Coupled-mode theory of the polarization dynamics inside a microring resonator with a uniaxial core

Luis Cortés Herrera Xiaotong He Jaime Cardenas Govind P. Agrawal

University of Rochester

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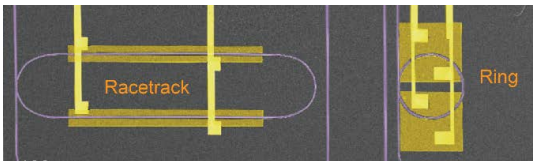
Lithium-niobate (LN) microcavities[1]



Cheng Wang et al. (2018). "Nanophotonic lithium niobate electro-optic modulators". In: *Optics express* 26.2, pp. 1547–1555

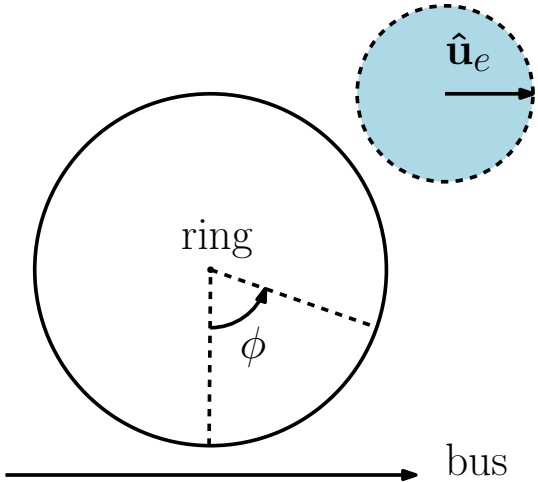
New smart-cut technology allows fabrication of LN microcavities

LN microring resonators enable

- low-voltage EO modulators
- broadband EO frequency comb generation
- ultra-efficient parametric wavelength conversion
- Kerr comb generation

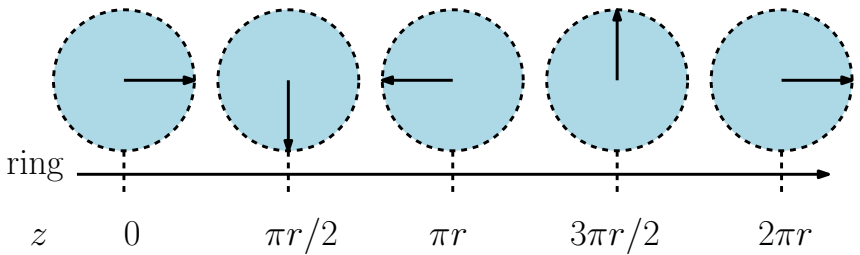
[1] Di Zhu et al. (2021). "Integrated photonics on thin-film lithium niobate". In: *arXiv preprint arXiv:2102.11956*.

LN material birefringence and cavities



LN is a uniaxial crystal
The Z crystal axis is its extraordinary axis
For efficient EO, LN modulators are X-cut or Y-cut, with Z-axis in plane of propagation
The angle between the direction of propagation and the extraordinary axis varies continuously

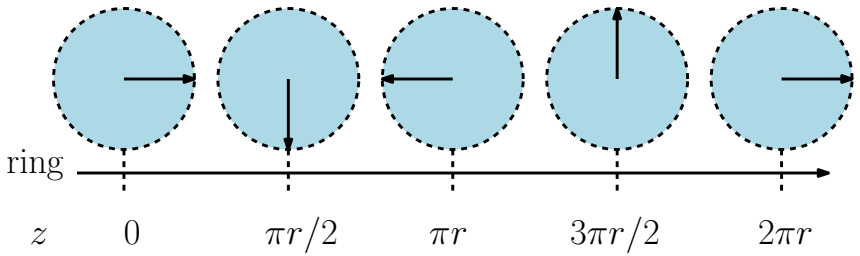
Zero-bending model



Neglects other effects of bending (bending losses, field displacement)
Accurate if ring radius much larger than wavelength and cross-section dimensions[2]

[2] Charles Vassallo (1991). *Optical waveguide concepts*. English. Vol. 1. New York;Amsterdam; Elsevier. ISBN: 9780444886842;0444886842;

Coupling between transverse and longitudinal fields



In thin-film rings, TE field is in plane-of-propagation (x)
TM field has longitudinal E field (z)
Diagonal permittivities (ϵ_{xx} and ϵ_{zz}) change along ring,
So indices of TE and TM modes vary along ring
Non-diagonal ϵ_{xz}, ϵ_{zx} couple TE and TM fields

Coupled-mode equations

Applying Maxwell's equations to ZBM[3],

$$-i\frac{\mathrm{d}}{\mathrm{d}\phi}\begin{pmatrix} a_s \\ a_p \end{pmatrix} = H(\phi)\begin{pmatrix} a_s \\ a_p \end{pmatrix}, \tag{1}$$

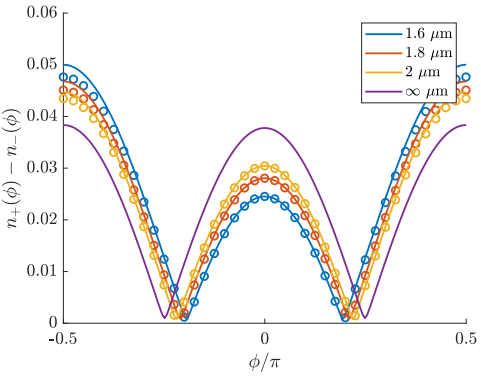
$$H(\phi) = \frac{1}{2}\left(\Delta_0 + \Delta_1 \cos 2\phi\right)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \text{variation of effective indices}$$

$$+ \kappa \sin 2\phi \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \text{polarization coupling}$$

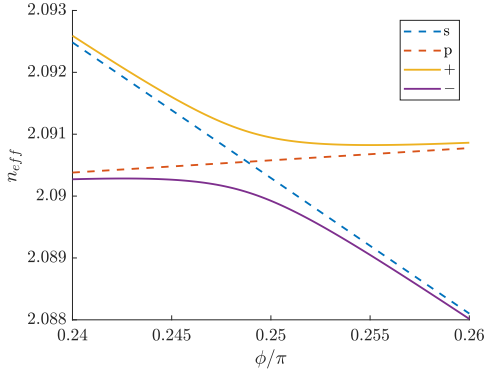
[3] Luis Cortes-Herrera et al. "Coupled-mode theory of the polarization dynamics inside a microring resonator with a uniaxial core". Under review.

Effective indices of local modes

Simplified Hamiltonian $H(\phi)$ is accurate for thin, horizontal

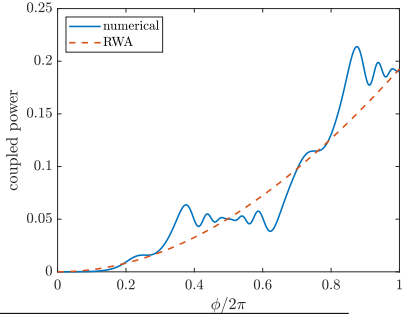


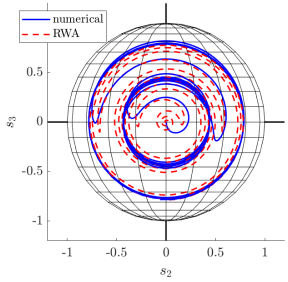
Index anti-crossings highlight coupling



Resonant coupling

As in QM[4], coupling is resonant when $\Delta_0 = 2m$, for $m \in \mathbb{Z}$
Rotating-wave approximation (RWA) becomes accurate



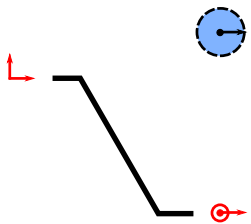


[4] MP Silveri et al. (2017). "Quantum systems under frequency modulation". In: *Reports on Progress in Physics* 80.5, p. 056002.

Polarization rotators

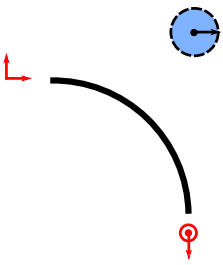
Losses ~ 0.1 dB/cm (Zhu et al. 2021)

Piecewise



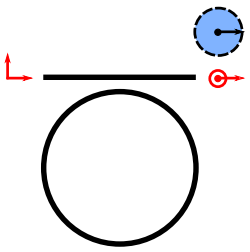
$L \sim 1$ mm

Adiabatic



$L \sim 1$ cm

Resonant



$L \sim 100$ μm, narrowband

Conclusions

Birefringence of LN induces non-trivial polarization dynamics along microrings

For small effective index detuning, polarization coupling can become resonant

Polarization coupling can be leveraged to design passive polarization rotators