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.

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S. A. Schulz *et al.*, J. Opt. **12** (2010)
L. O'Faolain *et al.*, Opt. Express **18**, 27627 (2010)
J.-P. Hugonin *et al.*, Opt. Lett. **32**, 2638 (2007)

A tool for $\chi^{(3)}$ nonlinear optics

- Third Harmonic Generation

B. Corcoran *et al.*, Nat Photonics **3**, 206 (2009)

- Degenerate Four Wave Mixing

C. Monat *et al.*, Opt. Express **18**, 22915 (2010)

- Stimulated Raman scattering

J. F. McMillan *et al.*, Opt. Lett **31**, 1235 (2006)

- 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...

C. Koos *et al.*, Opt. Express **15**, 5976 (2007)

Slot Photonic Crystal Waveguides (SPCW)

- Combination of two types of confinements:
 - Slowed pulse $\rightarrow$ 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

(IEF / CTU-MINERVE)

A. Di Falco *et al.*, Appl. Phys. Lett. **92**, 083501 (2008)
J. Gao *et al.*, Appl. Phys. Lett. **96**, 051123 (2010)

The extrinsic loss issue

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

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

S. Mazoyer *et al.*, *Optics Express* 18 (14), 14654-14663 (2010).

=> The issue of minimizing losses in slotted PhC waveguides is of paramount importance for applications

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 **50 μm 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 $\Rightarrow$ slot waveguide
- 2) Slot waveguide $\Rightarrow$ Fast light PhC Slot waveguide
- 3) Fast light PhC Slot waveguide $\Rightarrow$ Slow light PhC Slot waveguide

Z. Wang *et al.*, Opt. Lett. **34** (10), 1498,(2009).

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

C. Caer *et al.*, *Optics Letters* **37**, 3660 (2012)

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Optical Coherent Tomography (OCT)

Collab. Alfredo DE ROSSI
(THALES-TRT)

1mm-long slot photonic crystal waveguide

$a=400$ nm, $W_{1.4}=1.4\sqrt{3}a=970$ nm
 $r=105$ nm, $W_{slot}=100$ nm

- Mode partially confined in the slot

- Cut-off wavelength around $\lambda=1590$ 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

Collab. Alfredo DE ROSSI
(THALES-TRT)

Variable slot photonic crystal waveguides: $50\mu\text{m} \Rightarrow 1\text{mm}$

Collab. Alfredo DE ROSSI
(THALES-TRT)

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

- Moderate losses for $L=200\mu\text{m}$
- E-beam writing field: $300\mu\text{m}$
 $\Rightarrow$ influence of the stitching errors

Potentials for light-matter interactions

Let A_{eff} be defined as: $P = 0.5 |\mathbf{E}_{slot}|^2 \eta^{-1} A_{eff}$

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

with $\phi = \frac{\int_{slot,a} \epsilon_r |\mathbf{e}|^2 dS dx}{\int_{S,a} \epsilon_r |\mathbf{e}|^2 dS dx}$

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

Increase of n_g from 6 to 20
 $\Rightarrow A_{eff}$ is reduced by a factor
 of 5 down to around $0.02 \mu m^2$
 (down to 10 times lower than
 the diffraction limit)

Slotted Photonic Crystals: a great opportunity for the design of ultra-small resonators

Slot Photonic Crystal cavities: the state-of-the art (1)

August 1, 2010 / Vol. 35, No. 15 / OPTICS LETTERS 2523

Refractive index sensing with an air-slot photonic crystal nanocavity

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

Etching of the underlying SiO₂ layer

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

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: ~ 20 dB
- $\Delta\lambda/\Delta n=500\text{nm}/\text{RIU}$

SPCW cavities: the design approach (1)

Our SPCW ...

+ the light cone loss minimization

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IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 12, NO. 6, NOVEMBER/DECEMBER 2006

Ultrahigh- Q Nanocavities in Two-Dimensional Photonic Crystal Slabs

Takashi Asano, Bong-Shik Song, Yoshihiro Akahane, and Susumu Noda, *Member, IEEE*

SPCW cavities: the design approach (2)

- Starting slot photonic crystal waveguide: $a_0=400$ nm and $W_{slot}=100$ 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.

3D-FDTD optimization of the slot PhC cavity (MEEP/MIT)

Characterization setup

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 ($P_{in}=5\text{mW}$)
- **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 $\sim 26,000$
 - $V \approx 0.03(\lambda/n)^3 \Rightarrow Q/V \approx 700,000$
 - 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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