Designing High Performance Devices in Silicon Using Subwavelength Structures

Presented by: OSA Optoelectronics Technical Group
The OSA Optoelectronics (PO) Technical Group Welcomes You!

DESIGNING HIGH PERFORMANCE DEVICES IN SILICON USING SUBWAVELENGTH STRUCTURES

27 September 2018 • 10:00 EDT

OSA Optoelectronics Technical Group
Technical Group Leadership 2018

Chair

Winnie Ye
Carleton University, Canada

Vice Chair

Daniele Melati
National Research Council Canada, Canada
Technical Group at a Glance

• **Focus**
  • This group’s interests are in the field of semiconductor lasers, amplifiers, LEDs and super luminescent diodes.
  • Over 4,500 members within OSA

• **Mission**
  • To benefit YOU
  • Webinars, e-Presence, publications, technical events, business events, outreach
  • Interested in presenting your research? Have ideas for TG events? Contact winnie.ye@carleton.ca

• **Find us here**
  • Website: www.osa.org/OptoelectronicsTG
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Today’s Webinar

**Designing High Performance Devices in Silicon Using Subwavelength Structures**

Prof. Robert Halir

University of Malaga (Spain)
Andalusian Institute for Nano-medicine and Biotechnology (Bionand)

Designing high performance devices in silicon using subwavelength structures

Robert Halir, Universidad de Málaga (Spain), www.photonics-rf.uma.es
Many thanks to:

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Why silicon photonics?

- Silicon microelectronics (the “age of silicon”)
- High contrast (Δn=2), small features (≈100nm)
- High speed photodetection and modulation
- Hybrid integration of III-V lasers
- Commercial use: Luxtera, Acacia, ...
- Only a few CMOS compatible materials available.

“Handbook of Silicon Photonics”, Laurent Vivien, 2013 + “Silicon Photonics Design” Lukas Chrostowski, Online course
“Silicon photonics circuit design” Wim Bogaerts, Laser and Photonics Reviews 12, 2018
A surging field of research

Subwavelength integrated photonics

Pavel Cheben, Robert Halir, Jens H. Schmid, Harry A. Atwater & David R. Smith

Nature 560, 565–572 (2018) | Download Citation

P. Cheben et al., Nature 560, 2018
This webinar is not about...

Metasurfaces

M. Khorasaninejad, Nano Lett. 16, 2016

Inverse design

A. Y. Piggot, Nature Photonics 9, 2015
B. Shen, Nature Photonics 9, 2015

Isabelle Staude & Jörg Schilling

I. Staude, Nature Photonics 11, 2017
Subwavelength grating (SWG) waveguide

Small pitch \([\Lambda < \lambda/(2n_{\text{eff}})]\) avoids diffraction. Synthesizes an artificial material.

\[
\begin{align*}
n_{xx}^2 & \approx \frac{L}{\Lambda} n_{Si}^2 + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^2 \\
n_{zz}^{-2} & \approx \frac{L}{\Lambda} n_{Si}^{-2} + \left(1 - \frac{L}{\Lambda}\right) n_{SiO_2}^{-2}
\end{align*}
\]

S. M. Rytov, Sov. Phys. JETP 2, 1956

Rigorous formulas for \(n_{xx}\) and \(n_{zz}\): Luque-González, Optics Letters 43, 2018
Subwavelength grating (SWG) waveguide

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S. M. Rytov, Sov. Phys. JETP 2, 1956

Engineer the refractive index through duty-cycle.
Subwavelength grating (SWG) waveguide

- SWG waveguide has lower effective index than the silicon wire.
- SWG waveguide supports loss-less Bloch-Floquet mode.
- Loss-less integration with silicon wire waveguides.

P. Cheben, Optics Letters 35, 2010
Subwavelength grating (SWG) waveguide

Precautions: leakage

Reduced effective index: substrate leakage for $n_{\text{eff}} < 1.6$

J. D. Sarmiento-Merenguel, Optics Letters 41, 2016
Disorder (jitter) of ~5nm produces losses for wide (multimode) waveguides.

A. Ortega-Moñux, Optics Express 25, 2017
Fiber-to-chip coupling

Grating couplers

Radiated beam profile

$\phi$-1

$\Lambda$

$\Lambda d_c$

$H$

Buffer layer (BOX)

Substrate

R. Halir, Optics Letters 34, 2009
Fiber-to-chip coupling

Silicon – near infrared

With bottom mirror

Grating couplers

Germanium – mid infrared

D. Benedikovic, Optics Express 23, 2015

J. Kang, Optics Letters 42, 2017
Fiber-to-chip coupling

0.32dB Loss, PDL<0.05dB
BW>100nm, MFD=3.2um

P. Cheben, Optics Express 14, 2006
P. Cheben, Optics Express 23, 2015
T. Barwicz, OFC 2016, M2I.3 (IBM)
Enhanced cladding interaction

Sensors and modulators

\[ \Delta n_{eff} = c \int \Delta n(x, y)^2 \left| E(x, y) \right|^2 \, dx \, dy \]

Delocalize field

Enhanced cladding interaction


\[ \Delta n_{eff} = c \int \Delta n(x, y)^2 \left| E(x, y) \right|^2 dx \, dy \]

Delocalize field
Enhanced cladding interaction

490nm / RIU

Demonstration of enhanced bulk sensing

Flueckiger, Optics Express 24, 2016

Sensors and modulators

Demonstration of surface sensing

H. Yan, Optics Express 24, 2016
Enhanced cladding interaction

580nm / RIU

Electro-optic polymer
40GHz bandwidth

E. Luan, J. Selected Topics Quantum Eletronics 25, 2018

Z. Pan, Laser and Photonics Reviews 12, 2018
Intra-waveguide index engineering

Single-mode waveguide bends

90 dB/cm → 17 dB/cm for r = 5μm

Multi-mode waveguide bends

Intermodal crosstalk 5dB → 20dB for r=30μm

Z. Wang, Optics Letters 41, 2016

H. Xu, Laser and Photonics Reviews 12, 2018
Polarization management

Y. Xiong, Optics Letters 39, 2014 + Y. He, OFC 2017, Th1G.6

L. Liu, Optics Letters 41, 2016

Polarization independent coupler

Covers entire C-band

13dB ER over 40nm
Narrow Bragg filters

Mid-IR suspended waveguides

R. Soref, Nature Photonics 4, 2010

Suspended waveguide at 7.7µm

J. Soler Penadés, Optics Letters 43, 2018

Suspended, slotted rings at 2.2µm

J. Soler Penadés, Optics Letters 39, 2014

W. Zhou, J. Applied Physics 123, 2018
OUTLINE

Refractive Index
   Fundamentals
   Applications & Devices

Dispersion & Anisotropy
   Fundamentals
   Applications & Devices
Anisotropic and dispersive properties

\[ n = \begin{bmatrix} n_{xx} & 0 \\ 0 & n_{zz} \end{bmatrix} \]

\[
\left( \frac{k_x}{n_{zz}} \right)^2 + \left( \frac{k_z}{n_{xx}} \right)^2 = k_0^2
\]

Luque-González, Optics Letters 43, 2018

P. Cheben et al., Nature 560, 2018

R. Halir et al., Laser and Photonics Reviews 9, 2015
Exploiting dispersion

Broadband directional coupler

5x bandwidth enhancement

Densely spaced waveguides

Exploiting anisotropy

"Relaxed" TIR:  
\( n_{\text{core}} > n_{xx} \)

Evanescent decay:  
\( k_x \propto n_{zz} \)

Crosstalk reduced by 30dB.

Exploiting anisotropy & dispersion

Broadband beam-splitter

\[ L_{\text{MMI}} = \frac{3}{2} L_{\pi} \]

\[ L_{\text{conv}}^{\pi} \approx \frac{4W^2}{3\lambda n_{\text{core}}} \]

\[ L_{\pi}^{\text{aniso}} \approx \frac{4W^2}{3\lambda} \frac{n_{zz}^2}{n_{xx}} \]

R. Halir, Laser and Photonics Reviews, 2016
Can we engineer anisotropy?

Changing the duty-cycle

\[ n_{xx} \approx \frac{L}{\Lambda} n_{Si}^2 + \left( 1 - \frac{L}{\Lambda} \right) n_{SiO_2}^2 \]

Wide index range
Small feature sizes
Both polarizations affected equally
Tilted Sub-λ structures

\[ \theta \]

\[ \bar{\varepsilon} = R^{-1}(\theta) \begin{bmatrix} n_{xx}^2 & 0 & 0 \\ 0 & n_{xx}^2 & 0 \\ 0 & 0 & n_{zz}^2 \end{bmatrix} R(\theta) \]

Luque-González, Optics Letters 43, 2018
Tilted Sub-λ structures

**TE 0°**

**TM 0°**

**TE 30°**

**TM 30°**

Engineer TE effective index with constant feature size! TM unaffected!

Luque-González, Optics Letters 43, 2018
Tilted Sub-λ structures

Luque-González, Optics Letters 43, 2018
Tilted Sub-\(\lambda\) structures

\[ L = 3L_{\pi}^{TM} = 2 \cdot 3L_{\pi}^{TE} \]

Extinction ratio > 20dB  Insertion Losses < 1.5dB  120nm bandwidth  (3D FDTD)

A. Herrero, Optics Letters, submitted
Conclusions

> 300nm BW

Tailor anisotropy


TEC2016-80718-R

FPU16/06762

QUESTIONS?

photonics-rf.uma.es
Simulation – Floquet modes and 3D FDTD

\[ E(x, y, z + \Lambda) = E(x, y, z)e^{i(2\pi/\lambda_0 \cdot \Lambda) \cdot n_F} \]

\[ n_{\text{eff}} = 2.2872741\cdot j2.1792e\cdot 10 \]

\[ \Delta \phi = (2\pi/\lambda_0 \cdot \Lambda) \cdot n_F \]

\[ \Delta \phi_i = (2\pi/\lambda_0 \cdot \Lambda) \cdot n_{F,i} \]

\[ n_{F,i+1} = \Delta \phi_i \cdot \lambda_i / (2\pi \cdot \Lambda) \]