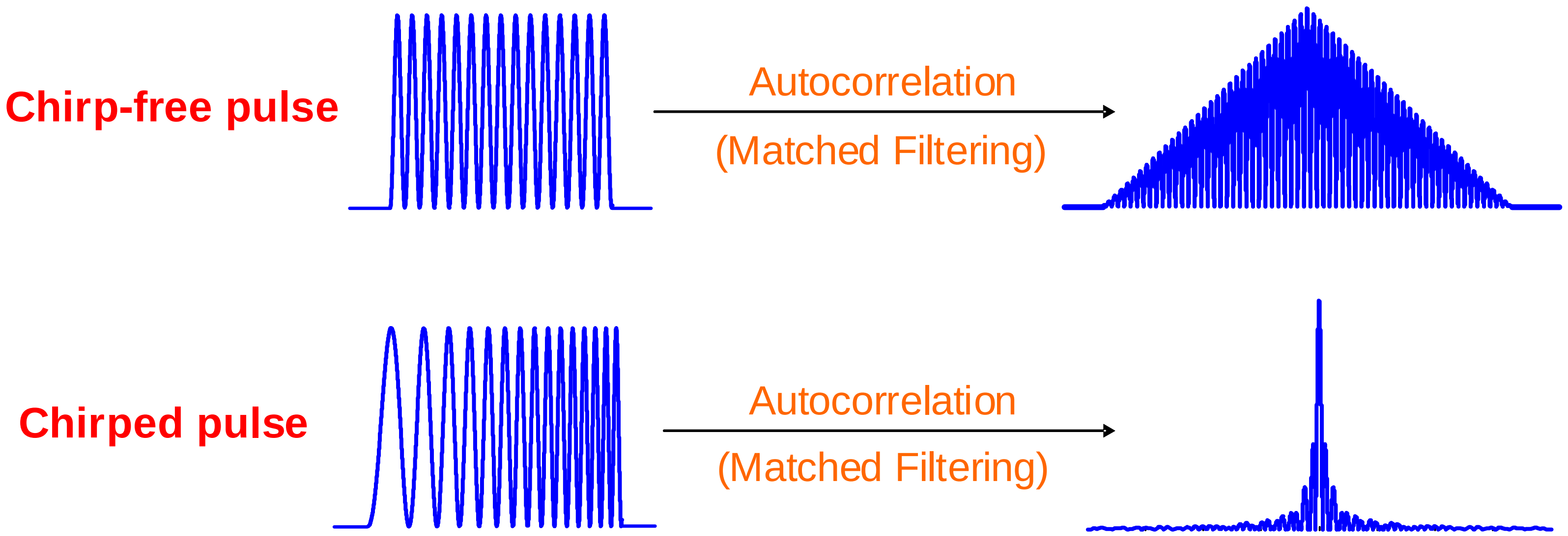
3) SiP:

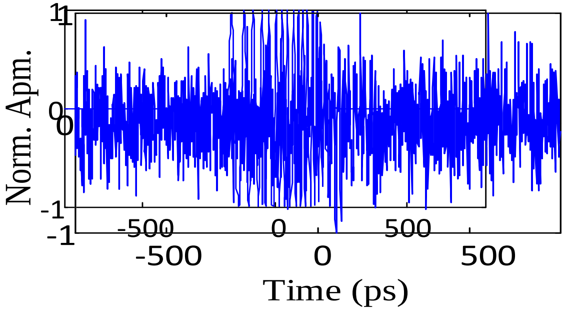
- A technology that allows optical devices to be made economically using the standard and well-developed CMOS fabrication process
- Most of the optical components, both passive and active, can be fabricated
- The key advantages include much **smaller footprint**, **low loss**, and **simple fabrication process and can be integrated with electronics (analog and dgital)**
- No optical amplification and light emission

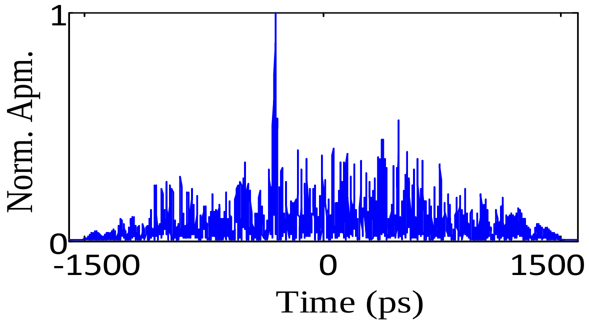
Outline

- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry-Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg grating for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg grating for multichannel signal processing
- Conclusion

Chirped RF waveform generation

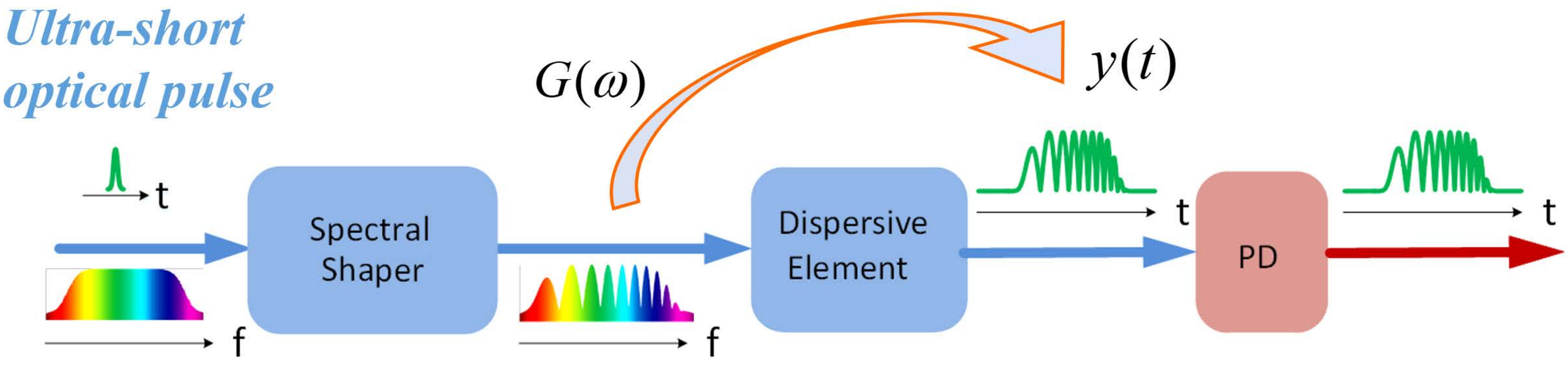






Chirped microwave pulse can be compressed by matched filtering, widely employed in Radar systems.

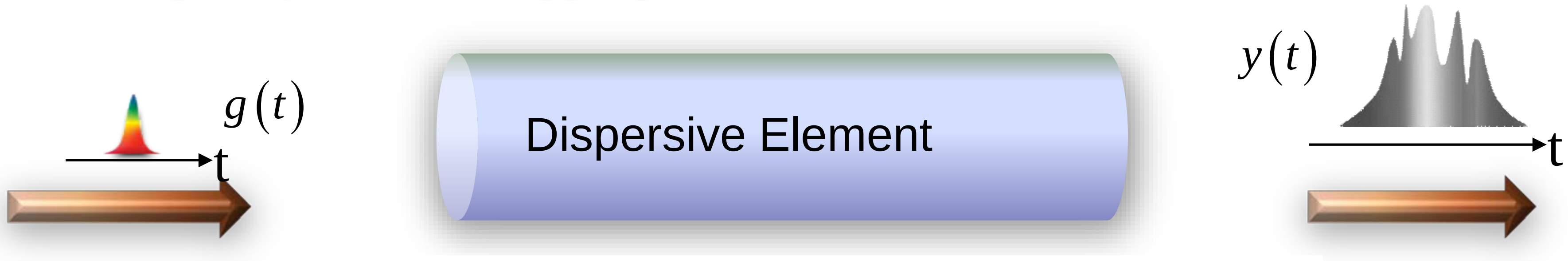
Photonic microwave waveform generation based on ***spectral shaping and frequency-to-time mapping***

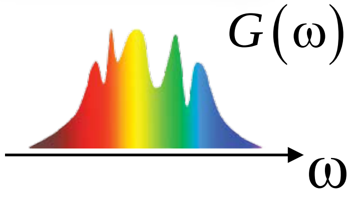


$$y(t) \propto G(\omega)\big|_{\omega=\frac{t}{\ddot{\Phi}}}$$

Photonic microwave waveform generation based on *spectral shaping and frequency-to-time mapping*

- **Frequency-to-time mapping**

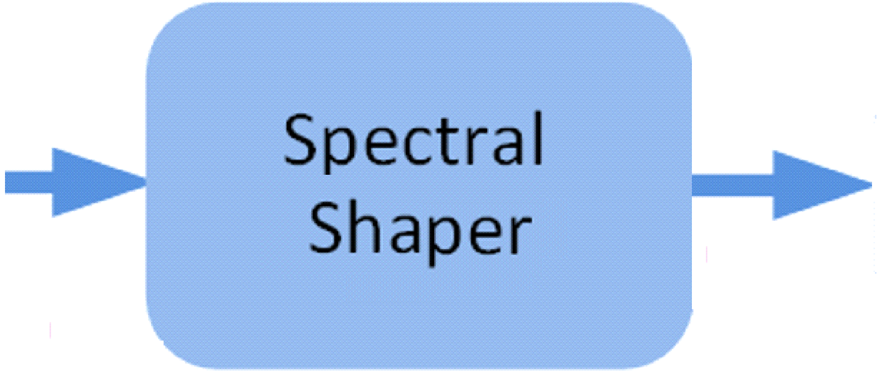


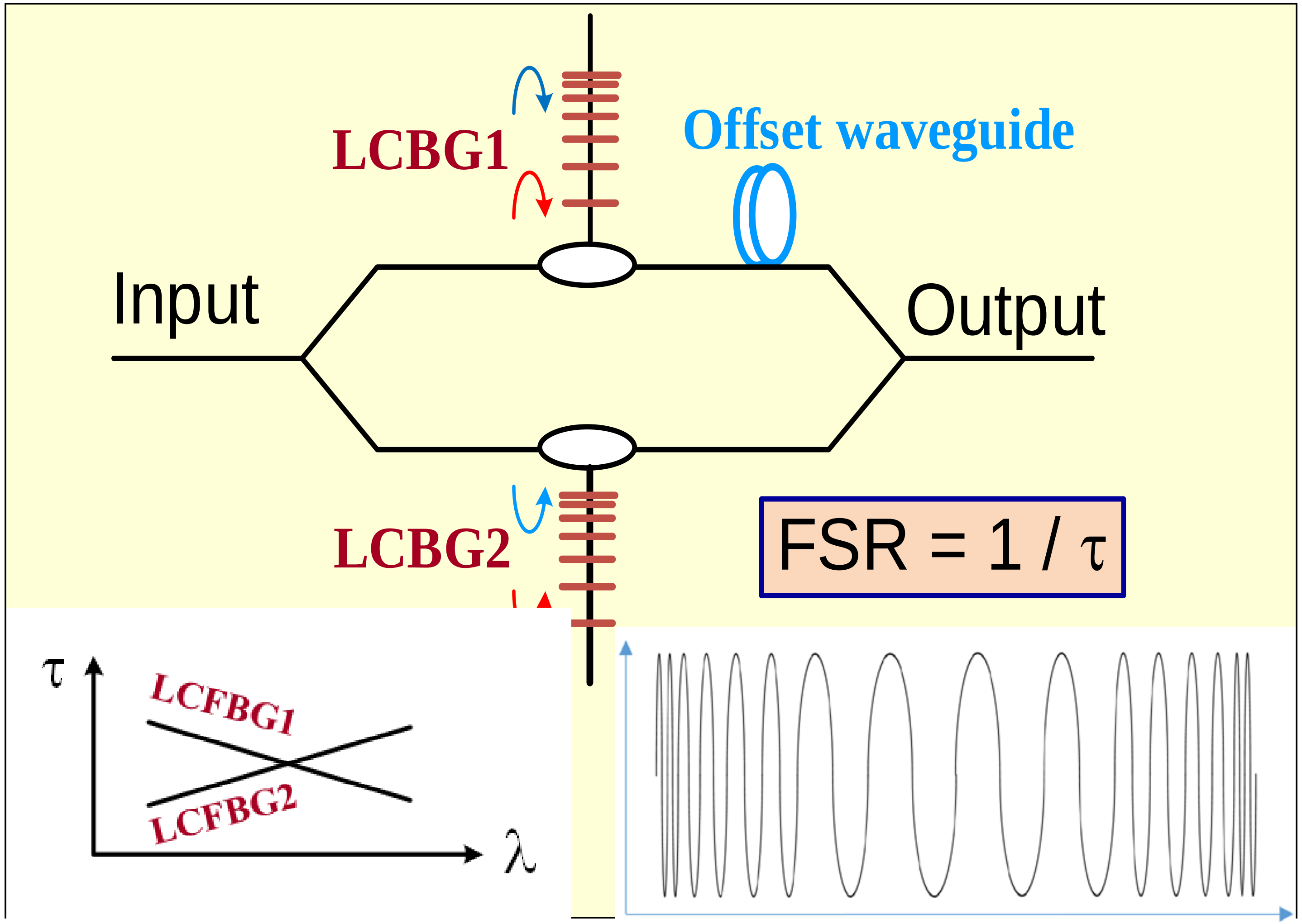


$$
\begin{aligned}
y(t) &= g(t) * \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right) = \int_{-\infty}^{\infty} g(\tau) \times \exp\left[j\frac{(t-\tau)^2}{2\ddot{\Phi}}\right] d\tau \\
&= \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right) \times \int_{-\infty}^{\infty} g(\tau) \times \exp\left(j\frac{\tau^2}{2\ddot{\Phi}}\right) \times \exp\left[-j\left(\frac{t}{\ddot{\Phi}}\right)\tau\right] d\tau \\
&\approx \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right) \times \int_{-\infty}^{\infty} g(\tau) \times \exp\left[-j\left(\frac{t}{\ddot{\Phi}}\right)\tau\right] d\tau \\
&= \exp\left(j\frac{t^2}{2\ddot{\Phi}}\right) \times G(\omega)\Big|_{\omega=\frac{t}{\ddot{\Phi}}} \approx G(\omega)\Big|_{\omega=\frac{t}{\ddot{\Phi}}}
\end{aligned}
$$

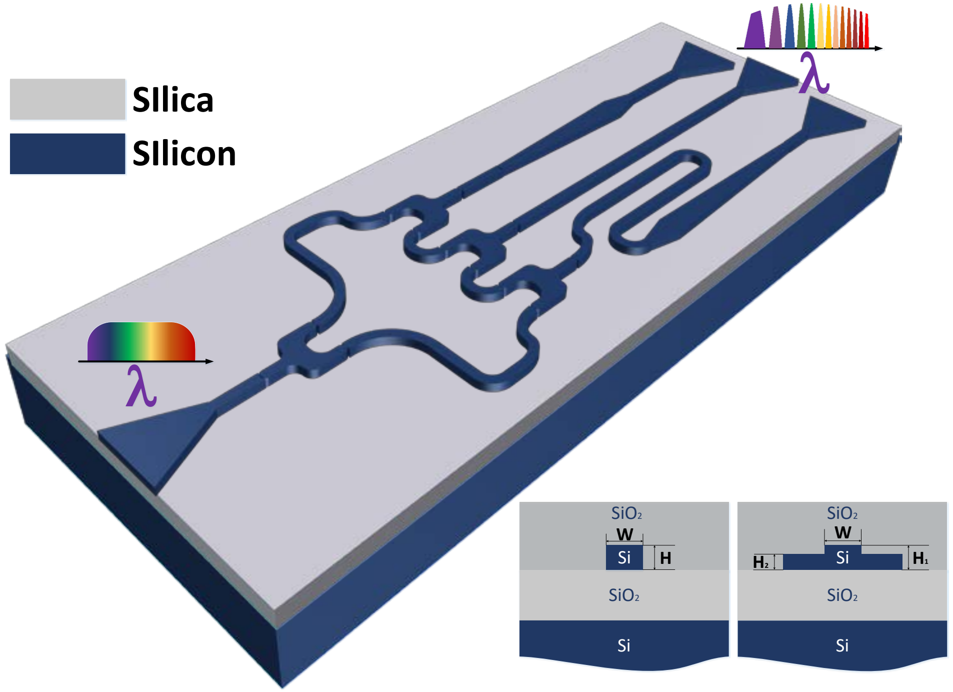
Wavelength-to-time mapping, namely dispersive Fourier transformation, is a fast and effective way to **measure optical spectrum in the time domain**.

On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings

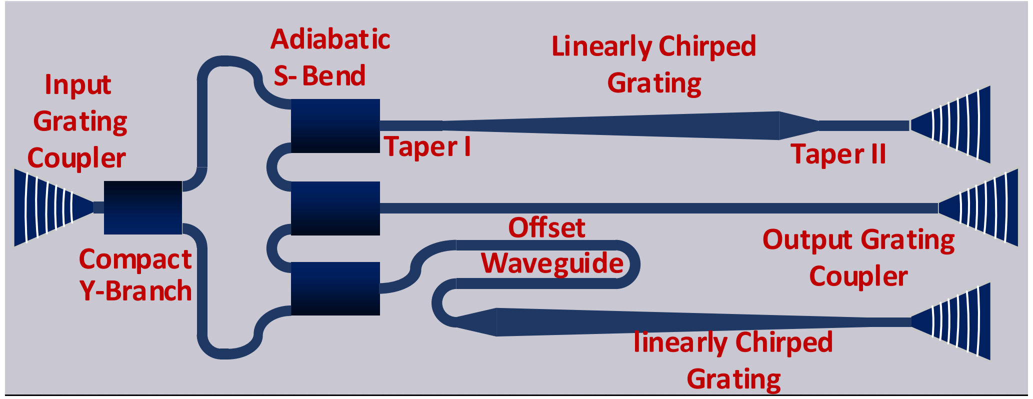




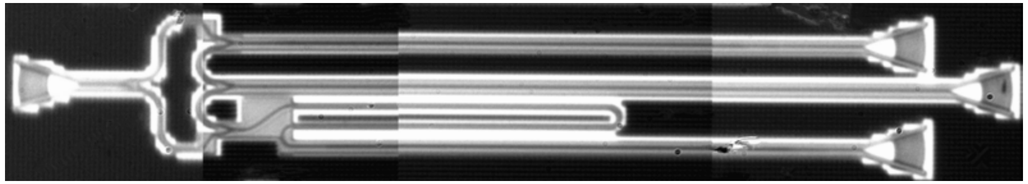
On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings



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

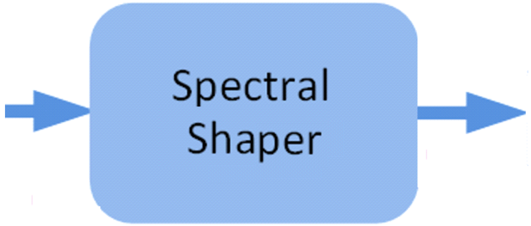


(a)



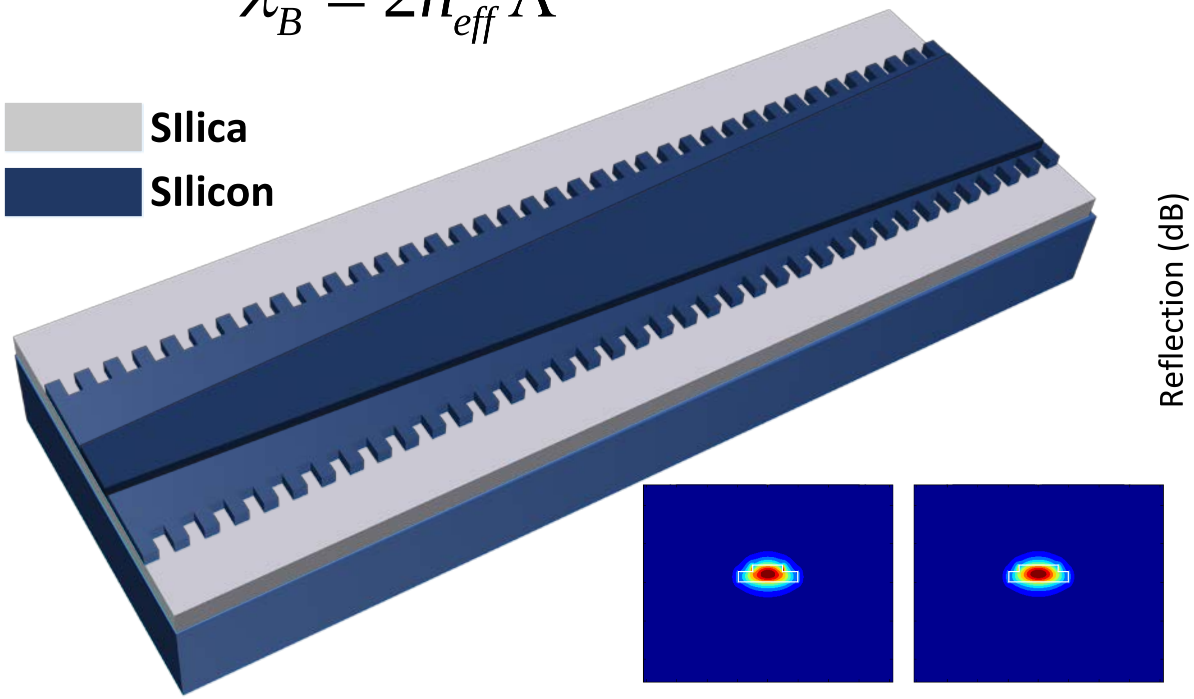
(b)

(a) Schematic layout of the designed on-chip spectral shaper; (b) Image of the fabricated spectral shaper captured by a microscope camera.

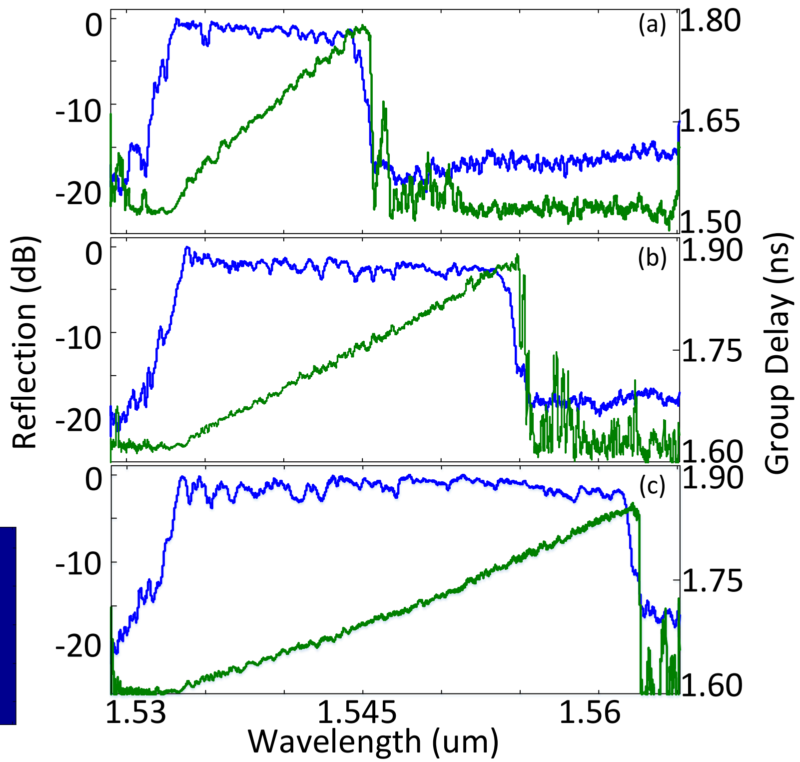


On-chip spectral shaper incorporating linearly chirped waveguide Bragg gratings

$$\lambda_B = 2n_{eff}\Lambda$$



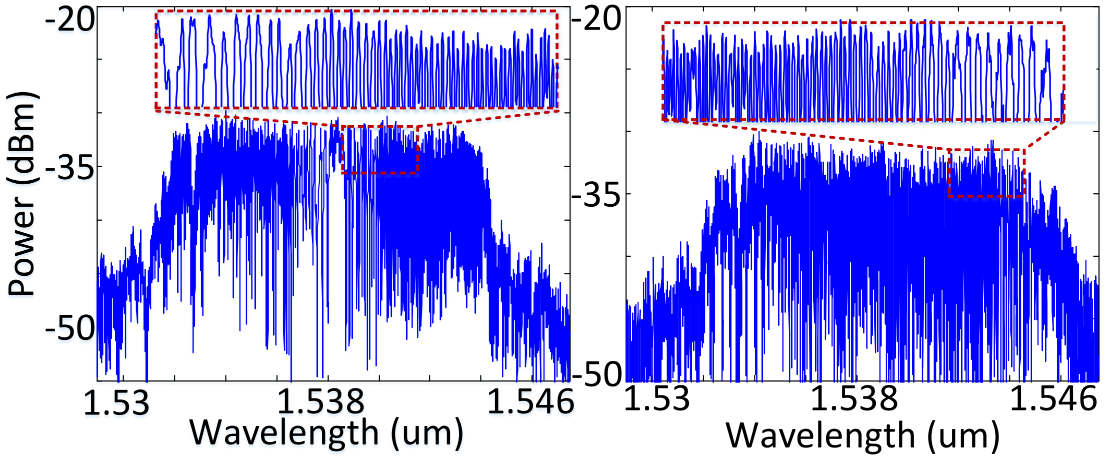
Perspective view of the proposed LC-WBG. (Inset: Simulated fundamental TE mode profile of the rib waveguide with the rib width of 500 nm (left) and 650 nm (right)).

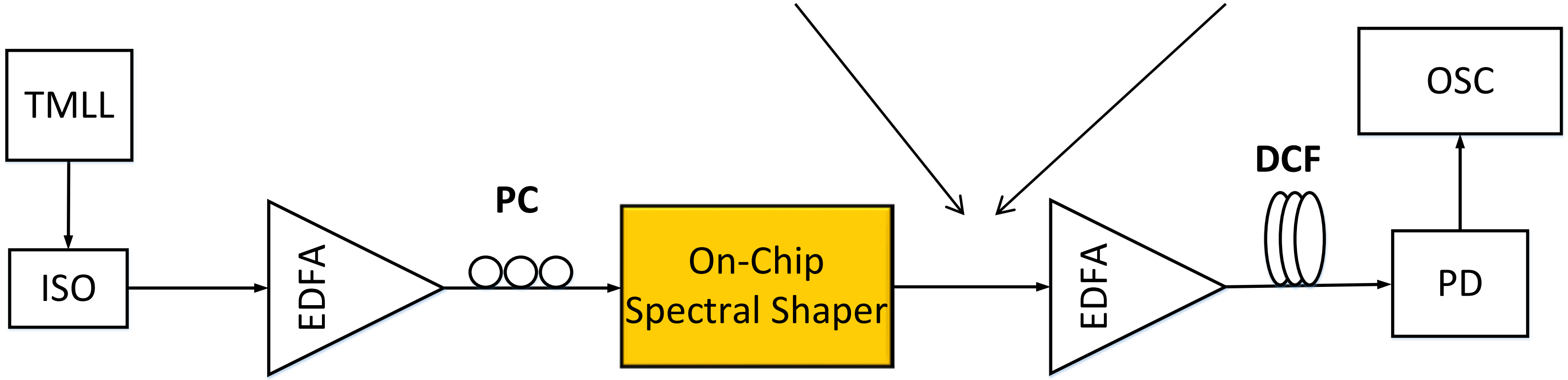


Measured spectral and group delay responses of the LC-WBG with the rib width increasing from 500 nm to (a) 550 nm, (b) 600 nm and (c) 650 nm along the gratings.

Experimental Results

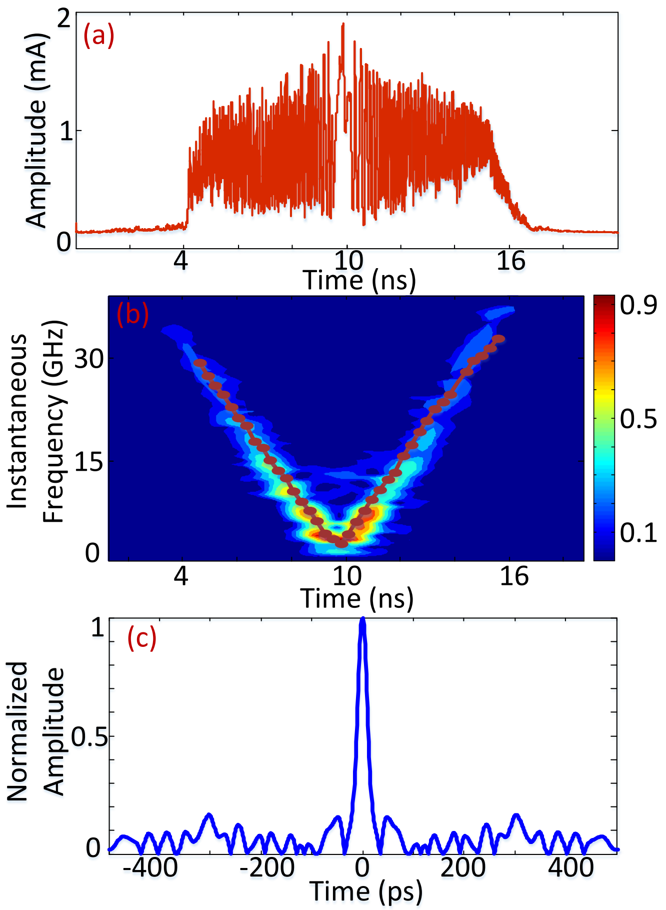
Measured spectral response of an on-chip spectral shaper when the length of the offset waveguide is (left) zero and (right) the length of the LC-WBG.



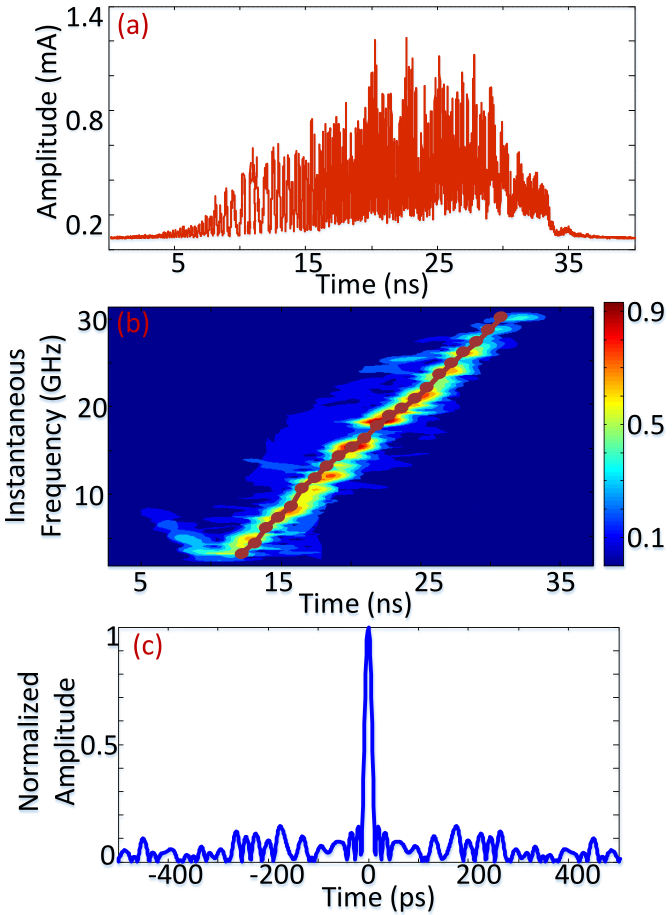


Experimental setup. TMML: tunable mode lock laser. ISO: Isolator; EDFA: erbium-doped fiber amplifier. PC: polarization controller. DCF: dispersion compensation fiber. PD: photodetector. OSC: oscilloscope.

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.



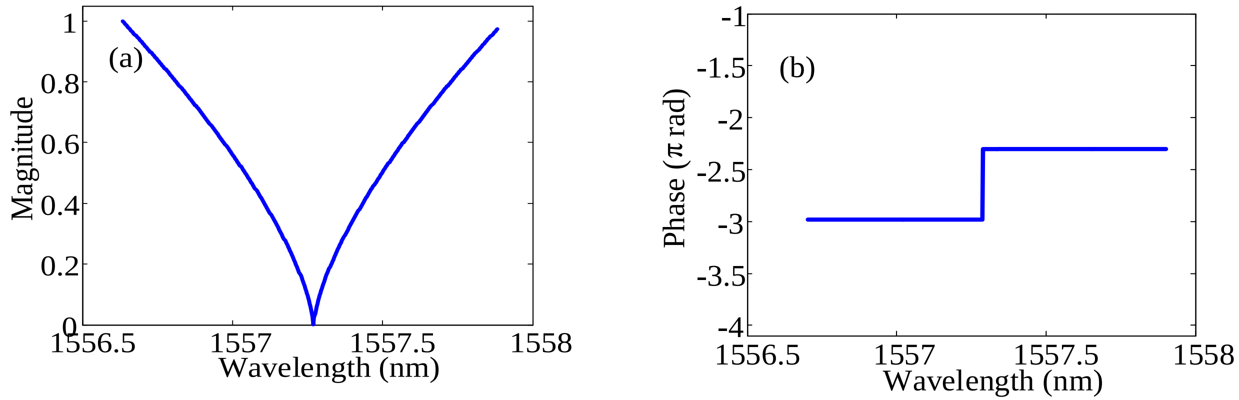
Experimental result: (a) the generated LCMW; (b) experimental spectrogram curve and numerical instantaneous frequency of the generated LCMW, and (c) compressed pulse by autocorrelation when the length of the offset waveguide equates to the length of LC-WBG.

Outline

- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry–Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg grating for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg grating for multichannel signal processing
- Conclusion

Photonic temporal differentiator

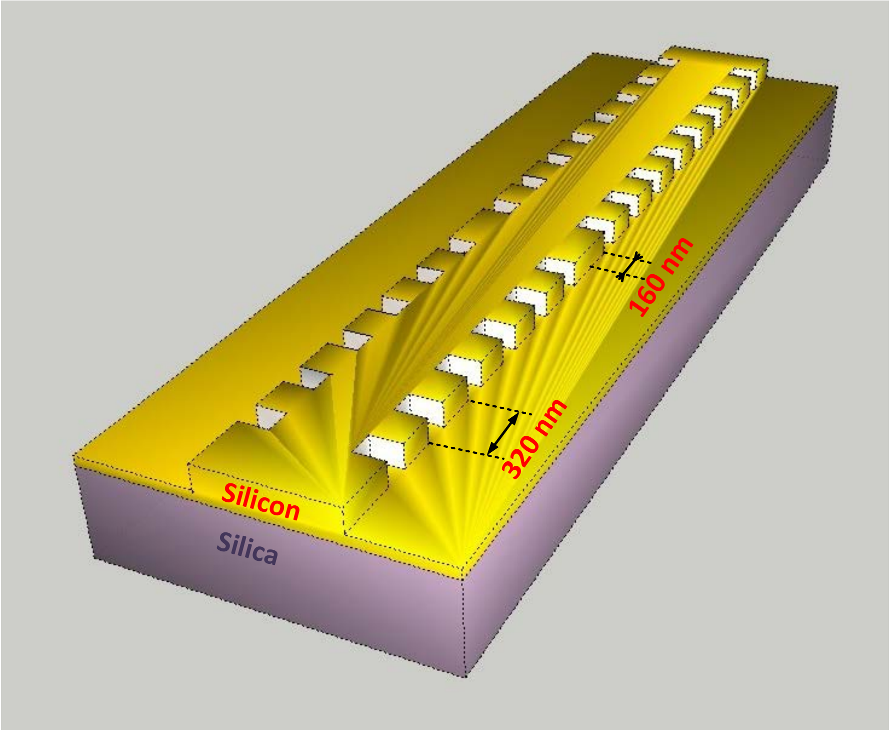
$$H(\omega) = j(\omega - \omega_0) = \begin{cases} e^{j\frac{\pi}{2}} \left|\omega - \omega_0\right|, & \omega > \omega_0 \\ e^{-j\frac{\pi}{2}} \left|\omega - \omega_0\right|, & \omega < \omega_0 \end{cases}$$



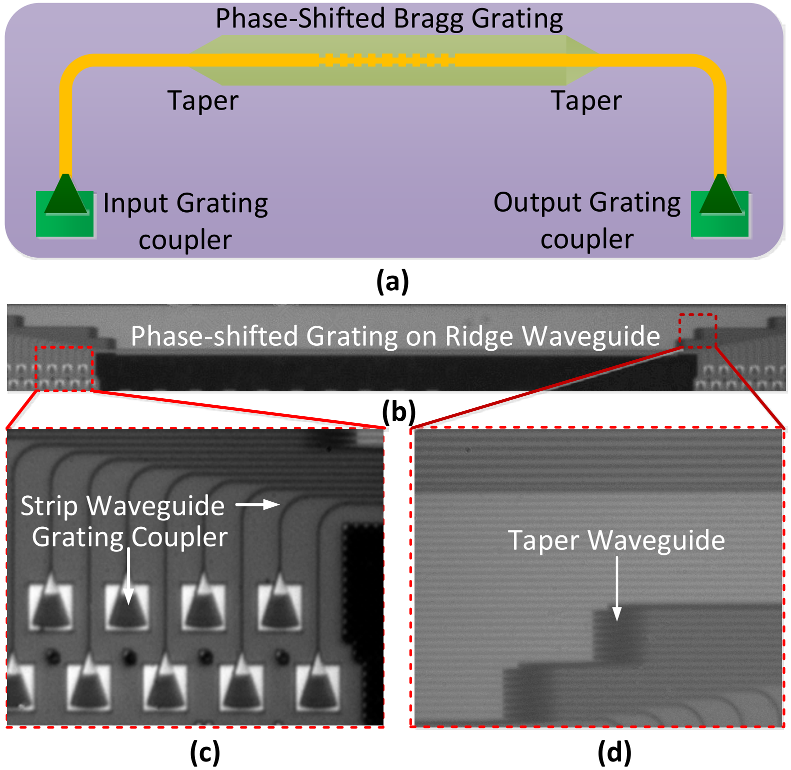
Magnitude and phase response of a differentiator.

Applications: phase to intensity conversion in an optical phase-modulated system.

Photonic microwave temporal differentiator using an integrated phase-shifted Bragg grating

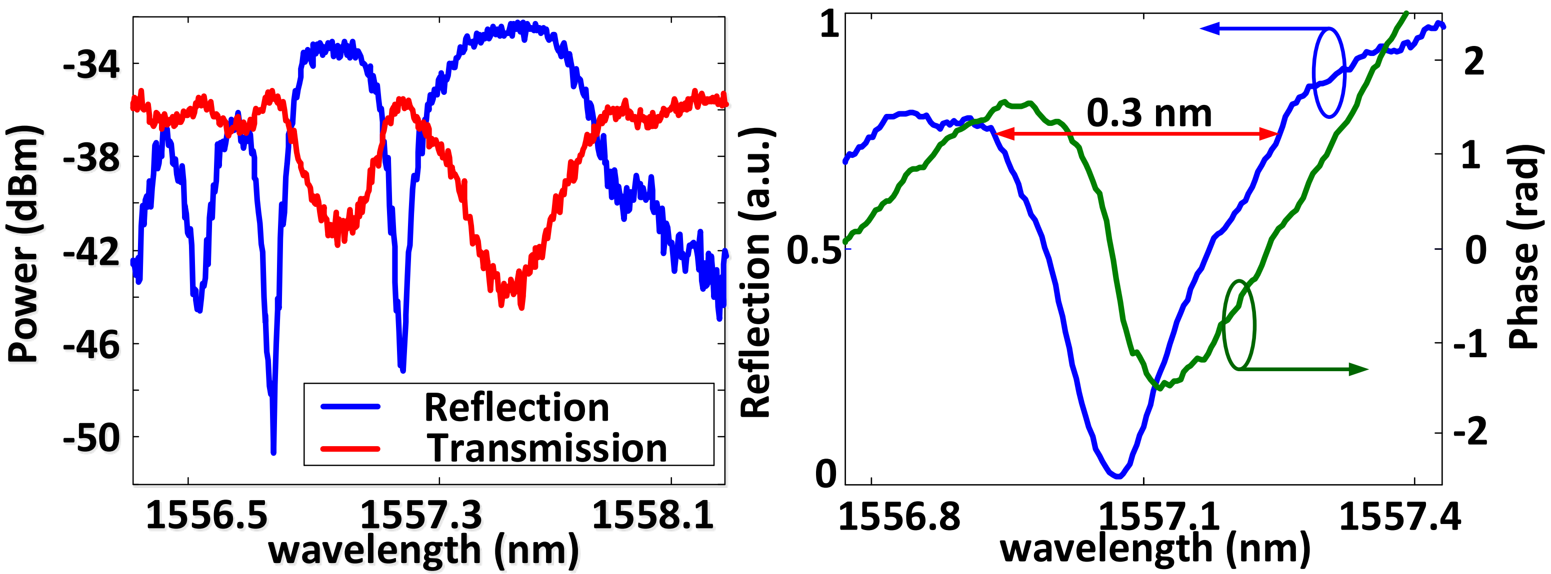


Configuration of the phase-shifted Bragg grating (PSBG) in a silicon-on-insulator ridge waveguide.



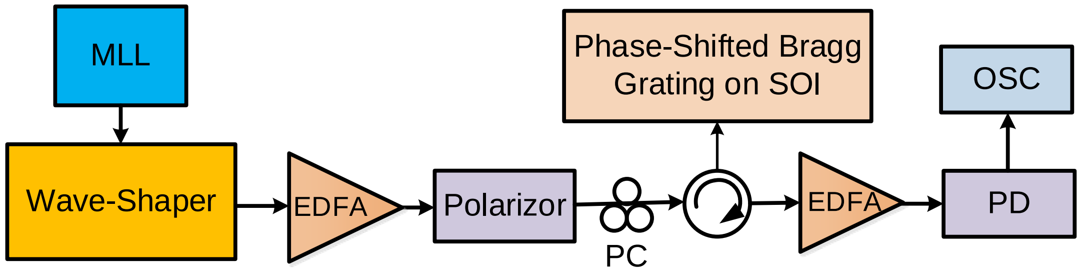
(a) Schematic layout. (b) Image of the fabricated device. (c) Image of the grating couplers and the strip waveguides. (d) Image of the taper waveguides for the transition between the strip waveguides and ridge waveguides.

Experimental Results

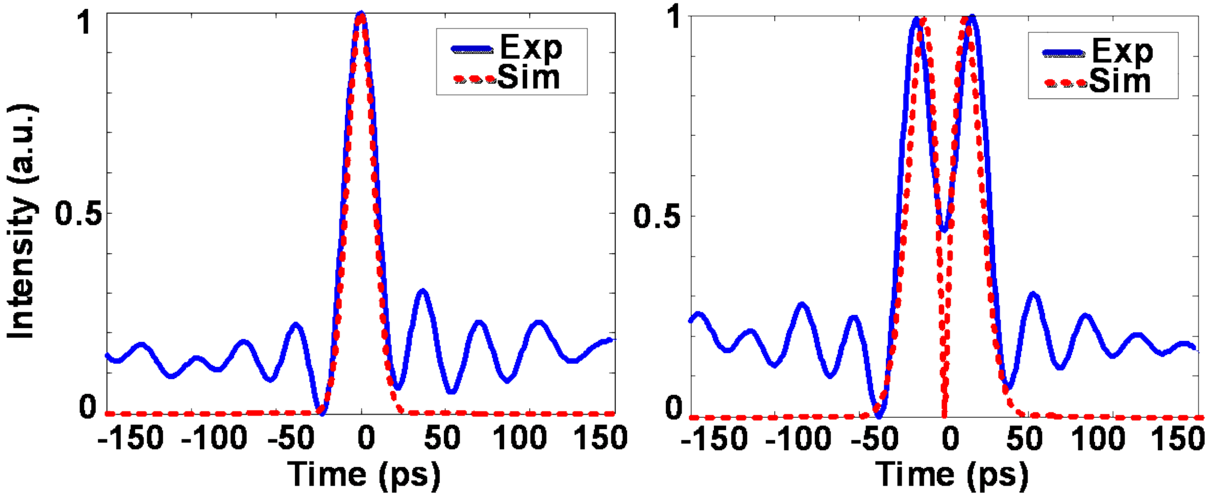


(**Left**) Measured reflection and transmission spectral responses of the fabricated PSBG on a ridge waveguide with a designed corrugation width of 125 nm. (**Right**) Zoom-in view of the reflection notch and its phase response.

Experimental Results



Experimental setup. MML: mode lock laser. EDFA: erbium-doped fiber amplifier. PC: polarization controller. PD: photodetector. OSC: oscilloscope.



(**Left**) An input Gaussian pulse with an FWHM of 25 ps, and (**Right**) the temporally differentiated pulses by simulation and experiment.

Outline

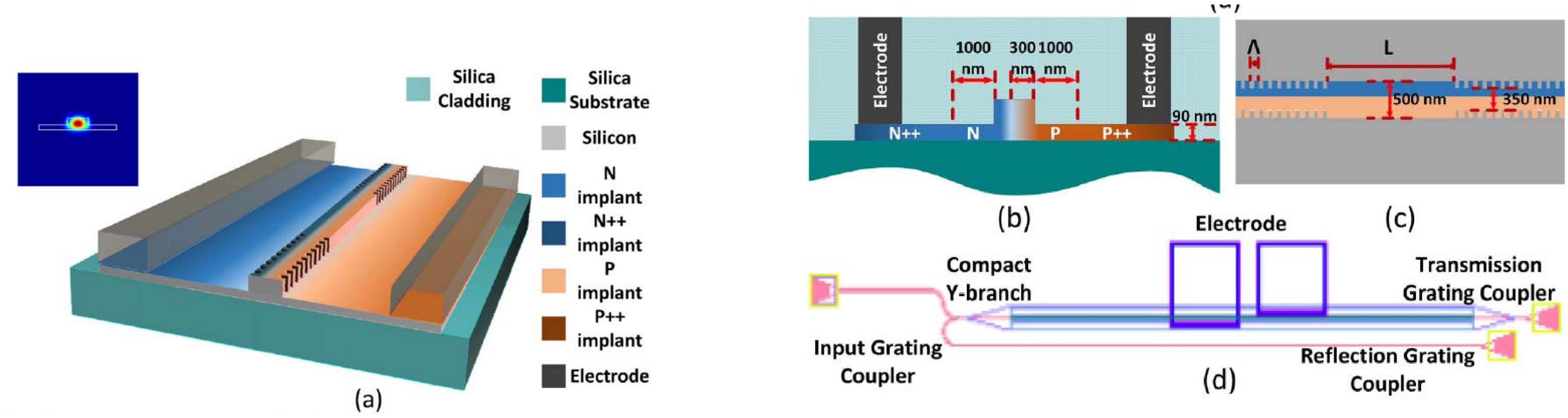
- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry–Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg grating for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg grating for multichannel signal processing
- Conclusion

Letter Vol. 40, No. 13 / July 1 2015 / *Optics Letters* 3153

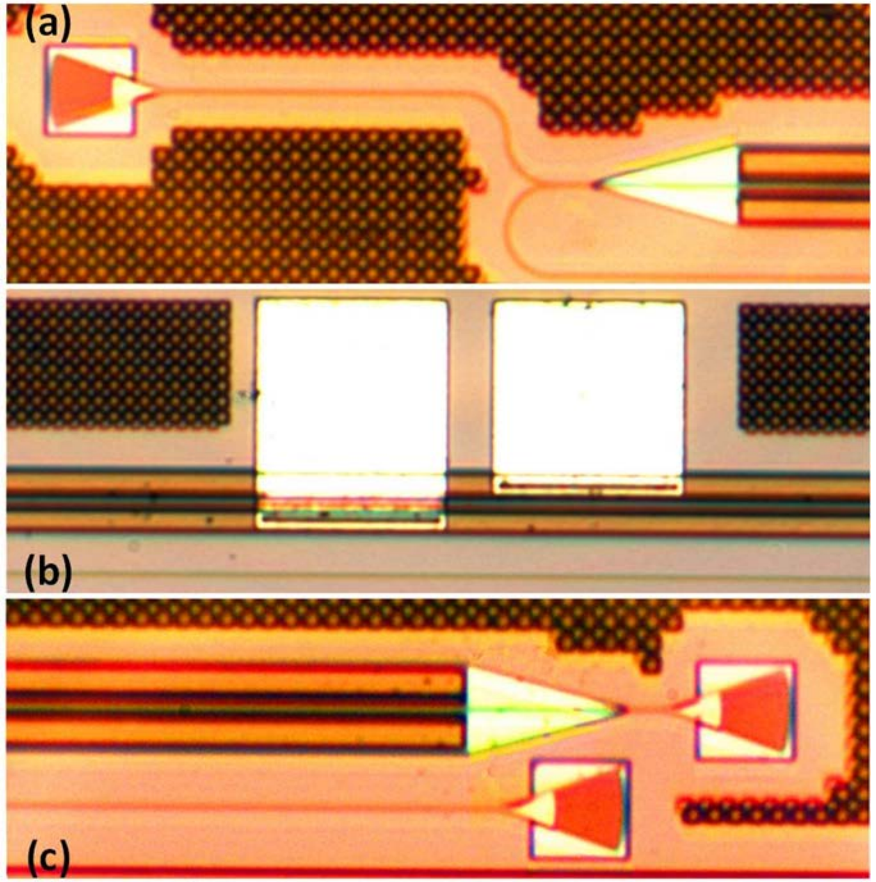
Optics Letters

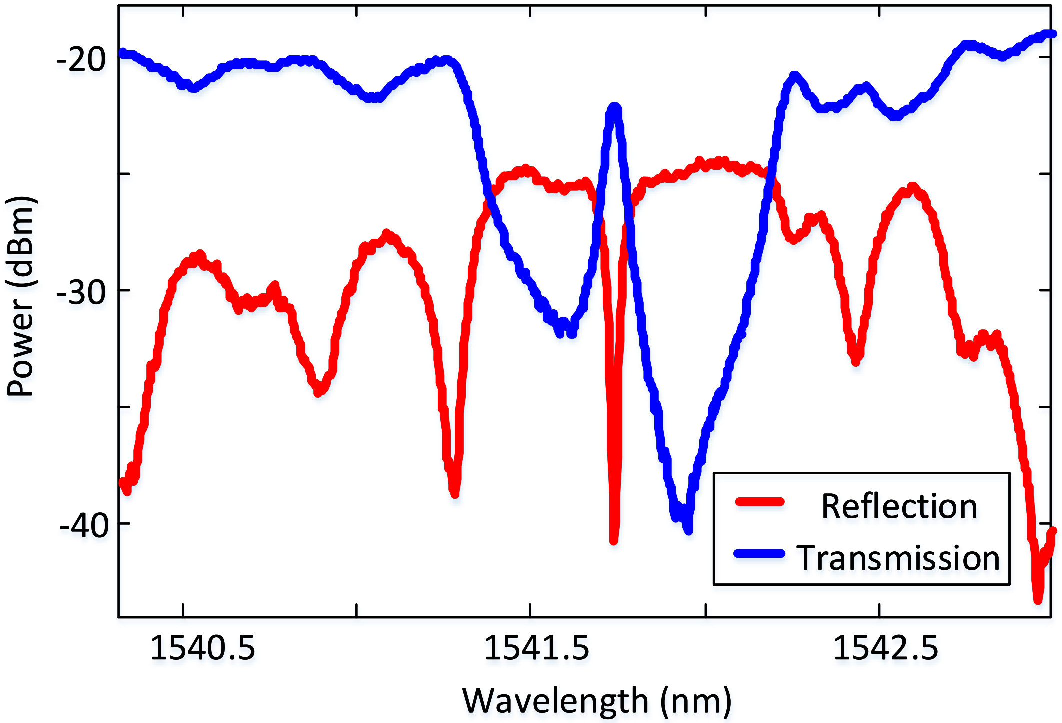
Silicon-based on-chip electrically tunable sidewall Bragg grating Fabry–Perot filter

WEIFENG ZHANG, NASRIN EHTESHAMI, WEILIN LIU, AND JIANPING YAO*



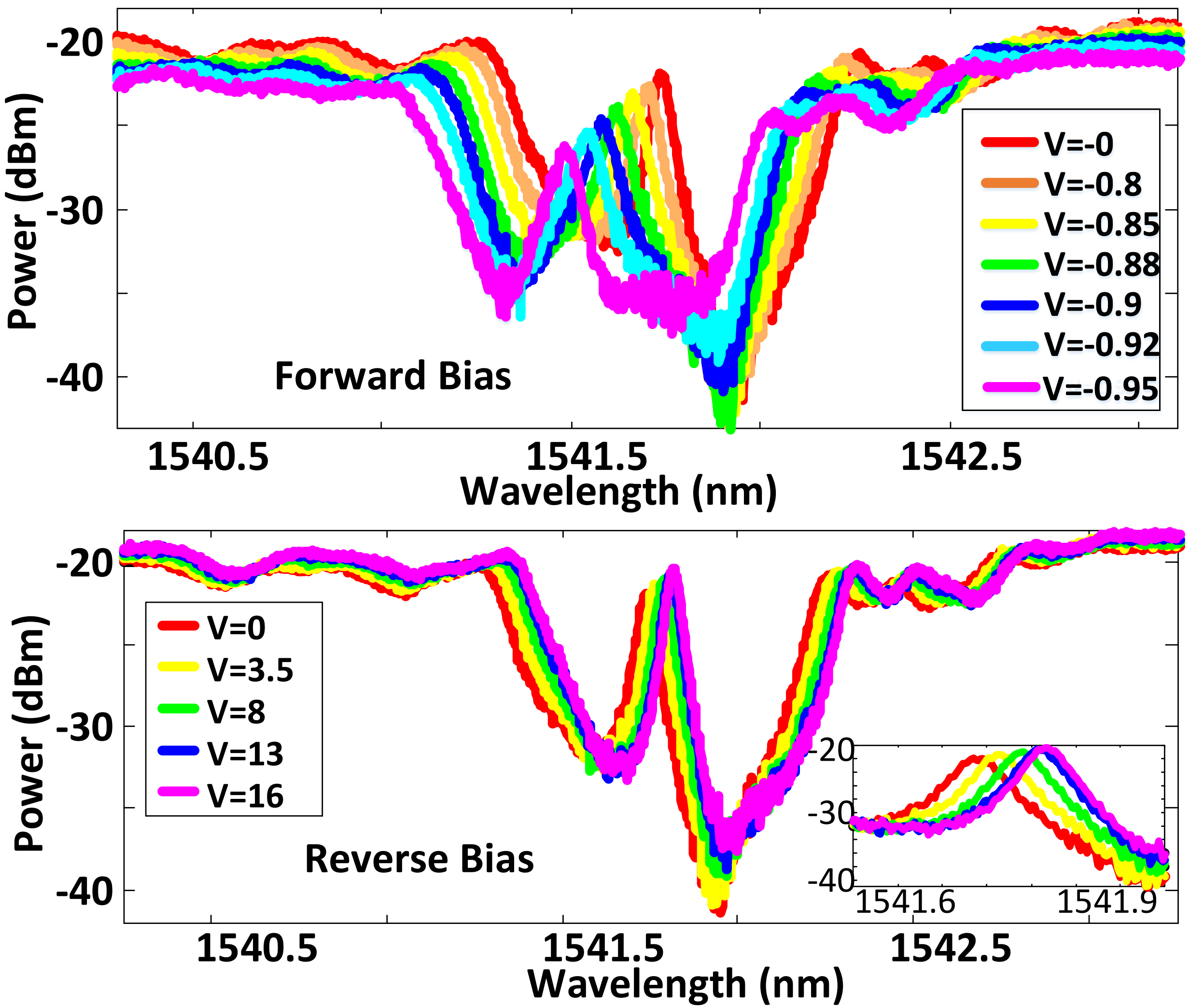
Silicon-based on-chip electrically tunable phase-shifted waveguide Bragg grating





Measured spectra when a zero bias voltage is applied. The notch in the reflection band has a 3-dB bandwidth of 46 pm with a Q-factor of 33,500, and an extinction ratio of 16.4 dB.

Silicon-based on-chip electrically tunable phase-shifted waveguide Bragg grating

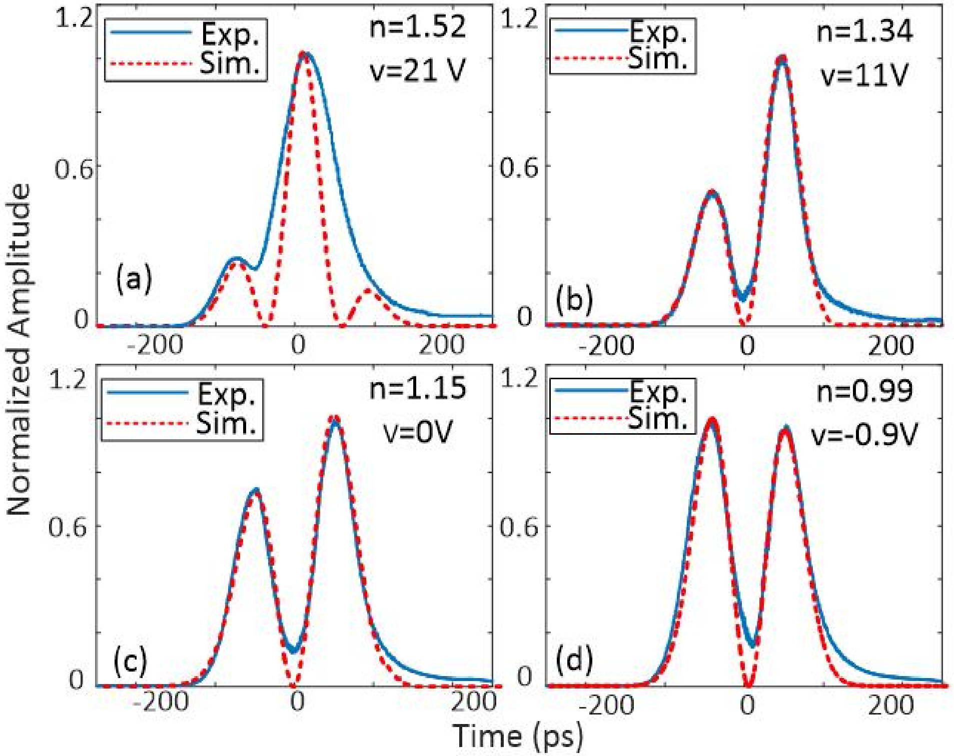


Blue-shift of the transmission spectrum when the PN junction is forward biased.

Red-shift of the transmission spectrum when the PN junction is reverse biased.

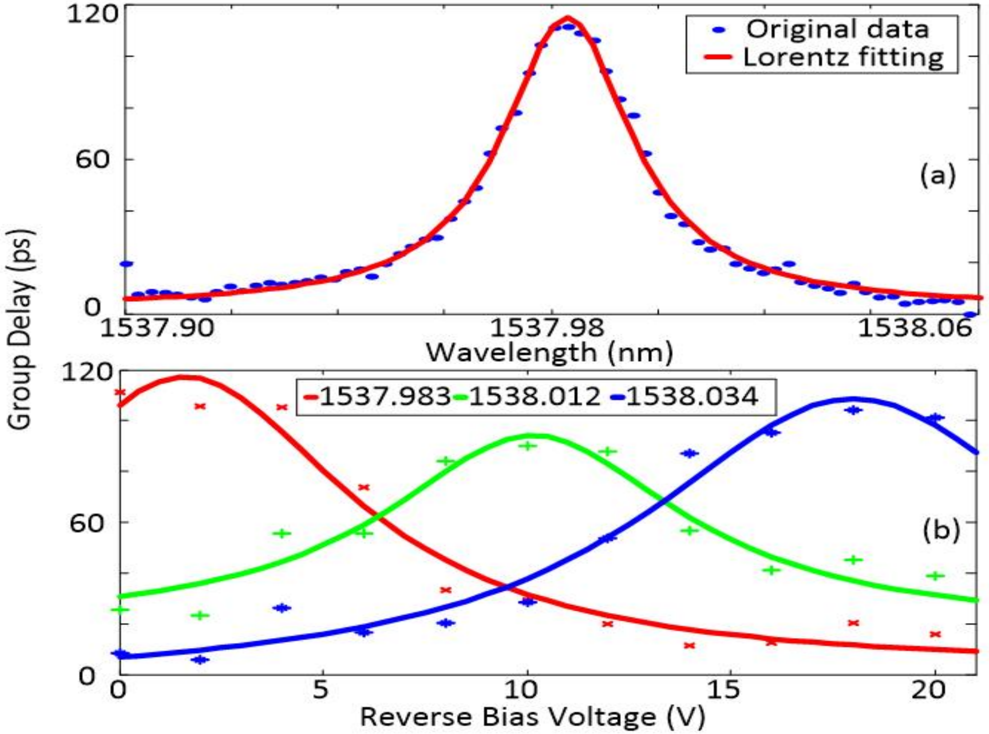
Silicon-based on-chip electrically tunable phase-shifted waveguide Bragg grating

Application 1: Tunable fractional-order photonic temporal differentiator



The resonance wavelength is shifted. A fixed resonance wavelength with a tunable phase-shift is desired.

Application 2: Tunable optical delay line



By incorporating multi-phase-shifted blocks in the PS-WBG, a delay line with a wider bandwidth could be realized .

Outline

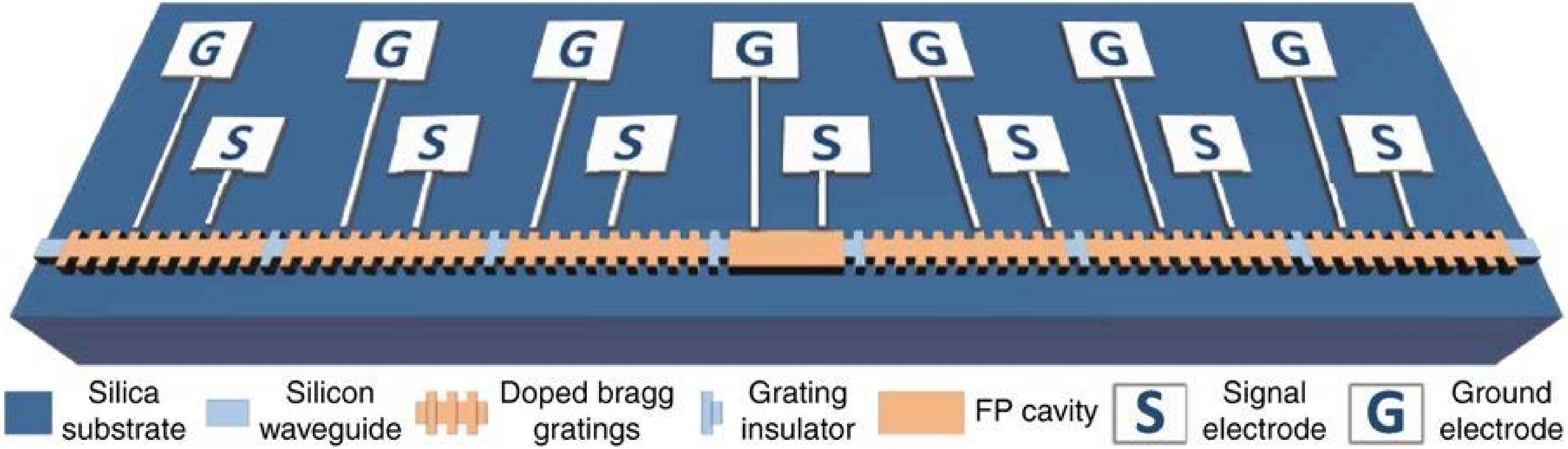
- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry–Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg grating for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg grating for multichannel signal processing
- Conclusion

ARTICLE

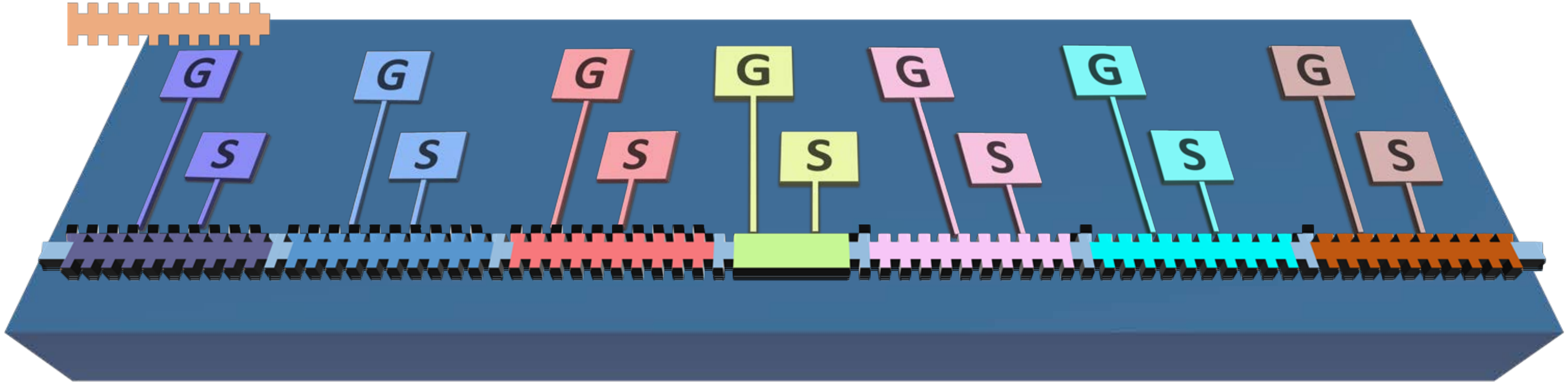
DOI: 10.1038/s41467-018-03738-3 OPEN

A fully reconfigurable waveguide Bragg grating for programmable photonic signal processing

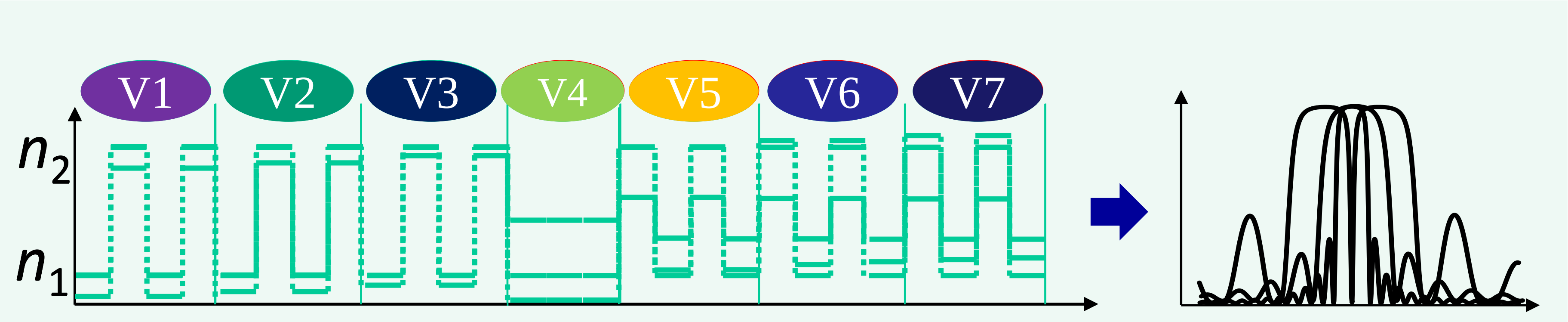
Weifeng Zhang[1] & Jianping Yao[1]



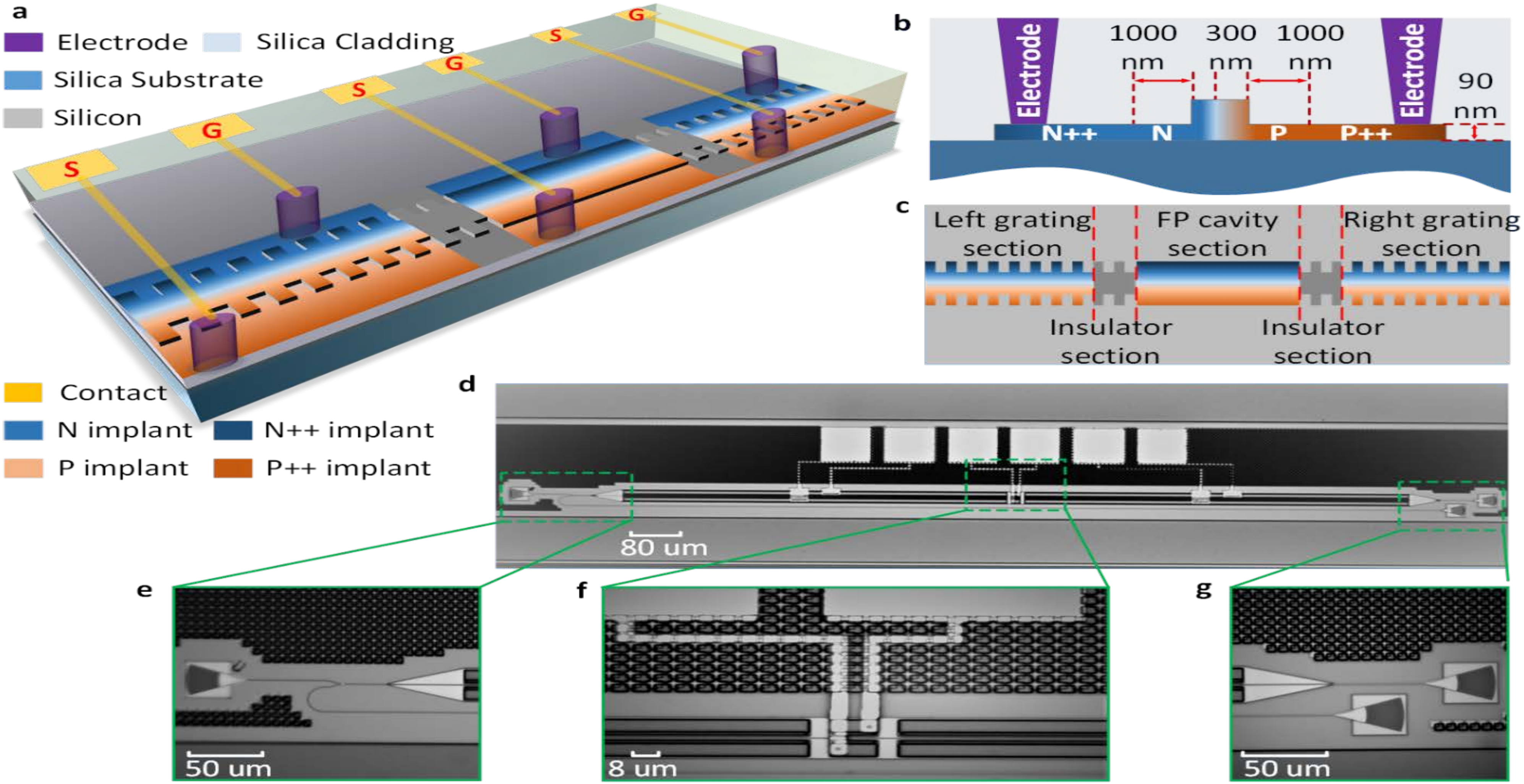
Grating design

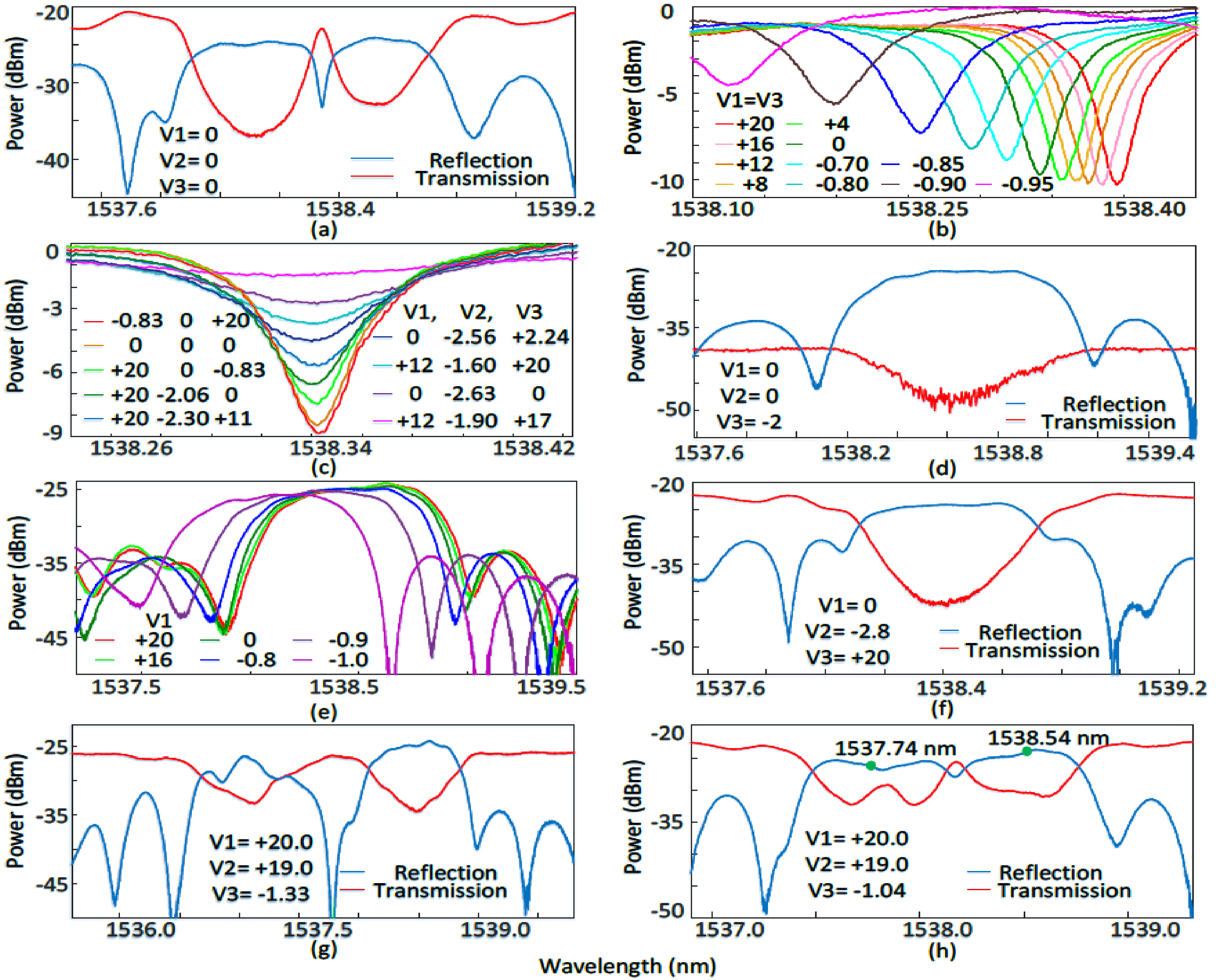


Wafer → Grating → Doping → Independent Electrodes → Voltage Control → Programmable grating



Grating design

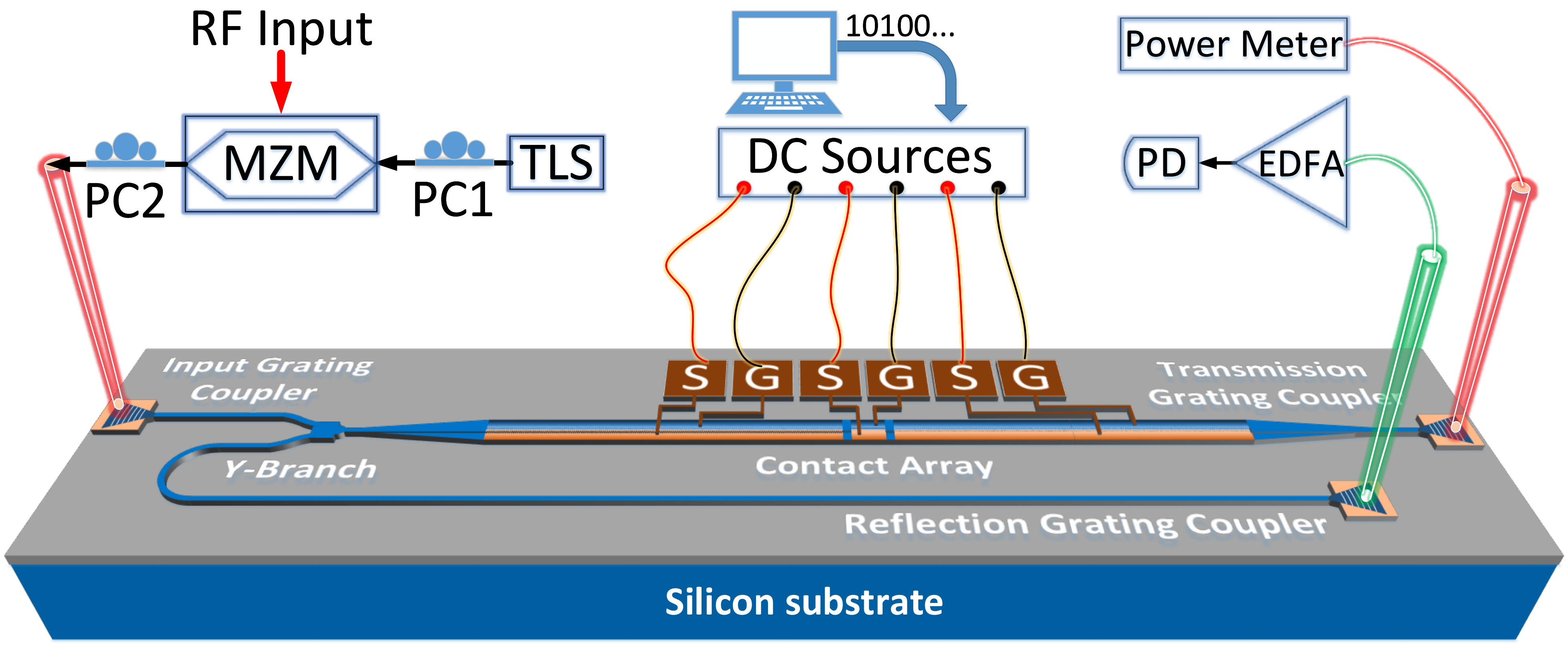




Measured reflection and transmission spectrums.

(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.

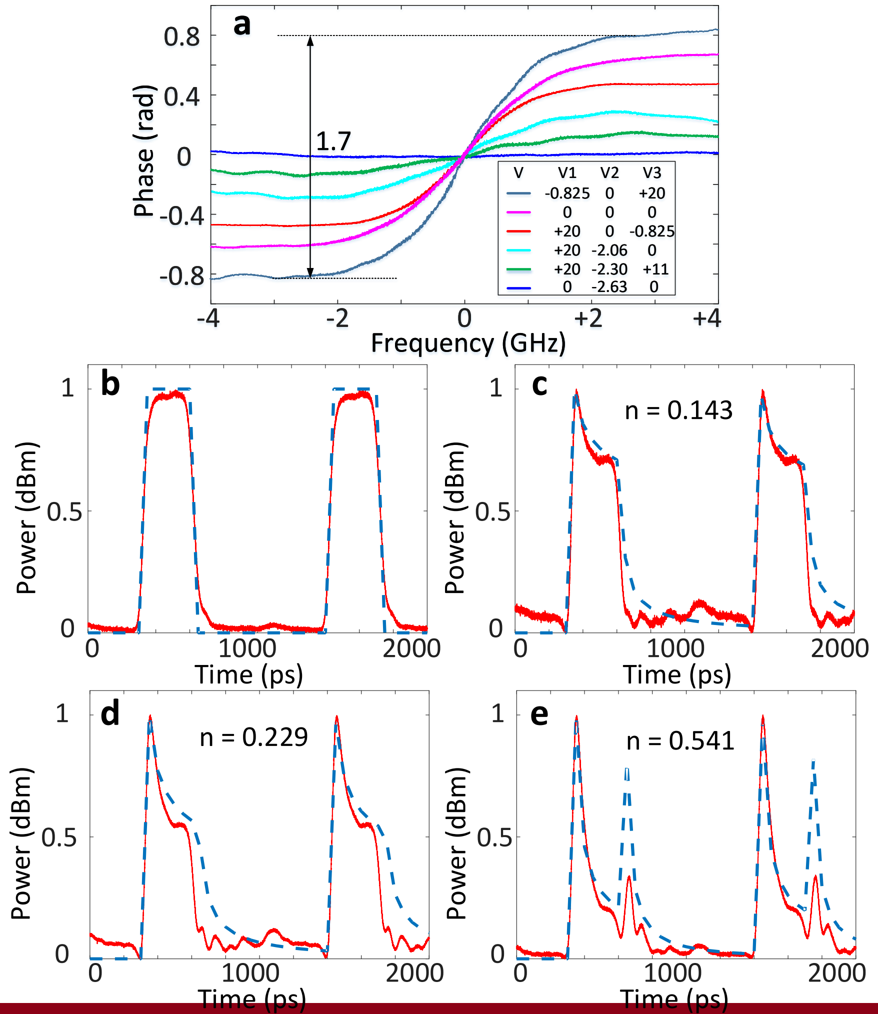
Programmable microwave signal processor



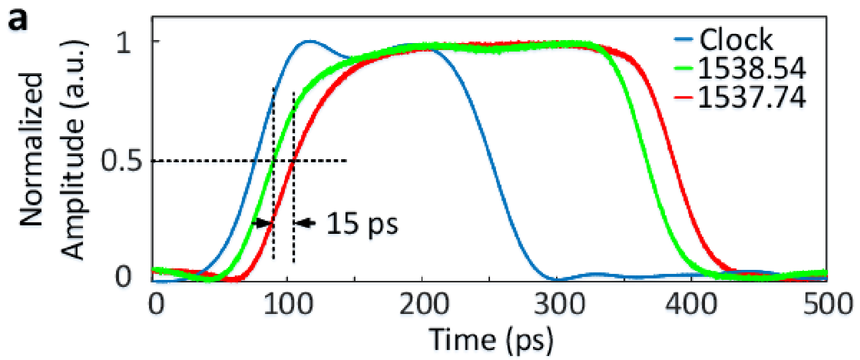
The experimental set-up consists of a tunable laser source (TLS), a polarization controller (PC), a Mach-Zehnder modulator (MZM), an erbium-doped fiber amplifier (EDFA) and a photodetector (PD).

Experimental demonstration

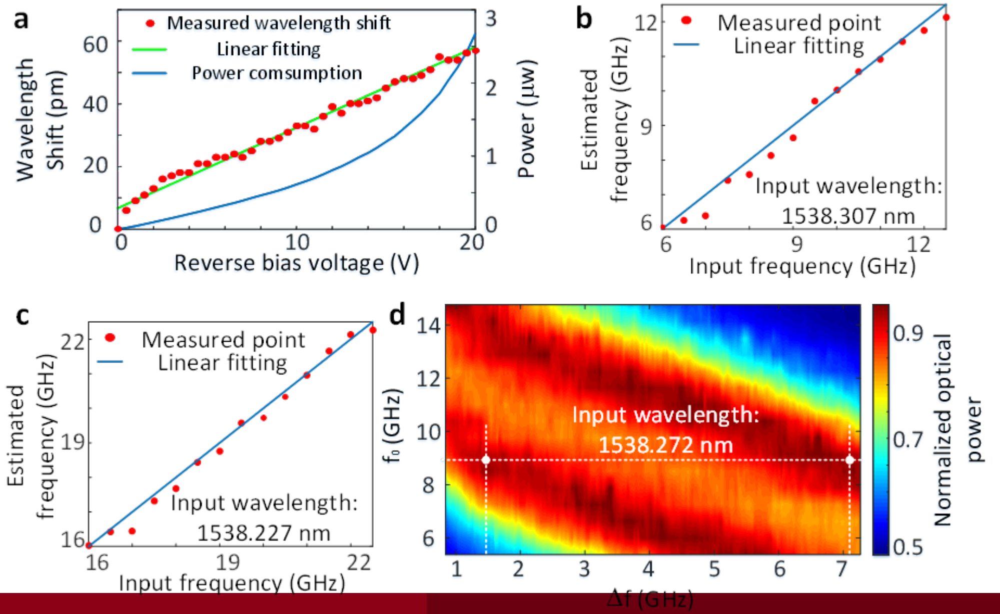
Function 1: Photonic temporal differentiation



Function 2: Microwave time delay



Function 3: Microwave frequency identification

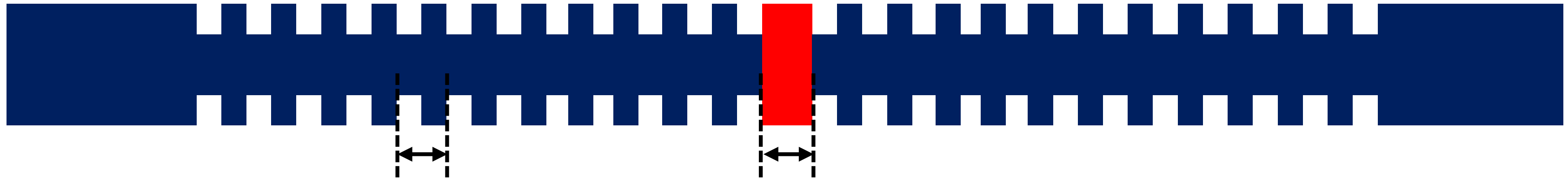


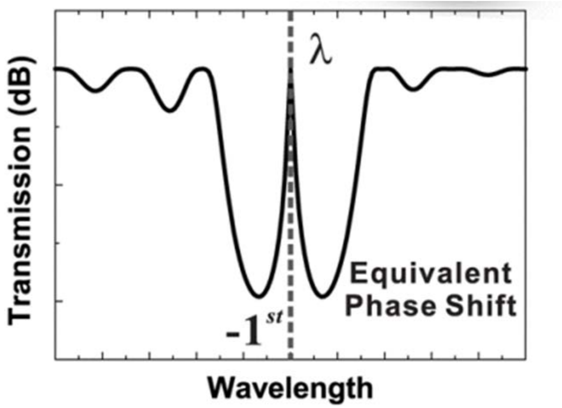
Outline

- Photonic Integrated Circuits - Material Systems
- Silicon photonic gratings
  - Chirped Bragg gratings for RF generation
  - Phase-shifted gratings for temporal differentiation
  - Electrically tunable Fabry-Perot Bragg grating for signal processing
  - Fully reconfigurable waveguide Bragg grating for programmable photonic signal processing
  - Electrically programmable equivalent-phase-shifted waveguide Bragg grating for multichannel signal processing
- Conclusion

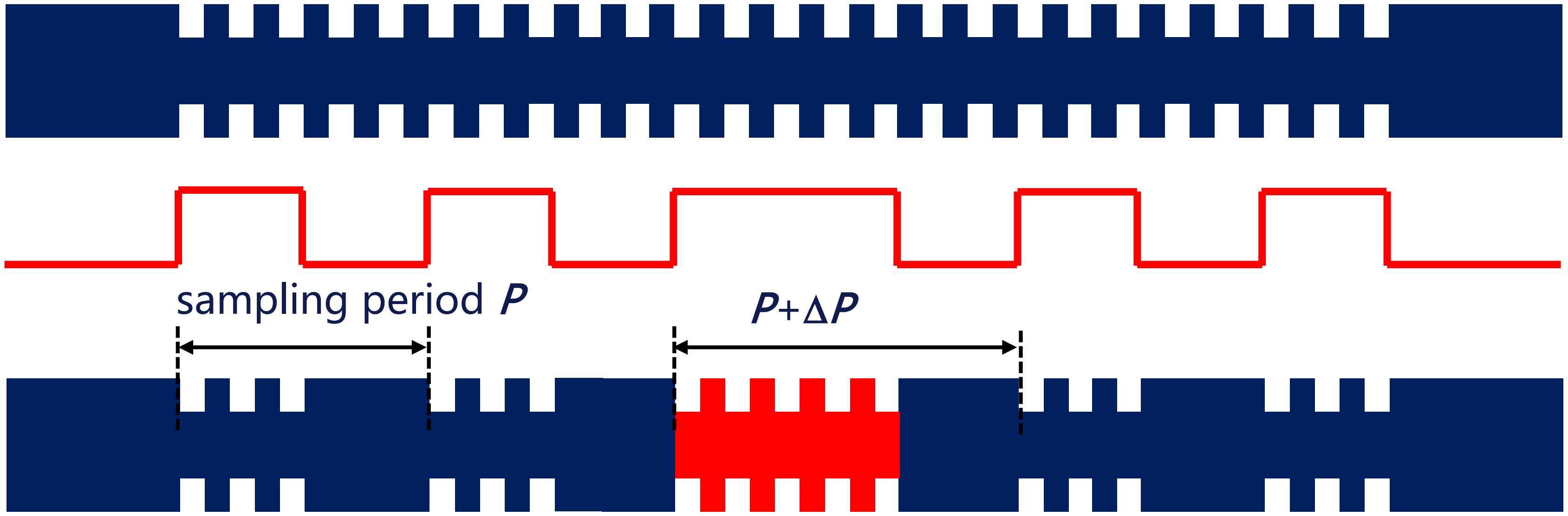
Equivalent-phase-shifted Bragg grating

✓ Conventional phase-shifted waveguide Bragg grating





✓ Equivalent-phase-shifted (EPS) waveguide Bragg grating



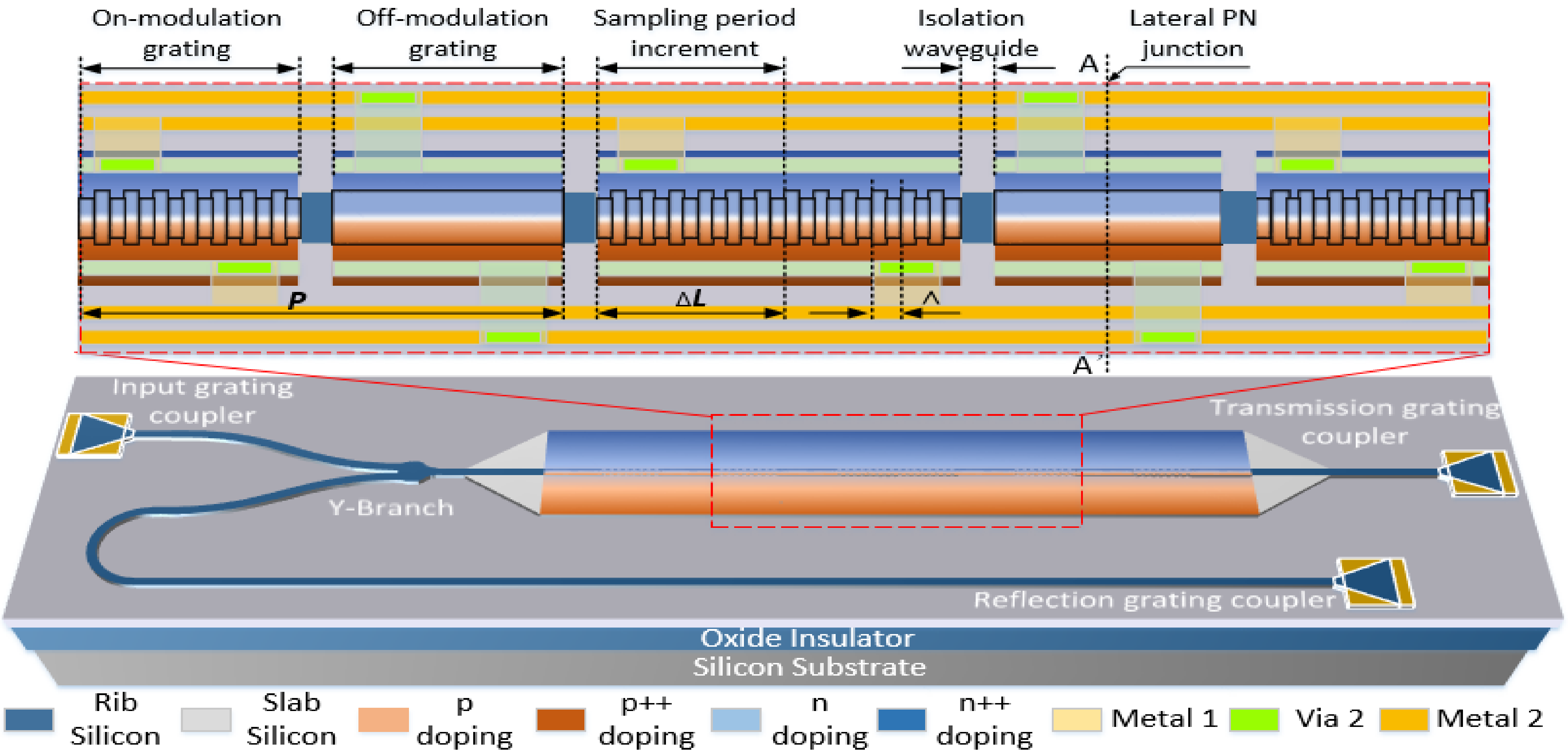
Uniform grating
+
Sampling function
↓
EPS grating

$$\theta = 2m\pi\frac{\Delta P}{P}$$

equivalent phase shift

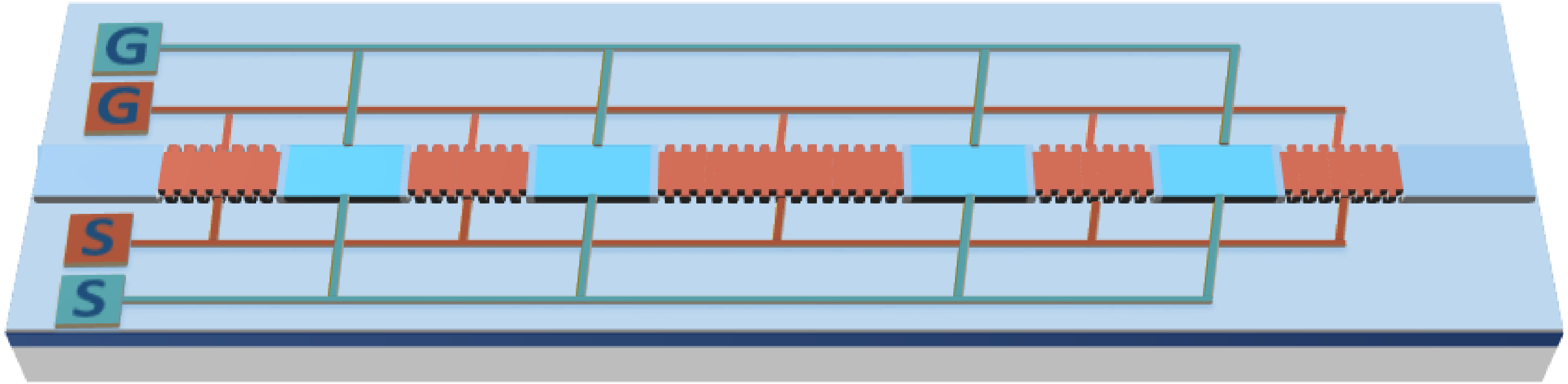
Feature size three orders of magnitude larger → easy to fabricate

Programmable EPS grating design



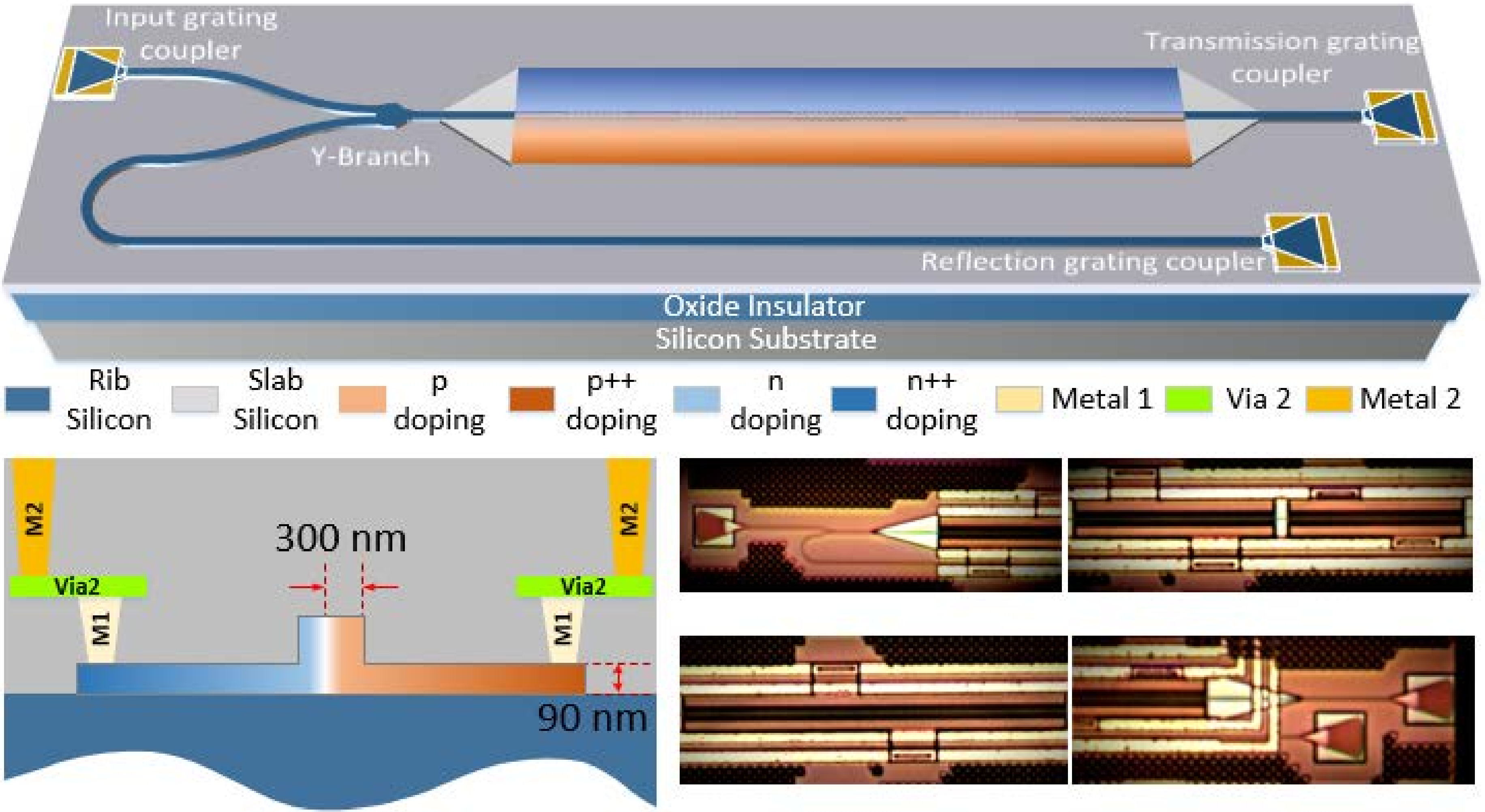
W. Zhang and J. P. Yao, *J. Lightw. Technol.*, 37, 314-322 (2019).

Programmable EPS grating design

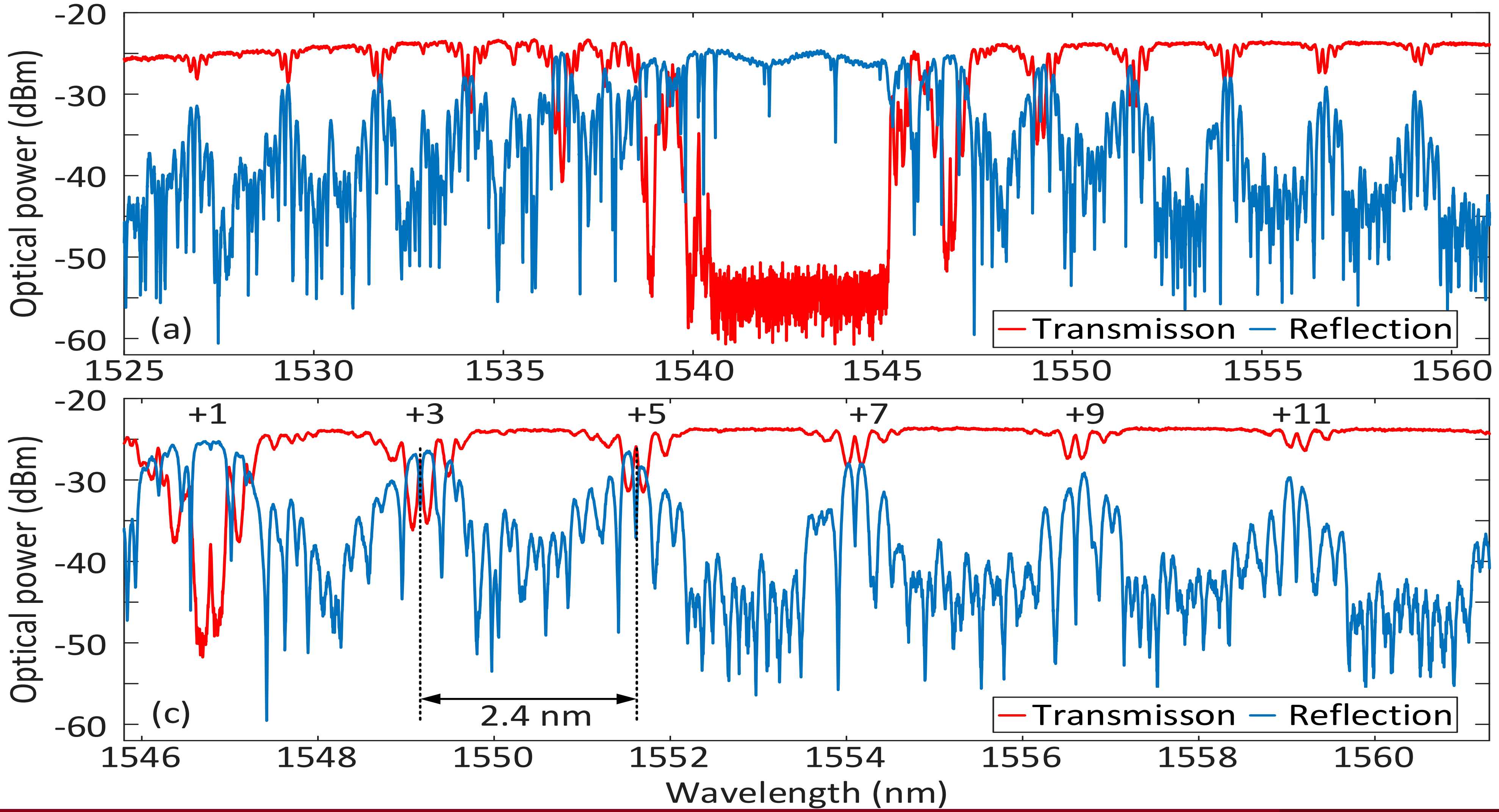


Wafer → Grating → Doping → Independent Electrodes → Voltage Control → Programmable EPS Grating

Programmable EPS grating design



Performance evaluation: static state

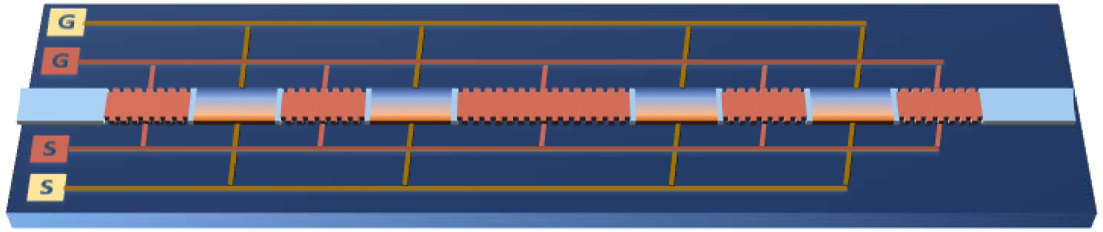


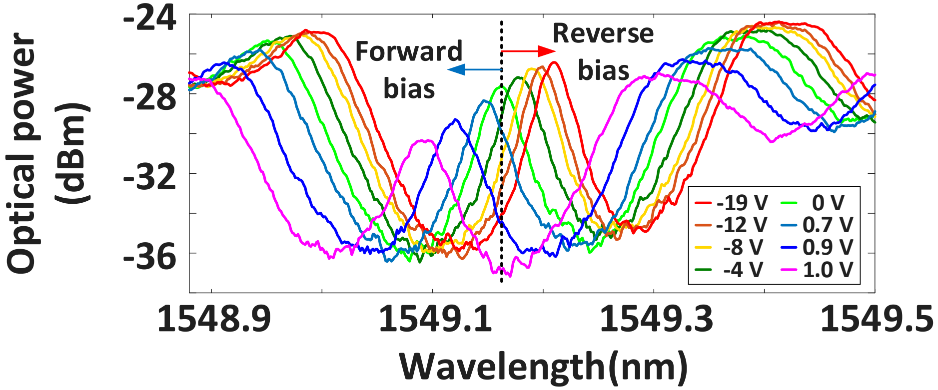
$$\theta = 2m\pi\frac{\Delta P}{P}$$

Equivalent Phase Shift

Performance evaluation： independent test

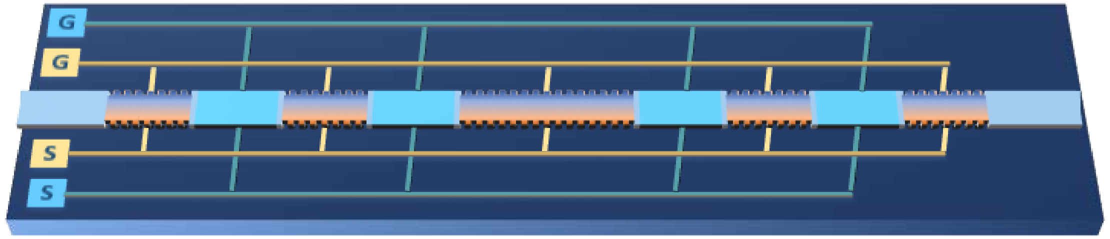
- ✓ Applying and tuning a bias voltage to the PN junctions in the on-modulation grating sections

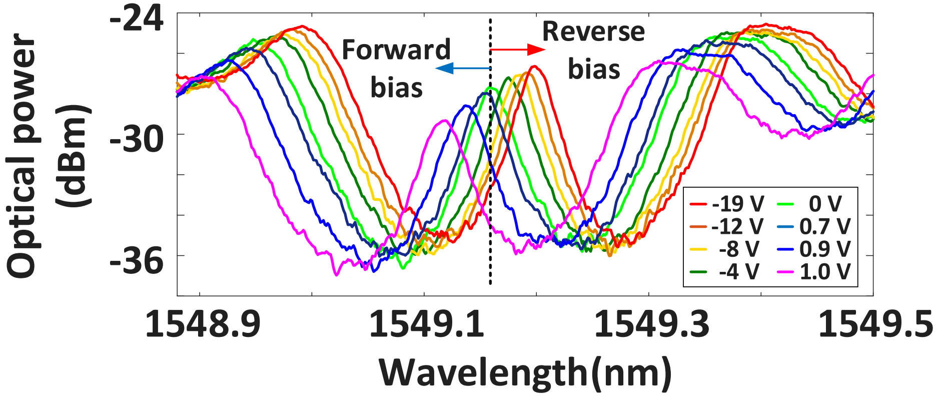




+3rd channel spectral response tuning

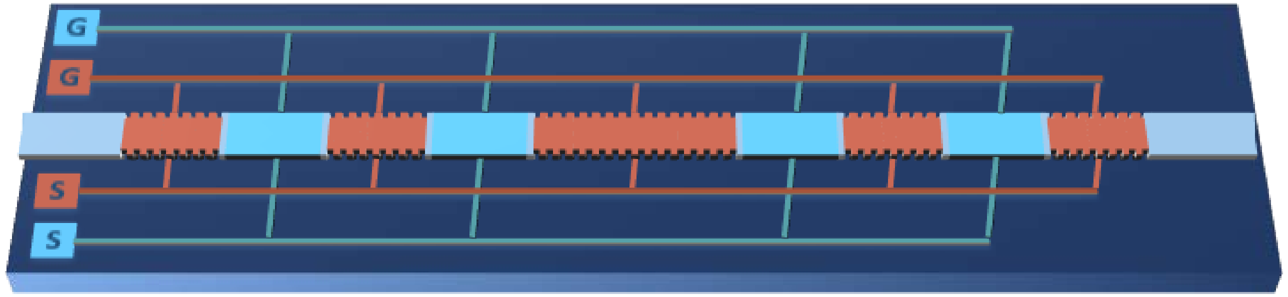
- ✓ Applying and tuning a bias voltage to the PN junctions in the off-modulation grating sections





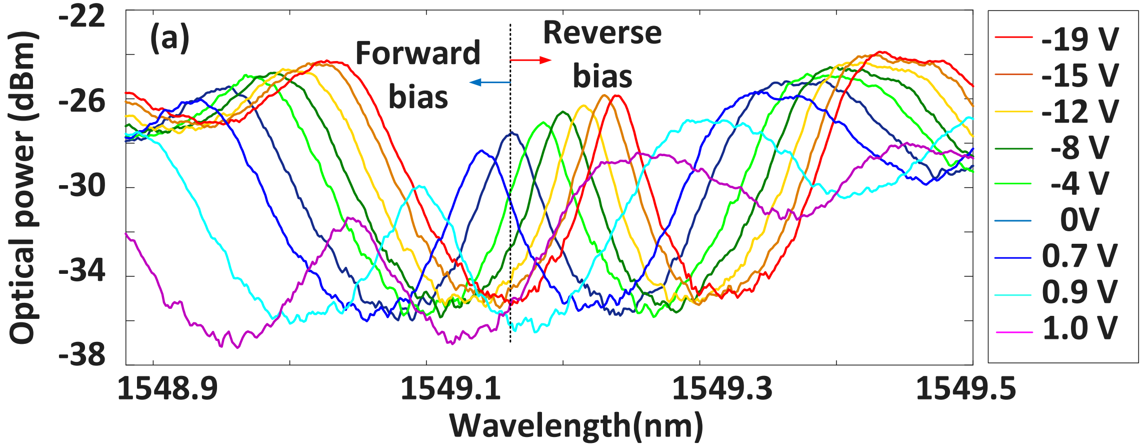
+3rd channel spectral response tuning

Performance evaluation: programmability

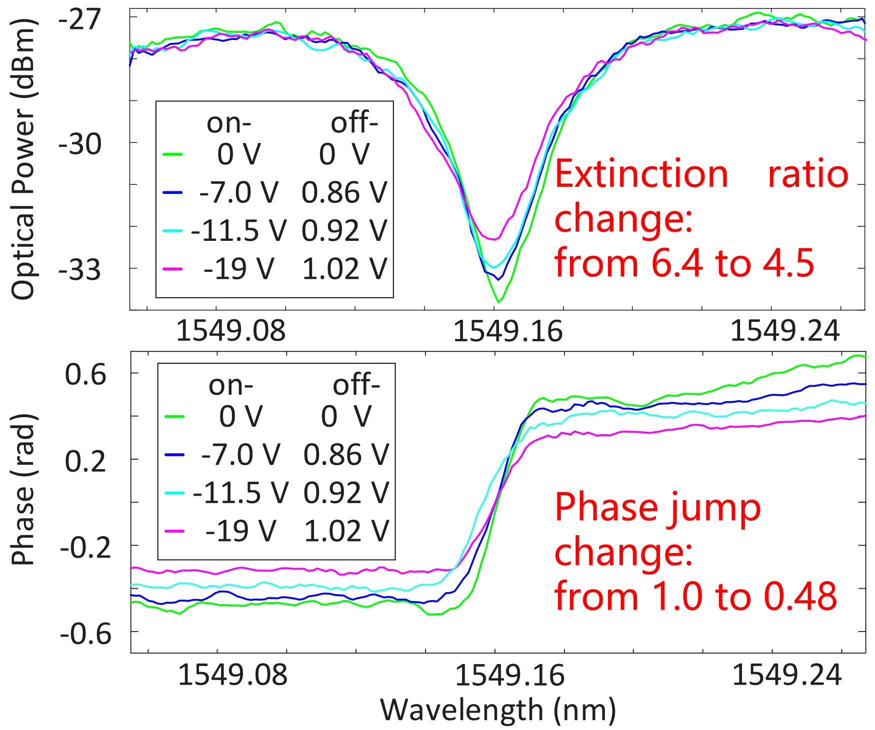


✓ 2. Tuning the extinction ratio while the 3rd channel notch wavelength is maintained unchanged for different bias voltages.

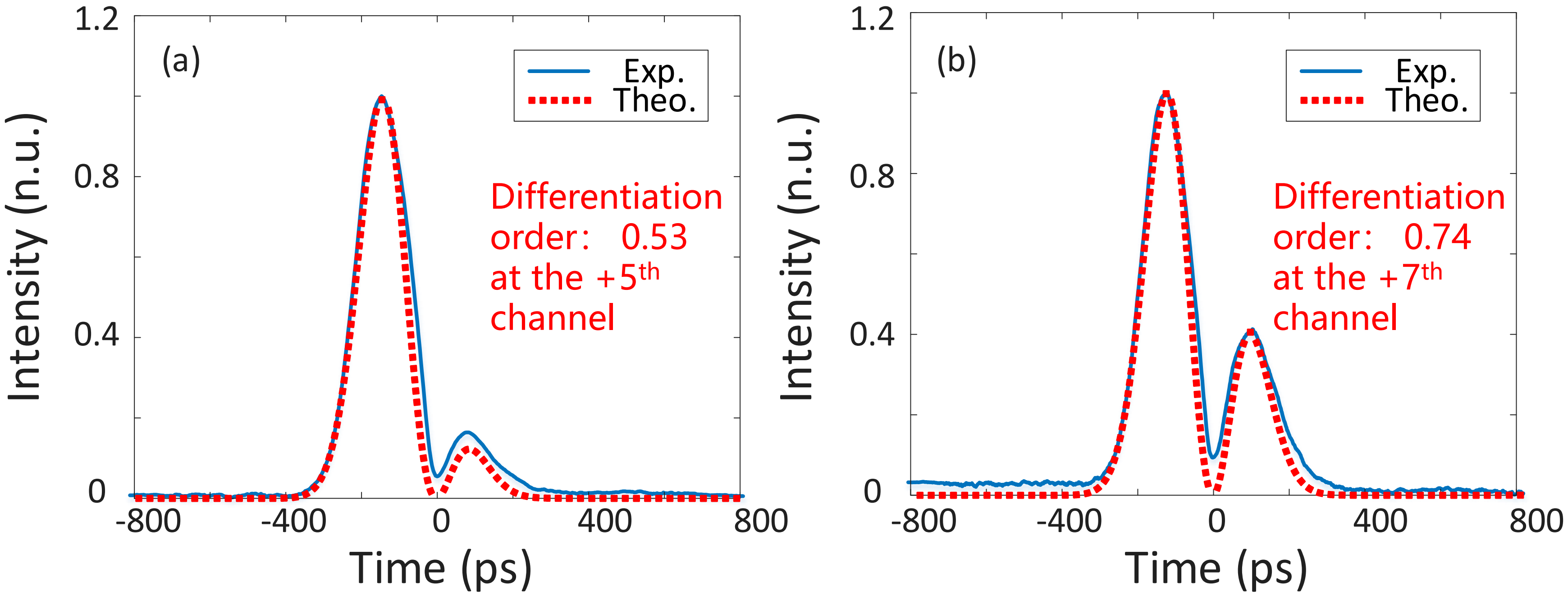
✓ 1. The two bias voltages are simultaneously and synchronously changed from −19 to +1 V.



+3rd channel spectral response tuning



Multichannel signal processing: temporal differentiation



A multichannel temporal differentiator with a channel spacing of 2.4 nm is experimentally demonstrated. The figure shows the measured temporally differentiated pulses corresponding to a differentiation order of (a) 0.53 at the +5th channel, and (b) 0.74 at the +7th channel.

Conclusion

- Silicon photonics is a solution for ultra-fast optical signal processing with reduce the size and cost.

- By electrical tuning, a silicon photonic grating can be made programmable and reconfigurable for various optical or microwave signal processing

- Heterogeneous integration may be needed to produce laser sources and optical amplifiers using III-V materials, to achieve monolithic photonic integrated signal processing systems (system on chip) - a key challenge for wide applications of silicon photonics.

Thank you

Acknowledgments

CMC Microsystems

NSERC Si-EPIC program