Surface phonon polaritons supported heat conduction

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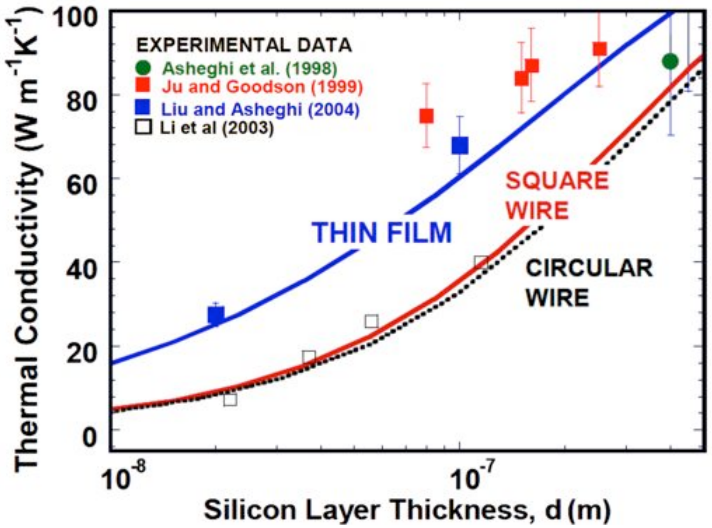
Increasing thermal conductivity at nanoscale

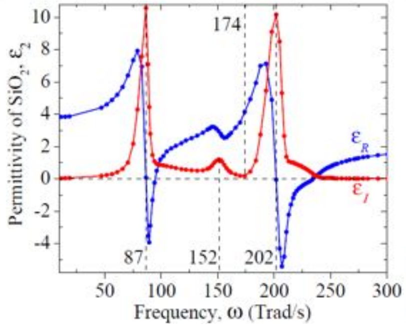
- **Downscaling of nanosystems tend to be limited by heat extraction**
- **Bulk thermal conductivity decreases with material size**



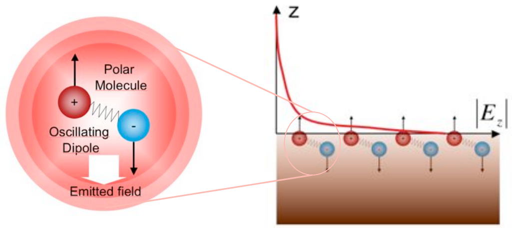
- **But nanosystems have very high surface/volume ratio**
- **Use surface effects to extract heat**

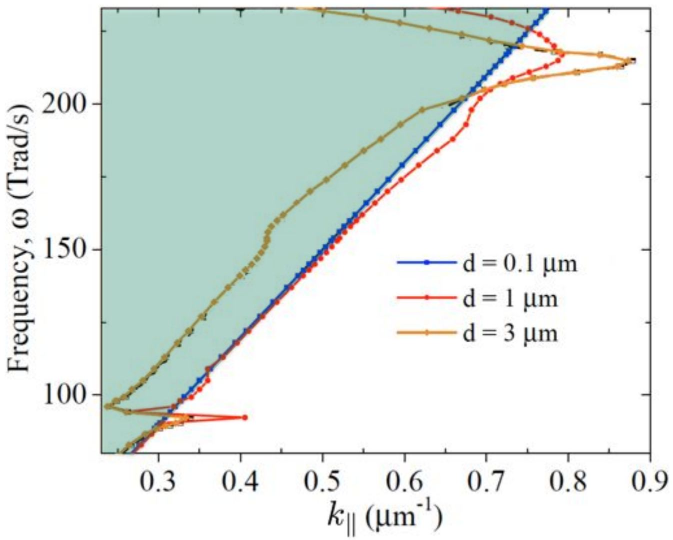
Surface Phonon Polaritons (SPhP)

- **Happens at the interface of polar materials and dielectrics**
- **Superposition of photon and phonon state**



E. Palik, Handbook of Optical Constants in solids (1985)





- **Part of the dispersion under the light line**

$$k_{\|} \geq \omega/c \Leftrightarrow k_{\perp} = i\sqrt{k_{\|}^2 - \omega^2/c^2}$$

- **Wavelength ~10 μm, corresponding to max of Planck's law at ambient**

Preliminary remark

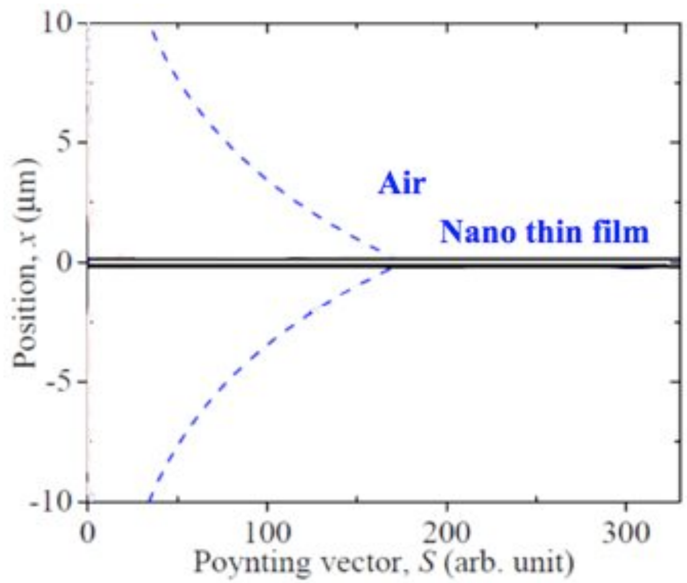
Longitudinal transport

- **We look at the propagation of the SPhP**

- **Good thing about nanosystems is that analytical calculations can be performed**

- **Perturbative calculations for** $k_{1,\perp} d \ll 1$
  - For SPhP @ 9 µm (SiO_2), d ~ 300 nm

- **Poynting vector:**



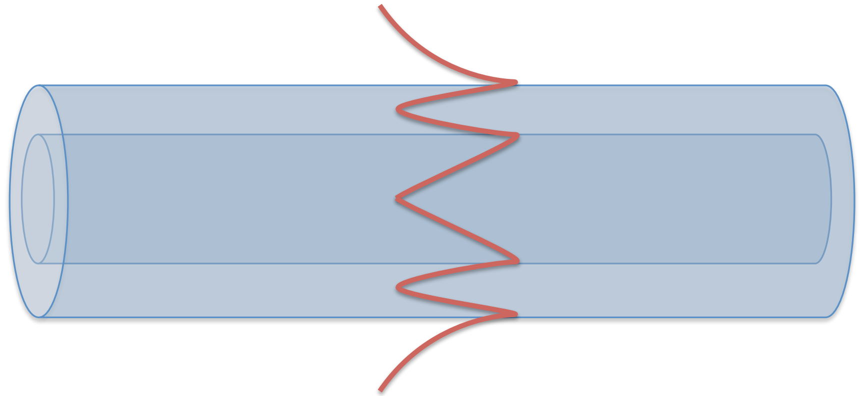
- **Thermal conductivity contribution of SPhP**

$$\kappa = \frac{1}{4\pi d}\int_0^\infty k_{\parallel}\Lambda\hbar\omega\frac{\partial}{\partial T}\frac{1}{e^{\frac{\hbar\omega}{k_B T}}-1}d\omega$$

D. Chen *et al.*, PRB **72**, 155435 (2005)

- **Only the propagation length Λ determines the thermal conductivity**

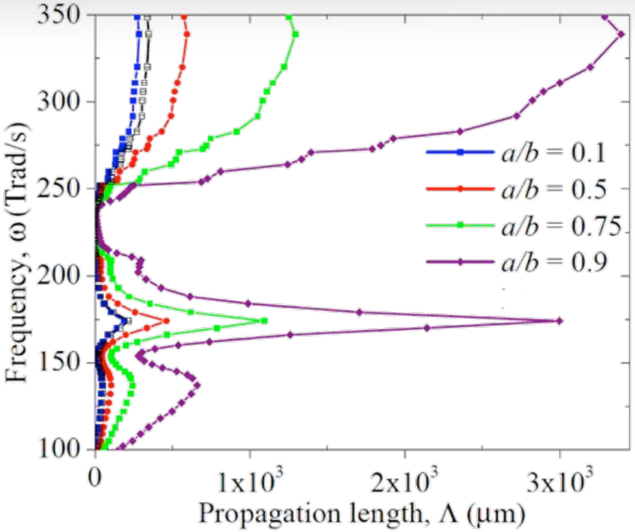
SiO_2 nanotubes

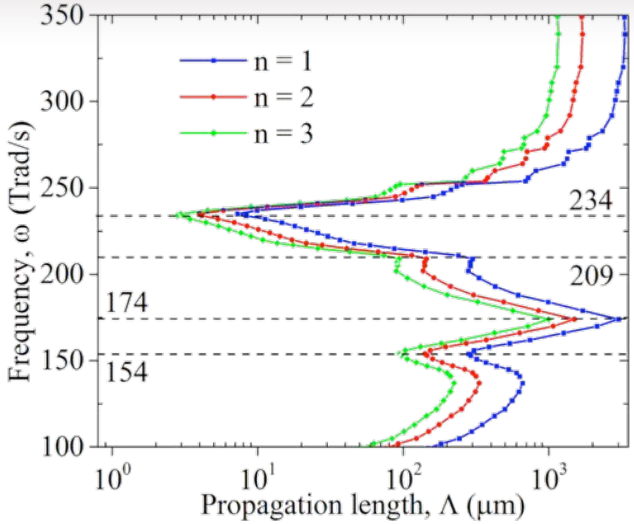


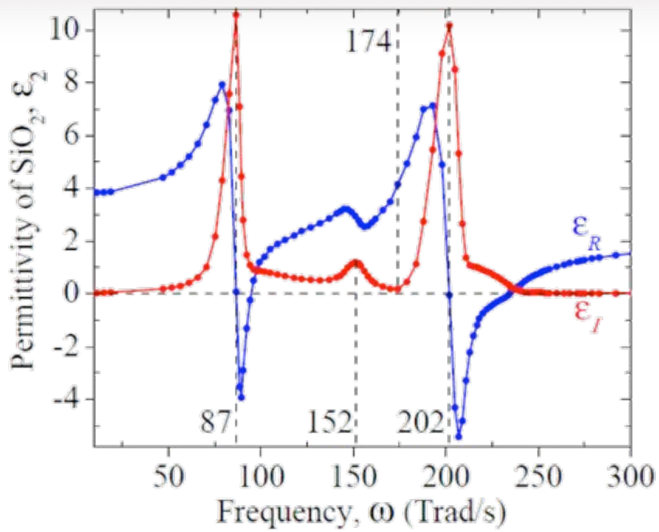
- **2D systems**
- **Coupling of radial modes**
- **Lot of angular modes**
- **For** $k_{1,\perp} d \ll 1$ **, the sole parameter is the inner to outer radius ratio**
- **SiO_2 widely used in microfabrication**

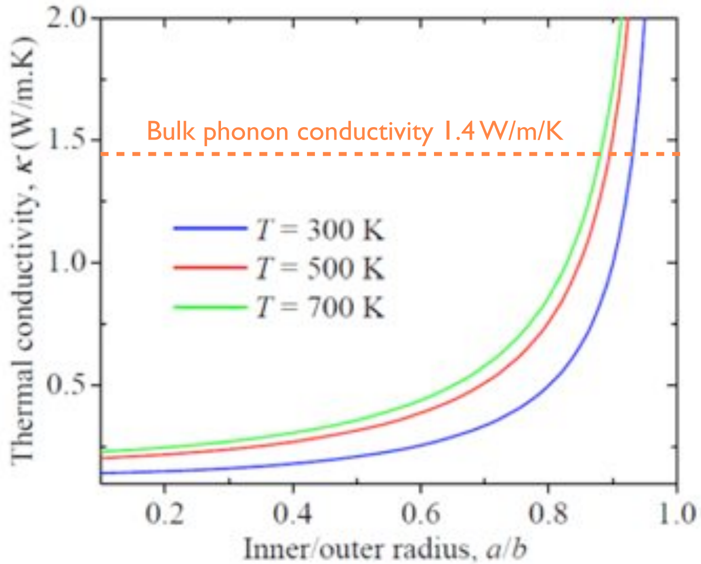
Analytical results

On SiO_2 nanotubes





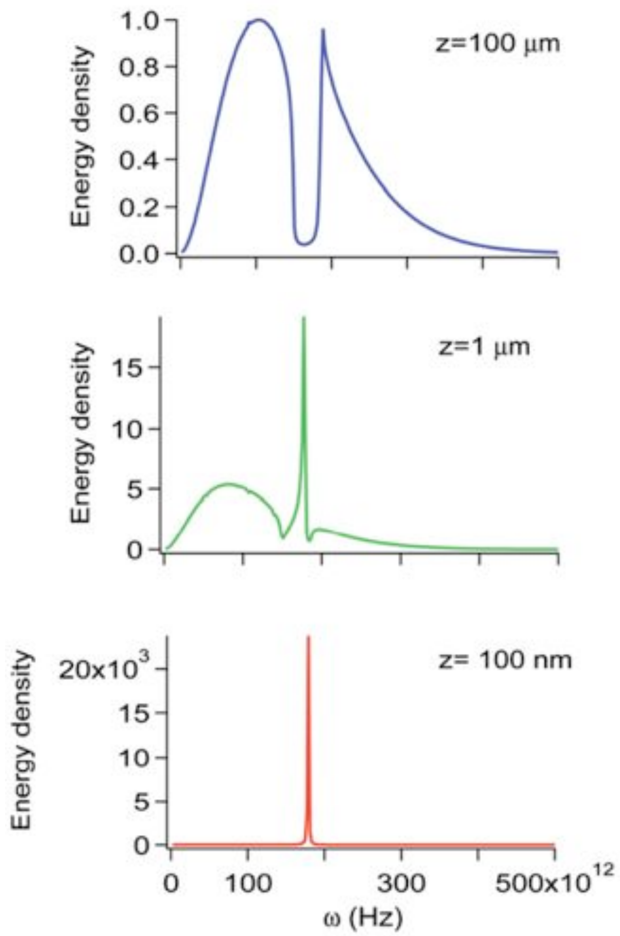




J. Ordonez-Miranda *et al.*, JAP **113**, 084311 (2013)

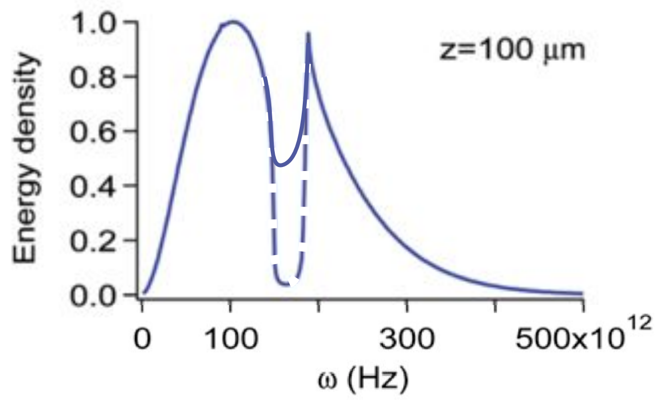
- **For large radii radio SPhP contribution > bulk**
- **Typical sizes**
  - Outer radius 3 μm
  - Thickness 300 nm

Quantifying this SPhP contribution?



K. Joulain *et al.*, *Surface Science Report* ***57*** *(3), 2005*

- **In the far field, the existence of the SPhP gives a dip in the emission**
- **If SPhP are diffracted, this dip will decrease**



Observe SPhP in far field

- **SPhP stand below the light cone, they are not radiated**

- **Usual schemes to couple SPhP:**
  - Grating
  - Internal total reflexion in prism

- **But the tube diffracts by itself!**

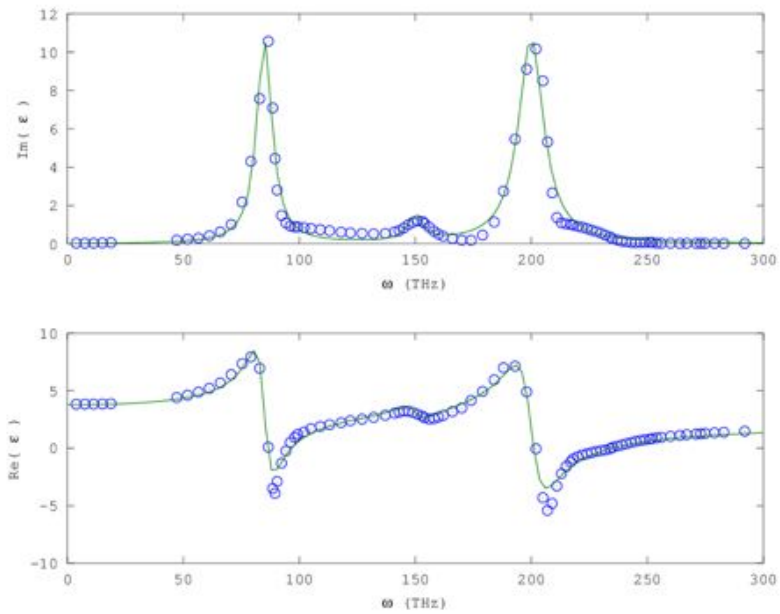
Modeling tube SPhP diffraction

- **Finite Difference in Time Domain**
  - Discretization of space and time
  - Polychromatic sources
  - Arbitrary systems shape

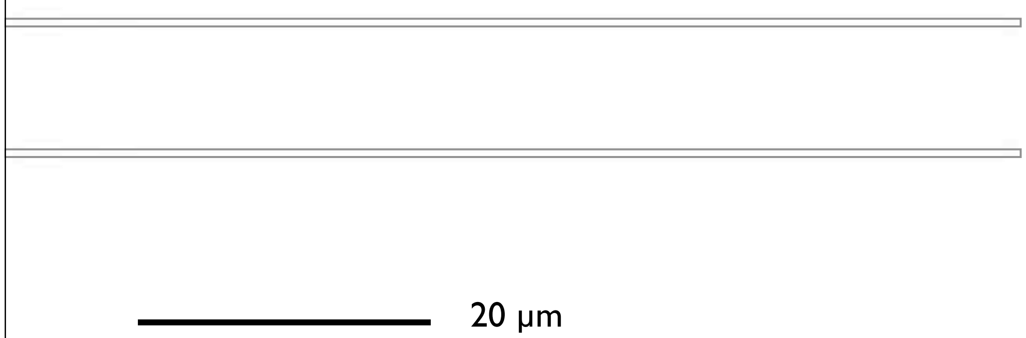
MEEP code

- **Lorentz model for SiO_2**

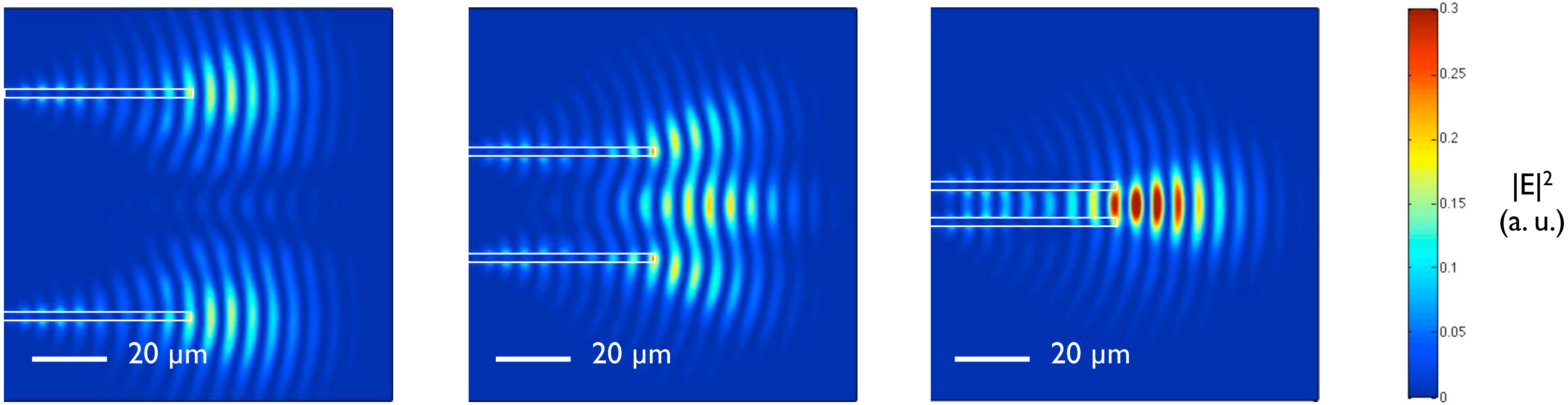
$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{j=1}^{3} \frac{\sigma_j \omega_j^2}{\omega_j^2 - \omega^2 - i\Gamma_j \omega}$$



SPhP propagation with FDTD

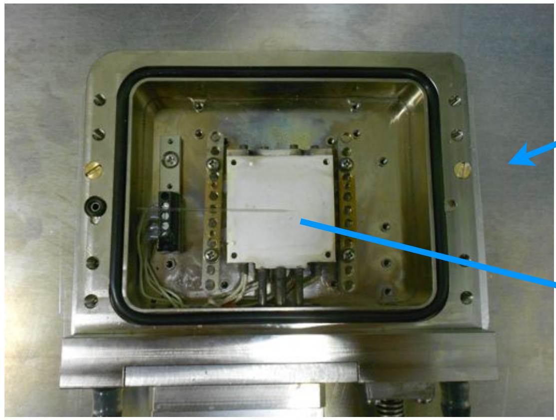


Angle of diffraction



- **For radii ~ λ_{SPhP} both sides of the tube interfer constructively and emits on a narrow angle cone 30°, compatible with standard Cassegrain objectives NA**

- **FTIR bench + IR microscope**



Conclusion

- **Use of SPhP to increase longitudinal conductivity in SiO_2 nanotubes**
- **Analytical computation shows the possibility to double the total conductivity**
- **FDTD simulation of SPhP diffraction in far field with nanotube**
- **Now looking for the spectral signature of SPhP in far field with FTIR measurement**