Winter College on Optics: Fundamentals of Photonics – Theory, Devices and Applications

10 – 21 February 2014

(Waveguide theory and) photonic circuit design

A. Melloni

Dip. Elettronica, Informazione e Bioingegneria
Politecnico di Milano
Italy
(Waveguide theory and) photonic circuit design

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Waveguide theory and photonic circuit design

- Waveguides (no theory...)
- The role of index contrast in waveguides (survey of technologies, type of waveguides, index contrast...)
  - Bends and advanced topics on bends (the matched bend,...)
- The dark side of integrated optical waveguides (backscatter, xtalk, losses, spurious modes, the (ng-neff) role....)
  - An excursus on ring resonators: history, spectral characteristics, applications, ...
- Circuits: MZ, rings, higher order filters, delay lines, ...
- The circuit approach (building Blocks, Circuit simulators and few slides on Aspic, our circuit simulator that will be used at the end of the course for hands-on session).
  - The structure of generic foundries and available generic foundries
Let's combine rings
# from Ring to Rings…

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Year</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Yariv</td>
<td>Caltech</td>
<td>1999</td>
<td>Microwave</td>
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<tr>
<td>C. Madsen</td>
<td>Bell Labs</td>
<td>1999</td>
<td>DSP</td>
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<tr>
<td>R. Orta</td>
<td>Politecnico Torino</td>
<td>1999</td>
<td>DSP</td>
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<tr>
<td>A. Melloni</td>
<td>Politecnico Milano</td>
<td>2002</td>
<td>Microwave</td>
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<tr>
<td>V. Van</td>
<td>Maryland Univ.</td>
<td>2006</td>
<td>Electronic/Microwave</td>
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<tr>
<td>Books from</td>
<td>I. Chremmos, O. Schwelb, D.G. Rabus, J. Hebneer</td>
<td>....</td>
<td></td>
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</tbody>
</table>

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from Ring to Rings…

Parallel coupled bandstop filter

Directly coupled bandpass filter (CROW)

Ring-loaded Mach-Zehnder filter
APF allows to shape the phase response

\[ \varphi_1(\omega) \quad \varphi_2(\omega) \]

FSR

2(N+1)\pi

2N\pi
Tunable bandwidth filter

Bandwidth tunability is obtained by varying $\Delta \phi$

FSR = 200 GHz
B = 23 GHz … 175 GHz
IL < 0.6 dB
ER > -18 dB
Coupled resonators
Direct coupled cavities vs cascaded cavities

Cascaded cavities (SCISSOR)

Direct coupled cavities (CROW)
Identical cavities?

1 cavity

K=0.01
1st order cavity $d=\lambda/2$

$B_{1\text{ cavity}}=1.2$ THz
$B_{\text{CROW}}=22.5$ THz

10 cavities

$B=1.2$ THz

100 cavities

$B=22$ THz

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CROW impedance matching

\[ Z_{\text{CROW}} = 2n_g(\omega) \]

\[ Z_W = n_{\text{eff}} \]

\[ n_{\text{eff}}^{(\lambda/4)} = n_{\text{eff}} \sqrt{2n_g} \]

-14 dB \rightarrow 0 dB

Quarter-wave matching

No impedance matching
Impedance Matching (Apodization)

\[ Z_W = n_{\text{eff}} \]

\[ Z_{CROW} = 2n_g(\omega) \]

Quarter-wave matching

\[ n_{\text{eff}}^{(\lambda/4)} = n_{\text{eff}}\sqrt{2n_g} \]

No impedance matching
Coupled ring resonators

IN

THROUGH

K_0

f_0

K_1

K_2

K_3

K_2

K_1

DROP

K_0
Progress in tuneable ring-CROW
F. Morichetti et al., *The first decade of coupled resonator optical waveguides: bringing slow light to applications.*
8-rings Bandpass filters in SOI

Return loss: -15 dB; IL 0.5 dB; In-band ripple <0.2 dB; Off-band rejection >50 dB
8-rings Bandpass filters in SOI

![Graph showing BER vs OSNR over 0.2 nm for different wavelengths (λ = 1536.27 nm, 1550.42 nm, 1564.75 nm).]
Thermal tuning

Thermal crosstalk

Δλ = 2.5 nm

28°C

Δλ = 0.06 nm

0.7°C

8 rings

7 rings

6 rings

5 rings

4 rings

3 rings
Tunable Delay lines
On-Chip Tunable delay… not an easy task !!!

Electronic

Microwave

Photonics
- let photons run around (coil of fiber)
- slow down photons
Recirculating buffer

**Discrete delay line, Packet(s) delay and Buffer**

**Technologies:**
- 2007 Glass for the spire + InP for the switch
- 2010 All Silicon (15 dB/ns)

**Trade off between waveguide attenuation and switch ER (limit)**

*Courtesy of John Bowers, University of California, Santa Barbara*
Slow down photons

\[ \text{velocity} = \frac{c}{\text{group refractive index}} \]

\( n_g \) of the material: Atomic resonances, band edge, EIT, CPO,…

\( n_g \) of the circuit: Resonators, Bragg Gratings, Photonic Crystals, Brillouin and Raman,…
Slow down photons
1 byte continuously tuneable delay at 10 and 100 Gbit/s demonstrated

\[ \lambda_r = \lambda_{\text{in}} \]
\[ \lambda_r \neq \lambda_{\text{in}} \]

F. Morichetti et al., Optics Express, Vol. 15, 25, December 2007
A. Canciamilla et al., Journal of Optics, IOP, 2010
A. Melloni et al., IEEE Photonics Journal, vol. 1, no. 4, 2010
The CROW in reflection

Locked rings (off-resonance)

\( \lambda_{in} \neq \lambda_{r} \)

Minimum delay

Intensity

Time [ps]

Frequency [GHz]

Delay [ps]
The CROW in reflection

- **Open rings (on-resonance)**: $\lambda_r = \lambda_{in}$
- **Locked rings (off-resonance)**: $\lambda_r \neq \lambda_{in}$

**Graphs:**
- **Intensity vs. Time [ps]**
  - TIME [ps]: -200 to 500
  - INTENSITY: 0 to 1
  - Peaks at $\lambda_{in}$ and $\lambda_{in} + 2$
- **Delay vs. Frequency [GHz]**
  - FREQUENCY [GHz]: -20 to 20
  - DELAY [ps]: 0 to 350

**Diagram Notations:**
- **In**, **Out**
- **M = 2**
**R-CROW: a reconfigurable delay line**

![Diagram of R-CROW](image)

- **Open rings** (on-resonance) with $\lambda_{in}$ and $\lambda_{r} \neq \lambda_{in}$.
- **Locked rings** (off-resonance) with $M = 4$.

**Graphs:**

- **Intensity** vs. **Time [ps]**
- **Delay [ps]** vs. **Frequency [GHz]**

F. Morichetti et al., Optics Express, no. 25, Dec. 2007
R-CROW continuous tuning

\[ M = 0 \]

- \( M \) is a parameter in the R-CROW tuning model representing the delay in picoseconds as a function of wavelength in nanometers.

The graph illustrates how the delay changes with wavelength, demonstrating the continuous tuning capability of the R-CROW circuit.
Data transmission at 10 Gbit/s

Intensity modulation
OOK NRZ @ 10 Gbit/s

100 ps

Reconfiguration
- hitless
- time 100 μs
- power 5 mW
Tuneable pulse delay @100Gbit/s

Fractional delay = 7.5 ps/RR

B = 87 GHz

Normalized intensity

Storage efficiency
0.66 bit/RR

Fractional loss
≈ 1.1 dB/bit

Pulse Broadening (1 byte)
≈ 20%
Final User: PICs design at a circuit level using a selected set of elementary functional elements (BBs), according to well defined rules (DKs).
Modelling of photonic Building Blocks

EM analysis
\[ \nabla \times \mathbf{E} = -j\omega \mathbf{B} \]
\[ \nabla \times \mathbf{H} = j\omega \mathbf{D} + \mathbf{J} \]
\[ \mathbf{B} = \mu \mathbf{H} \]
\[ \nabla \cdot \mathbf{D} = \rho \]

Numerical simulations
Simulation
\[ \begin{cases} 
\text{Simulation} \\
\text{exp}
\end{cases} \]

Characterization

BB model
Circuit approach (high abstraction level)
• realistic model
• no information on geometry & materials
• access only to input/output port waves
• very fast, suitable for large circuits

• group index
• width [um]

1 2 3 4

fundamental mode
Higher order mode
TE
TM

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BBs of the SAPPHIRE platform

- Straight & bent waveguides
- Waveguide crossing
- Directional couplers
- Grating assisted coupler (GAC)
- In/Out mode adapter
- Bragg gratings
- Ring resonators
- Heaters
BBs of the SAPPHIRE platform

- Straight & bent waveguides
- Waveguide crossing
- Ring resonators
- Directional couplers
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- Bragg gratings
- In/Out mode adapter
- Heaters
Design kits

**BB model**

\[ t_x = \sqrt{L} \exp \left( -j \frac{2\pi}{\lambda} L_{\text{opt}} \right) \left( -j \sin(\kappa L_c + \phi_0) \right), \]

**Design rules**
- BB connections
- Validity range of the model
- Layout constraints
- Quality assessment
  - ...

**Analytical model** (S matrix)

**Circuit parameters & variables**

**Mask layout**

**SAPPHIRE design manual**

Release 1 (July 2012)

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Libraries for ASPIC™ simulator

1600 BBs; 100 lambda points → 1 min

SAPPHIRE BBs

www.aspicdesign.com

Play with realistic BB

Direct exportation of the mask layout

Phoenix
CIRCUIT SIMULATOR

Aspic Design

Product
- ASPIC is a software for the analysis and design of integrated and hybrid optical circuits without restrictions in dimensions and complexity. Its model-based approach does not need descriptions at physical level, permitting to concentrate on the circuit functionality.
- ASPIC is complementary to classical electromagnetic simulators and is many orders of magnitude faster and less memory consuming.
- ASPIC is a powerful environment that allows to analyze complete optical circuits, calculate the spectral behavior, synthesize devices, realize virtual experiments, carry out “what if” and “worst case” analysis, compare measurements and simulations for parameter extraction, estimate the yield, study the impact of technological tolerances and much more...
- ASPIC can be used for “educational”, “proof of concept”, “research” and “virtual prototyping” purposes and will be your precious, invaluable and powerful tool to develop optical devices and circuits

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