Ultra-low volume tunable slot photonic crystal cavities for sensing

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Slow light in photonic crystal waveguides

- Strong enhancement of the optical field
- Engineering a flat group index curve can cancel the group velocity dispersion: this is done by tuning the hole lattice
- Losses mainly due to backscattering induced by disorder. Scale with $n_G^2$
- Slight stretch of the lattice constant at the interface between fast and slow modes ensures high injection efficiency.
A tool for $\chi^{(3)}$ nonlinear optics

- Third Harmonic Generation
  B. Corcoran et al., Nat Photonics 3, 206 (2009)

- Degenerate Four Wave Mixing

- Stimulated Raman scattering

- Self Phase matching
  C. Monat et al., Opt. Express 17, 2944 (2009)

However:
- Silicon nonlinearities are limited by Two-Photon Absorption and Free Carrier Absorption
- Silicon is centrosymmetric (no $\chi^{(2)}$ effects)
- Figure of merit of silicon is relatively low (< 0.9) compared to polymers

It is therefore preferable to confine the light in a nonlinear cladding layer...

Slot Photonic Crystal Waveguides (SPCW)

- Combination of two types of confinements:
  - Slowed pulse -> increased intensity
  - High index-contrast interface in the slot

- Two even guided modes depending on both photonic crystal and slot parameters
- One mode comes from the W1 defect line, the other from the slot waveguide

The extrinsic loss issue

Losses mainly due to backscattering induced by disorder. Scale with $n_G$ and $n_G^2$.

- Reflexions at the strip wg/PhC waveguide
- Out-of-plane mode Bloch coupling above the light line
- Disorder-induced losses
  - Backscattering and multiple scattering
  - Bandgap edge variations

$\Rightarrow$ The issue of minimizing losses in slotted PhC waveguides is of paramount importance for applications

S. Mazoyer et al., Optics Express 18 (14), 14654-14663 (2010).
Slotted photonic crystal waveguides

- Previous results: similar losses for fast waves ($n_G \sim 2-5$) as in W1 PhC waveguides
- No results for slow waves

Our recent works:
- Design of slotted PhC waveguides engineered to exploit the W1-like mode
- Fabrication of the structures of different lengths from 50µm to 1mm
- Optical characterization by using a modified Optical Low Coherence Reflectometry (OLCR) technique entitled Optical Coherent Tomography (OCT):
  - Measurement of the propagation losses as a function of the light group index
Management of the light coupling issue

Three steps are necessary:
1) Strip waveguide => slot waveguide
2) Slot waveguide => Fast light PhC Slot waveguide
3) Fast light PhC Slot waveguide => Slow light PhC Slot waveguide

Fabrication and characterization of the slot photonic crystal waveguides

- SOITEC 6” wafers of 260 nm Si film and 2 µm BOX
- 80kV e-beam lithography Nanobeam NB-4 forming the pattern in a ZEP-520A resist mask
- ICP RIE etching of the silicon
- Removal of the resist by O$_2$ plasma
- Cleavage of the sample

Optical Coherent Tomography (OCT)

Collab. Alfredo DE ROSSI (THALES-TRT)
1mm-long slot photonic crystal waveguide

- Mode partially confined in the slot
- Cut-off wavelength around \( \lambda = 1590 \text{nm} \)
- Delay ranging from 60ps to 100ps for \( n_G \) in the 5-21 range
- Good agreement of experimental dispersion results with 3D-PWE calculation
- Low loss for small \( n_G \) value, even for this long photonic crystal waveguide

\[ a = 400 \text{ nm}, \ W_{1.4} = 1.4\sqrt{3}a = 970 \text{nm} \]
\[ r = 105 \text{nm}, \ W_{\text{slot}} = 100 \text{nm} \]
Variable slot photonic crystal waveguides: 50µm=>1mm

Good reproducibility of the fabrication & consistency of the fabrication-and-characterization cycle

- Moderate losses for L=200µm
- E-beam writing field: 300µm
  => influence of the stitching errors
**Potentials for light-matter interactions**

Let $A_{\text{eff}}$ be defined as:

$$ P = 0.5 |E_{\text{slot}}|^2 \eta^{-1} A_{\text{eff}} $$

$$ A_{\text{eff}} = \frac{A_{\text{slot}} n_{\text{slot}}}{\phi n_g} $$

with

$$ \phi = \frac{\int_{S_{\text{slot},a}} \epsilon_r |e|^2 dS dx}{\int_{S_{a}} \epsilon_r |e|^2 dS dx} $$

FOM = $\frac{n_g}{n_{\text{slot}}} \phi$

Increase of $n_G$ from 6 to 20 => $A_{\text{eff}}$ is reduced by a factor of 5 down to around 0.02µm$^2$ (down to 10 times lower than the diffraction limit)
Slotted Photonic Crystals: a great opportunity for the design of ultra-small resonators
Refractive index sensing with an air-slot photonic crystal nanocavity

Jana Jágerská,* Hua Zhang, Zhaolu Diao, Nicolas Le Thomas, and Romuald Houdré

- Free-membrane structure
- Transmission: $\sim$23dB
- Q=26 000 for gases
- $\Delta\lambda/\Delta n=510$nm/RIU

Etching of the underlying SiO$_2$ layer
**Slot Photonic Crystal cavities: the state-of-the art (2)**

*Sensors 2013, 13, 3675-3710; doi:10.3390/s130303675*

Mark G. Scullion *, Thomas F. Krauss and Andrea Di Falco

- Free-membrane structure
- \( Q=4000 \) in water
- Transmission: \( \sim 20 \text{dB} \)
- \( \Delta \lambda/\Delta n=500\text{nm/RIU} \)
**SPCW cavities: the design approach (1)**

Our SPCW ...

+ the light cone loss minimization
SPCW cavities: the design approach (2)

- Starting slot photonic crystal waveguide: $a_x=400$ nm and $W_{\text{slot}}=100$ nm
- Double-step heterostructure by elongating the lattice constant in the propagation direction to $a_1=410$ nm and then $a_2=420$ nm, respectively.

$$V \approx 0.03 \left( \frac{\lambda}{n} \right)^3$$
Characterization setup

Tunable cw lasers (1370-1640 nm)

Channel switch

IR camera

TE filter

PD

BS

Sample on movable stage

Lensed fiber

CCD camera

Polarization controller

PMF

TE filter

Component tester

http://silicon-photonics.ief.u-psud.fr/
Filled slot PhC cavity: experimental results

Filling by a 1.46 index liquid.

• Good control of the fabrication steps
• Proper injection of light within the PhC structures
• High transmission level: -10dB with respect to the bandpass transmission
Filled slot PhC cavity: experimental results

- Measurements performed after covering the PhC structure by a Cargille liquid index ranging from ~1.35 to ~1.55: 1.345, 1.41, 1.448, 1.516, and 1.545.
- Normalization of the spectra by the input laser diode power (Pin=5mW)
- NO FILTERING APPLIED TO THE DATA
Filled slot PhC cavity: experimental results

- Well identified resonance peaks for the different index values.
- The spectrum asymmetry slightly increases with the vertical index mismatch.
Filled slot PhC cavity: experimental results

- Quality factors up to 26,000 for non-freestanding slotted photonic crystal cavities filled by liquids ensuring a good mechanical stability.
- Silicon photonics process (SOI wafers)
Conclusion

- **Slow light** slot photonic crystal waveguides:
  - Investigation of the slot PhC waveguide dispersion curve by direct group-velocity-time-of-flight optical measurements (OCT)
  - Experimental demonstration of low losses for group index values up to $n_G=20$

- **Non-freestanding silicon** slot PhC cavities **infiltrated by liquids**:
  - With Q-factors ~ 26,000
  - $V \approx 0.03(\lambda/n)^3 \implies Q/V \approx 700,000$
  - Intrinsic Q-factor is above 200,000
  - Transmission on resonance is 20% in the best cases
  - Sensitivity of devices around 225 nm/RIU

⇒ **Biosensing and/or non linear optics by filling the slot with organic materials**
Thank you for your attention

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