Phonon-polariton based nano-split ring resonators

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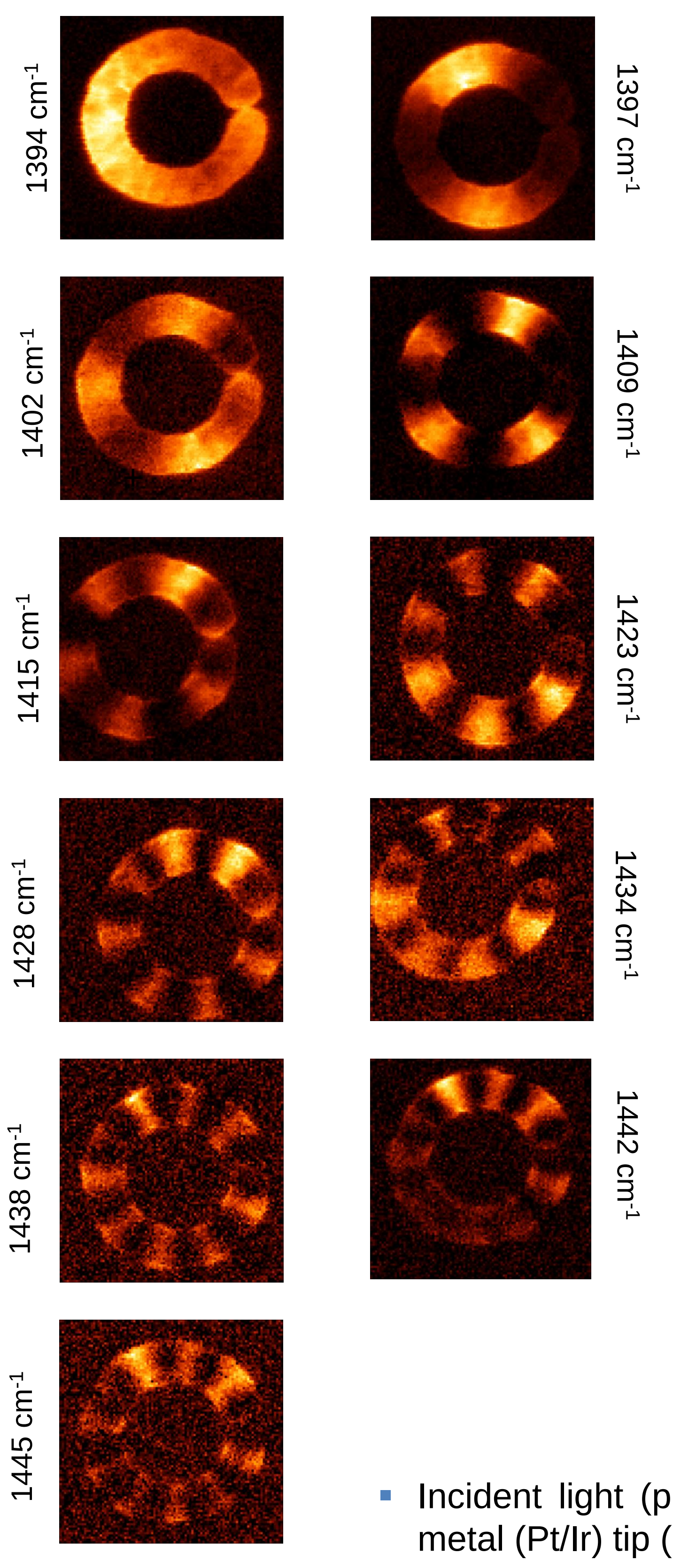
Abstract

Phonon-polaritons are being studied under a broad range of aspects including slow light, hyperbolic materials response, and localized resonances. Here, we show the use of phonon-resonance based conductance to engineering split ring resonators (SRRs) with high qualtiy factors, designed to operate in the reststrahlen band around 1400 cm^{-1}. SRRs have proven to be a useful tool in the fields of metamaterials, light matter interaction and non-linear optics. An important limitation in these applications are the ohmic losses in gold and other metals. In contrast, transvers optical phonons have large oscillator strength and low scattering rates [1]. We present monochromatic near-field images of phononic SRRs which reveal narrow-band localized resonances. We find that these localized modes can be described as LC-modes supported by hybridized surface modes[2,3], and propose the use of a lumped element model to describe the LC-resonance for the strongly dispersive AC-conductance found in polar materials.

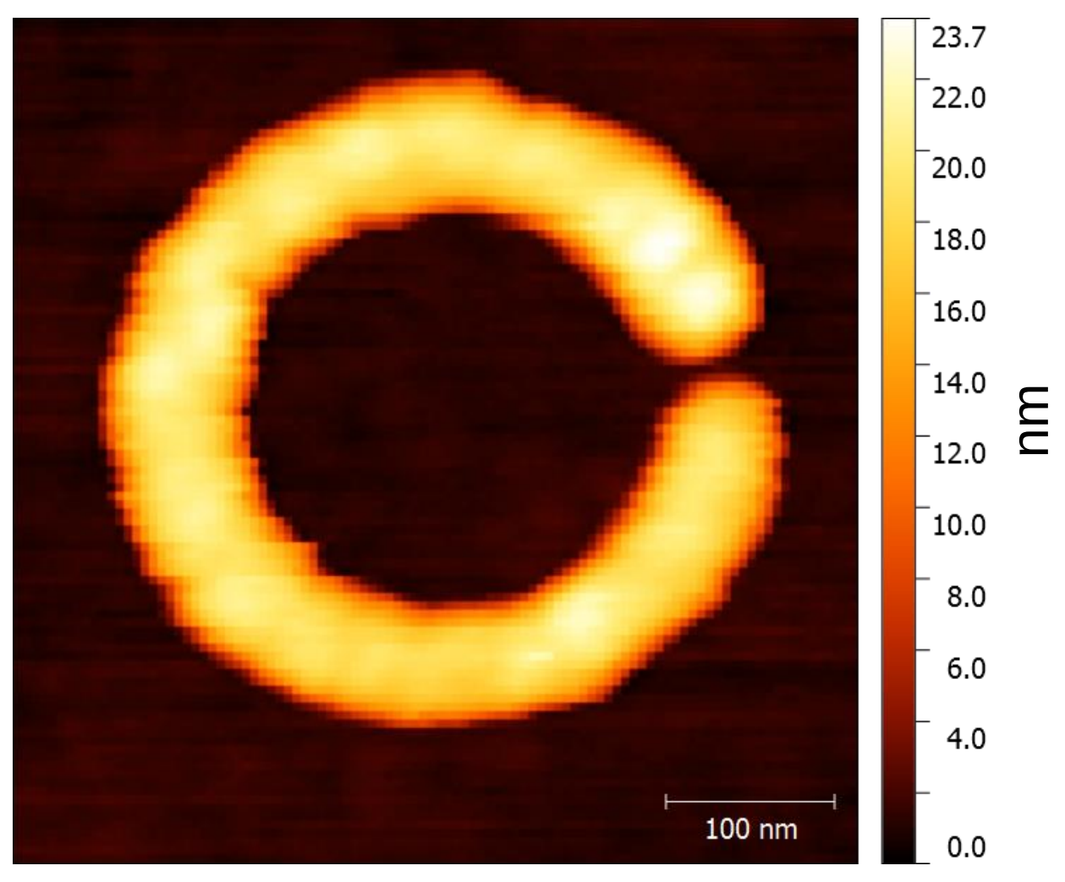
[1] A. J. Giles, et al., Nature materials 17.2 (2018), DOI:10.1038/nmat5047
[2] P. Li et al. Nano Letters (2016) DOI:10.1021/acs.nanolett.6b03920
[3] F. J. Alfaro-Mozaz et al., Nature Communications 8 (2017), DOI: 10.1038/ncomms15624

Nanoimaging of high-order modes in h-BN SRRs

Near-field signal $|S_3|$

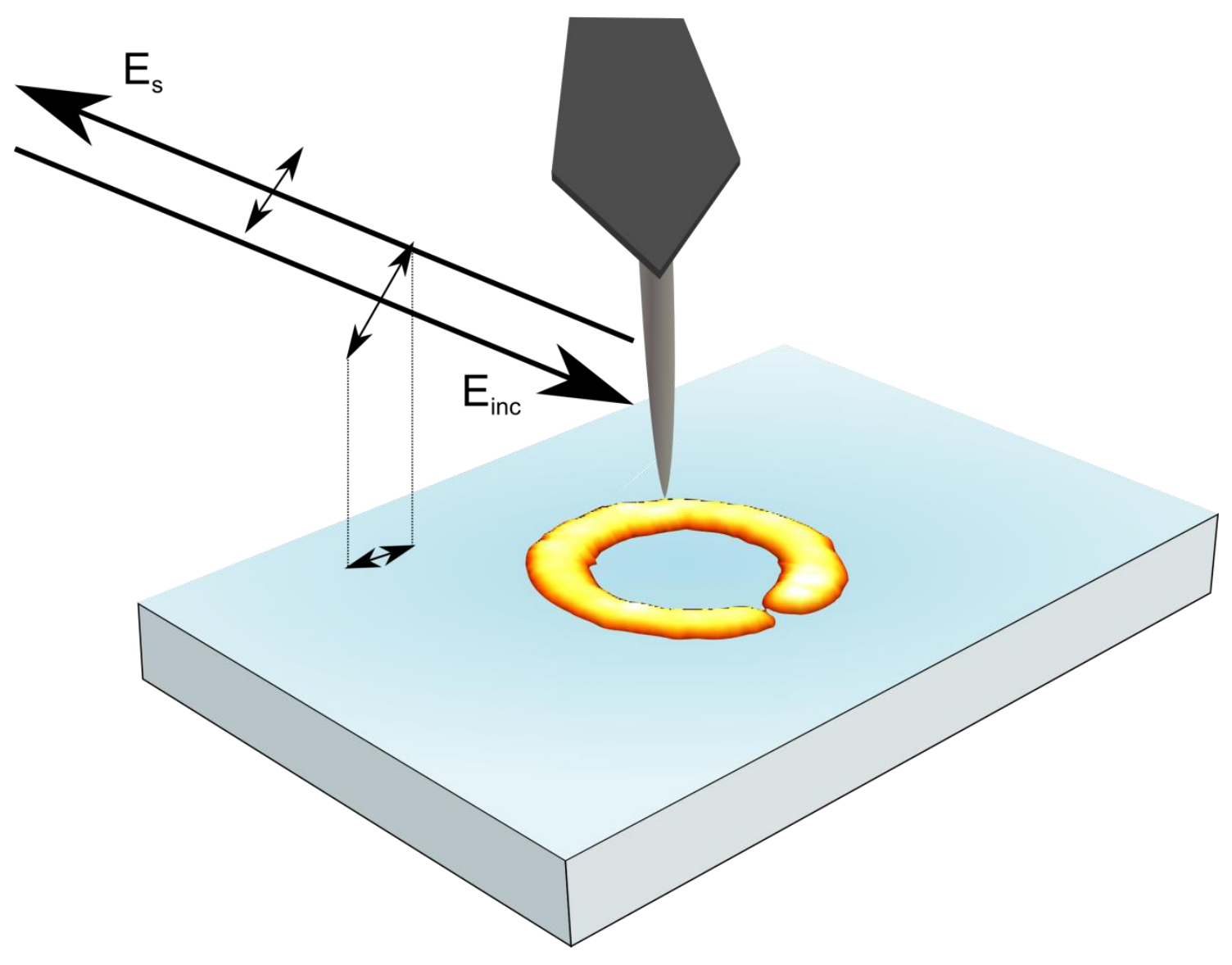


Topography



- 17 nm thin h-BN flake on CaF$_2$ ($\varepsilon_r = 2$)
- Rings with 320 nm diameter, gap <50 nm
- ^{10}B enriched h-BN [1] ($\nu_{TO} = 1393\ \mathrm{cm}^{-1}$)

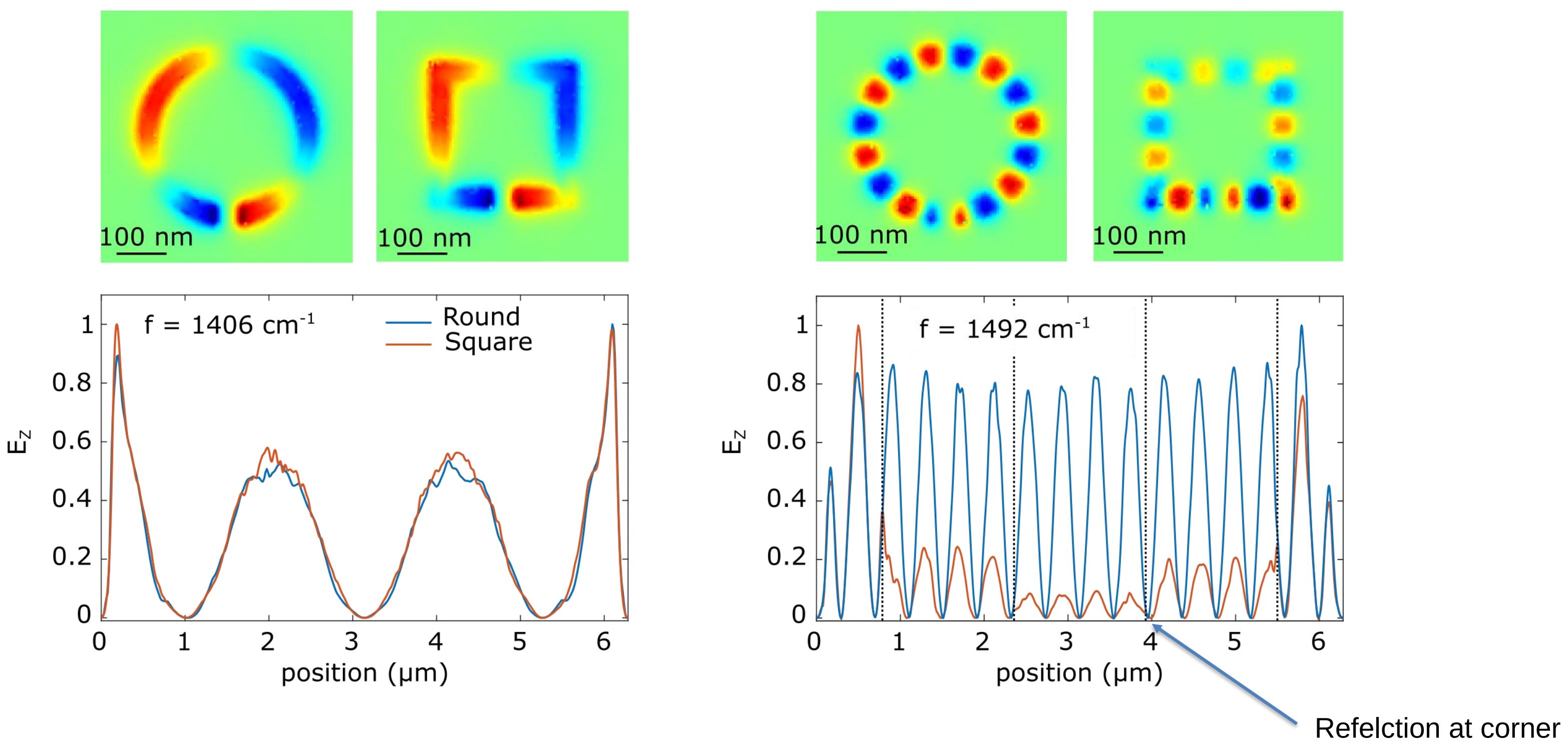
Measurement scheme



- Incident light (polarized along AFM-tip) is mainly scatterd by the metal (Pt/Ir) tip (SRR scattering cross section much smaller)

Influence of bending angle

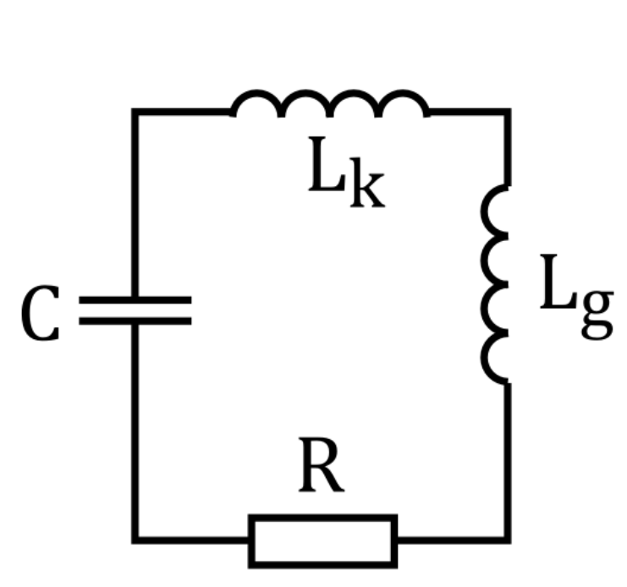
Comsol simulations of round and square SRR with identical circumference



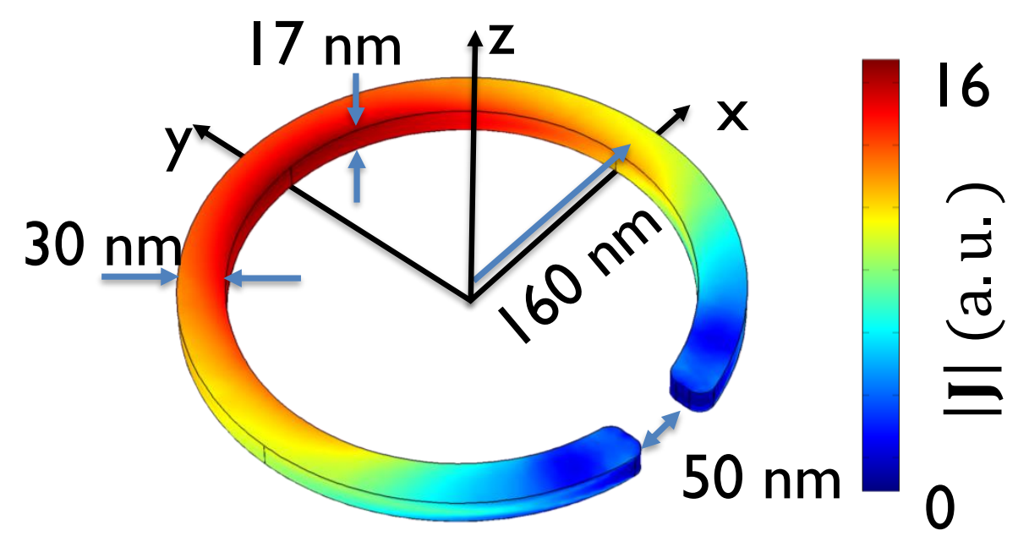
- Mode distribution along the circumference is independet of actual geometry
- Reflection at edges for $\lambda_p \lesssim w$ (the nanowire width)

Lumped elements model

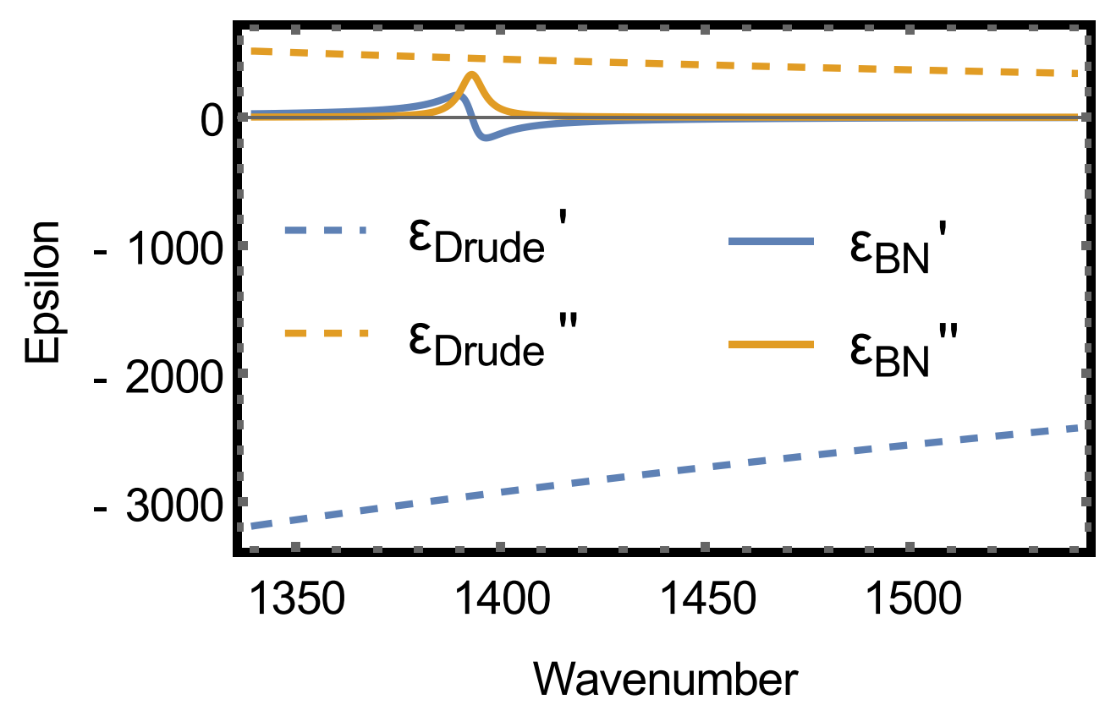
Lumped elements LC model

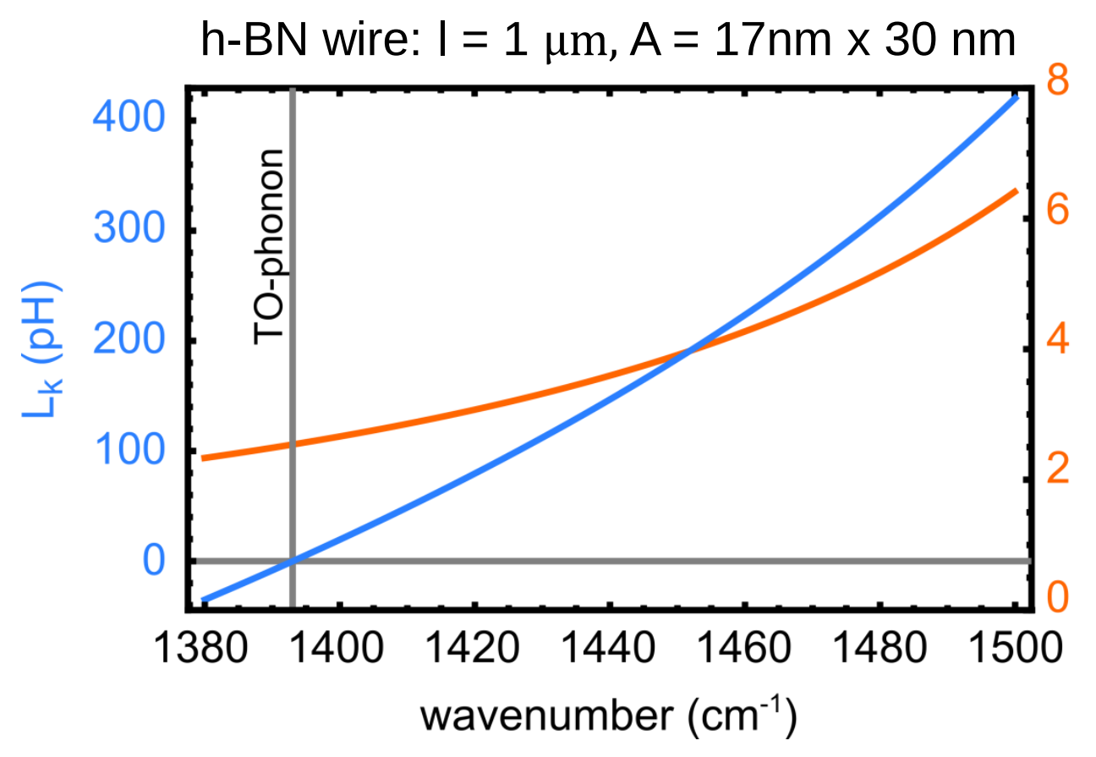


Current distribution (FEM simulation)



Material distribution – effects of dispersion and losses





- Strong phononic dispersion leads to frequency dependent material response, resonant modes are given by fix points of the equation:

$$\omega_{LC} = \sqrt{\frac{1}{\left(L_g + L_k(\omega_{LC})\right)C} - \frac{R(\omega_{LC})^2}{4\left(L_g + L_k(\omega_{LC})\right)^2}}$$

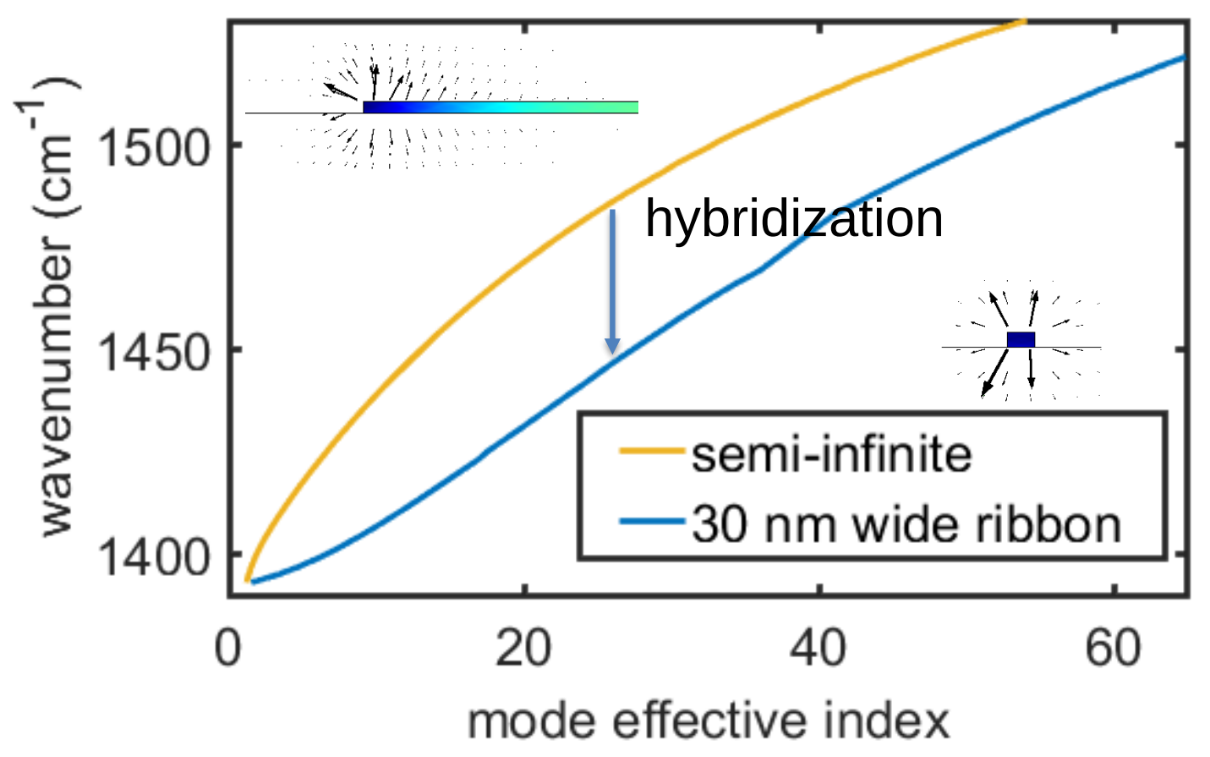
- Geometric contribution: $C \approx 1\ \mathrm{aF}$ and $L_g \approx 0.1\ \mathrm{pH}$
- Material contribution: kinetic inductance $L_k = \mathrm{Re}\left[\frac{i}{\omega\sigma}\frac{l}{A}\right]$, and resistance $R = \mathrm{Im}\left[\frac{i}{\sigma}\frac{l}{A}\right]$

➢ Solution for ω_{LC} exists only close to TO-phonon

➢ Modes at higher frequencies supported by waveguide modes formed by propagating phonon polaritons

Displacement current from waveguide modes

Waveguide mode dispersion

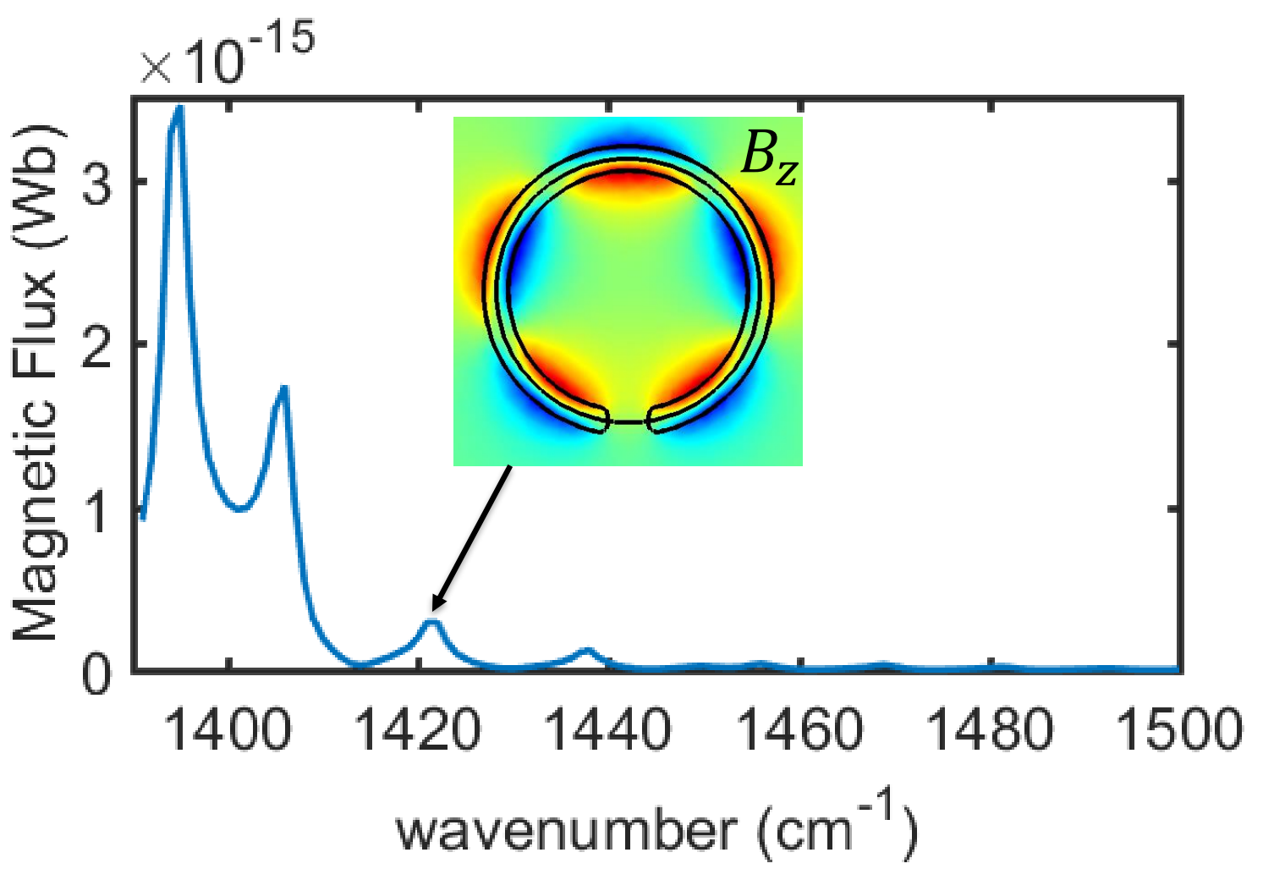


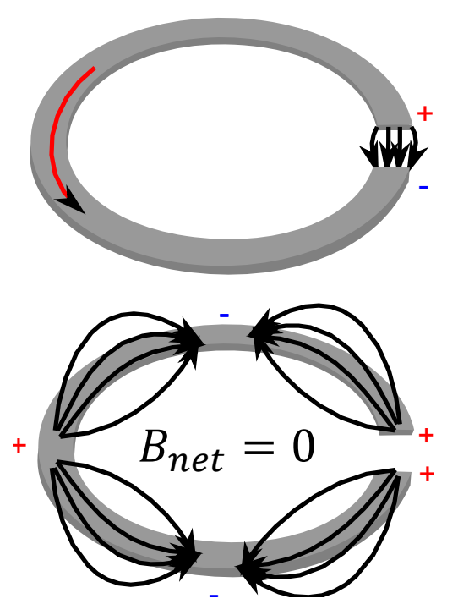
- Lateral surface modes dominate dispersion in narrow h-BN ribbons [3]
- Strong hybridization of lateral surface modes due to kinetic inductance of displacement currents

➢ Homogeneous current density accross full cross section

➢ Electric fields on the inner and outer circumference are either in phase (symmetric mode) or out of phase (asymmetric mode which is only weakly confined)

Magnetic flux through resonator center for asymmetric modes





Asymmetric modes:

- Strong field enhancement in gap
- Net magnetic flux through resonator

Symmetric modes

- Strong out-of plane field at the gap

- For excited LC-modes, net current flow arround the ring structure can be inferred by finite magnetic flux through resonator center

➢ Waveguide modes provide current channel with low kinetic inductance, enabling LC-like excited modes

Outlook

➢ Integration with electro-optic materials for light detection/generation in compact devices

➢ Exploit mode confinement for sensing

➢ Investigation of strong coupling in highly dispersive cavities

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