Simulating the response of planar photonic structures under the strain of surface acoustic waves

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Outline

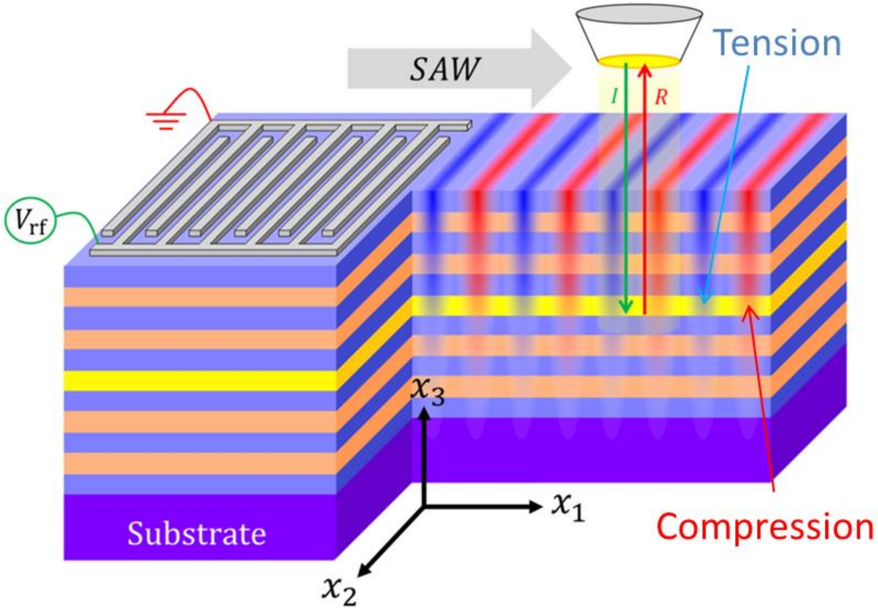
Motivation

Surface acoustic wave (SAW) model

- Calculation of acoustic and piezoelectric properties of solids
  - Bulk, films, layered structures

Planar optical microcavity (POMC) model

- Reflectance spectrum
- Electric field mode confinement
- Quality factor
- Photon dispersion



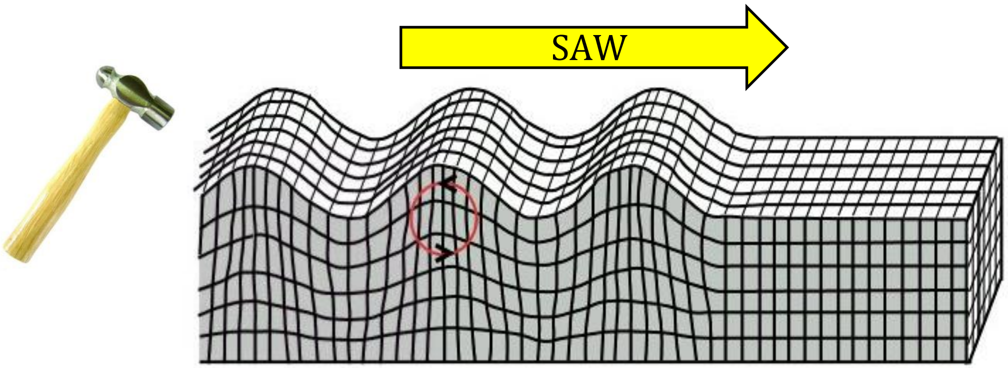
Acousto-optic modulation model

- SAW + POMC
- Strong light-phonon interaction
  - Appearance of new cavity resonances
  - Folding of the photon dispersion
  - Tuning of cavity resonances with SAW strain

Conclusions

Motivation

SAWs: elastic waves propagating on the surface of solids



Modulation of dielectric properties of solids

Applications:

- Mobile, Wireless communication
- Sensors, filters, resonators….

Research

- Long range carrier, spin transport
- Tuning of energy levels in nanostructures

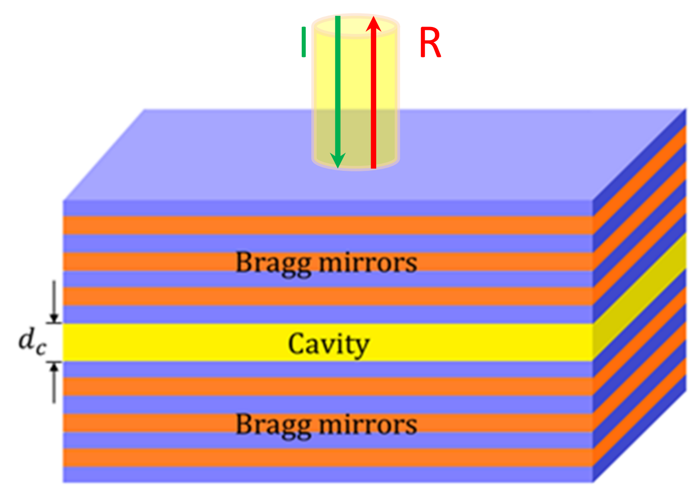
POMC: periodic array of refractive index

- Light confinement in the optical cavity
- Applications in photonics

Enhancement of interaction with light emitters

Light-matter coupling

- Strong coupling
    - Light-matter entangled states
- Weak coupling
    - Emission gain (QDs, nanowires, etc.)



SAWs on piezoelectric crystals

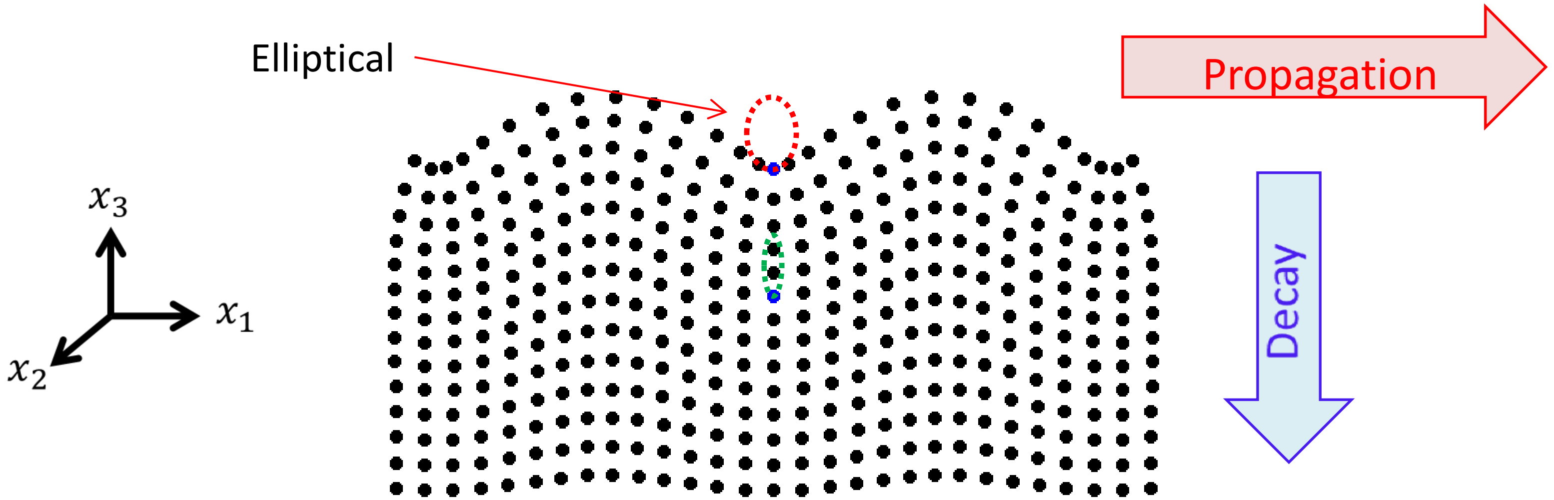
$T_I = c_{IJ} S_J + d_{kI} E_k$ (3D Hooke's law + Converse piezoelectricity)

$D_k = \epsilon_{kl} E_l + d_{kI} S_I$ (Dielectric field relation + Direct piezoelectricity)

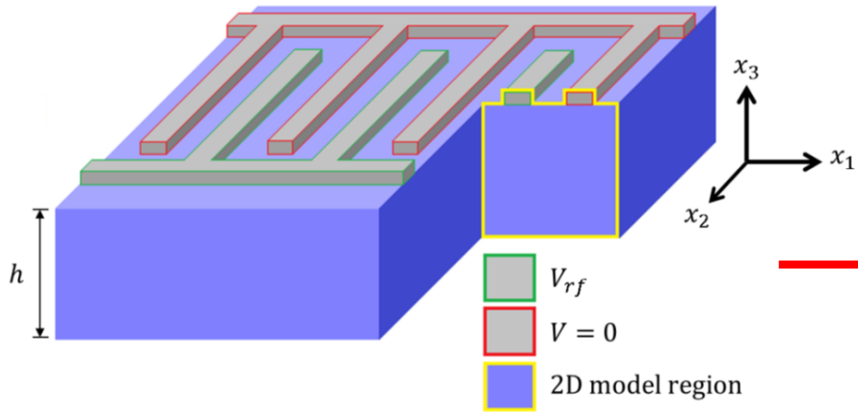
(c_{IJ}, d_{kI} and ϵ_{kl} are tensorial material properties)

SAWs compose a set of solutions to the wave equation

$$\rho \frac{\partial^2 u_i}{\partial t^2} = c_{IJ} \left(\frac{\partial^2 u_l}{\partial x_j \partial x_k} \right) + d_{kI} \left(\frac{\partial^2 \phi}{\partial x_j \partial x_k} \right)$$



2D SAW model



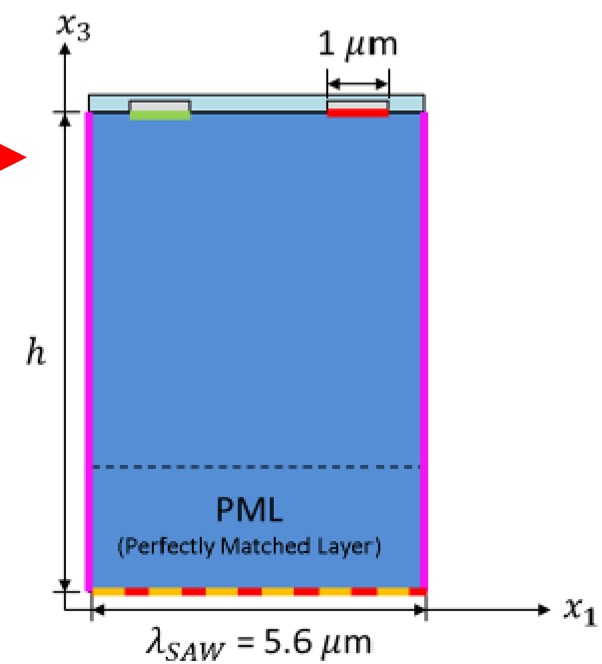
Interdigital transducers (IDTs)

- E-shaped aluminium electrodes
- Designed by lithography
- Wavelengths: $\lambda_{SAW} \sim 1 \rightarrow 20$ μm
- Frequencies: $f_{SAW} \sim 0.1 \rightarrow 1$ GHz
- $v_{SAW} = \lambda_{SAW} f_{SAW}$

Material	Geometry	Thickness (nm)
Air	Top cover	300
Aluminium	IDTs	200
$ZnO/LiNbO_3$	Substrate	14000

Solid Mechanics module

Projection into a 2D "unit cell"

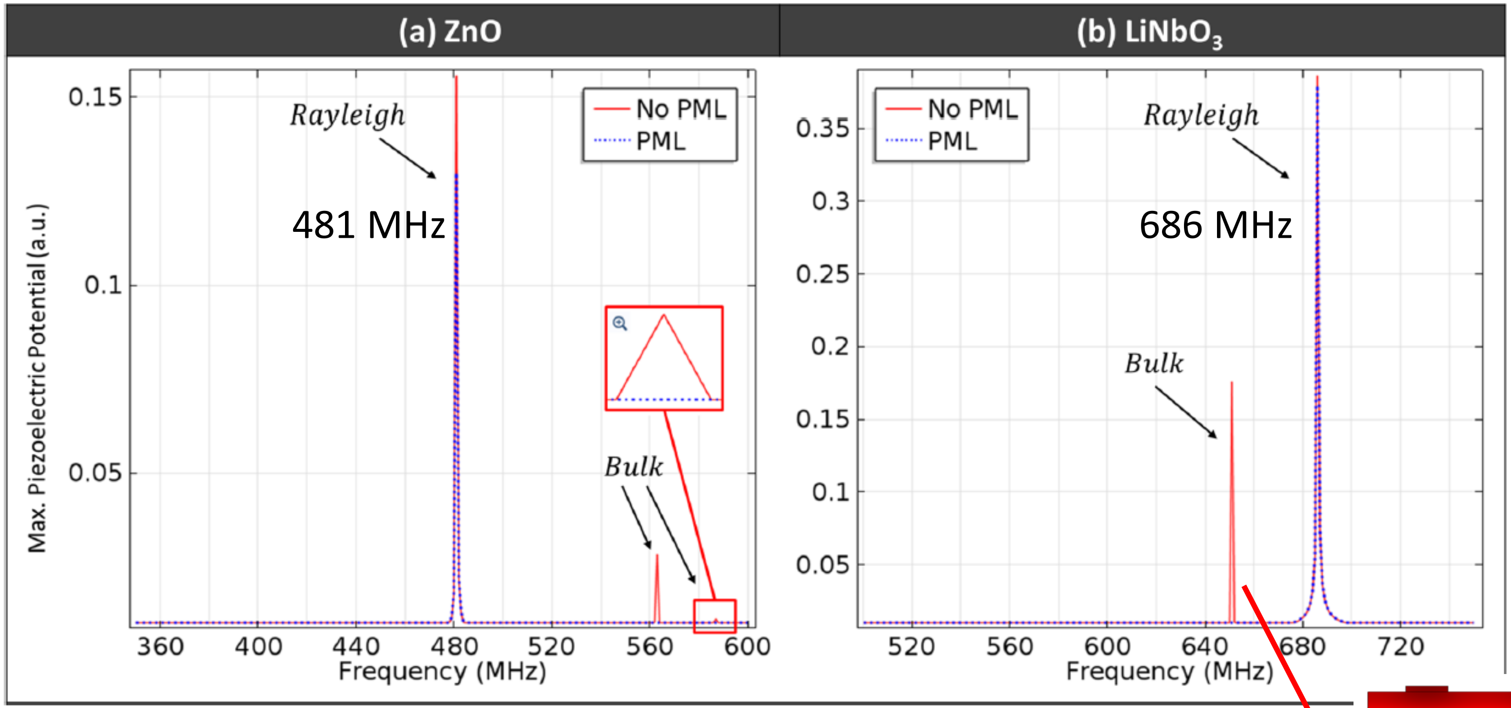


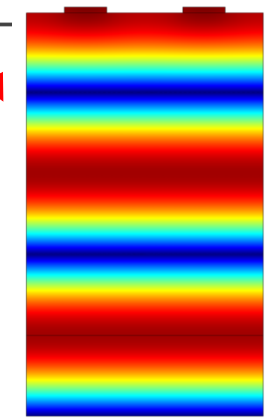
Boundary Conditions	
V_{rf}	Applied Electric Potential
V = 0	Ground
$\lvert\vec{u}\rvert = 0$	Fixed Constraint
Continuity	Periodic Condition

PML: Perfectly Matched Layer → Force solution to decay to the substrate

The SAW model: searching for Rayleigh SAWs

Frequency sweeps seeking for Rayleigh SAWs





Estimated velocities agree well with the literature

$$v^{ZnO} \approx 2694\ m.s^{-1} \qquad v^{LiNbO3} \approx 3843\ m.s^{-1}$$

$$*\ v^{ZnO} \approx 2700\ m.s^{-1} \qquad **\ v^{LiNbO3} \approx 3900\ m.s^{-1}$$

*X. Y. Du et al. *Appl. Phys. Lett.*, 93:094105, 2008. **A. J. Slobodnik Jr. *Physical Sciences Research Papers, N-477*, AFCRL-72-0082, 1972.

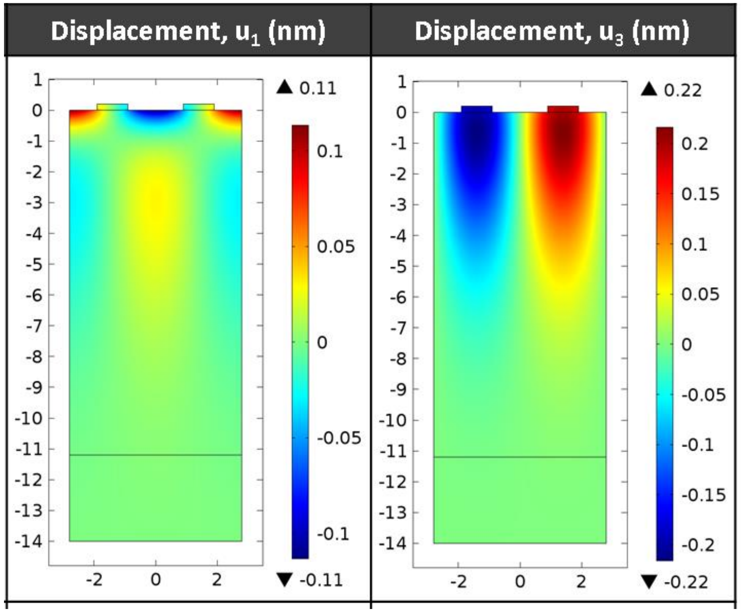
The SAW model eigenmodes: ZnO (f_{saw}= 481 MHz)

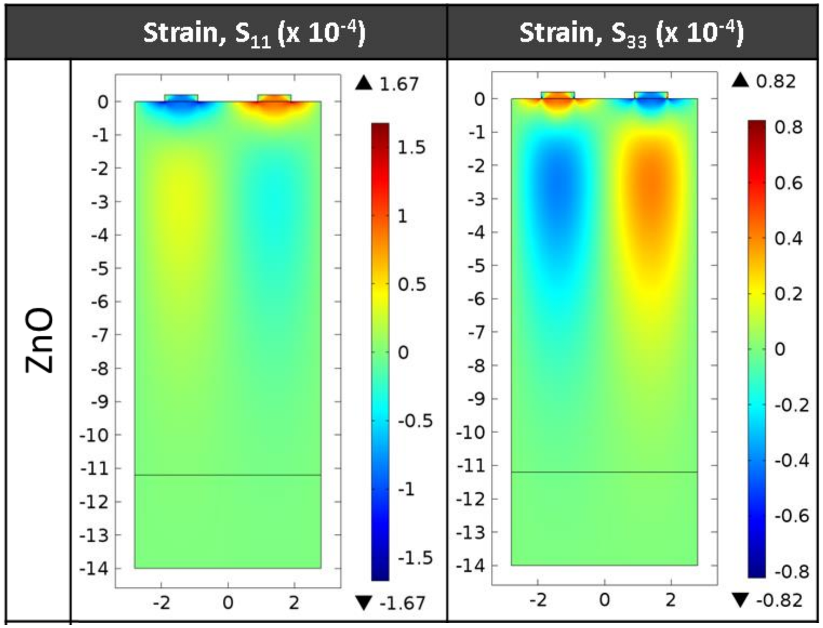
Rayleigh SAW modes obtained

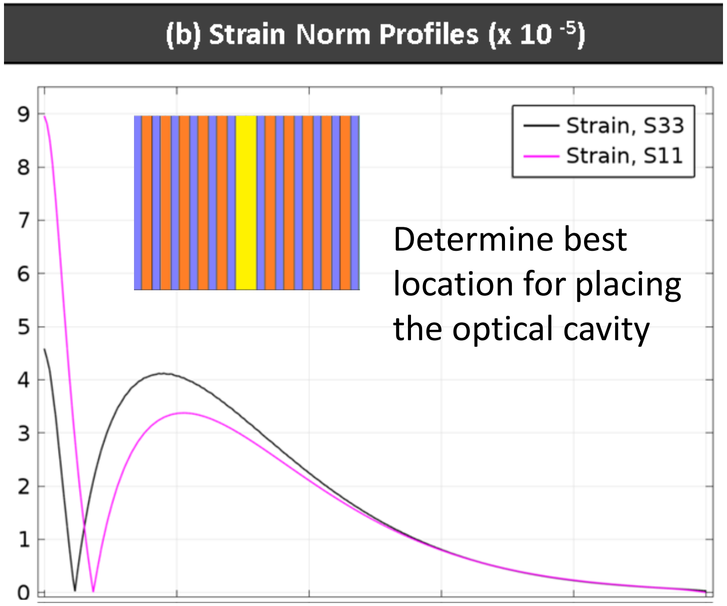
- Waves confined at the surface
- Exponential decay to the substrate
- u_1 and u_3
  - Elliptical displacement
  - Phase difference = $\pi/2$

Strain modulation

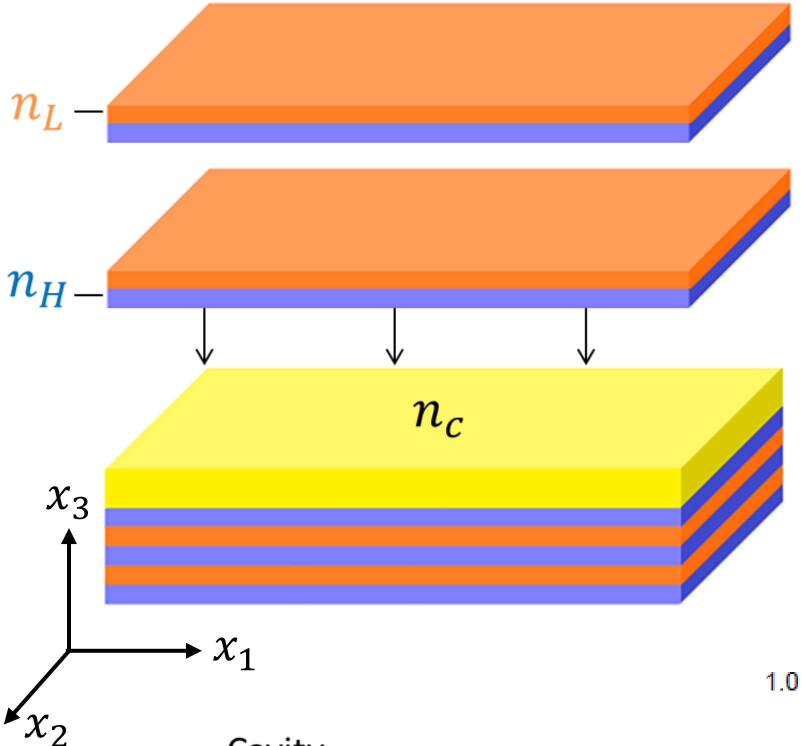
- Typical values: 10^{-5} to 10^{-3}
- S_{33}: main responsible for the modulation of POMCs







The planar optical microcavity



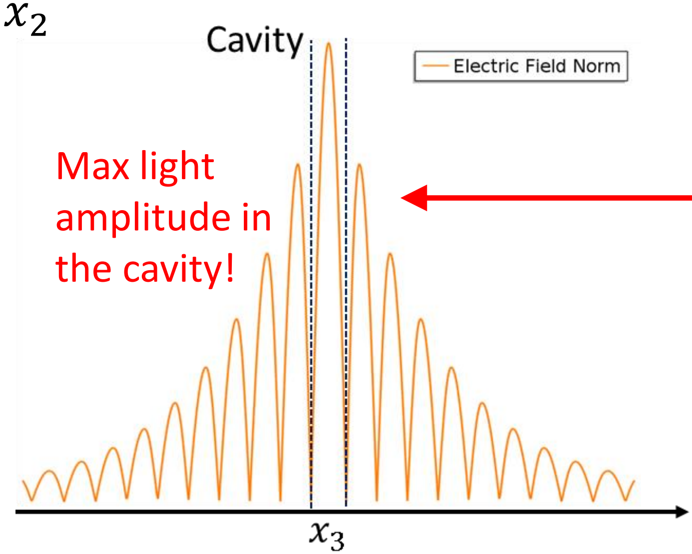
"Defect" layer inserted

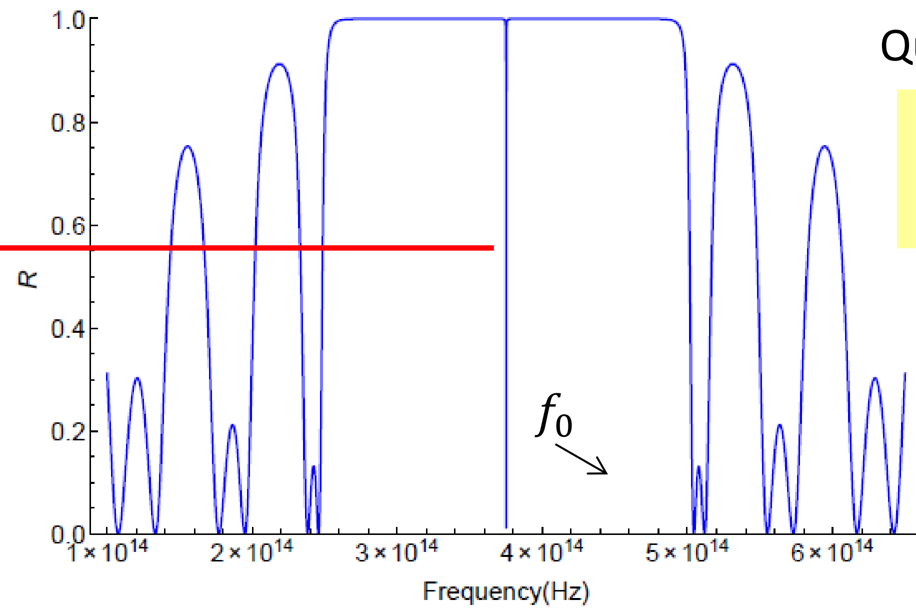
Maximum reflectance and PBG width:

$$n_c d_c = \frac{\lambda_0}{2}$$

$$n_H d_H = n_L d_L = \frac{\lambda_0}{4}$$

Optical resonance appears!





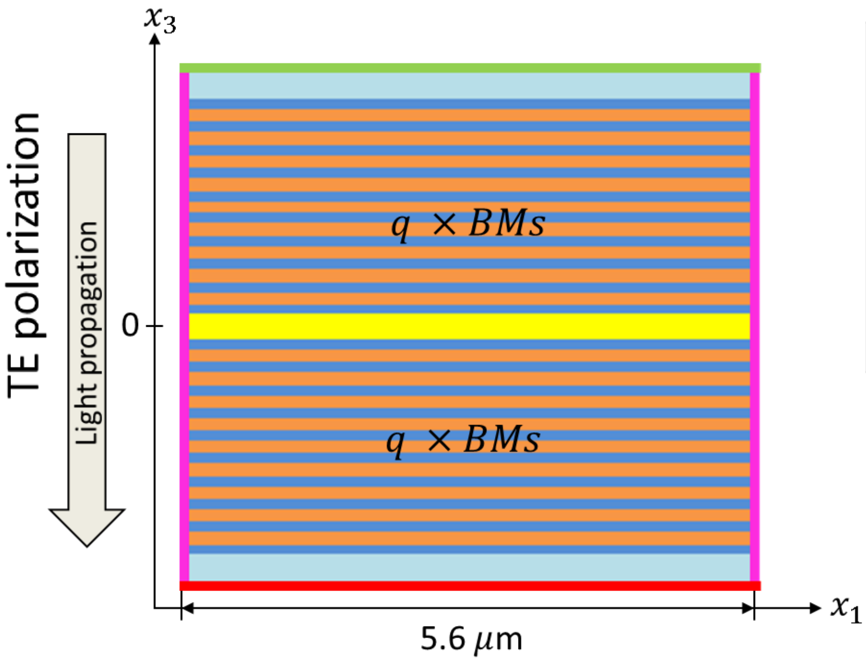
Quality factor

$$Q = \frac{f_0}{\Delta f_0}$$

The POMC model

Electromagnetic waves module

800nm POMC with Bragg mirrors composed of either ZnO/SiO_2



Material	Ref. index	Thickness (nm)
Air	1	300
ZnO	1.974	101.32
$LiNbO_3$	2.175	91.95
SiO_2	1.453	137.65
SiO_2	1.453	275.29

Boundary Conditions	
Port 1	Light excitation, measure of R
Port 2	Light absorption, measure of T
Continuity	Floquet periodicity

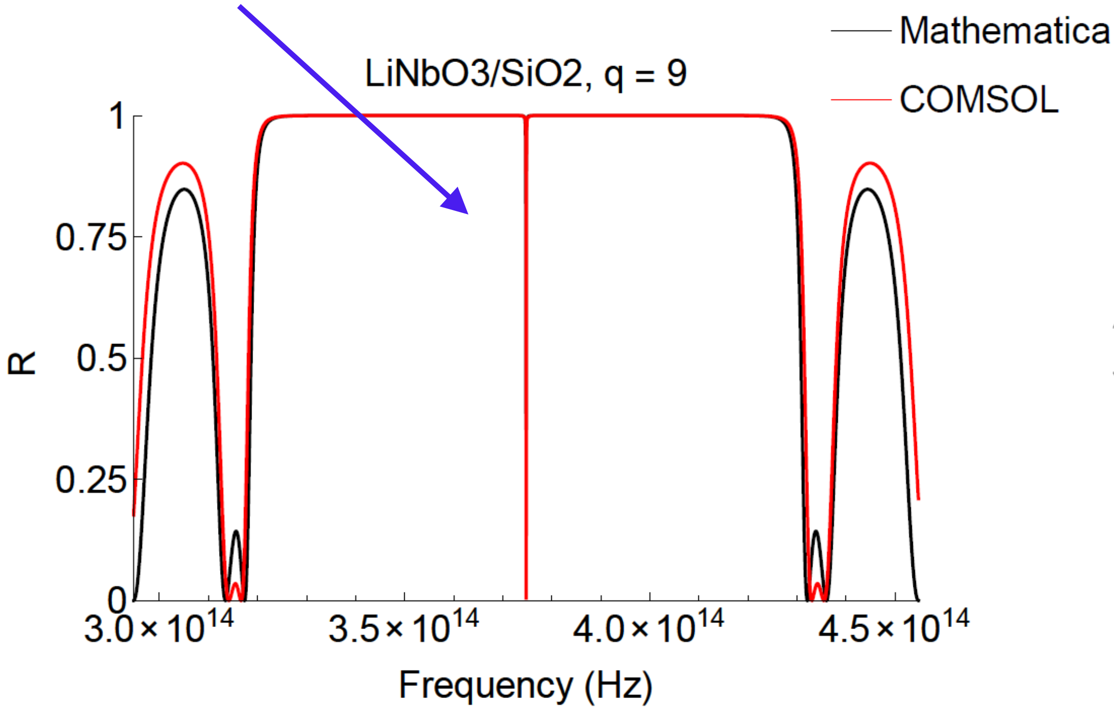
- SiO_2: good ref. index contrast with ZnO and $LiNbO_3$, compatible with CMOS
- Frequency Sweeps: obtain the spectral curves of reflectance
- Angle resolved reflectance: periodic port
- Eigenvalue solver: light electric field components
- Normalization factor: maximum electric field in the cavity

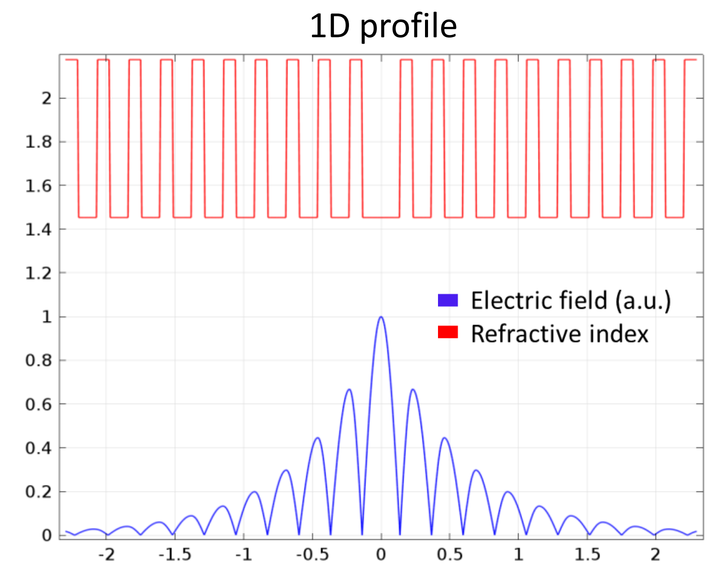
The planar optical microcavity model: results

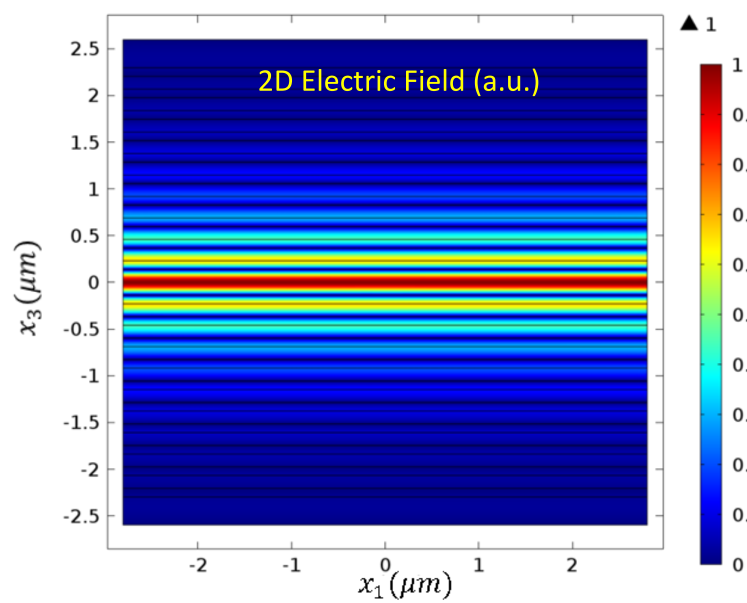
800nm POMC

- Reflectance obtained
- PBG characterized
- Predicted resonance frequency 374.74 THz
- Electric field confinement
  - 1D and 2D plots

- Very good agreement to the TM method

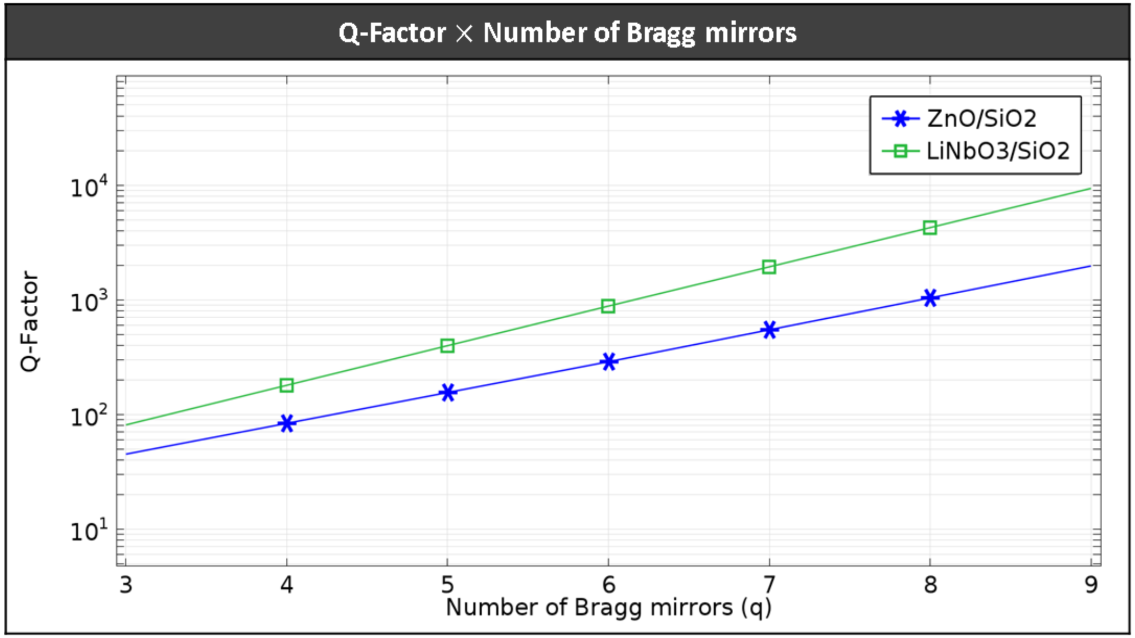


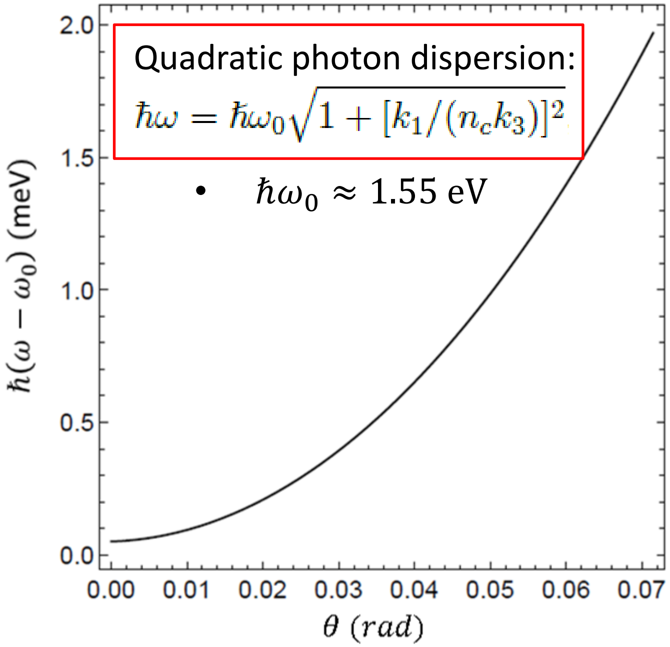




The planar optical microcavity model: results

This was observed for several *q* values.... **and light incidence angles!**



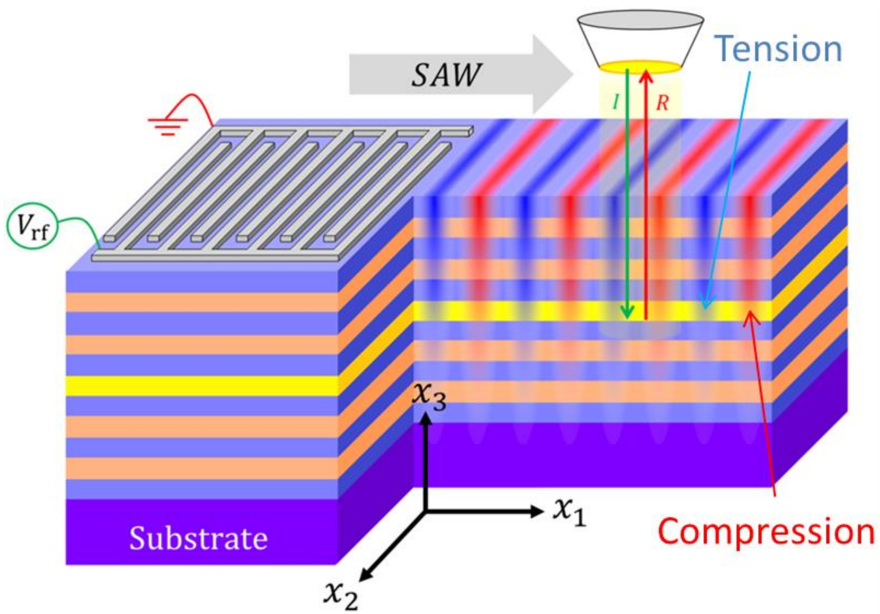


Using this model, we

- verified the unilateral optical confinement in the cavity
- characterized the reflectance and Q-factors for several *q* values (up to 10^4 for ~ 10 BMs)
  - good agreement with experimental results (ZnO/SiO_2)
- Constructed the photon dispersion for the POMC

The acousto-optic modulation model

Consider the following setup



SAW strain induces regions of tension and compression

The effective changes induced to the optical thickness of the cavity is given by*

$$\frac{\Delta\omega}{\omega} = -\left[\frac{\Delta n_c}{n_c} + \frac{\Delta d_c}{d_c}\right] = -\left[\frac{\Delta n_c}{n_c} + S_{33}\right]$$

Acousto-optic modulation

SAW-induced thickness modulation

$n = \sqrt{\epsilon}$ ⟹

The dielectric modulation follows from the tensorial equation:

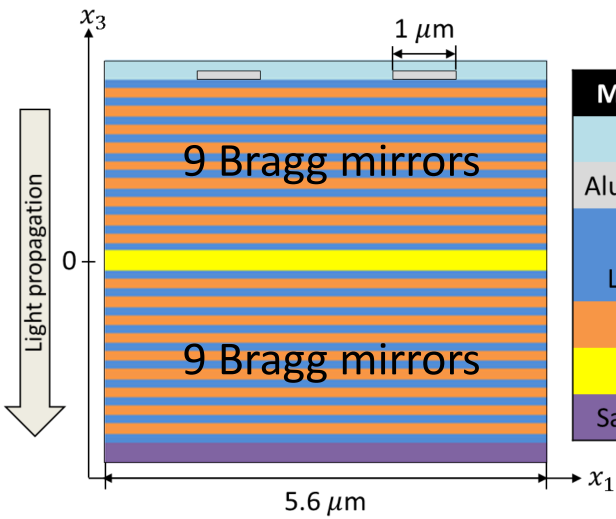
$$\Delta\epsilon_{il} = -\epsilon_{ij} p_{ijmn} \epsilon_{kl} S_{mn}$$

where p_{ijmn} is the acousto-optic tensor.

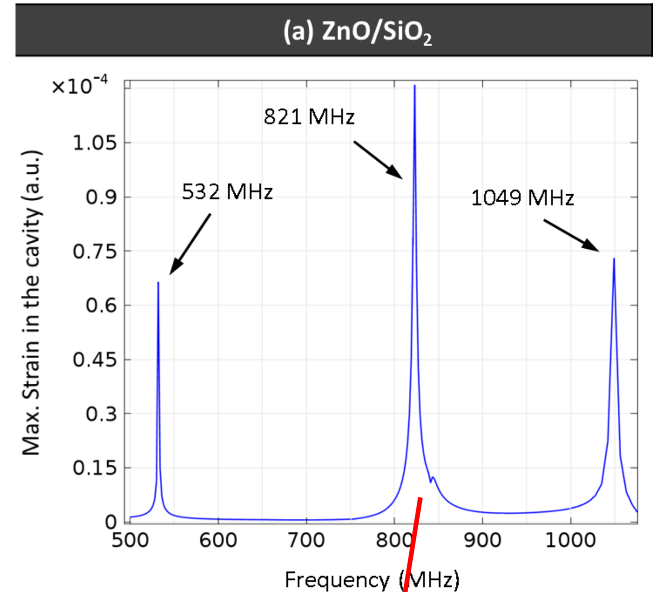
*M.M. de Lima et al. *Reports on Progress in Physics*, 68:1639, 2005.

The acousto-optic modulation model

Solid Mechanics + Electromagnetic waves modules



Material	Geometry	Thickness (nm)
Air	Top cover	300
Aluminium	IDTs	200
ZnO	High ref. index layer	101.32
$LiNbO_3$	High ref. index layer	91.95
SiO_2	Low ref. index layer	137.65
SiO_2	Cavity	275.29
Sapphire	Substrate	300

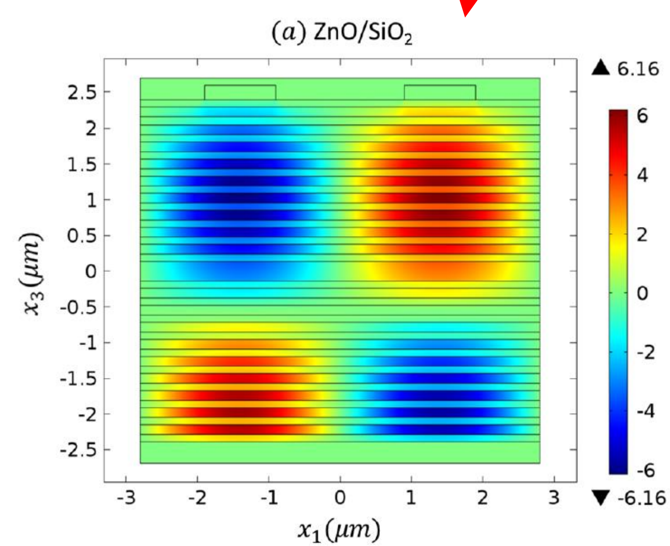


- **Boundary conditions kept**
- **Included a Sapphire substrate:**
  - Transparent
  - Hard

Simulation steps:

1. SAW modes evaluated
   - refractive index modulation
2. Optical modes evaluated

$$\left(\frac{\Delta n}{n}\right)_3$$



*P. D. Batista et al. *Applied Physics Letters*, 92:133502, 2008.

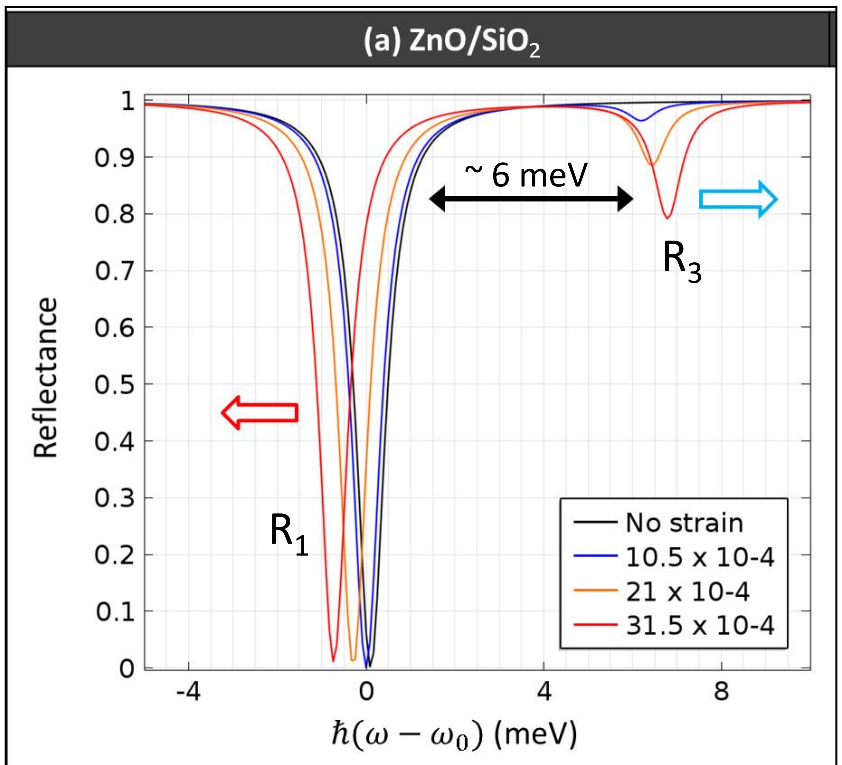
The acousto-optic modulation model: optical modes

Normal light incidence

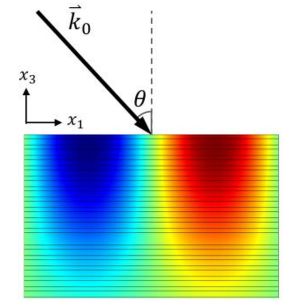
As strain is increased

- 2 resonances appear
- R_1 redshifts
- R_3 blueshifts

Near-resonance optical reflectance



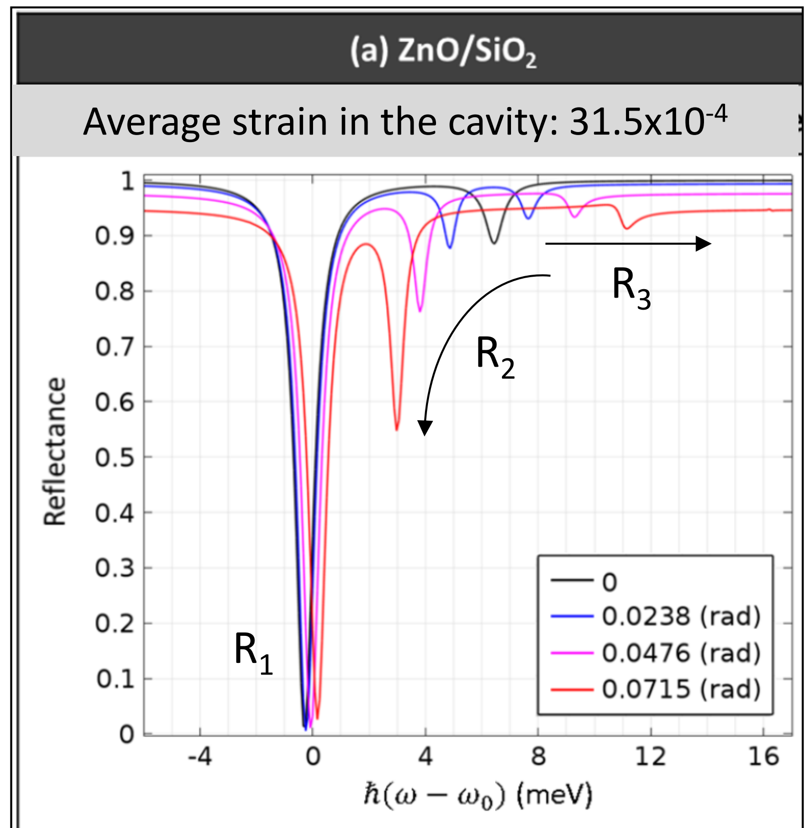
Oblique light incidence



As incidence angle increases

- 3 resonances appear
- R_2 redshifts

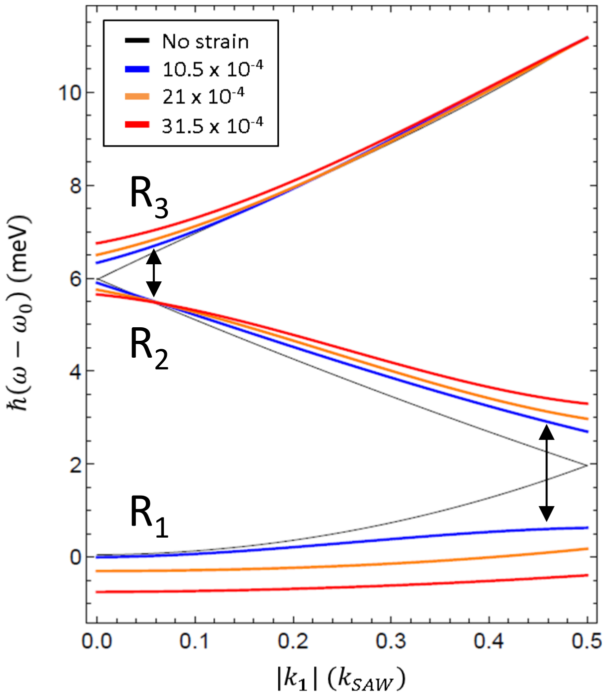
Near-resonance optical reflectance



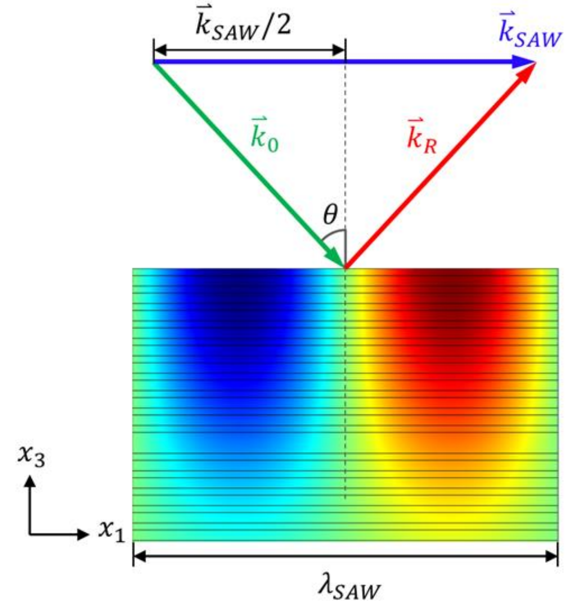
The acousto-optic modulation model: optical modes

When the SAW is turned ON

- SAW strains ⇒ **dynamic optical superlattice**
- Periodicity along x_1 is thus created, diffracting incoming light beams
- Photon dispersion is **folded into a mini Brillouin zone** (MBZ) between $k_1 \in [-k_{SAW}/2, k_{SAW}/2]$
- Increase of strain strengthens the phonon-photon interaction ⇒ **Energy gaps open up**



$$\theta_{max} = Sin^{-1}\left(\frac{k_{SAW}}{2k_0}\right) \approx 0.0715\, rad$$



*Experiments: M.M. de Lima et al. *Phys. Rev. Lett.*, 94:126805, 2005.

Conclusions

Acoustic model

- Prediction of SAW resonances
  - Good agreement with experimental results
- Mode characterization
- Sample engineering

Optics model

- Prediction of modes
- Light confinement observed
- Reflectance, Q-factors, dispersions characterized
- Good agreement with the TM method

SAW + POMC interaction

- Strong photon-phonon interaction
- Splitting and shifting of optical resonances
- Folding of photon dispersion
- Dynamic optical superlattice

Thank you for your attention!

Acknowledgements

FAPESP

CAPES

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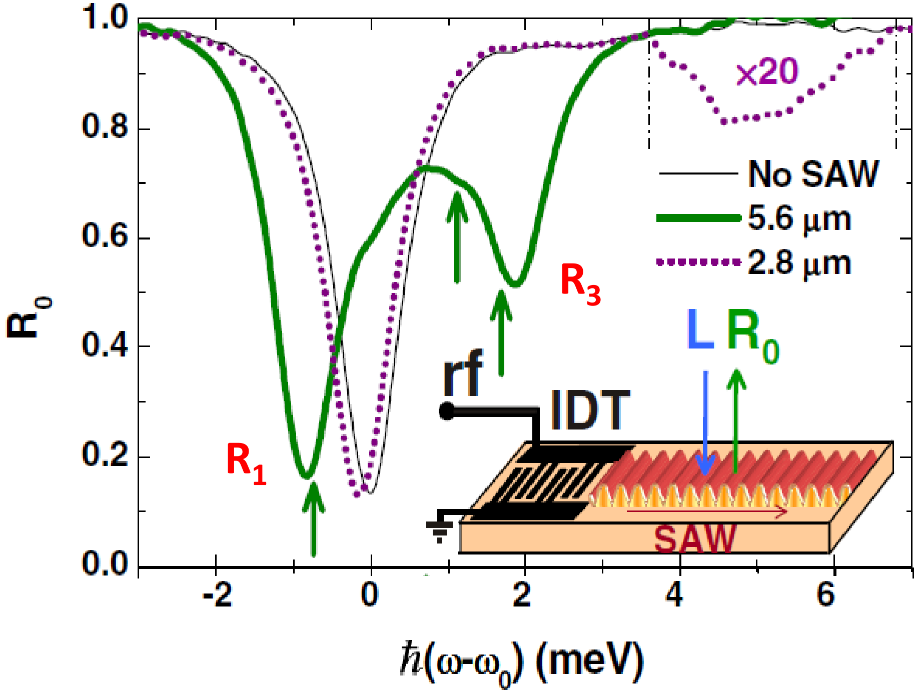
Conselho Nacional de Desenvolvimento Científico e Tecnológico

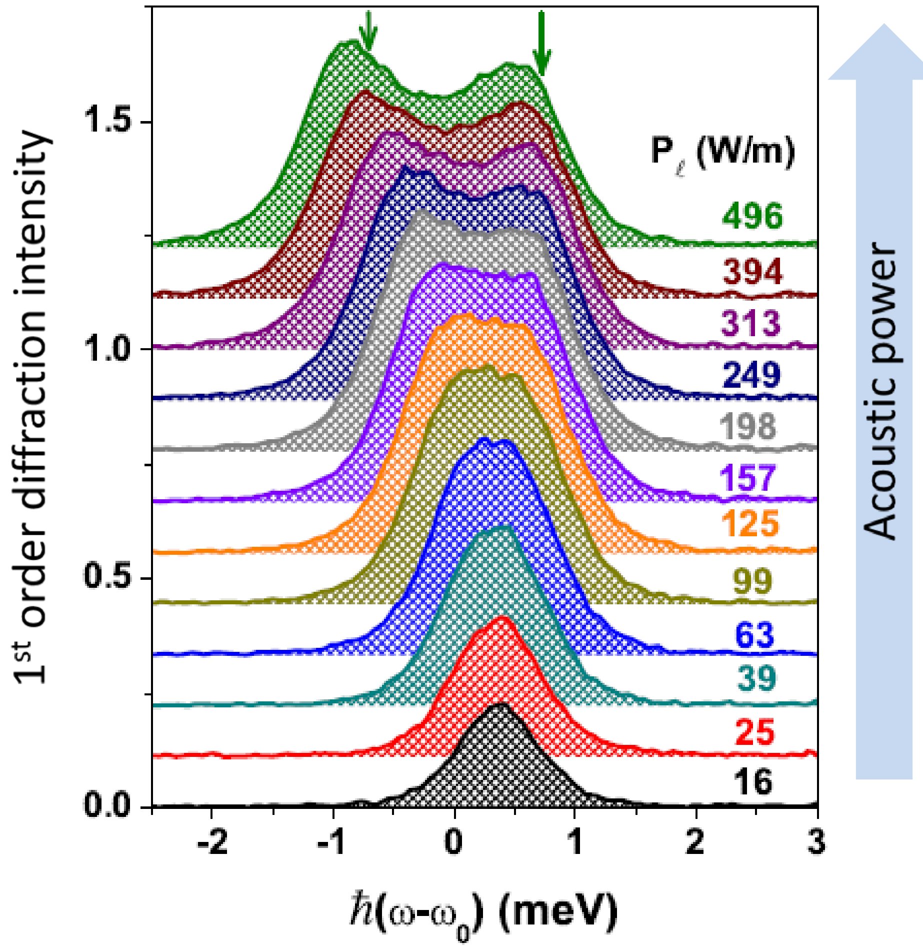
The acousto-optic modulation model: optical modes

Experimental reports on $\lambda/2$ GaAs/AlAs POMCs (Q = 1200)*

Normal incidence



$$\theta_{max} = Sin^{-1}\left(\frac{k_{SAW}}{2k_0}\right)$$ (right border of the MBZ)



- Two pronounced modes observed
- As we observed in our model

*M.M. de Lima et al. *Phys. Rev. Lett.*, 94:126805, 2005.