Fast and accurate calculation of Q factor of 2D photonic crystal cavity

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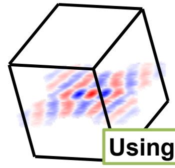
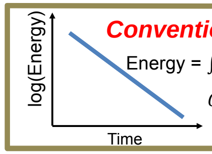
Background

Analysis of 2D PhC cavities

- Resonant wavelength ● Q factor ● Mode profile …



Conventional method to obtain Q : Calculate the energy decay



$$\text{Energy} = \iiint_{All}\left(\frac{1}{2}\varepsilon E^2 + \frac{1}{2}\mu H^2\right)dV$$

$$Q = \frac{\omega_0}{\left|\frac{d\log(E)}{dt}\right|}$$

Energy calculation (sum calculation) + FDTD calculation for several ps → Require large computational resources

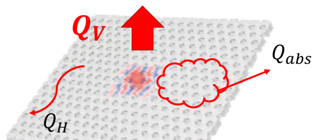
Idea & Motivation

K. Srinivasan and O. Painter, Opt. Express 10, 670 (2002).

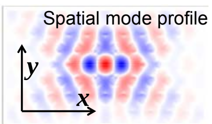
Out-of-slab radiation Q_V is the dominant cause of the cavity loss

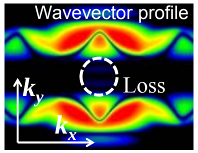
Light that does not satisfy total internal reflection radiates

Light cone (LC) $k_\parallel^2 \le (\omega_0/c)^2$



LC components = Cavity loss





Motivation

Want to reduce the computational resources by using 2D snapshot image instead of calculating the energy decay for long time.

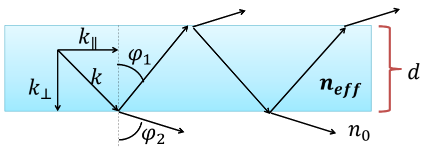
Idea

Calculate Q by integrating the $k_\parallel$-dependent loss rate in LC.

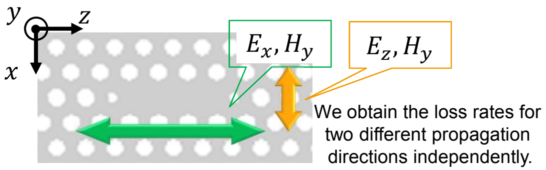
Calculation of the Q by using snapshot of wavevector profile

In-plane wavevector → angle of incident

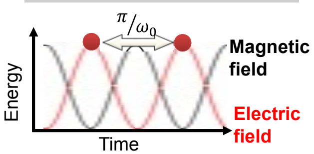
$$\varphi_1 = \tan^{-1}\left(\frac{k_\parallel}{k_\perp}\right), k_\perp = \sqrt{\left(\frac{n\omega_0}{c}\right)^2 - k_\parallel^2} \quad \varphi_2 = \sin^{-1}\left(\frac{n}{n_0}\sin\varphi_1\right)$$



1. The transmittance per reflection $T = \frac{n_0\cos\varphi_2}{n_{eff}\cos\varphi_1}|t|^2,\ t = \frac{2n_{eff}\cos\varphi_1}{n\cos\varphi_1 + n_0\cos\varphi_2}$
2. The reflection per unit time $N = \frac{c}{n_{eff}d}\cos\varphi_1$
3. Using n_{eff} instead of slab refractive index $n_{eff} = \iint_{all} k\cdot|E(k)|^2 dk \Big/ k_0 \cdot \iint_{all}|E(k)|^2 dk$



We obtain the loss rates for two different propagation directions independently.



We employed the timing when all the energy is at the electrical field.

The total out-of-slab radiation loss rate L

$$L_{E_x} = \iint_{LC}|E_x(k)|^2\cdot T(k, n_{eff})\cdot N(k, n_{eff})dk$$

$$L_{E_z} = \iint_{LC}|E_z(k)|^2\cdot T(k, n_{eff})\cdot N(k, n_{eff})dk$$

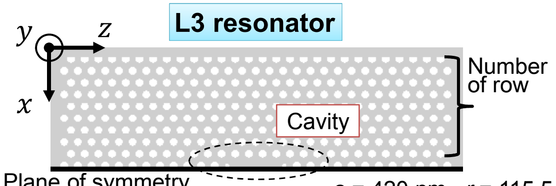
Calculation of the Q

$$Q = \omega_0\frac{U}{\left|\frac{dU}{dt}\right|} = \omega_0\frac{U_{E_x} + U_{E_z}}{U_{E_x}L_{E_x} + U_{E_z}L_{E_z}}$$

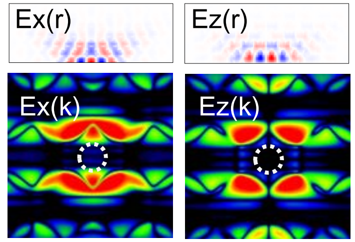
where, $U_E = \iint_{all}|E(k)|^2 dk$

Results

L3 resonator

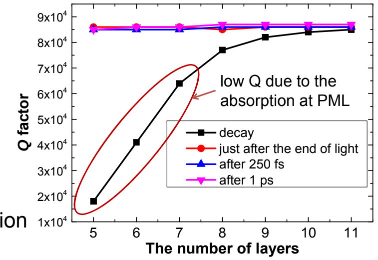


a = 420 nm , r = 115.5 nm



light source
λ_0 = 1570 nm
FWHM ≈ 3 nm

Using mode profile
i. 0 s
ii. 250 fs
iii. 1 ps
after the light excitation



Results:

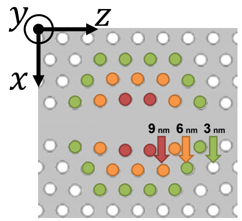
1. Accurate Q confirmed.
2. Required calculation step reduced: We can obtain Q from a 2D snapshot just after the excitation of the cavity
3. Required calculation volume reduced: We obtain Q_v, hence do not suffer from horizontal loss.

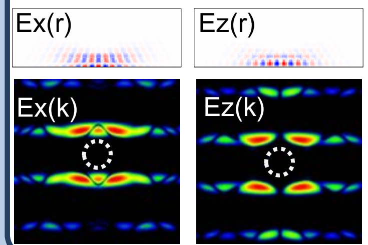
We can drastically **reduce the computation time**

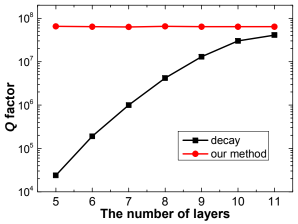
Width-modulated cavity

a = 420 nm , r = 108 nm

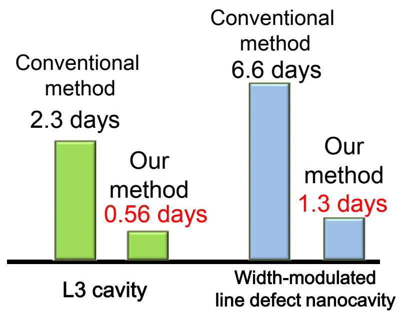
λ_0 = 1568 nm FWHM ≈ 0.8 nm







Computation time



Summary

- We developed a method that calculate the Q of a 2D PhC nanocavity directly from a 2D mode profile at the center of a PhC slab.
- This allows us to reduce both the calculation volume and the calculation step.
- We can shorten the time required to obtain an accurate Q value for an ultrahigh-Q PhC nanocavity.

Acknowledgement

Keio Spintronics Research Center, JSPS Core-to-core program, from the Japan Society for the Promotion of Science