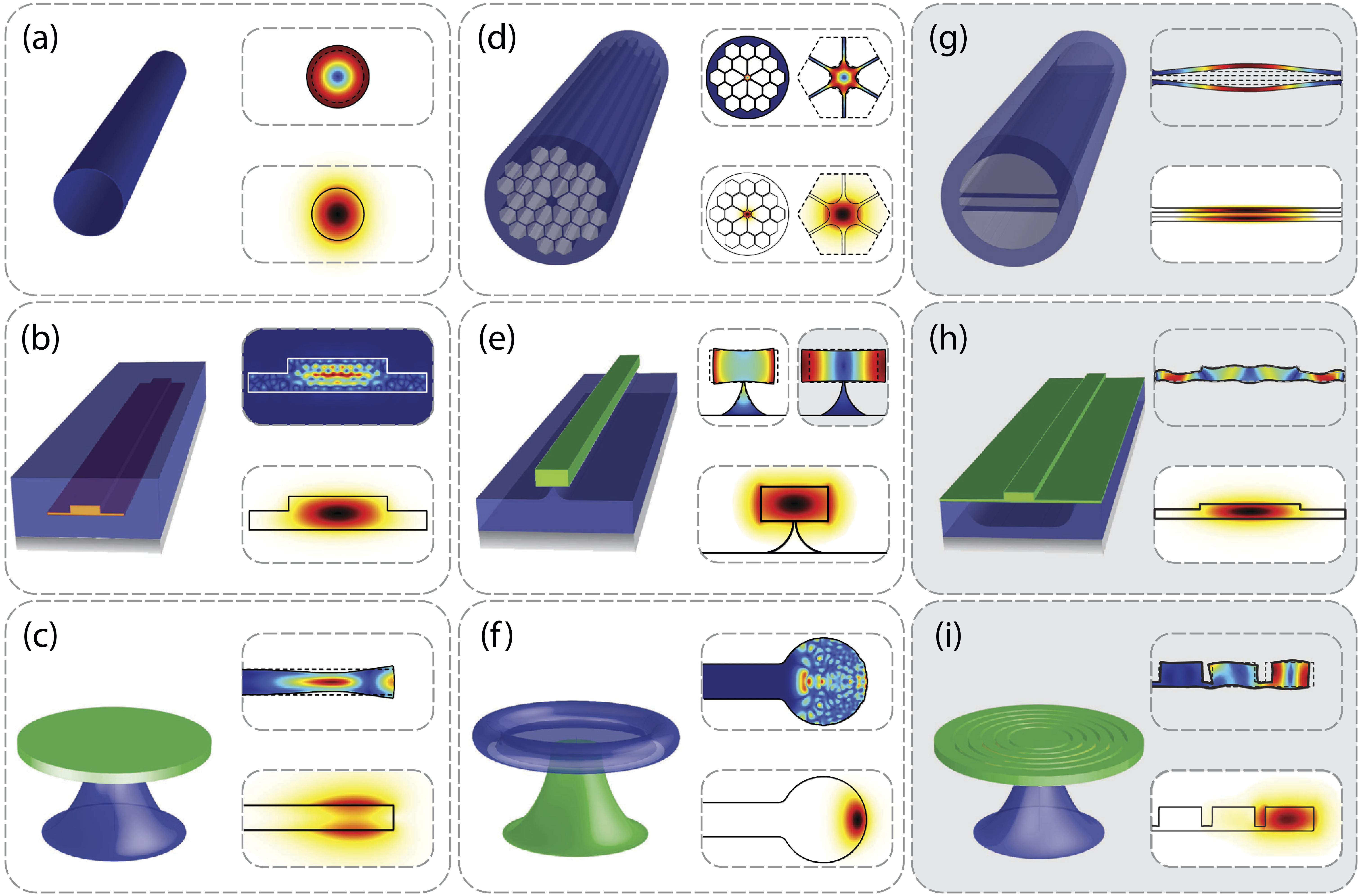
Harnessing wavelength-scale waveguides and cavities for Brillouin Optomechanics



Gustavo Wiederhecker
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Brazil

Outline

- Introduction to Brillouin Scattering
- Mechanical modes
- Optical modes
- Harnessing Brillouin interaction
- Optomechanical cavities
- Final remarks

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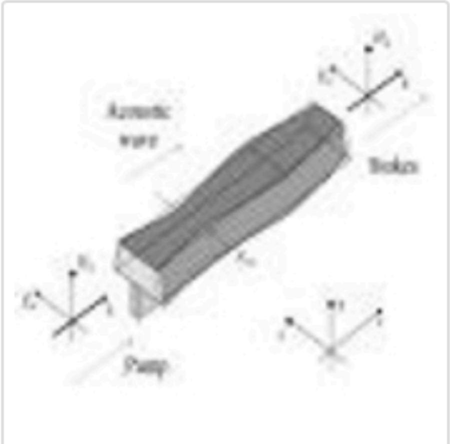
A good time to be a student

Journal of the Optical Society of America B Vol. 38, Issue 4, pp. 1243-1269 (2021) • https://doi.org/10.1364/JOSAB.416747



Brillouin scattering—theory and experiment: tutorial

C. Wolff, M. J. A. Smith, B. Stiller, and C. G. Poulton

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Review Article | Published: 19 August 2019

Brillouin integrated photonics

Benjamin J. Eggleton, Christopher G. Poulton, Peter T. Rakich, Michael. J. Steel & Gaurav Bahl

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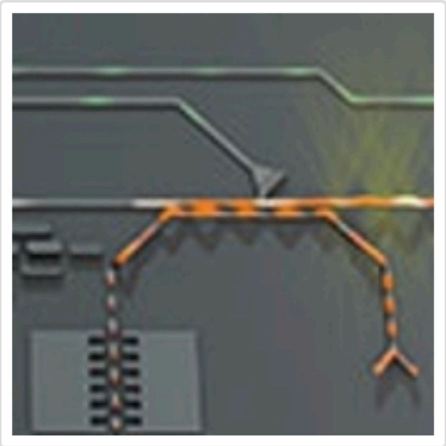

Controlling phonons and photons at the wavelength scale: integrated photonics meets integrated phononics

Amir H. Safavi-Naeini, Dries Van Thourhout, Roel Baets, and Raphaël Van Laer

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Integrated Photonics

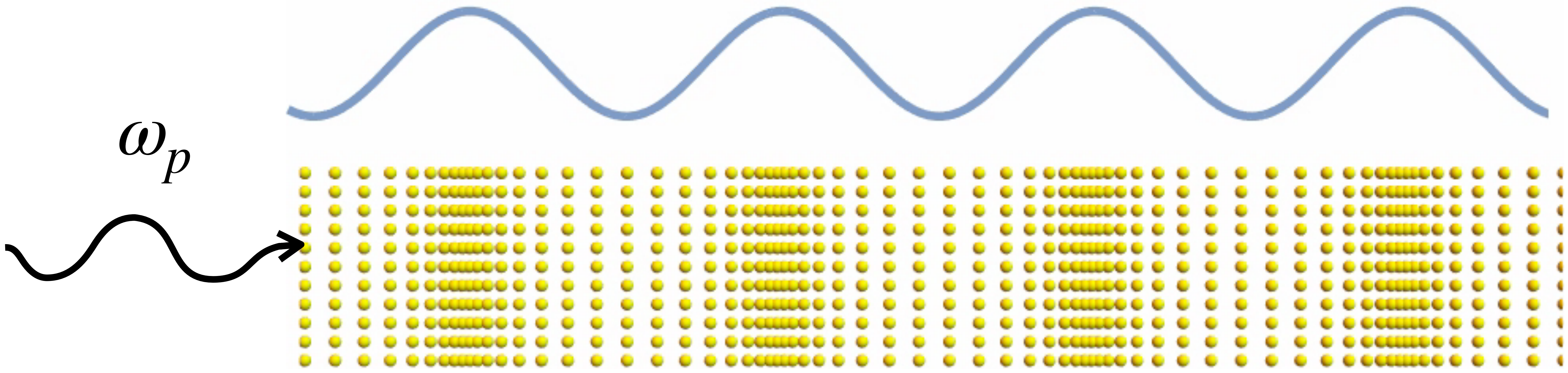
Image:
Lucas Gabrielli

- Modulation
- Switching
- Optical isolation
- RF photonics
- Detection
- Light generation

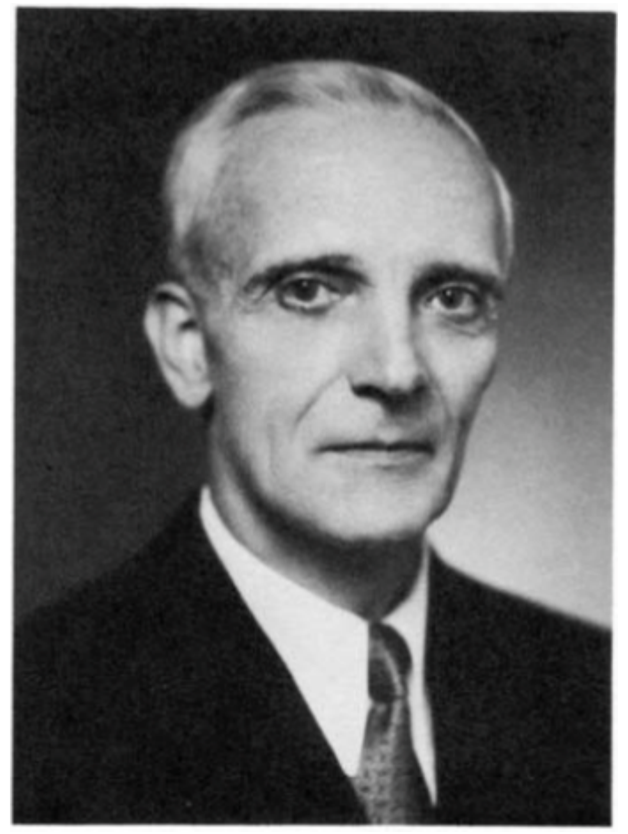
- Indirect bandgap
- Null electro-optic effect
- Large two-photon absorption

Silicon photonics review:
Thomson, D., et al. Journal of Optics, 18(7), 073003 (2018)

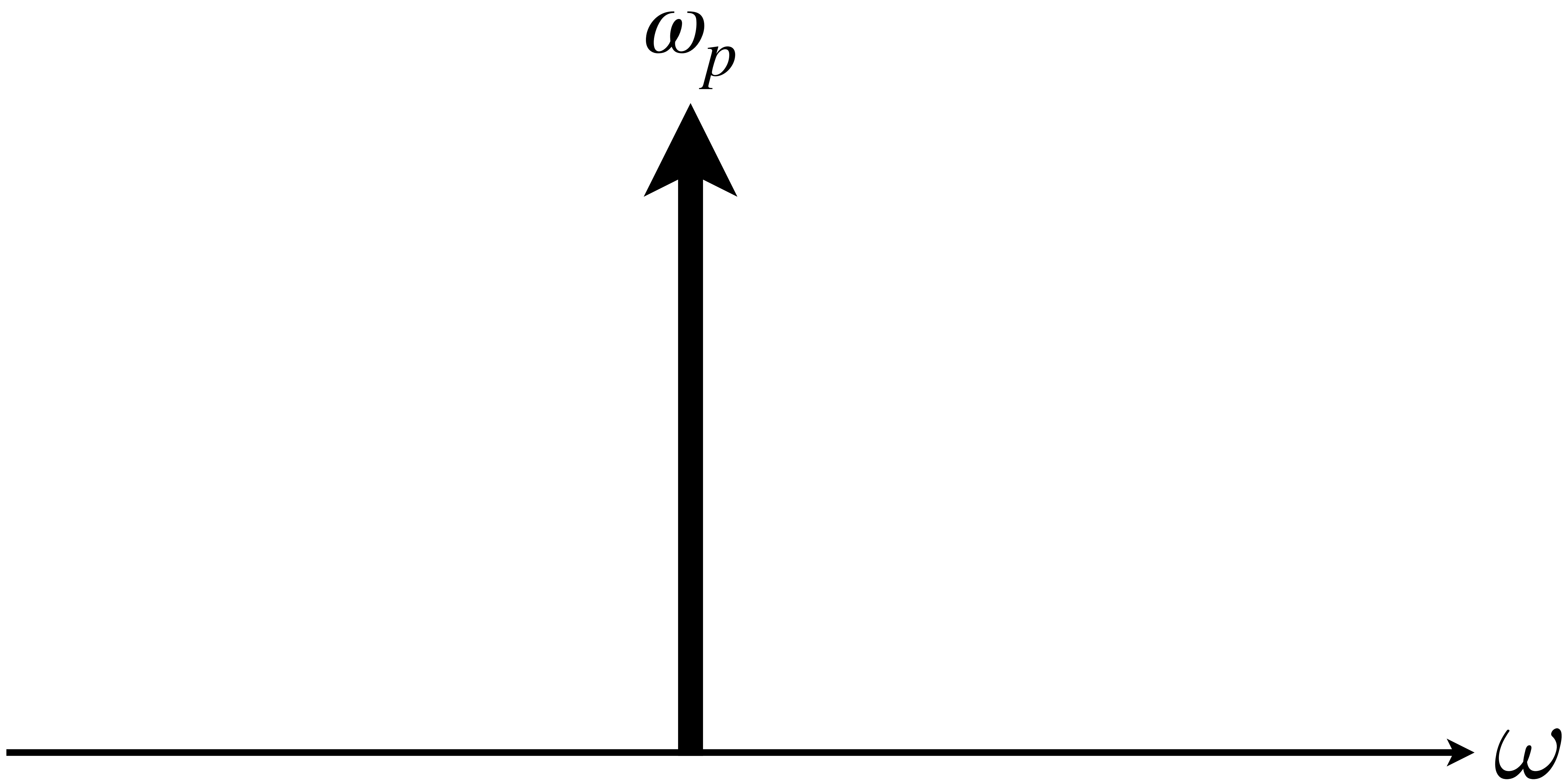
Brillouin scattering



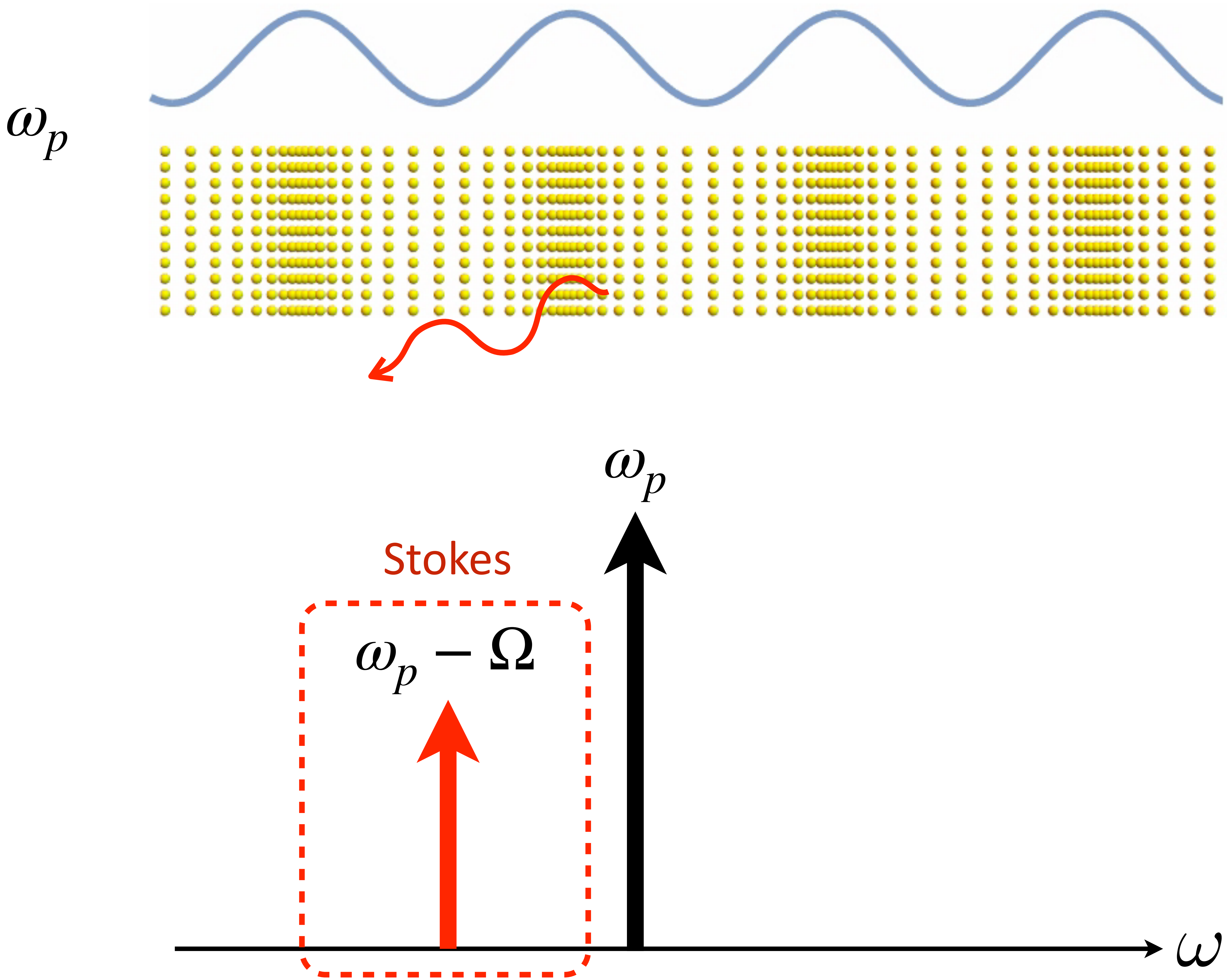
Moving
Bragg
Grating



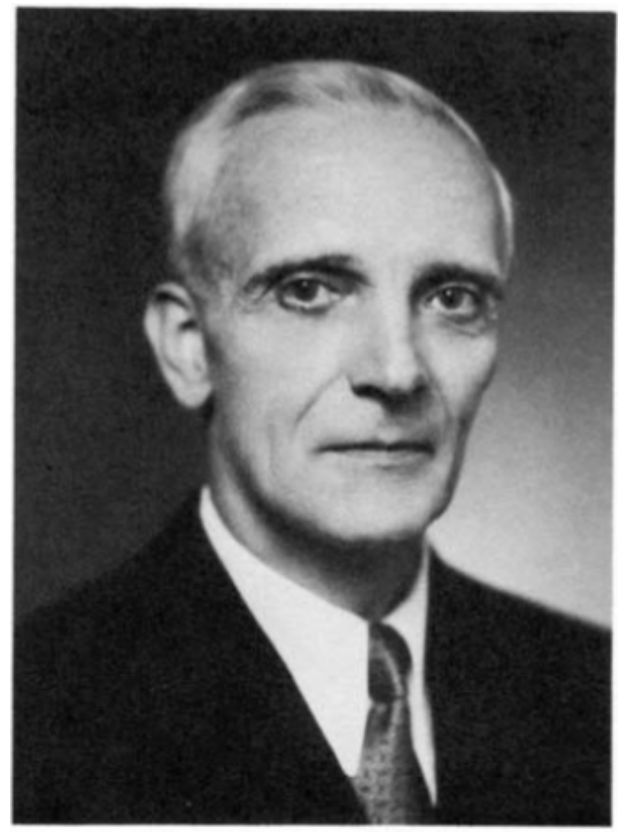
Brillouin L. Ann. Phys. (Paris) 17, 88 (1922)



Brillouin scattering



Moving Bragg Grating



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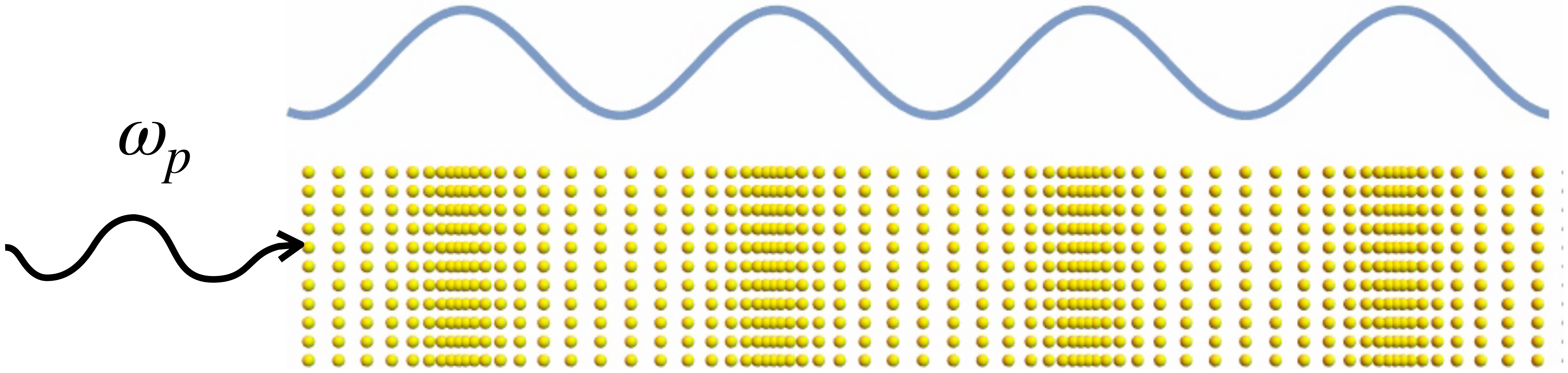

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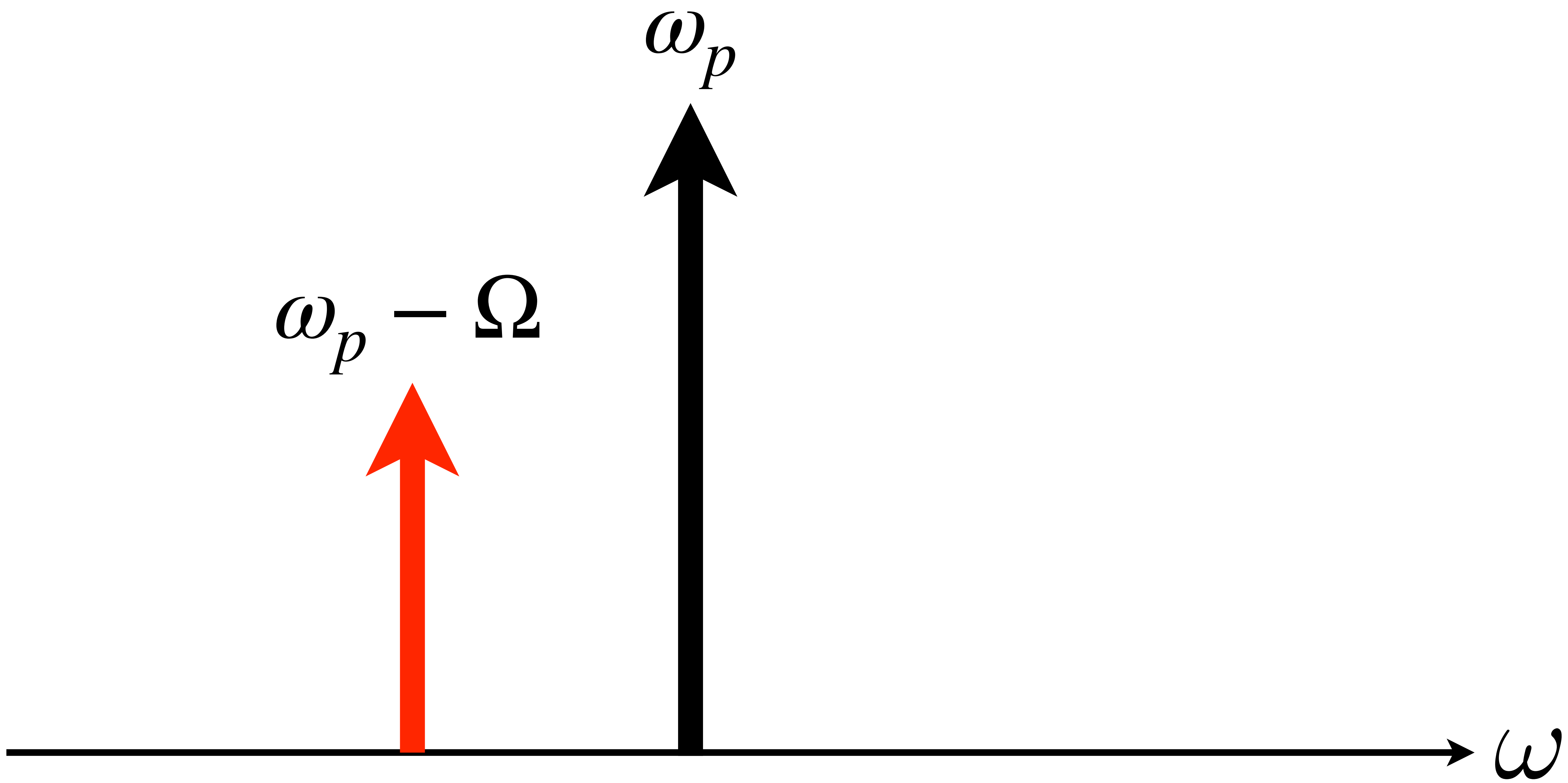

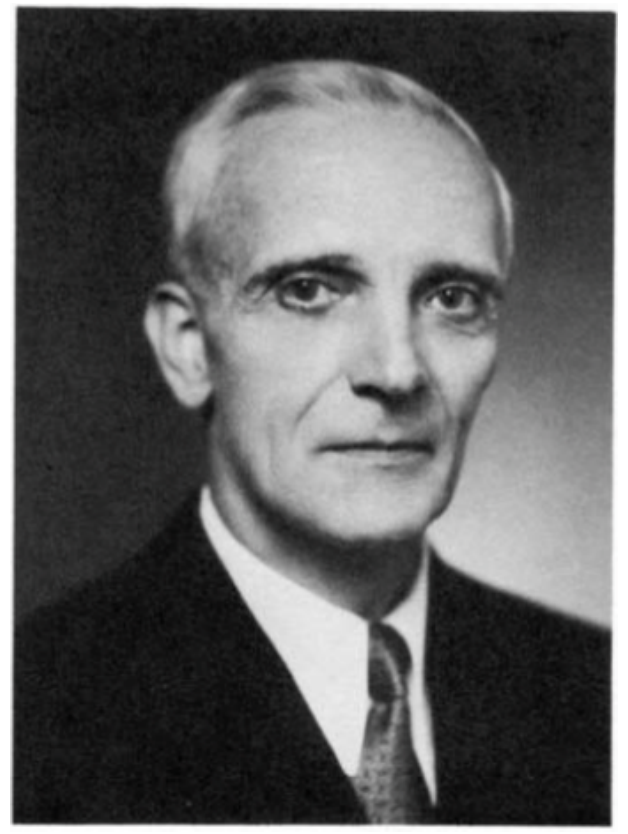

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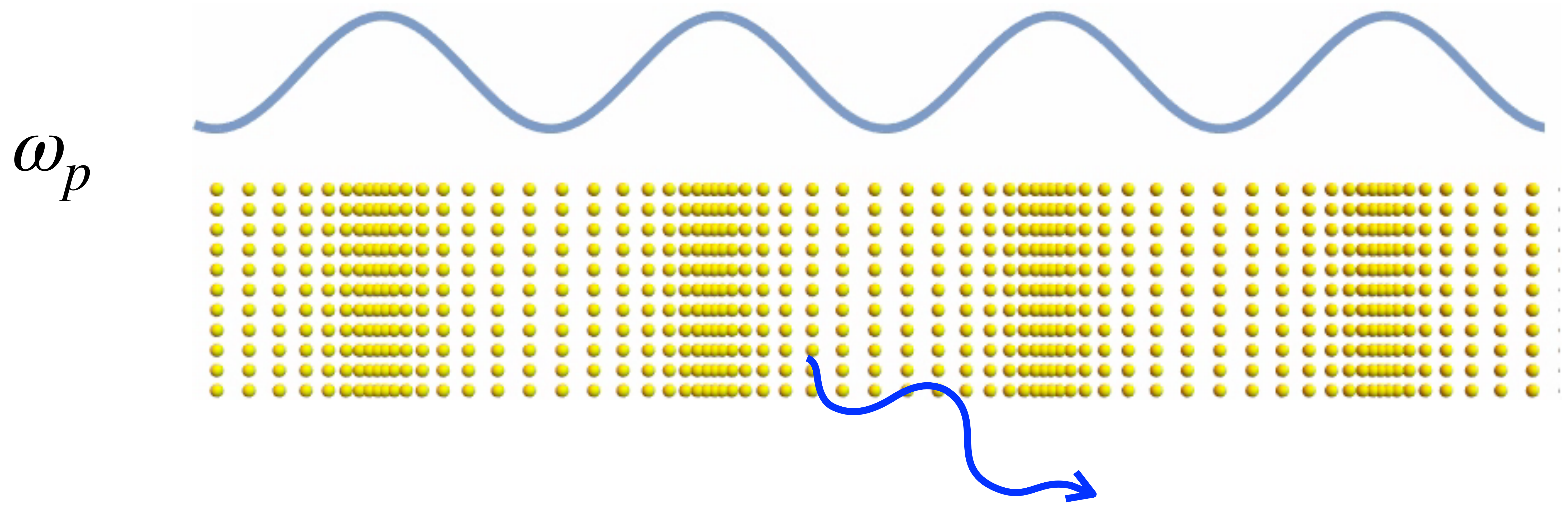

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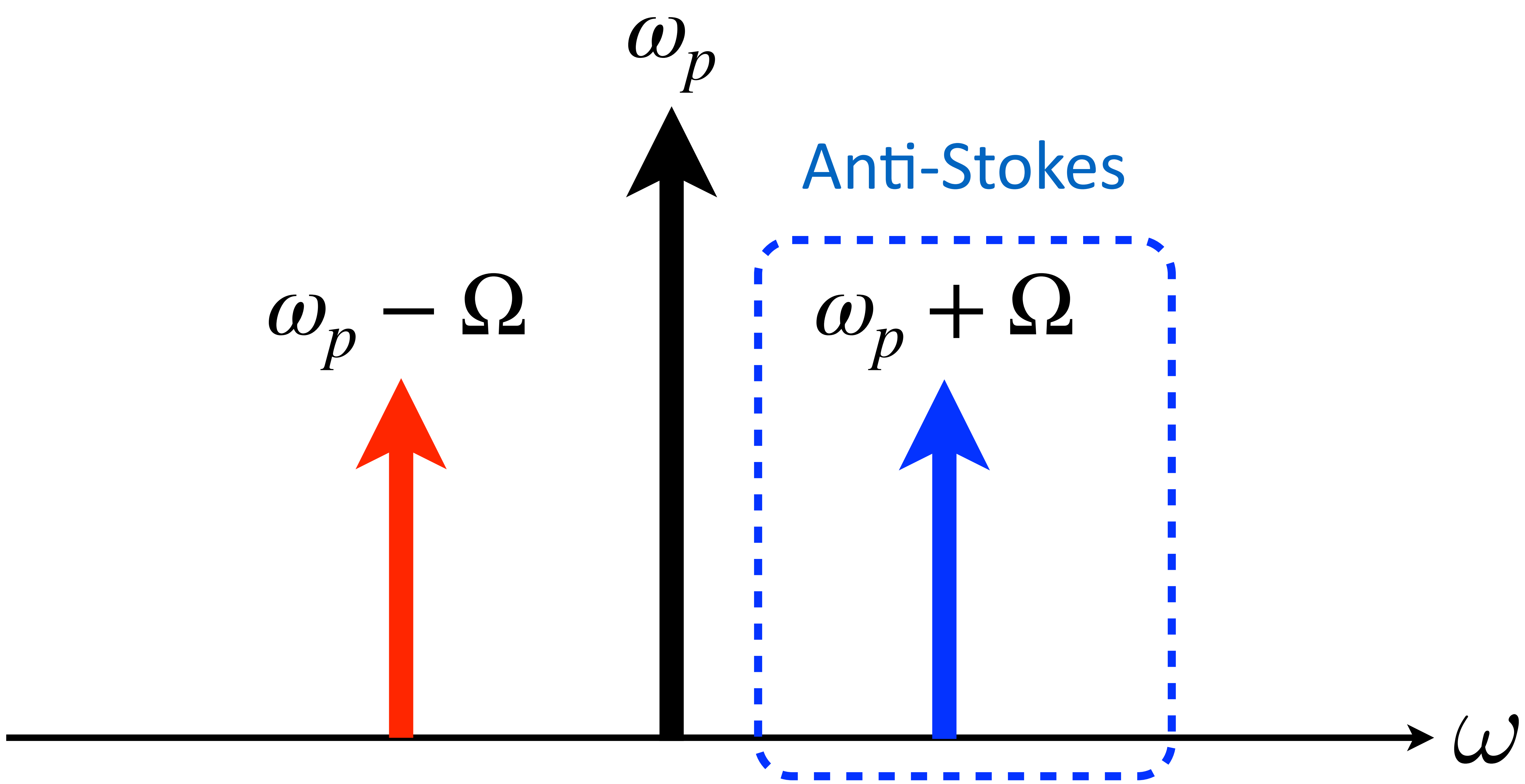

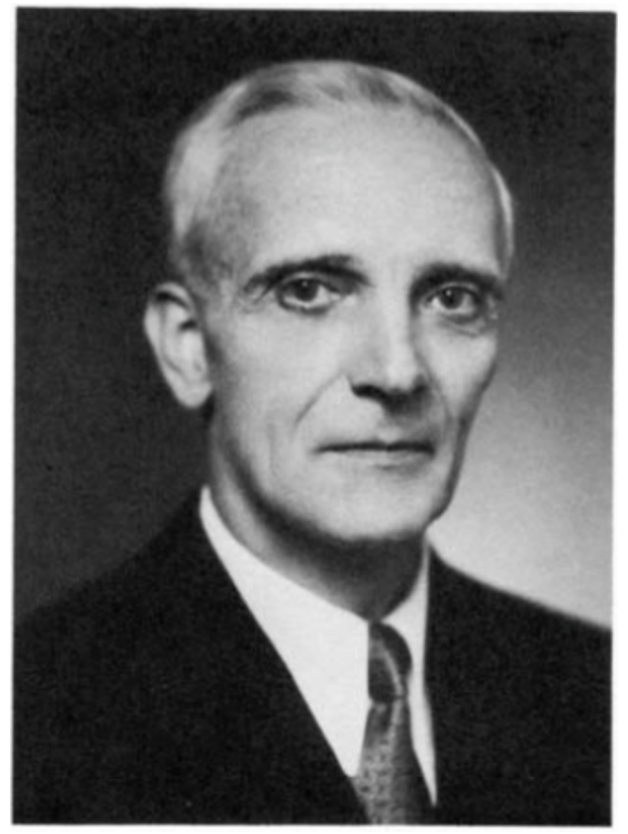

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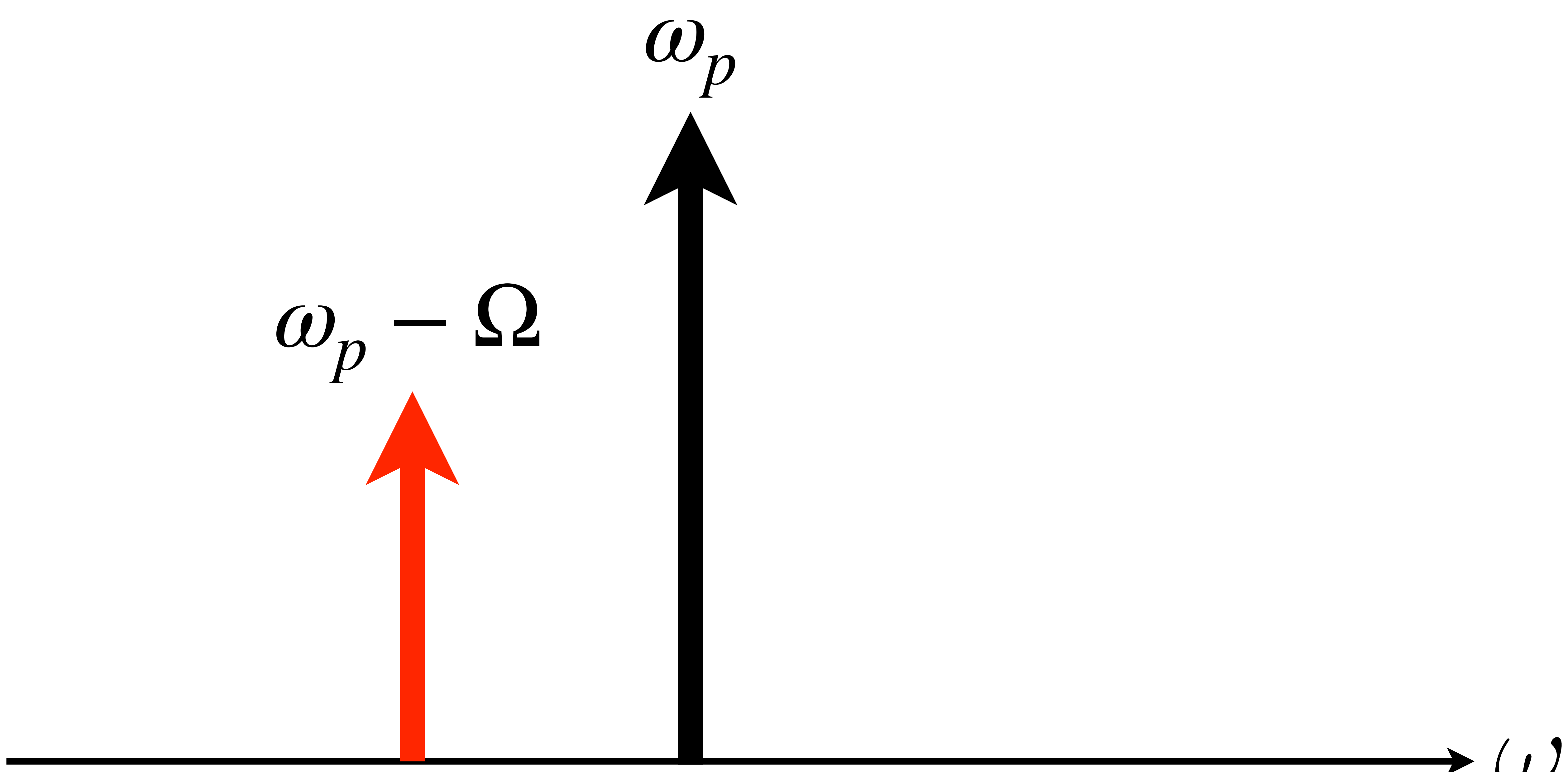

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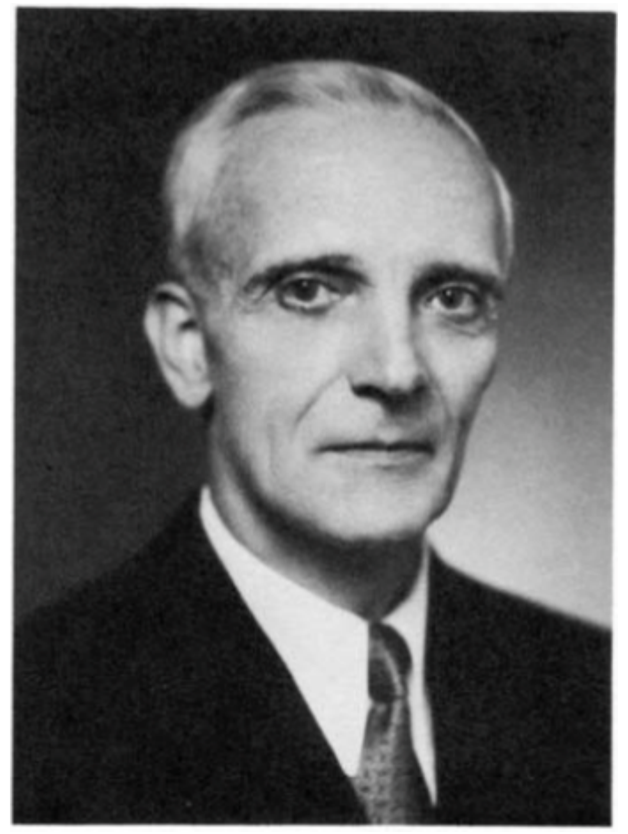

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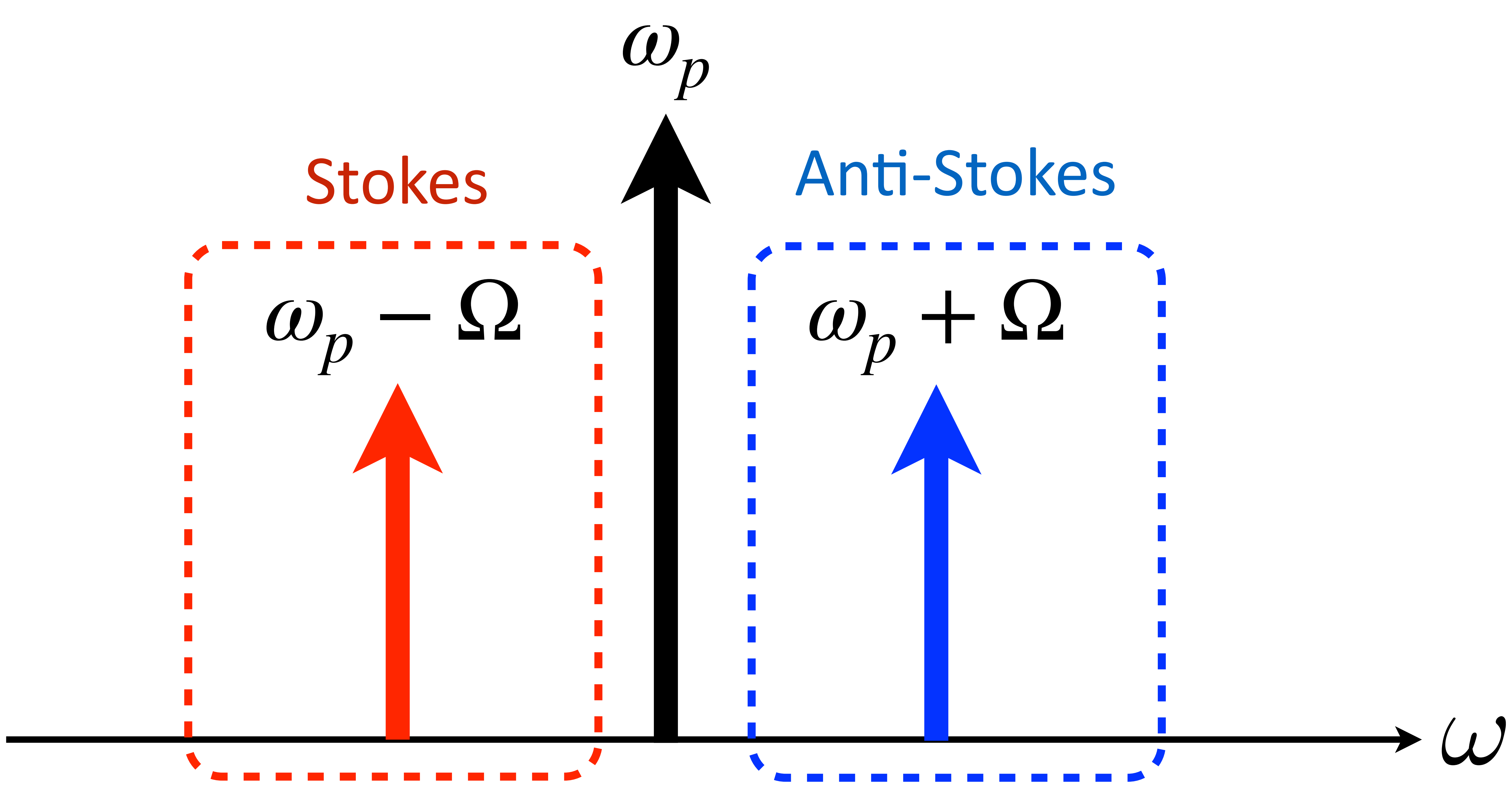
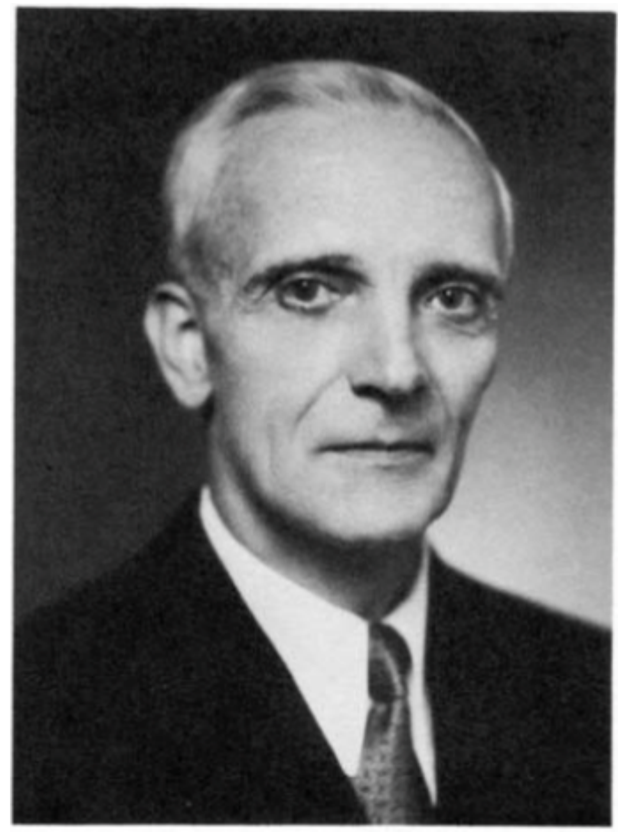
Interaction Hamiltonian

$$H_{int} = \hbar g a^\dagger a (b^\dagger + b)$$

Brillouin scattering



Moving Bragg Grating

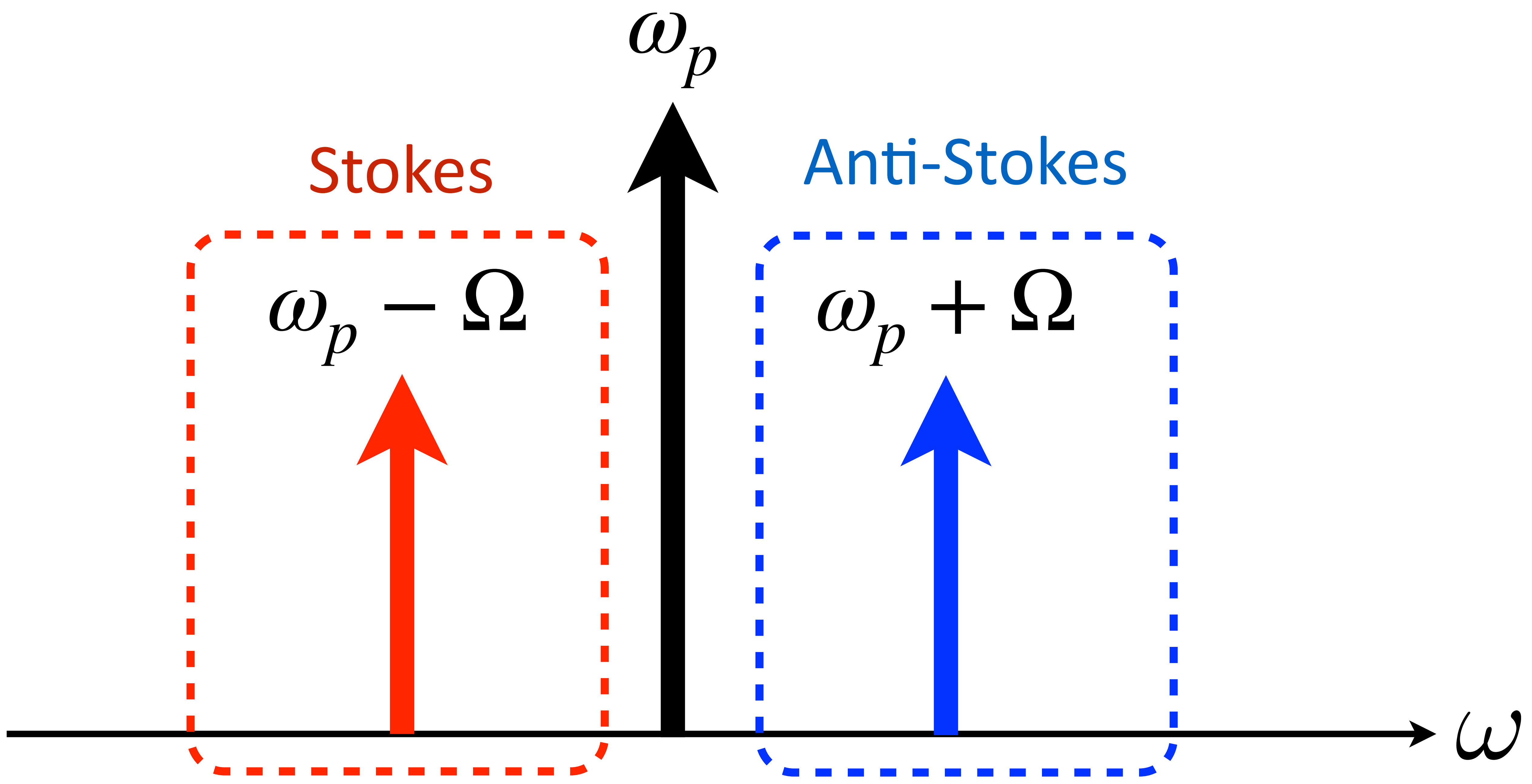


Brillouin L. Ann. Phys. (Paris) 17, 88 (1922)

Interaction Hamiltonian

$$\boxed{H_{int} = \hbar g a^\dagger a(\boxed{b^\dagger} + \boxed{b})}$$

Brillouin scattering

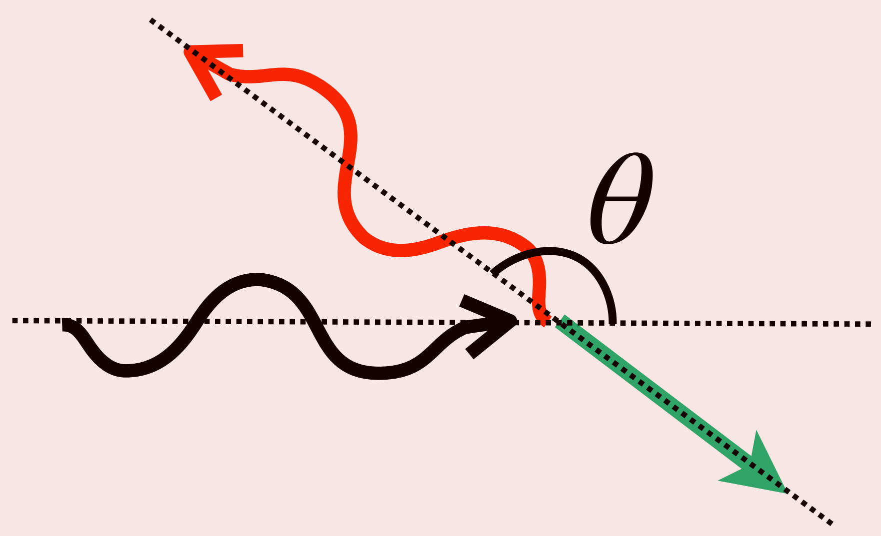


Interaction Hamiltonian

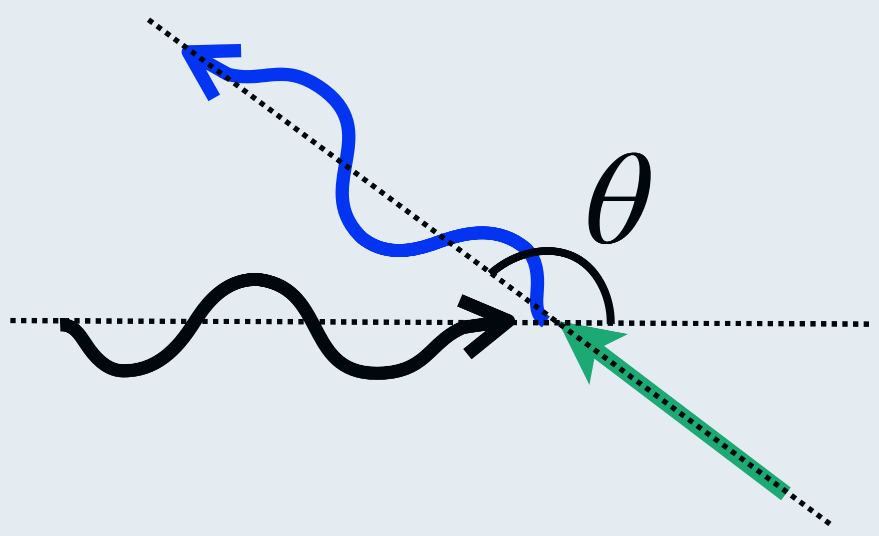
$$H_{int} = \hbar g a^\dagger a(b^\dagger + b)$$

Frequency shift depends on the scattering direction

$$|\mathbf{q}| \approx 2|\mathbf{k}|\sin(\theta/2)$$



$$\mathbf{k}_p - \mathbf{q} = \mathbf{k}_S$$



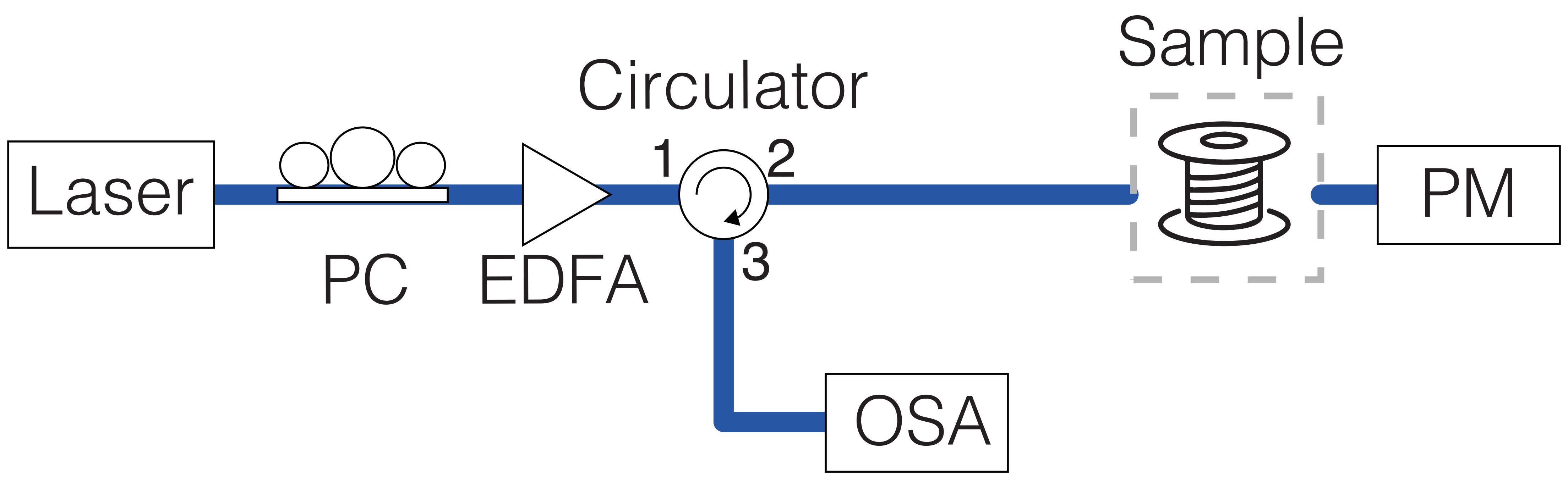
$$\mathbf{k}_p + \mathbf{q} = \mathbf{k}_{aS}$$

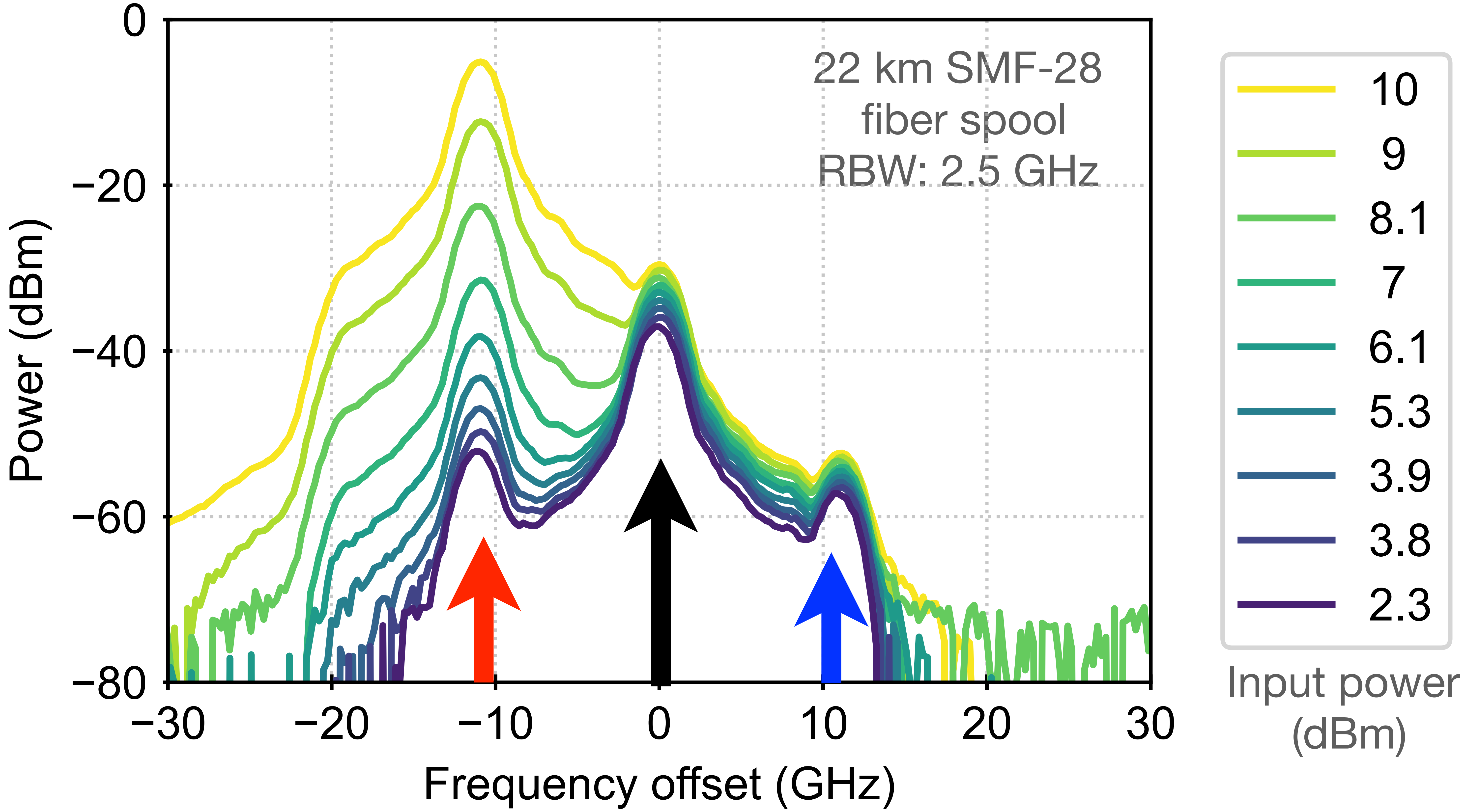
$$0 < |\mathbf{q}| < 2|\mathbf{k}|$$

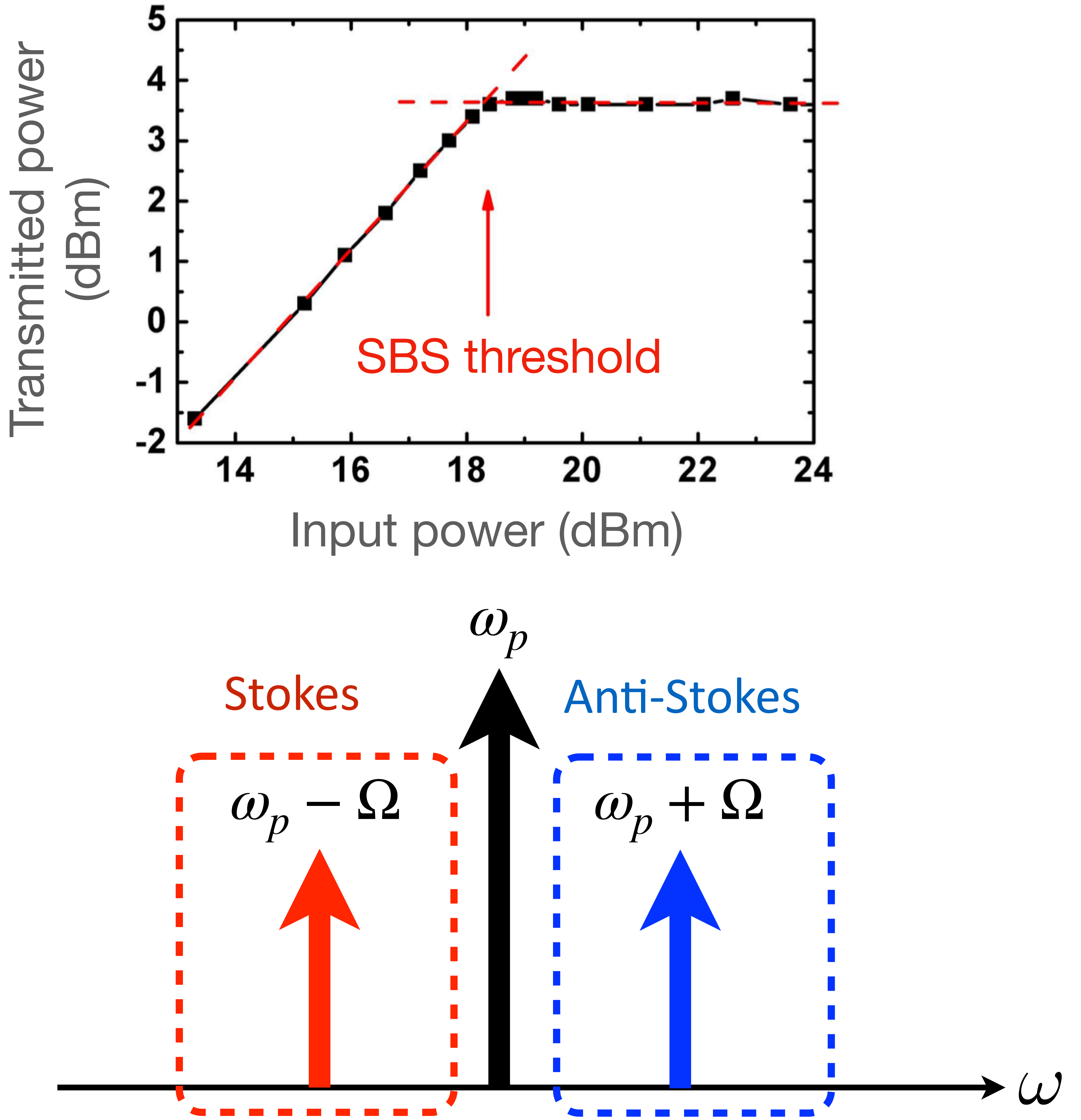
Forward (FW), $\theta = 0$

Backward (BW), $\theta = \pi$

Backward BS may grow strong in a standard optical fiber

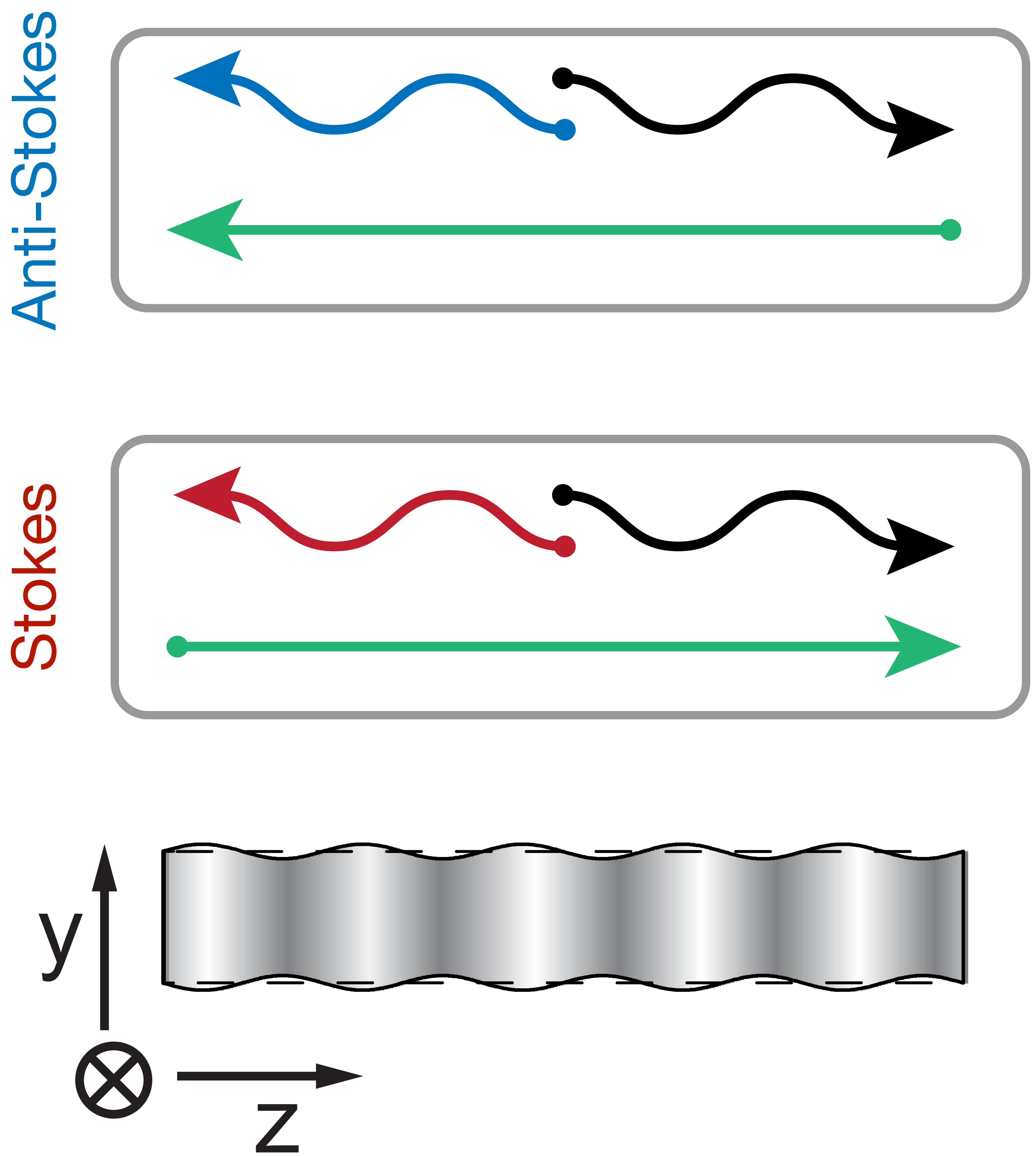






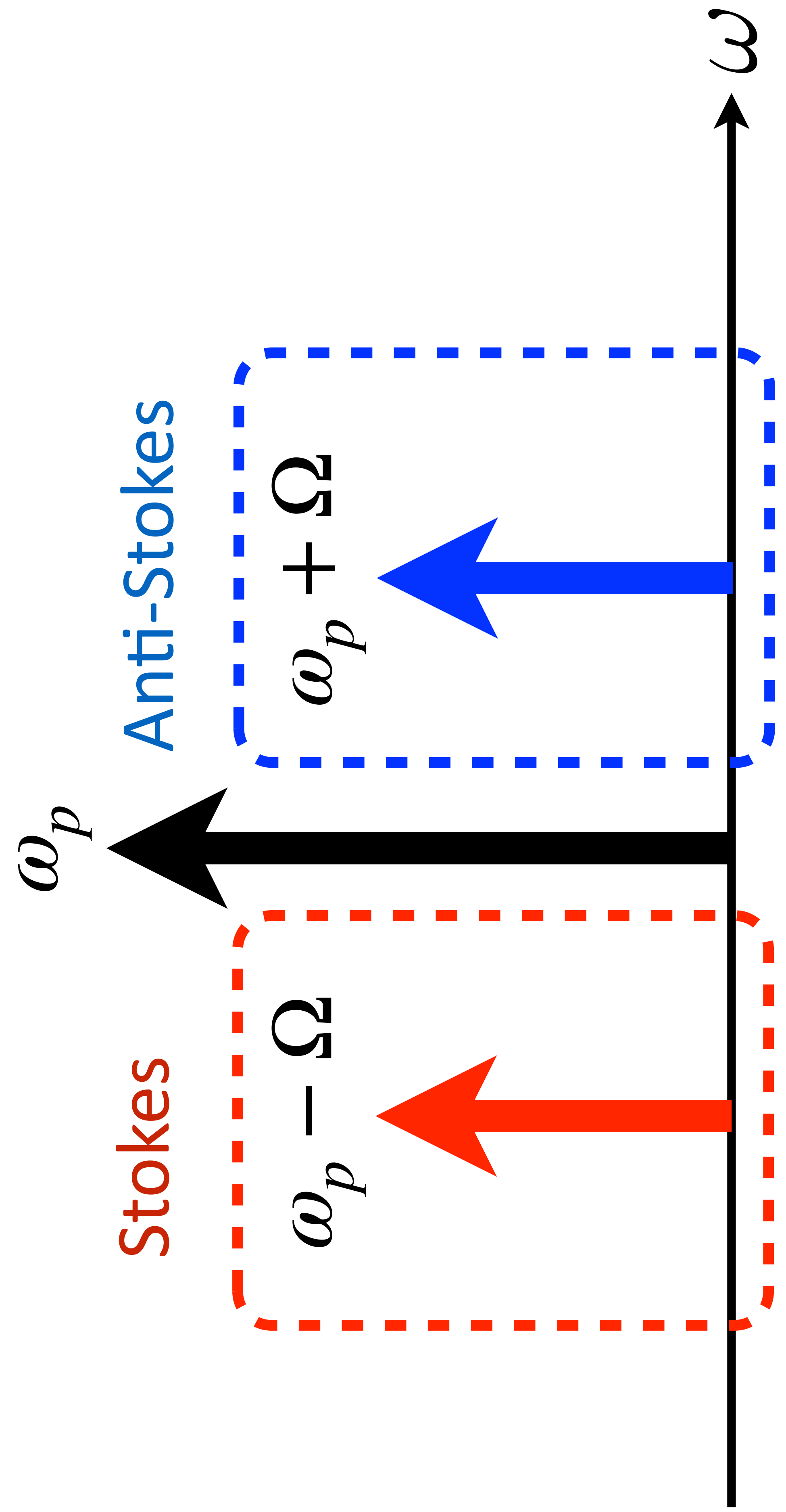
Momentum conservation (phase-matching)

Backward Scattering



$$q_{aS} = -\left(|k_{aS}| + |k_p|\right)$$

$$q_S = +\left(|k_S| + |k_p|\right)$$



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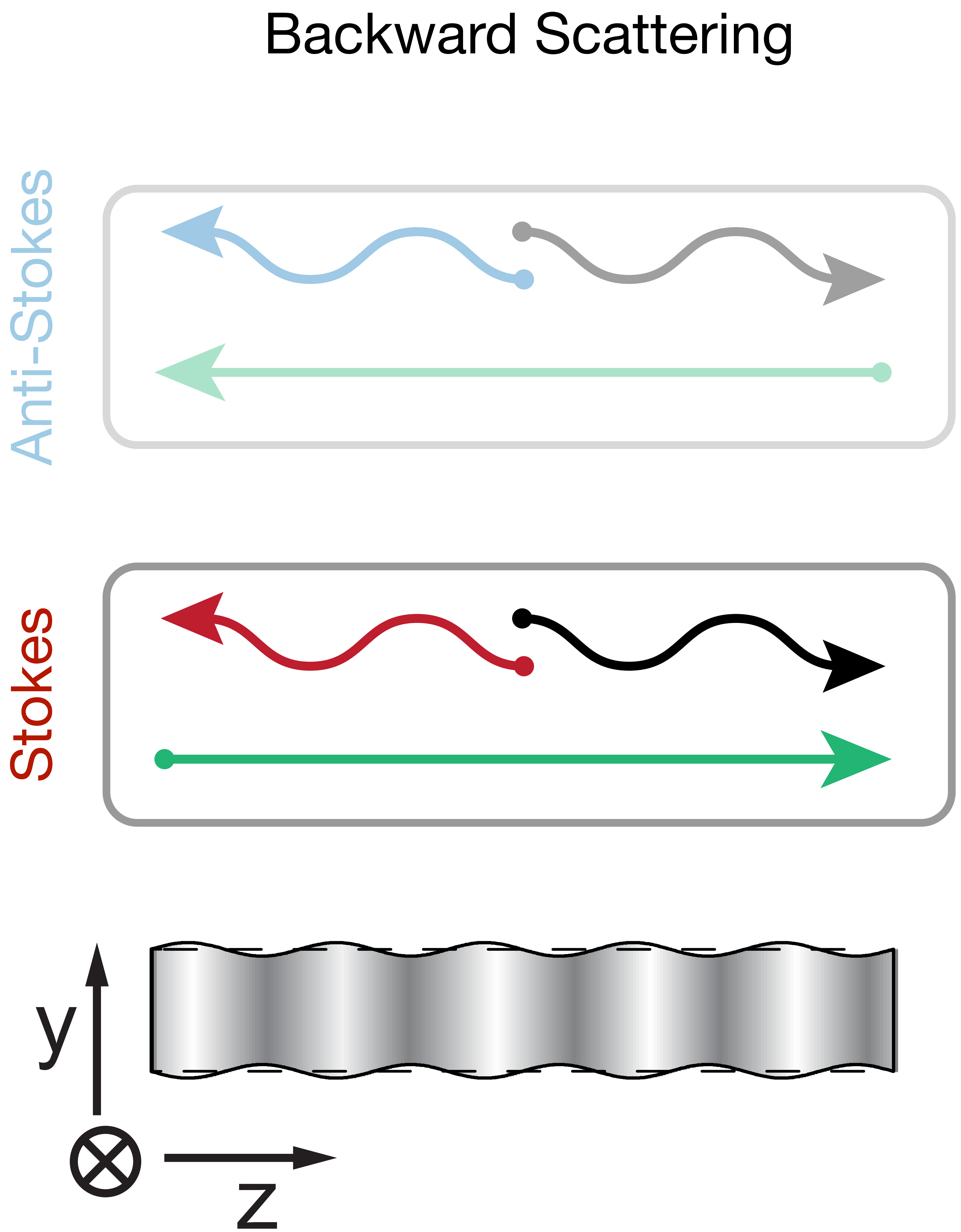

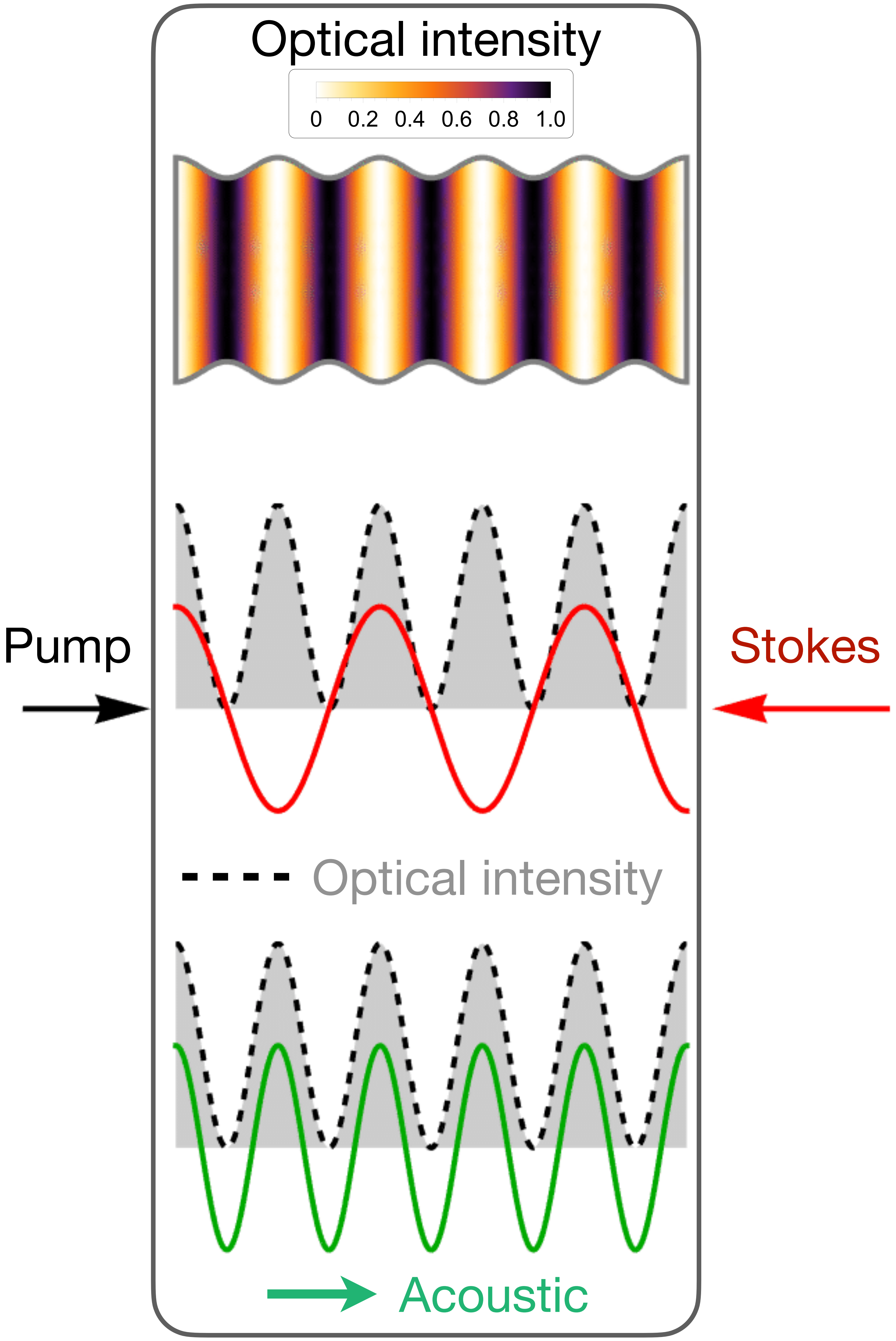

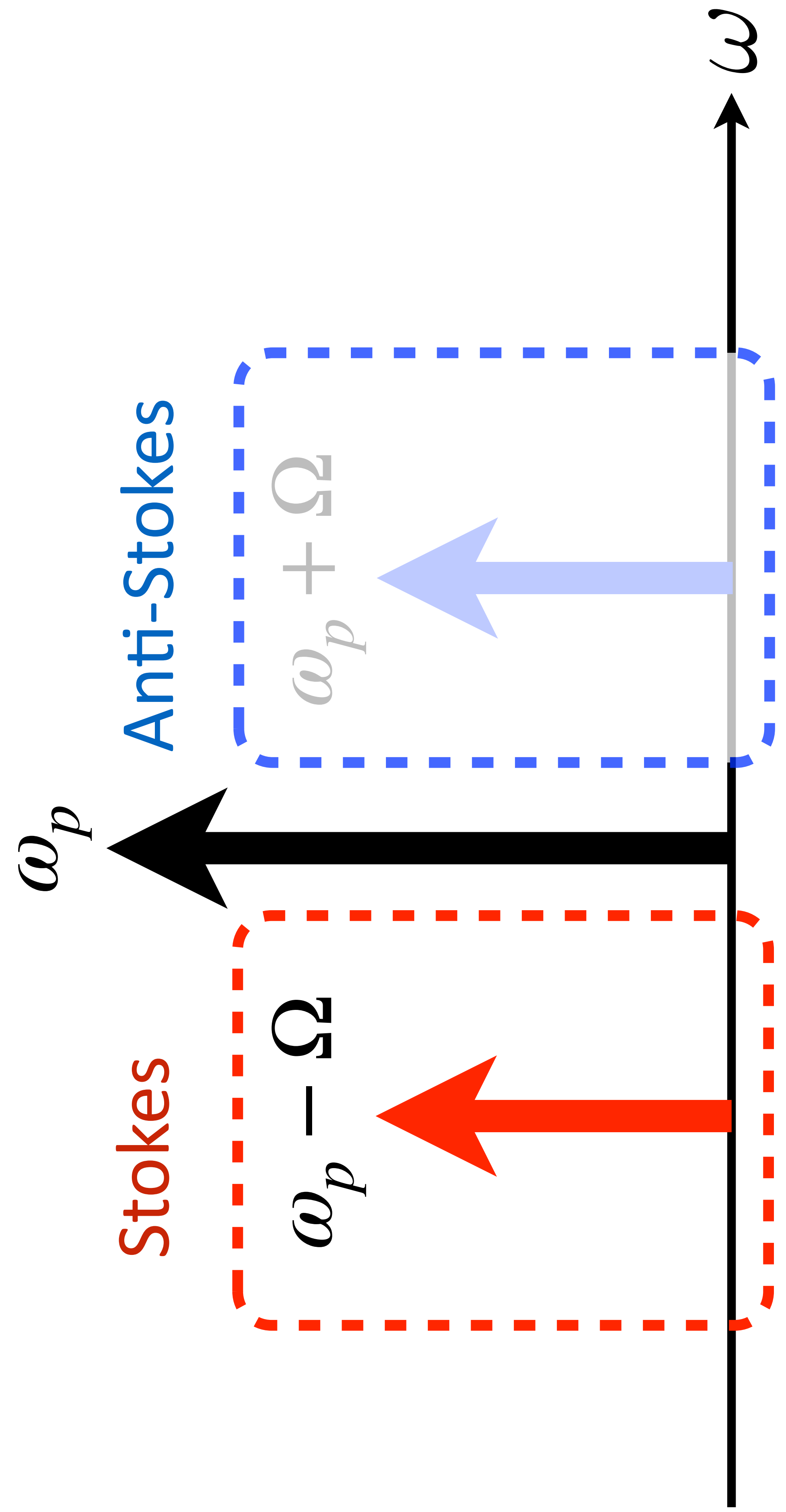

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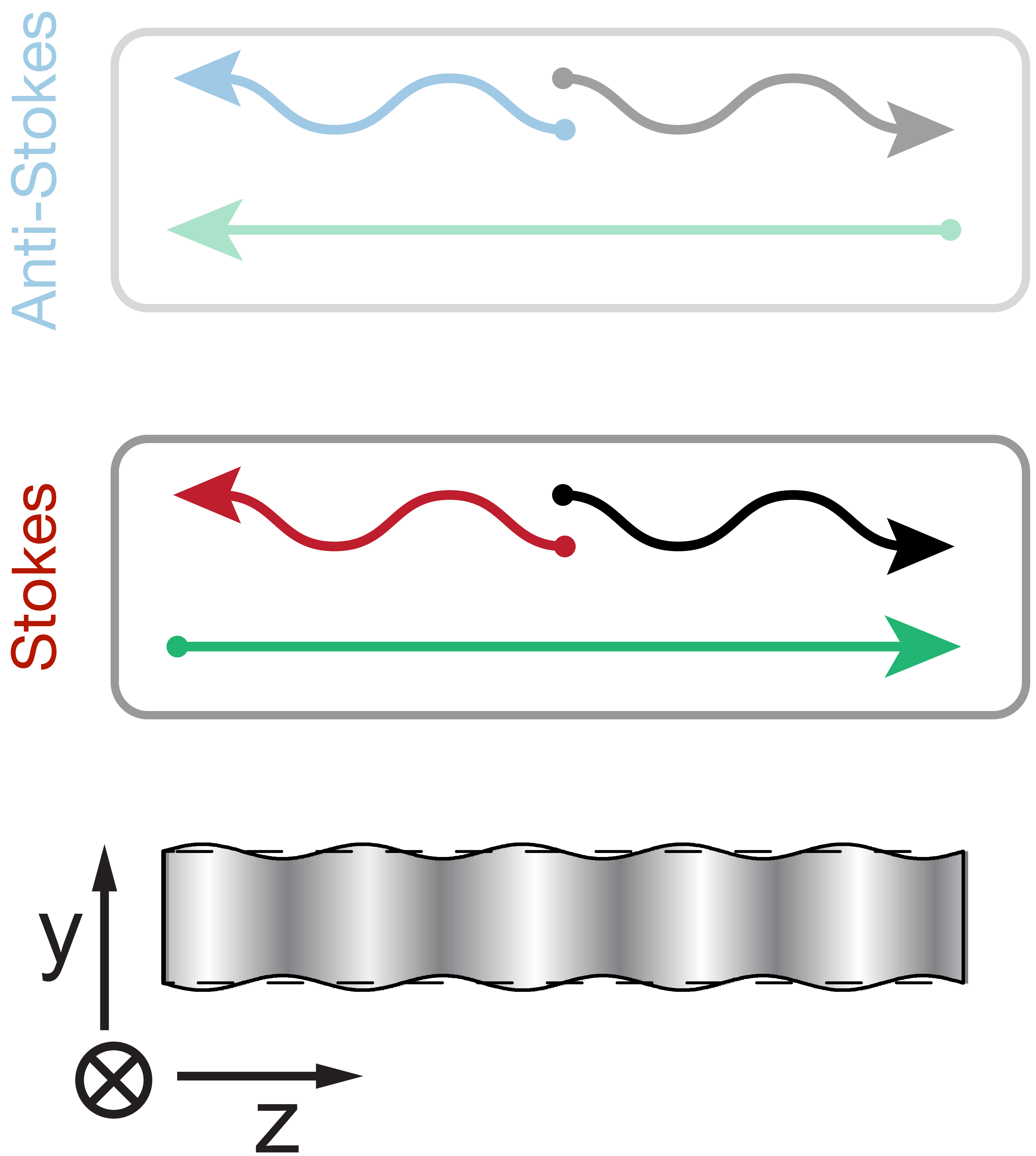

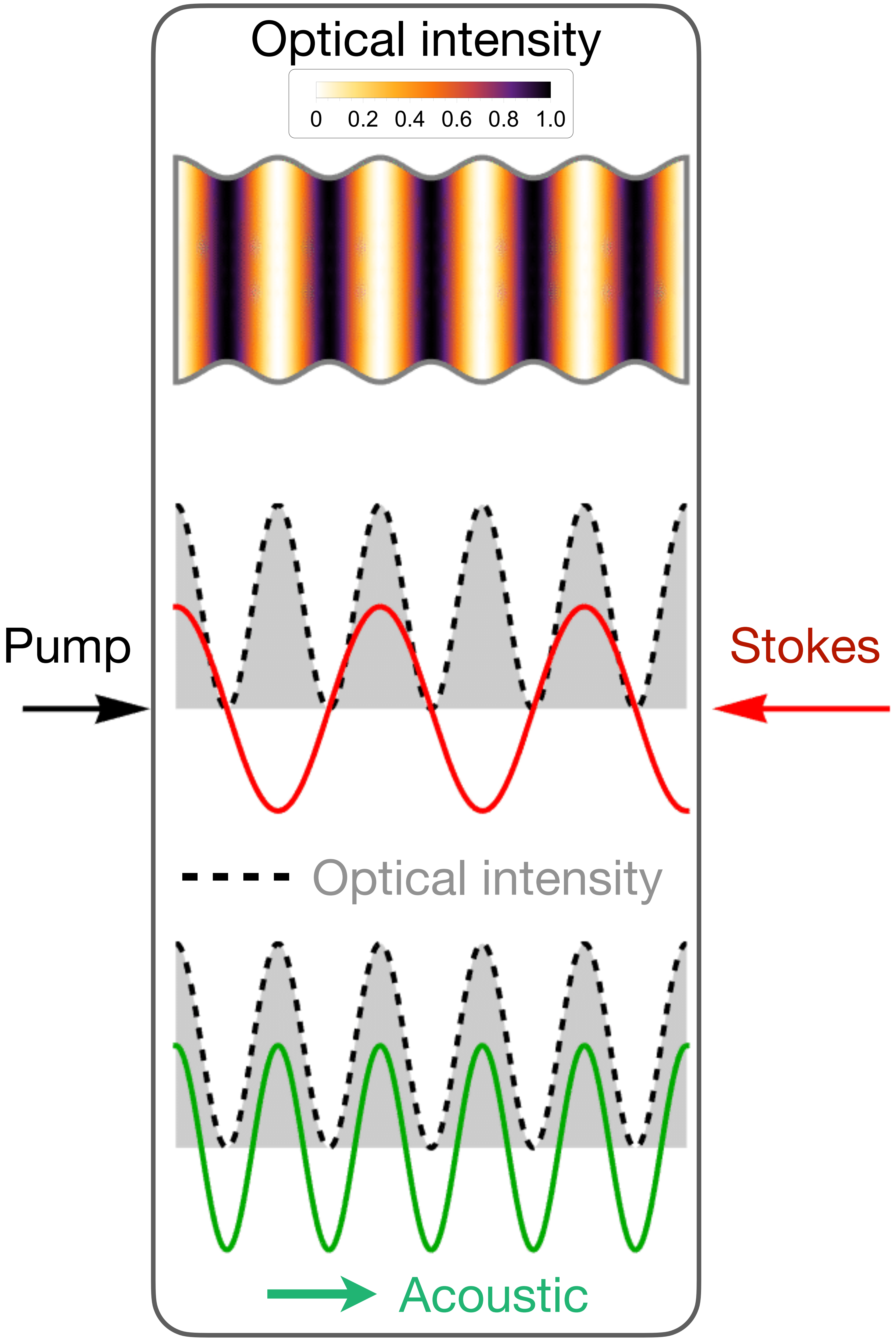

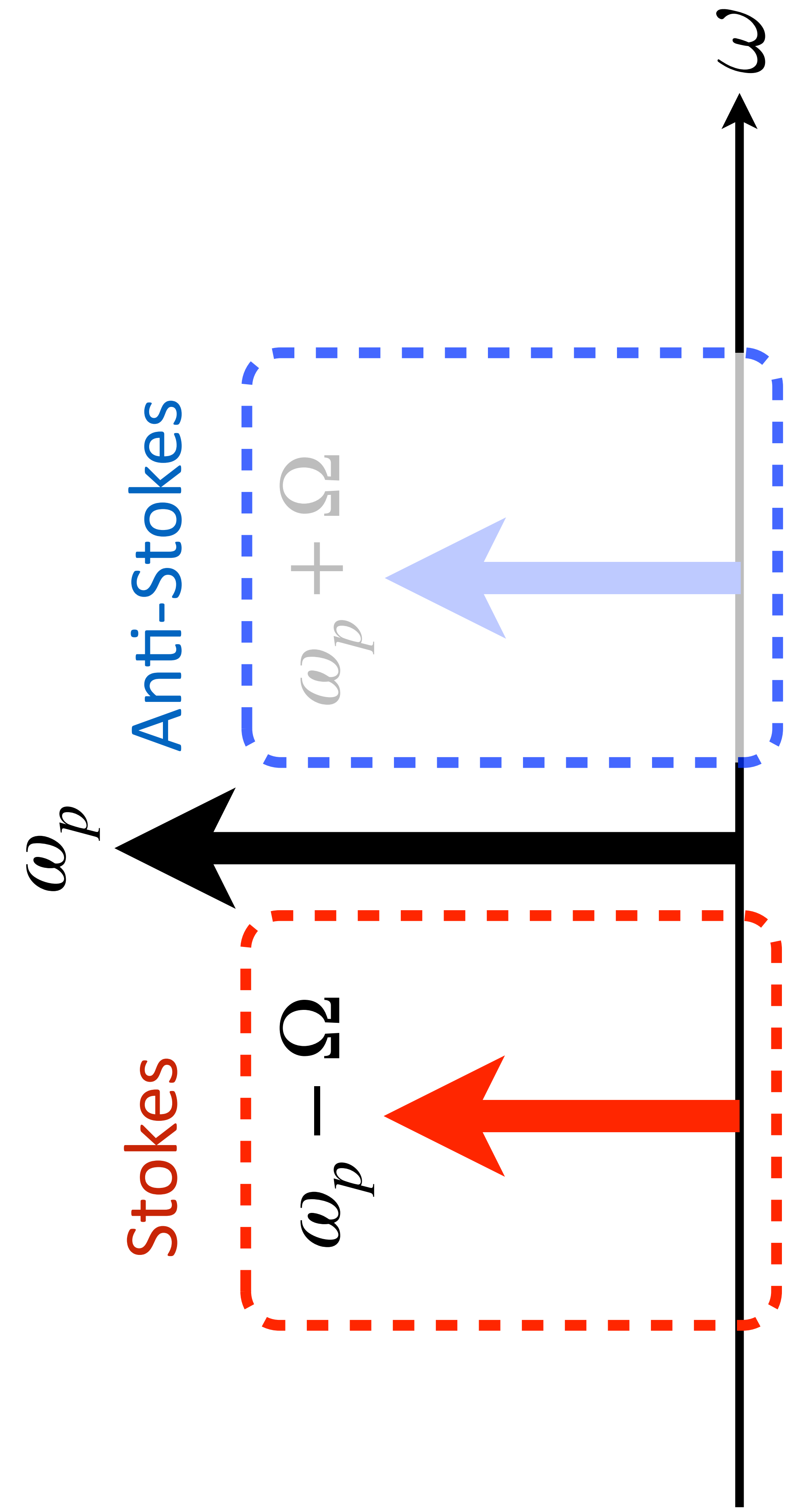

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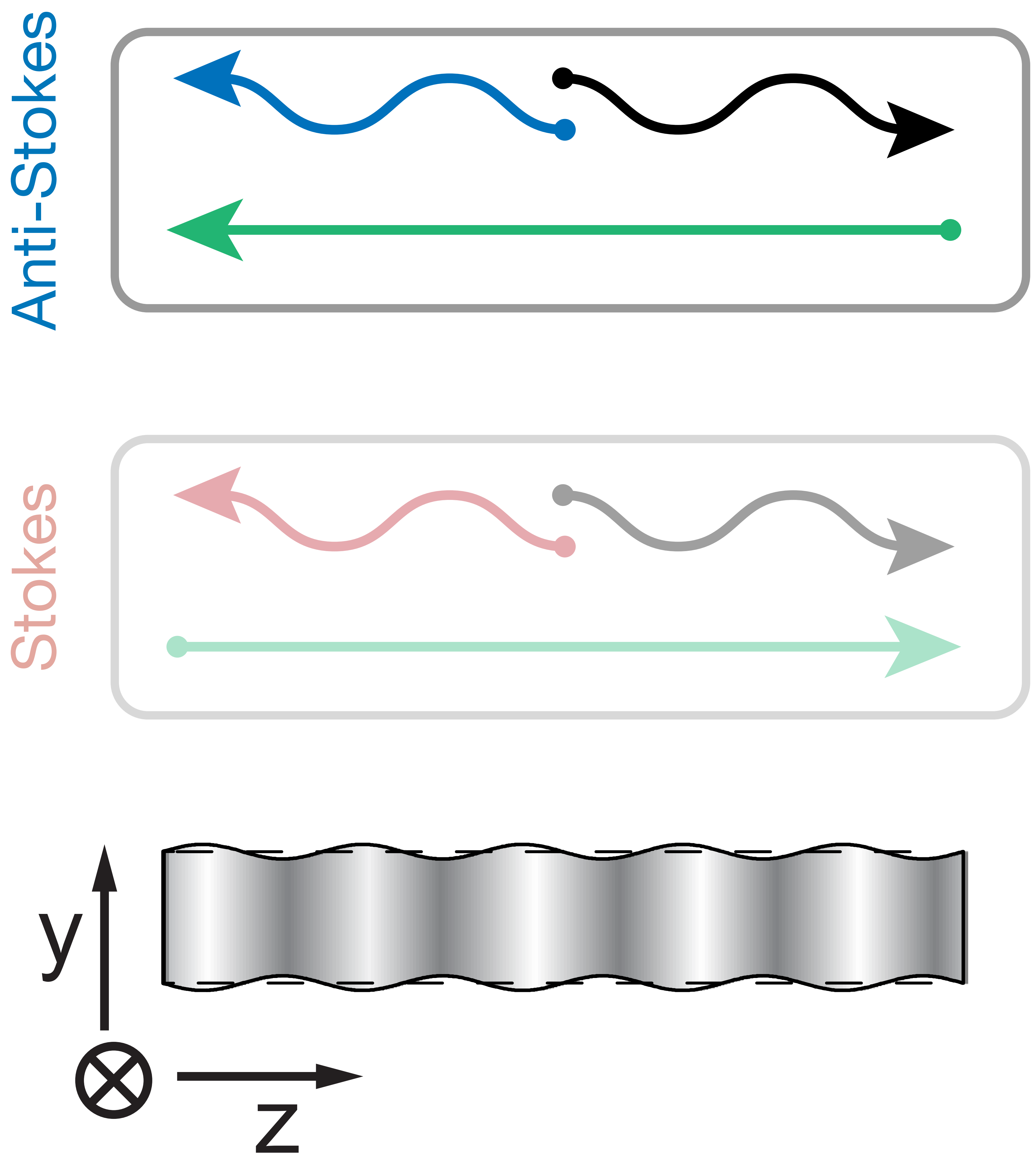

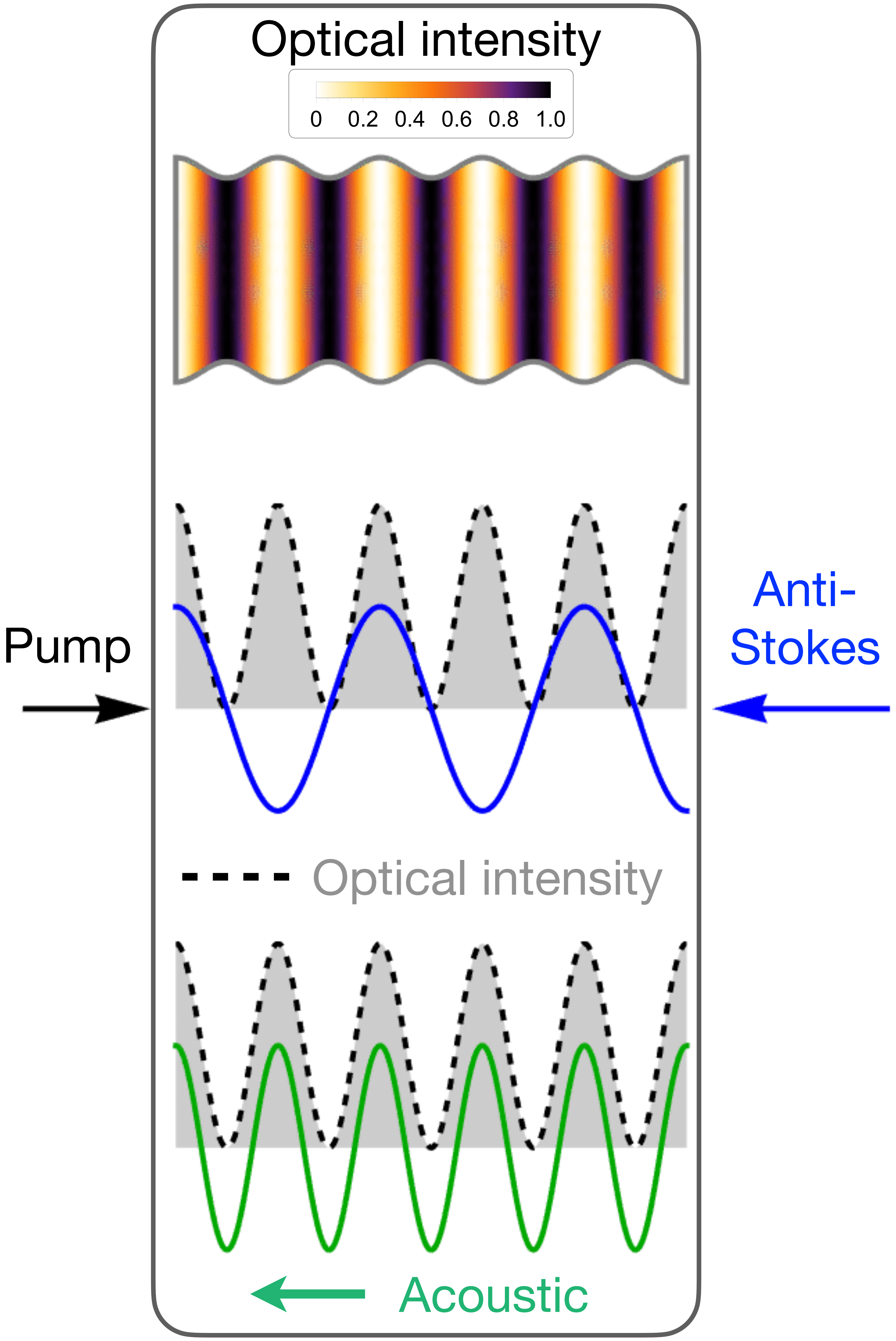

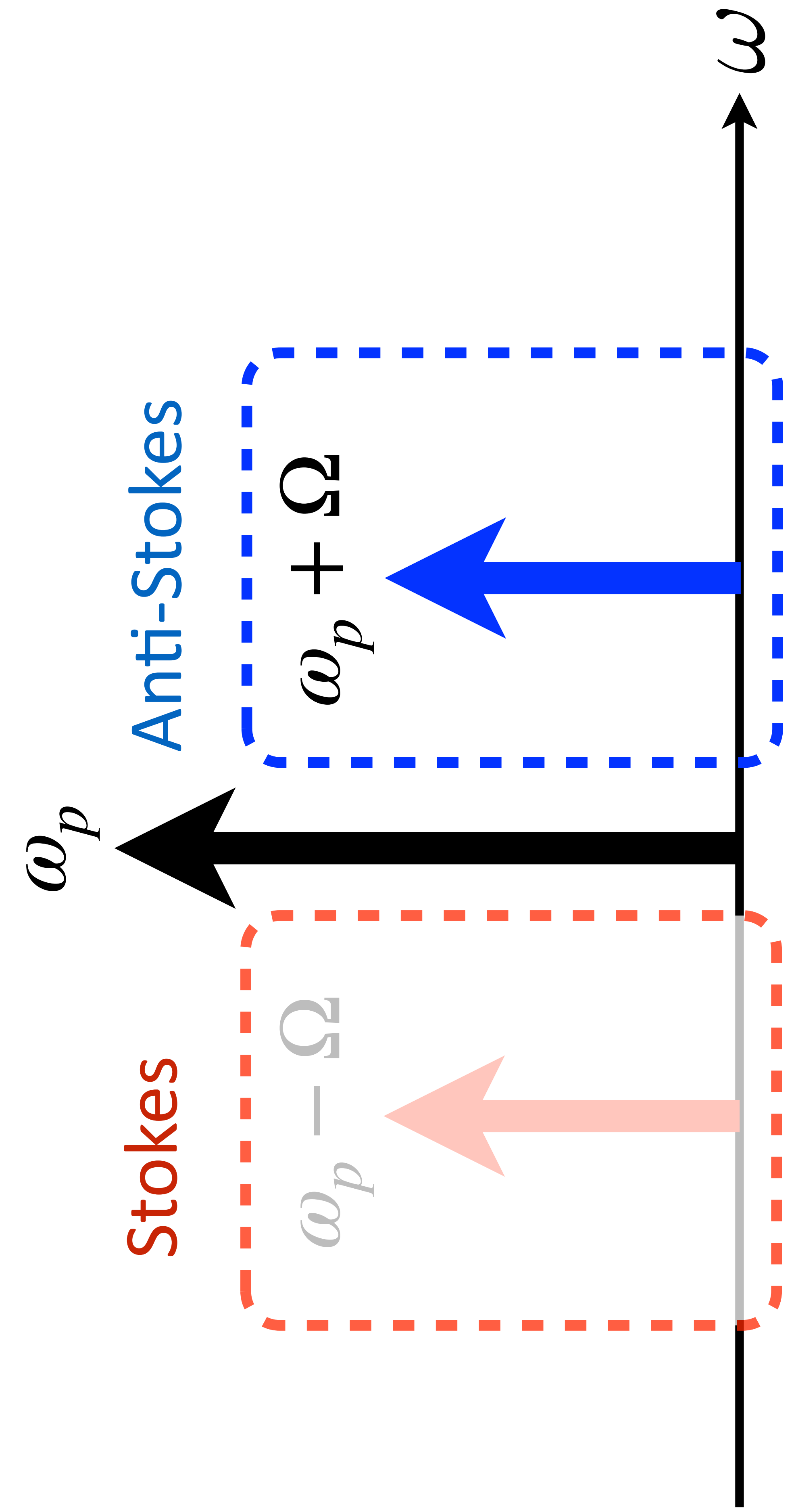

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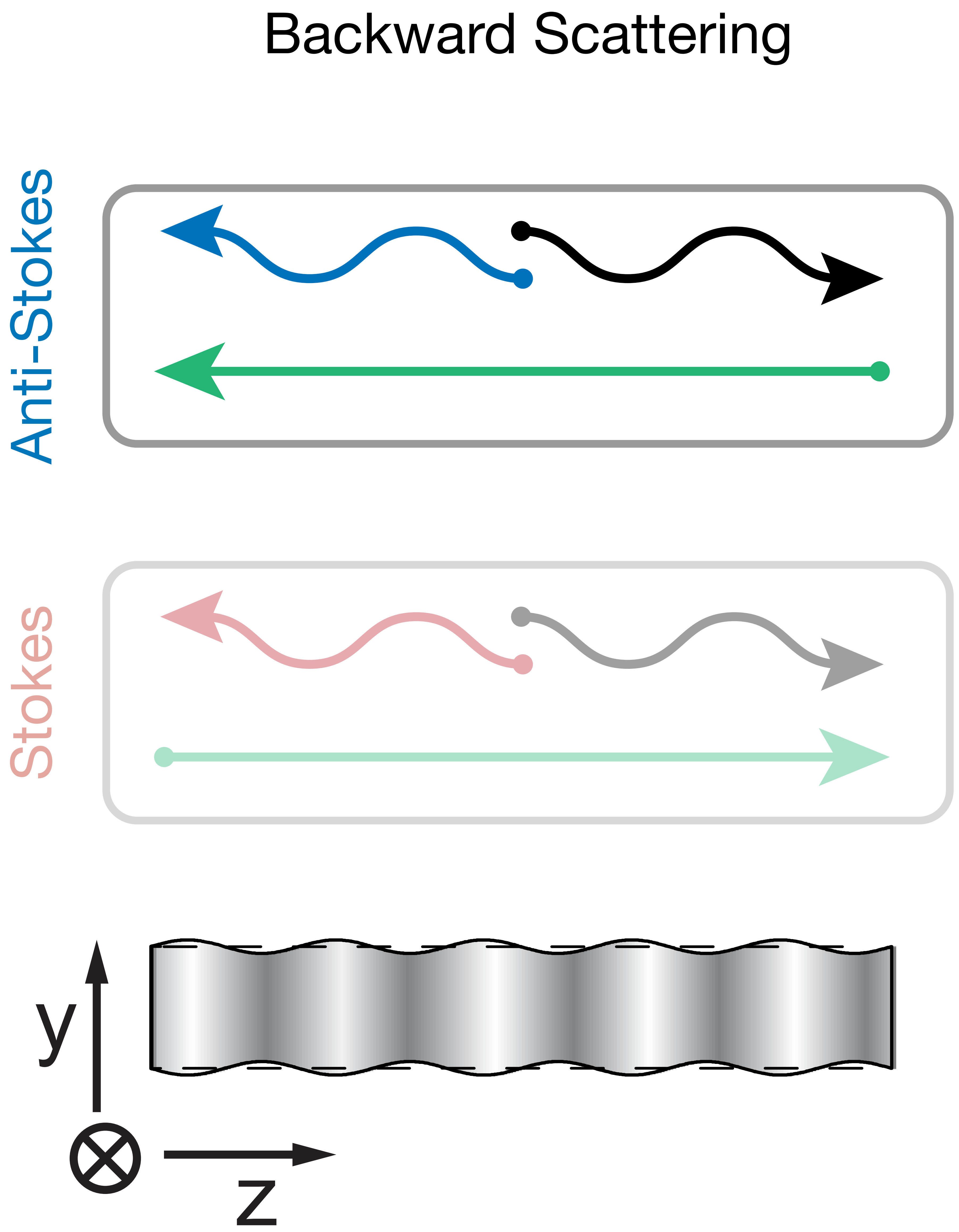
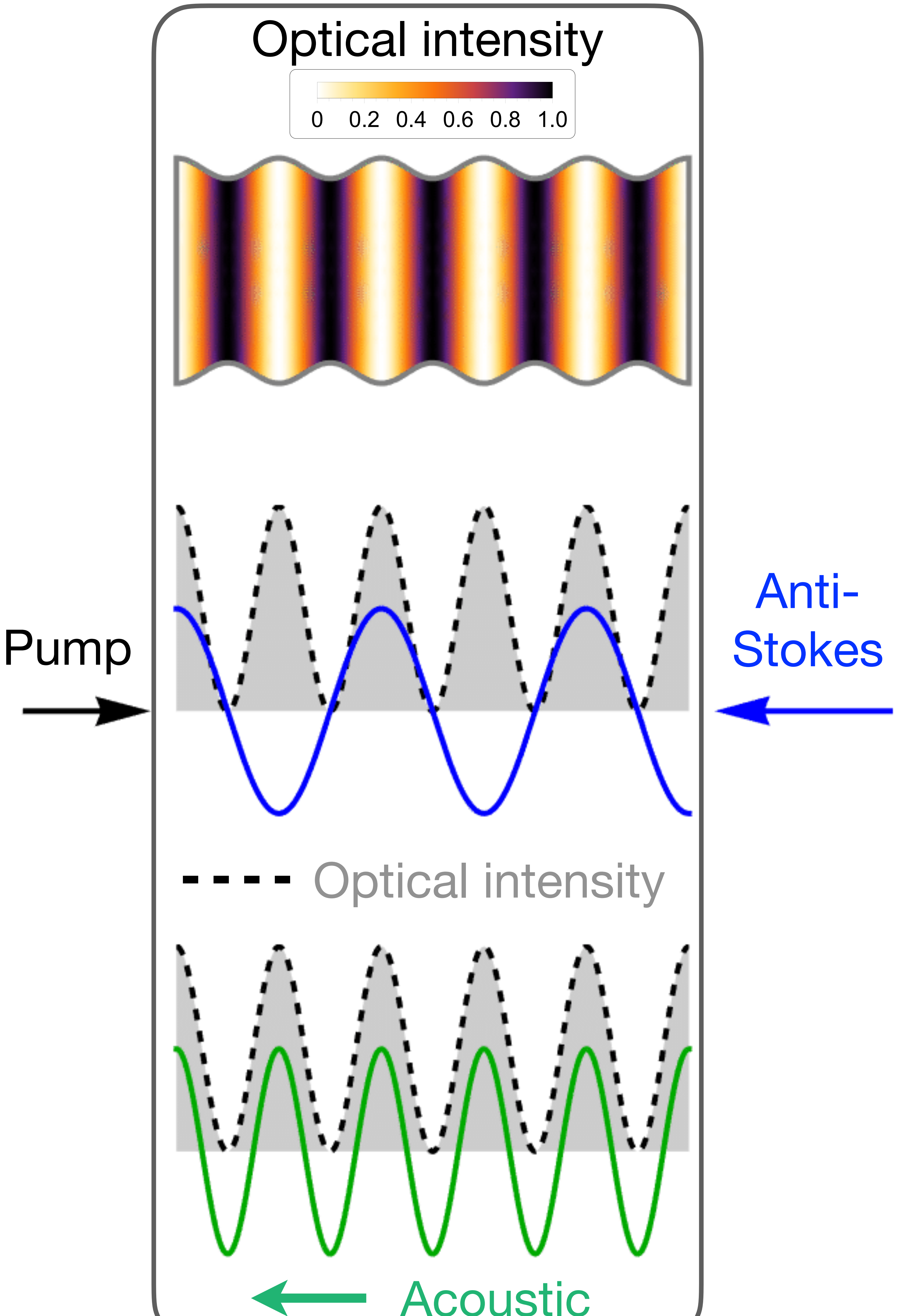
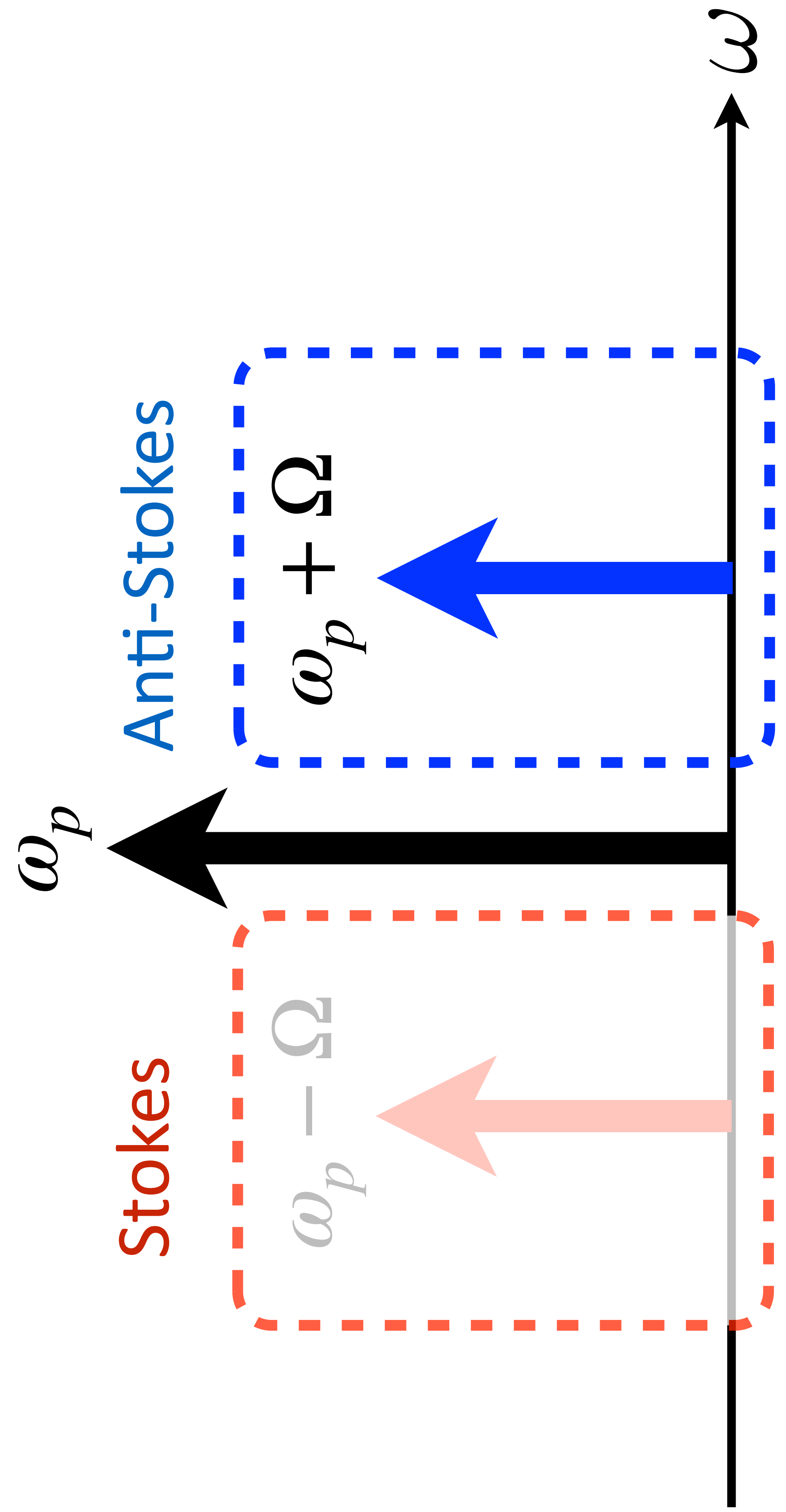
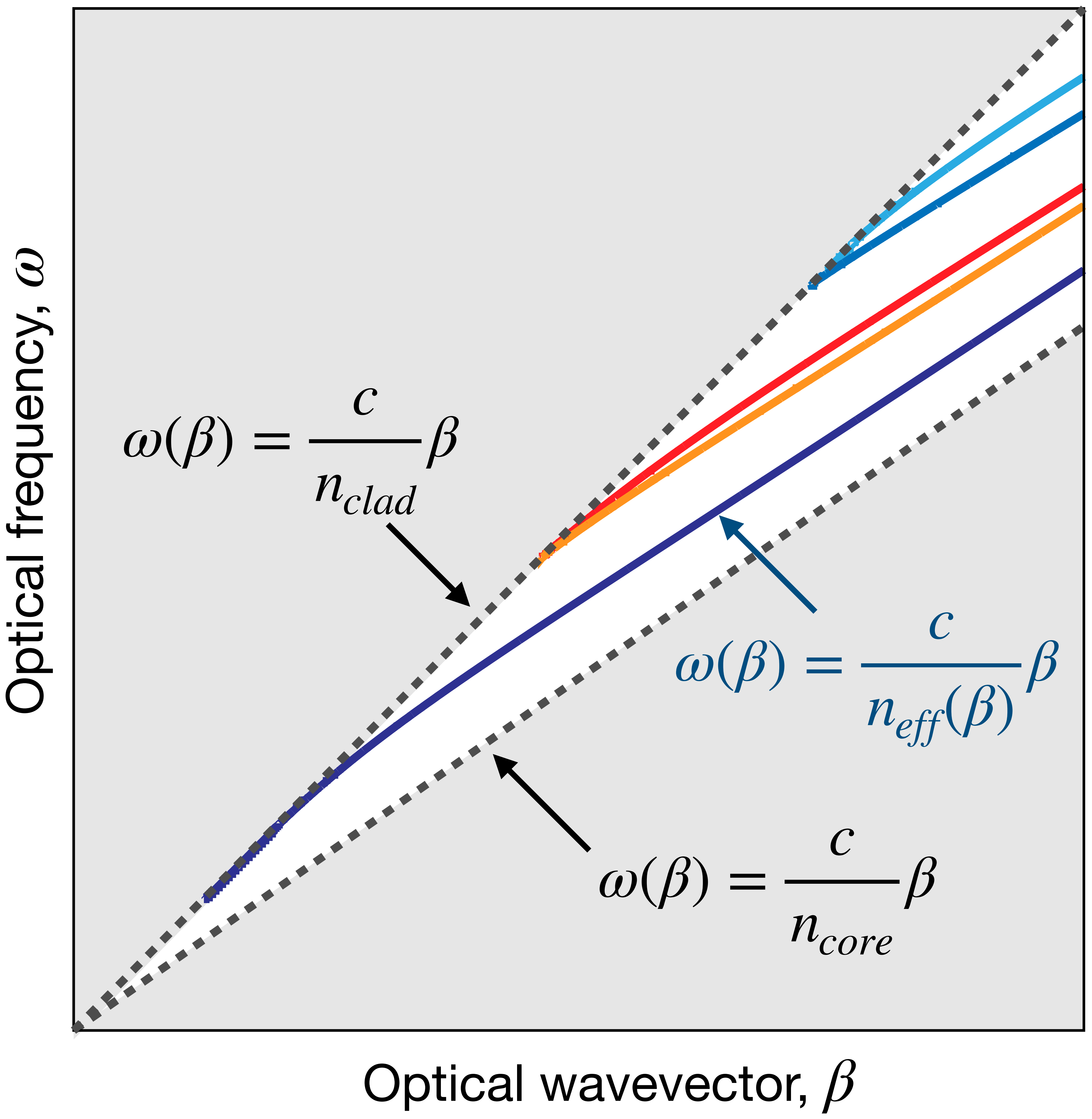


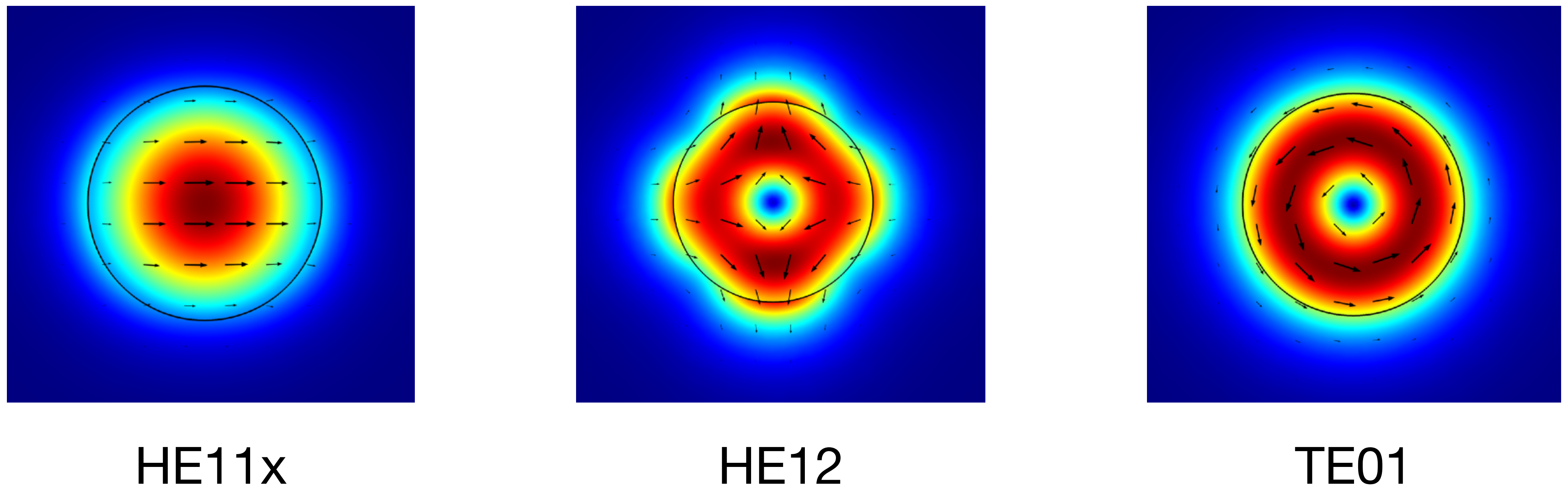




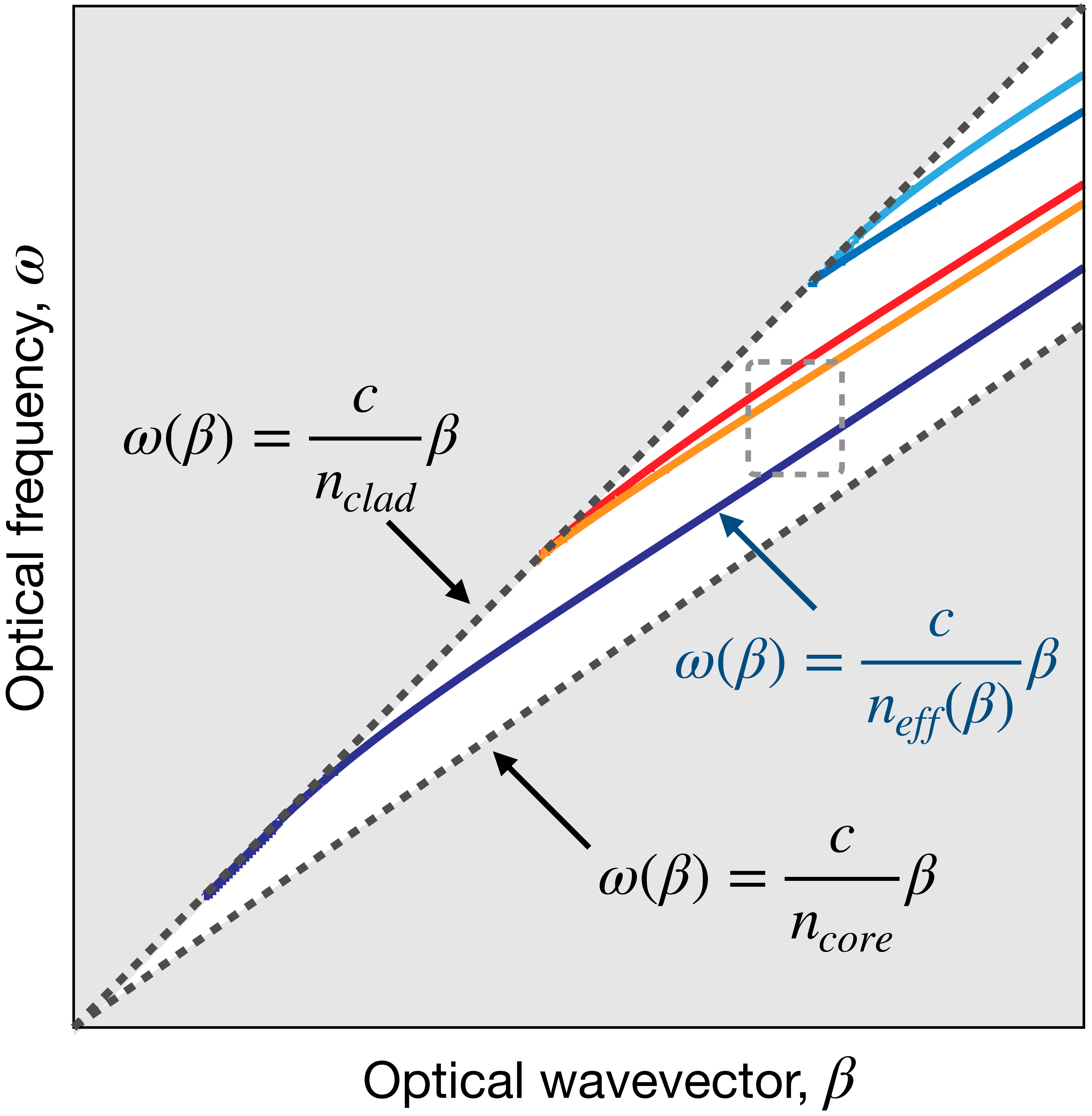
Phase-matching possibilities



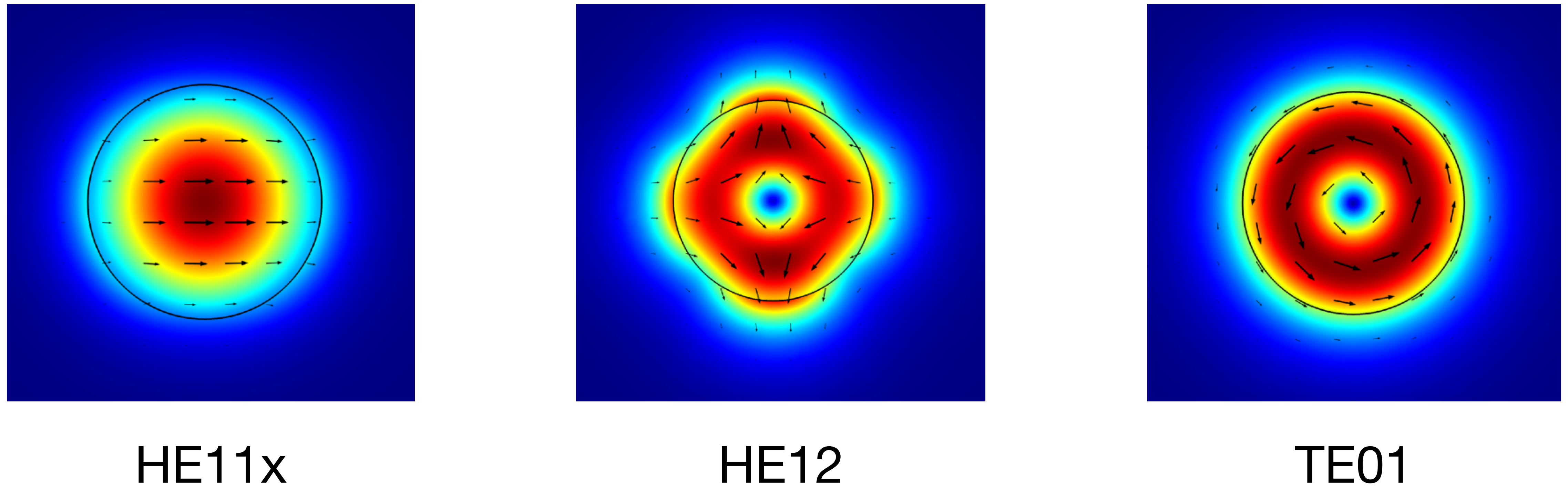
Representative lowest order modes of a cylindrical dielectric waveguide



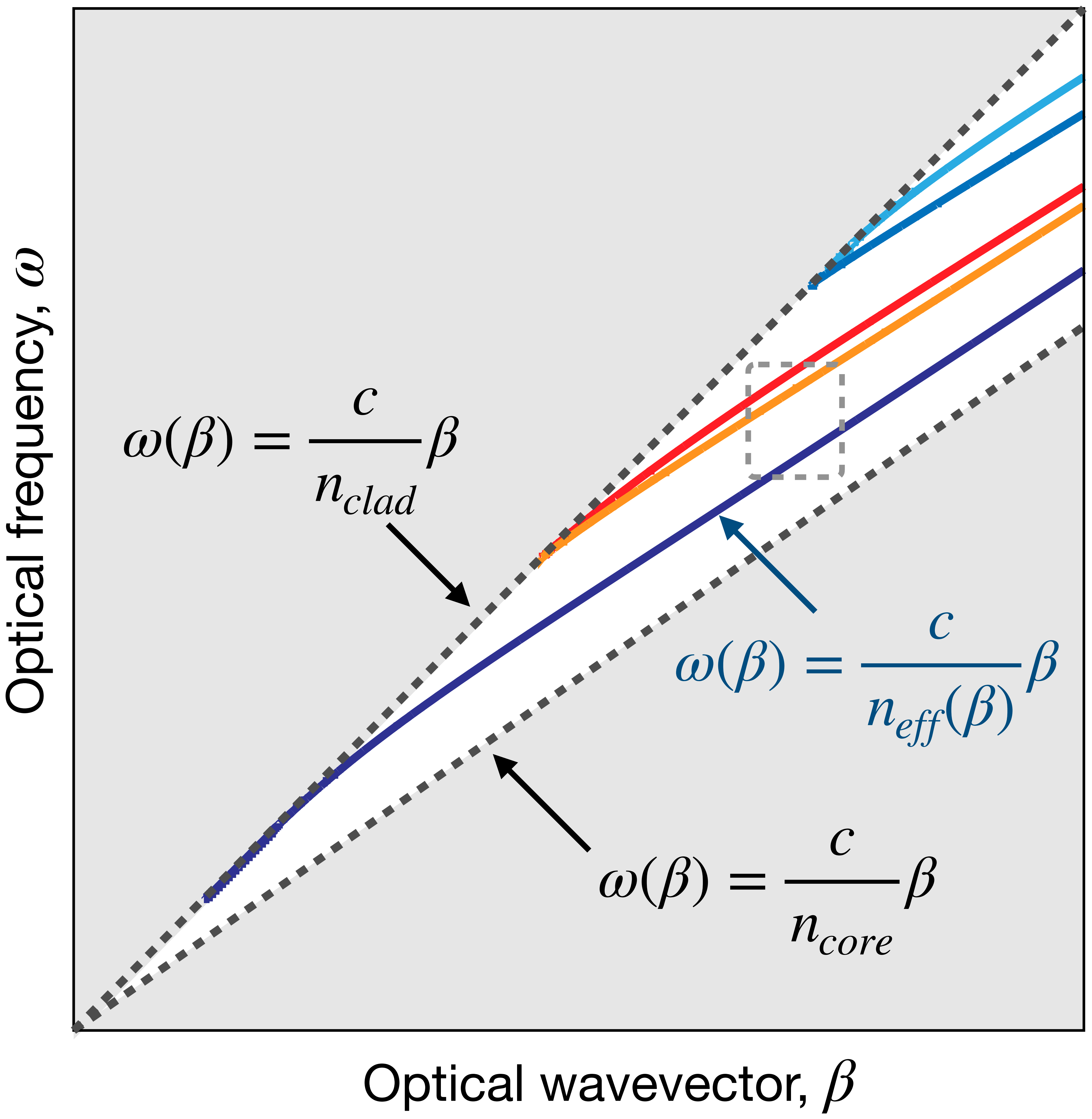
Phase-matching possibilities

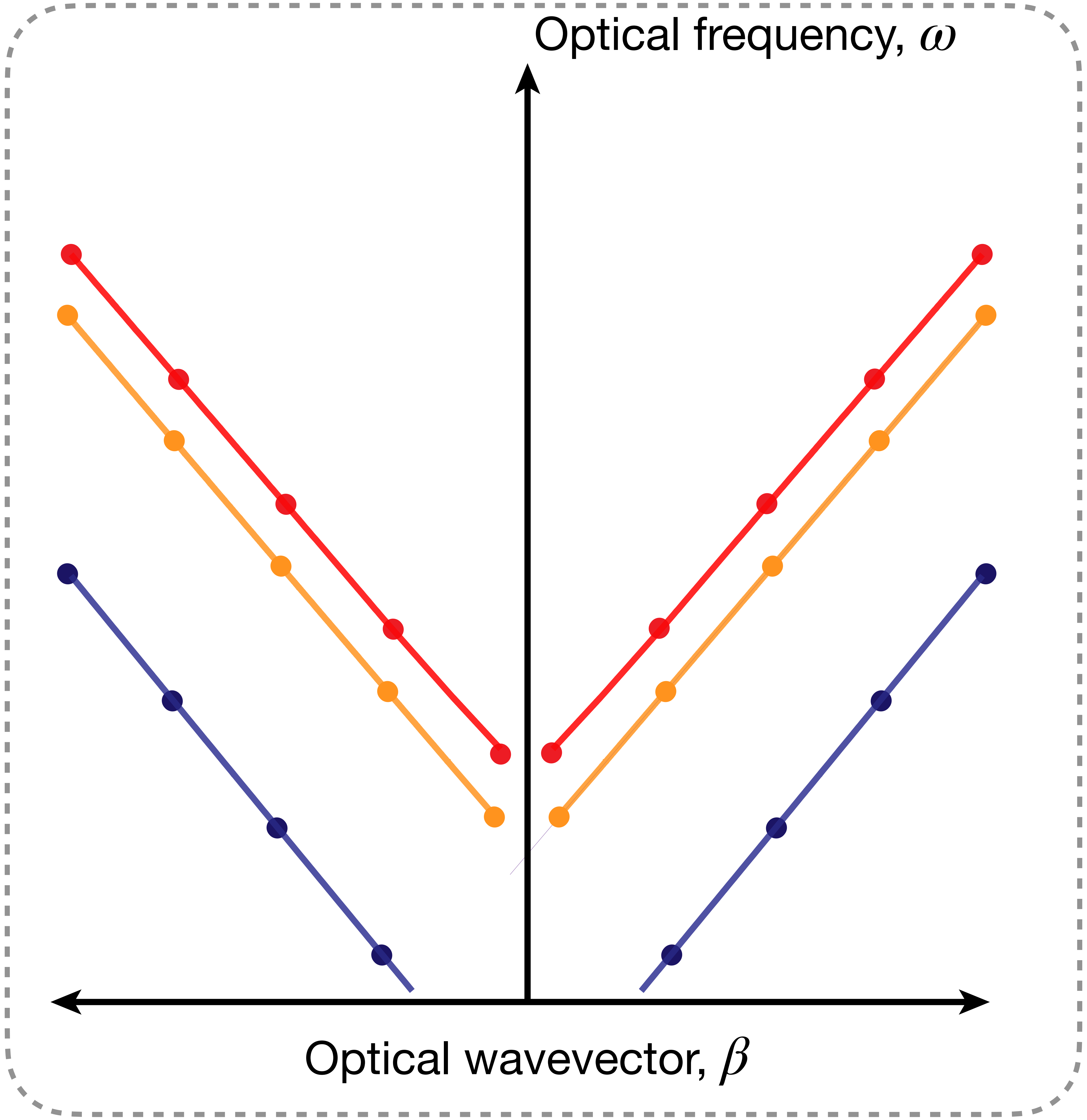


Representative lowest order modes of a cylindrical dielectric waveguide

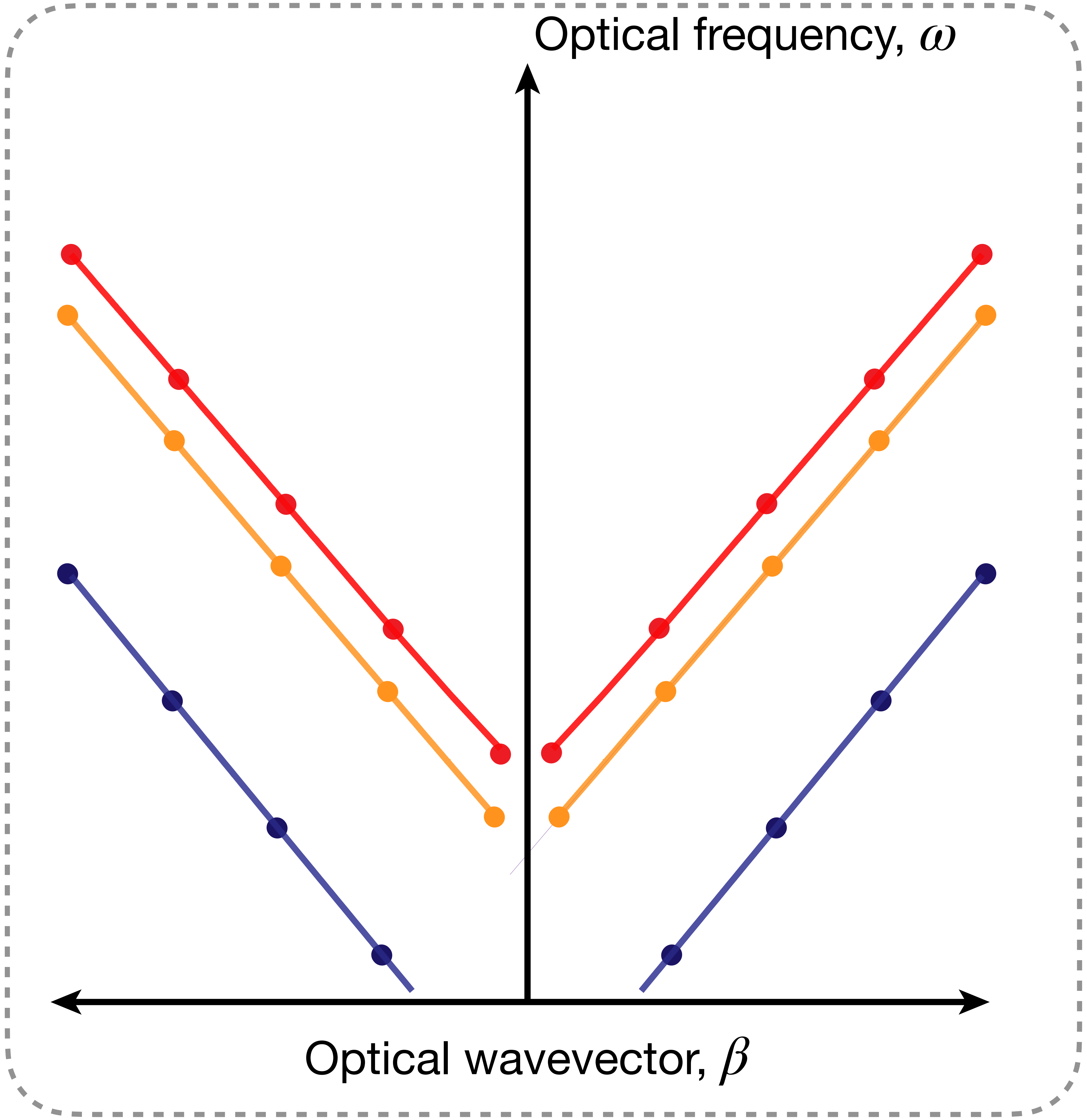


Phase-matching possibilities

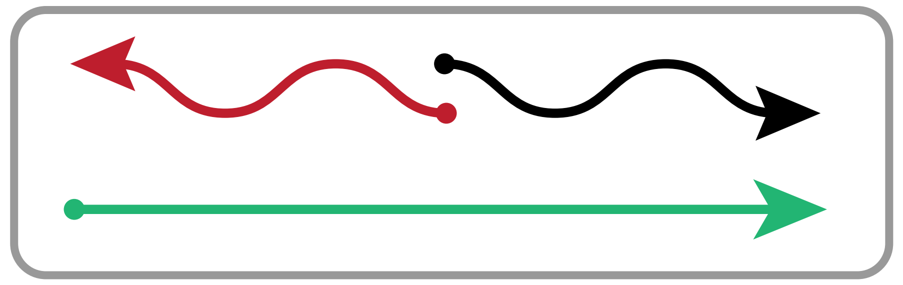


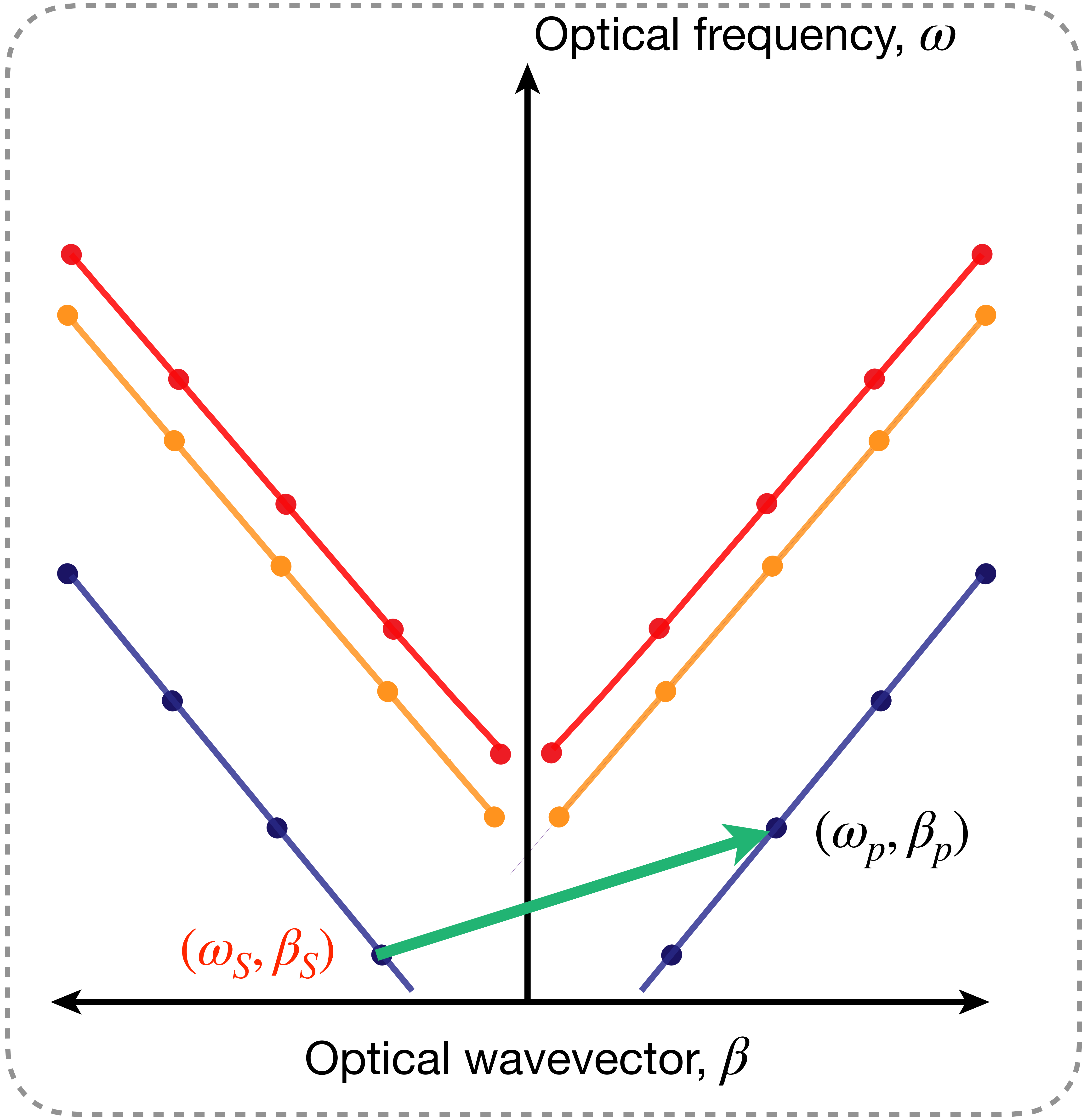


Phase-matching possibilities



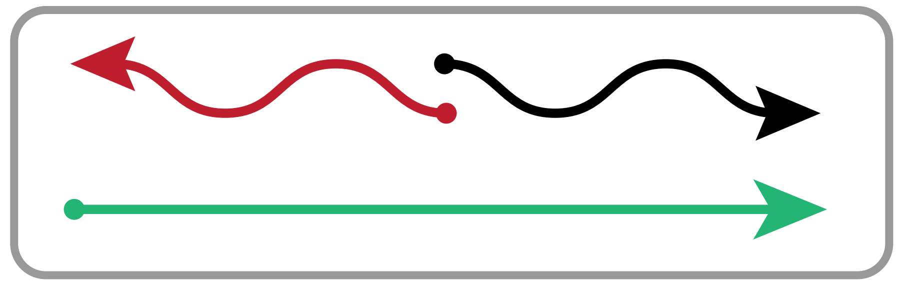
Phase-matching: intra-modal BW





$$q_S = +(|k_S| + |k_p|) \approx 2|k_p|$$

Phase-matching: intra-modal BW



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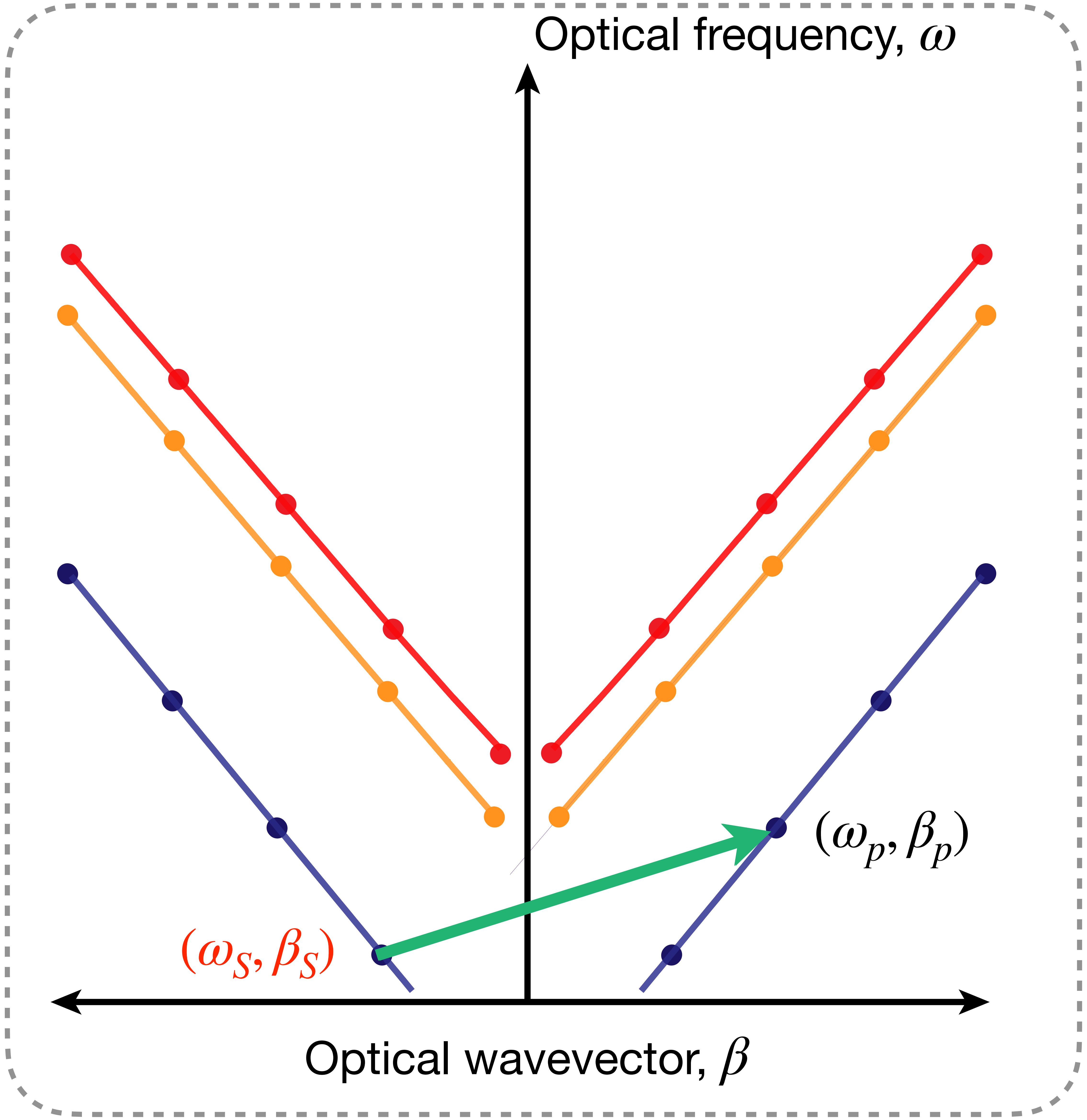

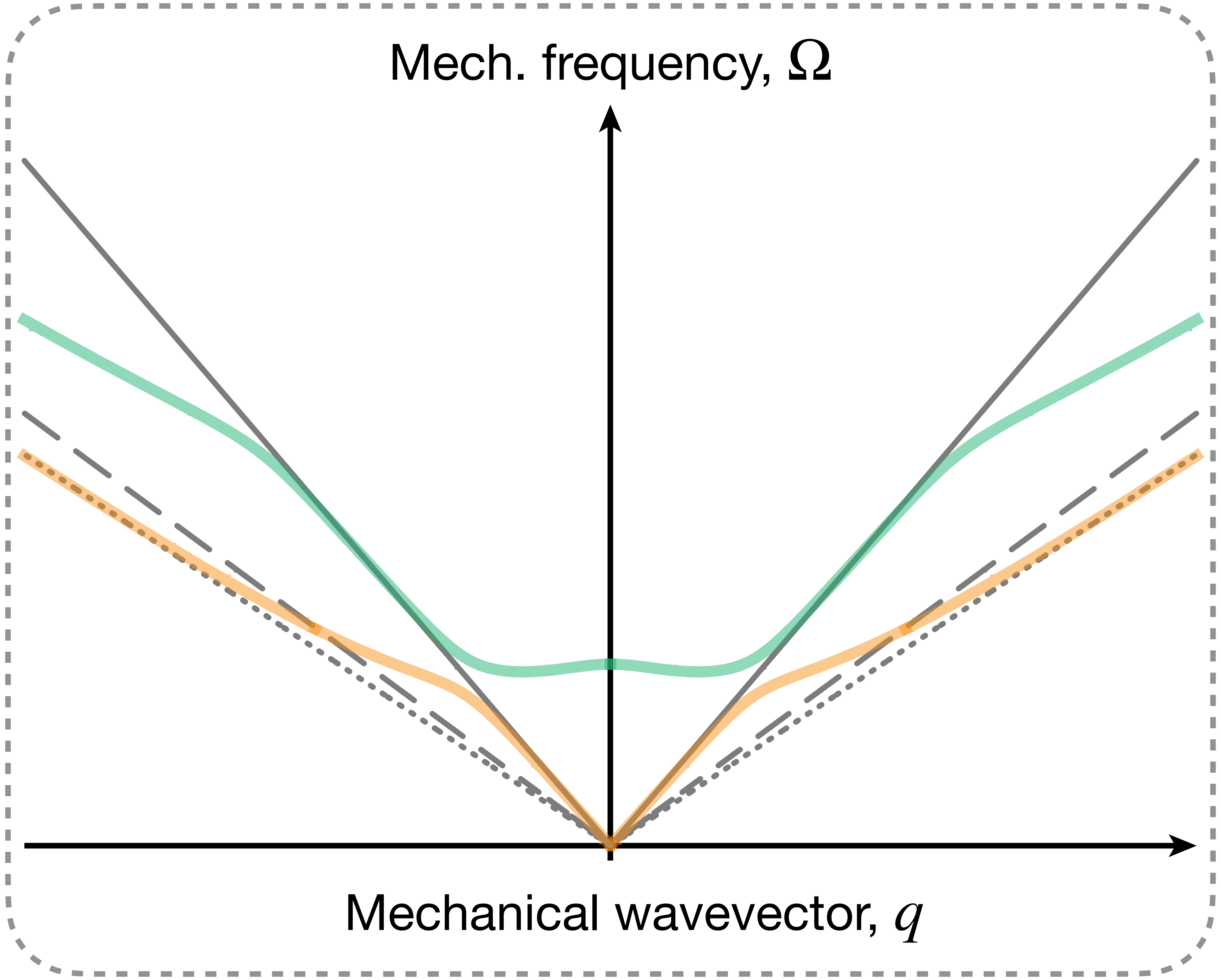

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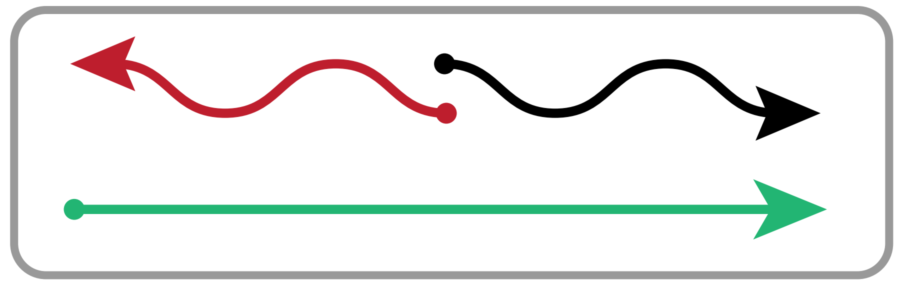
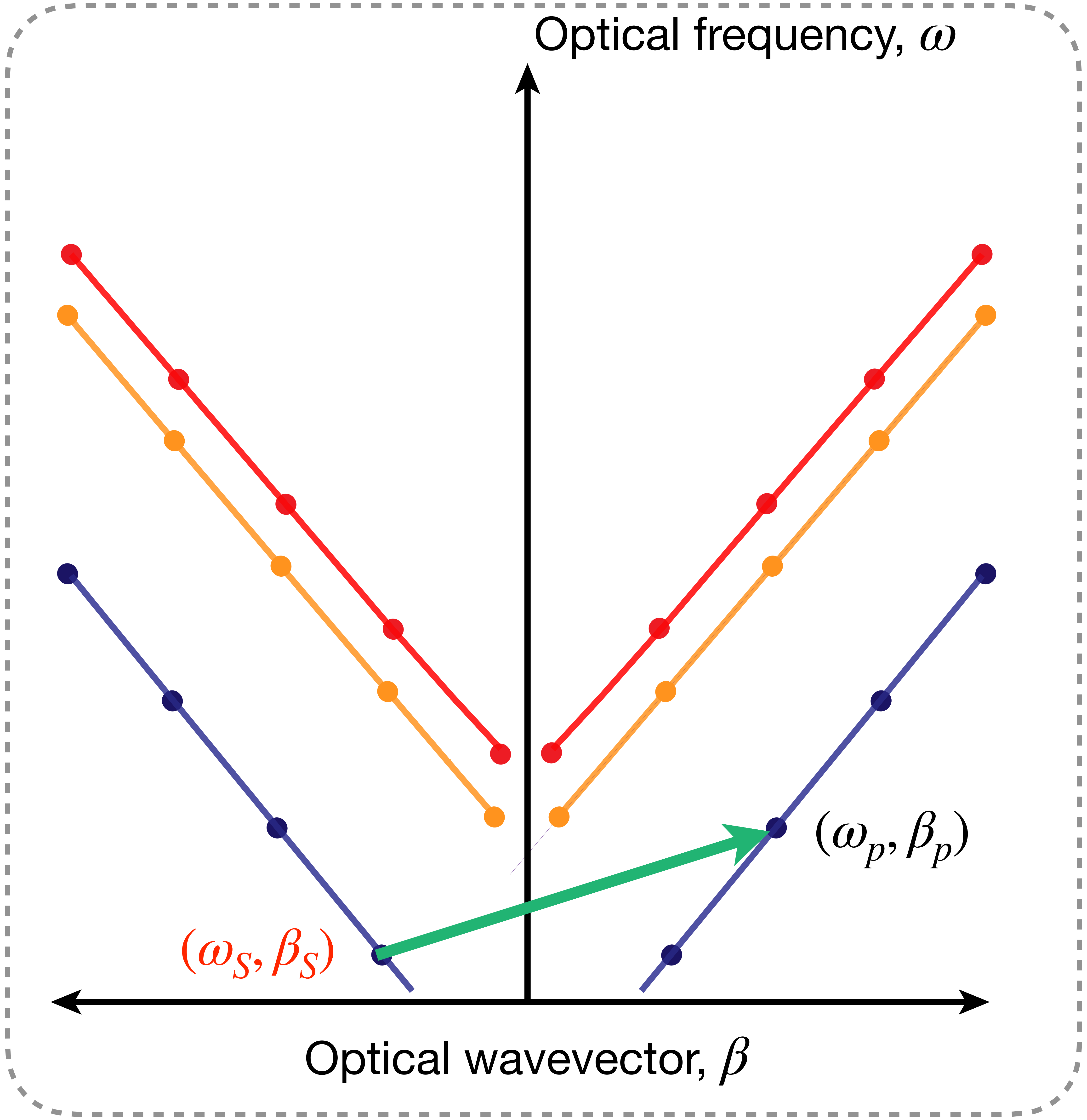
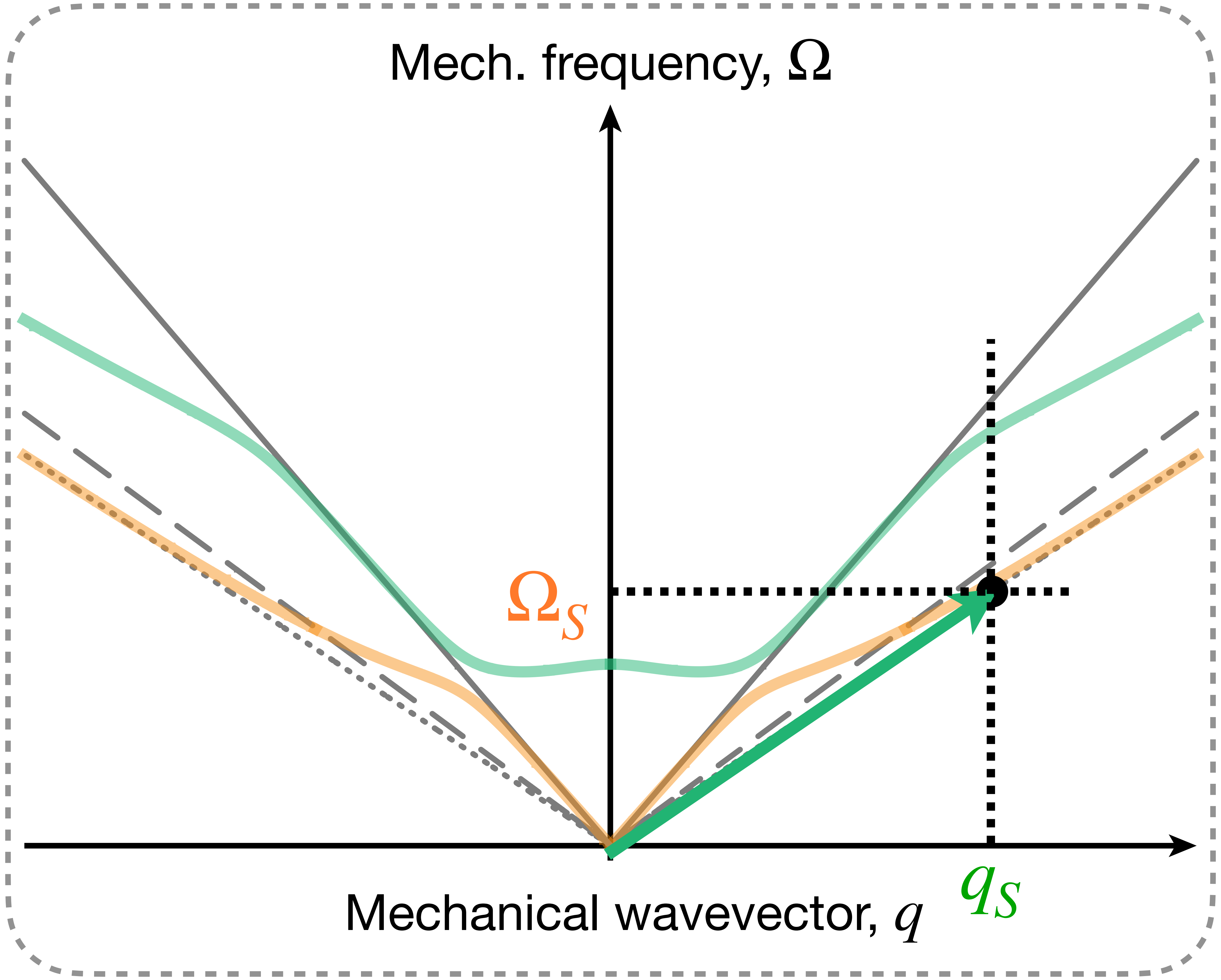


$$q_S = +(|k_S| + |k_p|) \approx 2|k_p|$$

$$q_S(\Omega_S) \approx 2\frac{\omega_p}{c}n_{eff}$$





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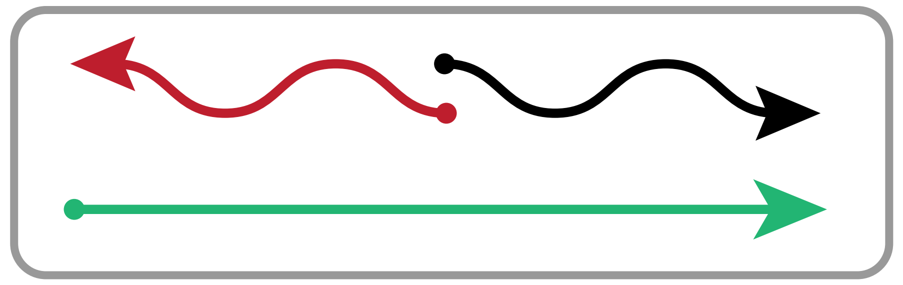
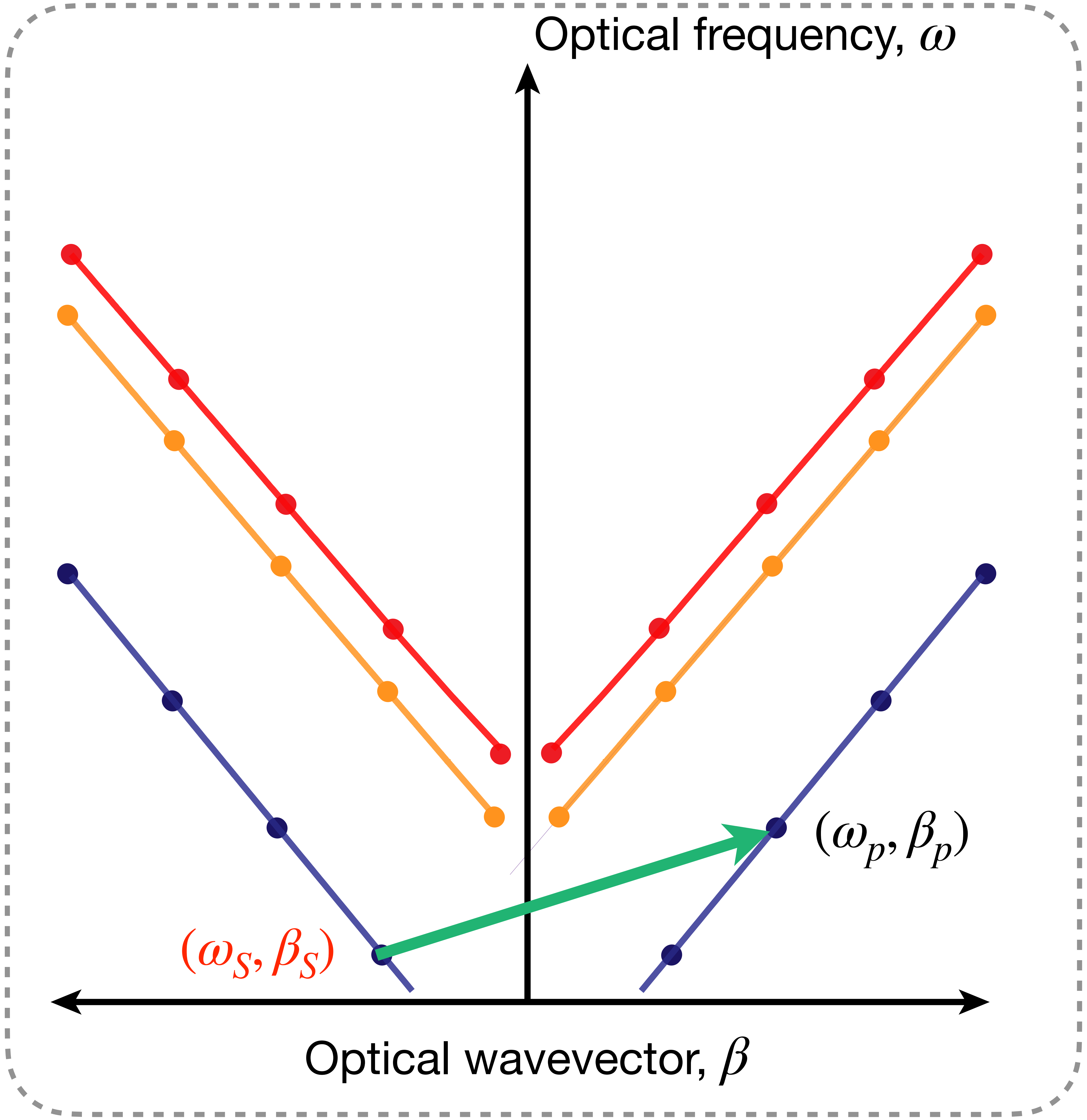
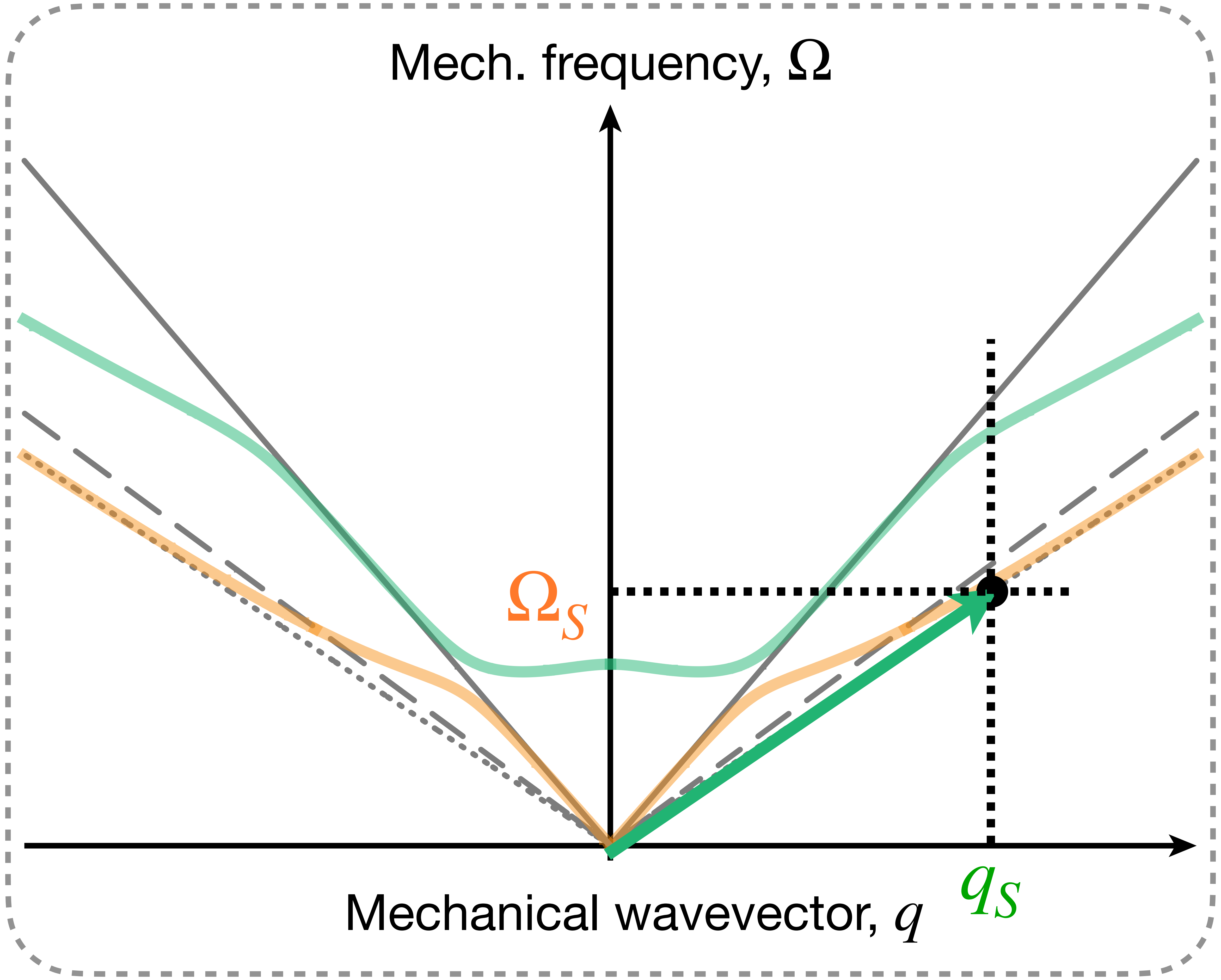


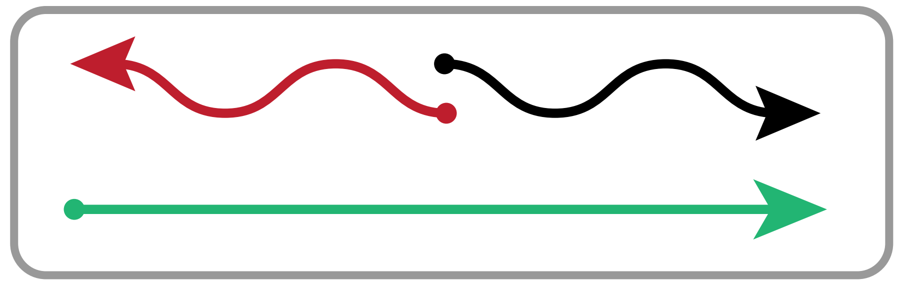


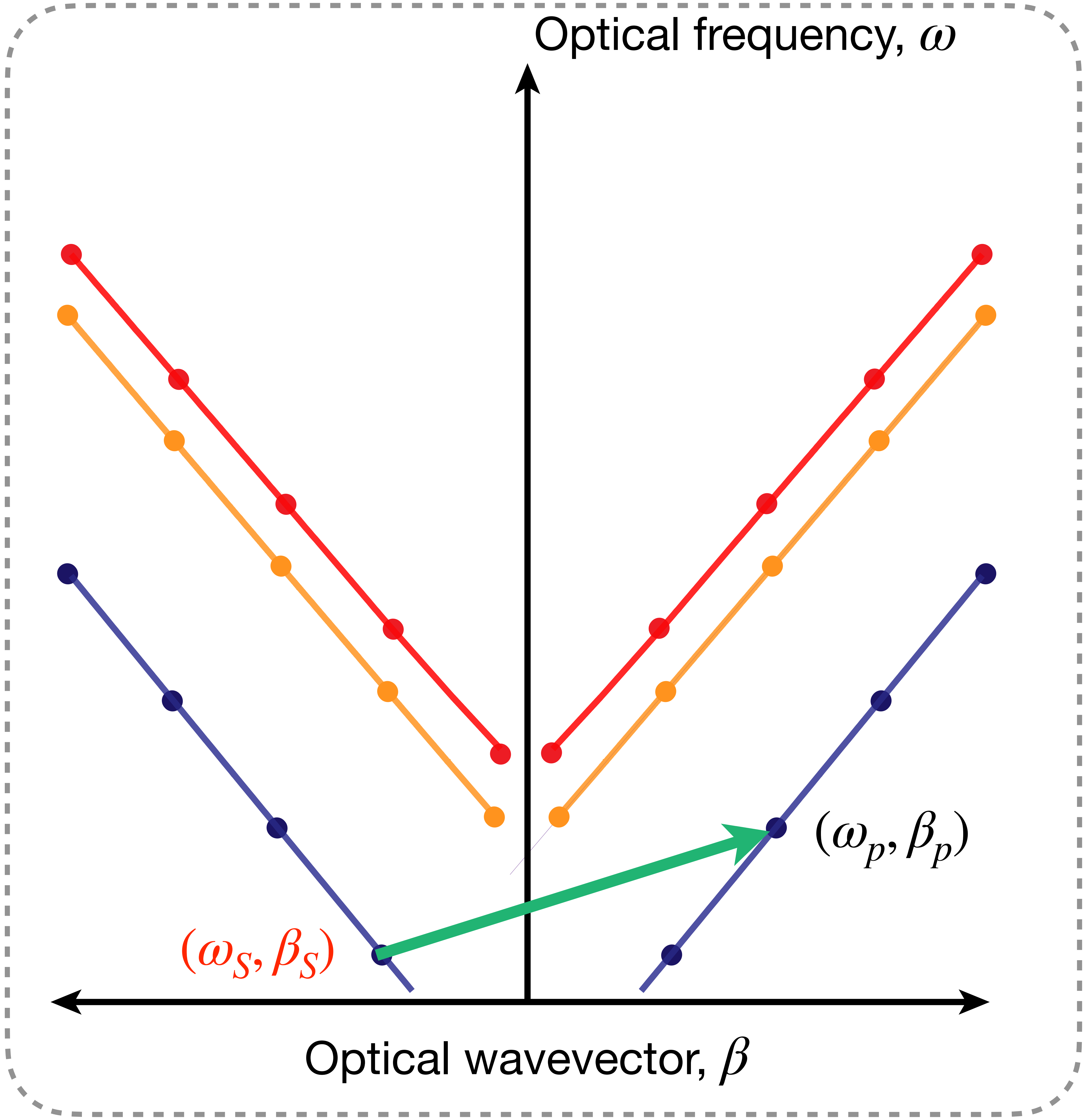
$$q_S = +(|k_S| + |k_p|) \approx 2|k_p|$$

$$q_S(\Omega_S) \approx 2\frac{\omega_p}{c}n_{eff} \approx \frac{\Omega}{v_{ac}} \rightarrow \boxed{\Omega_S \approx 2\frac{v_{ac}}{c}\omega_p n_{eff}}$$



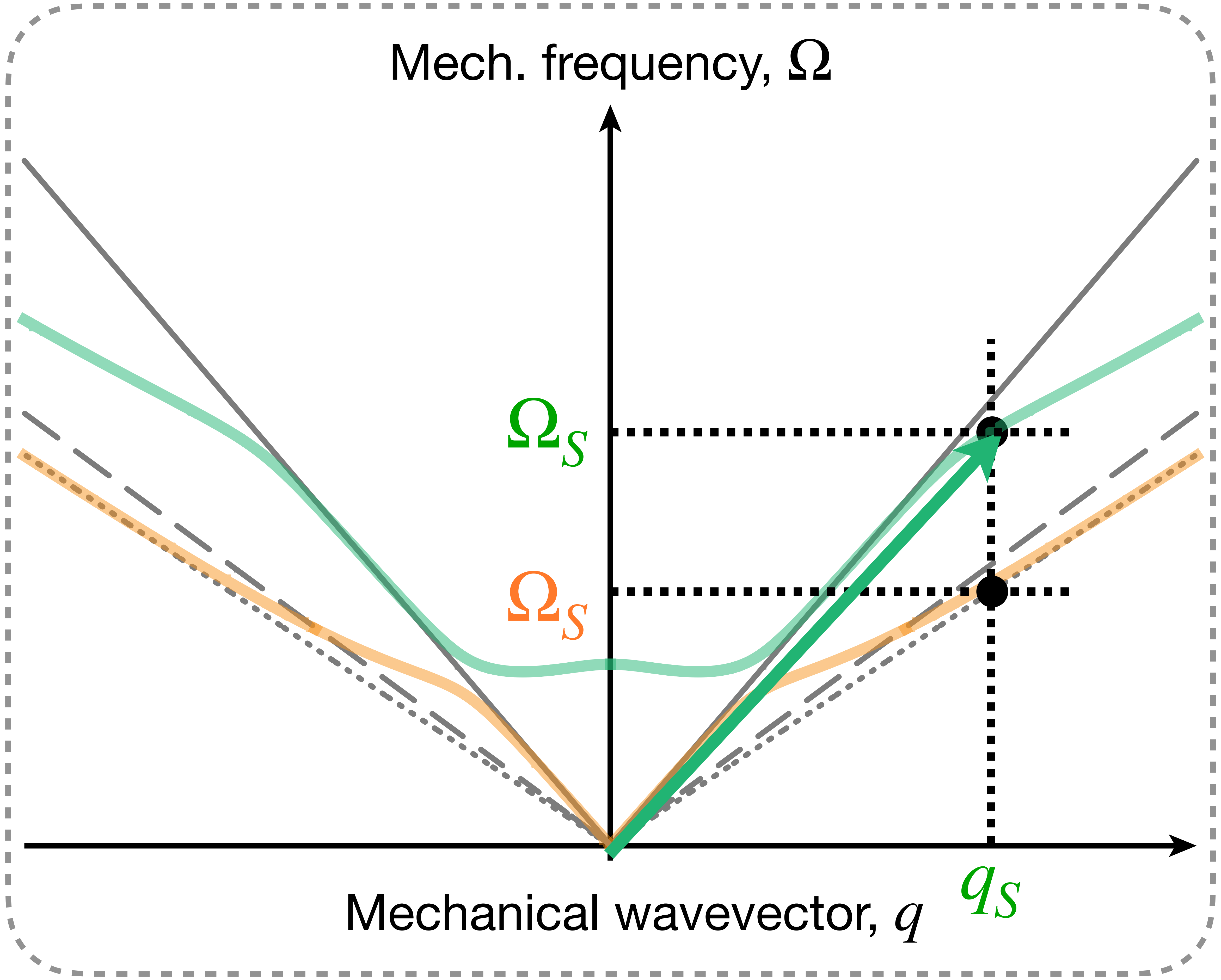
Phase-matching: intra-modal BW





$$q_S = +(|k_S| + |k_p|) \approx 2|k_p|$$

$$q_S(\Omega_S) \approx 2\frac{\omega_p}{c} n_{eff} \approx \frac{\Omega}{v_{ac}} \rightarrow \boxed{\Omega_S \approx 2\frac{v_{ac}}{c}\omega_p n_{eff}}$$



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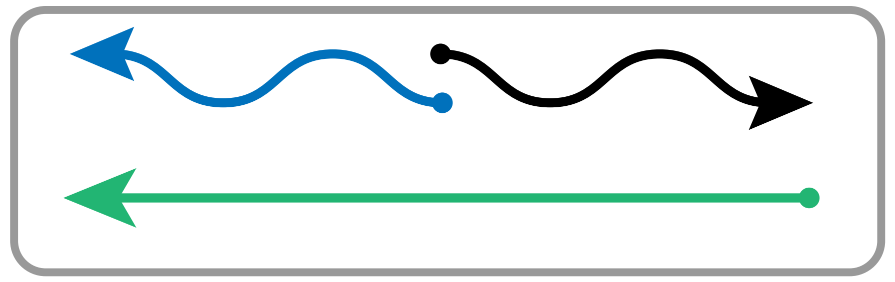
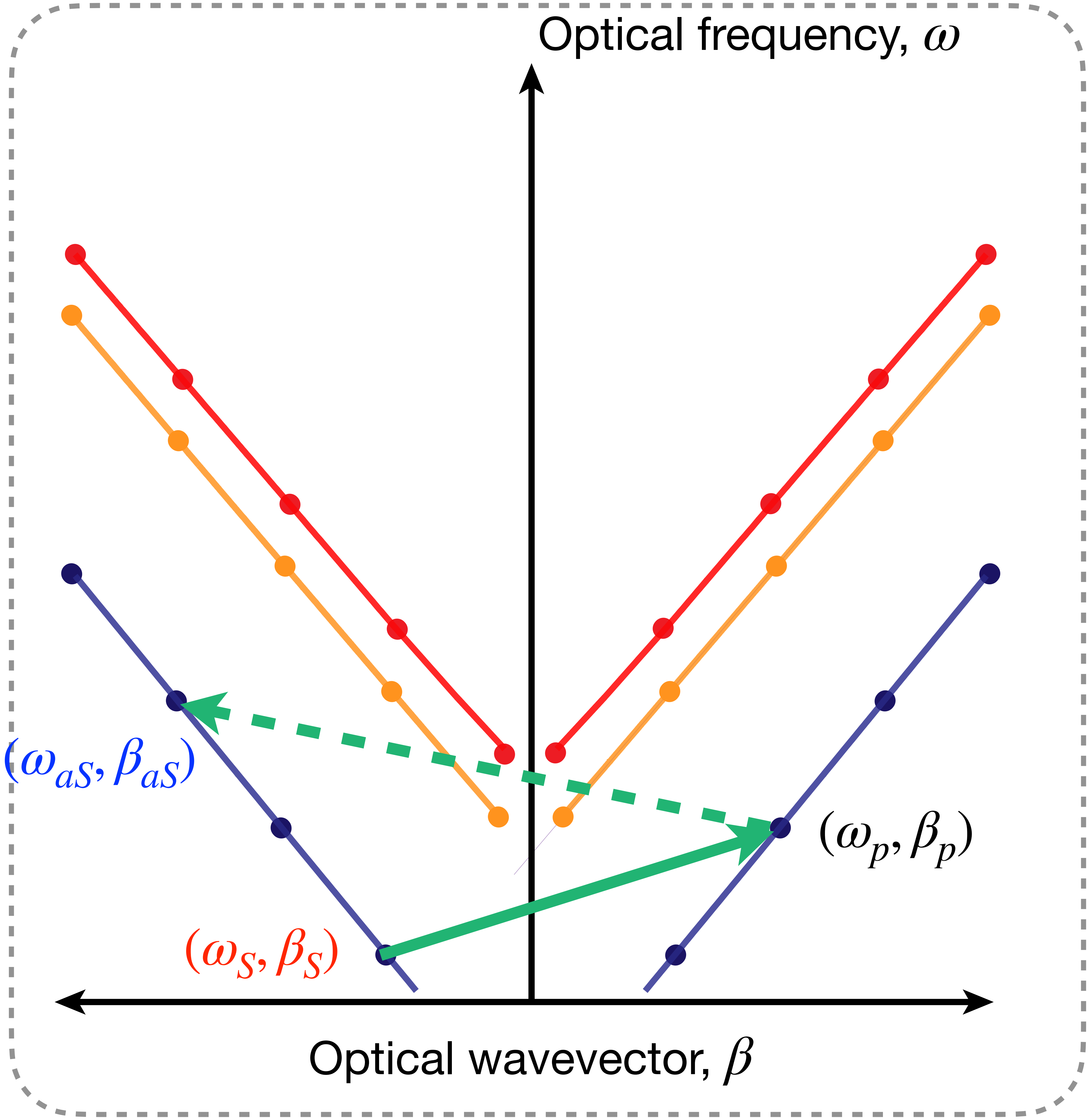
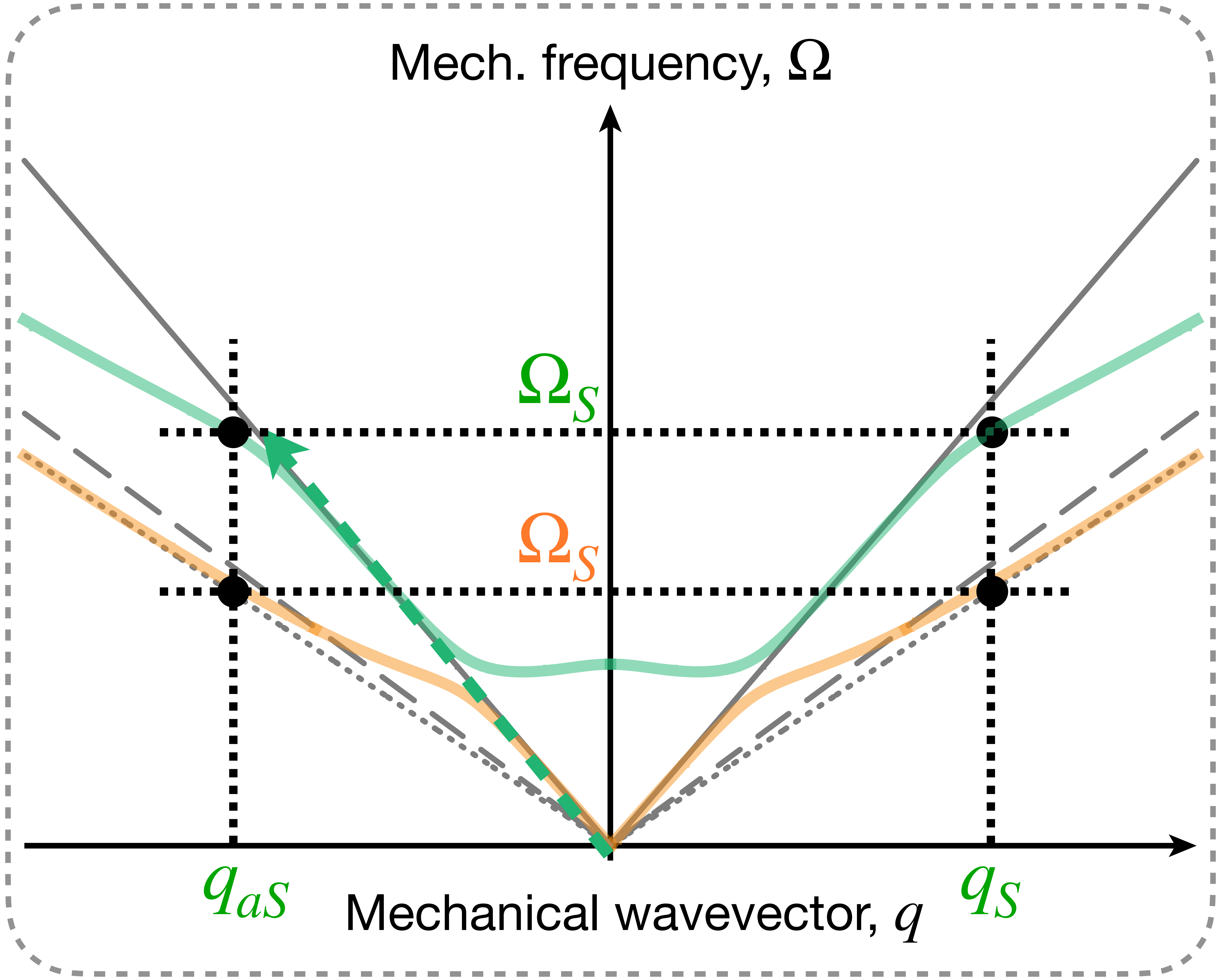


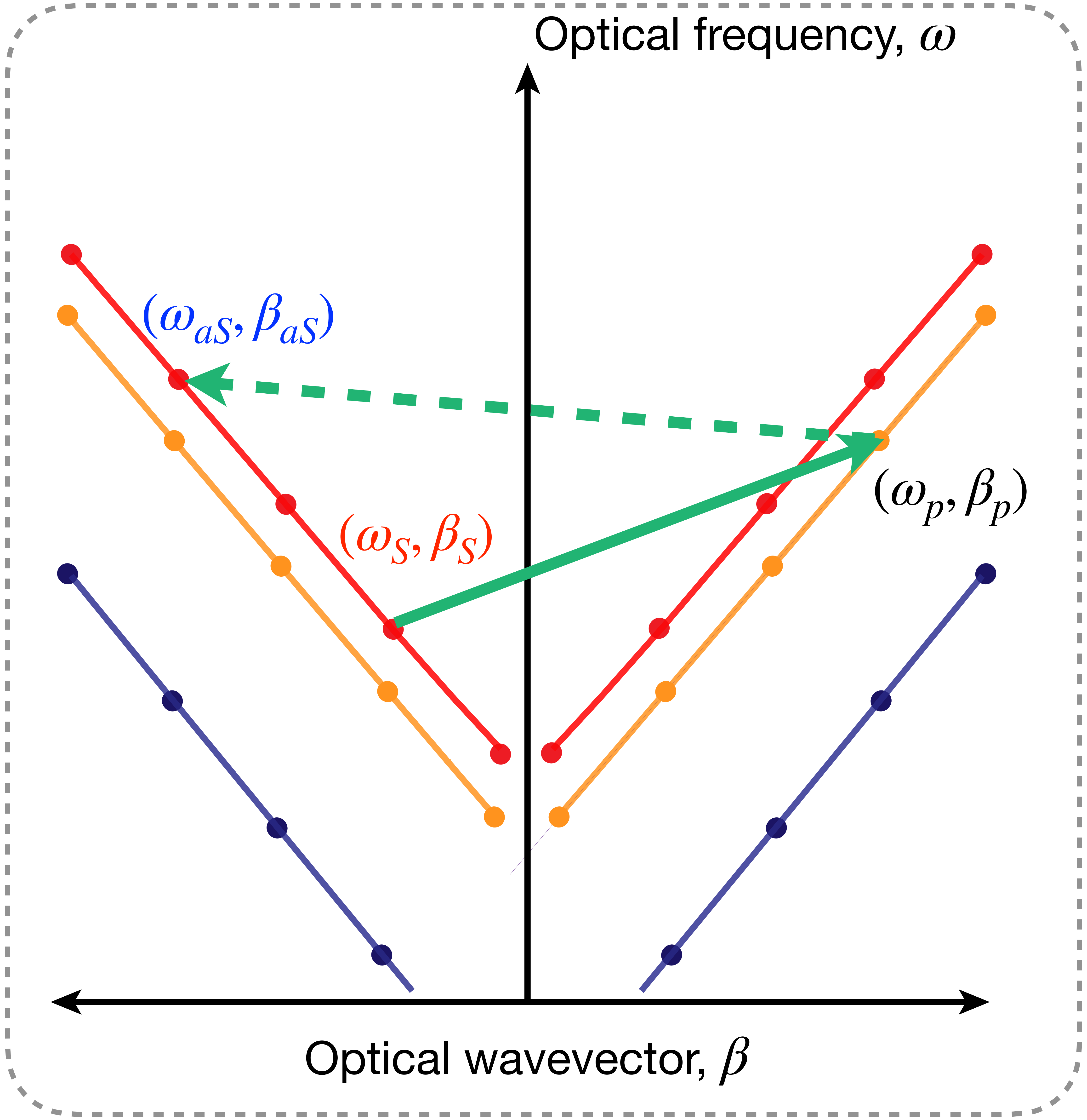
$q_{aS} = -(|k_S| + |k_p|) \approx -2|k_p|$

$\Omega_S \approx 2\frac{v_{ac}}{c}\omega_p n_{eff}$



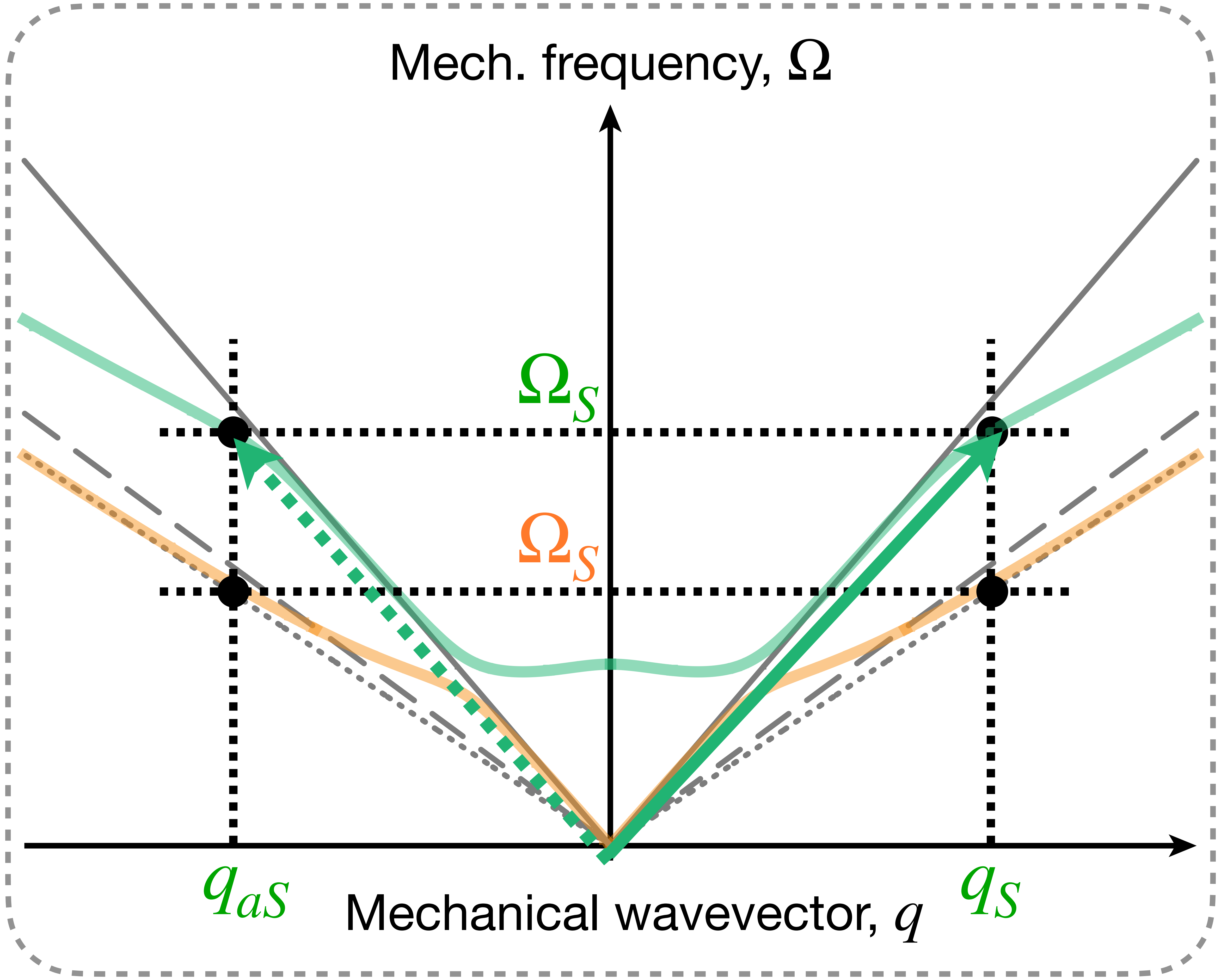


Phase-matching: inter-modal BW



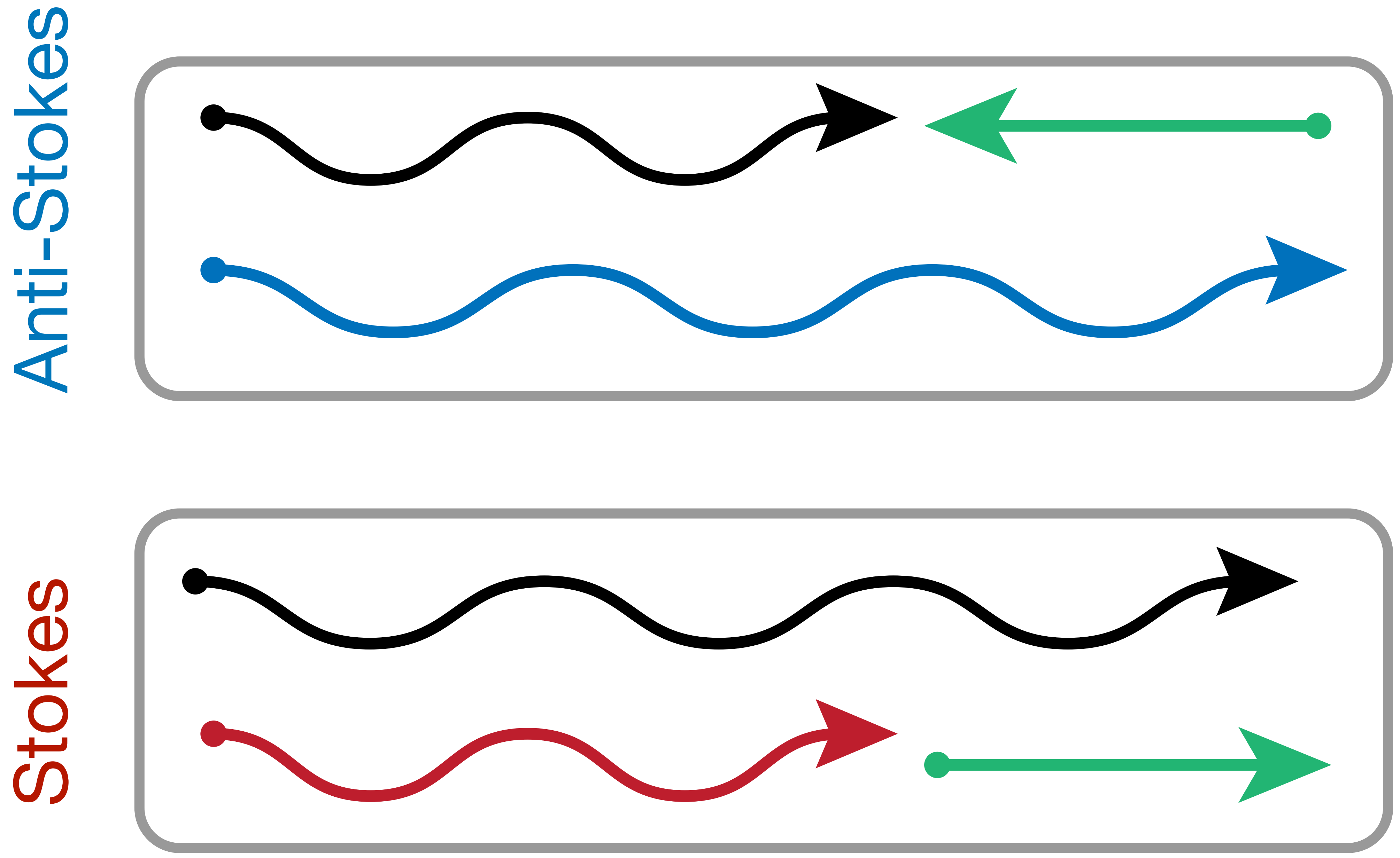
$q_S = +(|k_S| + |k_p|) \neq 2|k_p|$

$$\Omega_S \approx \frac{v_{ac}}{c}\omega_p(n_{eff}^{(p)} + n_{eff}^{(s)})$$



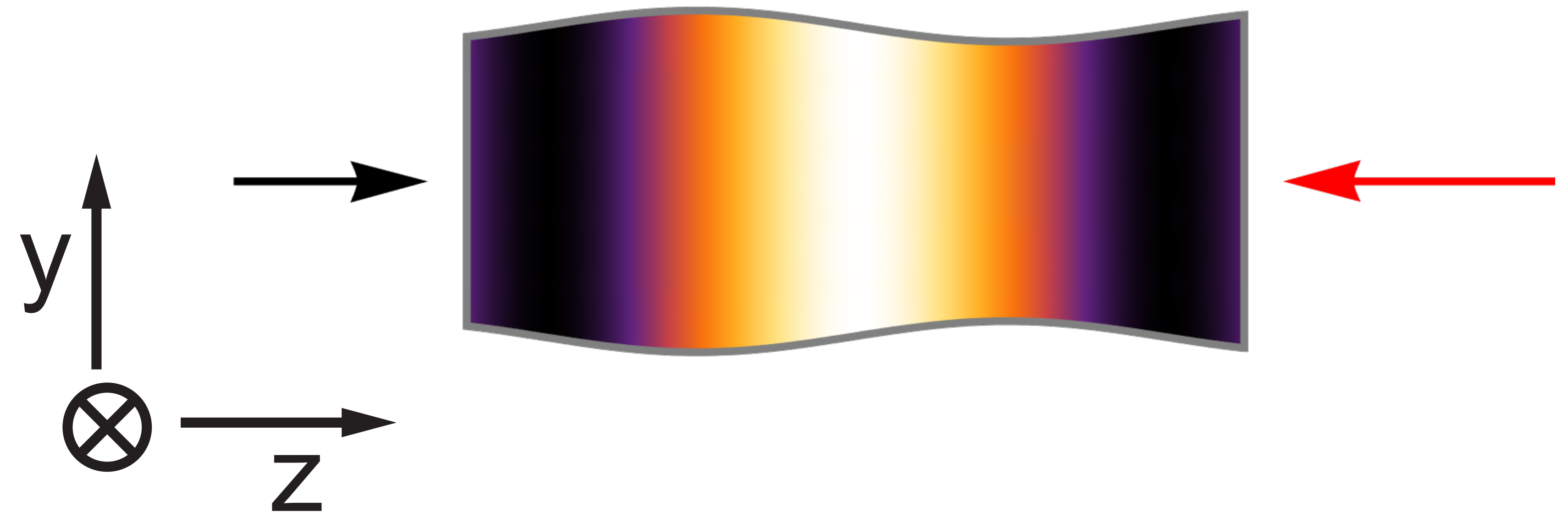
Phase-matching: inter-modal FW

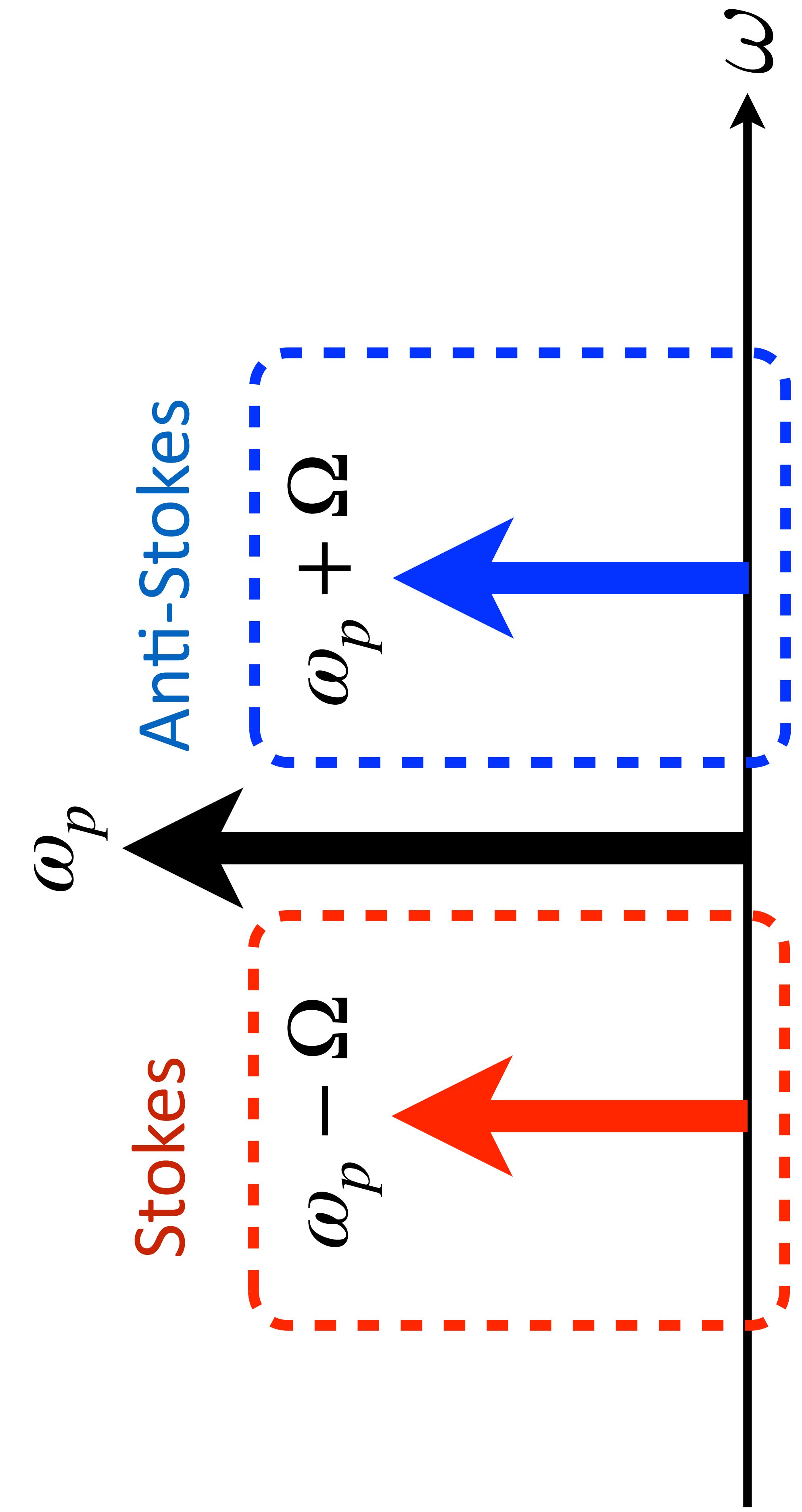
Forward Scattering (intermodal)



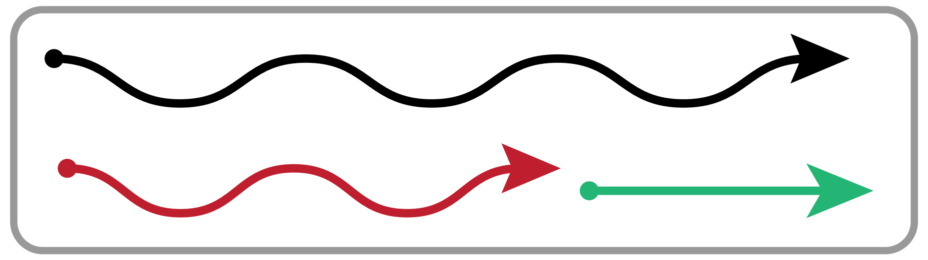
$$q_{aS} = (k_p - k_{aS})$$

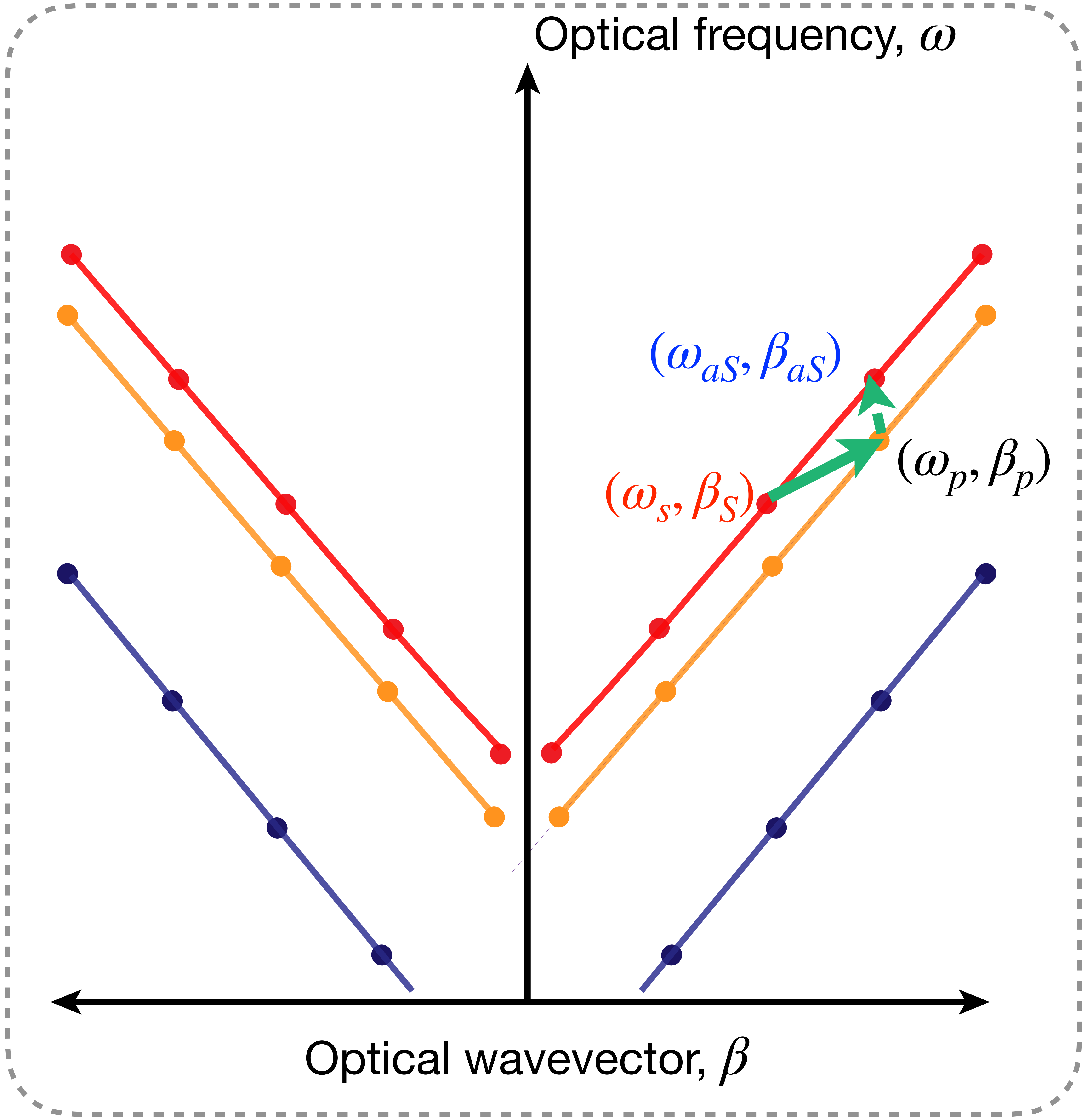
$$q_S = (k_p - k_S)$$





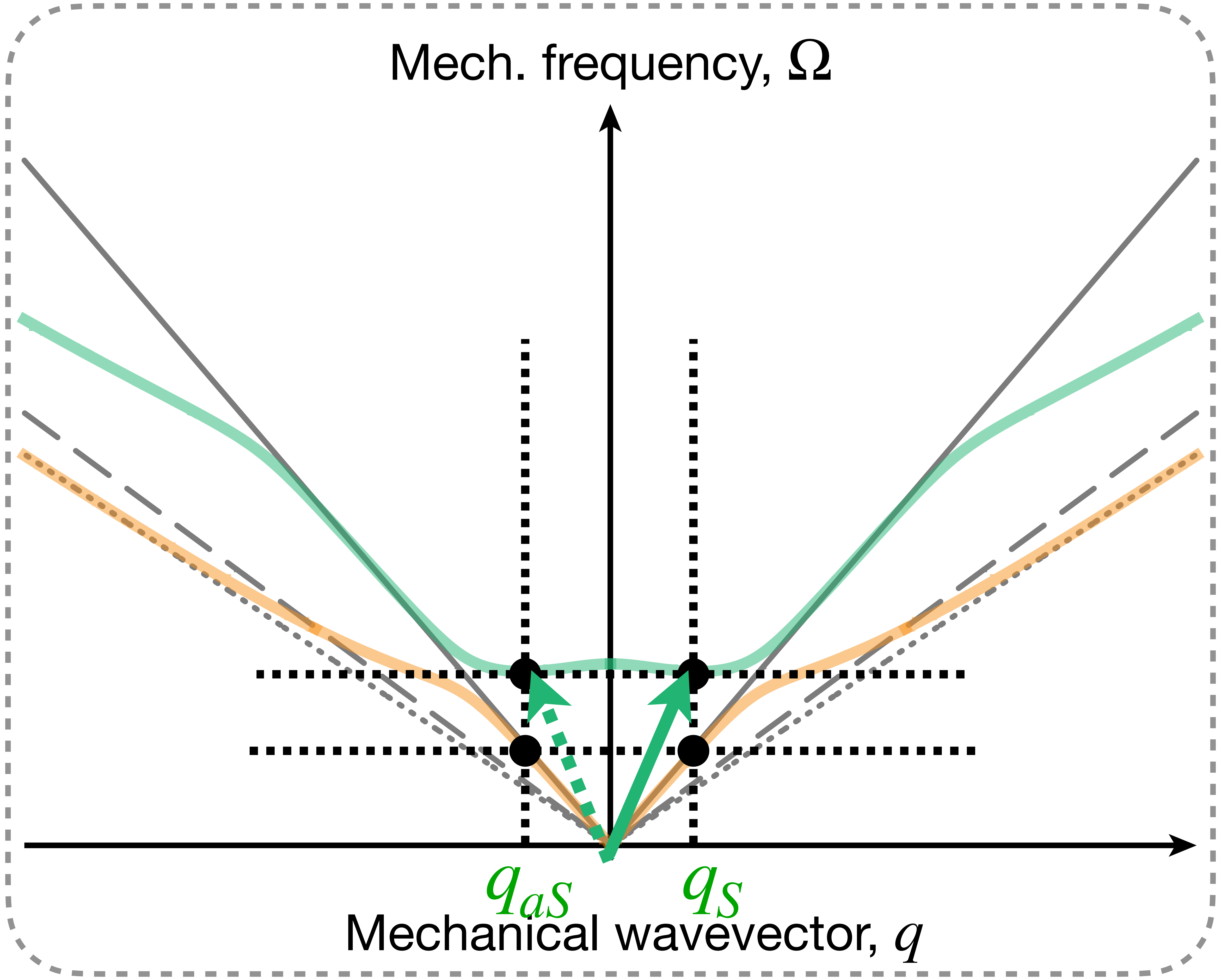
Phase-matching: inter-modal FW



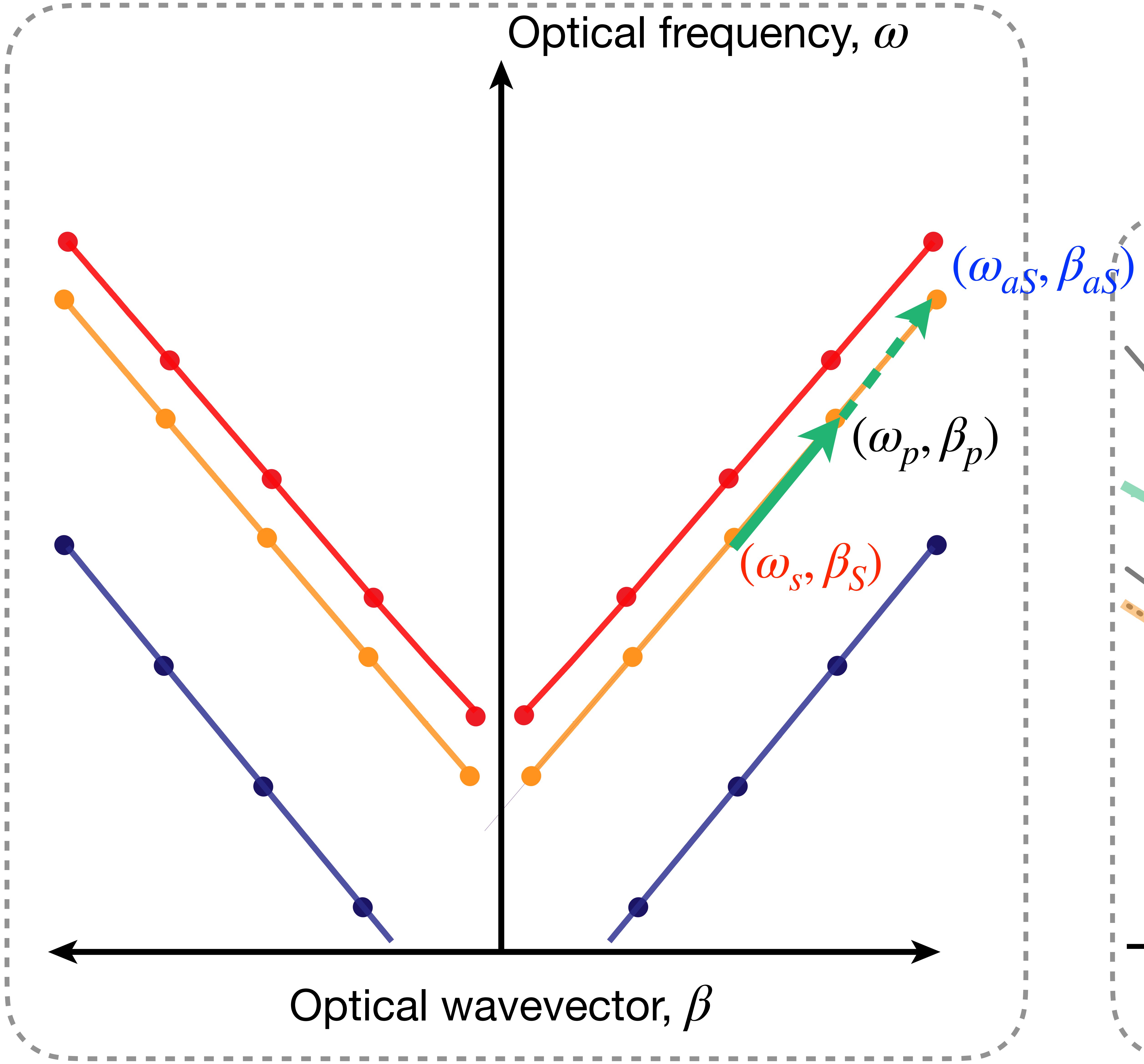


$$q_S = + (|k_p| - |k_S|) \neq 0$$

$$\Omega_S \approx \frac{v_{ac}}{c} \omega_p (n_{eff}^{(p)} - n_{eff}^{(s)})$$

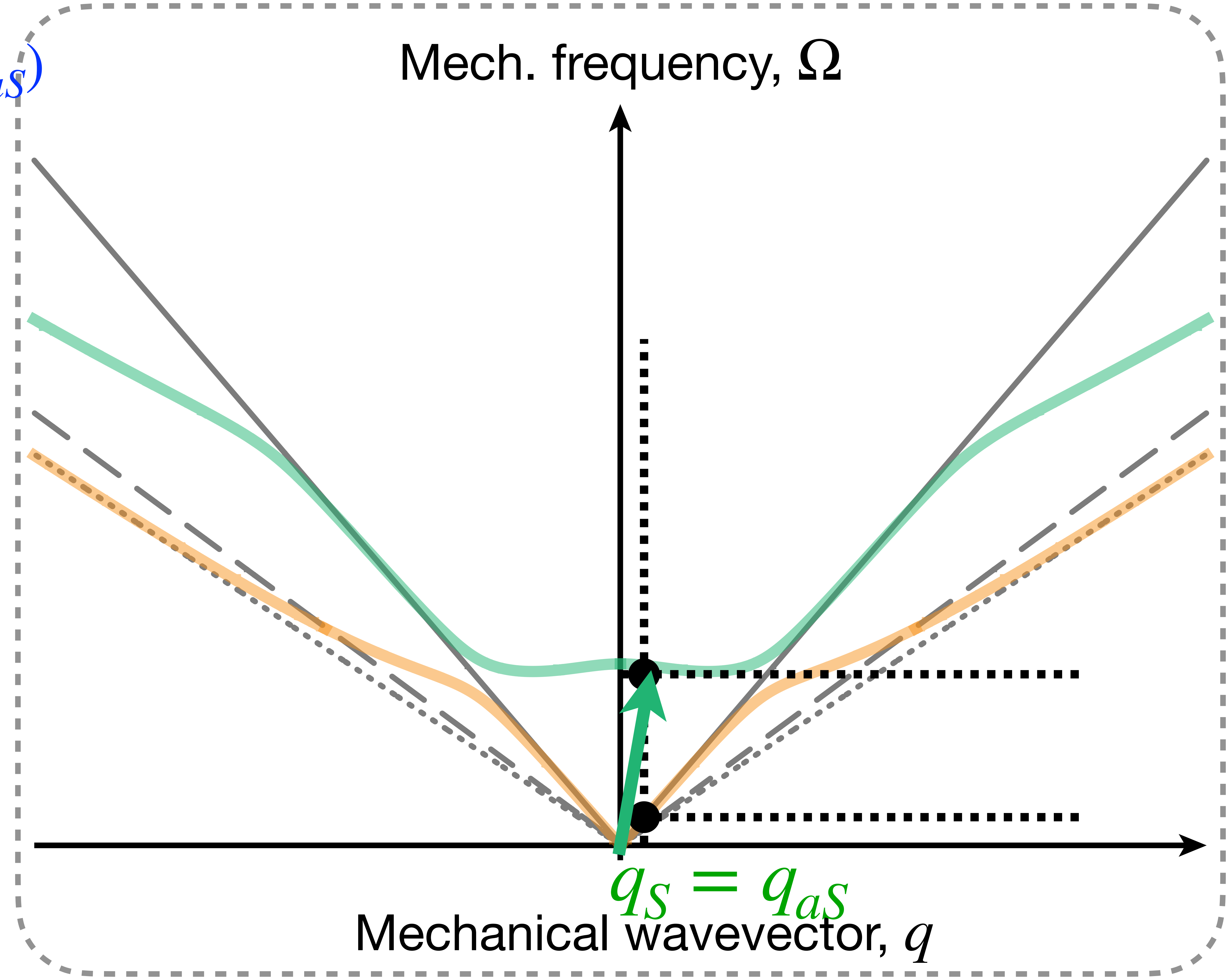


Phase-matching: intra-modal FW



$q_S = +(|k_p| - |k_S|) \approx 0$

$\Omega_S \approx \Omega_0$

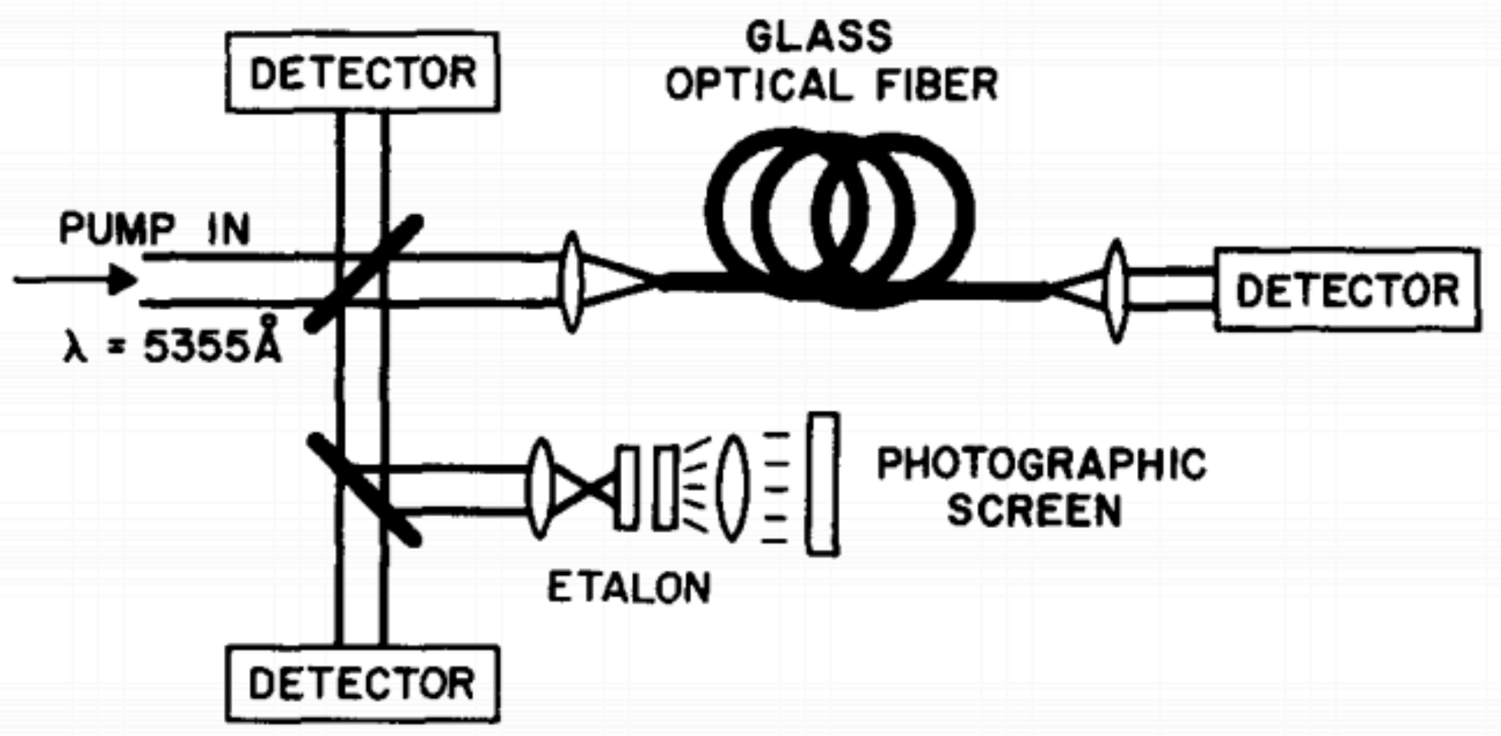


Stimulated Brillouin in optical fibers

Stimulated Brillouin scattering in optical fibers

E.P. Ippen and R.H. Stolen
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 16 August 1972)

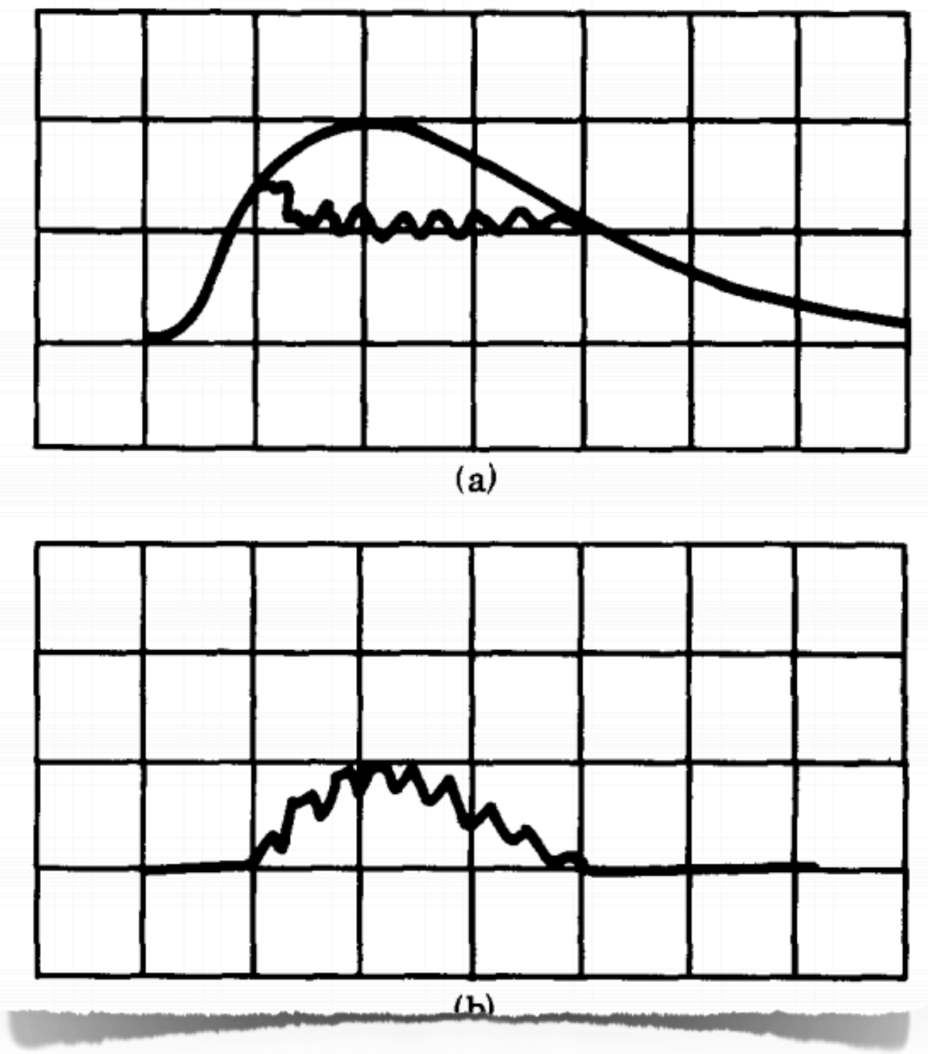
Observations of backward stimulated Brillouin scattering (SBS) in glass optical fibers are reported. Threshold for SBS has been achieved with less than 1 W of input power at 5355 Å. Relaxation behavior in the SBS signal has also been observed and is attributed to finite-cell-length oscillation. Experimental results are compared with theory, and the implied limitation to optical fiber transmission is discussed.



Optical Power Handling Capacity of Low Loss Optical Fibers as Determined by Stimulated Raman and Brillouin Scattering

R. G. Smith

The effect of stimulated Raman and Brillouin scattering on the power handling capacity of optical fibers is considered and found to be important especially when low loss optical fibers are used. A critical power below which stimulated effects may be neglected is defined for forward and backward Raman scattering and for backward Brillouin scattering. This critical power is determined by the effective core area A, the small signal attenuation constant of the fiber α, and the gain coefficient for the stimulated scattering process γ_0, by the approximate relation $P_{crit} \approx 20A\alpha/\gamma_0$. For a fiber with 20-dB/km attenuation and an area of 10^{-7} cm^2 $P_{crit} \approx 35$ mW for stimulated Brillouin scattering. For stimulated Raman scattering P_{crit} is approximately two orders of magnitude higher. It is concluded that these effects must be considered in the design of optical communication systems using low loss fibers.



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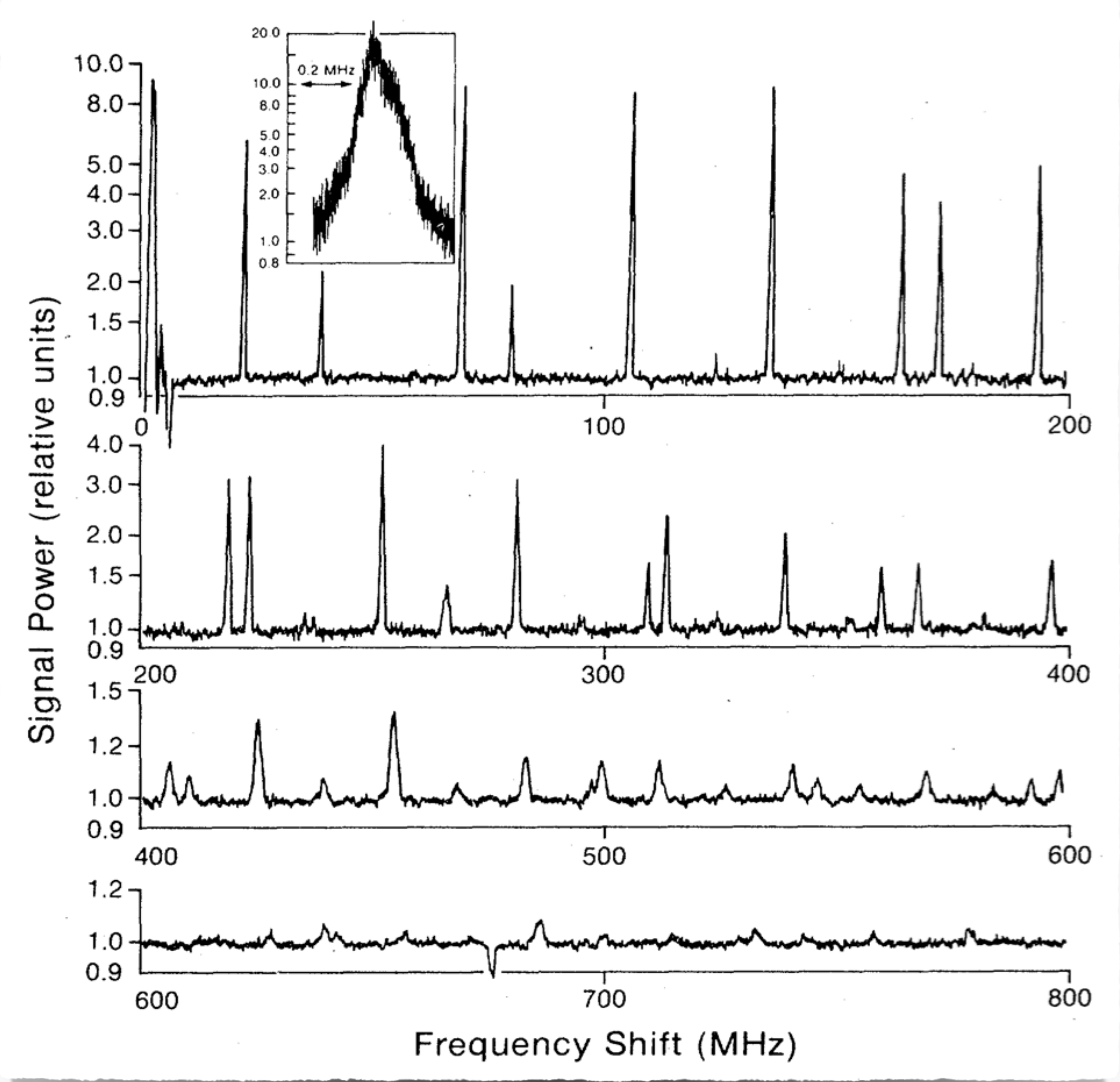
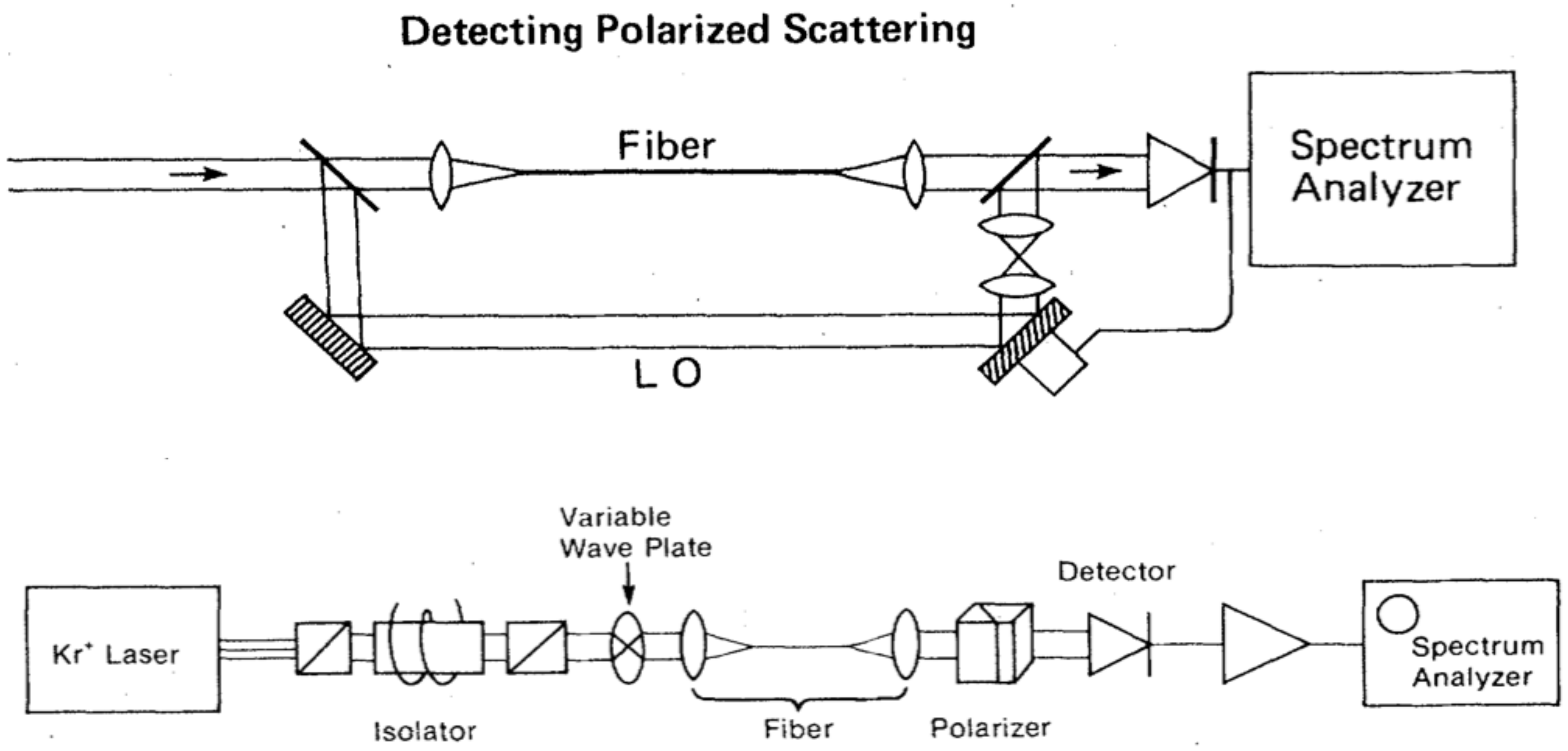
Ippen E P and Stolen R H (1972) Appl. Phys. Lett. 21 539–41 (August)

Forward Brillouin Scattering (aka GAWBS)





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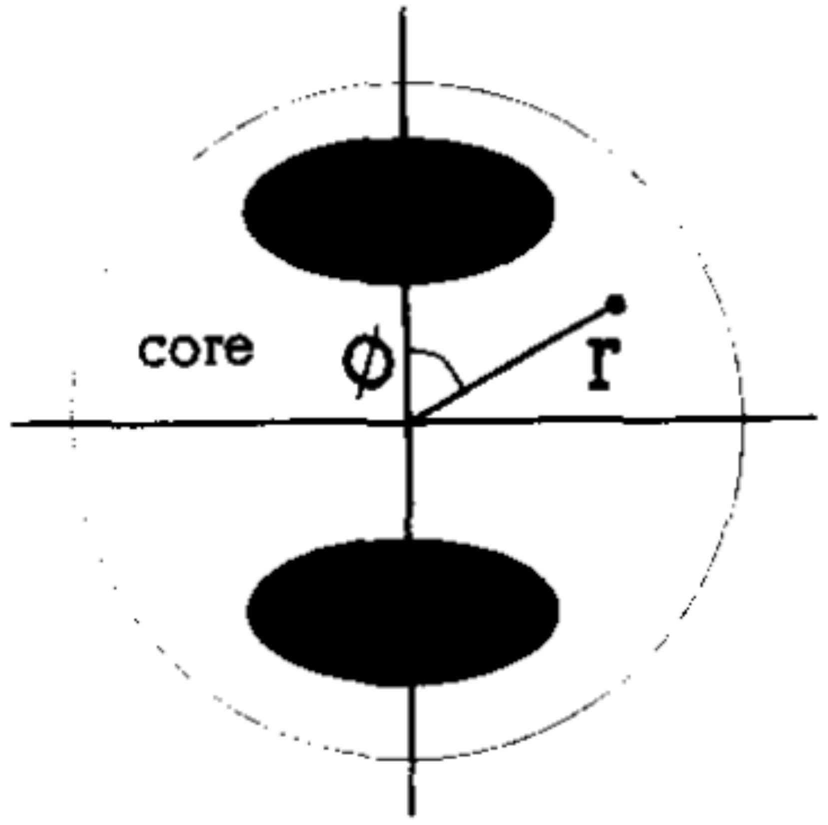
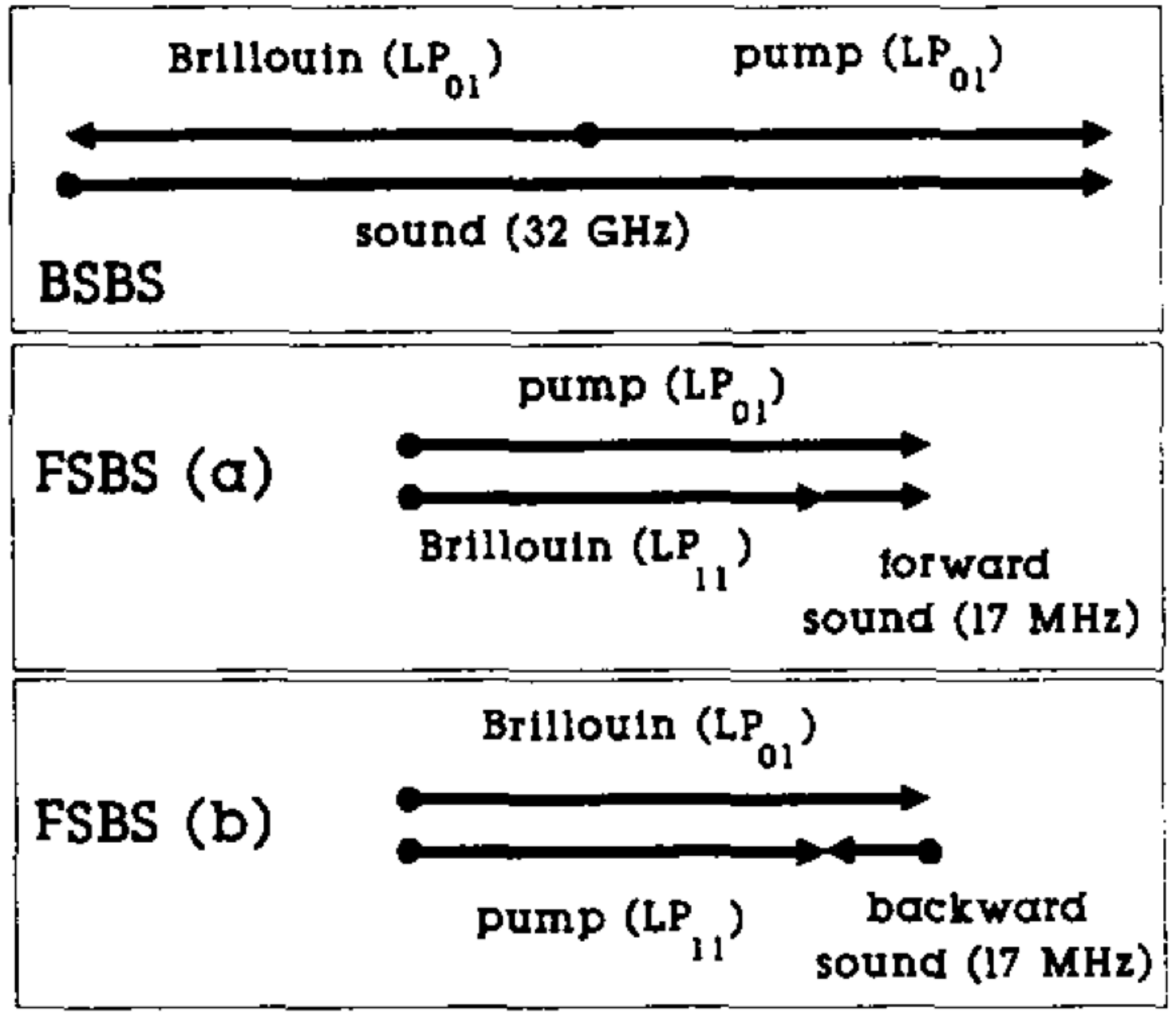
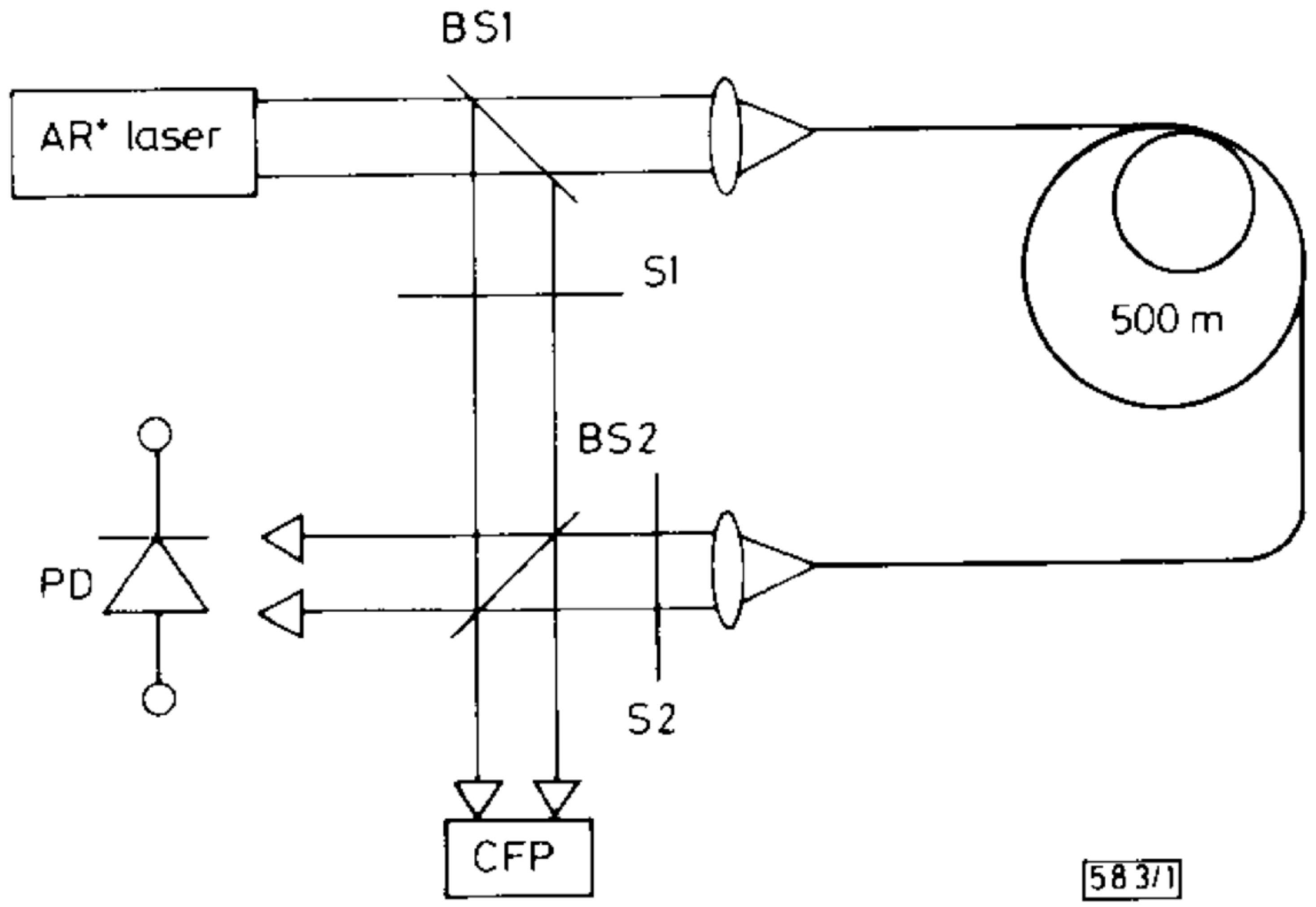
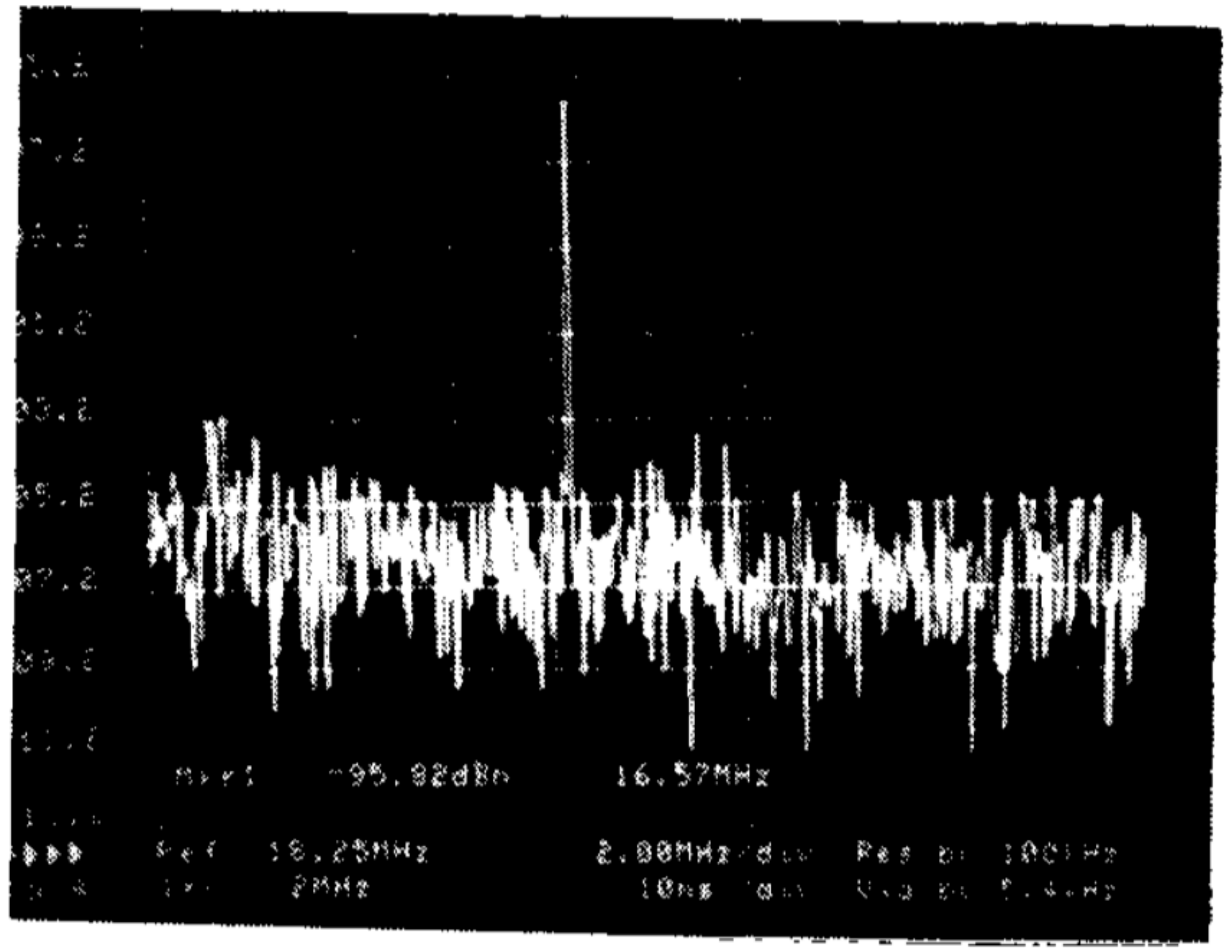
Inter-modal forward SBS









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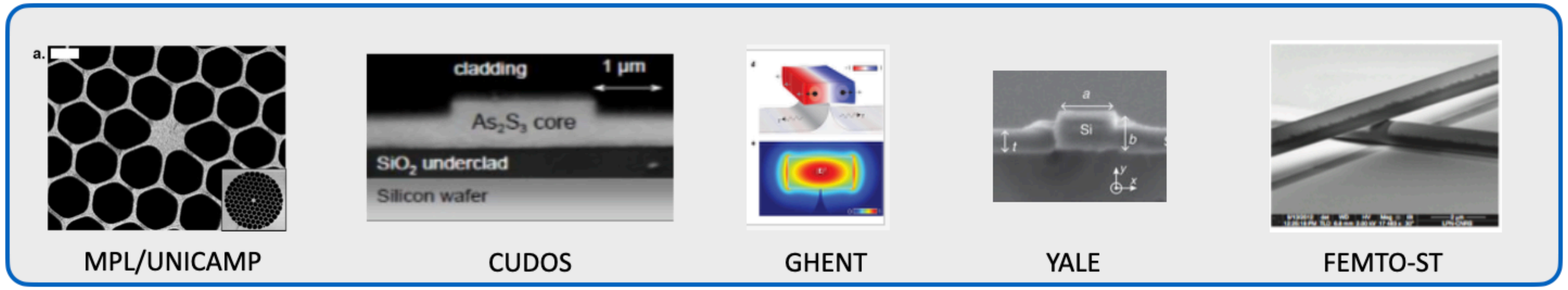
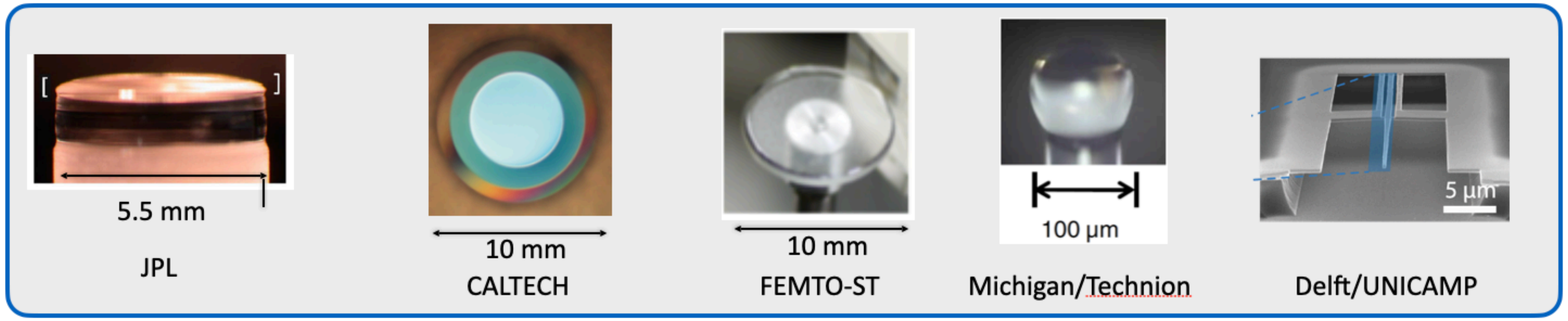
Light and sound interaction

Waveguides



Cavities



- Gyroscopes
- Sensors
- Amplifiers
- High spectral purity lasers
- RF signal processing
- Quantum states
- Quantum memories

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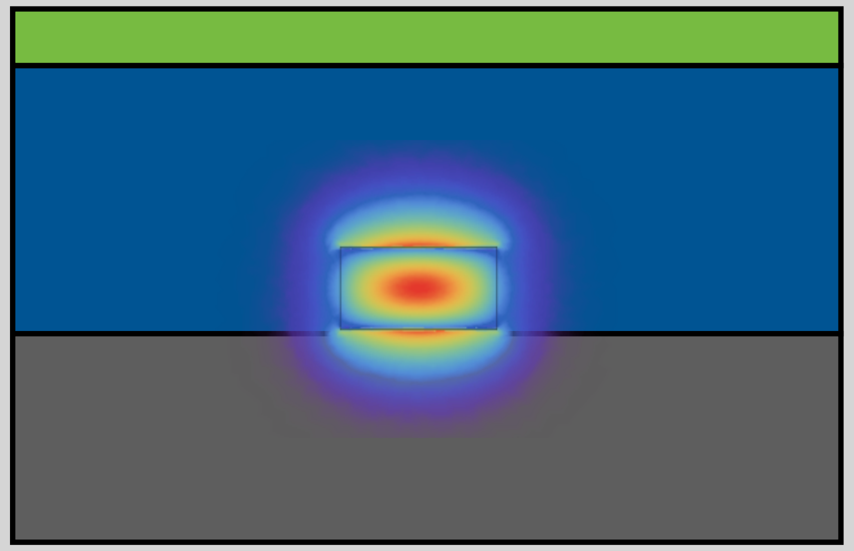
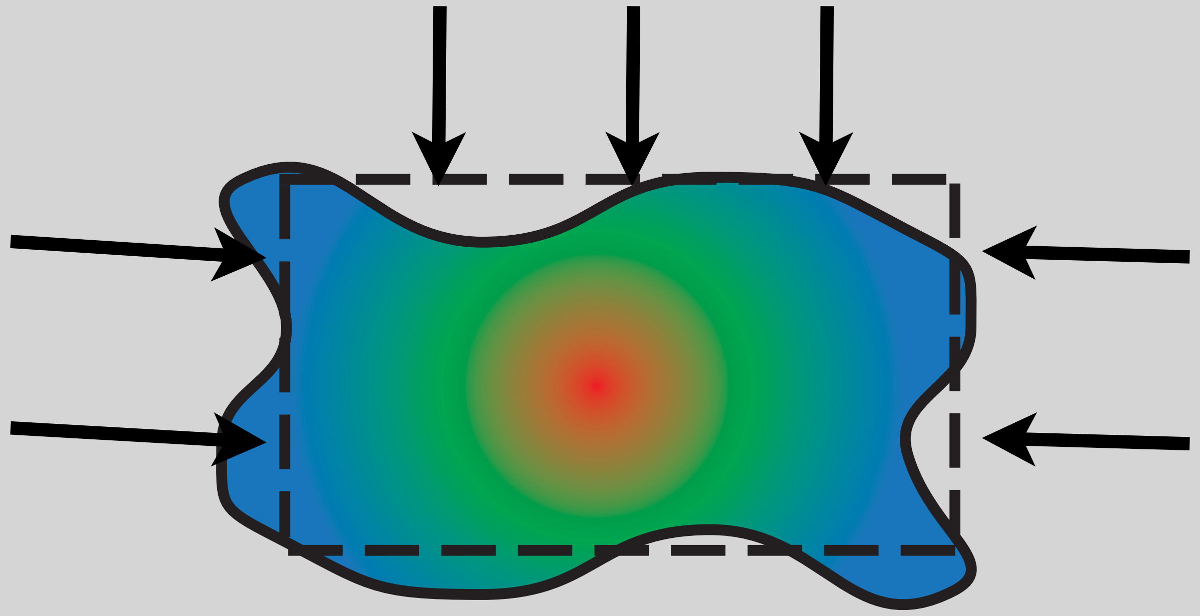
Light-sound interaction

Light perturb vibrations



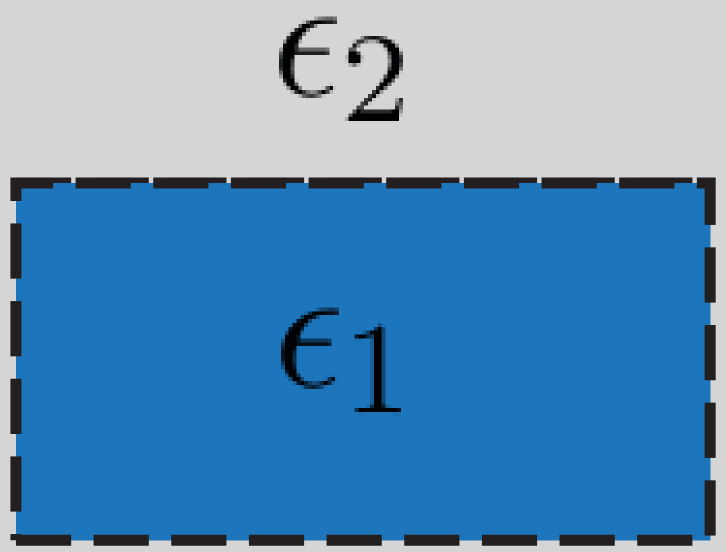
Optical intensity gradient



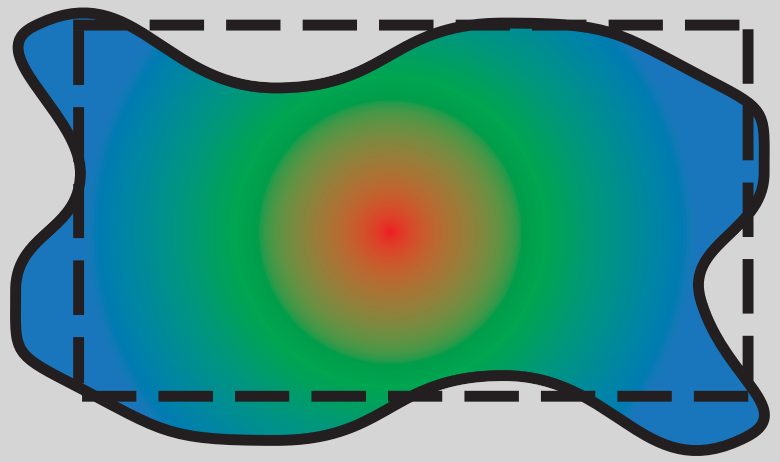
- boundary pressure
- body forces

deforms mechanical structure

Vibrations perturb light



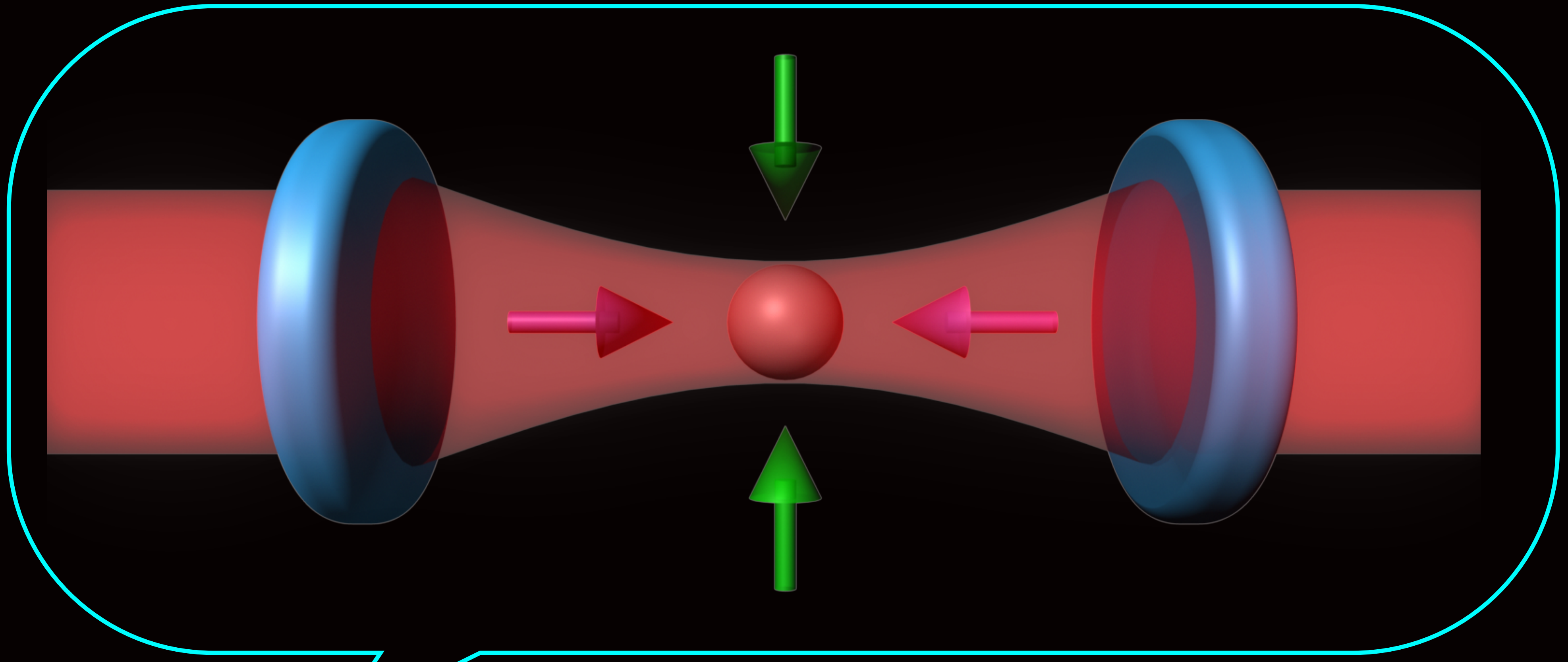
Dielectric waveguide

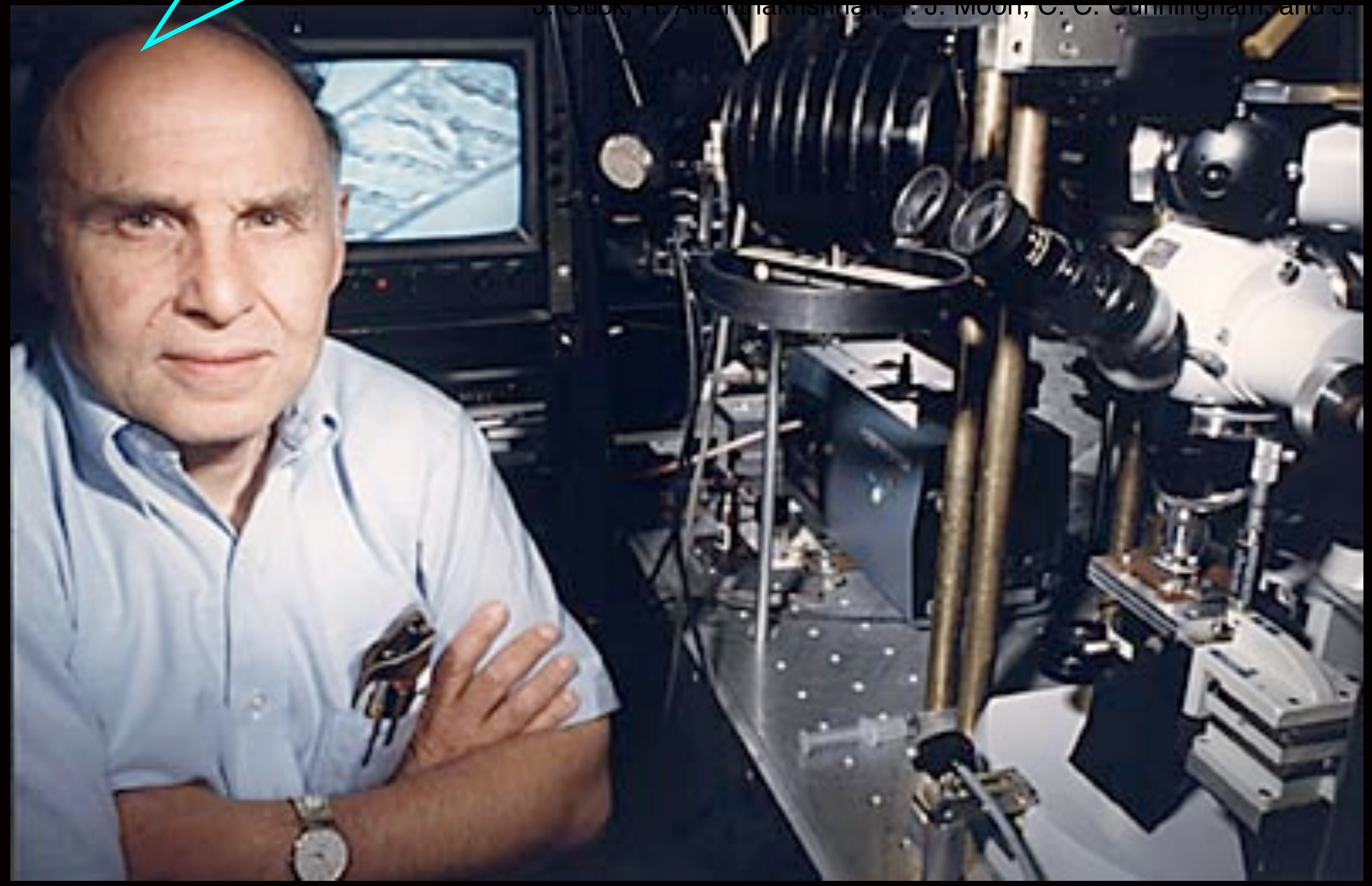


- boundary distortion
- photoelastic effect

refractive index modulation

Radiation pressure forces





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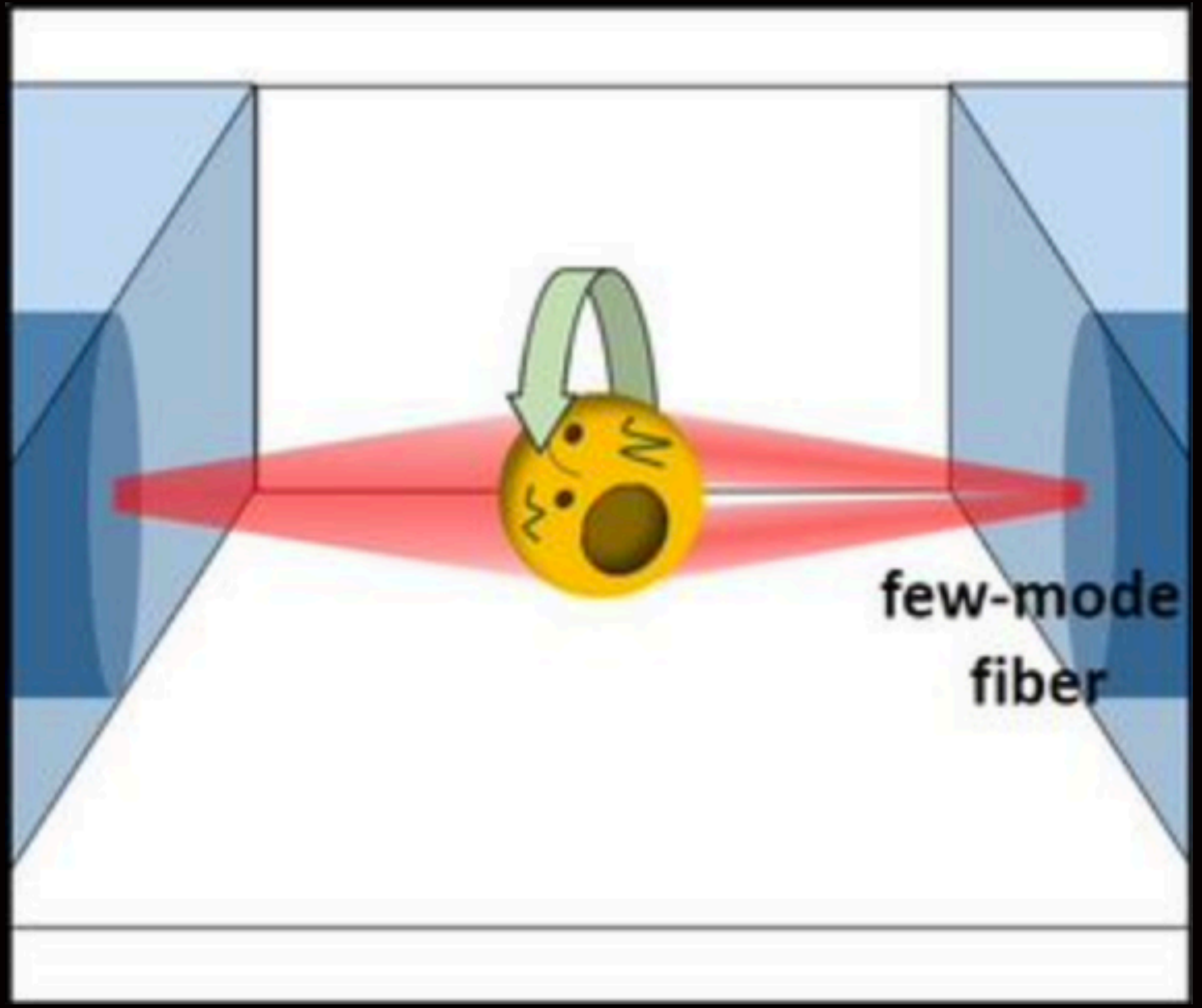

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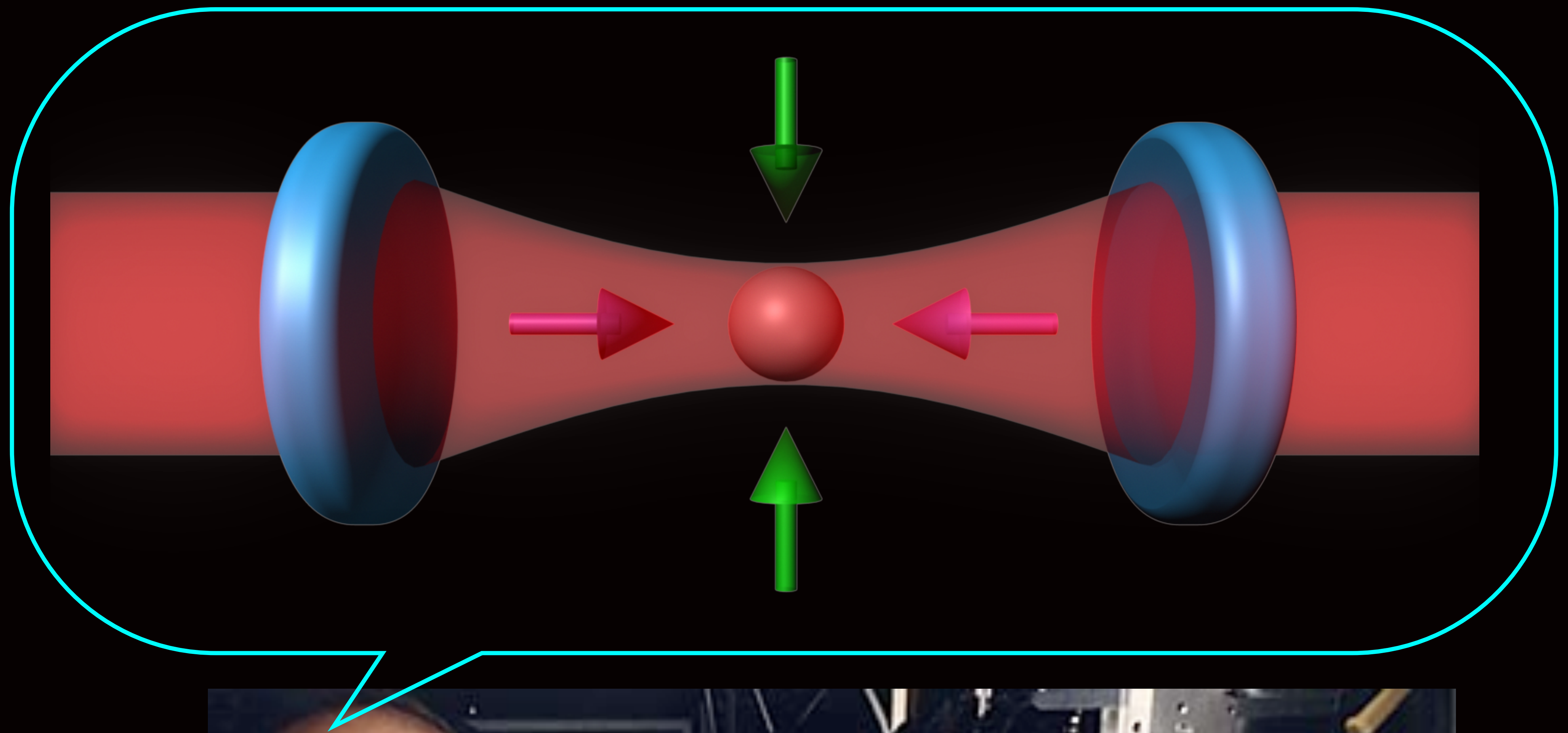
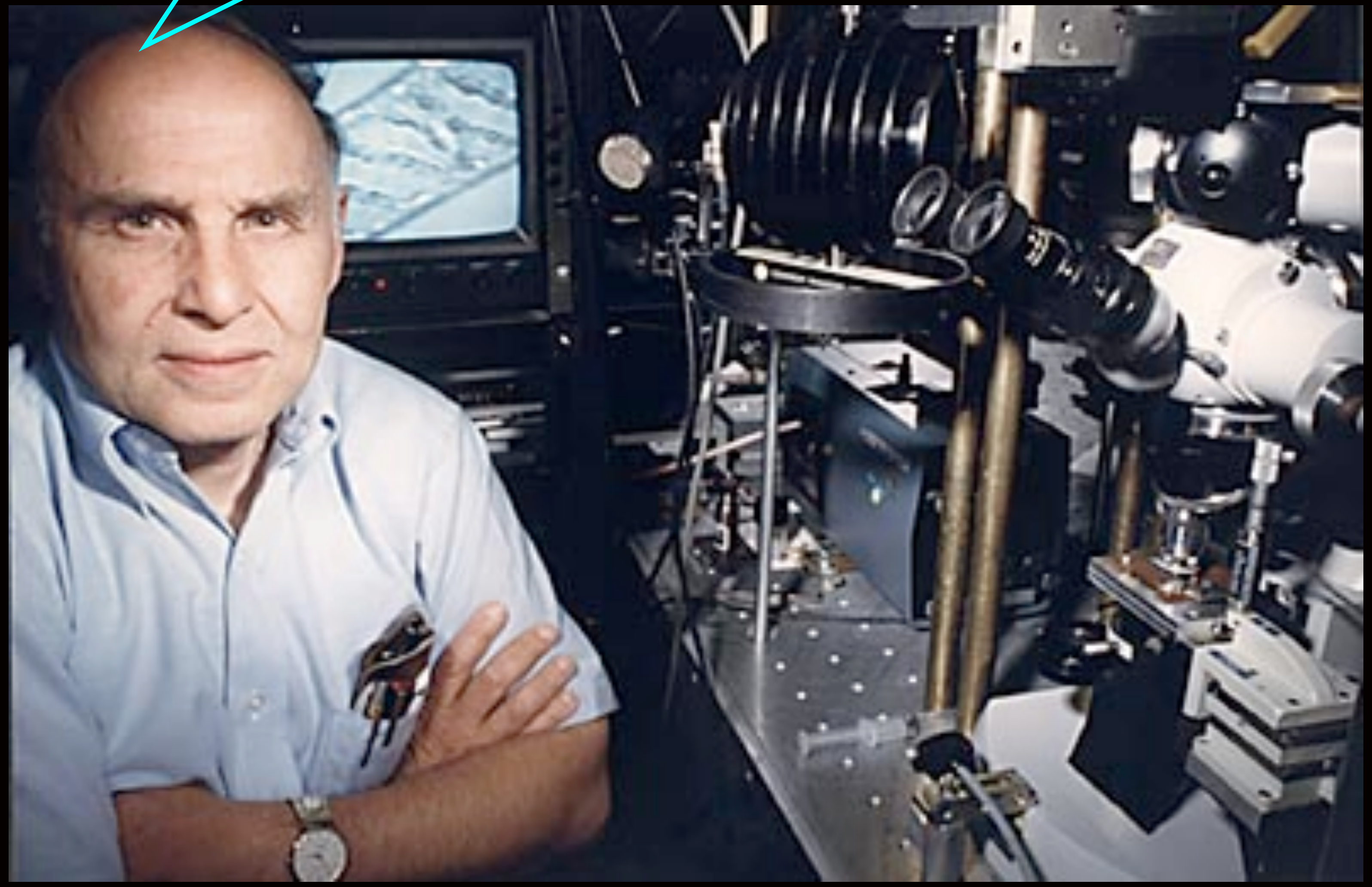
Radiation pressure forces





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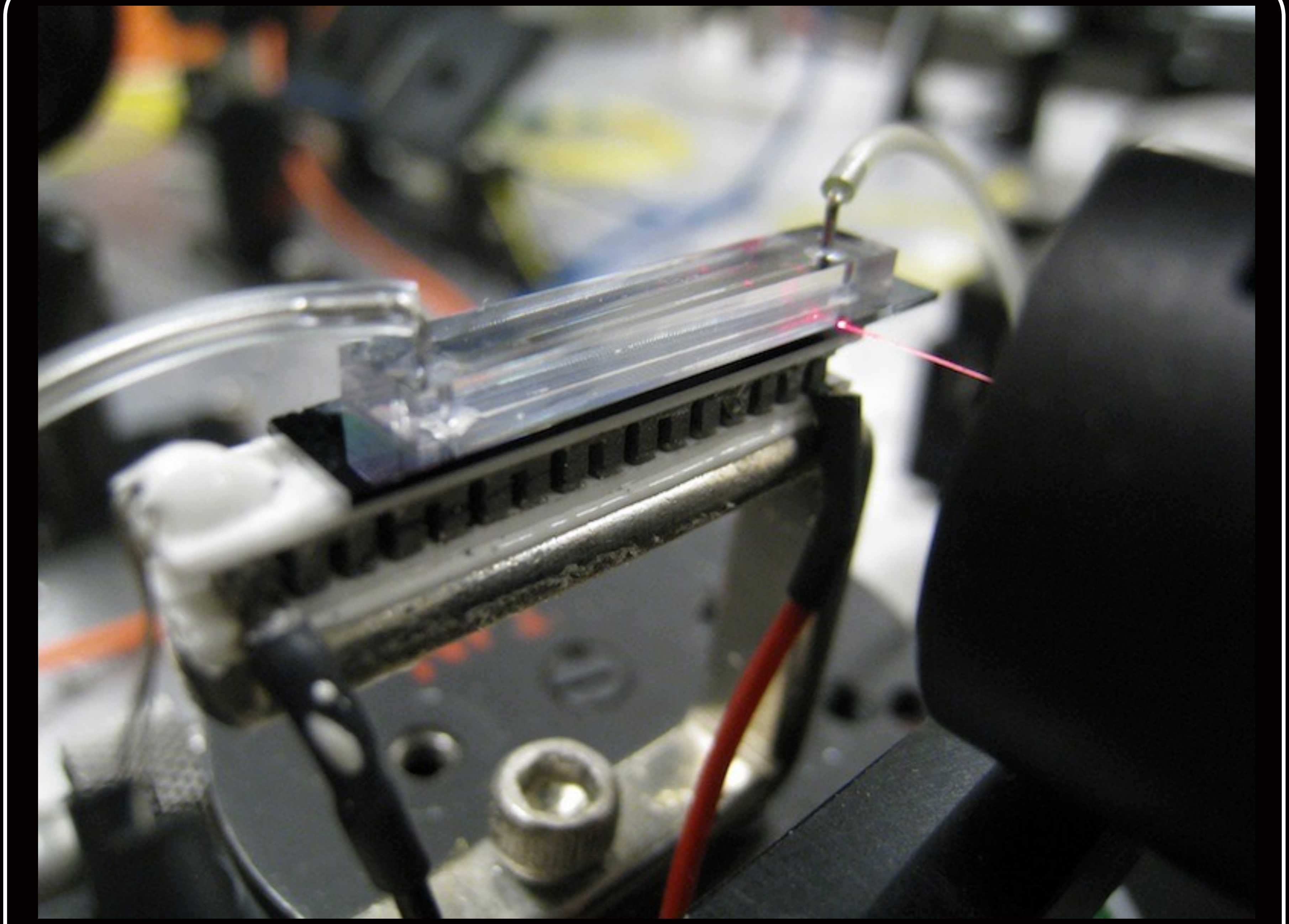
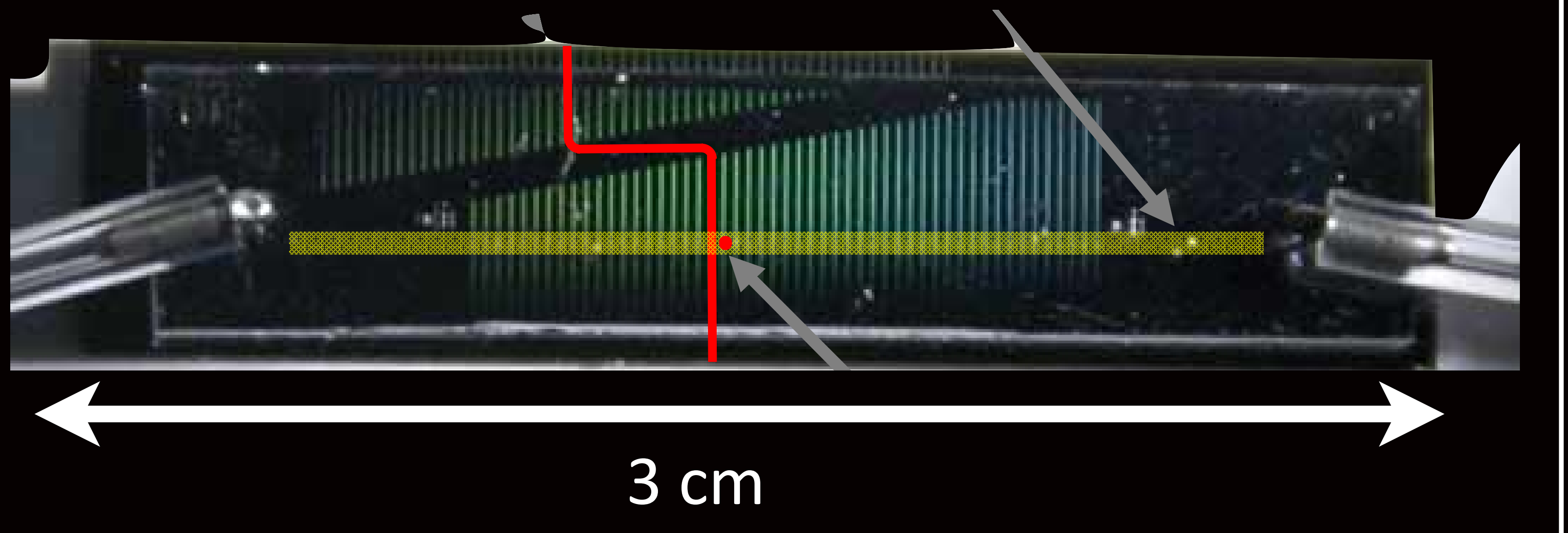
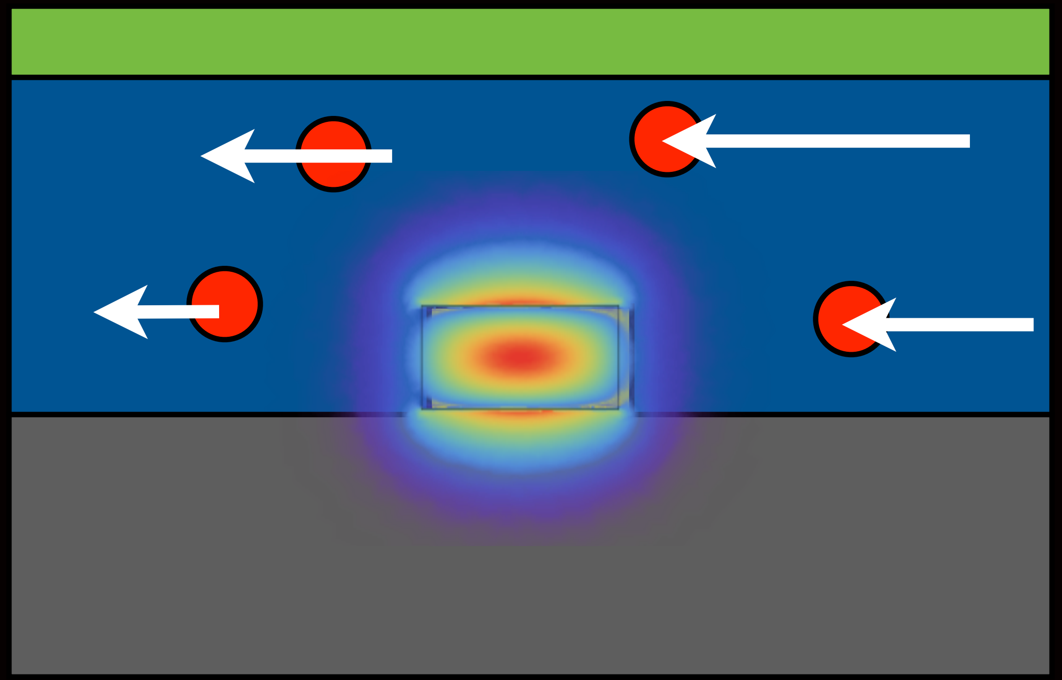


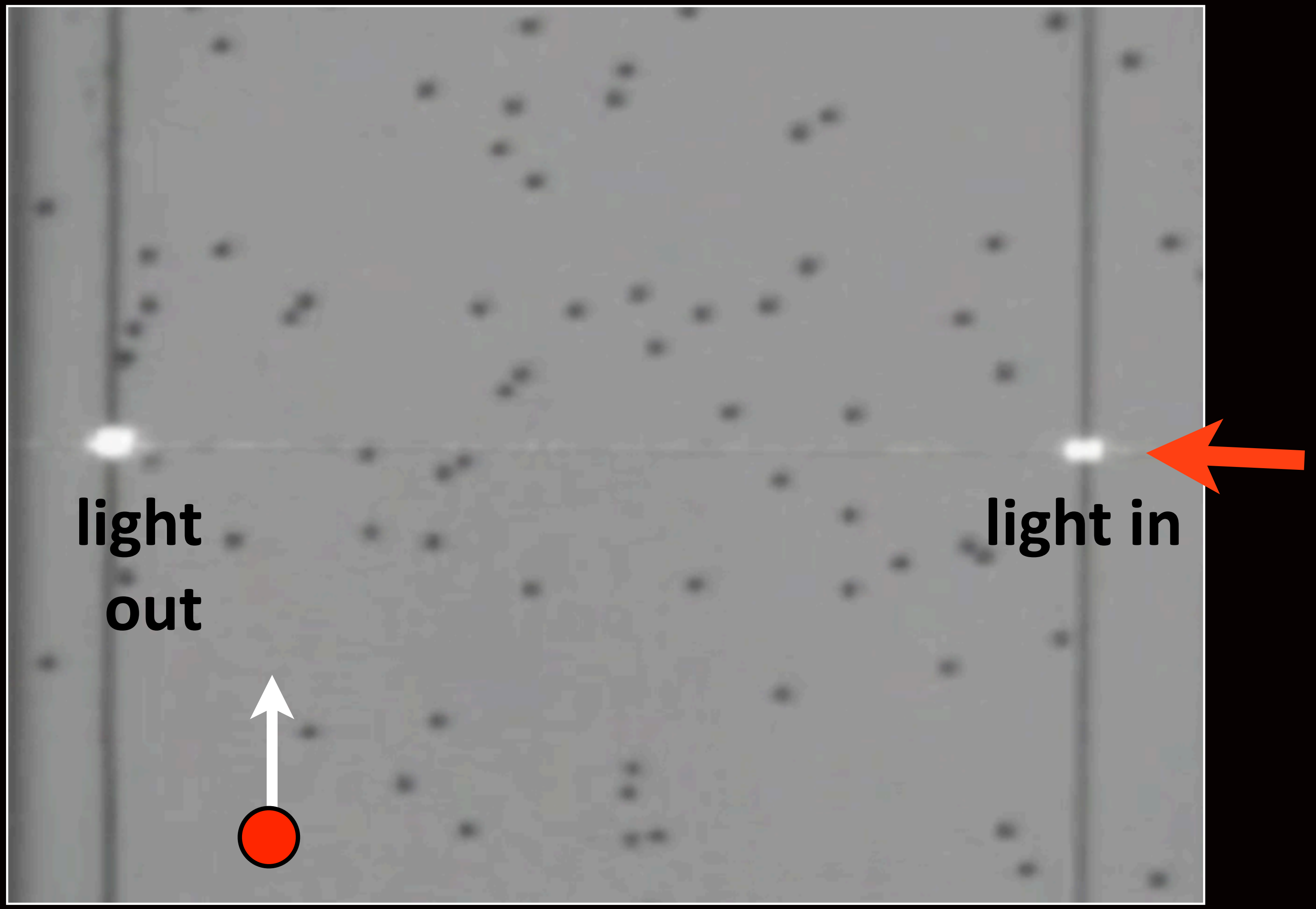


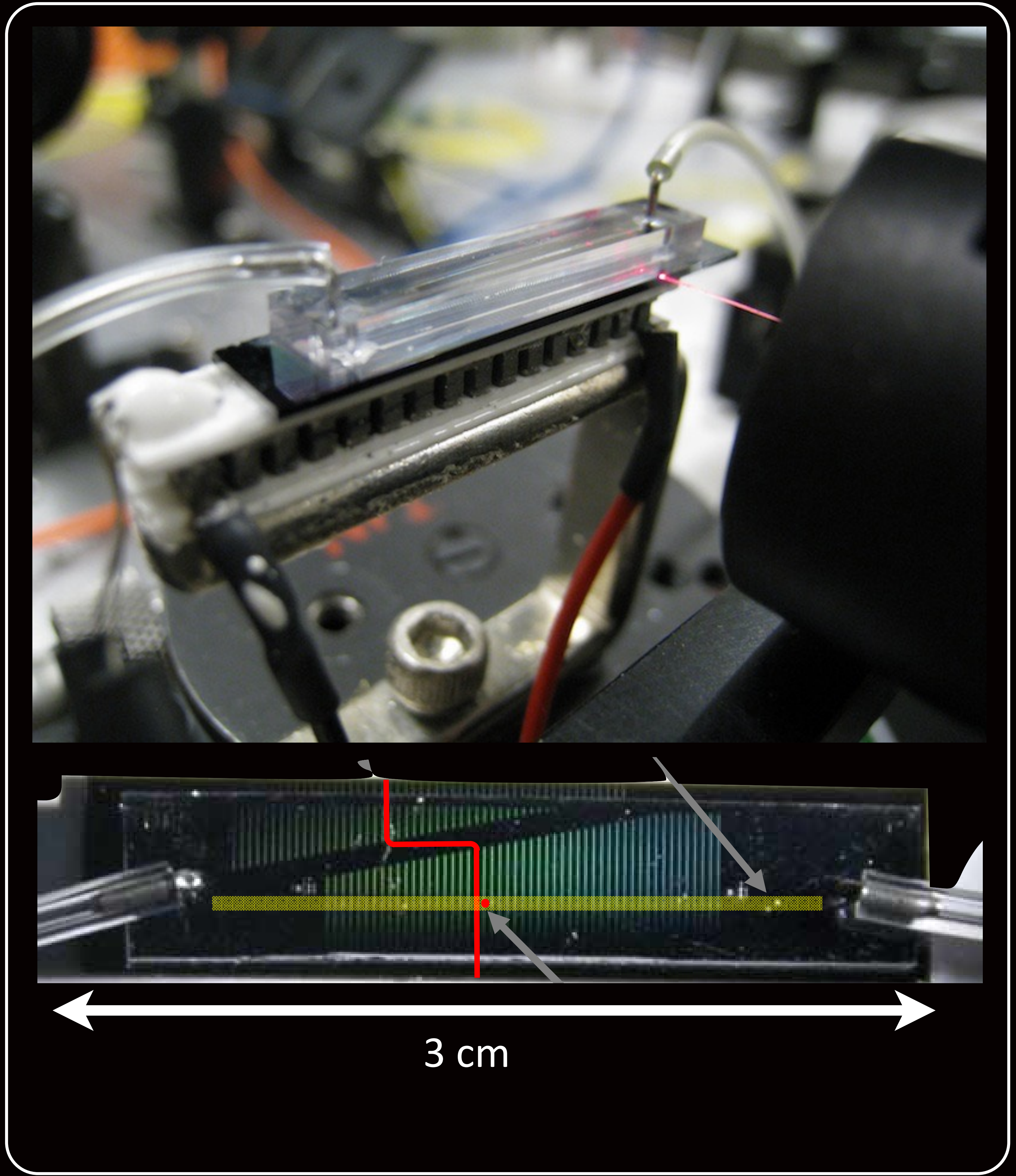
Integrated particle trapping setup

Radiation pressure forces



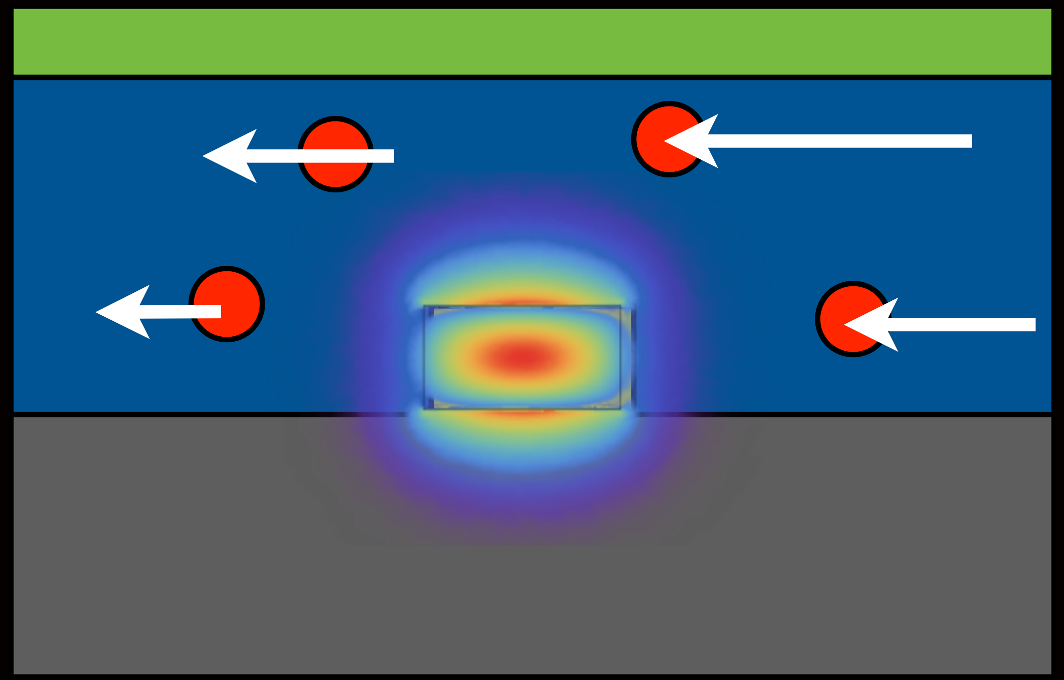
waveguide cross-section



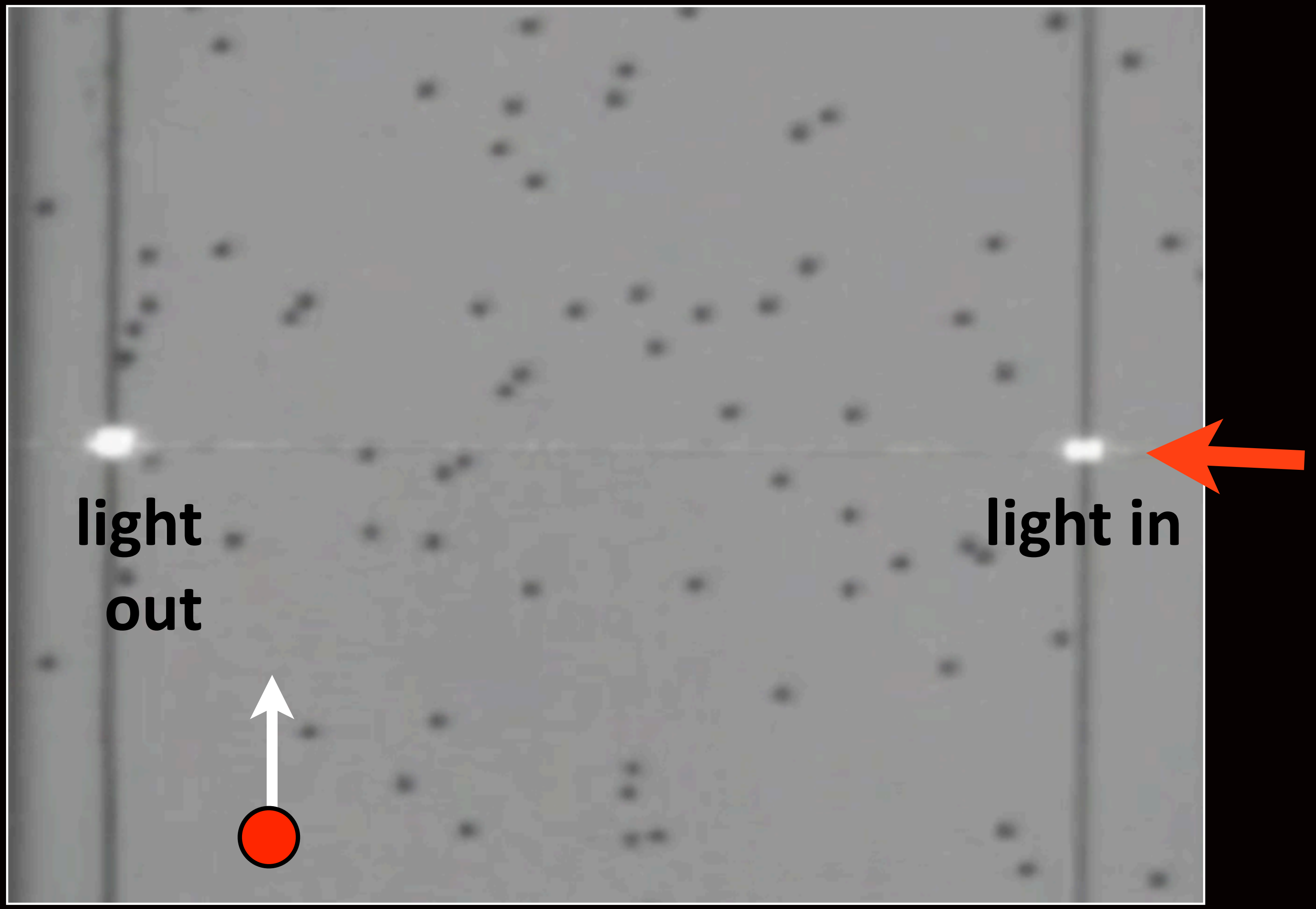


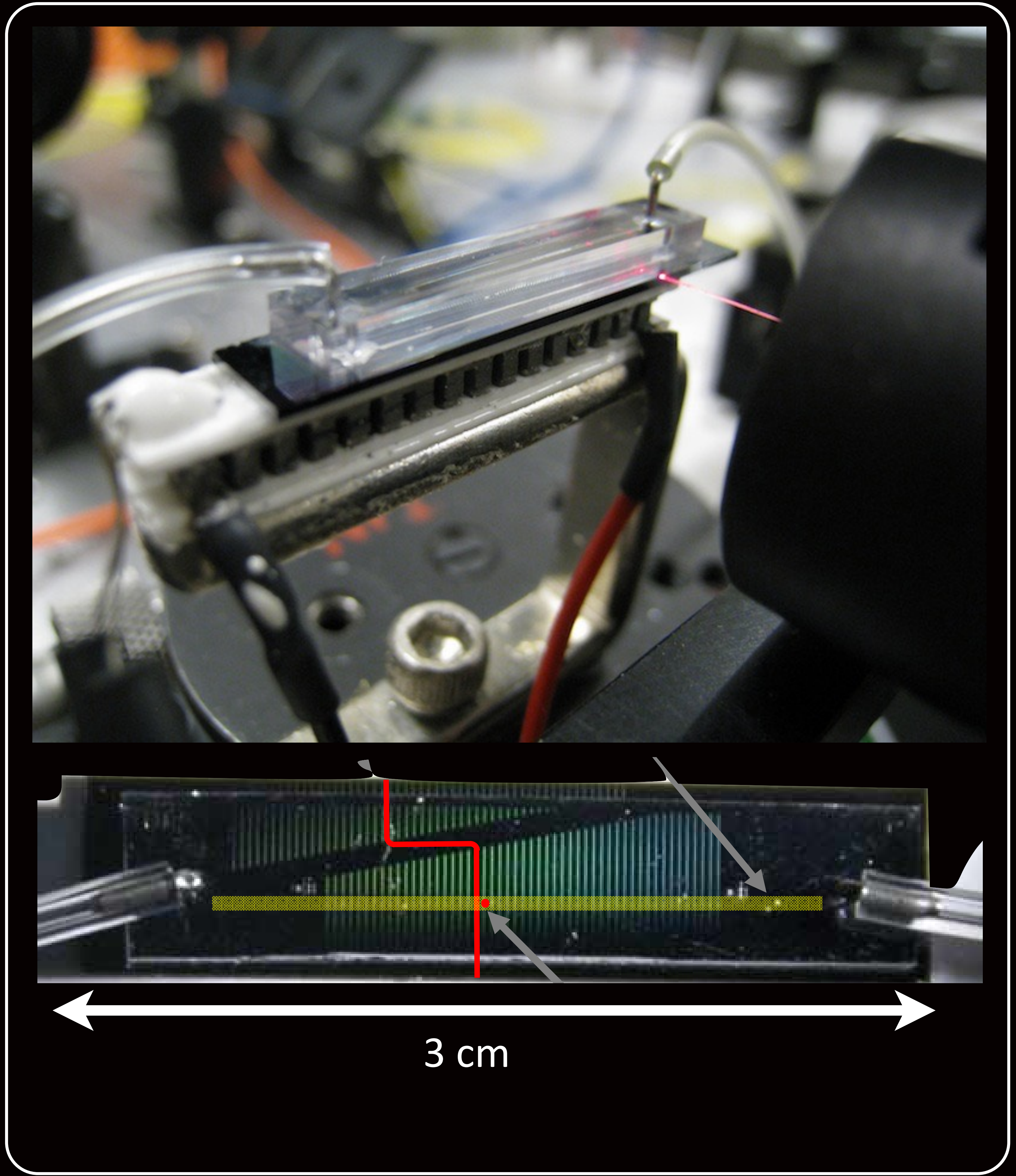
Integrated particle trapping setup

Radiation pressure forces



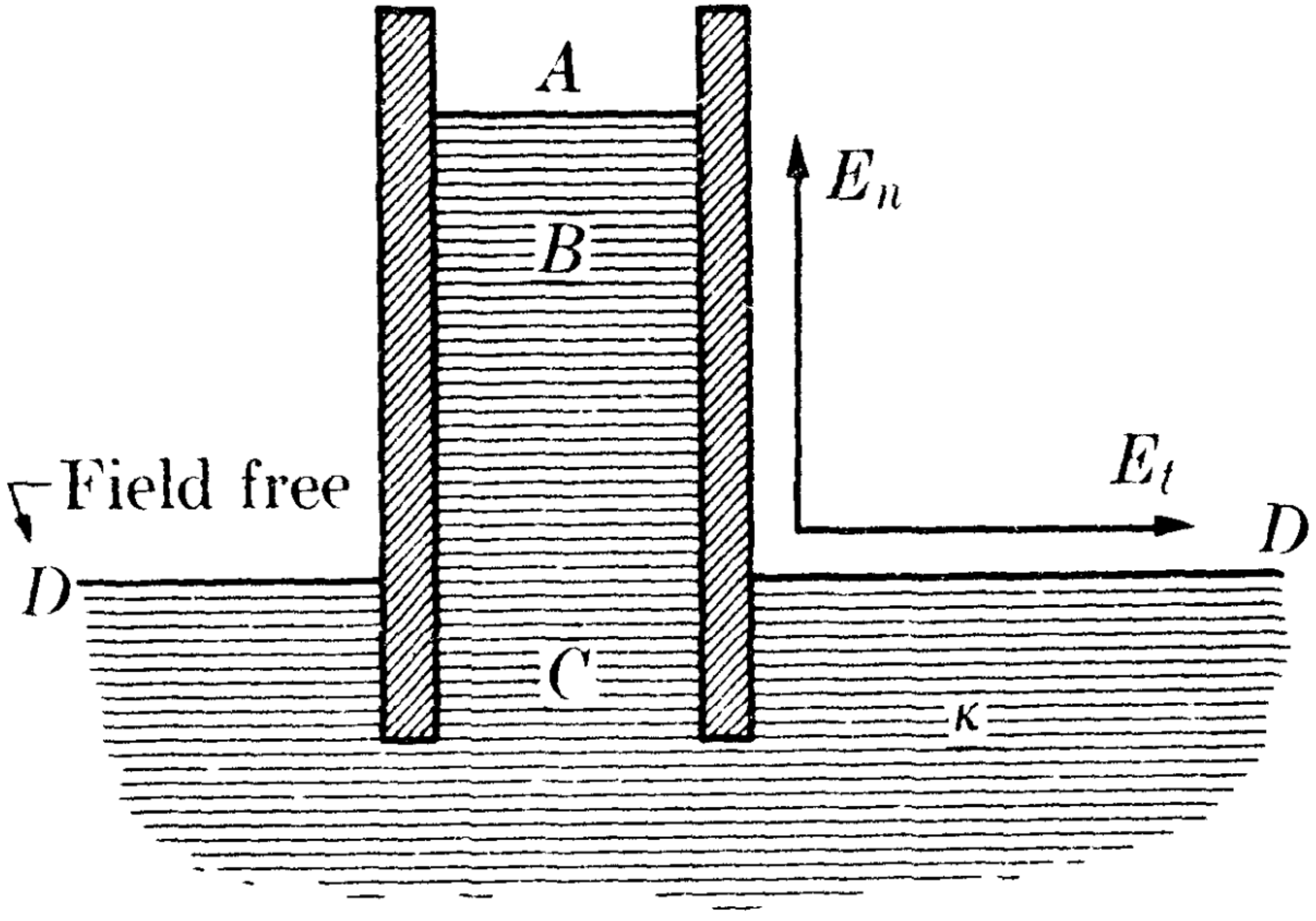
waveguide cross-section

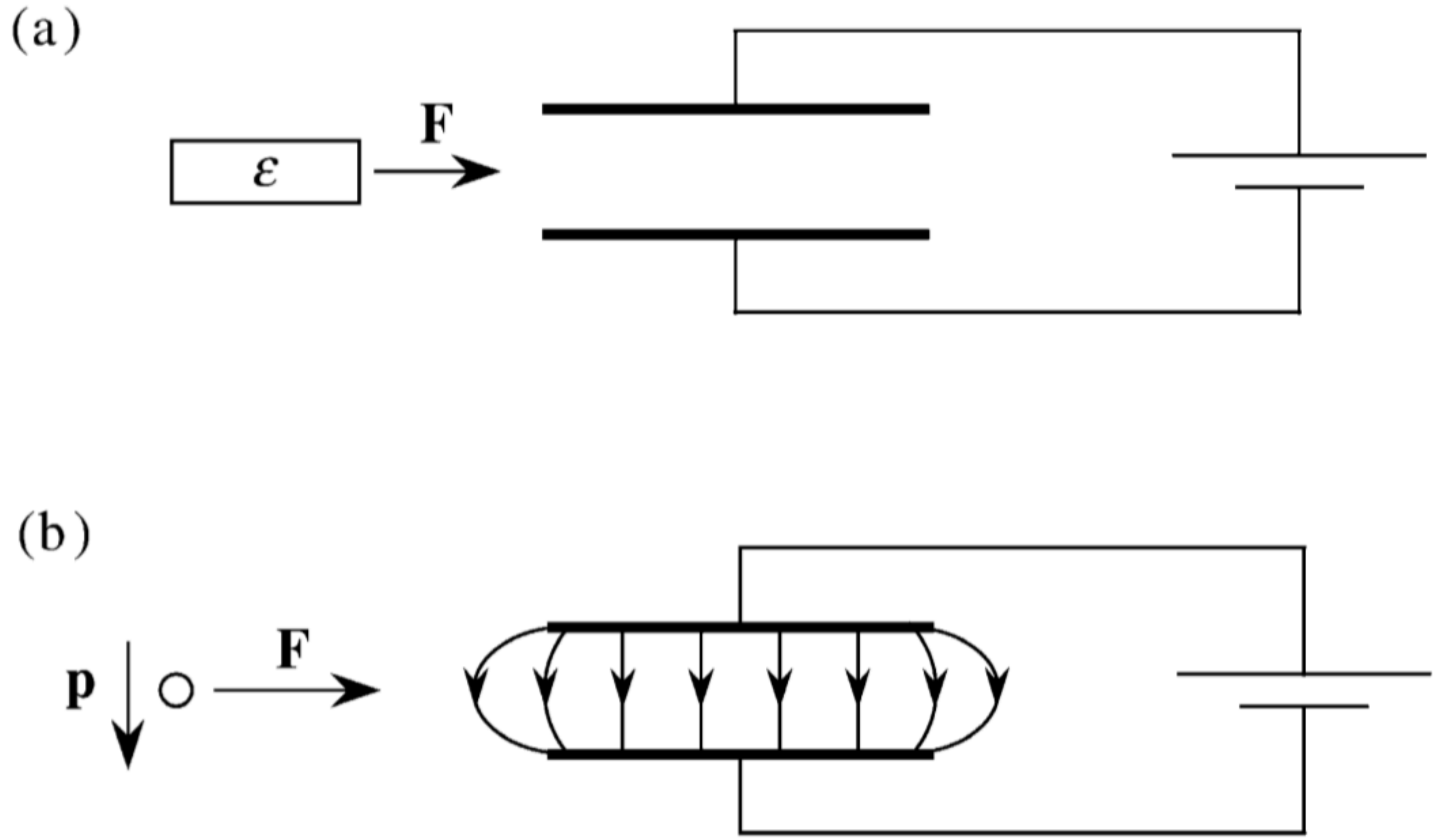




Integrated particle trapping setup

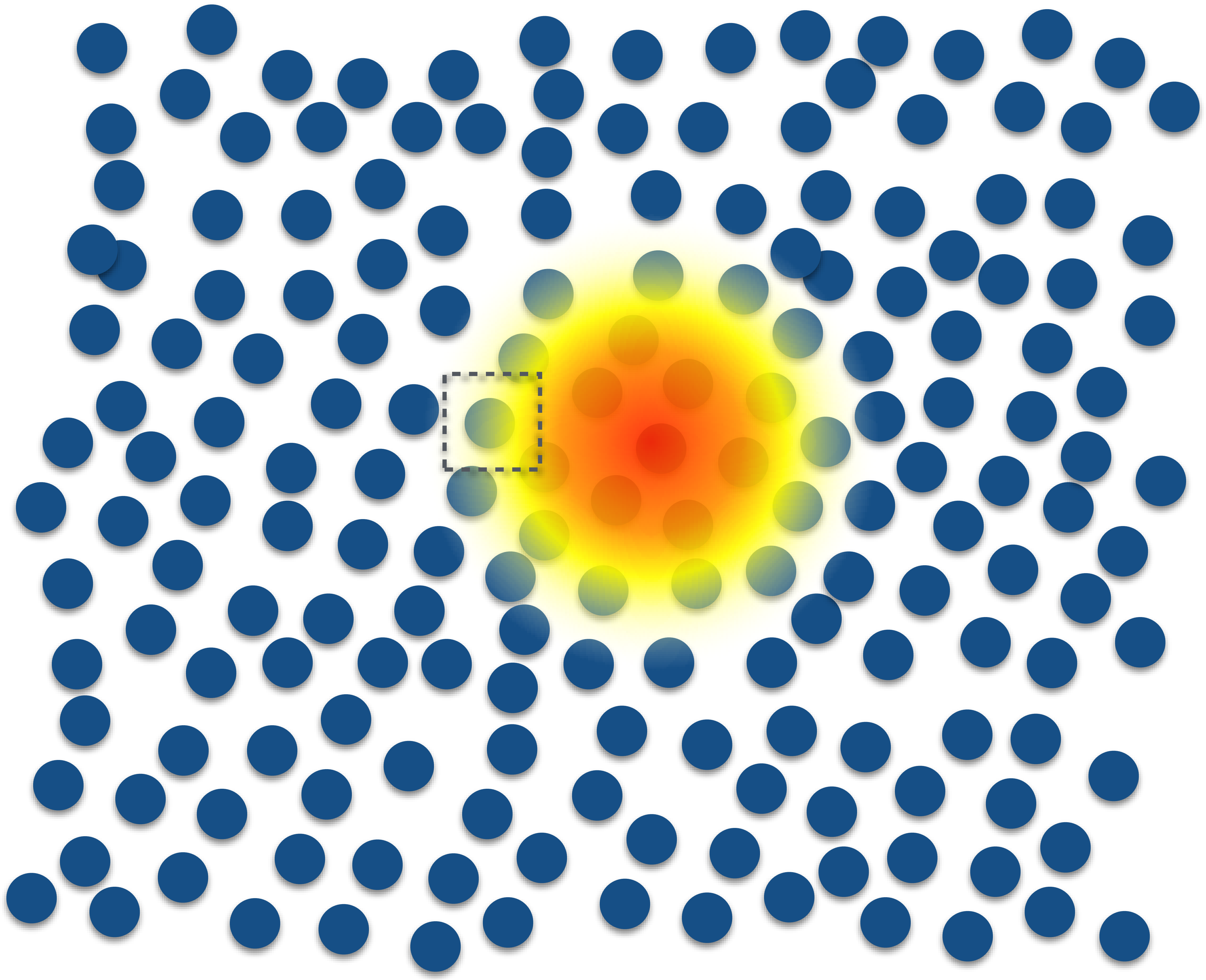
Origin of electrostriction





1. Panofsky, W. K. H. & Phillips, M. Classical Electricity and Magnetism: Second Edition. (Dover Publications, 2012) - Chapter 6 (section 6.6, 6.7)
2. Landau, L. D. et al. Electrodynamics of Continuous Media. (Elsevier Science, 2013). - Chapter 2 (Sections 11,12)
3. Boyd, R. W. . Nonlinear Optics. (Elsevier Science, 2008).

Origin of electrostriction

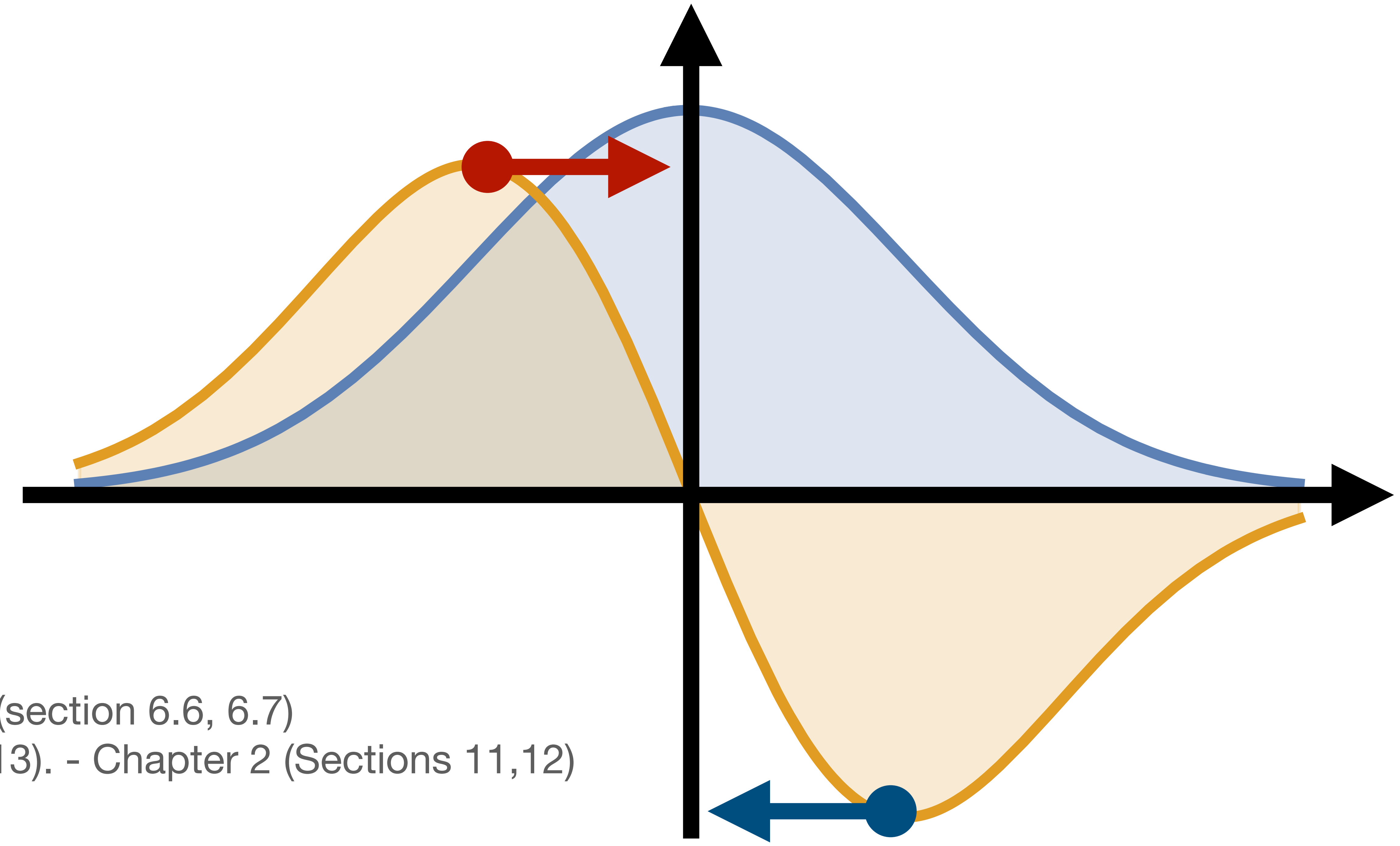


Energy stored in a single dipole

$p = \epsilon_0 \alpha E$ (α is the polarizability):

$$U = -\frac{1}{2}\epsilon_0 \alpha E^2$$

$$F = -\nabla U = \frac{1}{2}\epsilon_0 \alpha \nabla E^2$$



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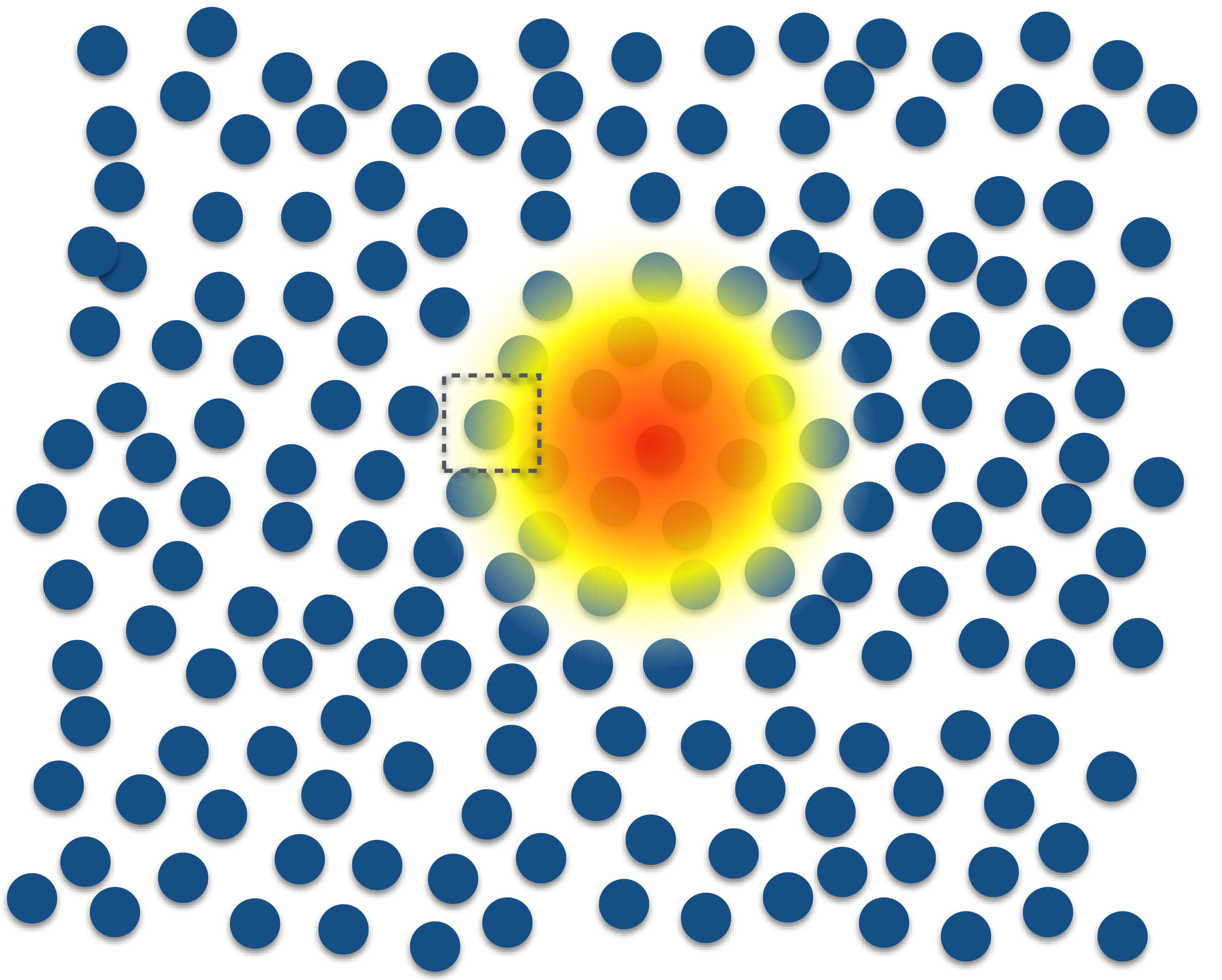
Origin of electrostriction



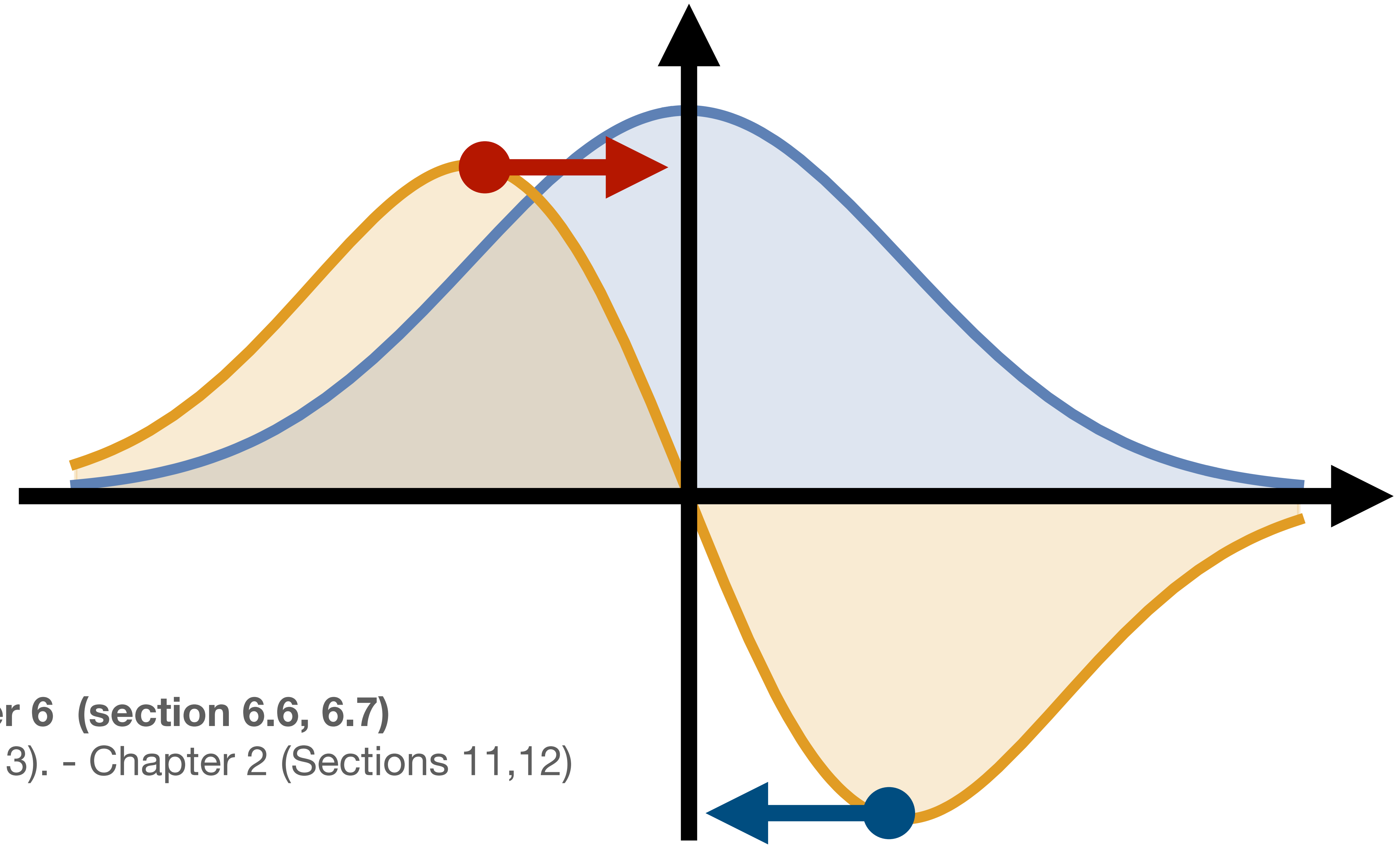
Energy stored in a single dipole $p = \epsilon_0 \alpha E$ (α is the polarizability):

$$U = -\frac{1}{2}\epsilon_0 \alpha E^2$$

$$F = -\nabla U = \frac{1}{2}\epsilon_0 \alpha \nabla E^2$$

$$\mathbf{F}_v = \rho \mathbf{E} \boxed{-\frac{\epsilon_0}{2} E^2 \nabla \kappa} + \boxed{\frac{\epsilon_0}{2} \nabla \left(E^2 \frac{d\kappa}{d\rho_m} \rho_m \right)}$$

Radiation pressure — Electrostriction



1. **Panofsky, W. K. H. & Phillips, M. Classical Electricity and Magnetism: Chapter 6 (section 6.6, 6.7)**
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Outline

- Introduction to Brillouin Scattering
- Mechanical modes
- Optical modes
- Harnessing Brillouin interaction
- Optomechanical cavities
- Final remarks

Mechanical modes

$$\frac{\partial}{\partial r_j} \boxed{T_{ij}(\boldsymbol{r}, t)} = \boxed{\rho_0(\boldsymbol{r}) \frac{\partial^2 U_i}{\partial t^2}} - \boxed{f_i(\boldsymbol{r}, t)}$$

Stress tensor acceleration External force

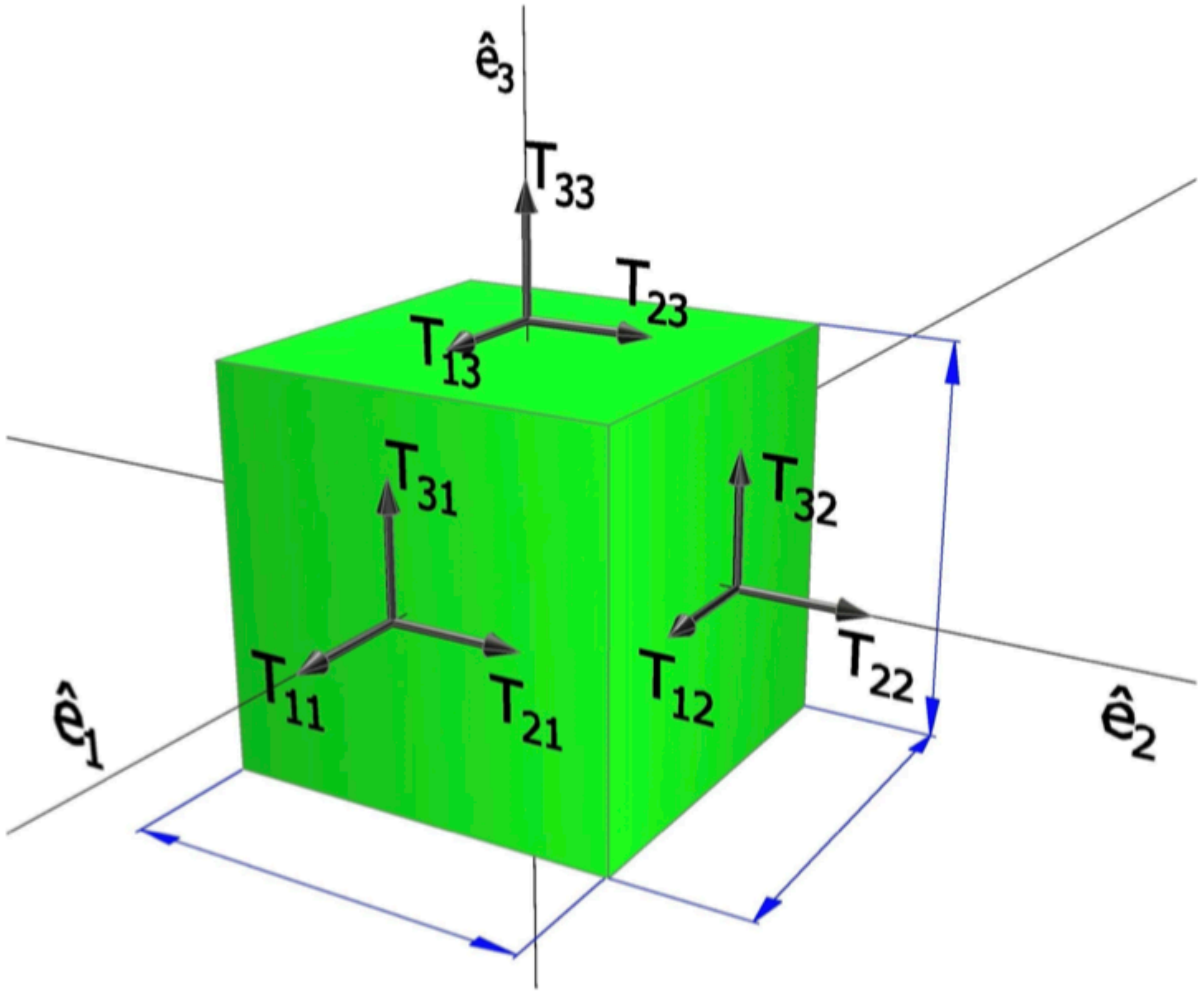
Mechanical modes

$$\frac{\partial}{\partial r_j}\boxed{T_{ij}(\boldsymbol{r},t)} = \boxed{\rho_0(\boldsymbol{r})\frac{\partial^2 U_i}{\partial t^2}} - \boxed{f_i(\boldsymbol{r},t)}$$

Stress tensor acceleration External force

$$T_{ij} = \boxed{c_{ijkl}S_{kl}} + \boxed{\eta_{ijkl}\frac{\partial S_{kl}}{\partial t}}$$

Stiffness (Hooke's law) Friction

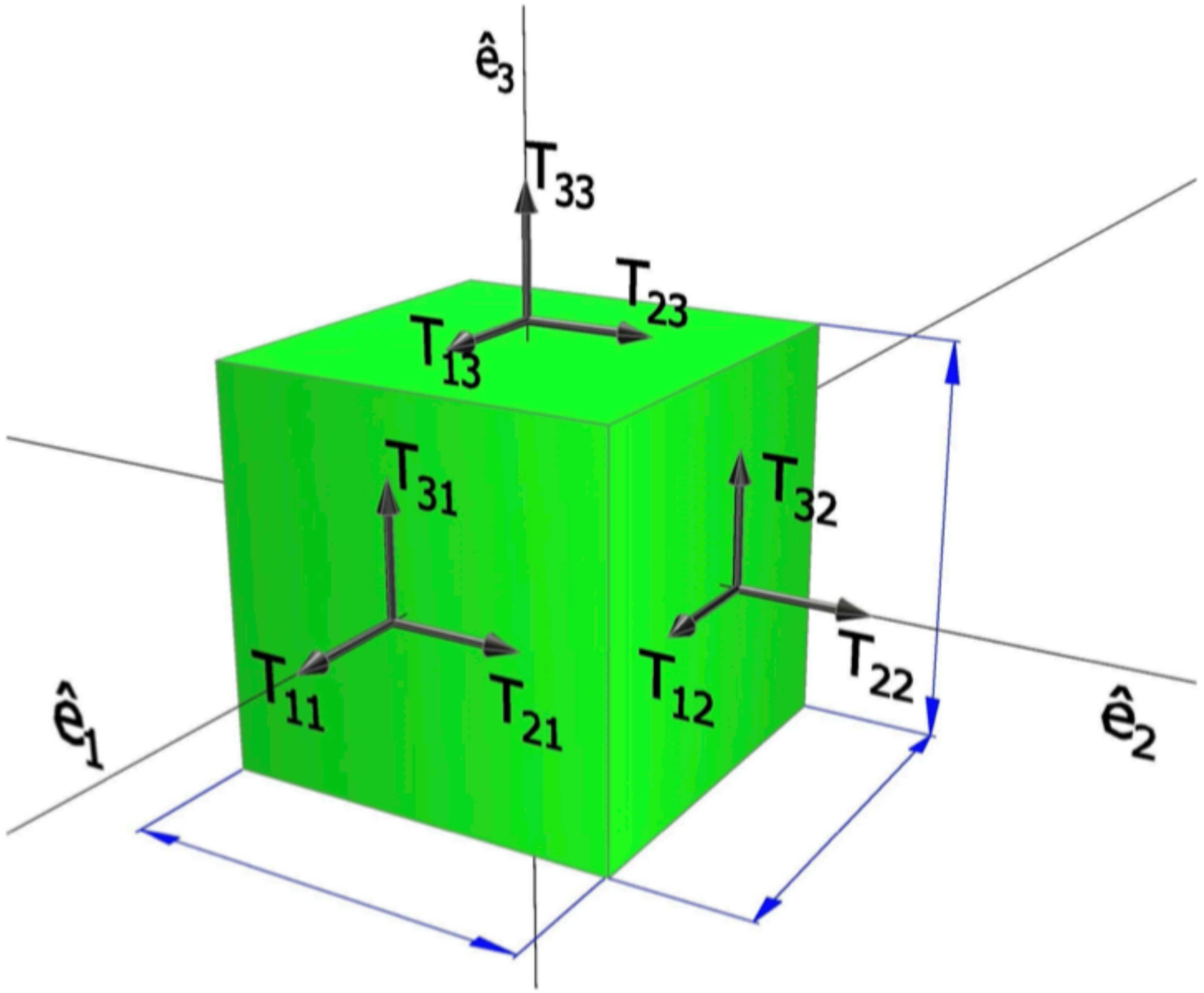


Mechanical modes

$$\frac{\partial}{\partial r_j}\underbrace{T_{ij}(\boldsymbol{r},t)}_{\text{Stress tensor}} = \underbrace{\rho_0(\boldsymbol{r})\frac{\partial^2 U_i}{\partial t^2}}_{\text{acceleration}} - \underbrace{f_i(\boldsymbol{r},t)}_{\text{External force}}$$

$$T_{ij} = \underbrace{c_{ijkl}S_{kl}}_{\text{Stiffness (Hooke's law)}} + \underbrace{\eta_{ijkl}\frac{\partial S_{kl}}{\partial t}}_{\text{Friction}}$$

$$S_{ij} = \frac{1}{2}\underbrace{\left(\frac{\partial U_i}{\partial r_j} + \frac{\partial U_j}{\partial r_i}\right)}_{\text{Strain Tensor}}$$



$$\underbrace{\left[(\lambda+2\mu)+\eta_{11}\frac{\partial}{\partial t}\right]\nabla(\nabla\cdot\boldsymbol{U})}_{\text{longitudinal waves } (\nabla\times\mathbf{u}=0)} - \underbrace{\left[\mu+\eta_{44}\frac{\partial}{\partial t}\right]\nabla\times\nabla\times\boldsymbol{U}}_{\text{shear-only } (\nabla\cdot\mathbf{u}=0)} = \rho\frac{\partial^2\boldsymbol{U}}{\partial t^2}$$

Elastic wave equation

Mechanical modes

$$\frac{\partial}{\partial r_j}\boxed{T_{ij}(\boldsymbol{r},t)} = \boxed{\rho_0(\boldsymbol{r})\frac{\partial^2 U_i}{\partial t^2}} - \boxed{f_i(\boldsymbol{r},t)}$$

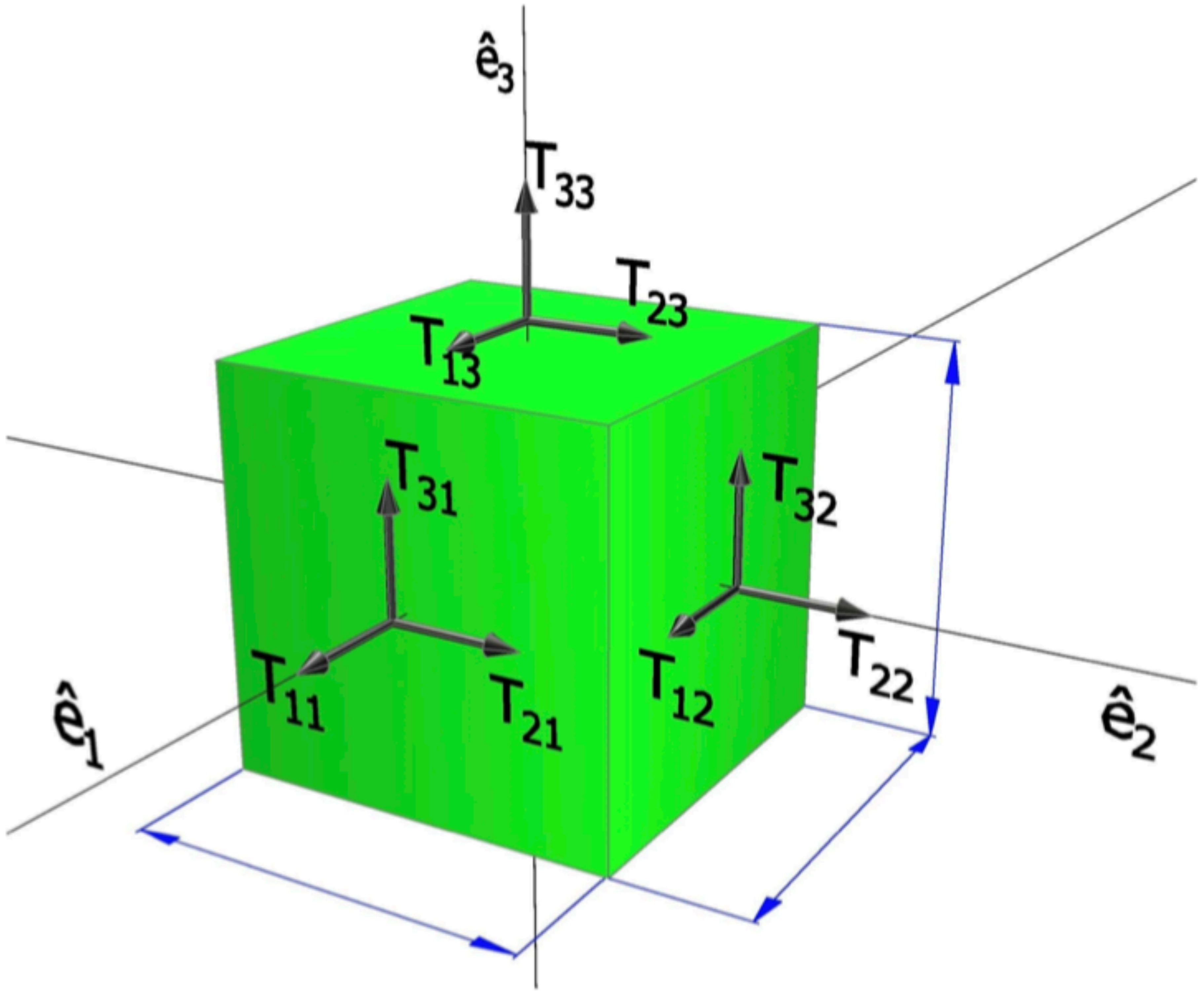
Stress tensor — acceleration — External force

$$T_{ij} = \boxed{c_{ijkl}S_{kl}} + \boxed{\eta_{ijkl}\frac{\partial S_{kl}}{\partial t}}$$

Stiffness (Hooke's law) — Friction

$$S_{ij} = \frac{1}{2}\boxed{\left(\frac{\partial U_i}{\partial r_j} + \frac{\partial U_j}{\partial r_i}\right)}$$

Strain Tensor



$$\boxed{\left[(\lambda+2\mu)+\eta_{11}\frac{\partial}{\partial t}\right]\nabla(\nabla\cdot\boldsymbol{U})} - \boxed{\left[\mu+\eta_{44}\frac{\partial}{\partial t}\right]\nabla\times\nabla\times\boldsymbol{U}} = \rho\frac{\partial^2\boldsymbol{U}}{\partial t^2}$$

longitudinal waves ($\nabla\times\mathbf{u}=0$) — shear-only ($\nabla\cdot\mathbf{u}=0$)

Elastic wave equation

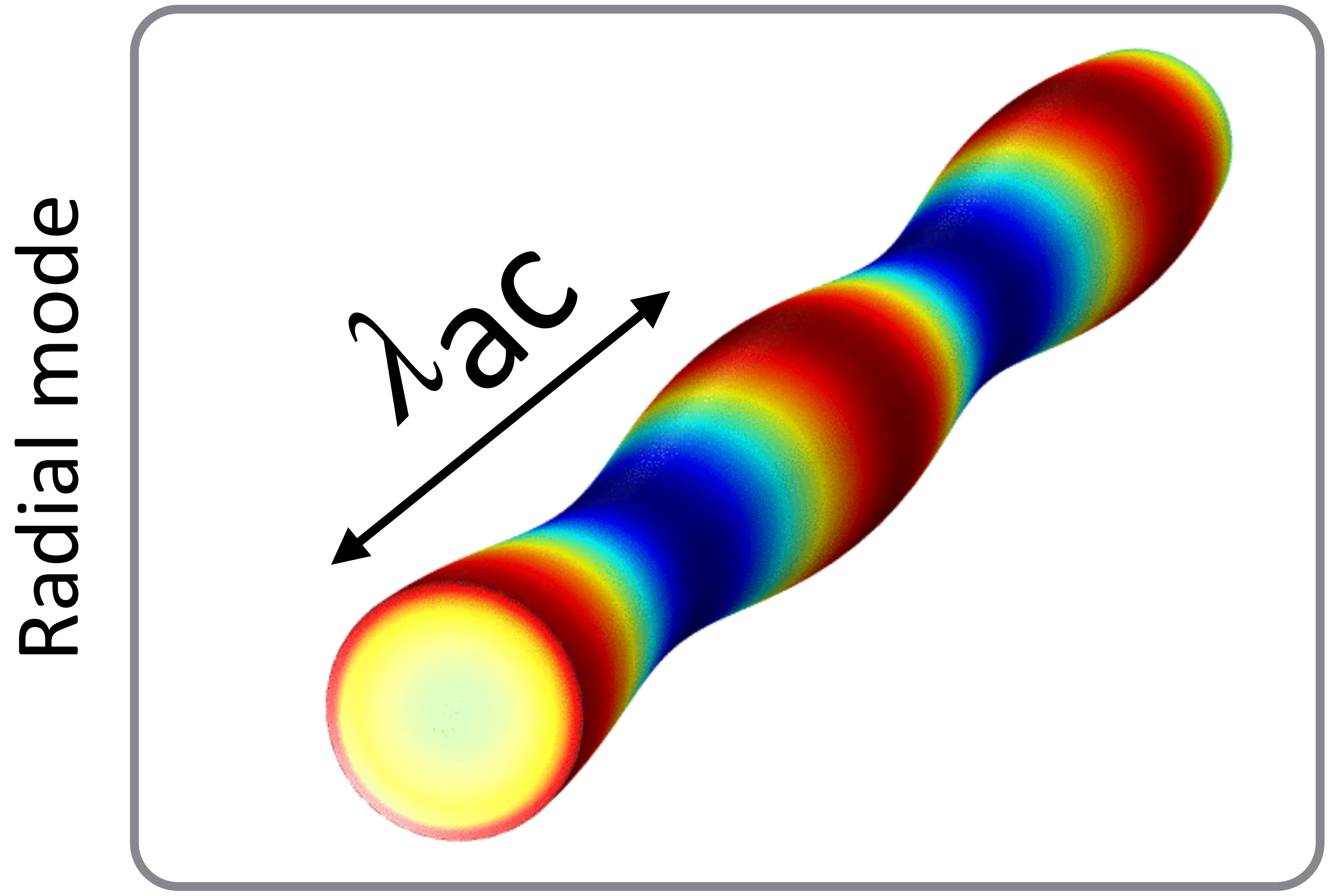
$$\begin{aligned}\boldsymbol{U}(\boldsymbol{r},t) &= \tilde{\boldsymbol{u}}^{(n)}(\boldsymbol{r})e^{-\mathrm{i}\Omega_n t} + \mathbf{c.c.}\\ &= \boldsymbol{u}^{(n)}(x,y)e^{\mathrm{i}[q_n z-\Omega_n t]} + \mathbf{c.c.}\end{aligned}$$

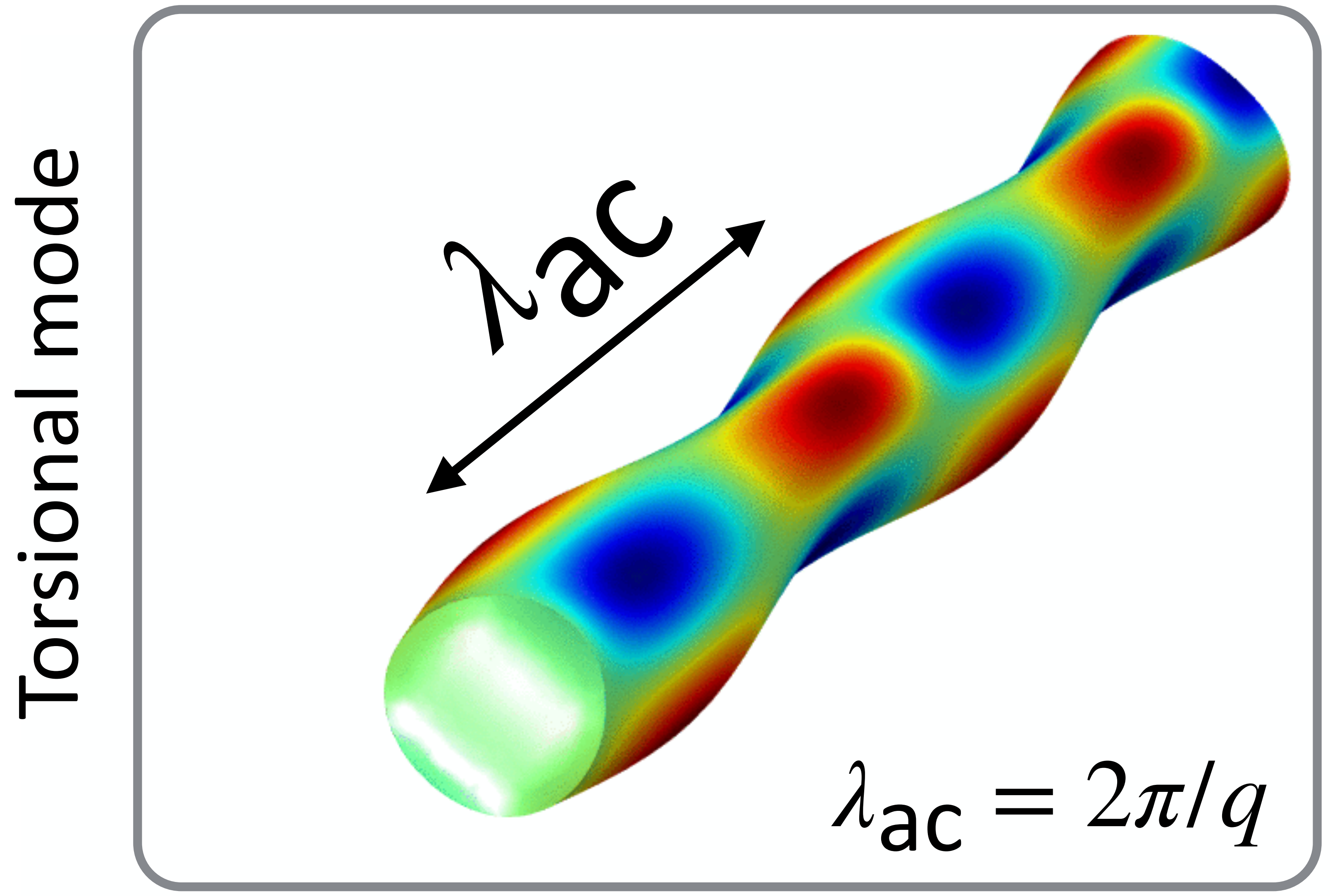
Waveguide mode ansatz

Mechanical modes

$$\underbrace{\left[(\lambda + 2\mu) + \eta_{11}\frac{\partial}{\partial t}\right]\nabla(\nabla \cdot \boldsymbol{U})}_{\text{longitudinal waves } (\nabla \times \mathbf{u} = 0)} - \underbrace{\left[\mu + \eta_{44}\frac{\partial}{\partial t}\right]\nabla \times \nabla \times \boldsymbol{U}}_{\text{shear-only } (\nabla \cdot \mathbf{u} = 0)} = \rho\frac{\partial^2 \boldsymbol{U}}{\partial t^2}$$

Elastic wave equation



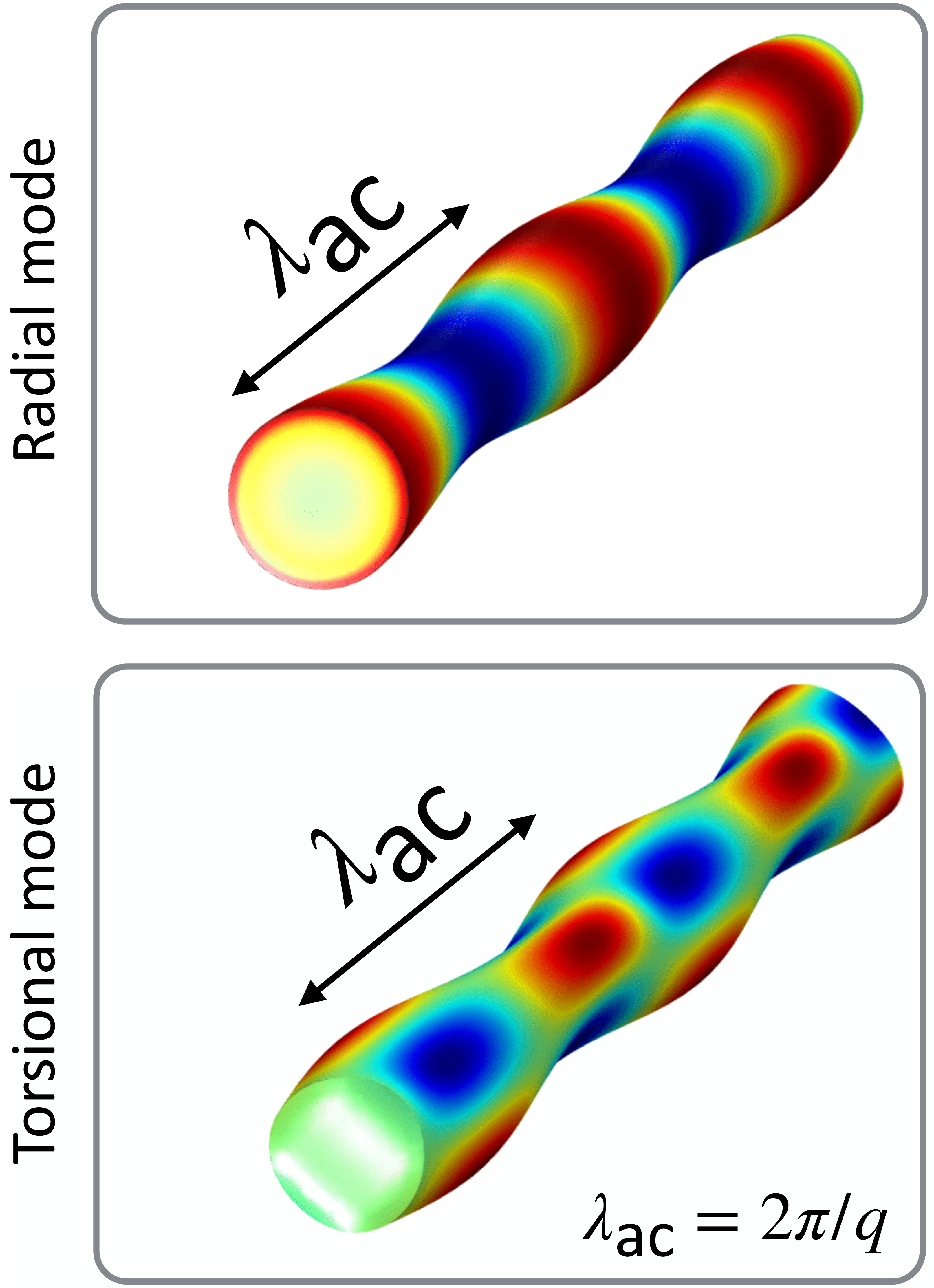


Mechanical modes

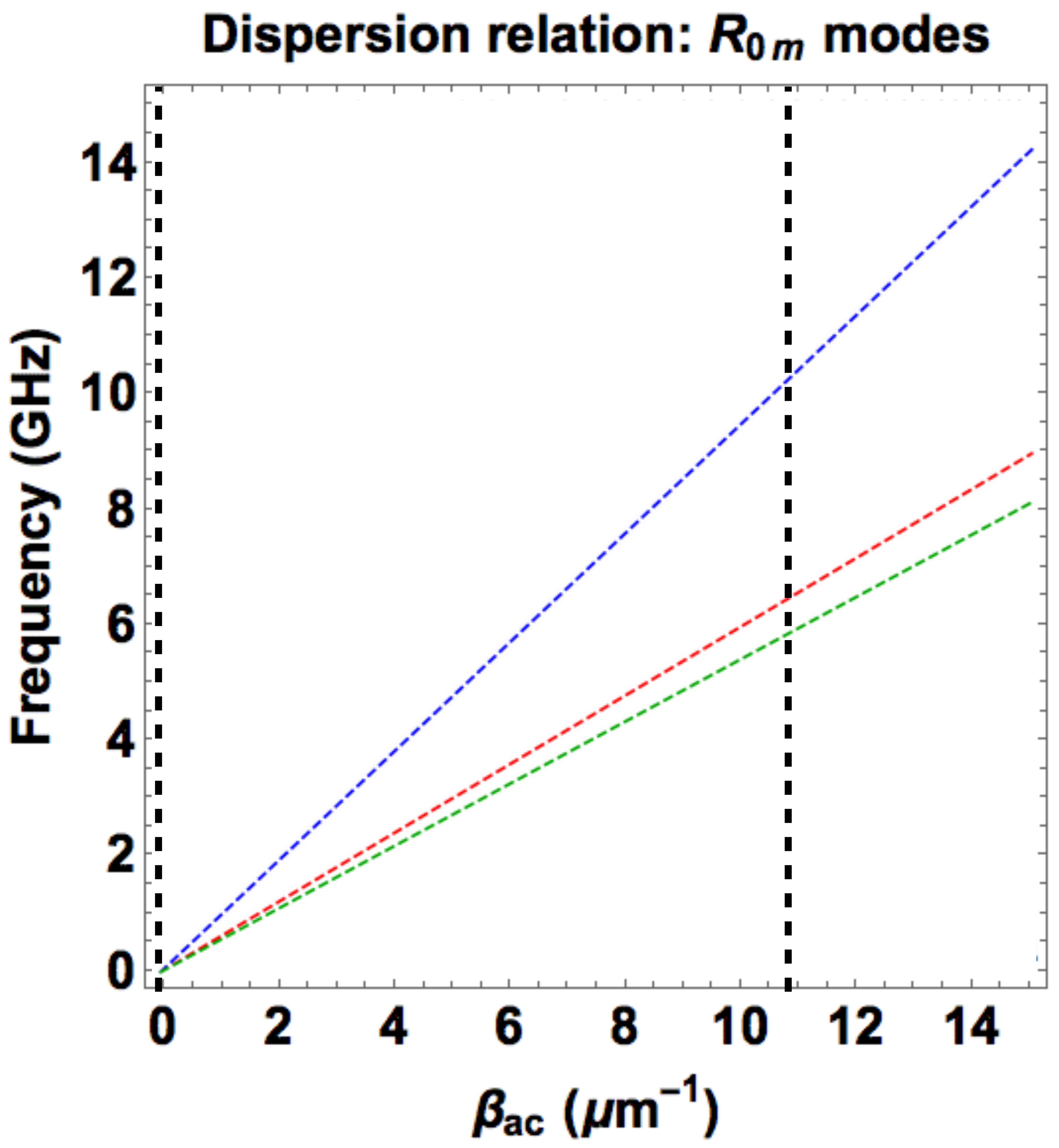
$$\left[(\lambda + 2\mu) + \eta_{11}\frac{\partial}{\partial t}\right]\nabla(\nabla\cdot\boldsymbol{U}) - \left[\mu + \eta_{44}\frac{\partial}{\partial t}\right]\nabla\times\nabla\times\boldsymbol{U} = \rho\frac{\partial^2\boldsymbol{U}}{\partial t^2}$$

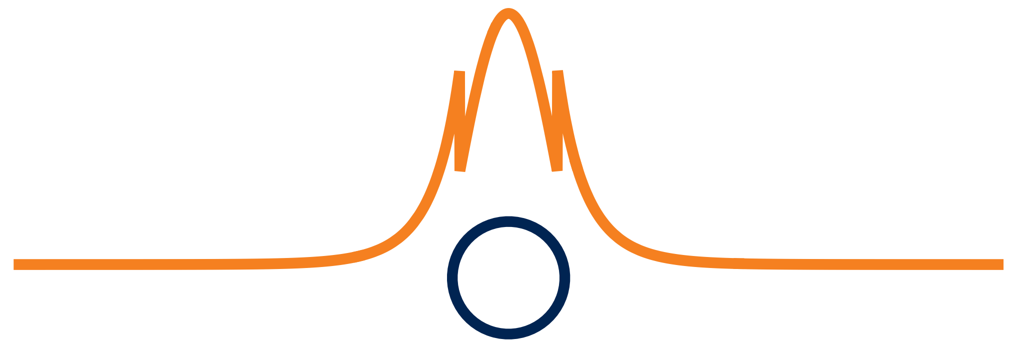
longitudinal waves ($\nabla\times\mathbf{u} = 0$) shear-only ($\nabla\cdot\mathbf{u} = 0$)

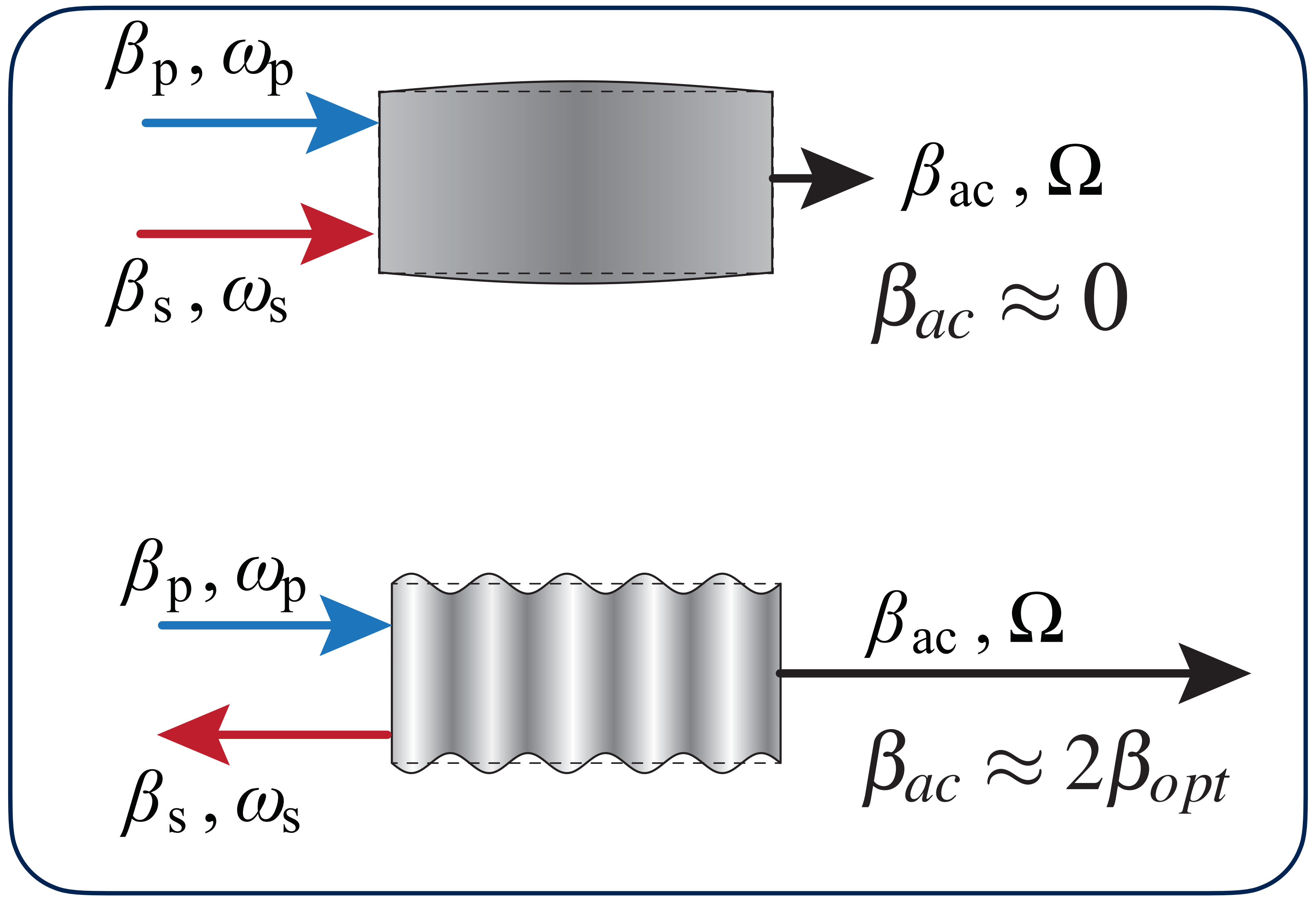
Elastic wave equation



Light-sound interaction: Brillouin scattering

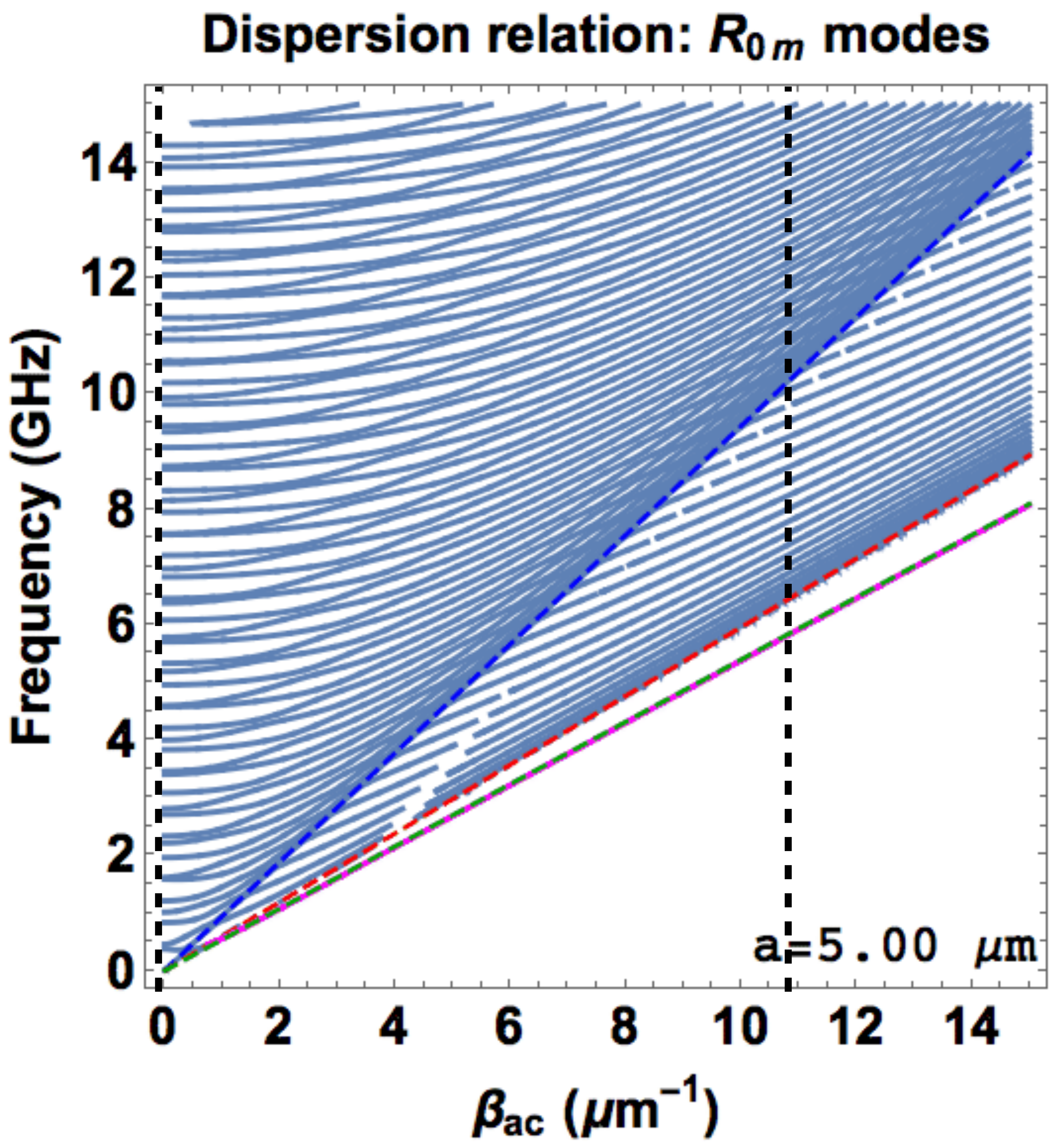


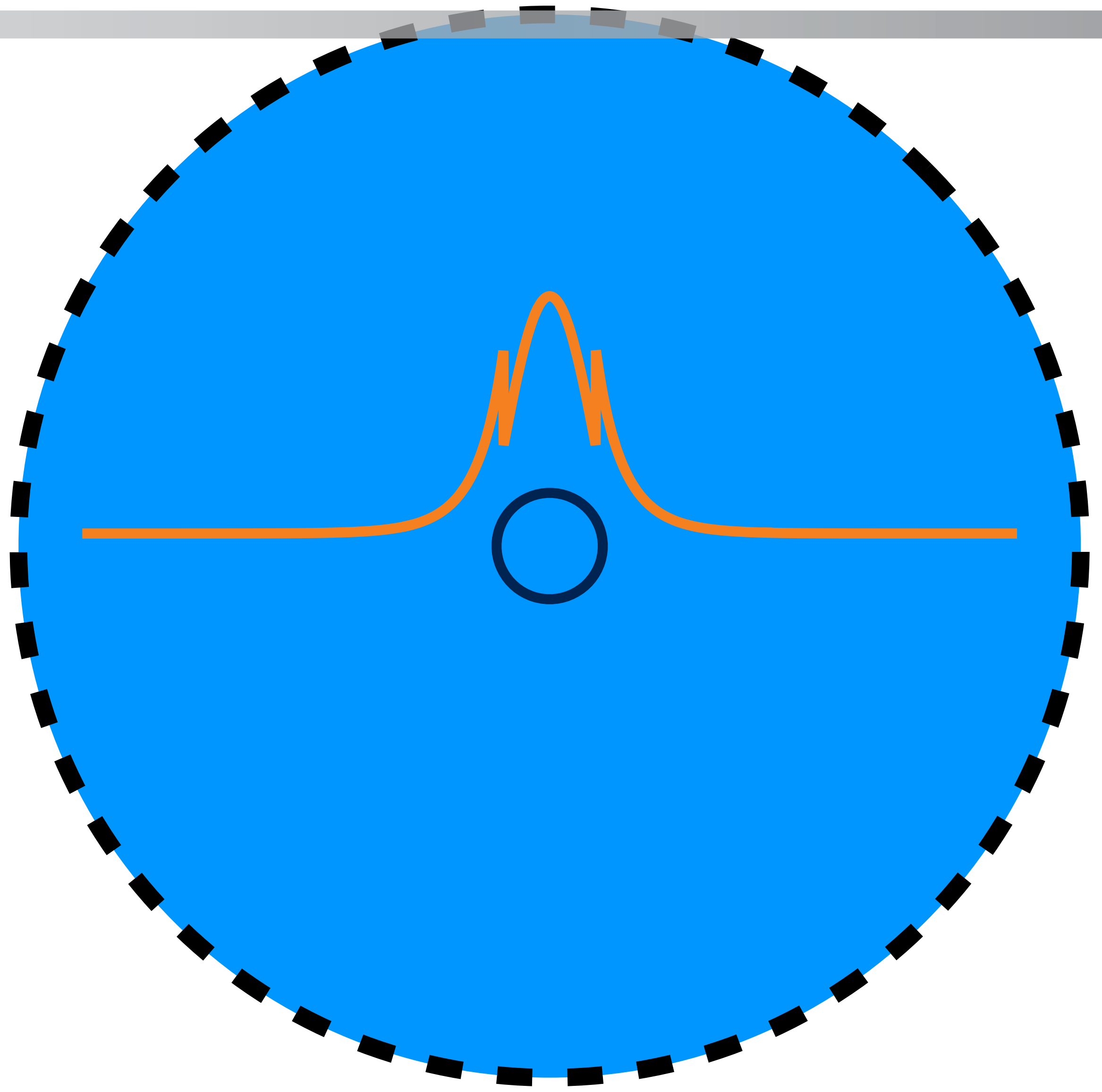


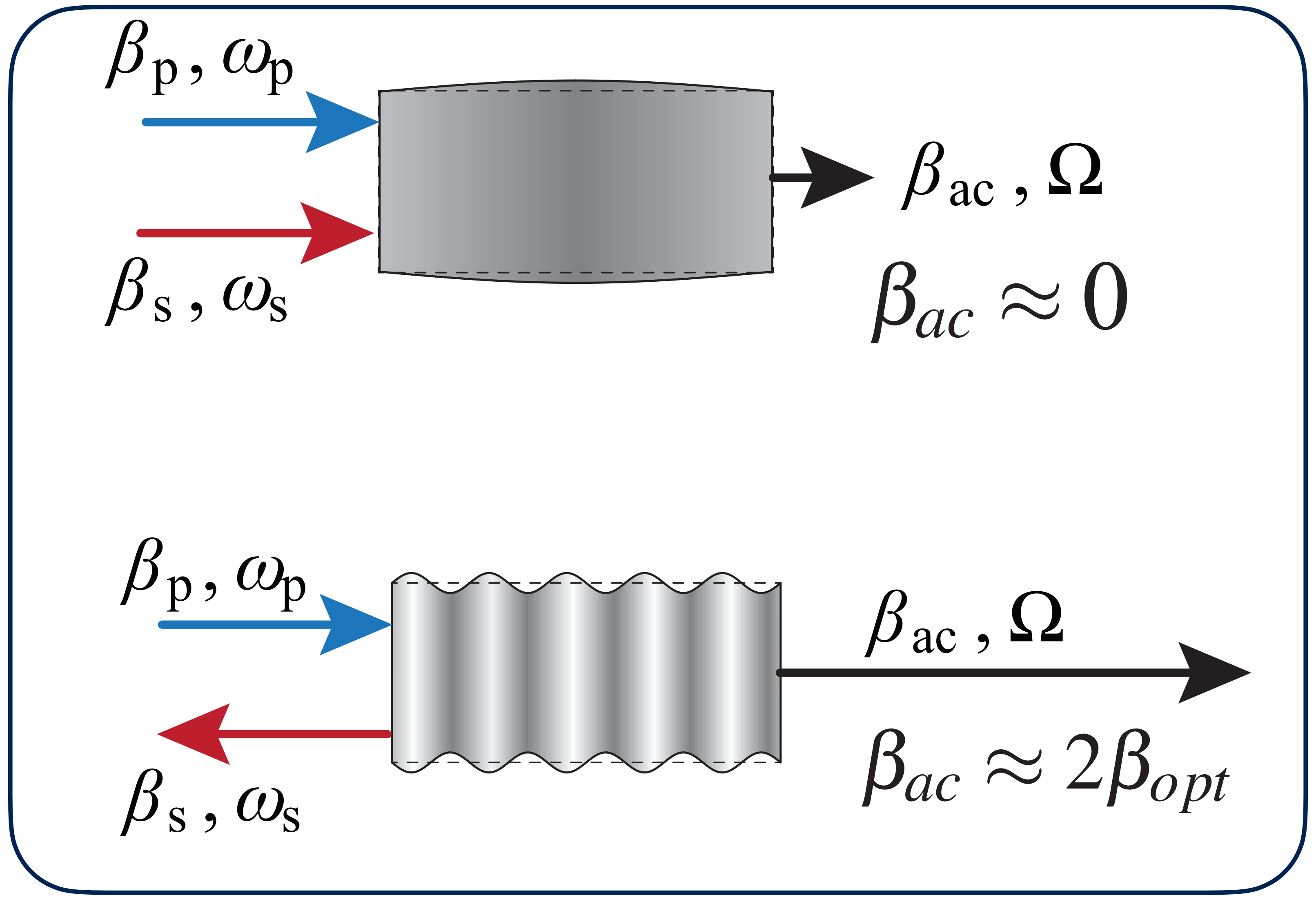


Phase matching for Stokes scattering

Light-sound interaction: Brillouin scattering







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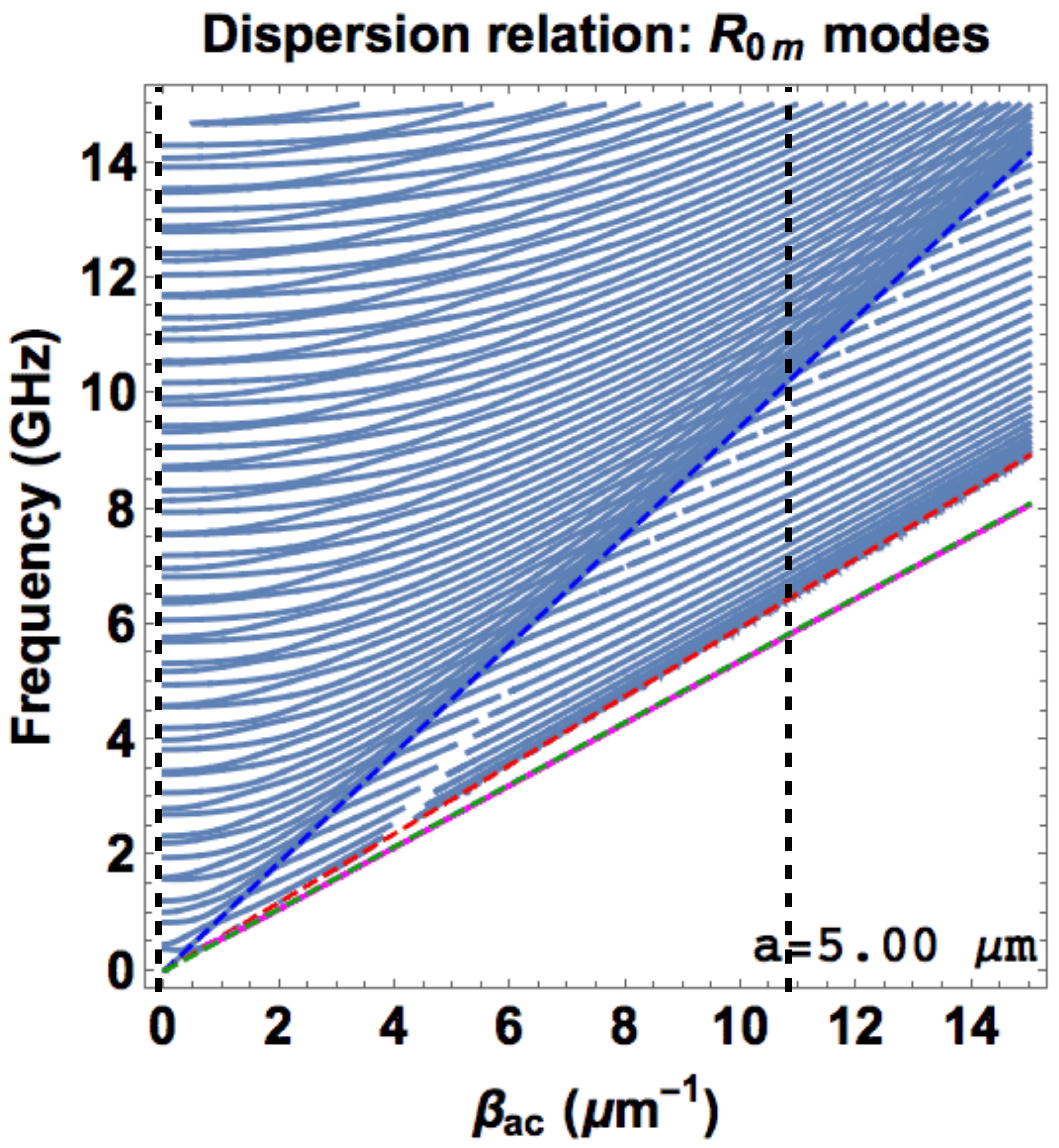
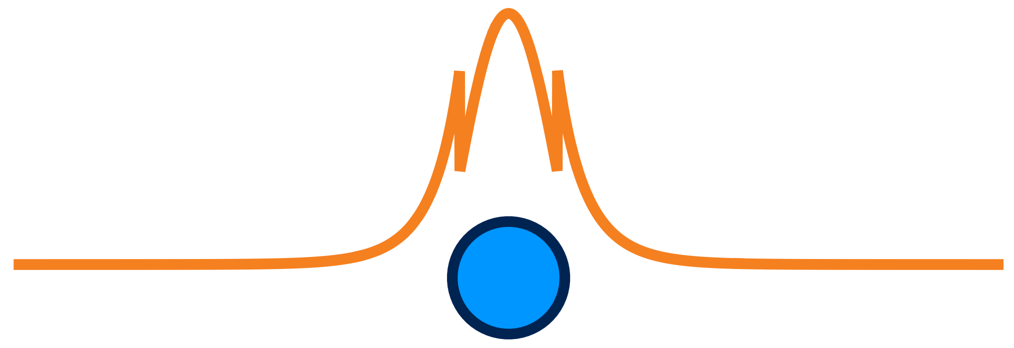
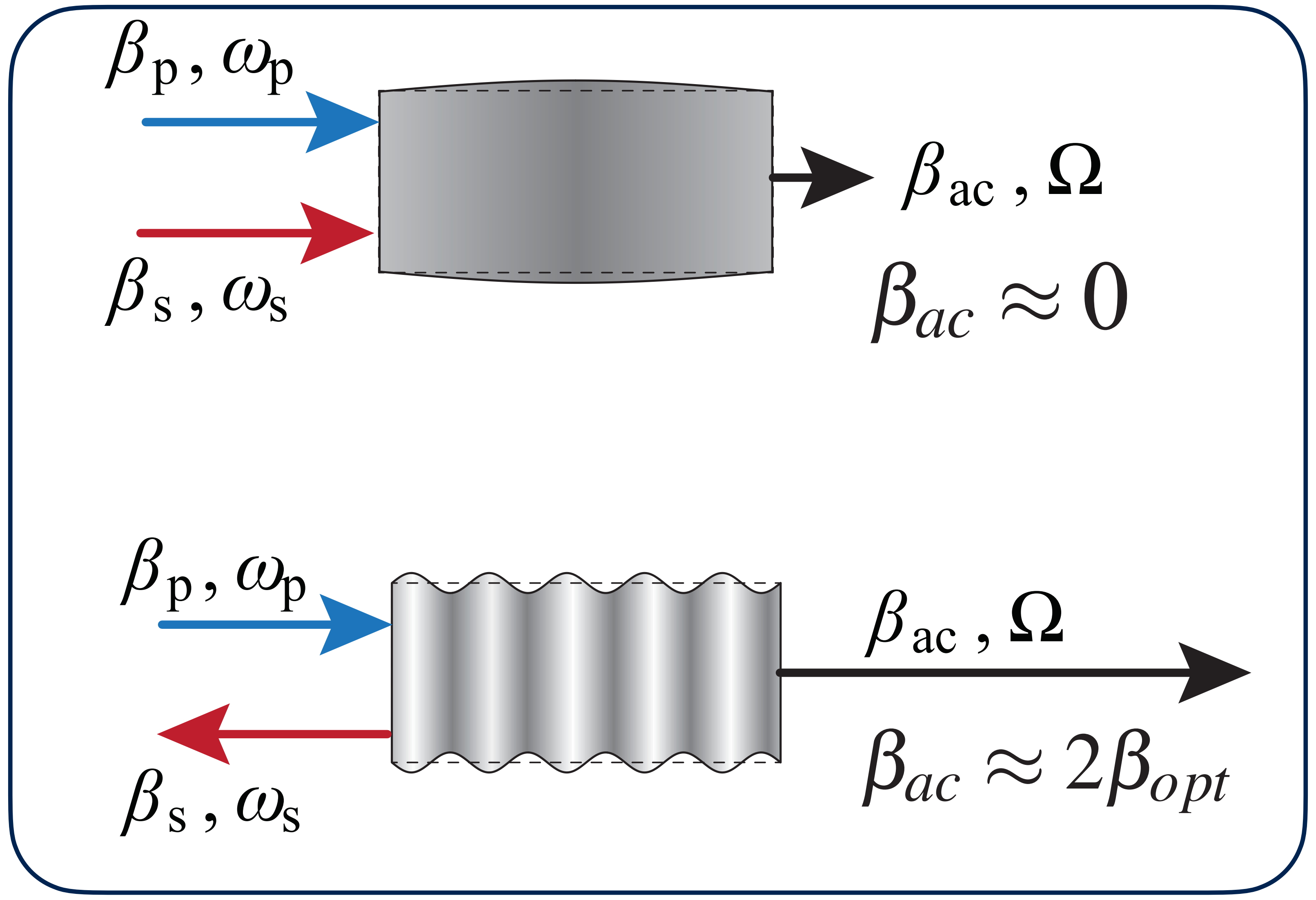






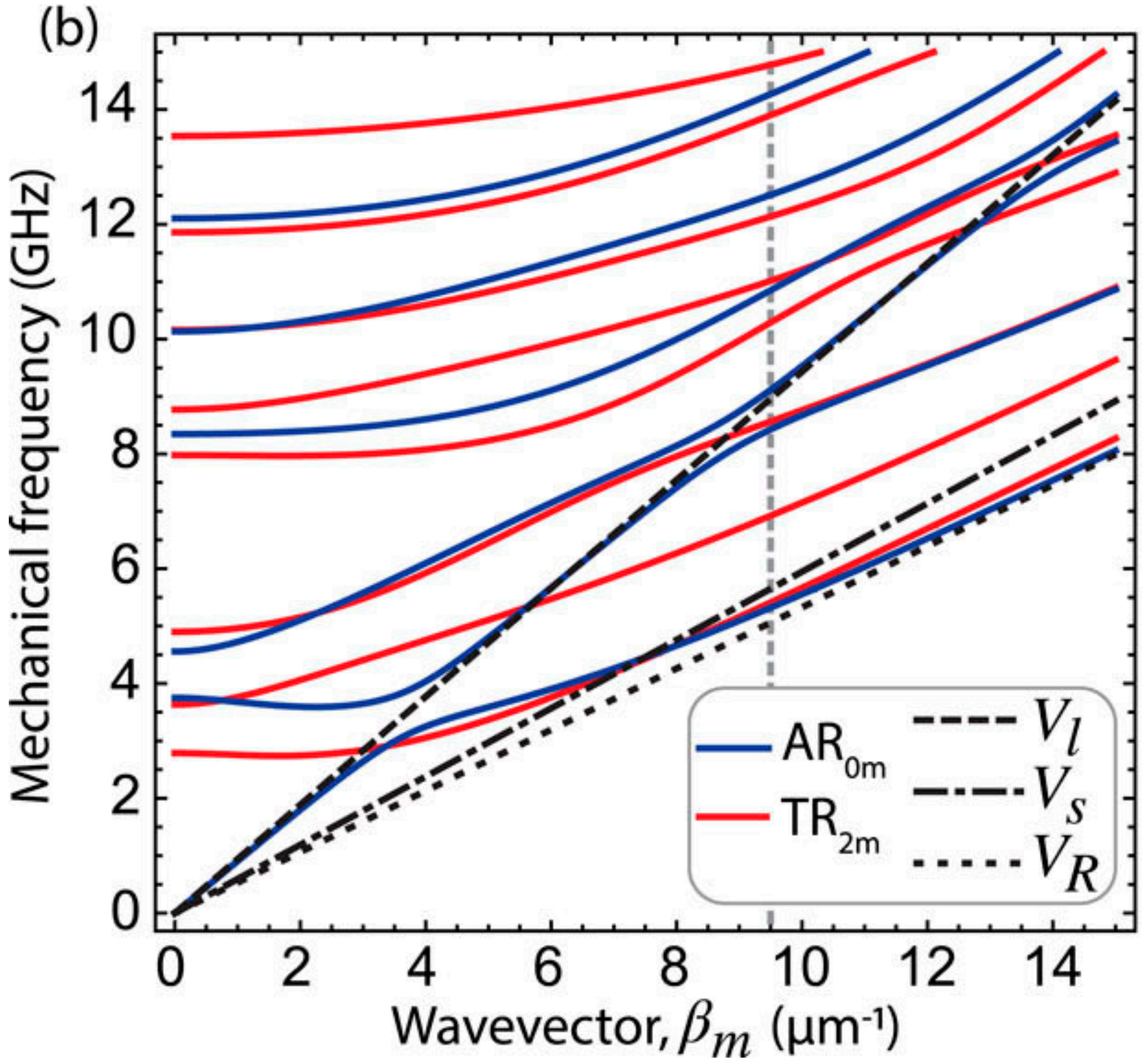
Phase matching for Stokes scattering

Mechanical modes

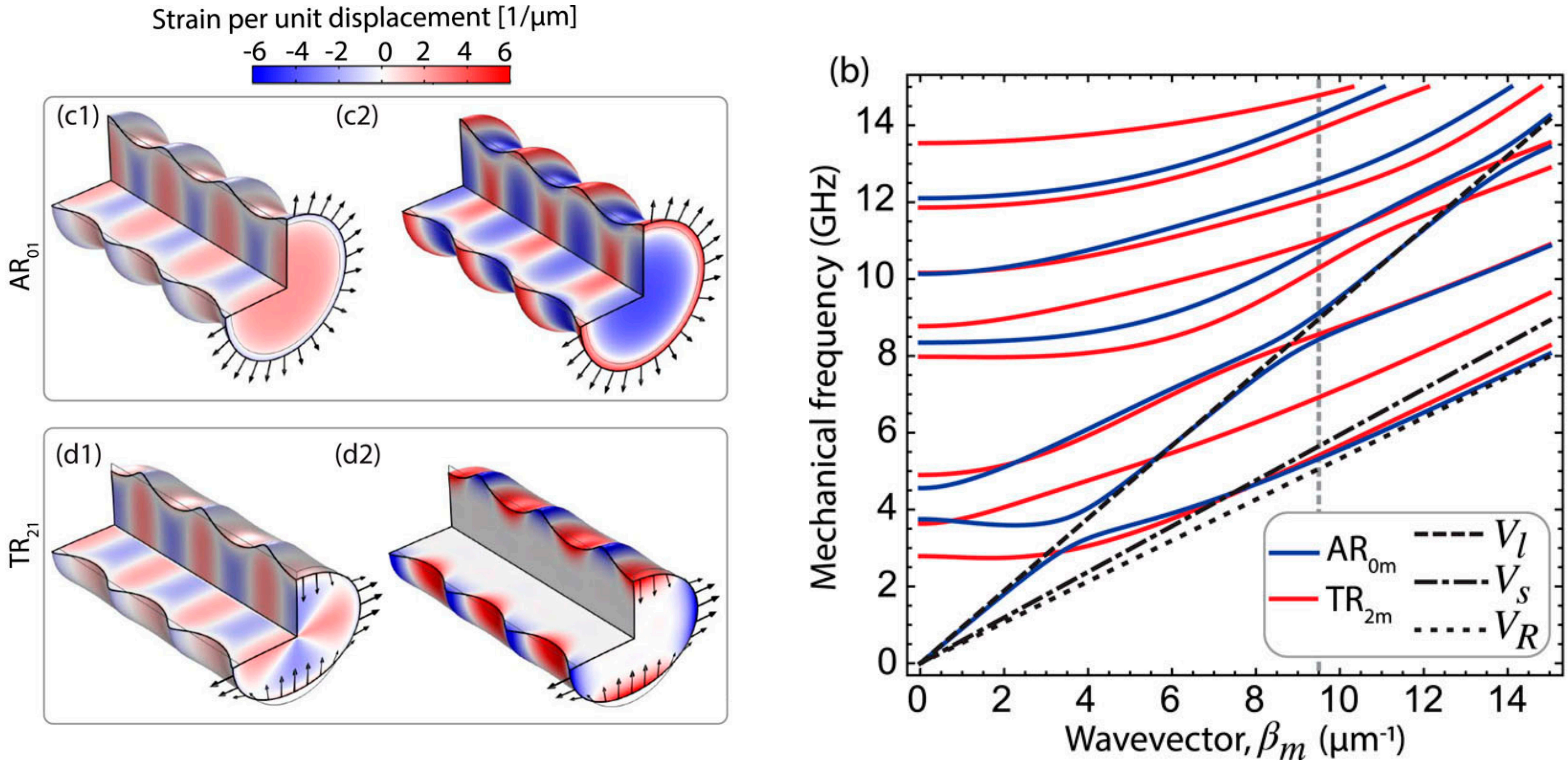
$$\underbrace{\left[(\lambda+2\mu)+\eta_{11}\frac{\partial}{\partial t}\right]\nabla(\nabla\cdot\boldsymbol{U})}_{\text{longitudinal waves } (\nabla\times\mathbf{u}=0)}-\underbrace{\left[\mu+\eta_{44}\frac{\partial}{\partial t}\right]\nabla\times\nabla\times\boldsymbol{U}}_{\text{shear-only } (\nabla\cdot\mathbf{u}=0)}=\rho\frac{\partial^2\boldsymbol{U}}{\partial t^2}$$

longitudinal waves ($\nabla\times\mathbf{u}=0$) shear-only ($\nabla\cdot\mathbf{u}=0$)

Elastic wave equation

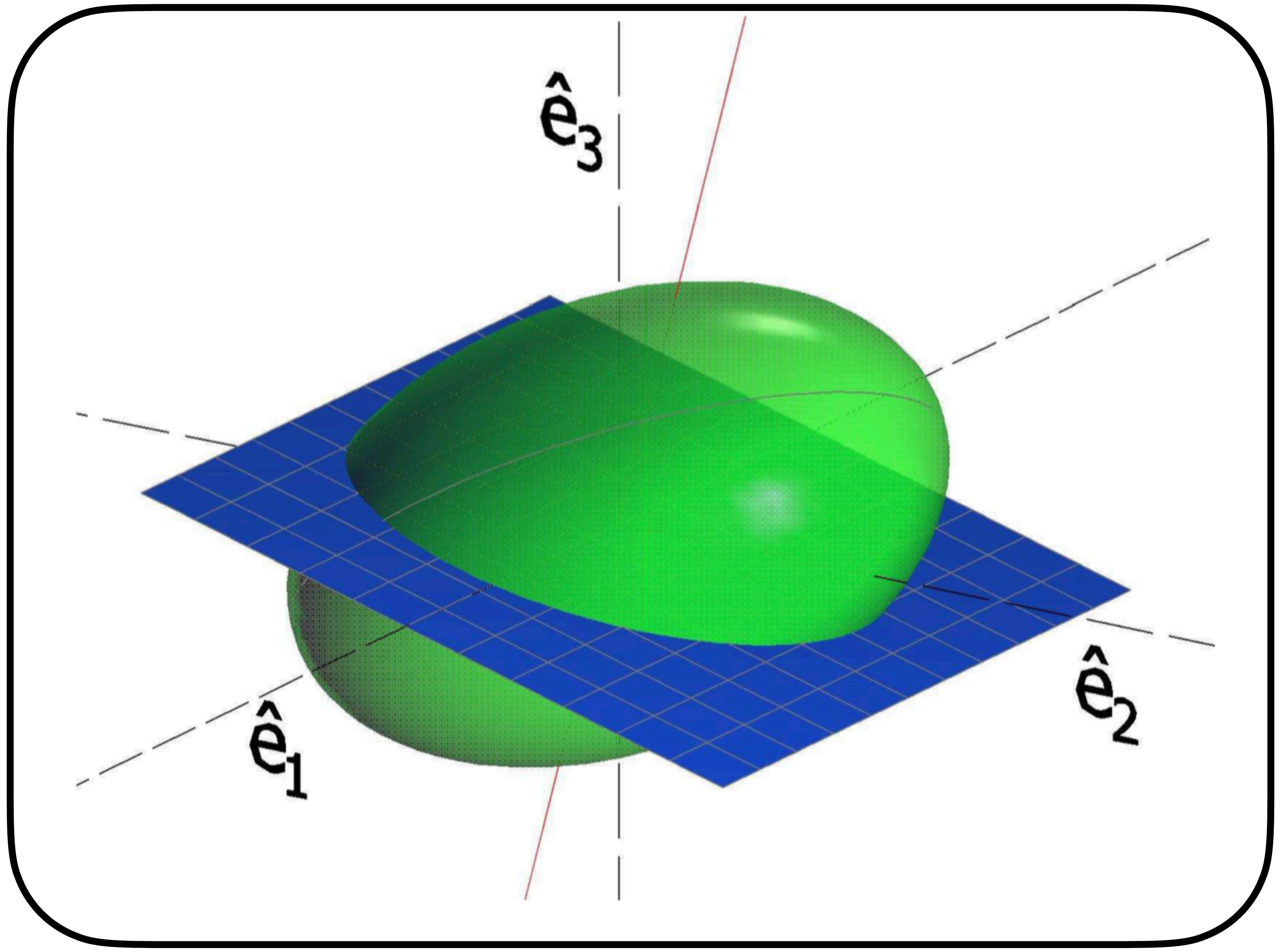


Mechanical modes



Mechanical modes (Photo-elastic effect)

Index ellipsoid



$$\beta_{ij}\epsilon_{jk} = \delta_{ik}$$

$$\beta_{ij}x_i x_j = 1$$

Mechanical modes (Photo-elastic effect)

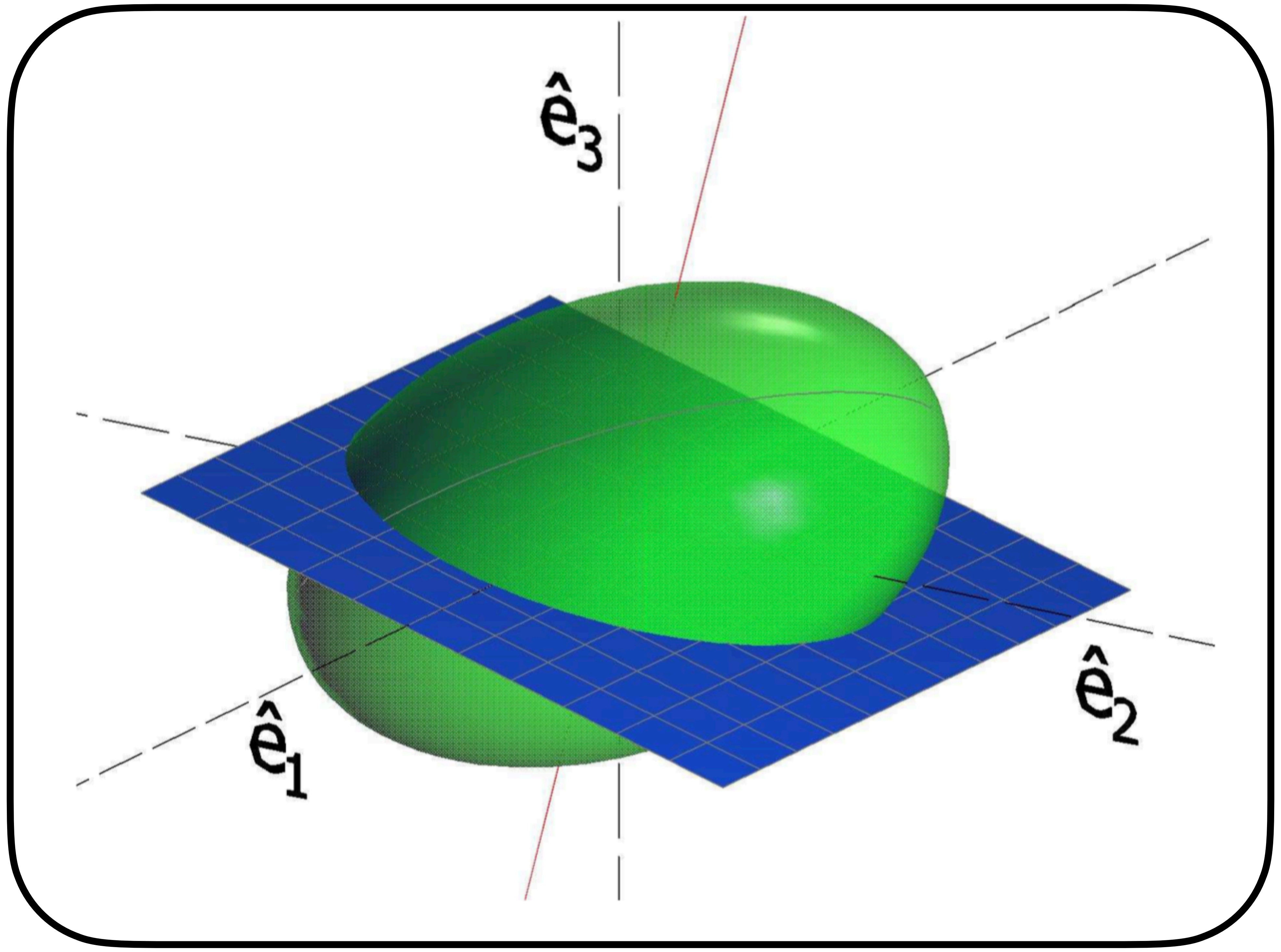
$$[\Delta\beta(\boldsymbol{r}; \overleftrightarrow{S})]_{ij} = p_{ijkl}(\boldsymbol{r}) S_{kl}(\boldsymbol{r})$$

Photo-elastic effect is described in terms of the "impermeability tensor" β_{ij}

$$S_I = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} S_{xx} \\ S_{yy} \\ S_{zz} \\ 2S_{yz} \\ 2S_{xz} \\ 2S_{xy} \end{bmatrix}$$

Voigt notation: Strain is a symmetric tensor

Index ellipsoid



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Voigt notation: Strain is a symmetric tensor

Perturbation $\Delta\beta_{ij}$

$$\Rightarrow \Delta\epsilon_{im}\beta_{mn} = -\epsilon_{im}\Delta\beta_{mn}$$

$$\Rightarrow \Delta\epsilon_{im}\beta_{mn}\epsilon_{nj} = -\epsilon_{im}\Delta\beta_{mn}\epsilon_{nj}$$

$$\Rightarrow \Delta\epsilon_{ij} = -\epsilon_{im}\Delta\beta_{mn}\epsilon_{nj}$$

$$\Rightarrow \Delta\epsilon_{ij} = -\epsilon_{im}\left(p_{mnrs}S_{rs}\right)\epsilon_{nj}$$

$$\Rightarrow \Delta\epsilon_{ij} = -\epsilon^2\left(p_{ijrs}S_{rs}\right)$$

$$\beta_{ij}\epsilon_{jk} = \delta_{ik}$$

$$\beta_{ij}x_ix_j = 1$$

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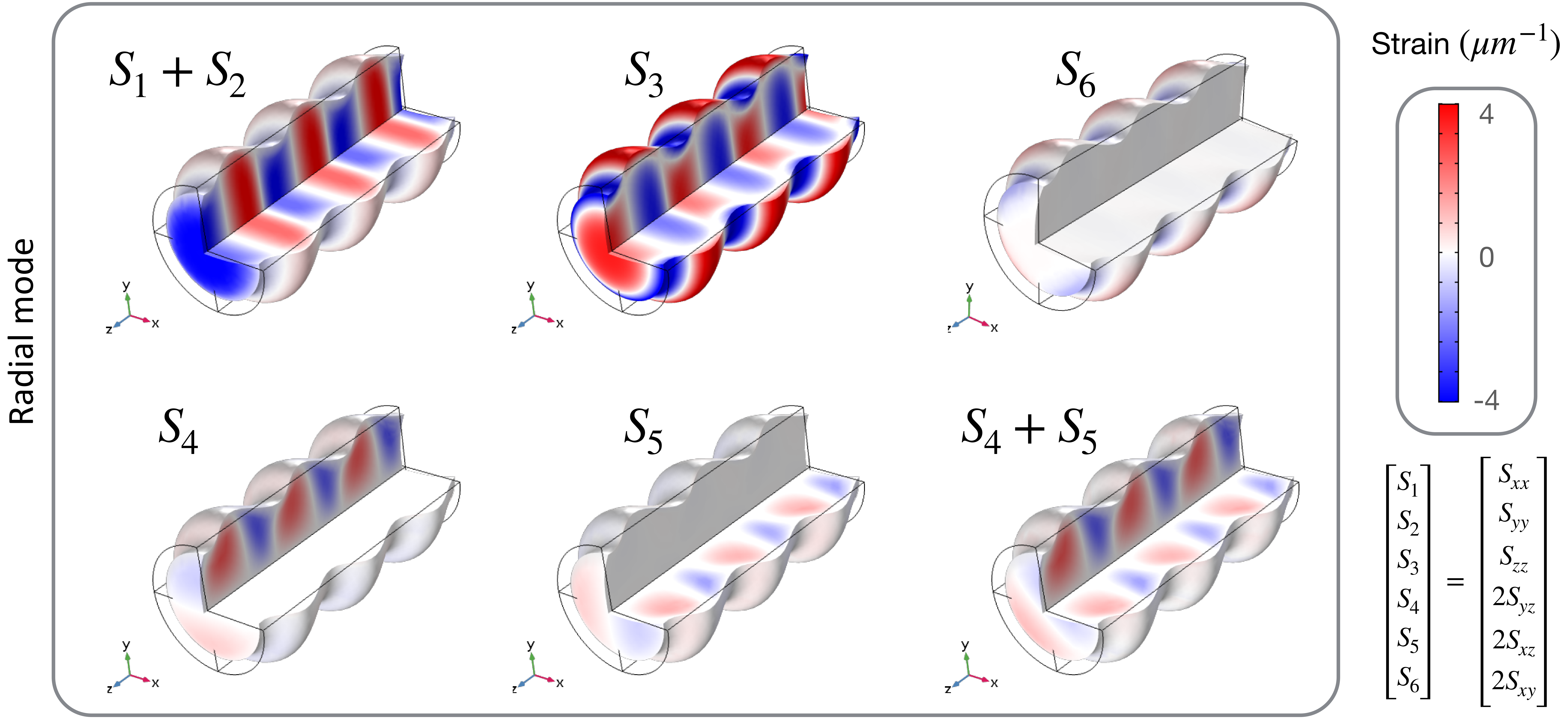
Voigt notation: Strain is a symmetric tensor

$$\boxed{\begin{aligned} &\Rightarrow \Delta\epsilon_{ij} = -\epsilon^2\left(p_{ijrs}S_{rs}\right) \\ &\Rightarrow \Delta\epsilon_I = -\epsilon^2 p_{IJ}S_j \end{aligned}}$$

$$\Delta\epsilon_I = -\epsilon^2 \begin{bmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix}$$

Mechanical modes (Photo-elastic effect)



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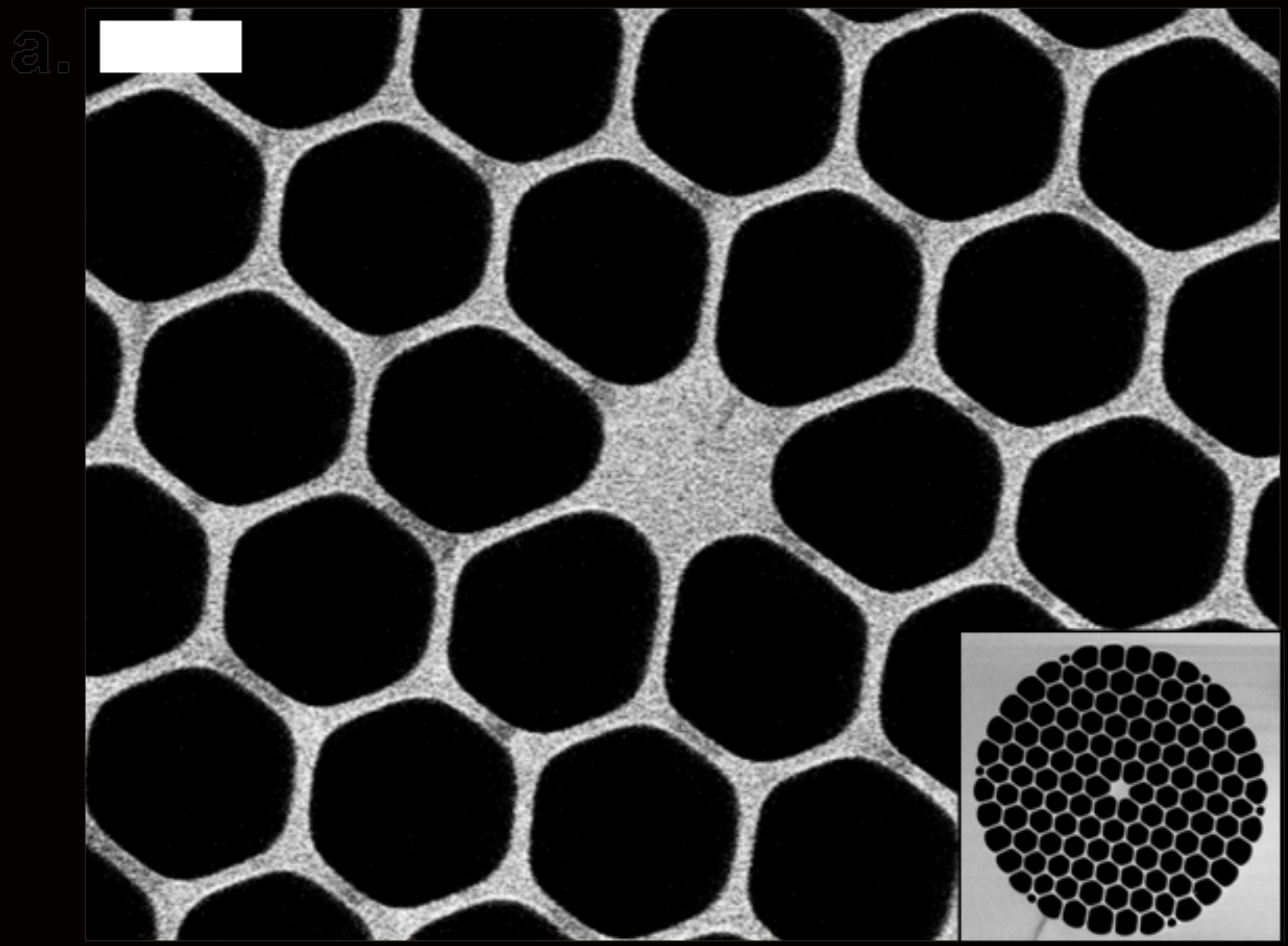
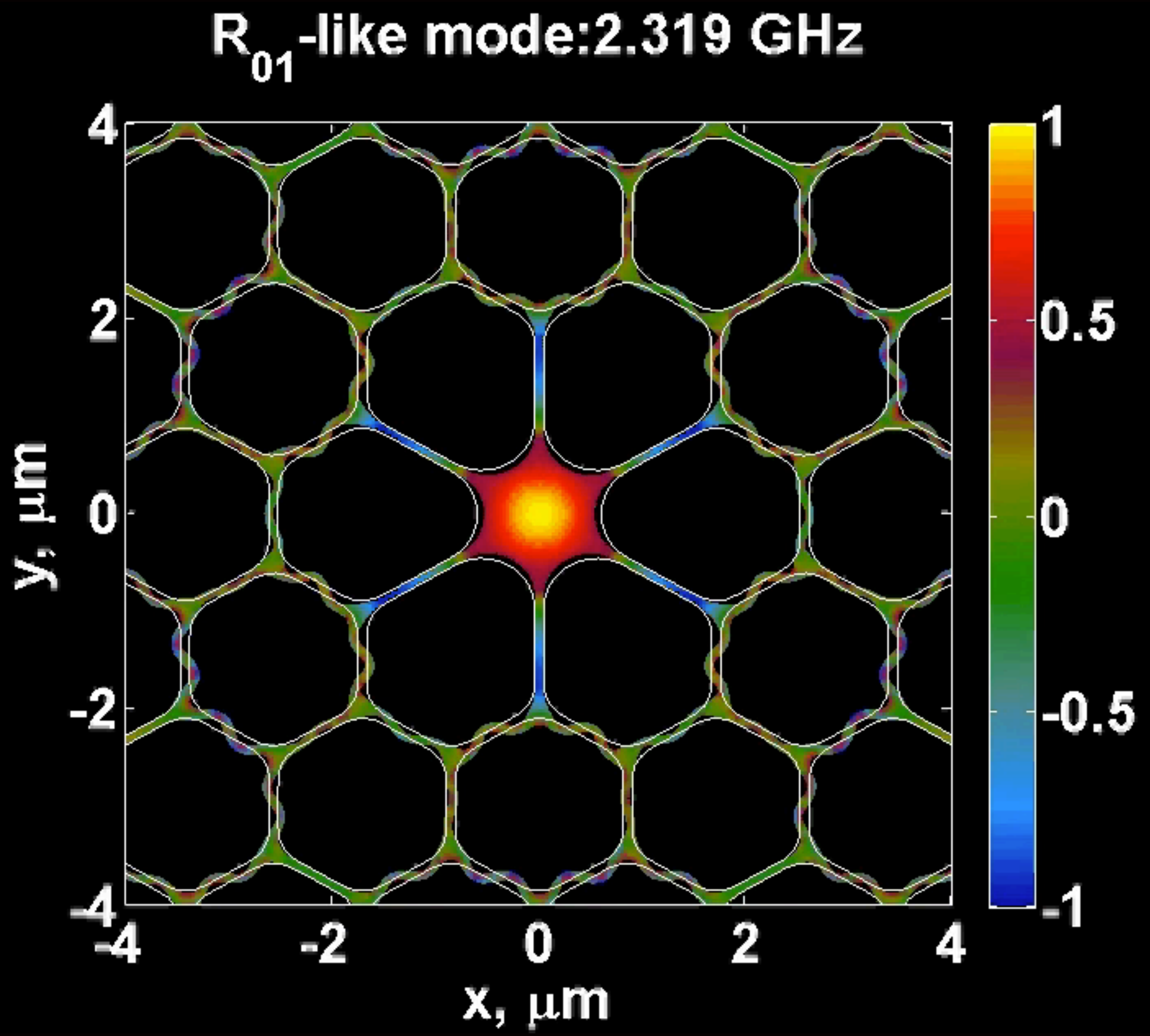
Brillouin Scattering in microwires





Wiederhecker, G. S., et al. (2008). PRL, 100(20), 203903.

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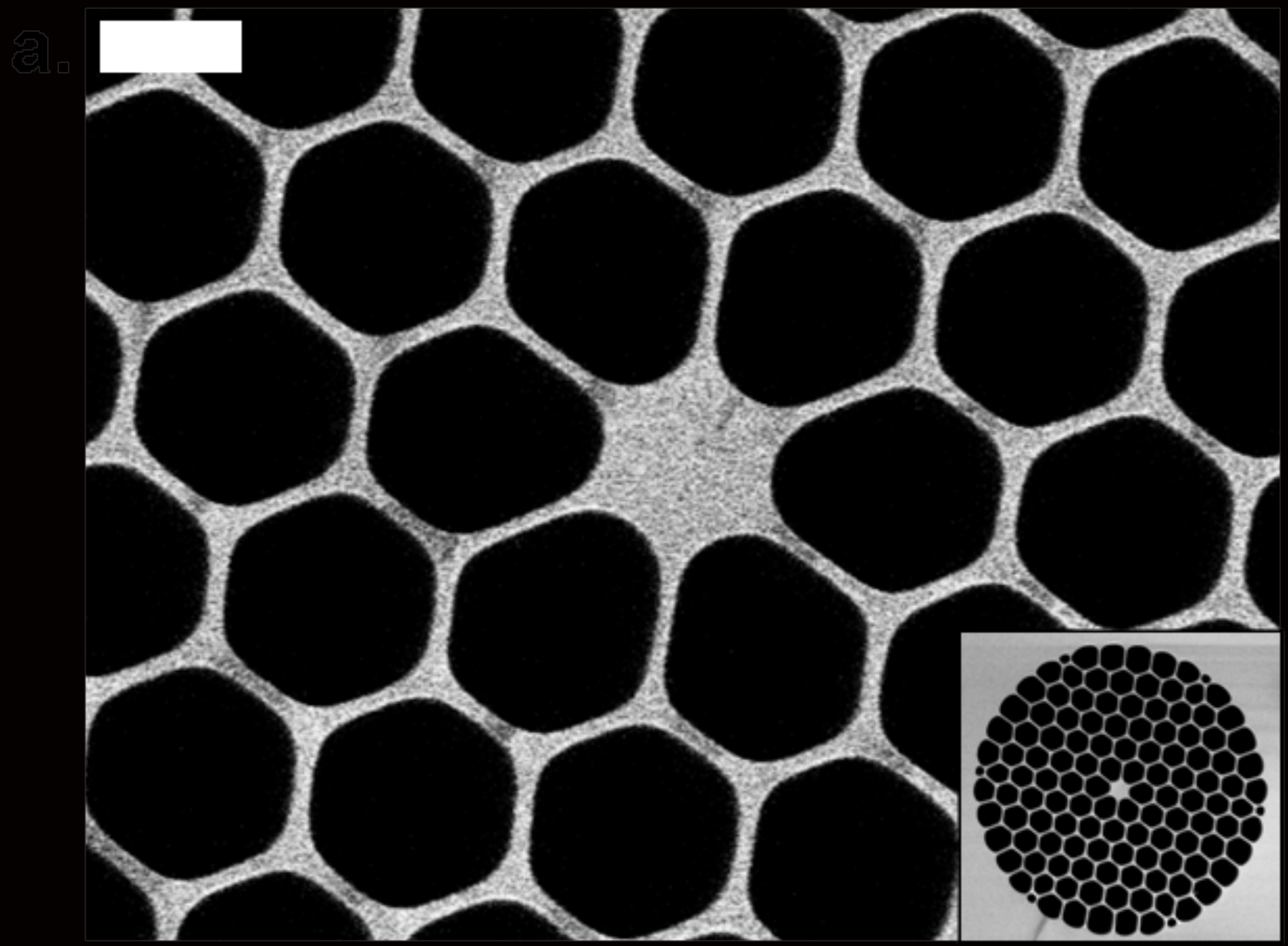

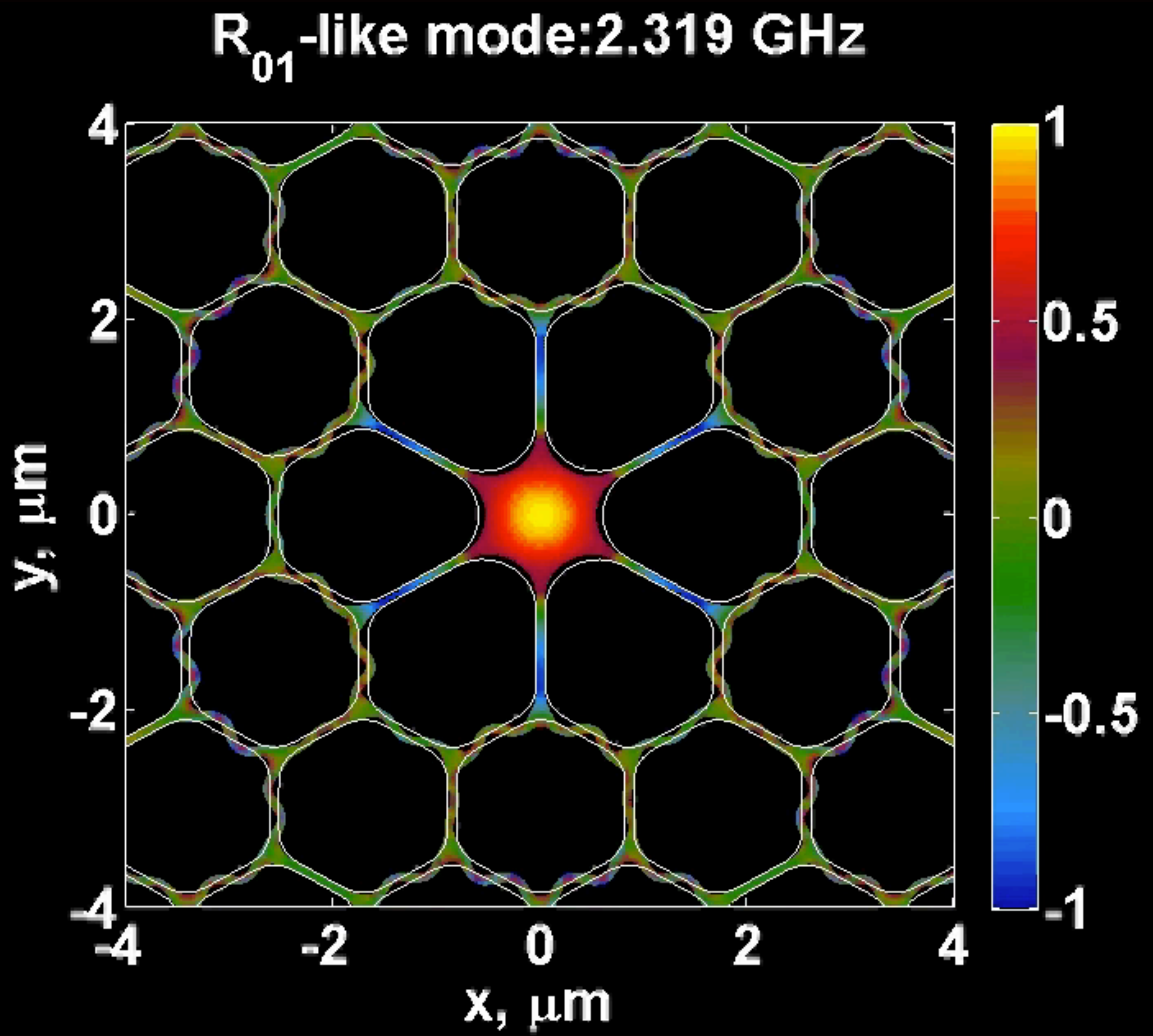

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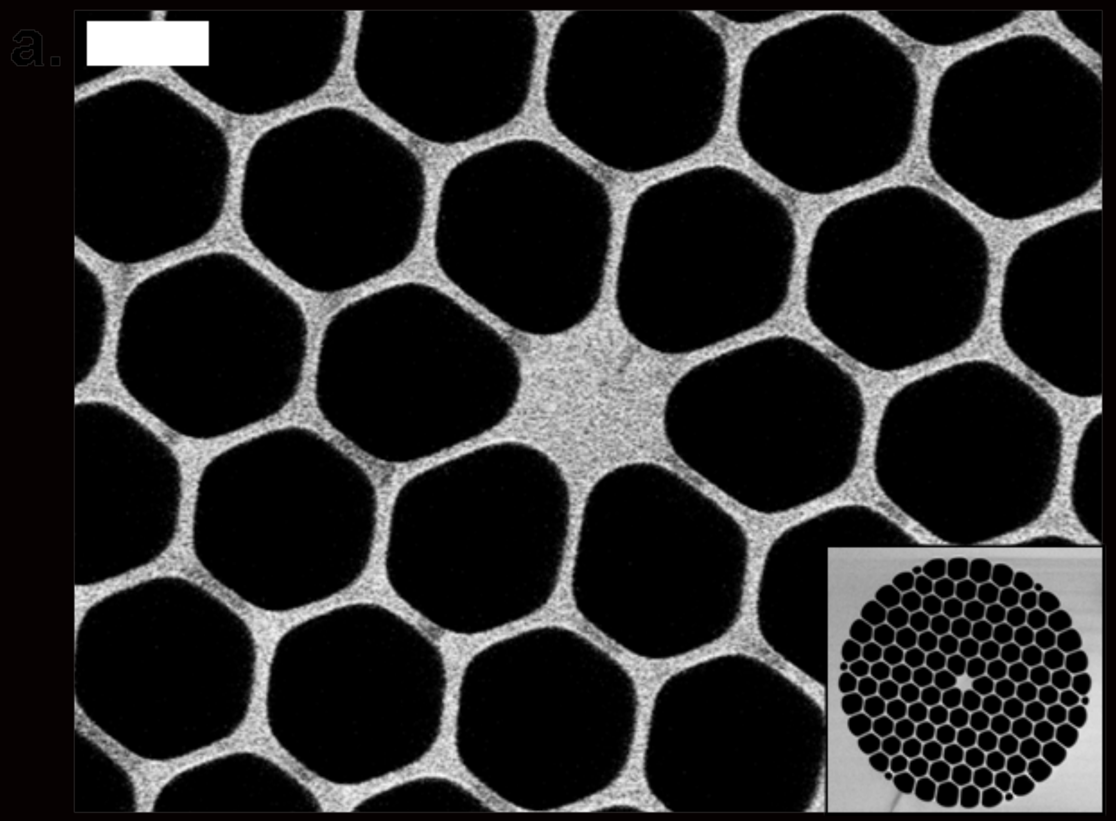

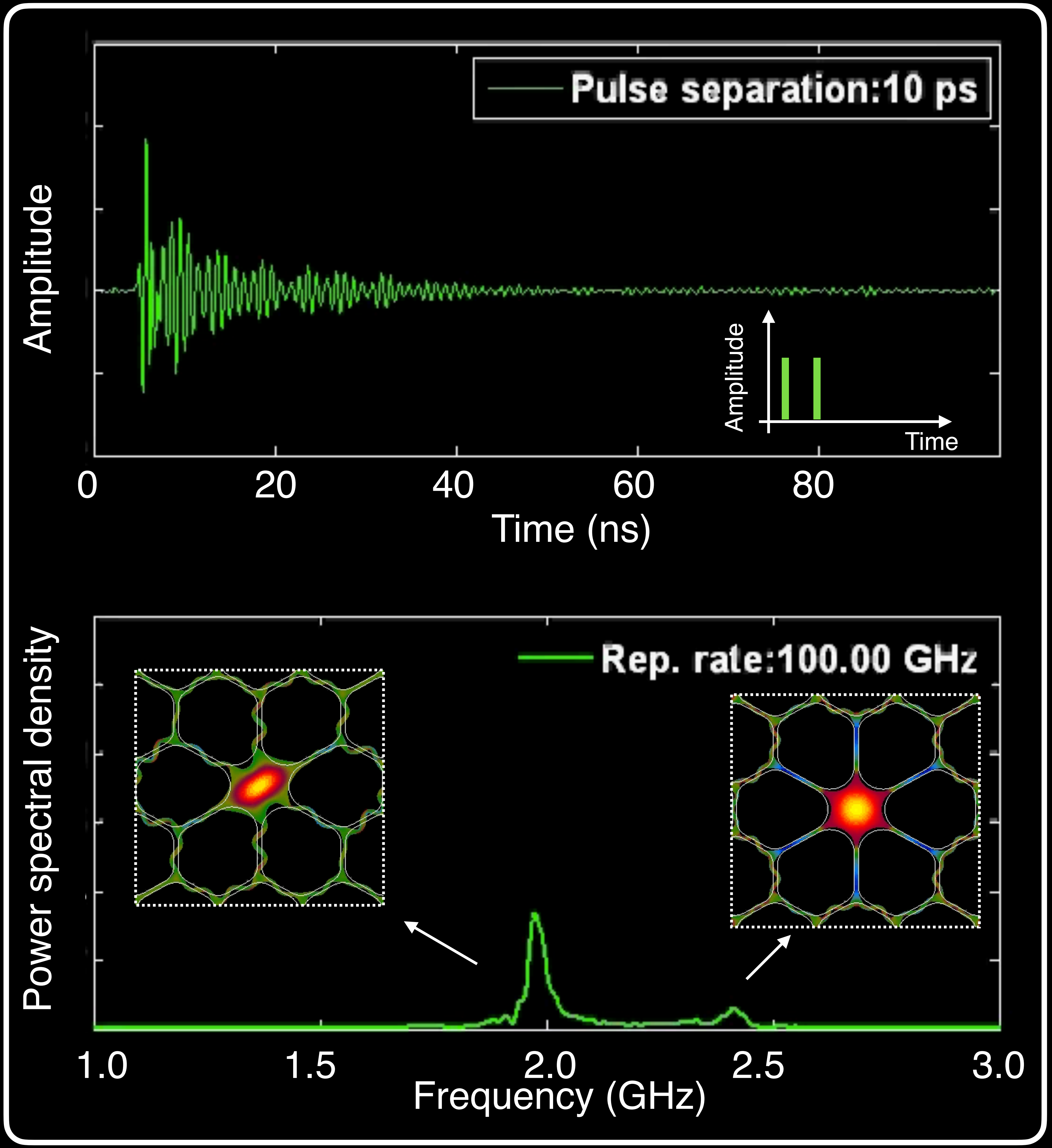

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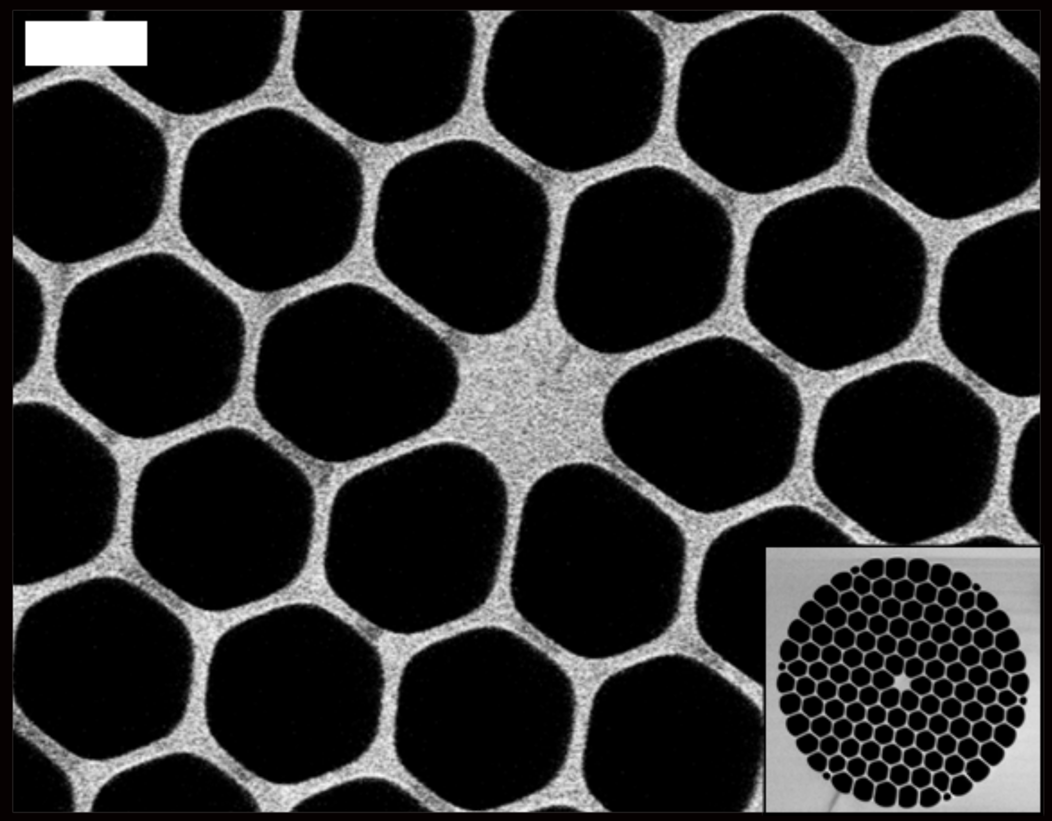

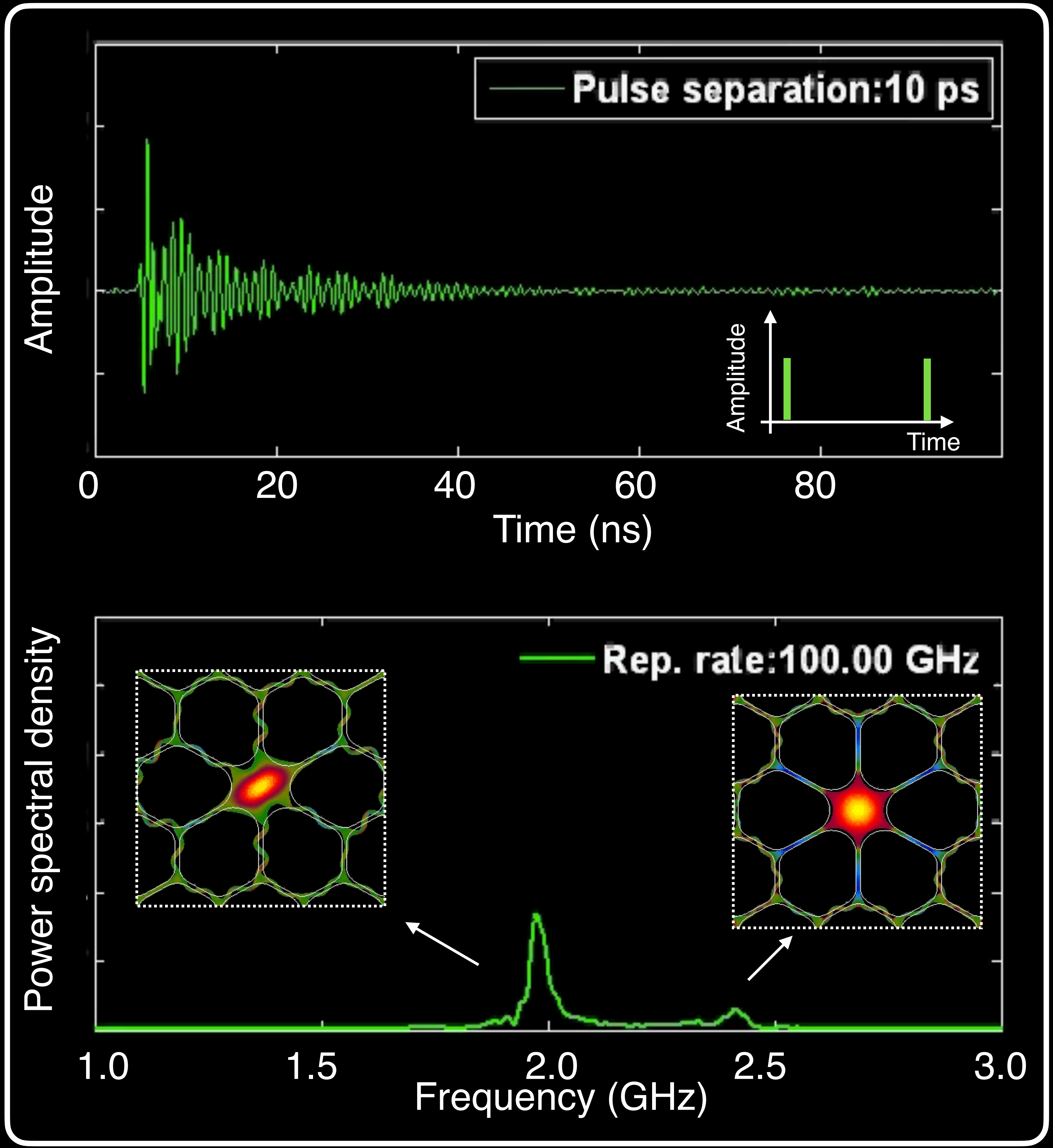

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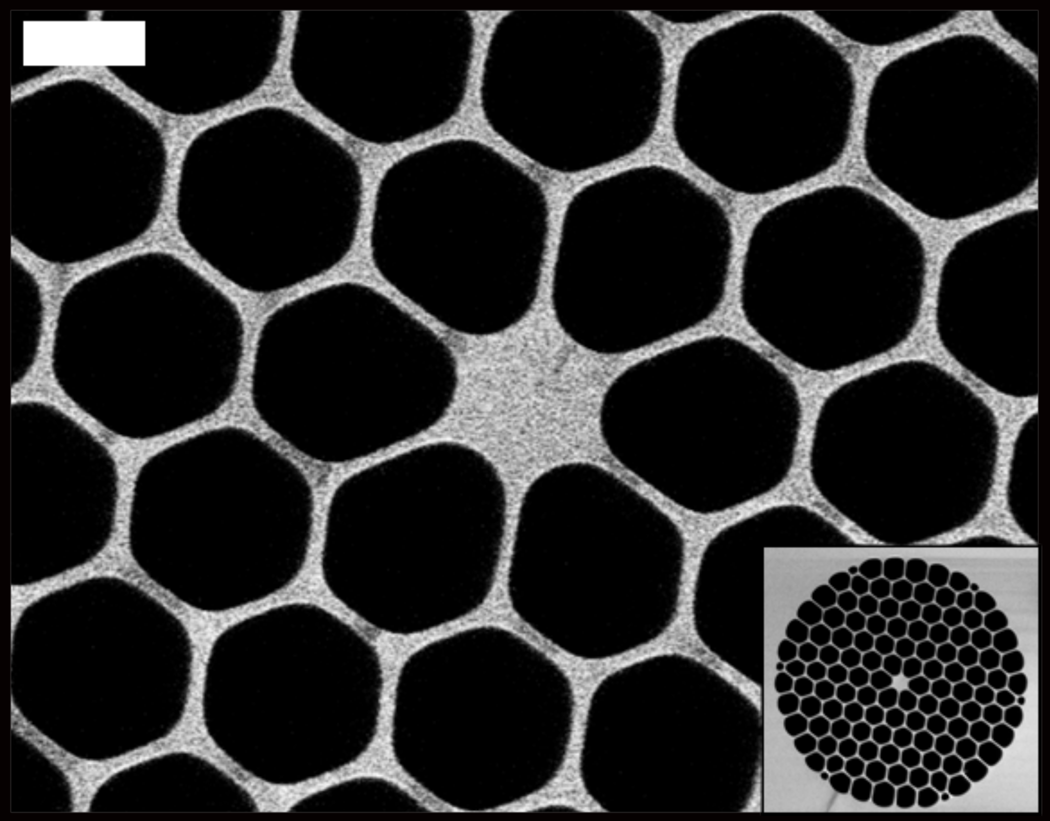
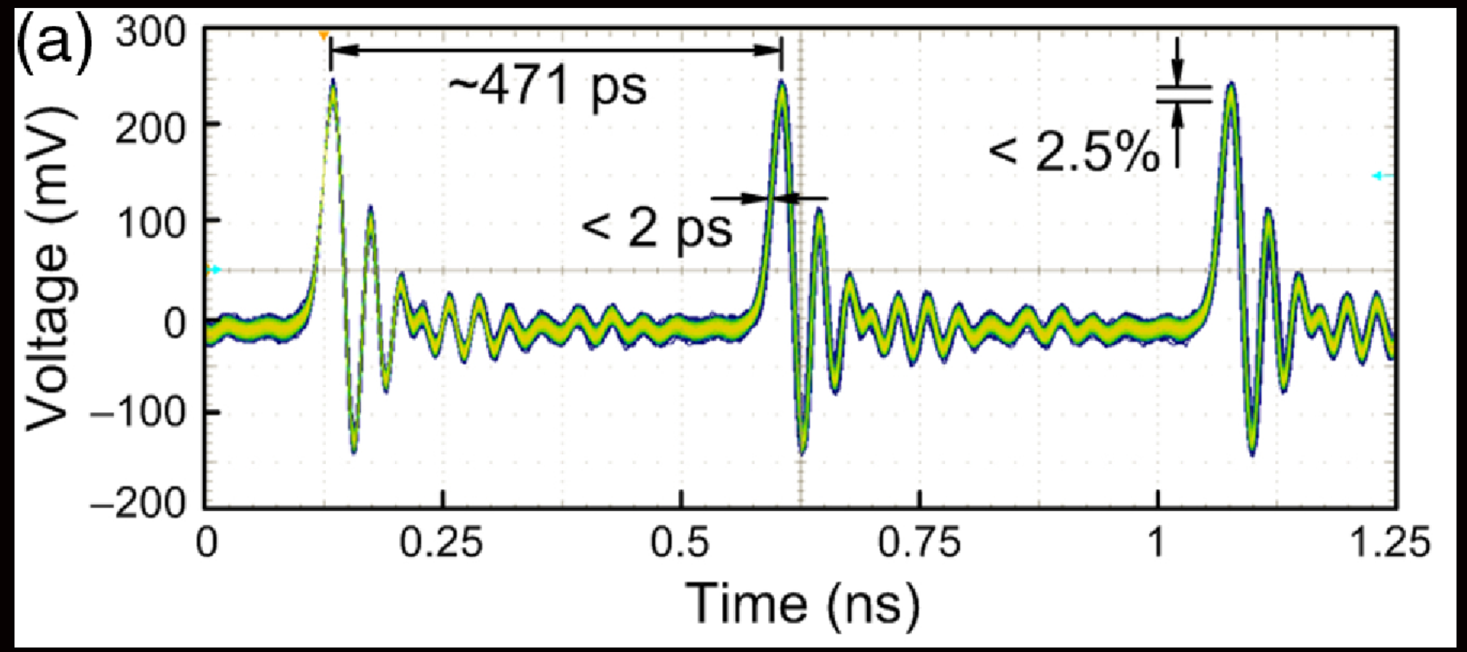
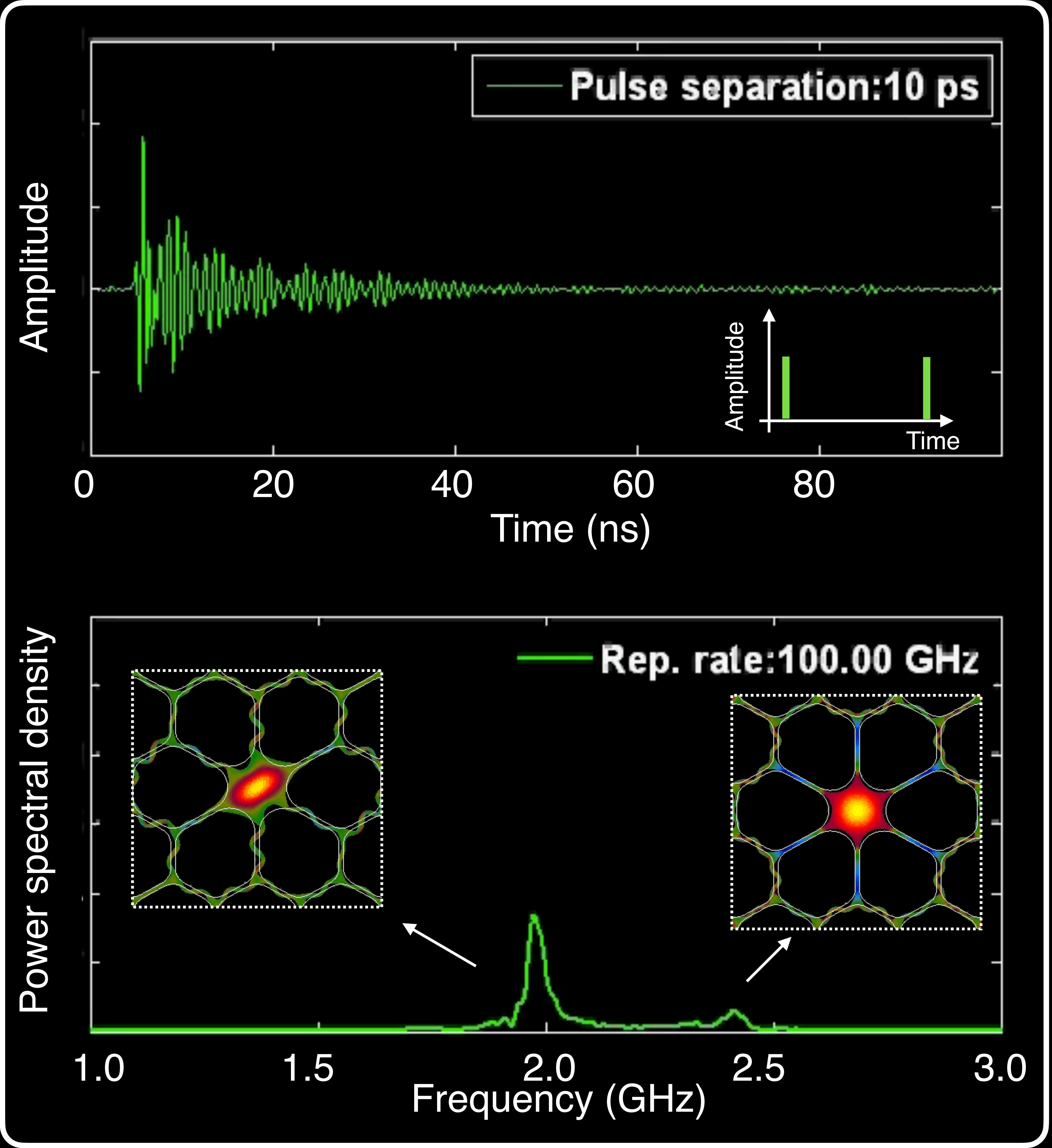




W. He, et al, Optics Express, 23(19), 24945-24954 (2015)
M. Pang, Optica, Vol. 2, Issue 4, pp. 339-342 (2015)



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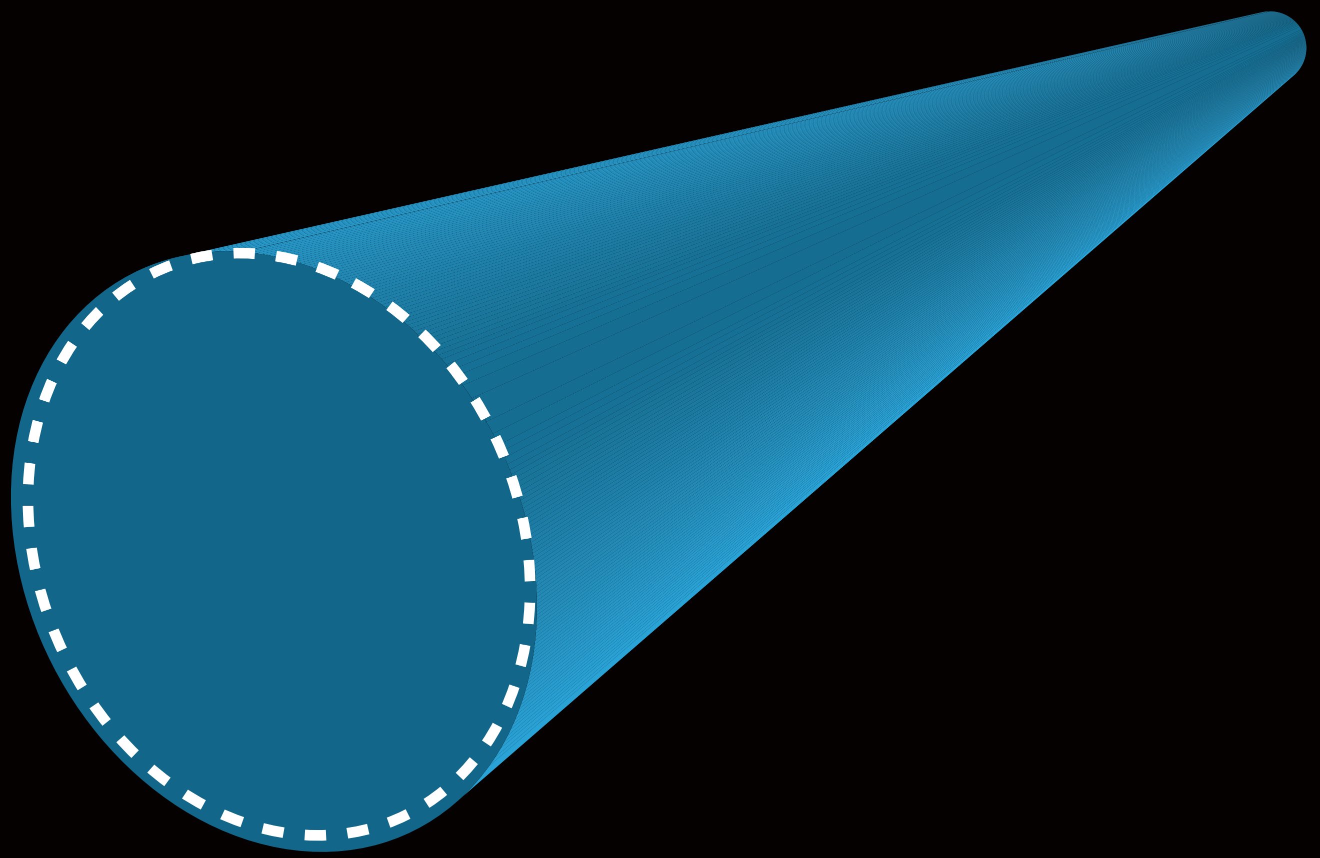
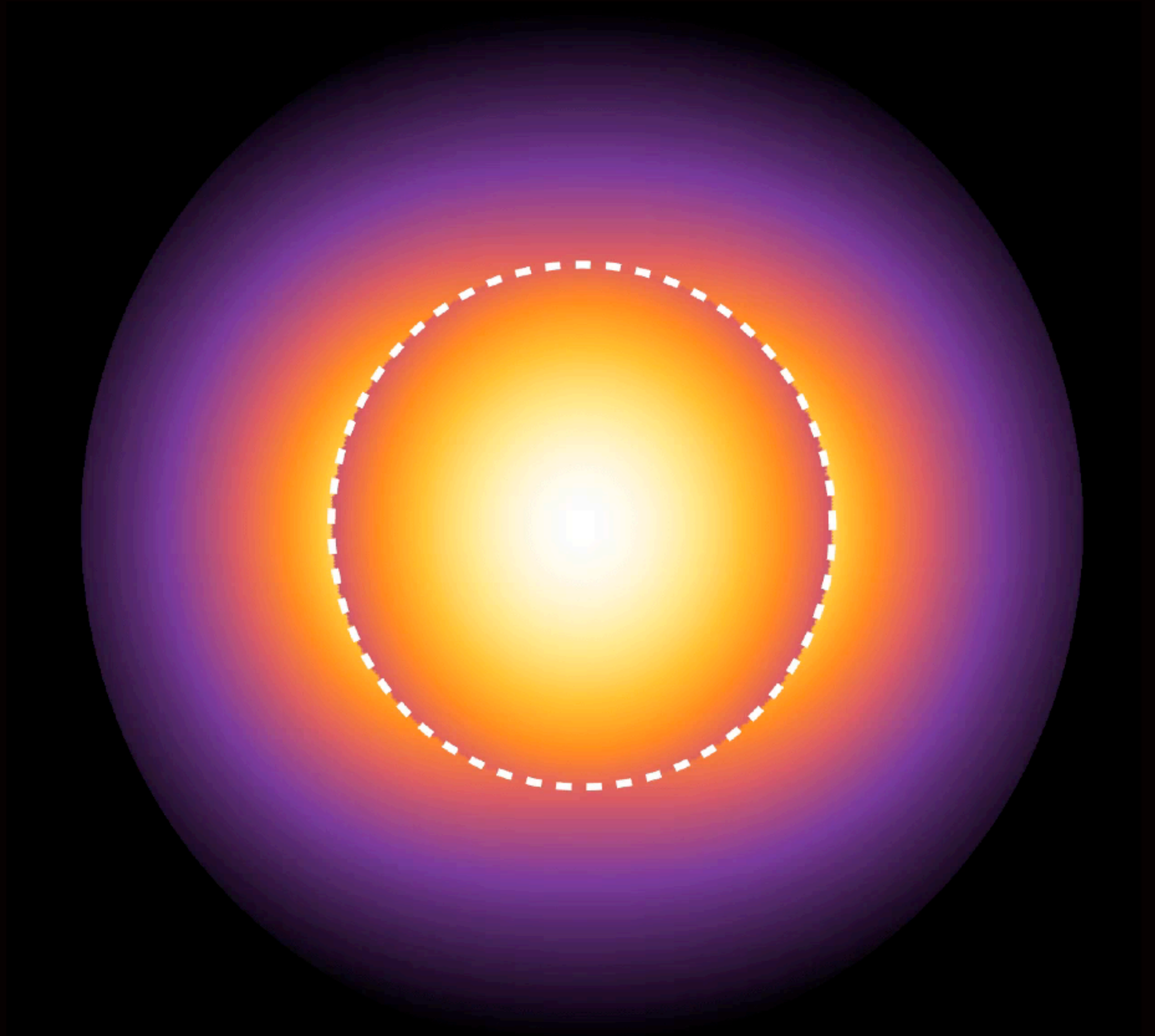
Outline

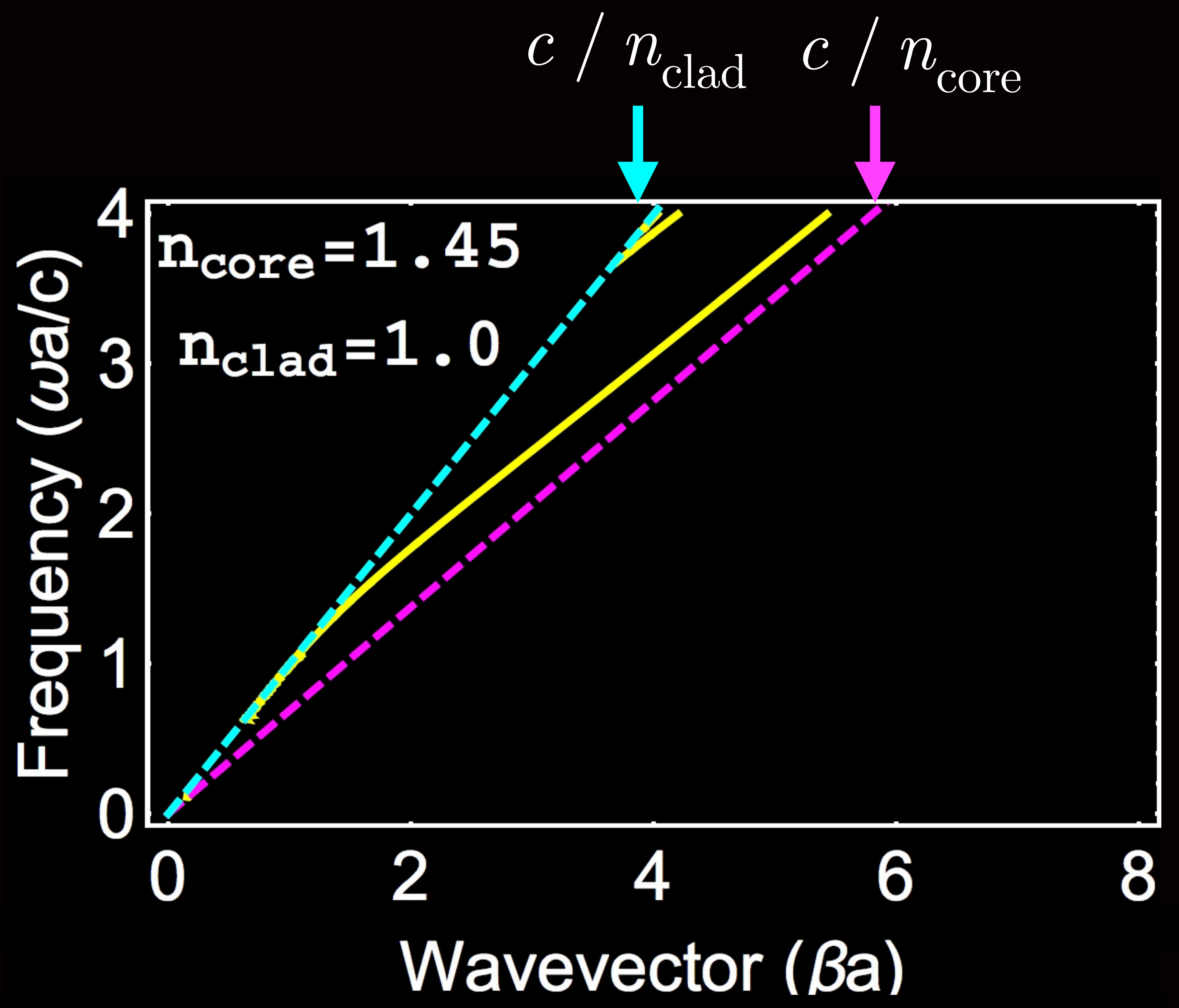
- Introduction to Brillouin Scattering
- Mechanical modes
- Optical modes
- Harnessing Brillouin interaction
- Optomechanical cavities
- Final remarks

Sub-wavelength confinement



$$n_{\mathrm{Si}} \approx 3.5$$
$$n_{\mathrm{SiO_2}} \approx 1.45$$


Electric field amplitude
HE_{11x} mode



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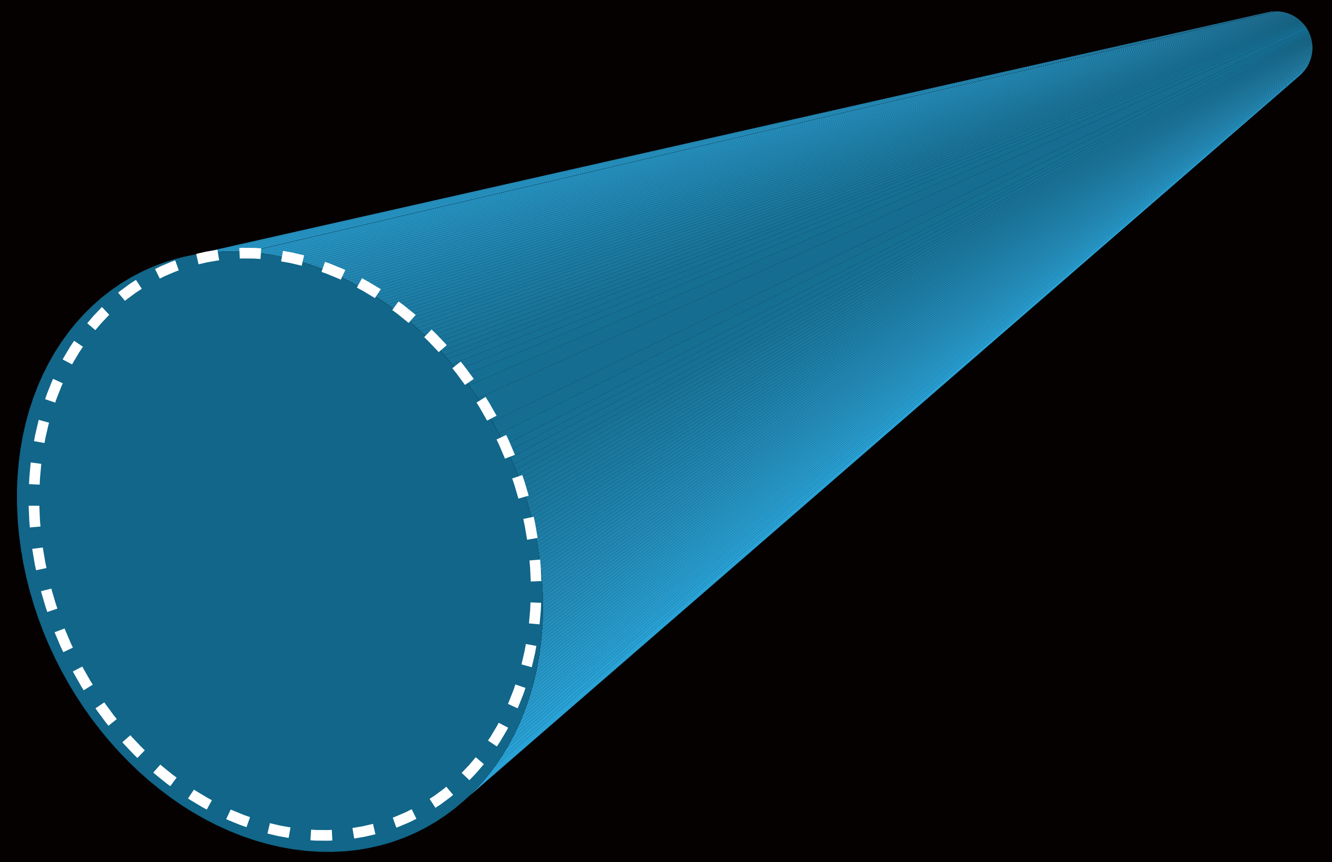

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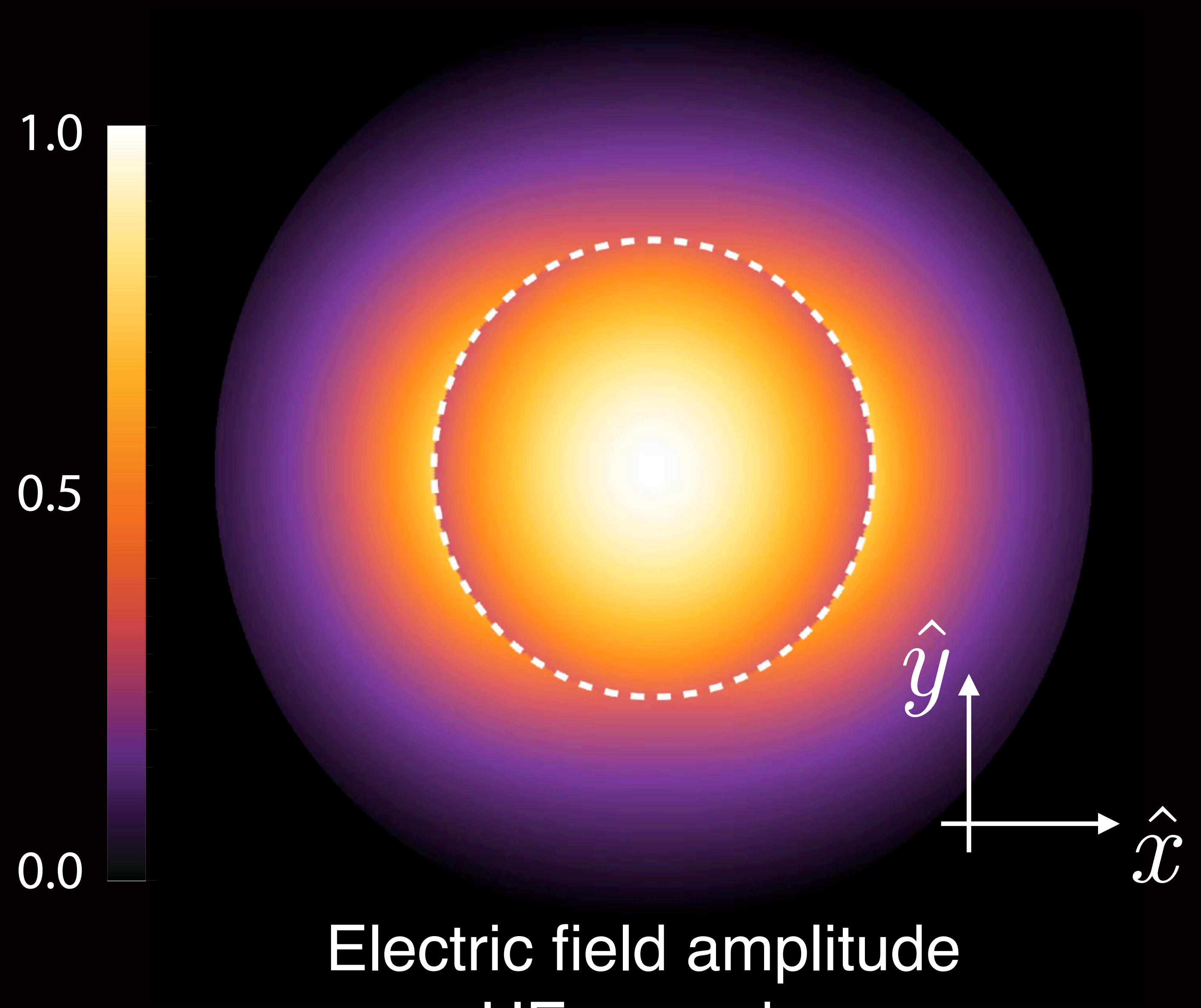

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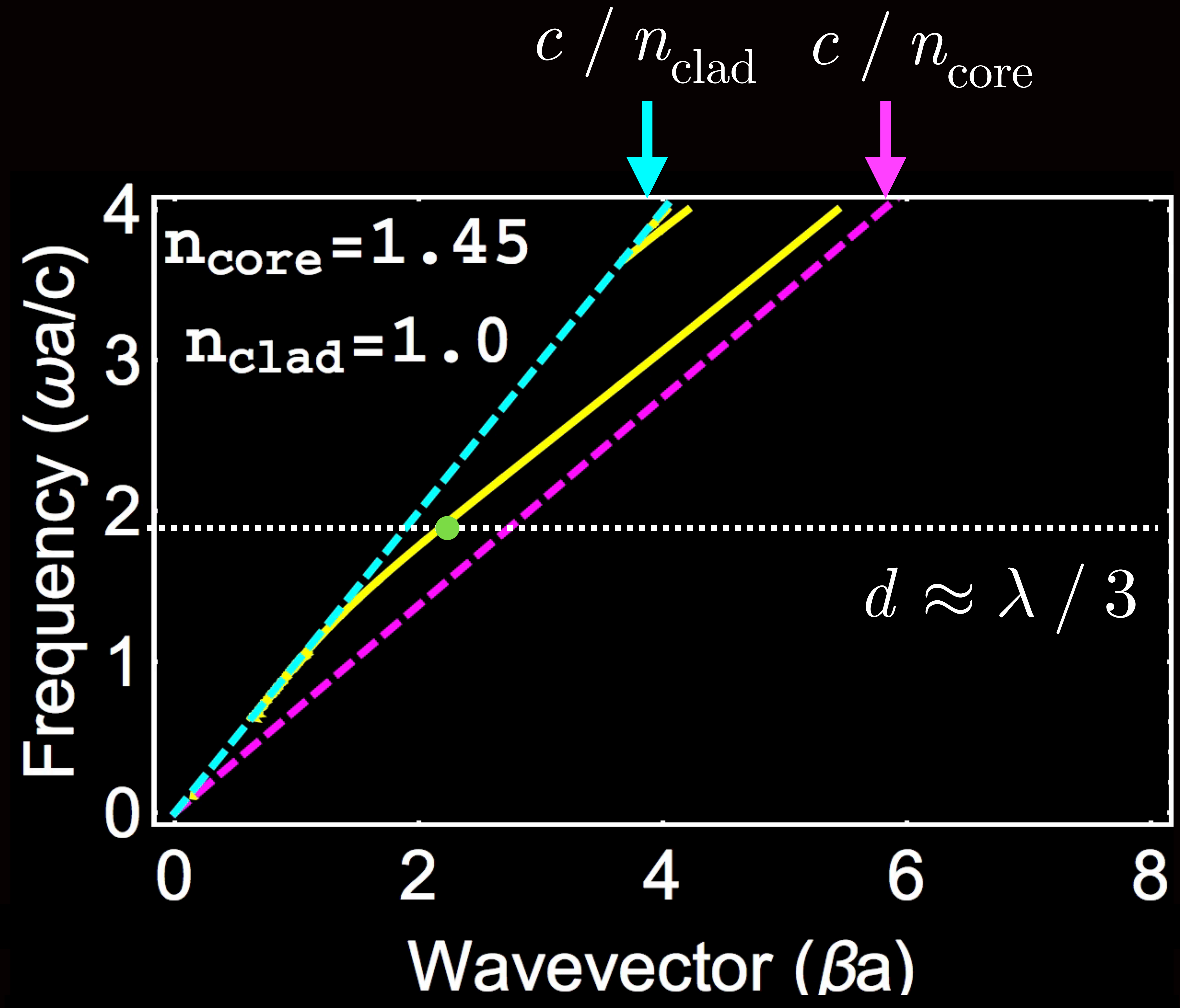

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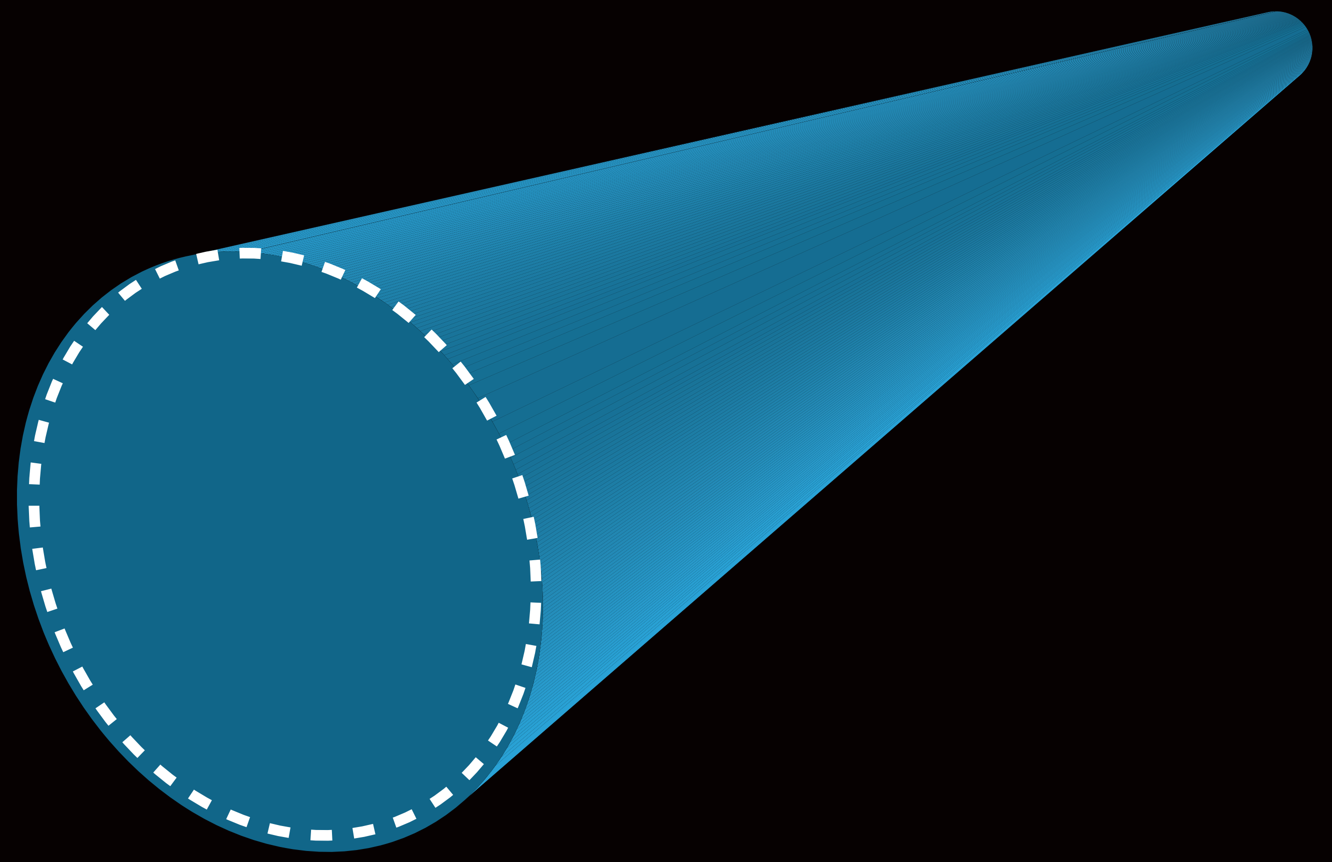

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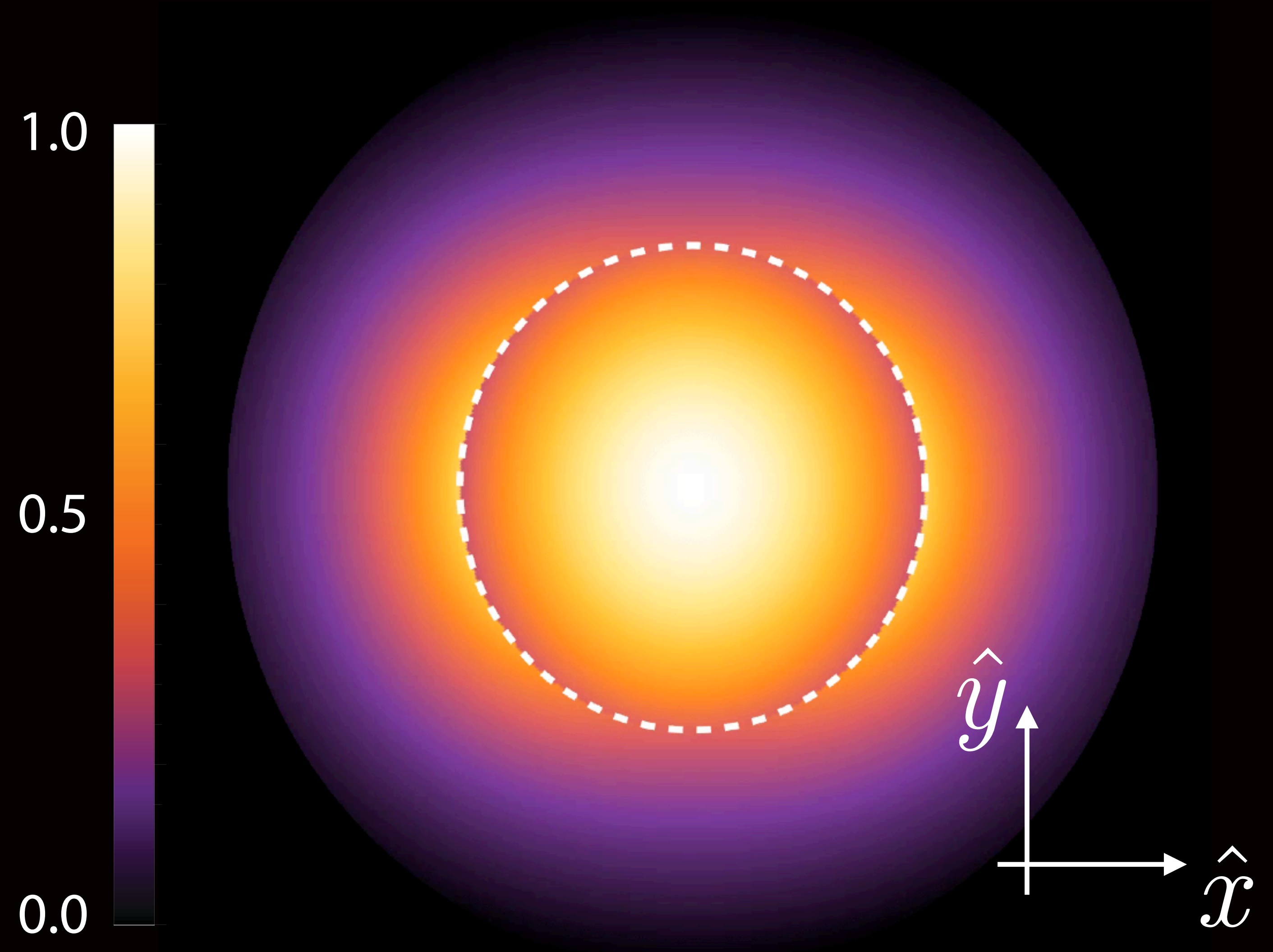

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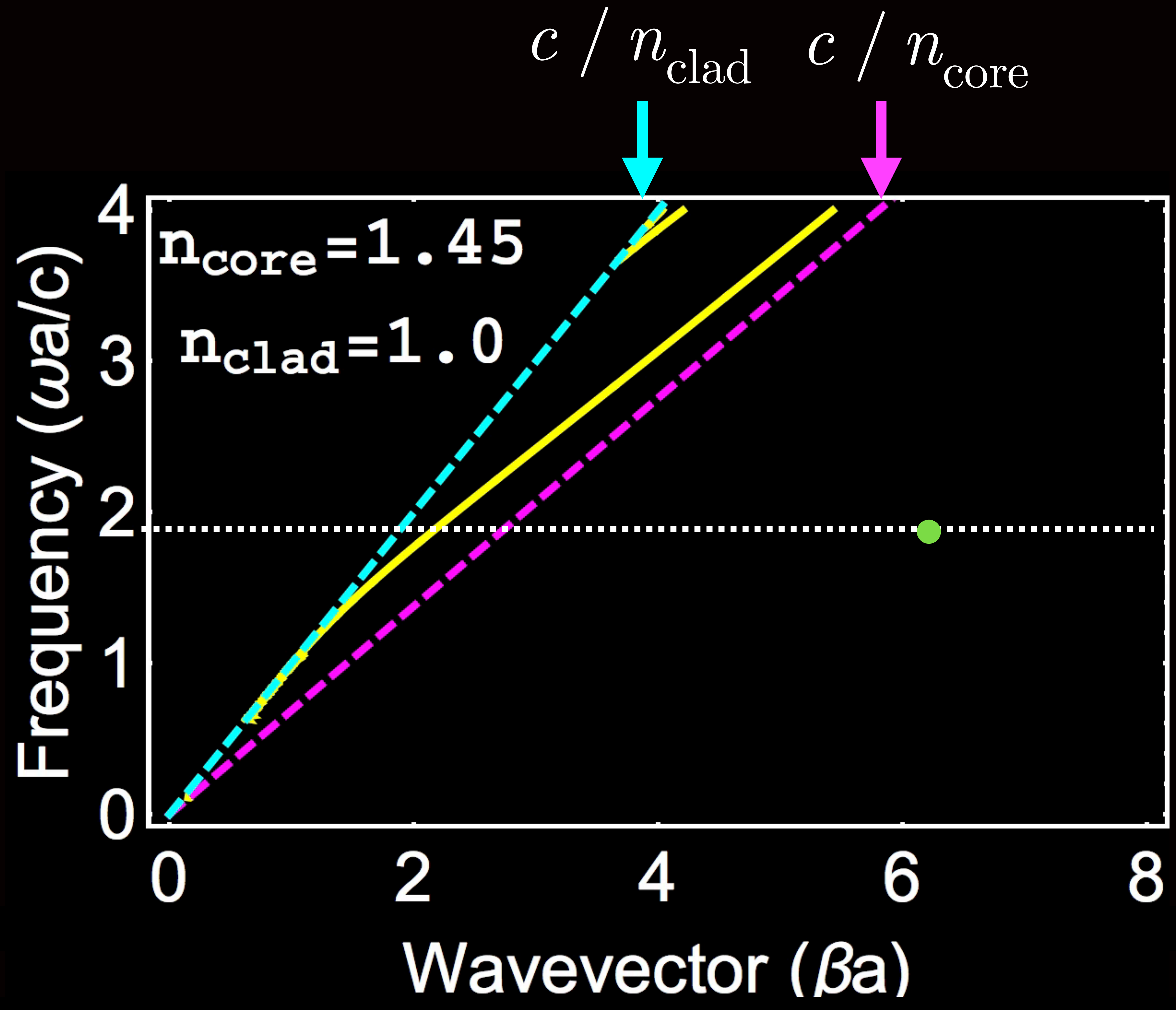

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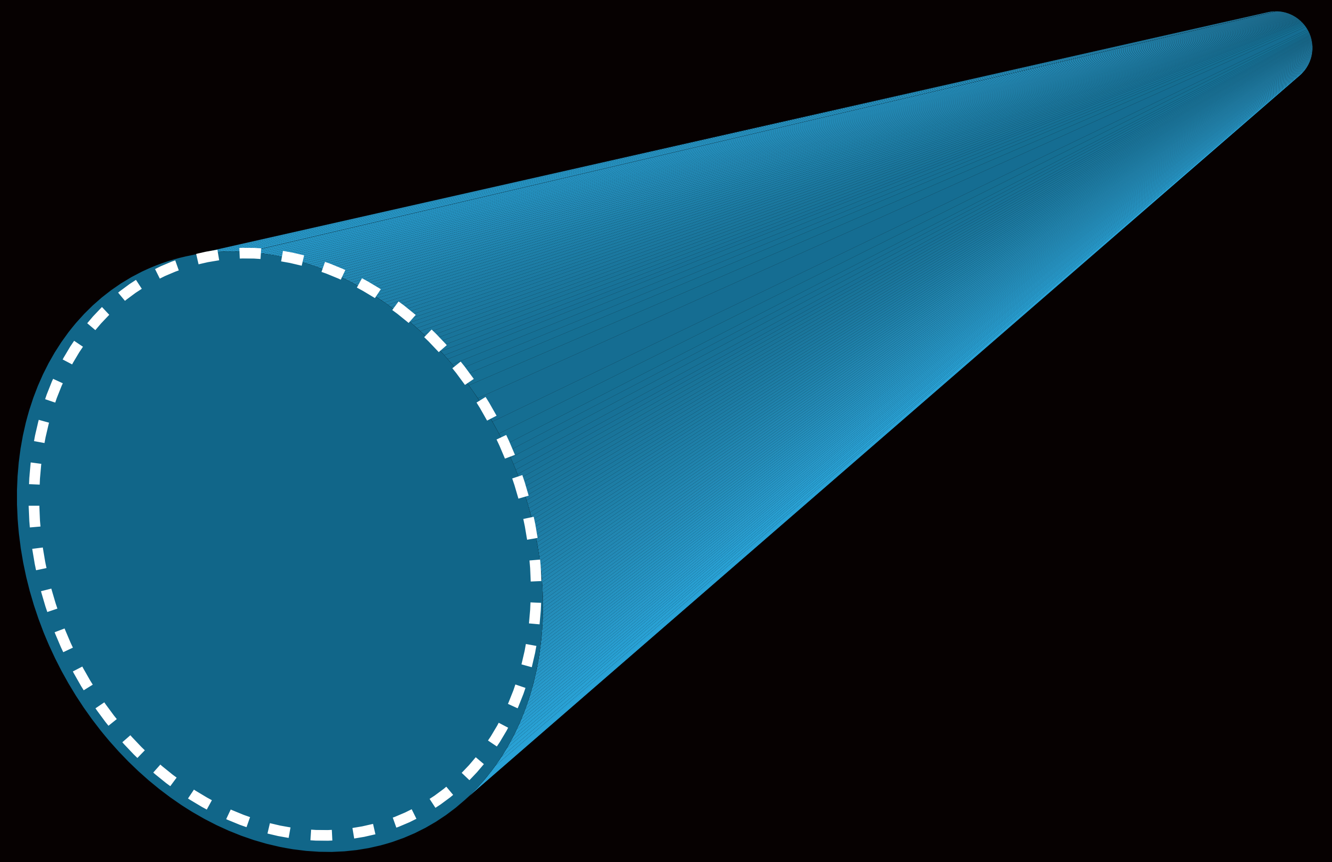

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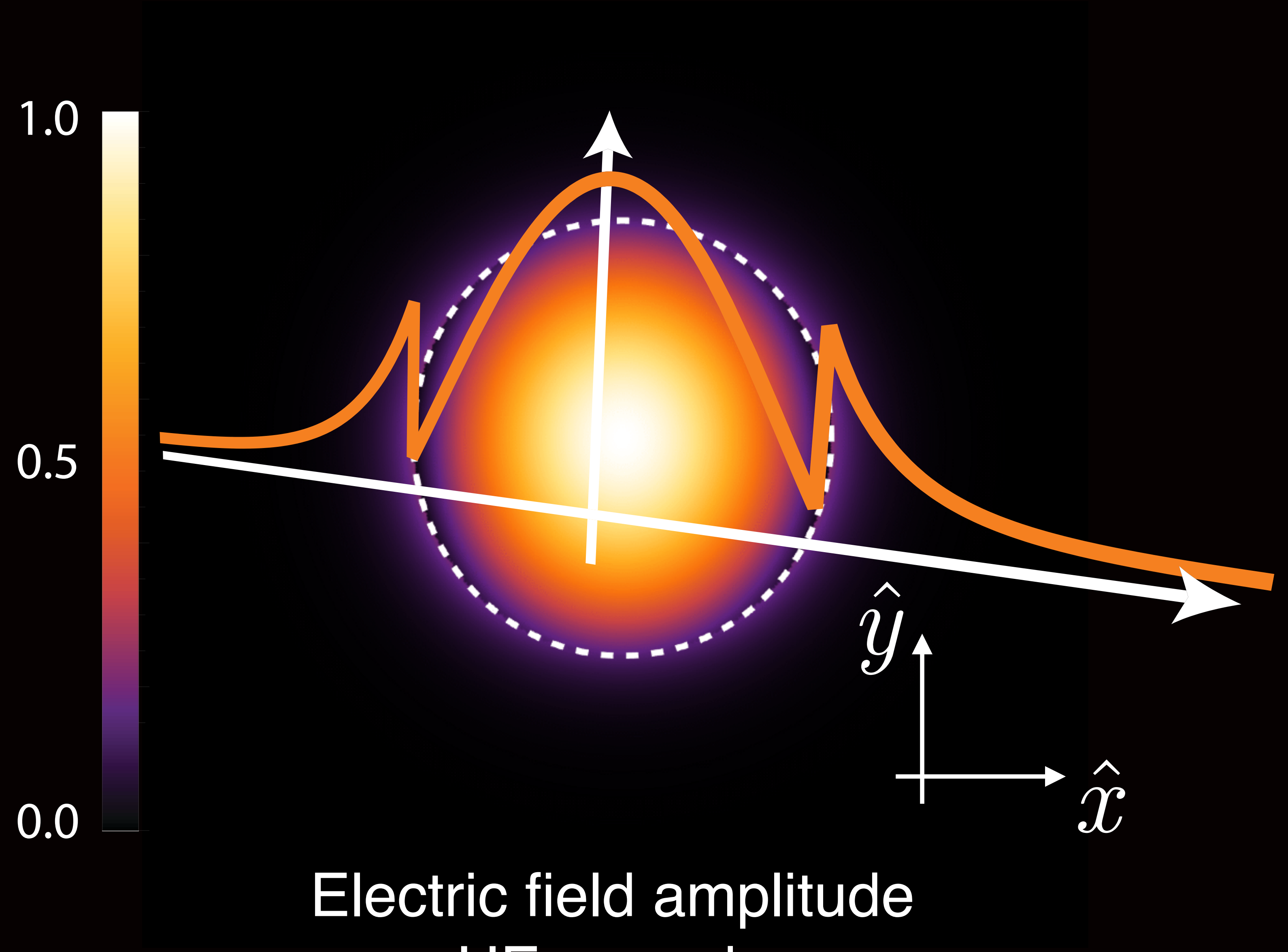

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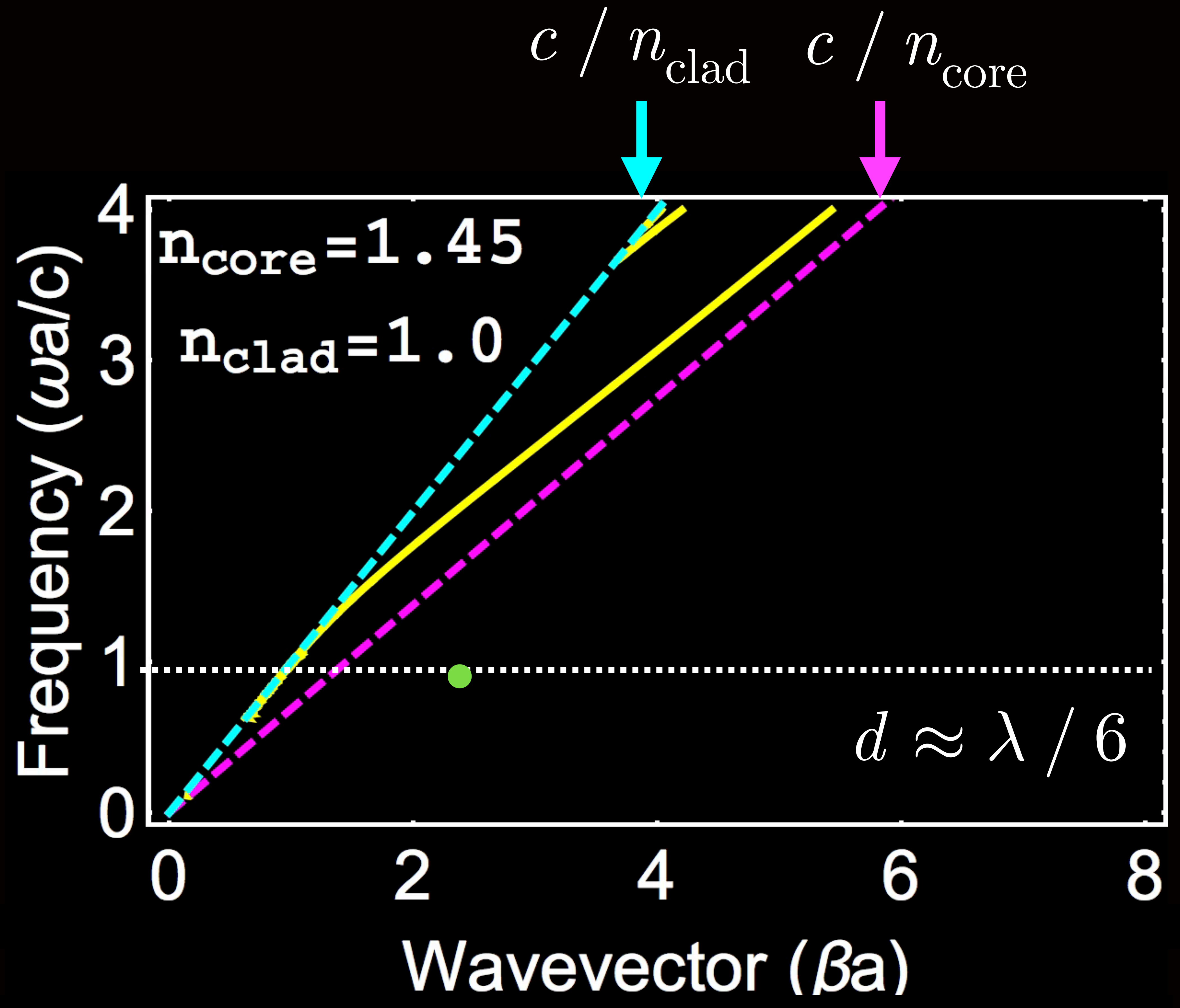

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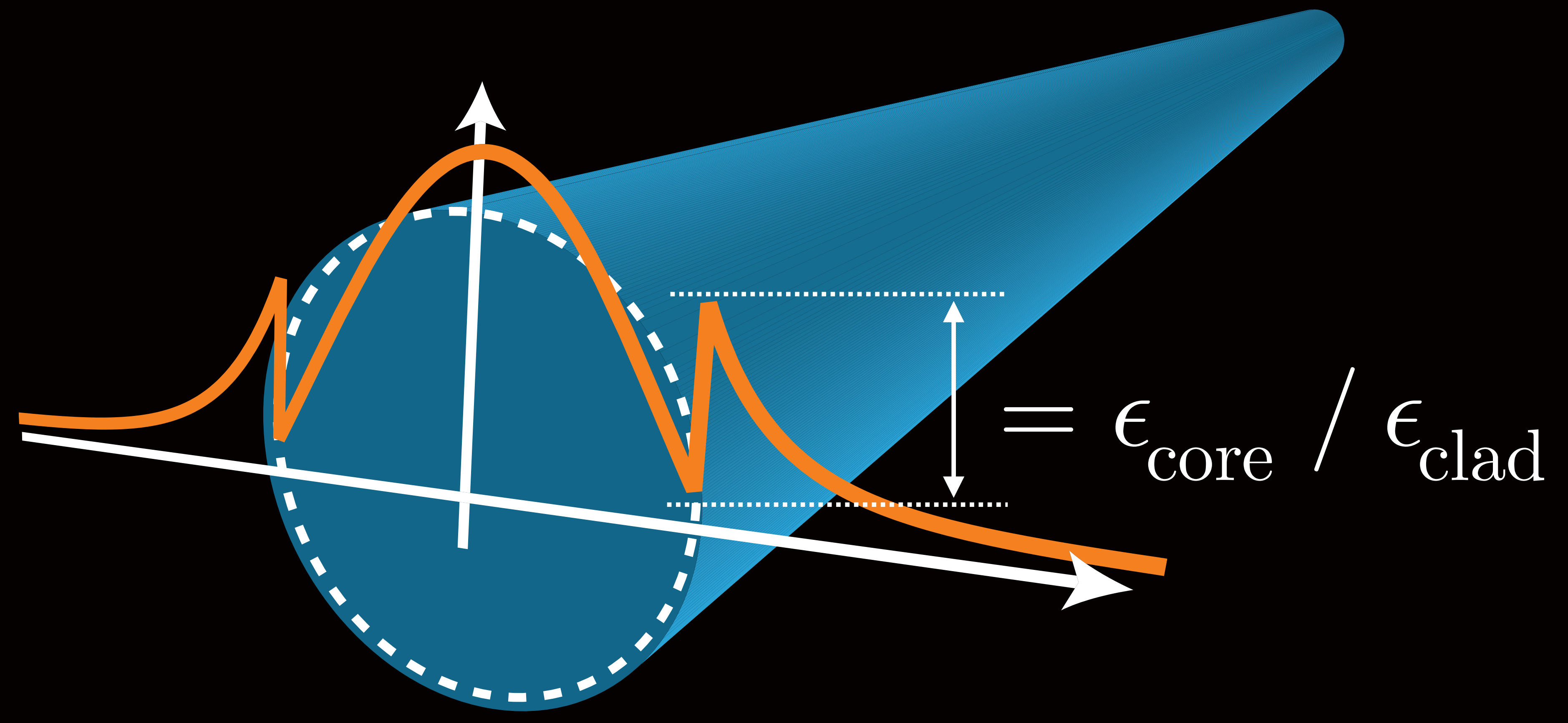

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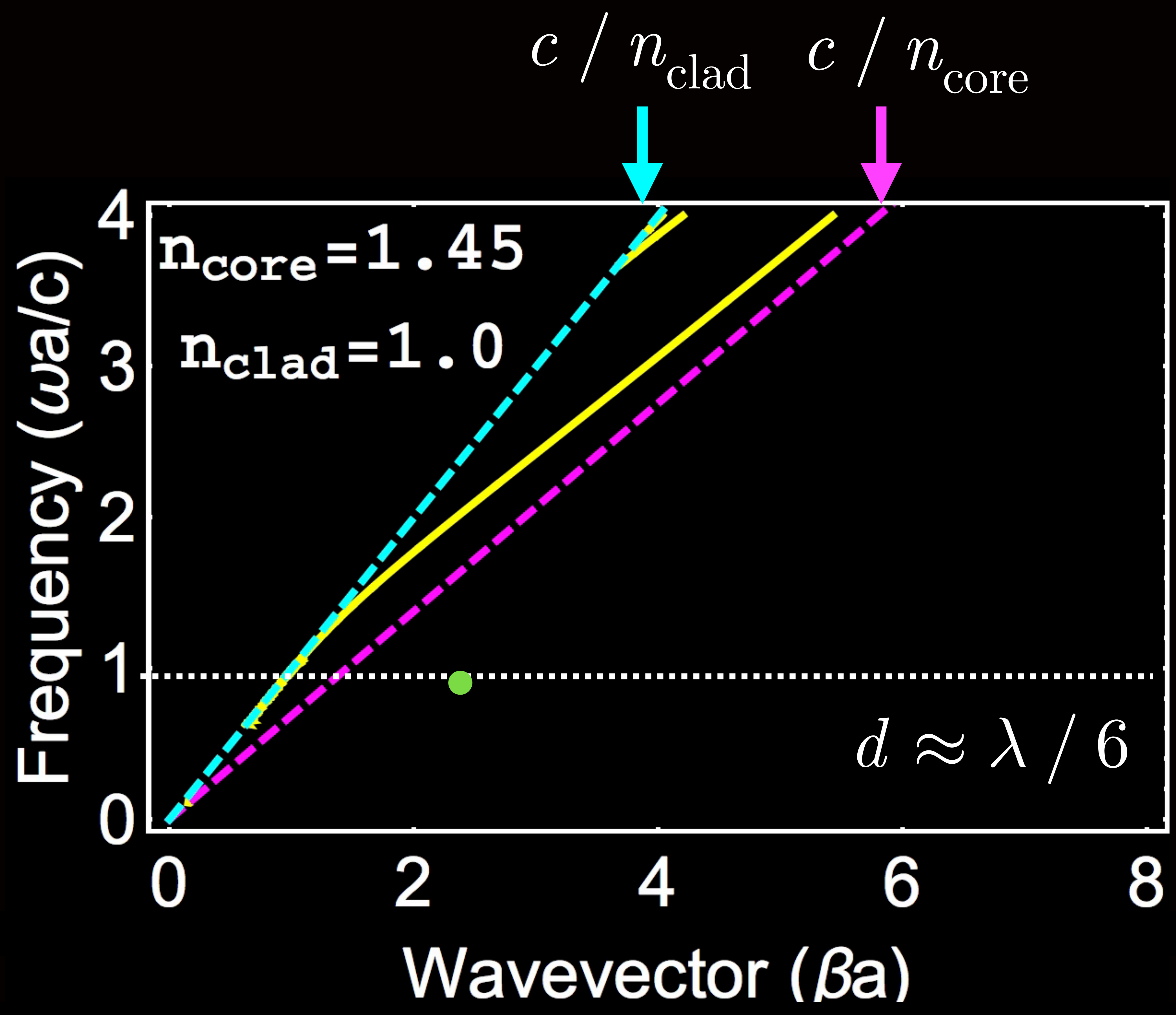

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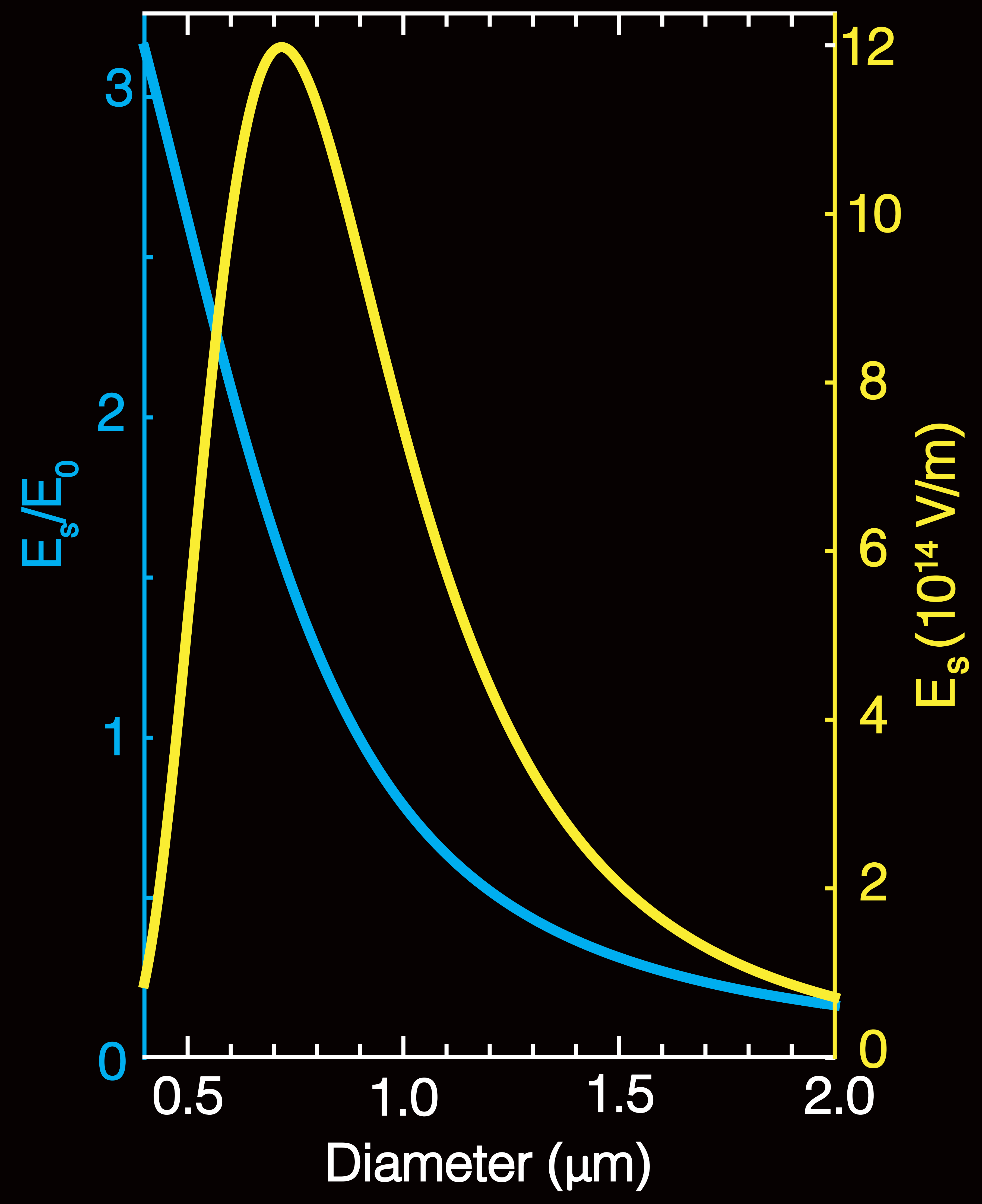
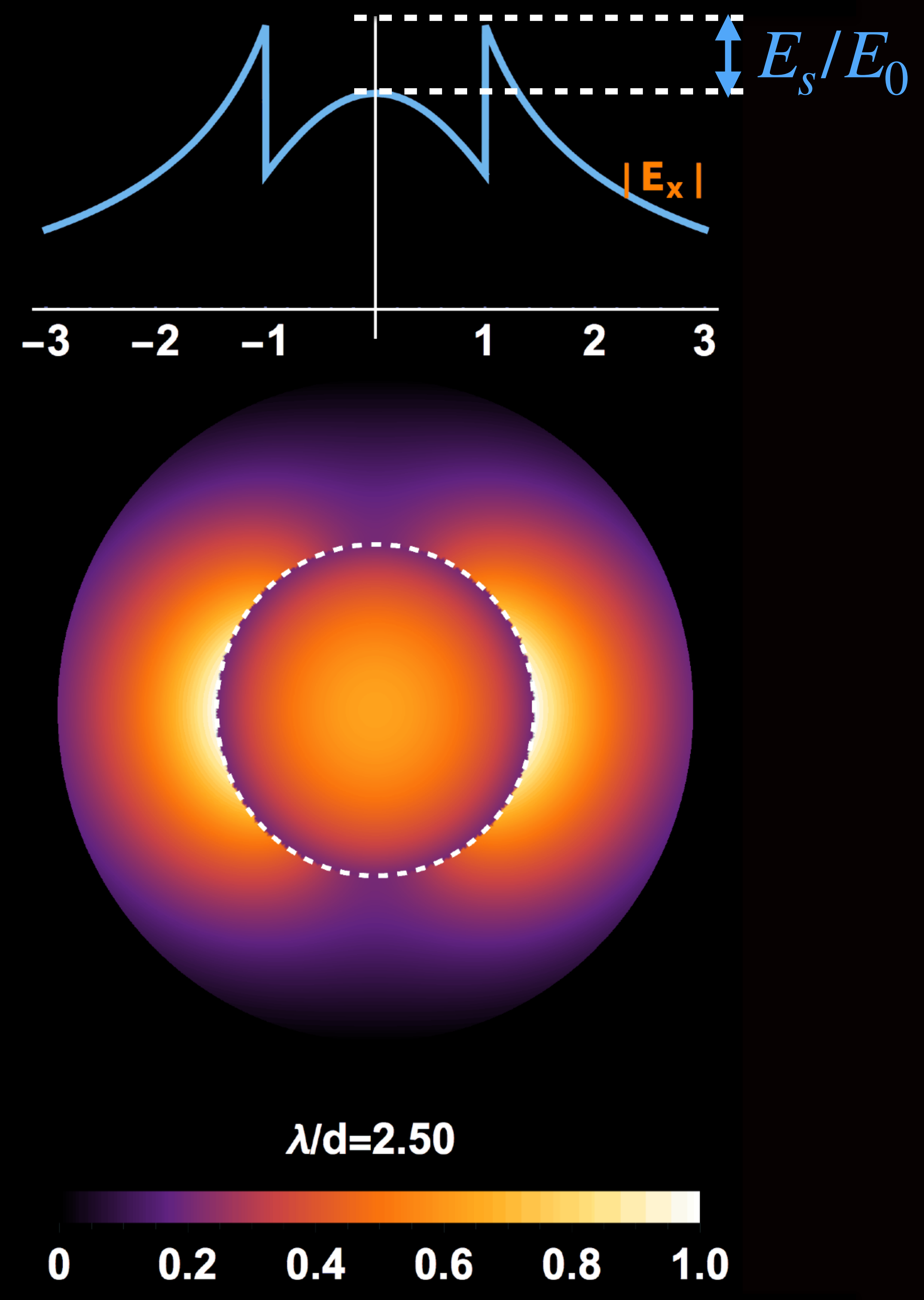
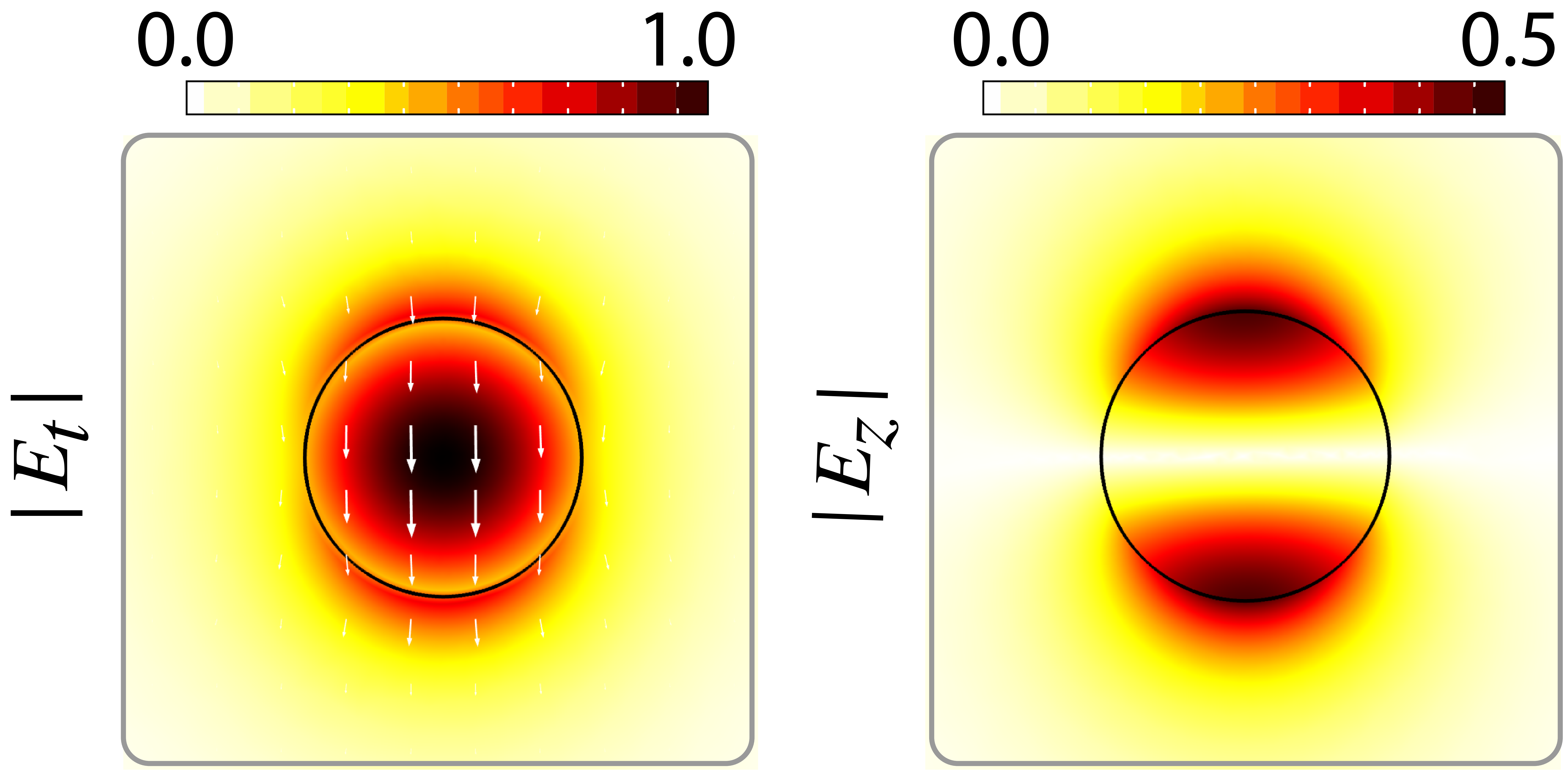




Vectorial modes



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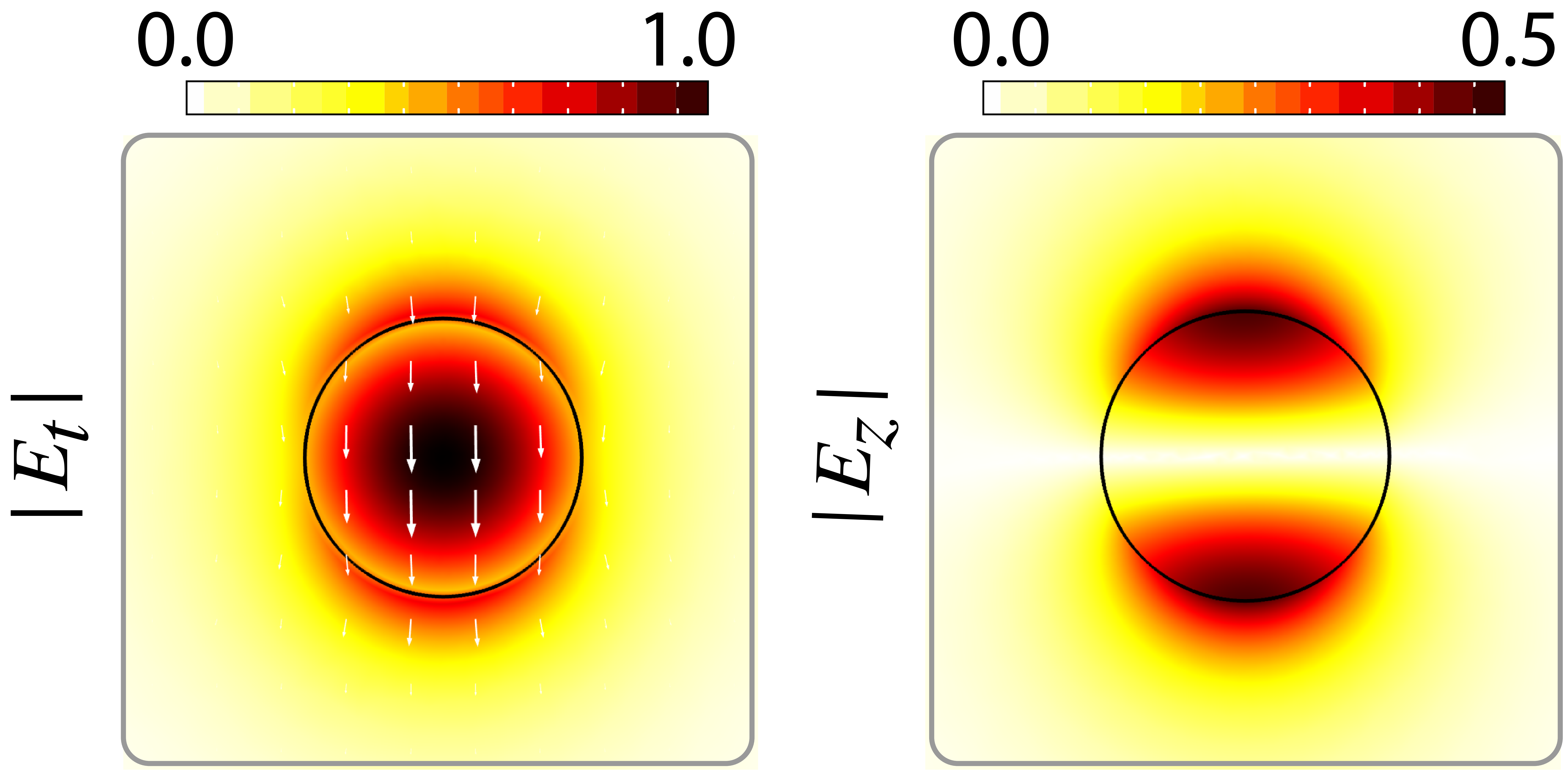
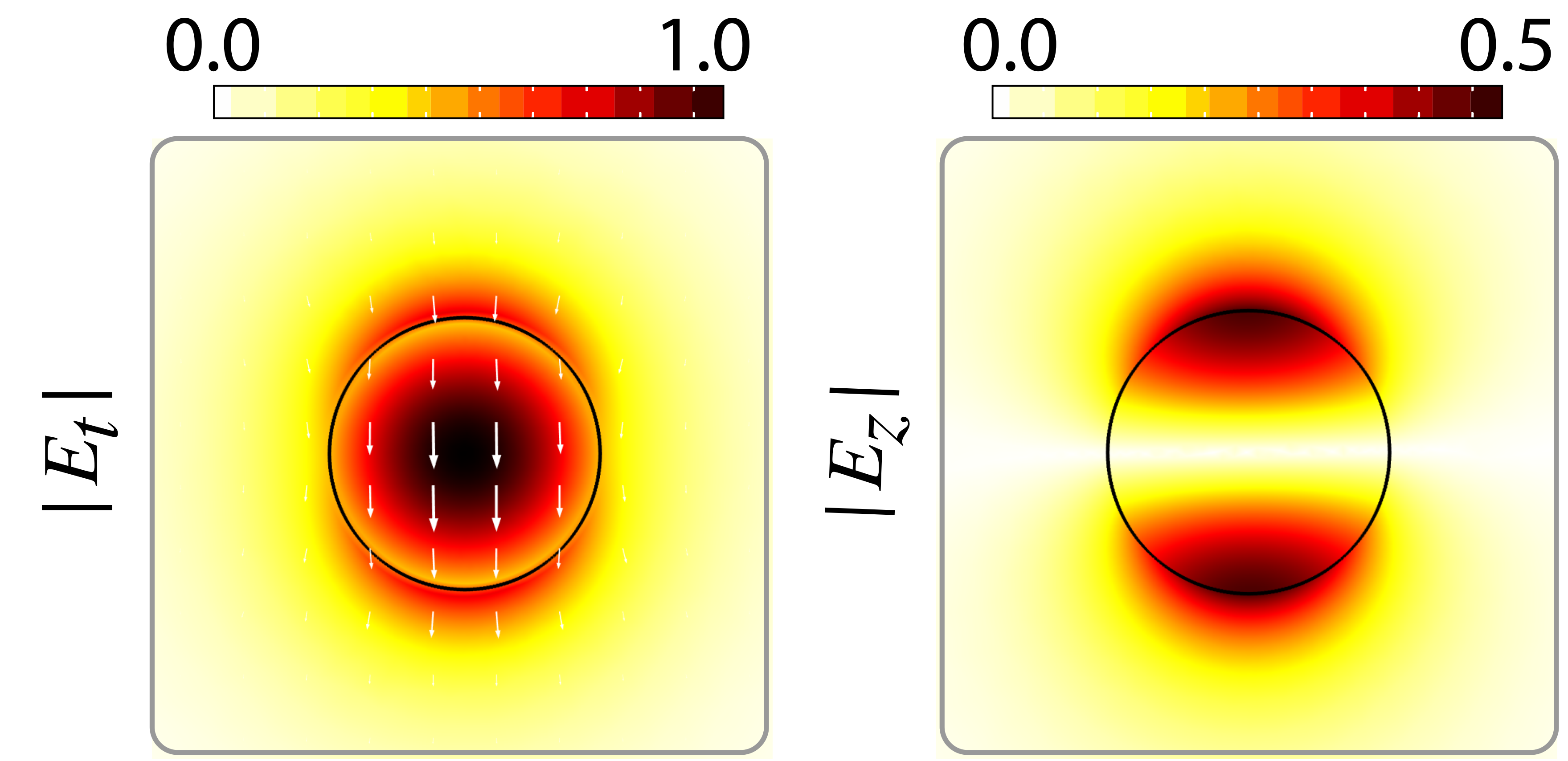
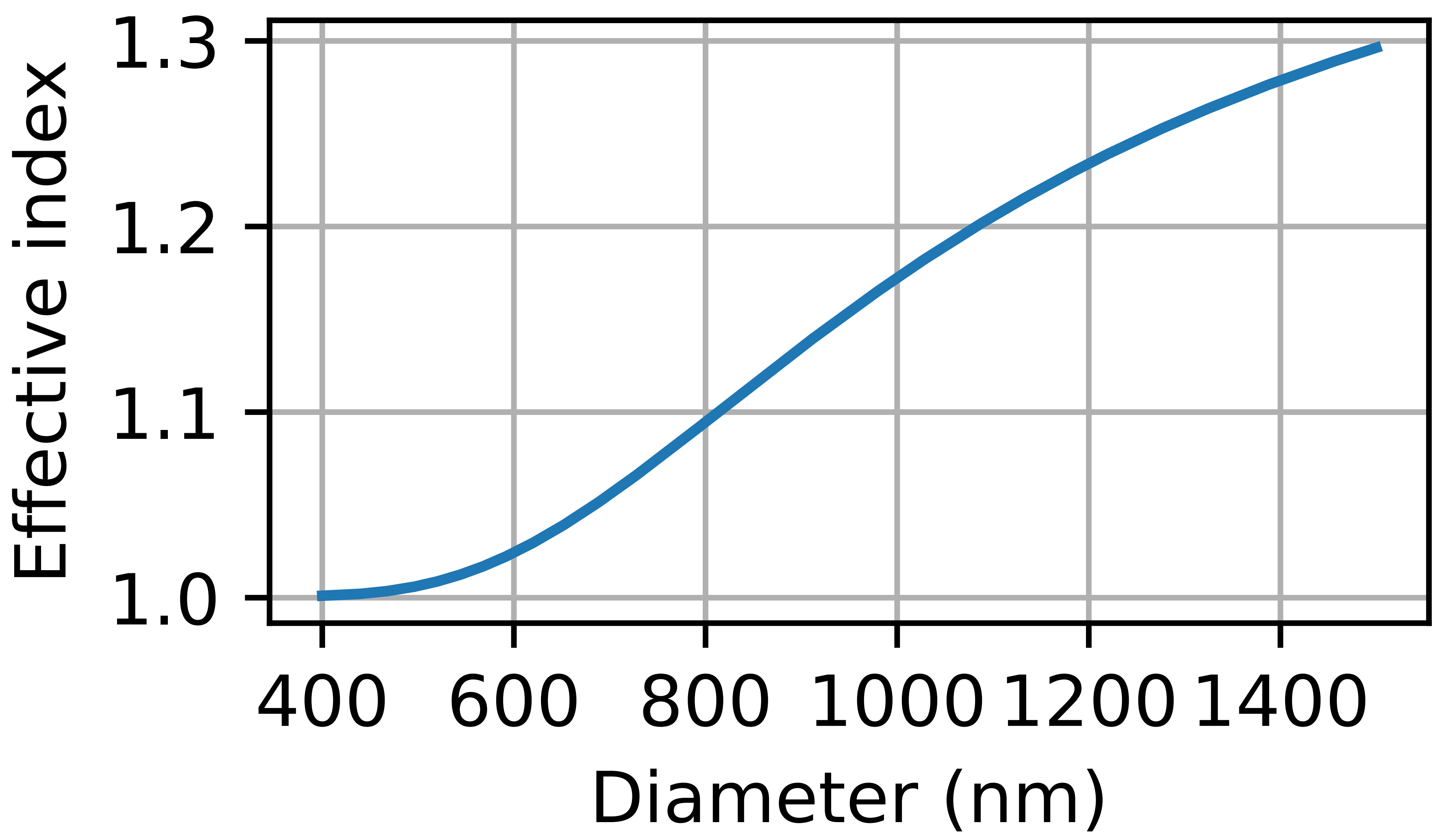
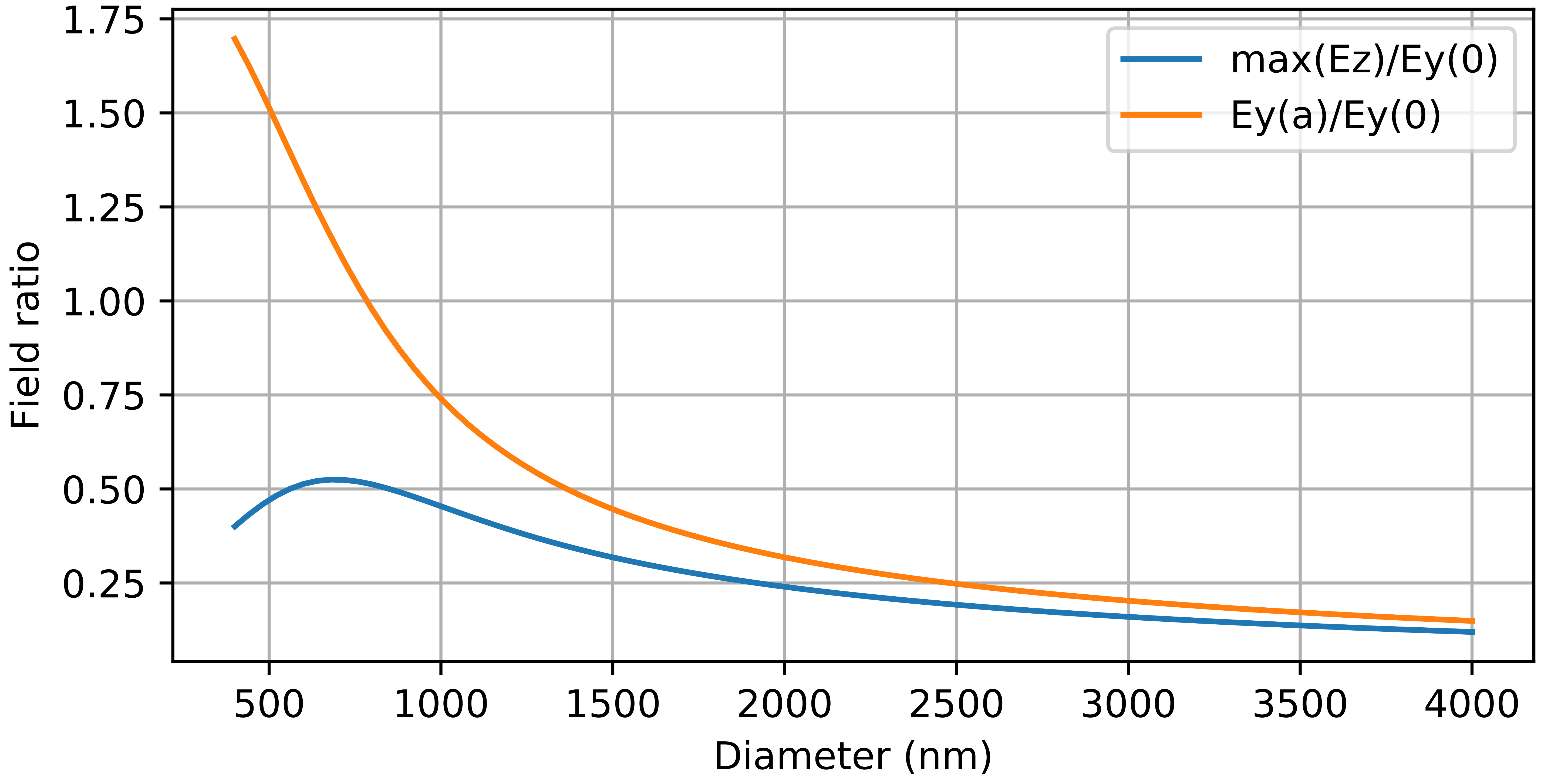


Estimate the ratio between E_z and E_y. Hint: $\vec{\mathscr{E}} = \vec{E}\, e^{i\beta z}$, use $\nabla . \mathbf{D} = 0$

Vectorial modes







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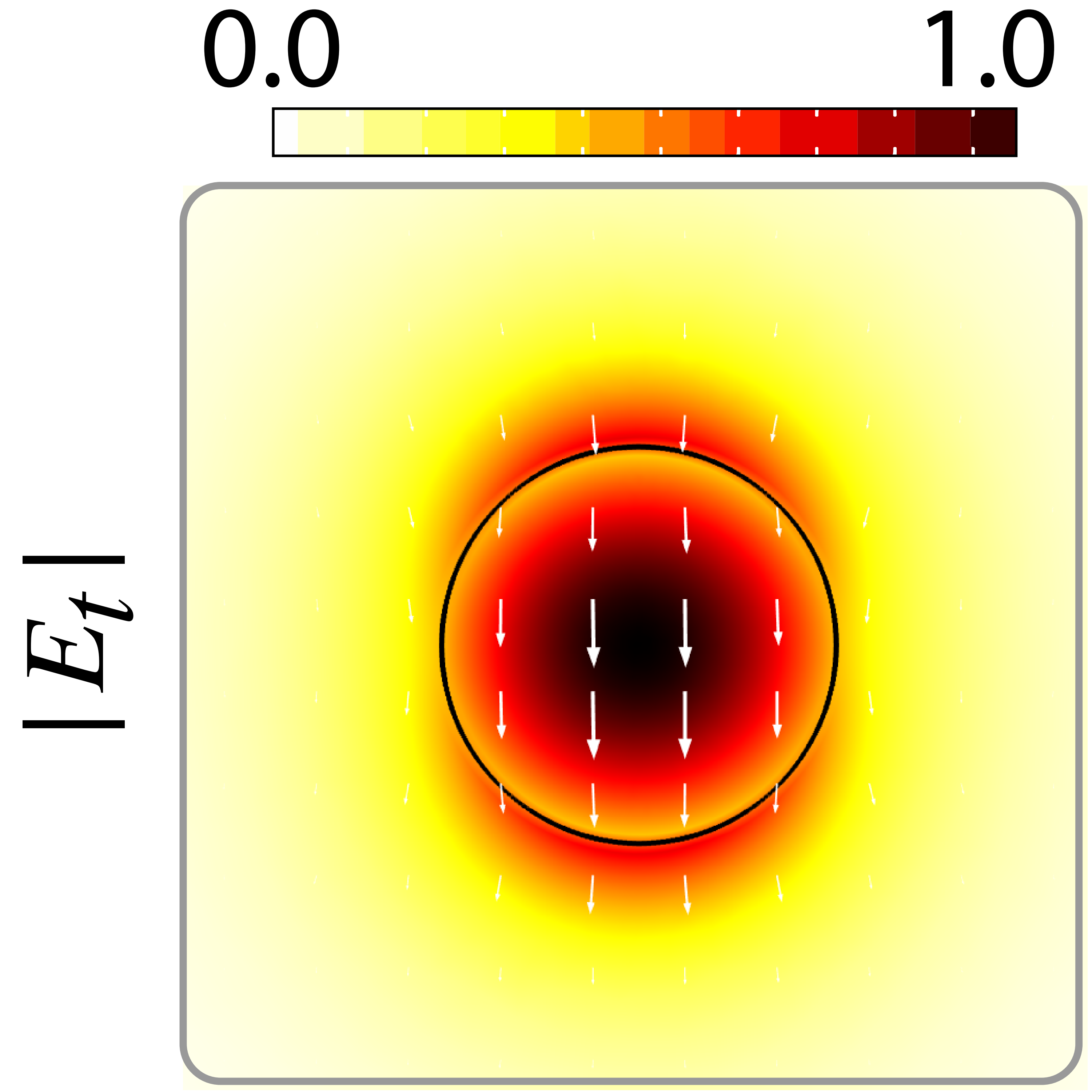

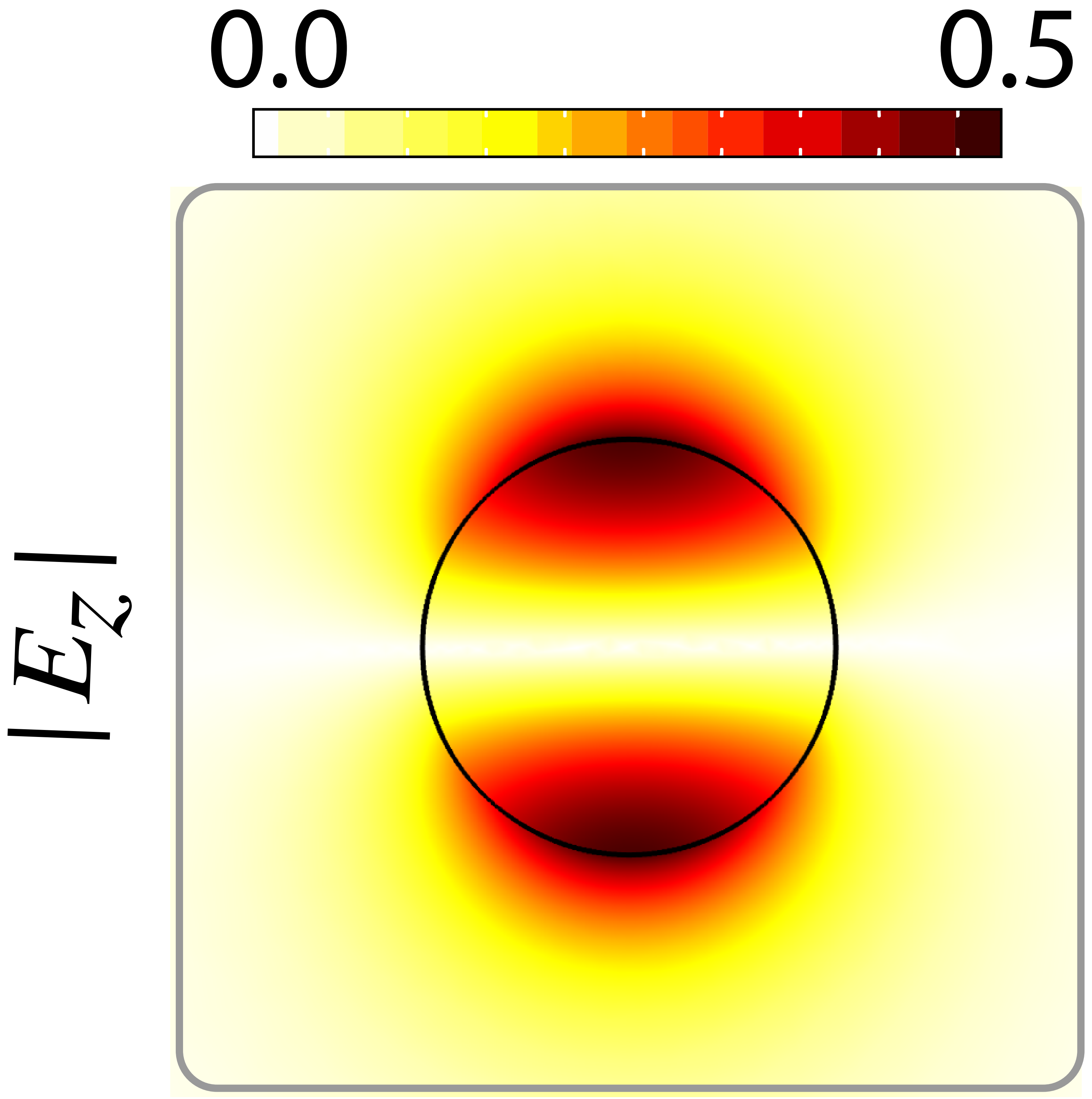

$$\nabla\,.\,\mathbf{D} = 0$$

$$\frac{E_z}{E_\mathrm{t}} \approx \frac{1}{2\pi n_\mathrm{eff}}\left(\frac{\lambda}{a}\right)$$

$$\frac{E_z}{E_\mathrm{t}} \approx 0.42$$

$n_{eff} = 1.17$; $2a = 1\mu$m; $\lambda = 1.55\mu$m

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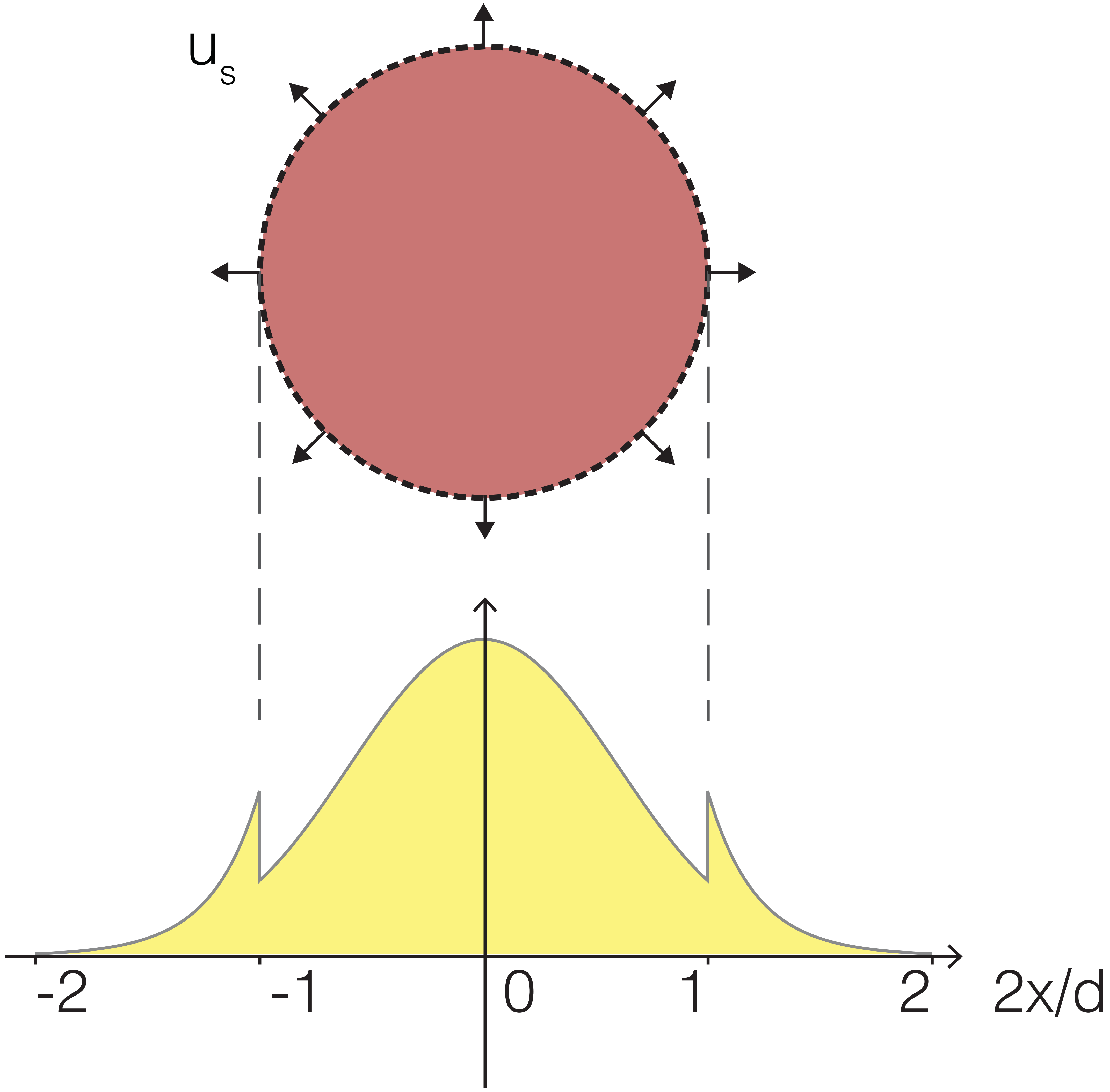
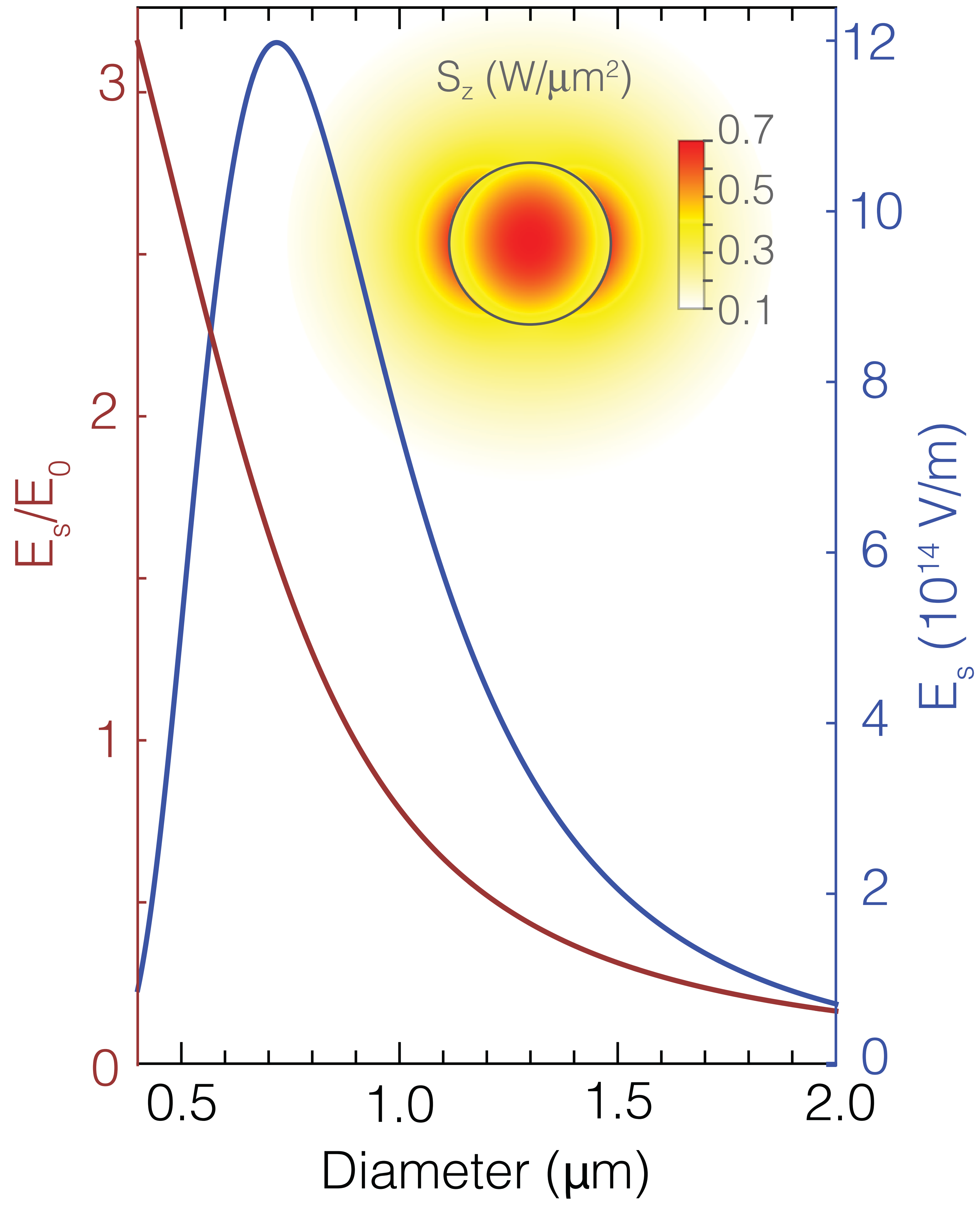
Photo-elastic (pe) vs. moving boundary (mb)





O. Florez et al. “Brillouin scattering self-cancellation,” Nat Comms, vol. 7, p. 11759, (2016).

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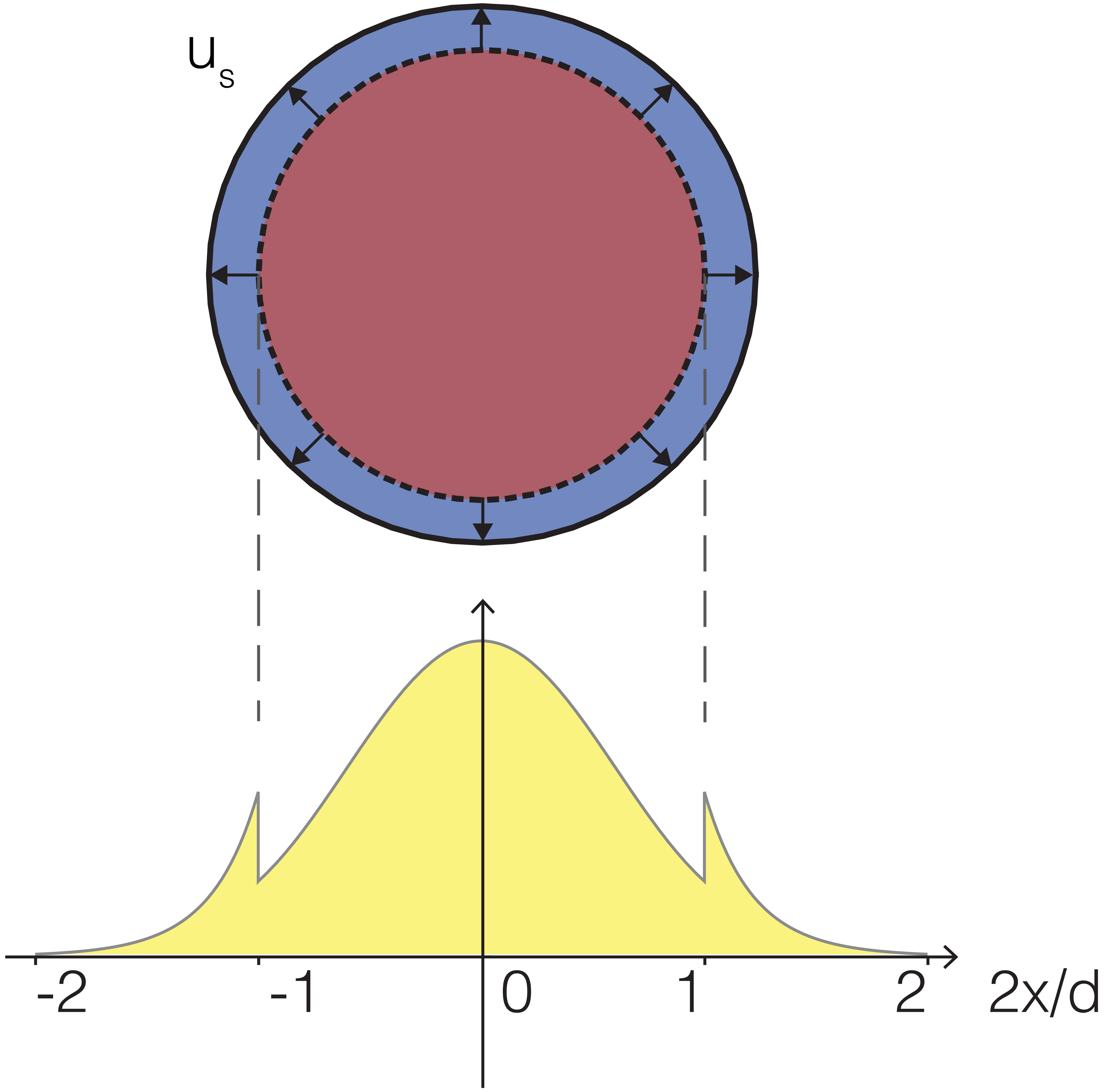

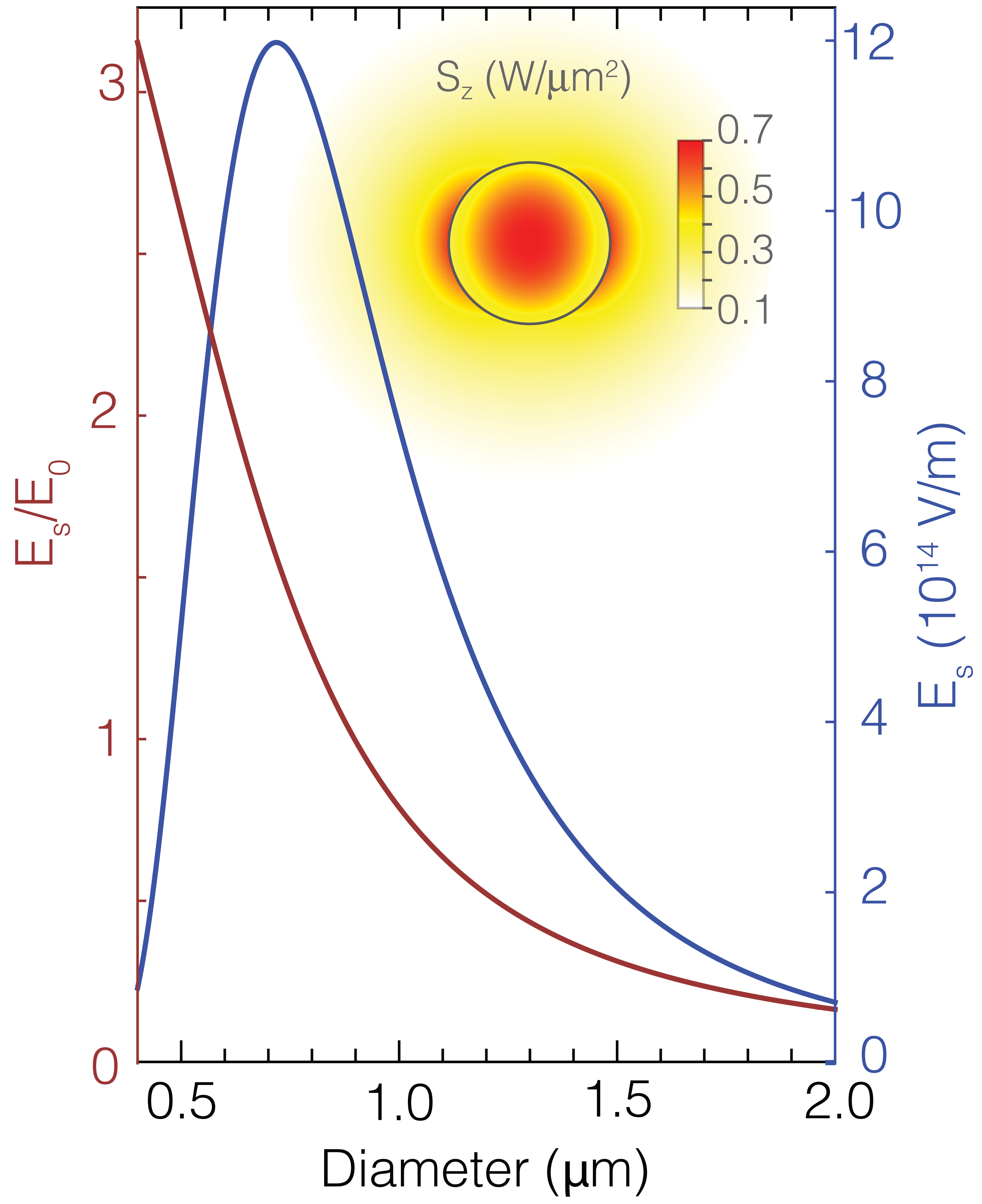

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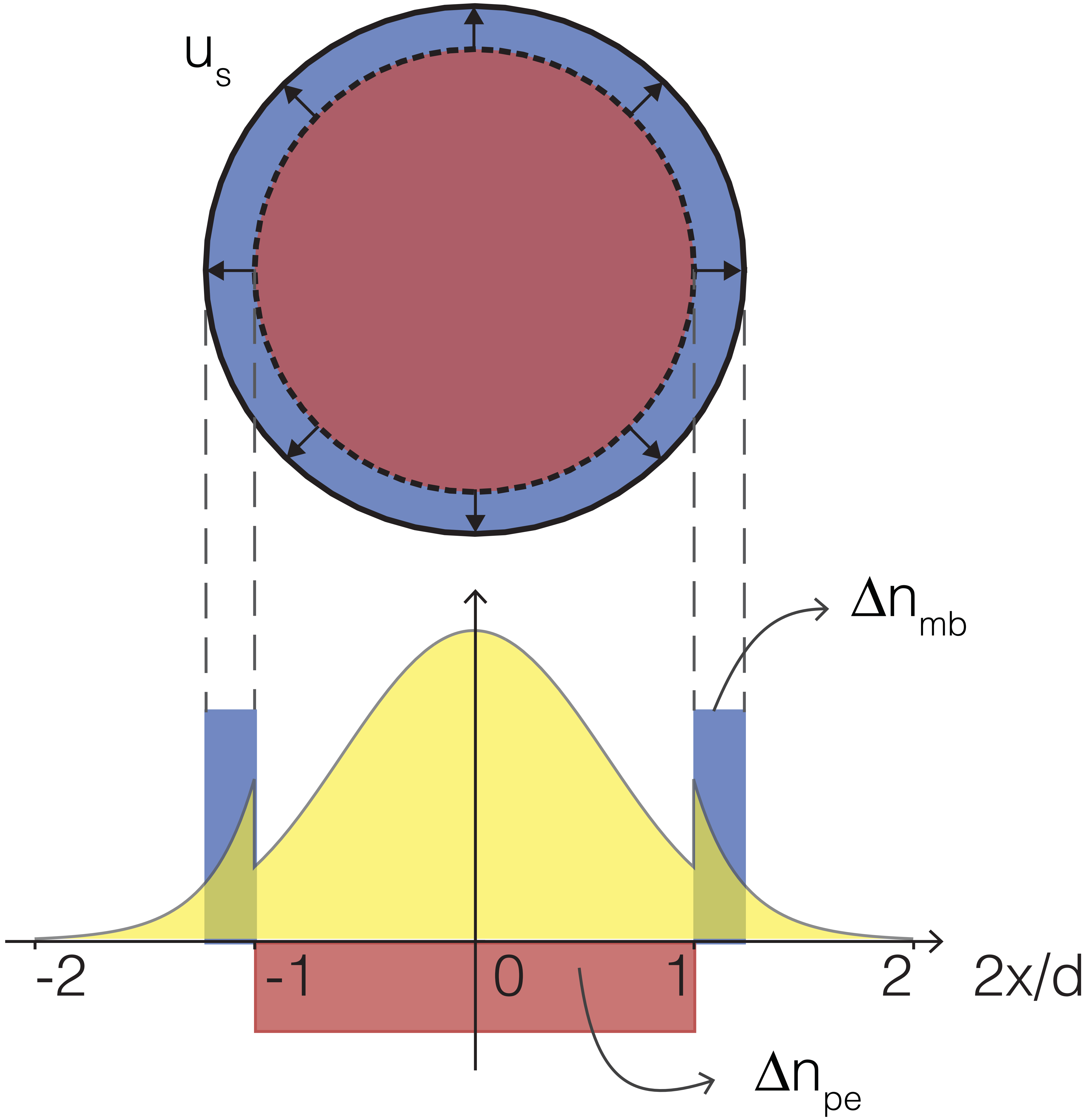

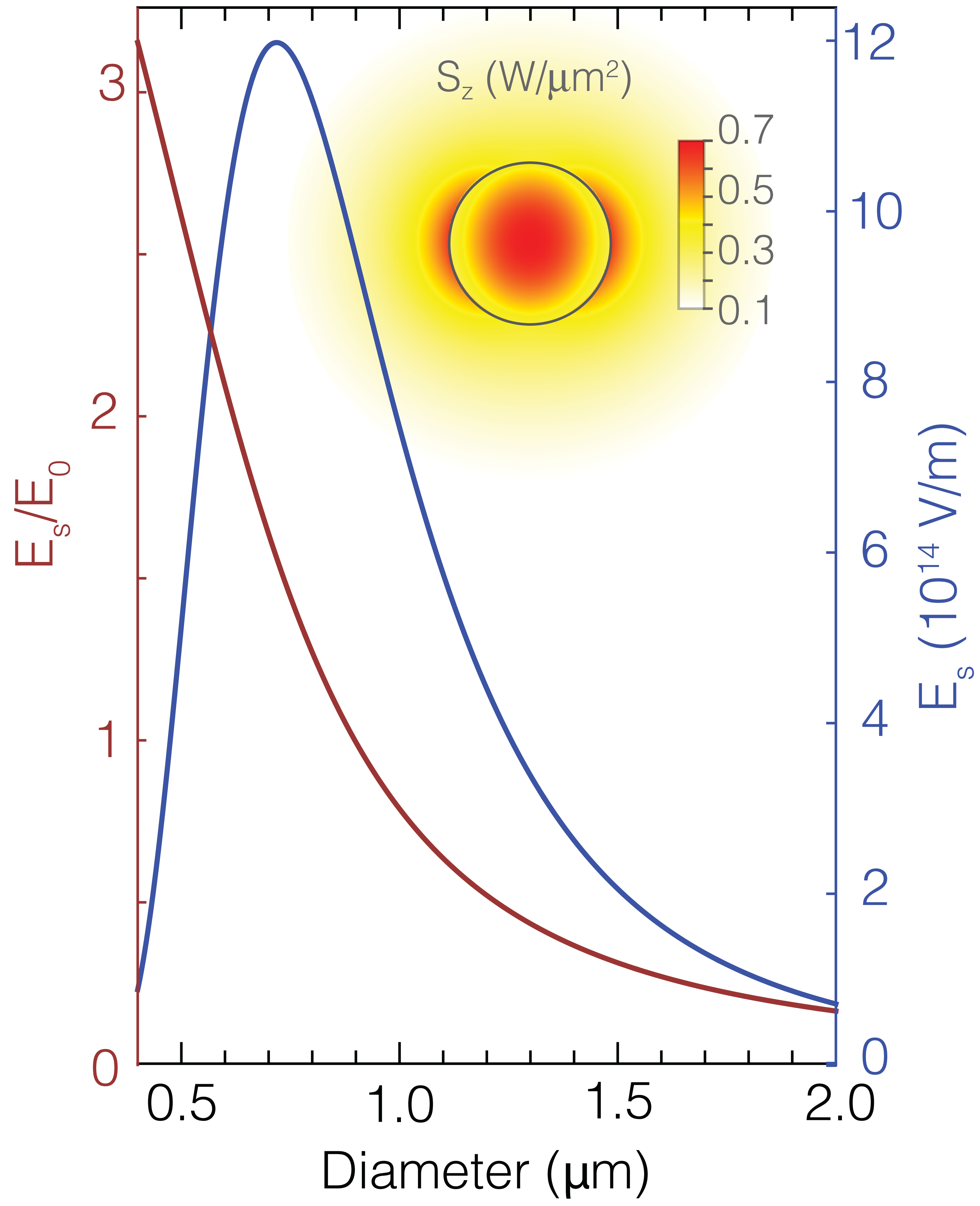

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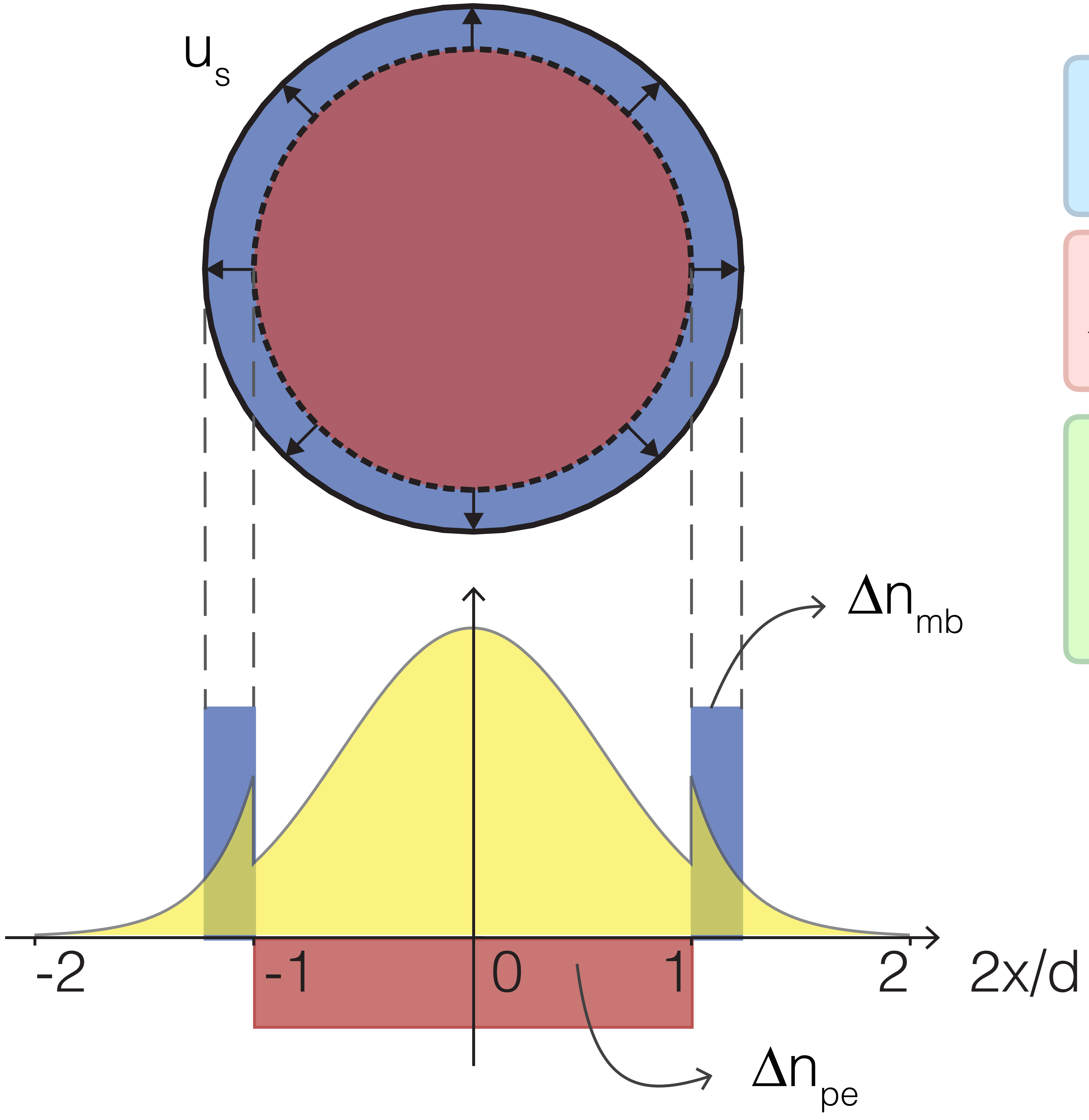


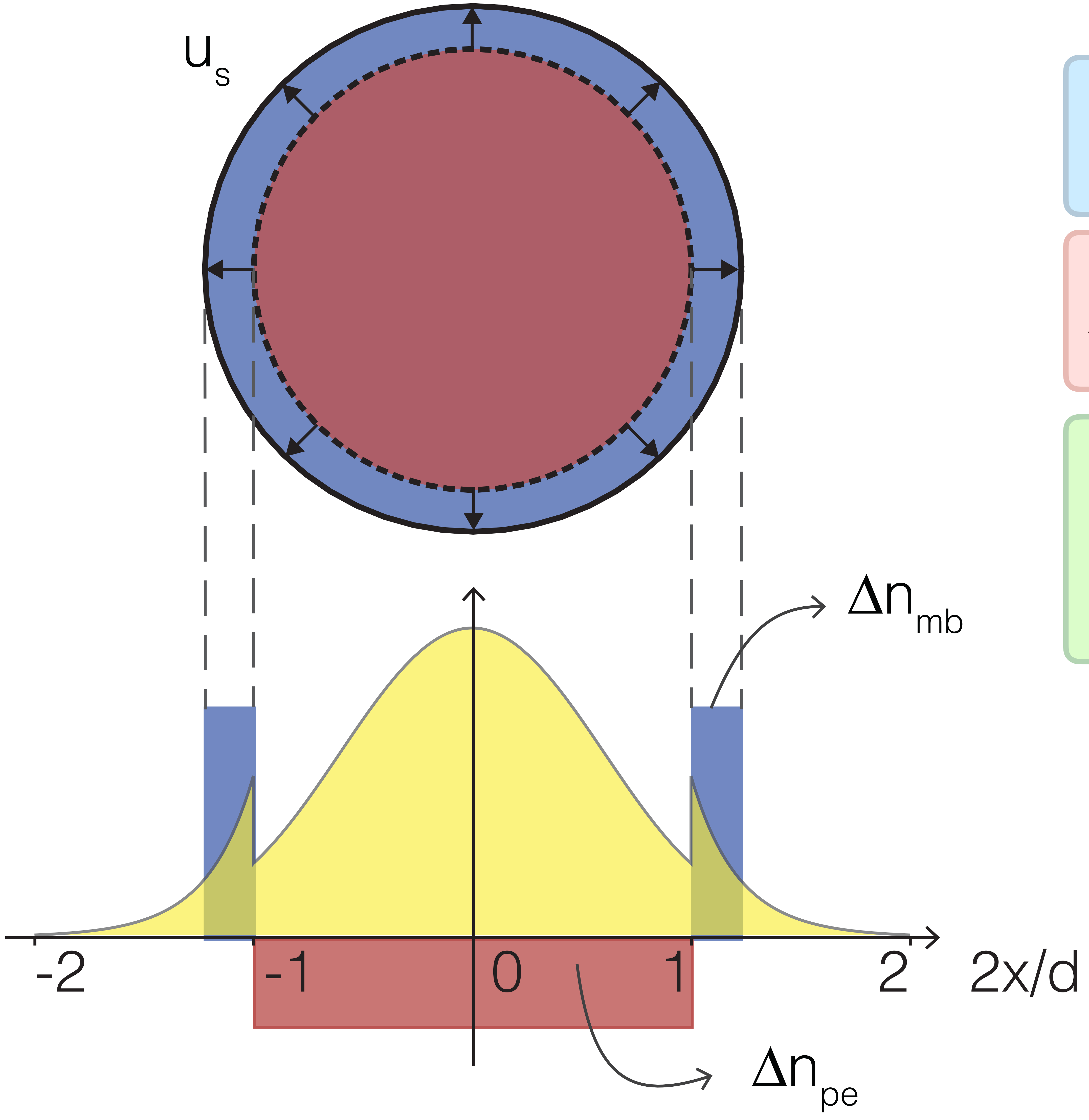
$$A_{\mathrm{mb}} = \pi u_s d$$

$$A_{\mathrm{pe}} = \pi d^2/4$$

$$\frac{\Delta n_{\mathrm{pe}} A_{\mathrm{pe}}}{\Delta n_{\mathrm{mb}} A_{\mathrm{mb}}}$$

O. Florez et al. "Brillouin scattering self-cancellation," Nat Comms, vol. 7, p. 11759, (2016).

Photo-elastic (pe) vs. moving boundary (mb)



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$$A_{\mathrm{pe}} = \pi d^2/4$$

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$$u_r = (2r/d)u_s$$

$$S_{rr} = \partial_r u_r = 2u_s/d$$

$$\Delta\epsilon_{\mathrm{pe}} = 2n\Delta n_{\mathrm{pe}} = -n^4 p_{11} S_r$$

$$\Rightarrow \Delta n_{\mathrm{pe}} = -n^3 p_{11} \frac{u_s}{d}$$

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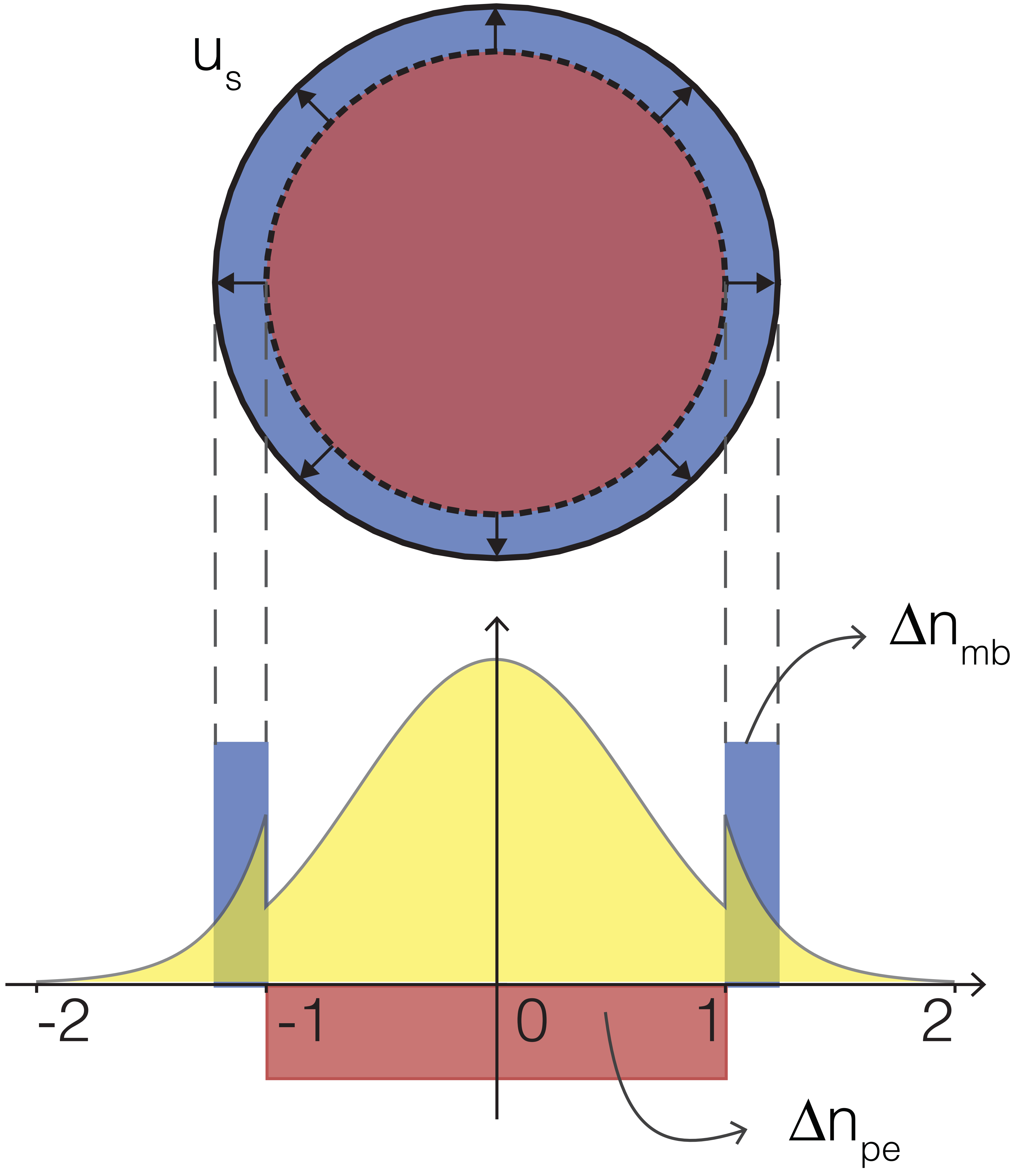

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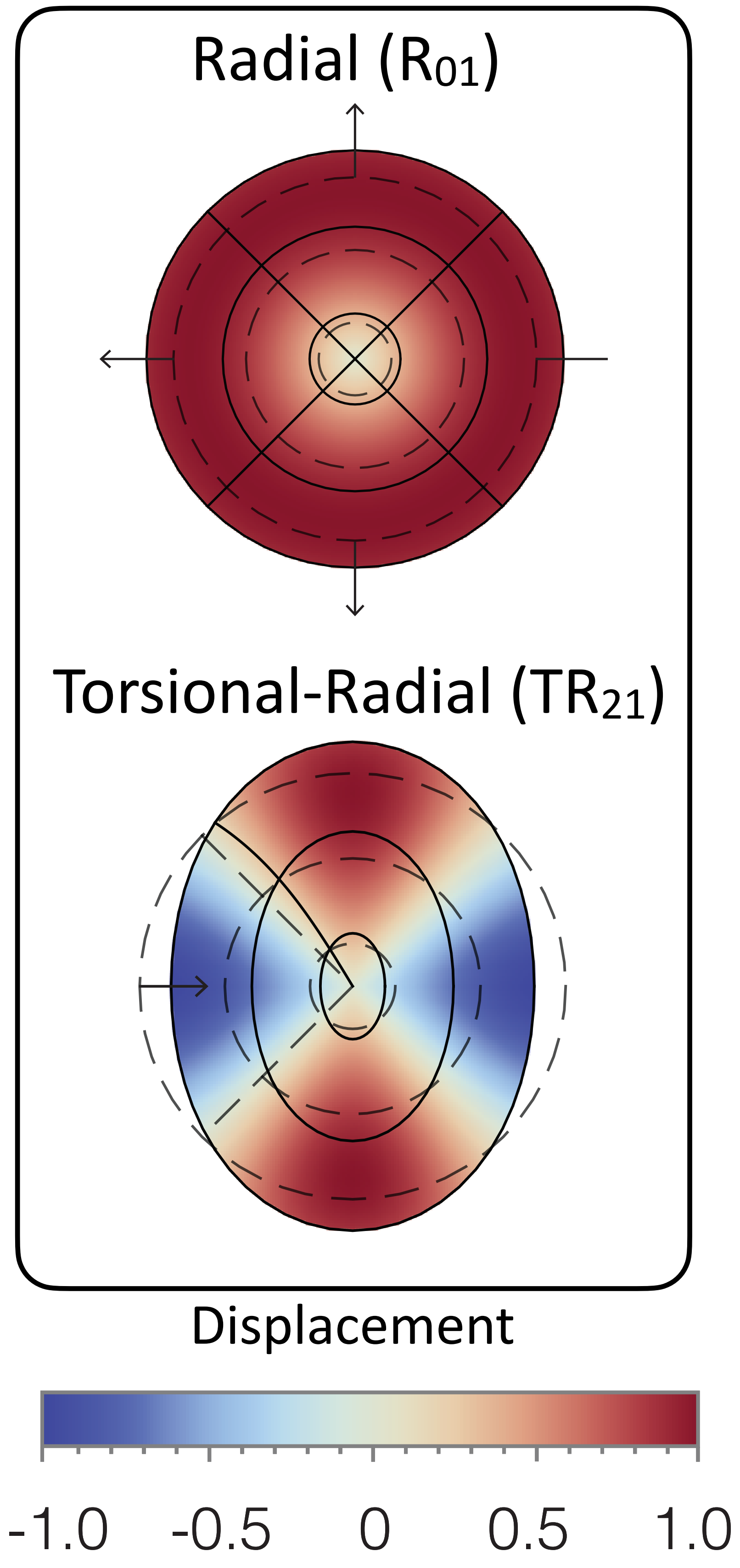
$$\Rightarrow \Delta n_{\mathrm{pe}} = -n^3 p_{11} \frac{u_s}{d}$$

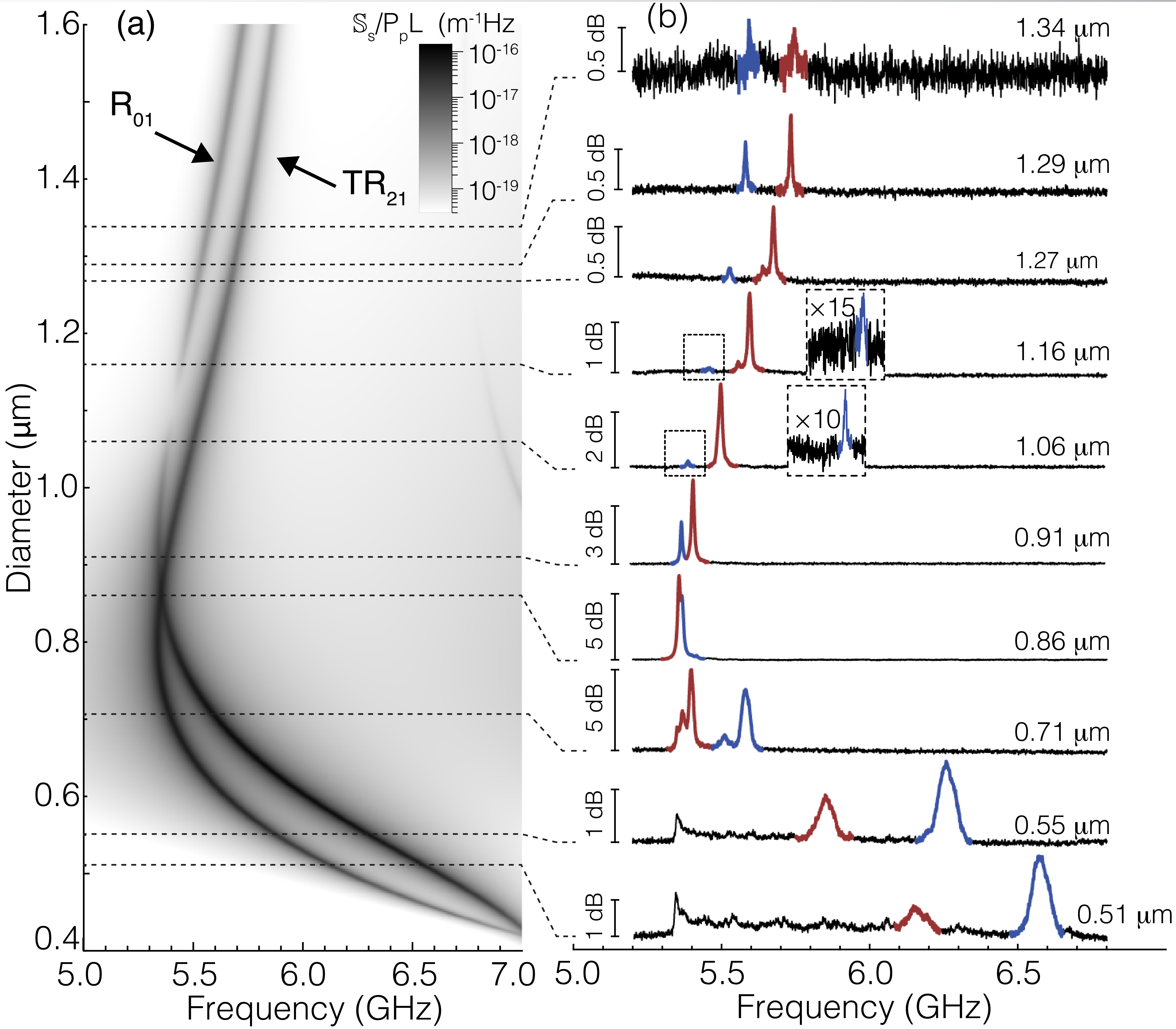
$$\Delta n_{\mathrm{mb}} = n_{\mathrm{glass}} - n_{\mathrm{air}}$$

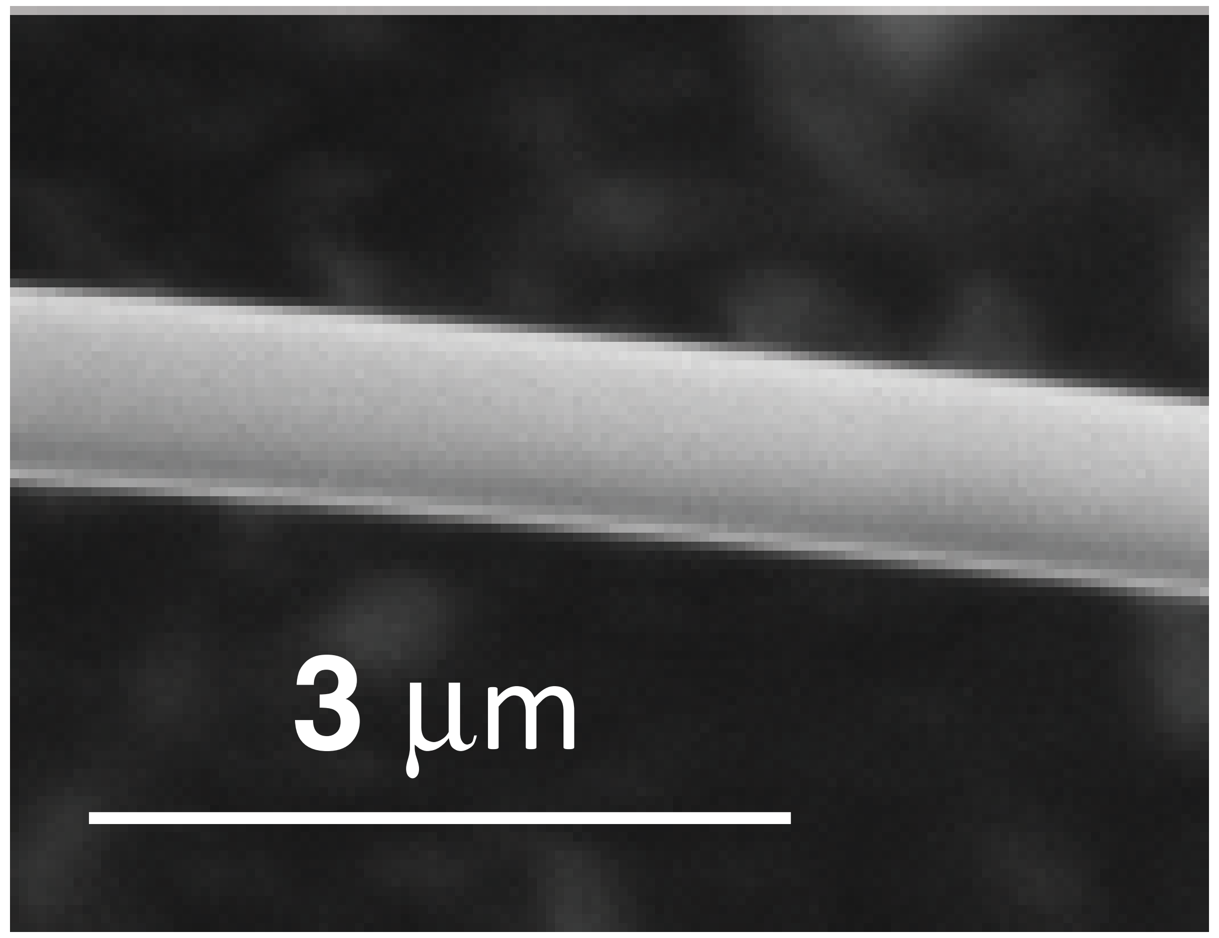
$$\frac{\Delta n_{\mathrm{pe}} A_{\mathrm{pe}}}{\Delta n_{\mathrm{mb}} A_{\mathrm{mb}}} = \frac{-n^3 p_{11}}{4\Delta n_{\mathrm{mb}}} \approx -0.2$$

O. Florez et al. "Brillouin scattering self-cancellation," Nat Comms, vol. 7, p. 11759, (2016).

Example: Brillouin Self-cancellation







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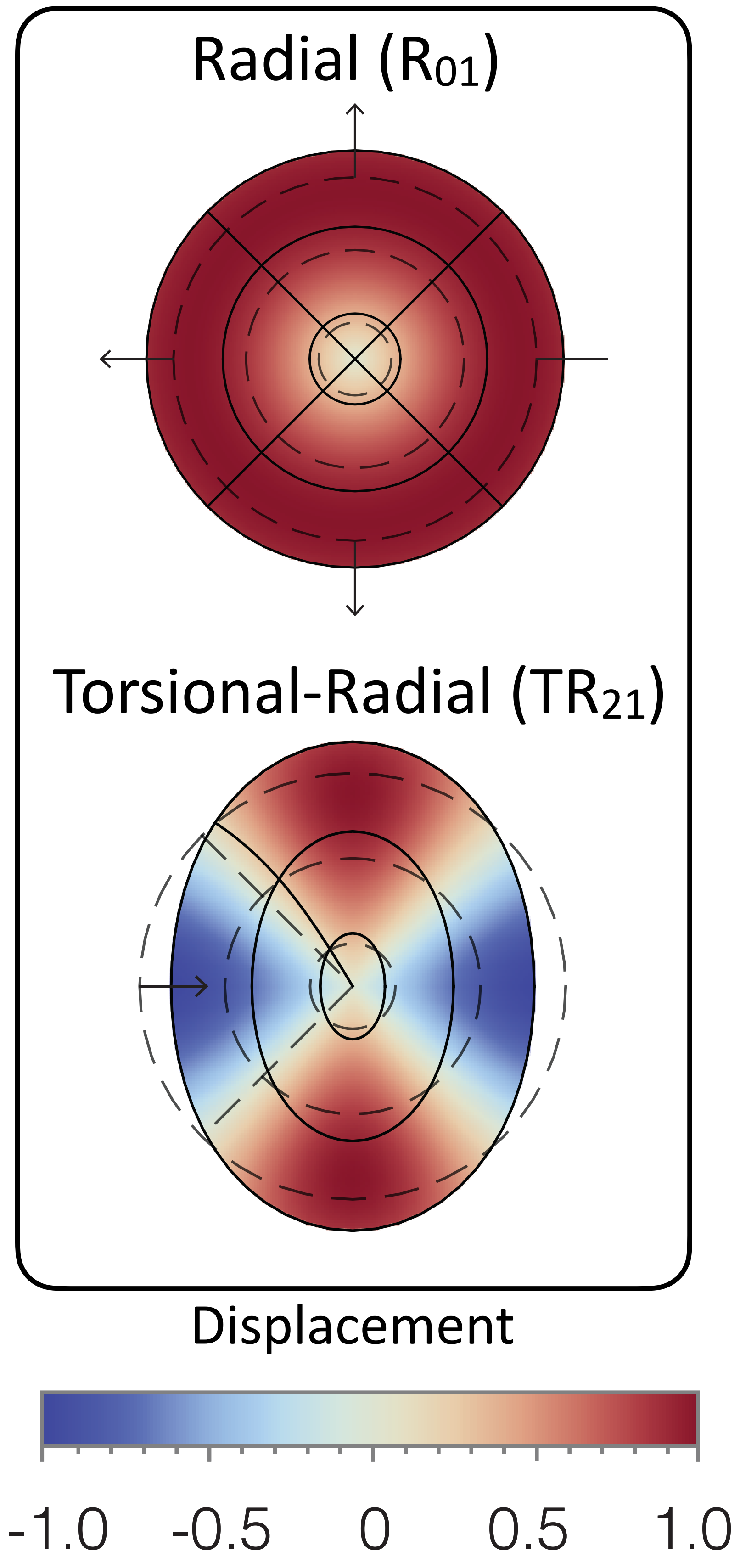

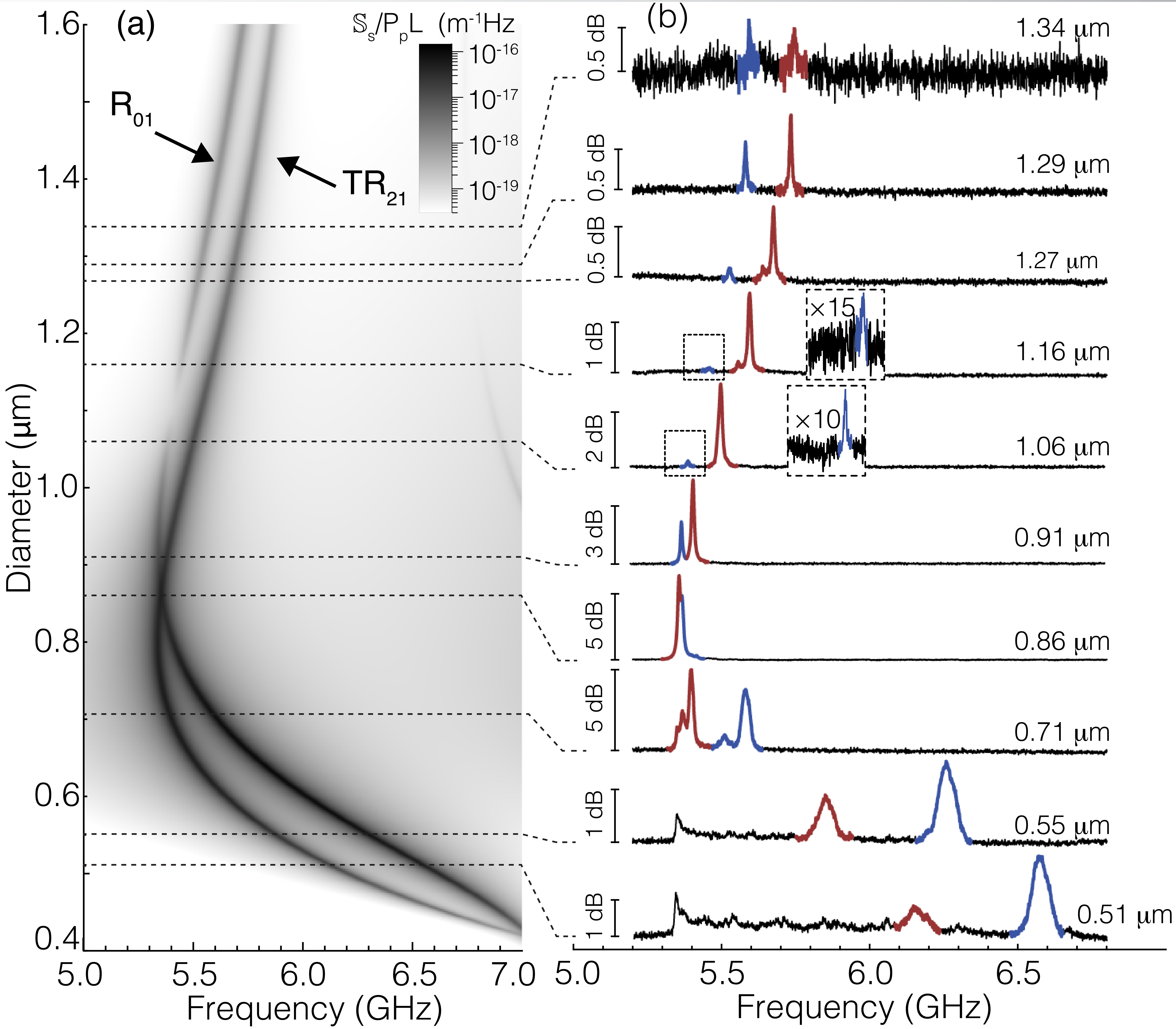

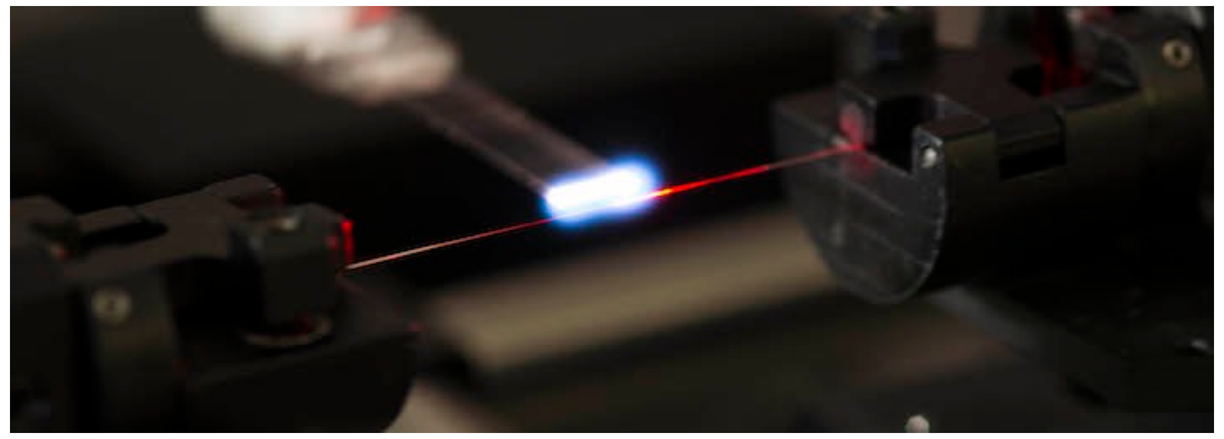

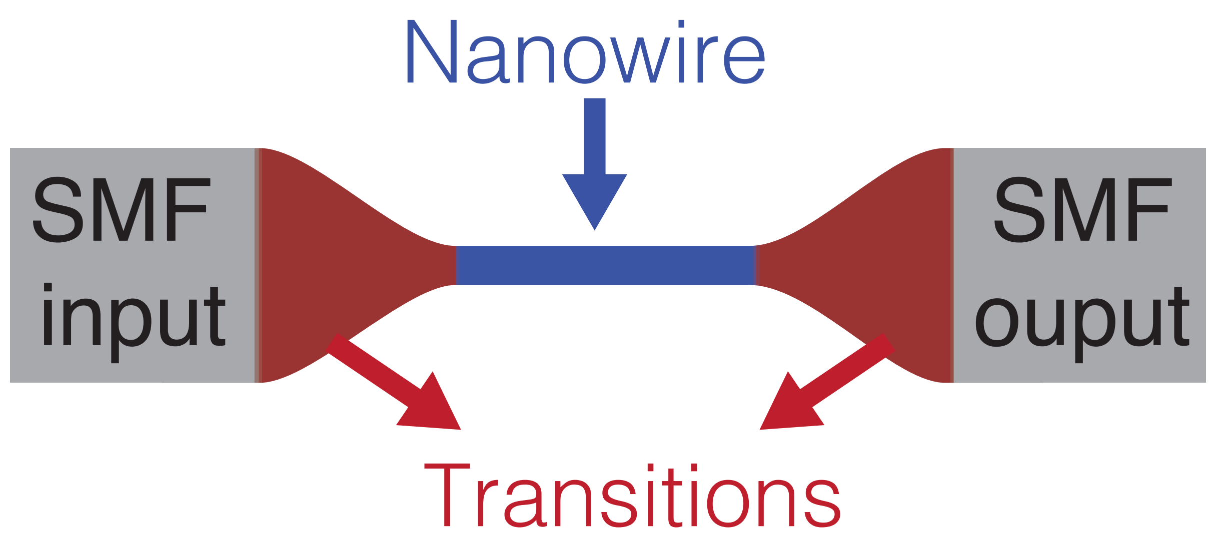

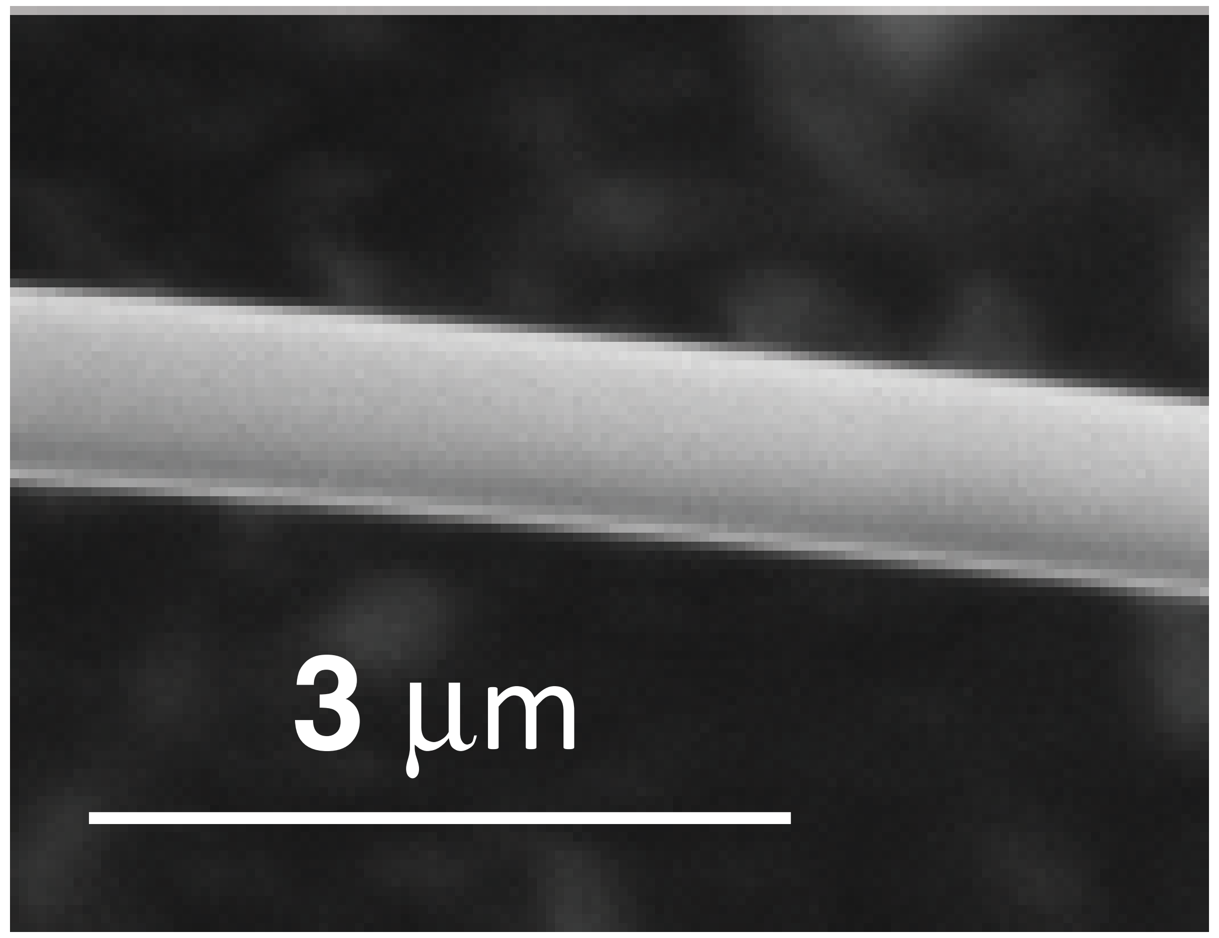

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Example: Brillouin Self-cancellation

Scattering of guided optical beams by surface acoustic waves in thin films

R. Normandin, V. C-Y. So, N. Rowell, and G. I. Stegeman
Department of Physics, University of Toronto, Toronto, Canada M5S 1A7
(Received 24 August 1978)

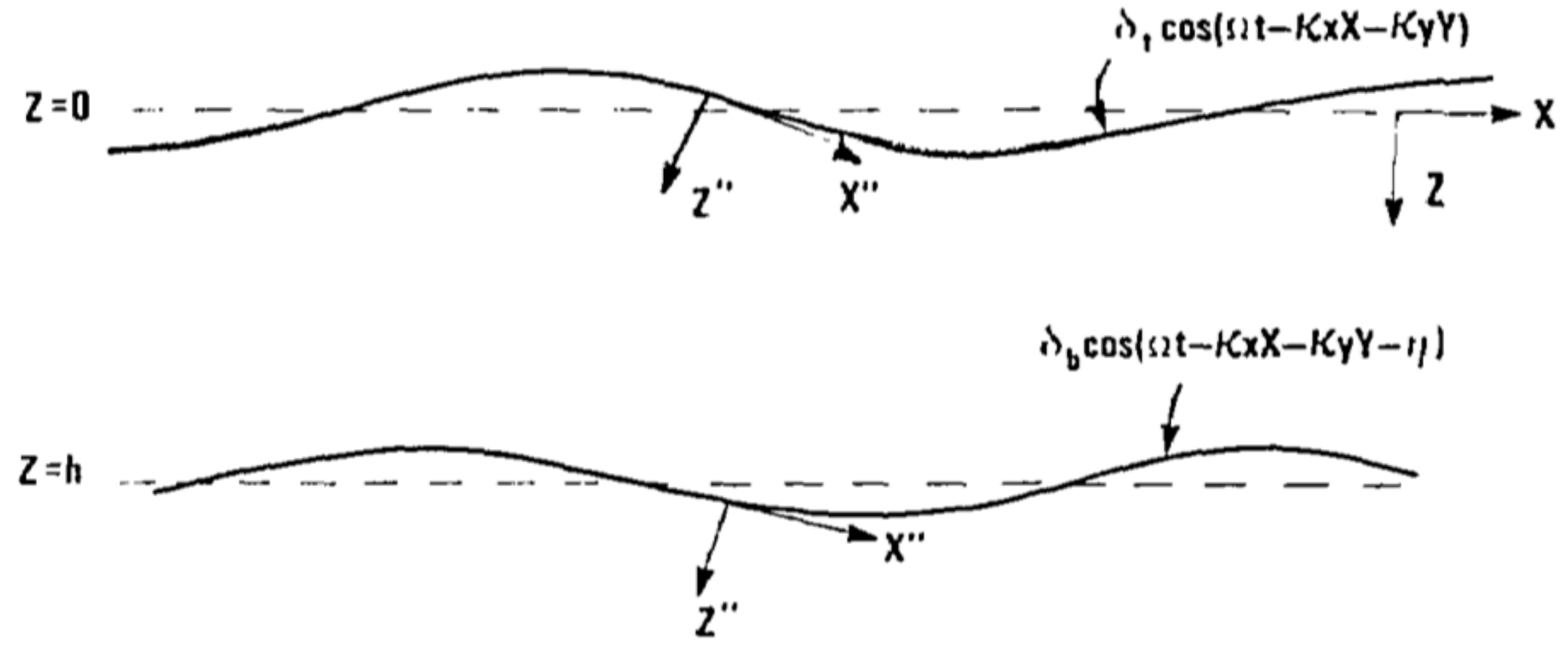

FIG. 4. Acoustically corrugated film surfaces.

"Numerical calculations for thin films of As2S3 and Corning 7059 glass on fused silica substrates indicate that the elasto-optic effect does not always dominate the scattering cross section and that the corrugation mechanism must often be taken into account."
G.I. Stegeman - 1979

R. Normandin, et al, J. Opt. Soc. Am. 69, 1153-1165 (1979)
Johnson, S. G., et al. Phys. Rev. E, 65(6), 066611.

The full Brillouin gain calculation

$$\left(v_p\partial_z + \partial_t + v_p\alpha_p/2\right)\tilde{a}_p = -\,i\tilde{g}_0\tilde{a}_s\tilde{b}$$

$$\left(\pm v_s\partial_z + \partial_t + v_s\alpha_s/2\right)\tilde{a}_s = -\,i\tilde{g}_0^*\tilde{b}^*\tilde{a}_p$$

$$\left[v_m\partial_z + \partial_t + \left(i\Delta_m + \gamma_m/2\right)\right]\tilde{b} = -\,i\tilde{g}_0^*\tilde{a}_s^*\tilde{a}_p,$$

1. Tomes, M., Marquardt, F., Bahl, G. & Carmon, T. Phys. Rev. A 84, 063806 (2011).
2. Wolff, C., Steel, M. J., Eggleton, B. J. & Poulton, C. G. Phys. Rev. A 92, 13836 (2015).
3. Van Laer, R., Baets, R. & Van Thourhout, D. Phys. Rev. A 93, 1–15 (2016).
4. Sipe, J. E. & Steel, M. J. New J. Phys. 18, 1–39 (2016).
5. Kharel, P., Behunin, R. O., Renninger, W. H. & Rakich, P. T. Phys. Rev. A 93, 1–12 (2016).
6. Wolff, C., Smith, M., Stiller, B., & Poulton, C. (2021). JOSAB, 38 (4), 1243-1269.

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Propagation **Detuning** **Loss**

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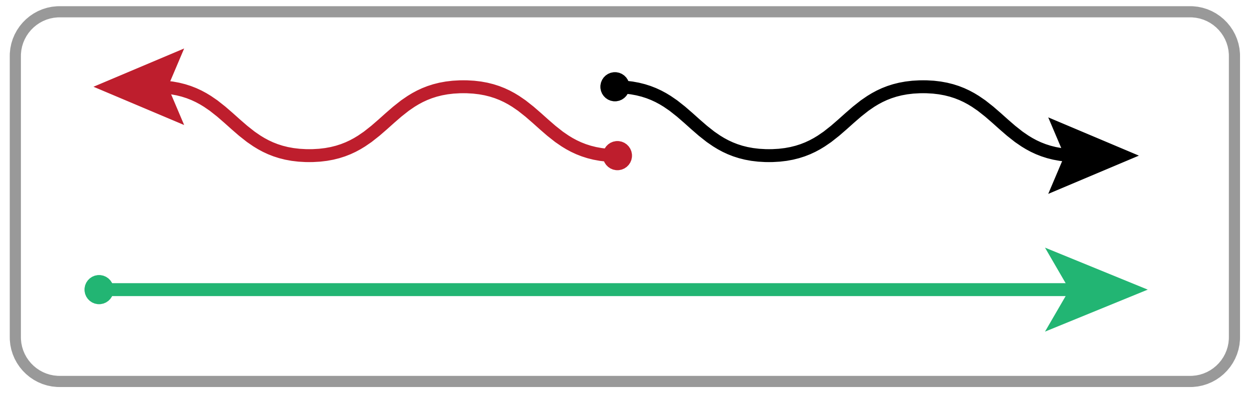
Propagation **Detuning** **Loss**

Polarization components: $\propto U(\mathbf{r})E(r)$

$$\begin{pmatrix}
b(a_1)^* & zk_2 + t(-\Omega+\omega_1) \\
(b)^*(a_1)^* & z(-2k_1-k_2) + t(\Omega+\omega_1) \\
b(a_2)^* & z(k_1+2k_2) + t(-2\Omega+\omega_1) \\
(b)^*(a_2)^* & -zk_1 + t\omega_1 \\
ba_1 & z(2k_1+k_2) + t(-\Omega-\omega_1) \\
(b)^*a_1 & -zk_2 - t(\omega_1-\Omega) \\
ba_2 & zk_1 - t\omega_1 \\
(\mathrm{b})^*a_2 & z(-k_1-2k_2) + t(2\Omega-\omega_1)
\end{pmatrix}$$



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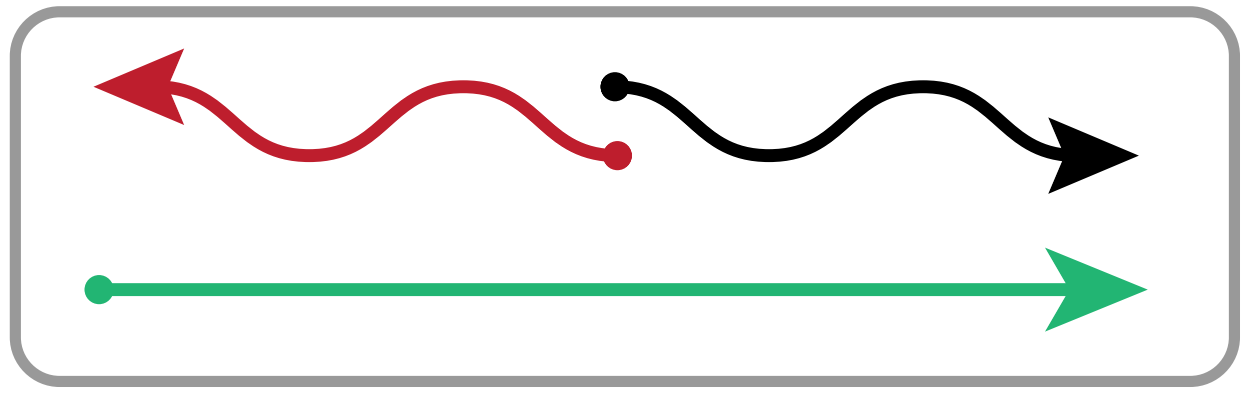
Propagation **Detuning** **Loss**

Acoustic drive: $\propto \nabla^2 E^2(r)$

$$\begin{pmatrix} -2q^2 & (a_2)^* & a_1 & qz - t\Omega \\ -2q^2 & (a_1)^* & a_2 & -qz + t\Omega \end{pmatrix}$$

Polarization components: $\propto U(\mathbf{r})E(r)$

$$\begin{pmatrix} b(a_1)^* & zk_2 + t(-\Omega + \omega_1) \\ (b)^*(a_1)^* & z(-2k_1 - k_2) + t(\Omega + \omega_1) \\ b(a_2)^* & z(k_1 + 2k_2) + t(-2\Omega + \omega_1) \\ (b)^*(a_2)^* & -zk_1 + t\omega_1 \\ ba_1 & z(2k_1 + k_2) + t(-\Omega - \omega_1) \\ (b)^*a_1 & -zk_2 - t(\omega_1 - \Omega) \\ ba_2 & zk_1 - t\omega_1 \\ (\mathrm{b})^*a_2 & z(-k_1 - 2k_2) + t(2\Omega - \omega_1) \end{pmatrix}$$



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- Steady state: $\partial_t = 0$
- Lossy mechanical wave (large γ_m/v_m)

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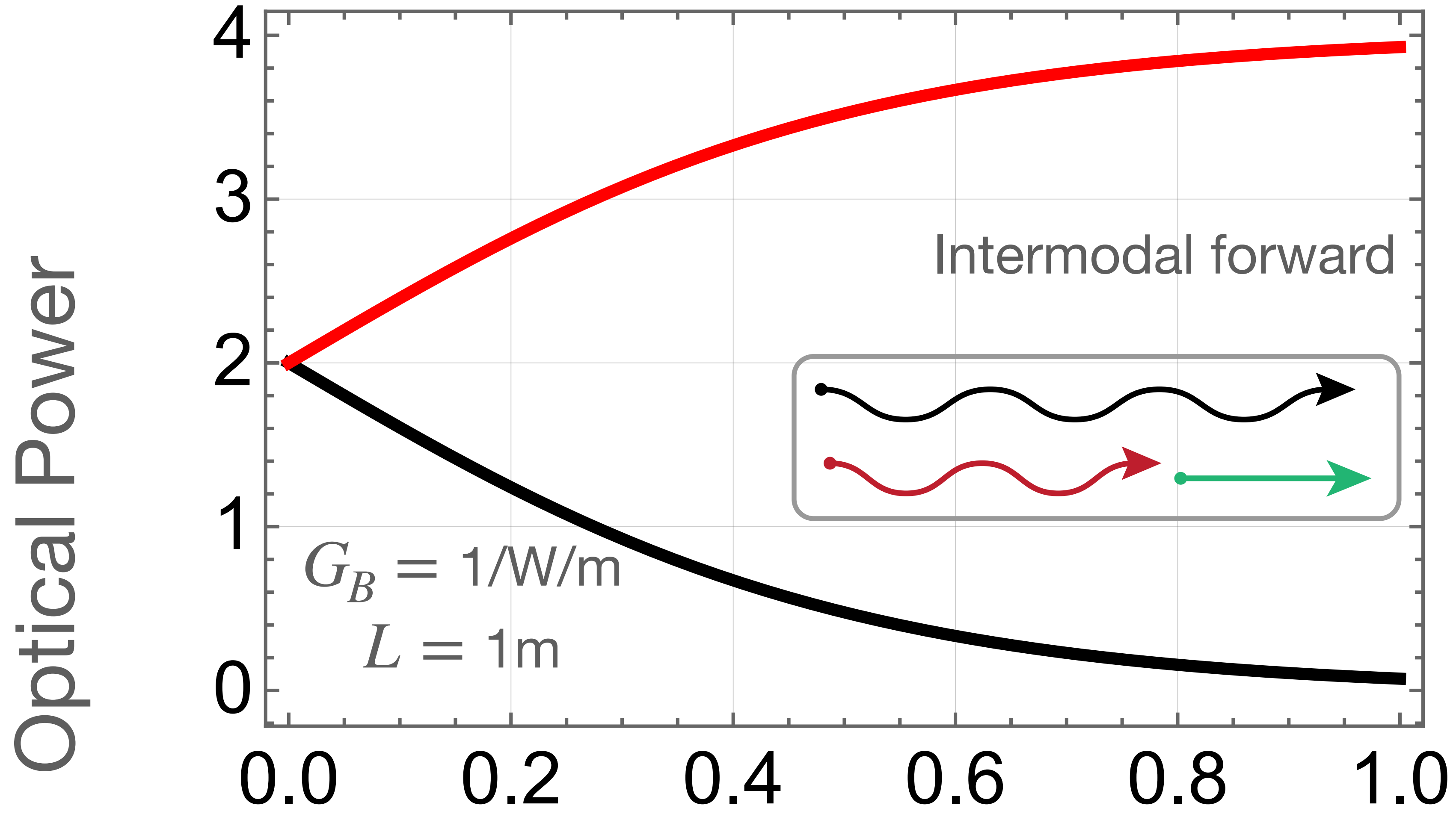

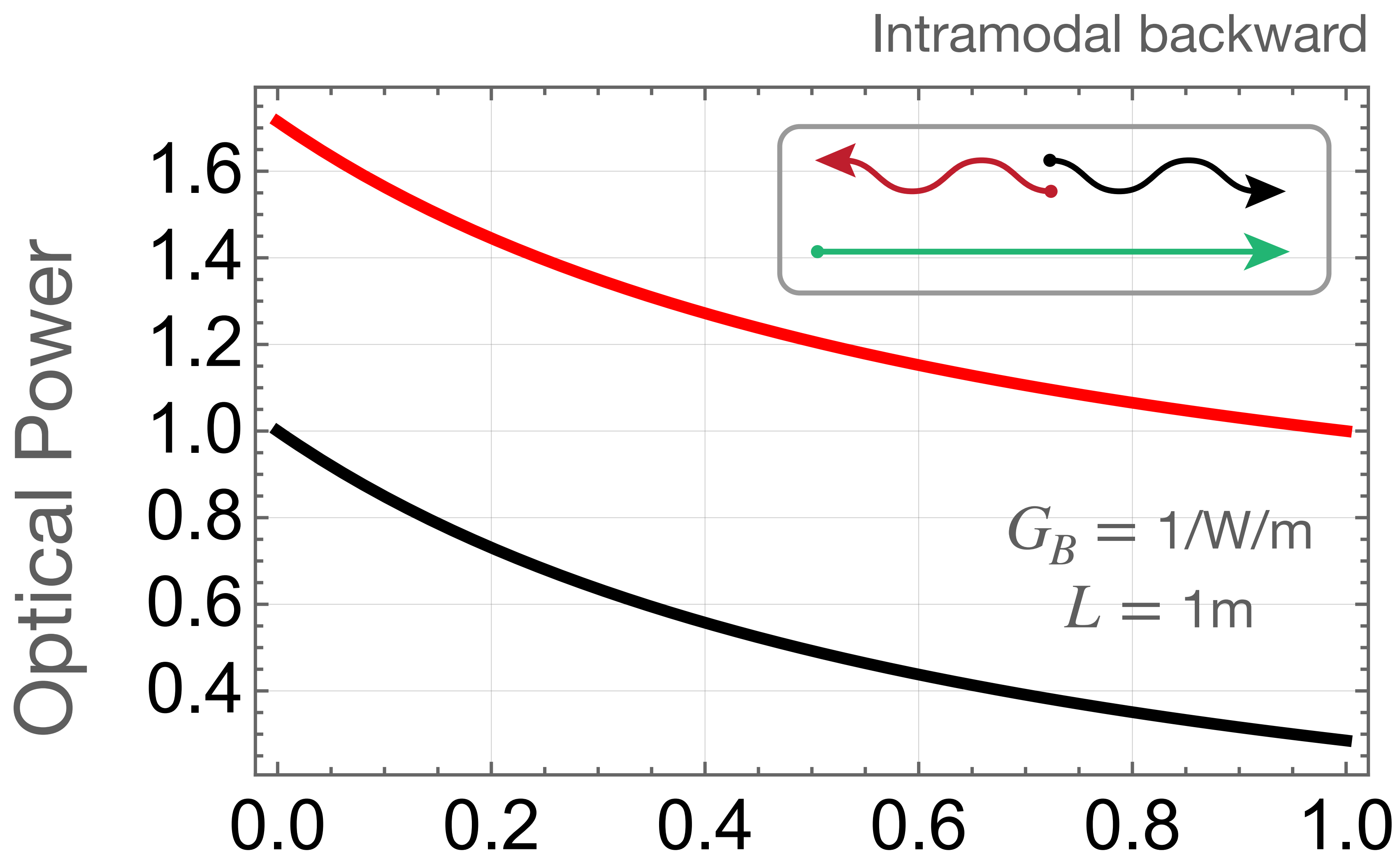

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Lorentzian lineshape

$$G_B(\Omega) = Q_m \frac{2\omega_p \boxed{\mathscr{L}(\Omega)}}{\boxed{\bar{m}_{\text{eff}}}\Omega_m^2} \left| \boxed{\int f_{\text{mb}}^{\text{wg}} dl} + \boxed{\int f_{\text{pe}}^{\text{wg}} dA} \right|^2$$

Effective mass | Overlap (MB) | Overlap (PE)

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Effective mass | Overlap (MB) | Overlap (PE)

Overlap (MB)

$$f_{\text{mb}}^{(\text{wg})} = \frac{\mathbf{u}^* \cdot \hat{n} \left(\delta\varepsilon_{\text{mb}} \mathbf{E}_{\text{p},\parallel}^* \cdot \mathbf{E}_{\text{s},\parallel} - \delta\varepsilon_{\text{mb}}^{-1} \mathbf{D}_{\text{p},\perp}^* \cdot \mathbf{D}_{\text{s},\perp} \right)}{\max(|\mathbf{u}|) N_{\text{p}}^{(\text{wg})} N_{\text{s}}^{(\text{wg})}}$$

$$\bar{m}_{\text{eff}} = \frac{1}{\max |\mathbf{u}_m|^2} \int \rho \, |\mathbf{u}_m|^2 \, dA$$

Effective mass

Overlap (PE)

$$f_{\text{pe}}^{(\text{wg})} = \frac{\mathbf{E}_{\text{p}}^* \cdot \delta\boldsymbol{\varepsilon}_{\text{pe}}^* \cdot \mathbf{E}_{\text{s}}}{\max(|\mathbf{u}|) N_{\text{p}}^{(\text{wg})} N_{\text{s}}^{(\text{wg})}}$$

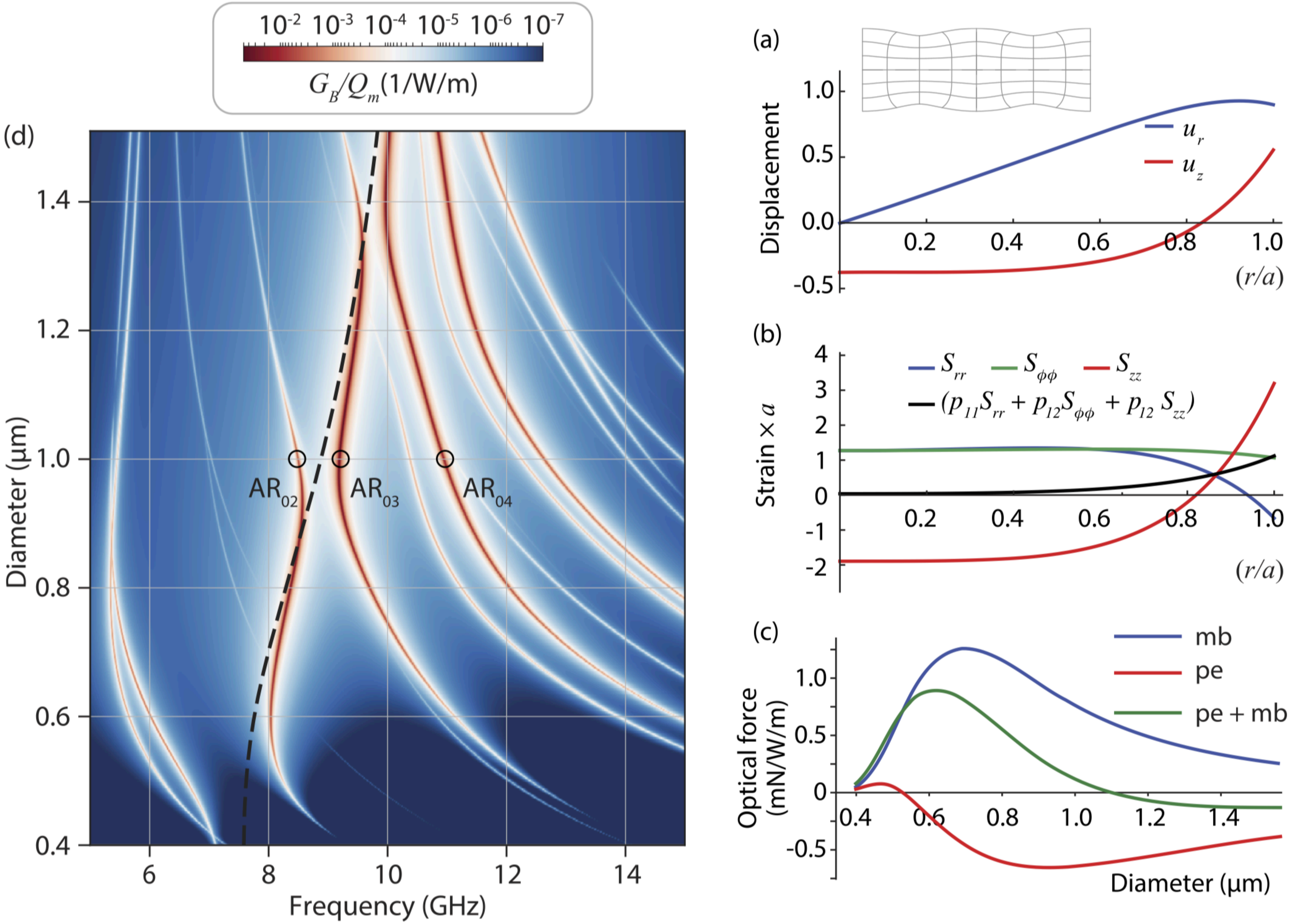
$$\left[f_{\text{pe}}^{\text{wg}} \right] = \text{N/W/m}^3$$
$$\left[f_{\text{mb}}^{\text{wg}} \right] = \text{N/W/m}^2$$

$$N_{\text{i}}^{\text{wg}} = \left(2\Re \left(\int \mathbf{E}_{\text{i}} \times \mathbf{H}_{\text{i}}^* \cdot \hat{z} dA \right) \right)^{1/2} \qquad N_{\text{i}}^{\text{cav}} = \left(\varepsilon_0 \int \varepsilon \, |\mathbf{E}_{\text{i}}|^2 dV \right)^{1/2}$$

Mode normalization

1. Wiederhecker, G. S., Dainese, P. & Alegre, T. P. M. Brillouin optomechanics in nanophotonic structures. APL Photonics 4, (2019).

Silica nanowire revisited

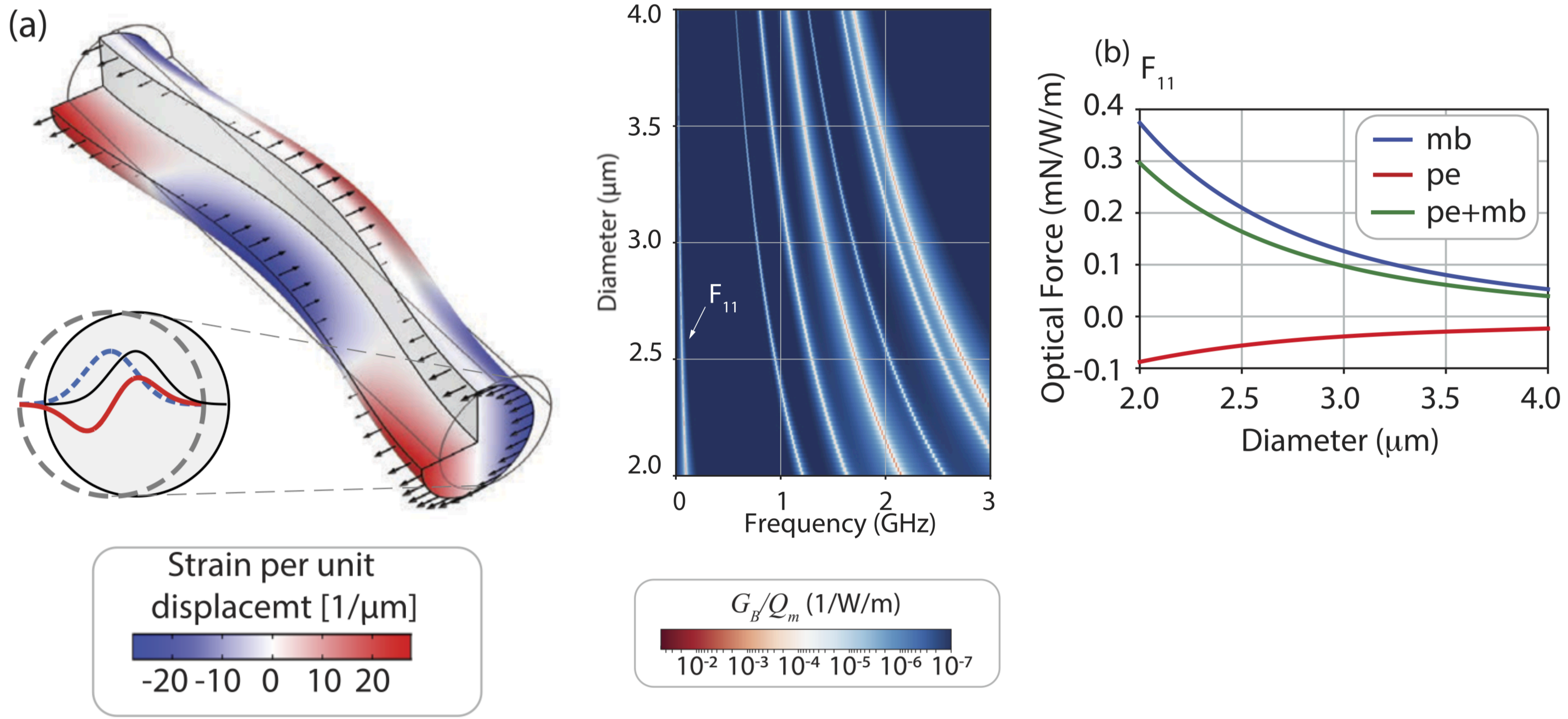


$$f_{\mathrm{mb}}^{(\mathrm{wg})} = \frac{\mathbf{u}^* \cdot \hat{n}\left(\delta\varepsilon_{\mathrm{mb}}\mathbf{E}_{\mathrm{p},\parallel}^* \cdot \mathbf{E}_{\mathrm{s},\parallel} - \delta\varepsilon_{\mathrm{mb}}^{-1}\mathbf{D}_{\mathrm{p},\perp}^* \cdot \mathbf{D}_{\mathrm{s},\perp}\right)}{\max(|\mathbf{u}|)N_{\mathrm{p}}^{(\mathrm{wg})}N_{\mathrm{s}}^{(\mathrm{wg})}}$$

$$f_{\mathrm{pe}}^{(\mathrm{wg})} = \frac{\mathbf{E}_{\mathrm{p}}^* \cdot \delta\boldsymbol{\varepsilon}_{\mathrm{pe}}^* \cdot \mathbf{E}_{\mathrm{s}}}{\max(|\mathbf{u}|)N_{\mathrm{p}}^{(\mathrm{wg})}N_{\mathrm{s}}^{(\mathrm{wg})}}$$

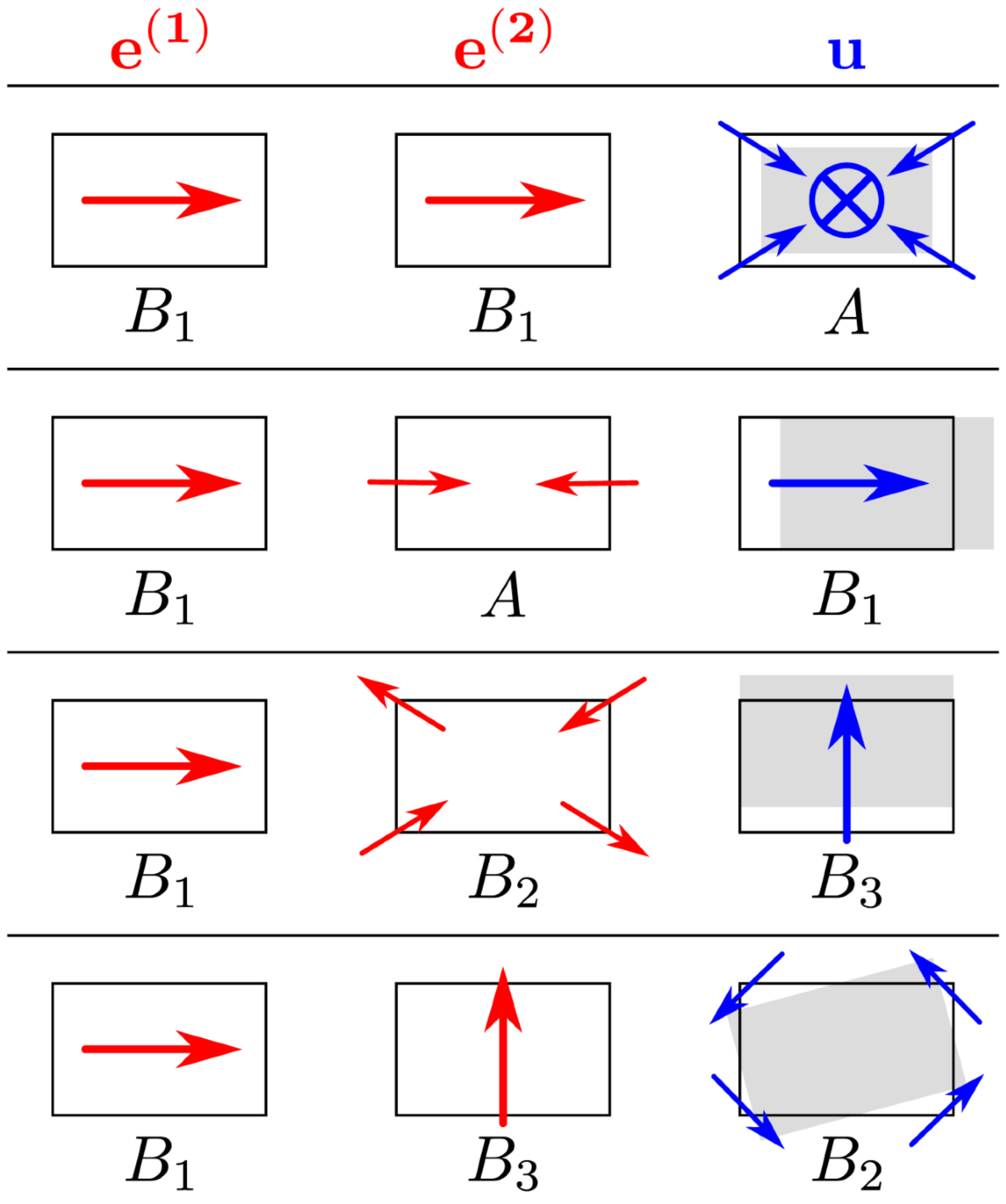
$$\delta\varepsilon_{\mathrm{pe}} = -\,\varepsilon_0 n^4 \mathbf{p} : \mathbf{S}$$

Silica nanowire revisited



The full recipe: group theory approach

Examples for group $\mathscr{C}_{2v}$



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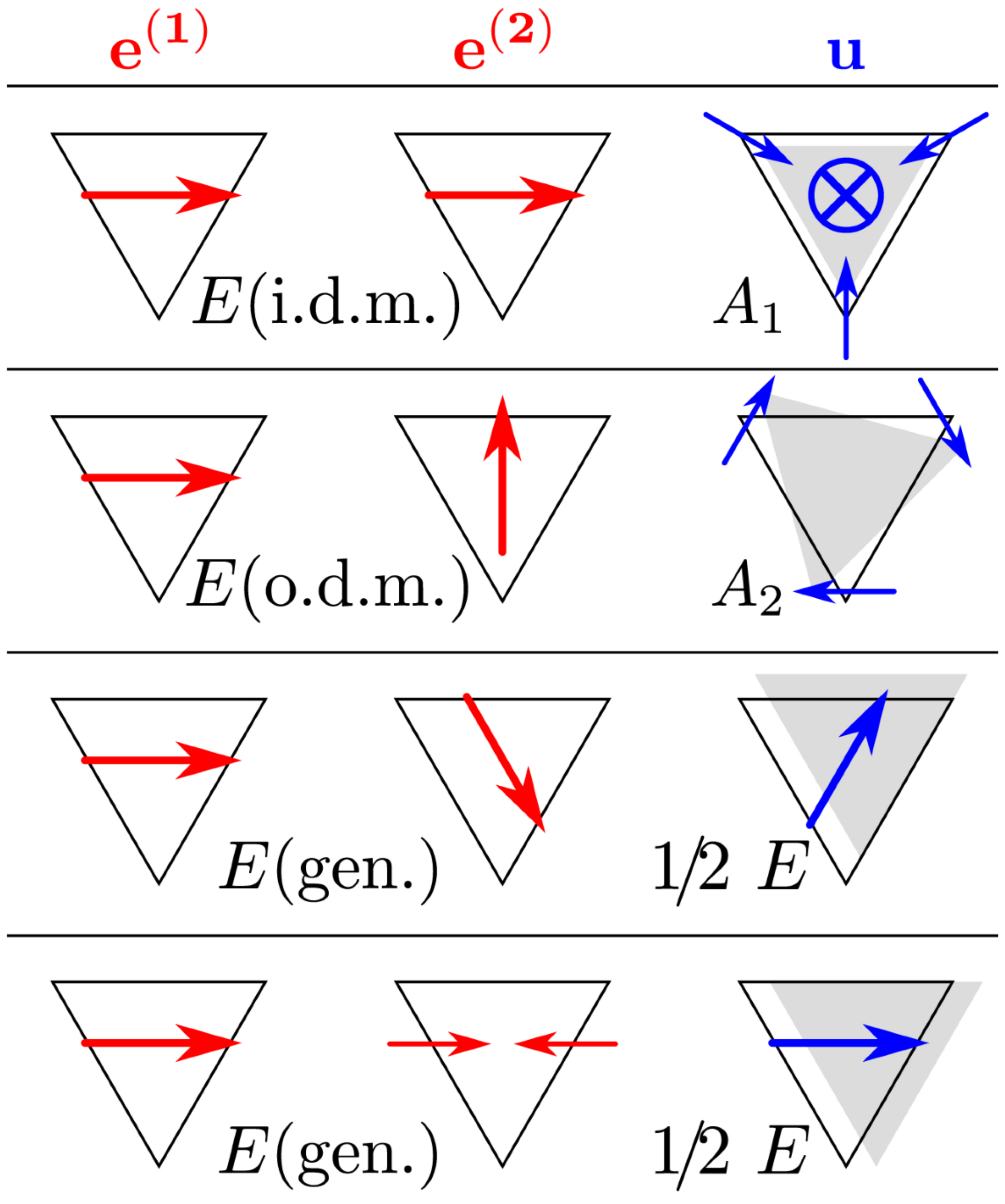
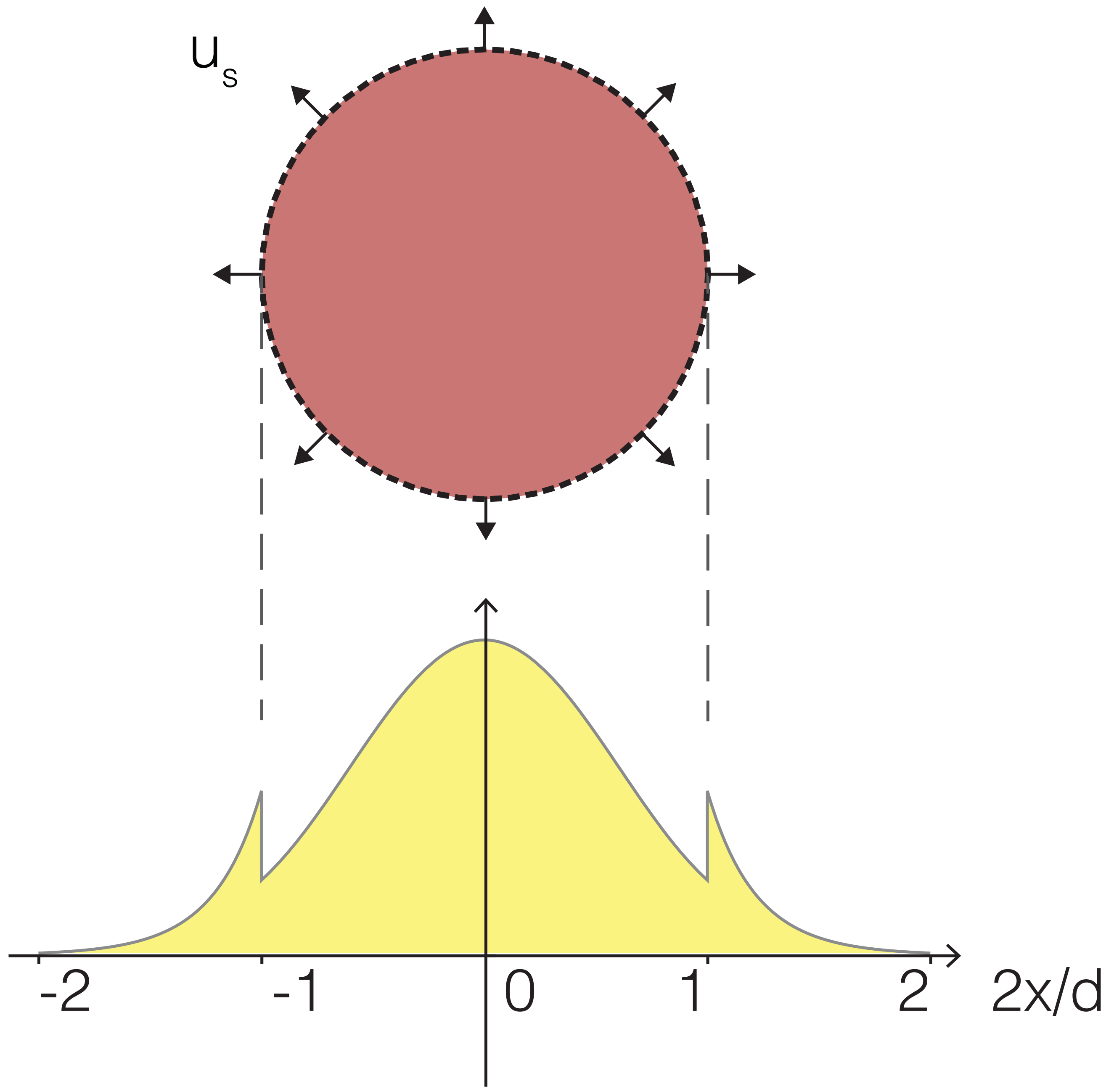


C. Wolff, M. J. Steel, and C. G. Poulton, "Formal selection rules for Brillouin scattering in integrated waveguides and structured fibers," Opt. Express 22, 32489-32501 (2014)

Brillouin interaction in waveguides



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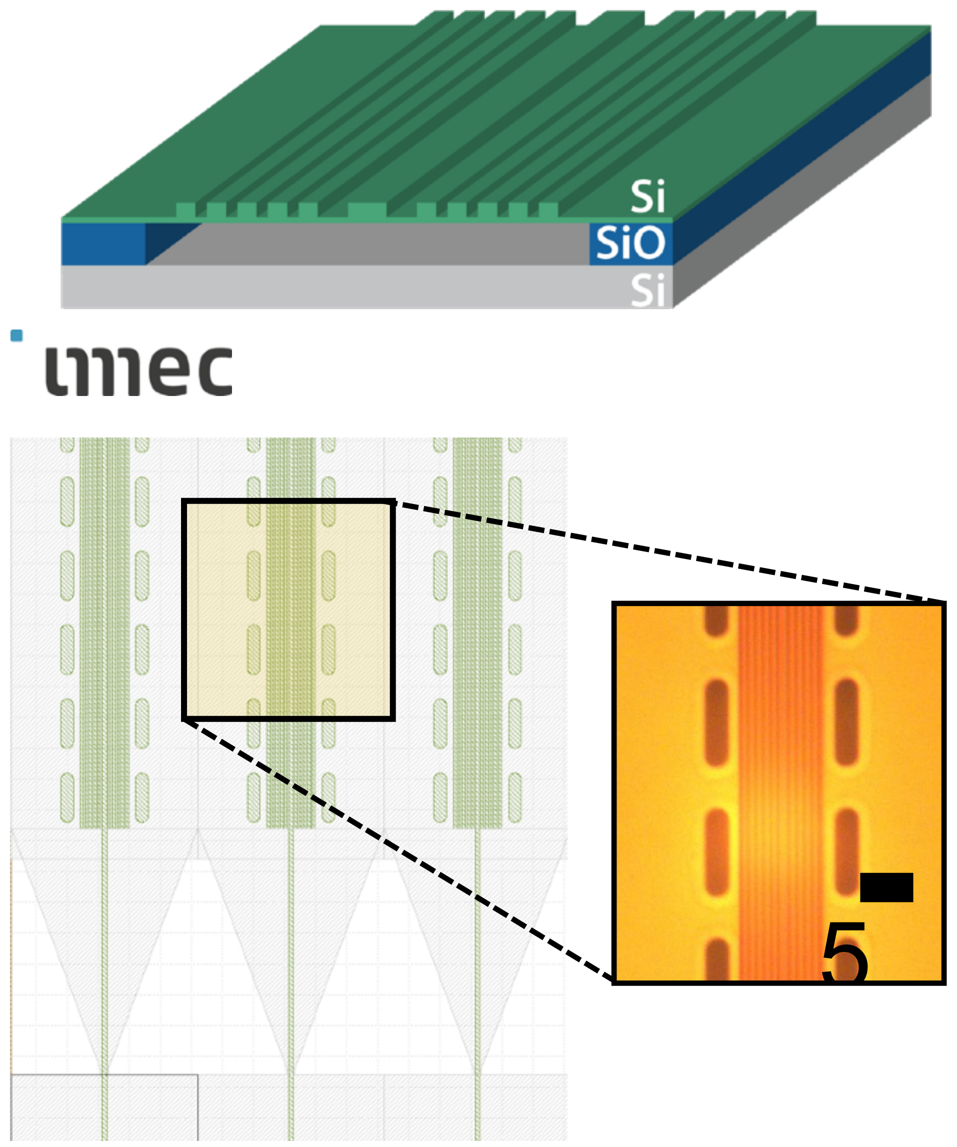

Zurita, R. O., et al.
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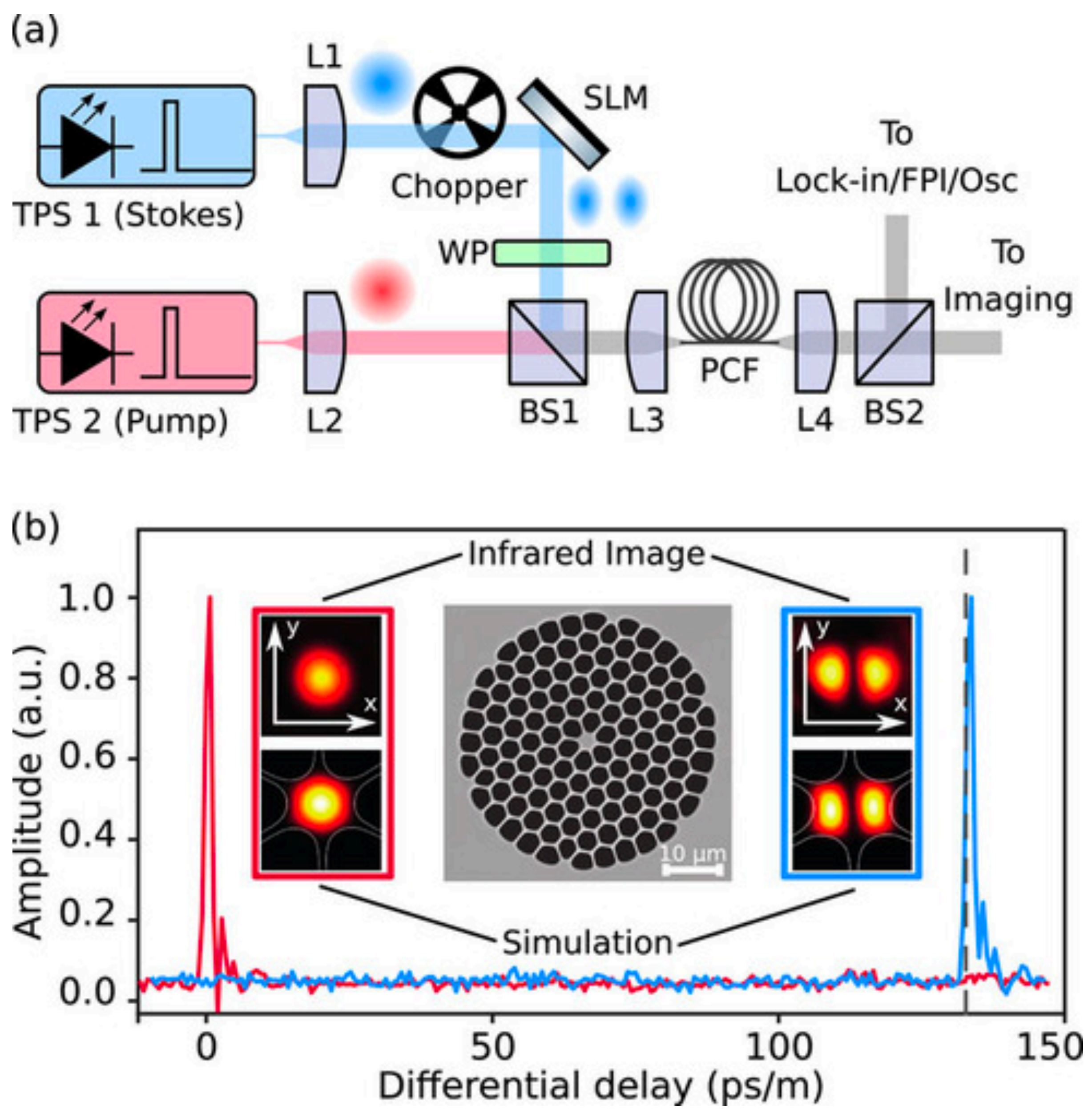
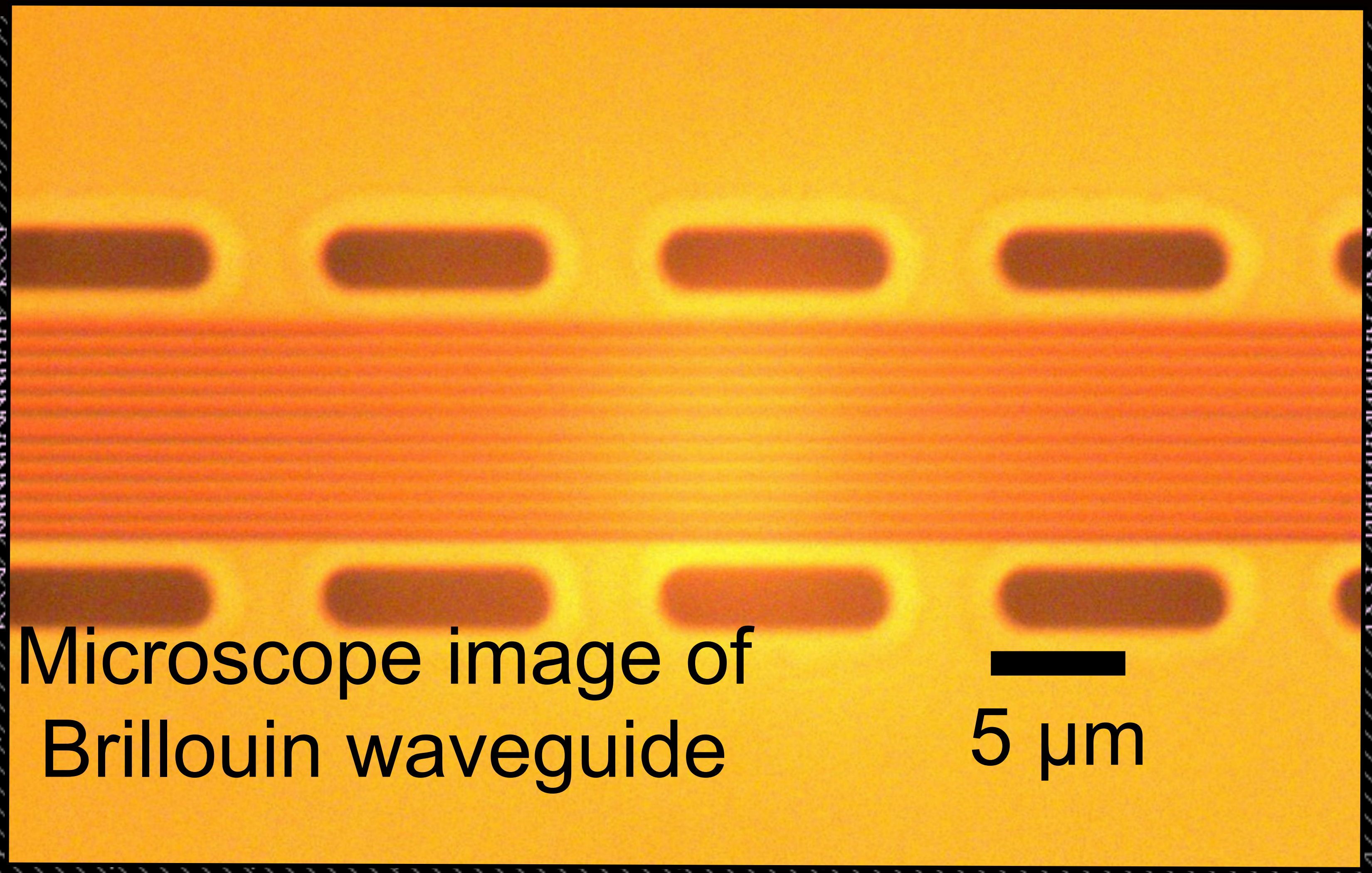


Jarschel, P. F. et al.
APL Photonics 6, 036108 (2021).

Backward Brillouin Scattering in silicon waveguide periodic lattices



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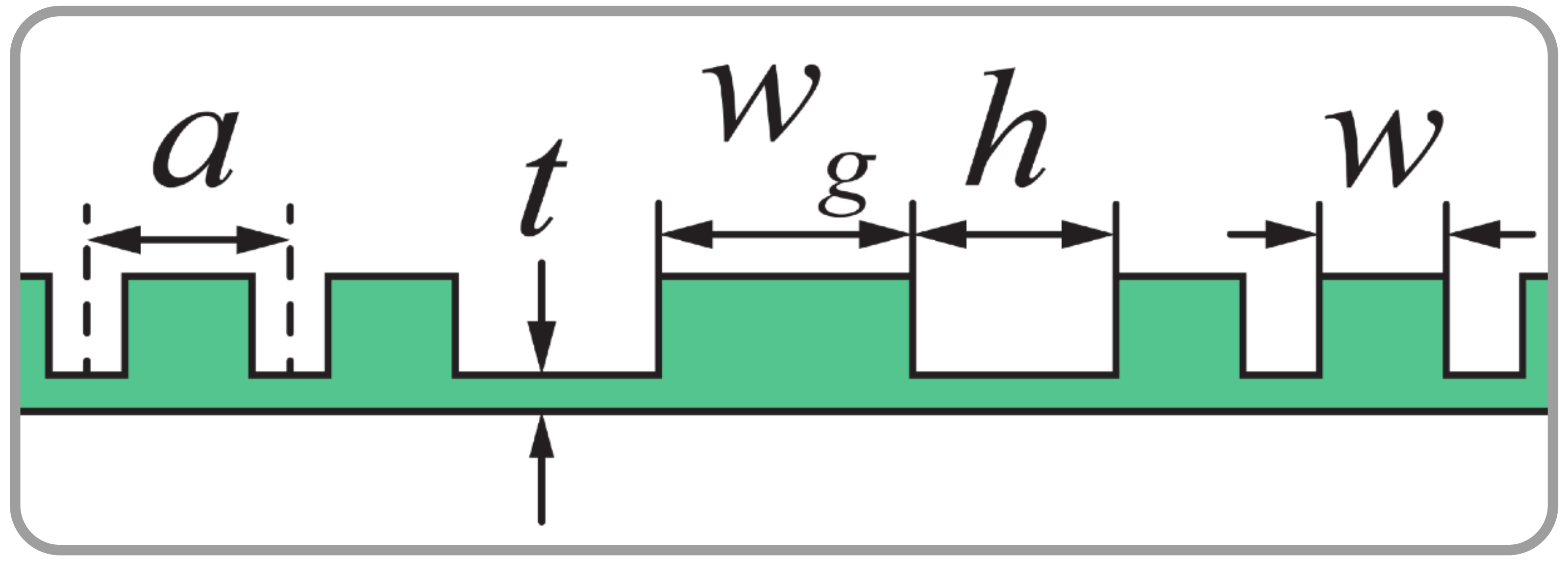
Waveguide Design



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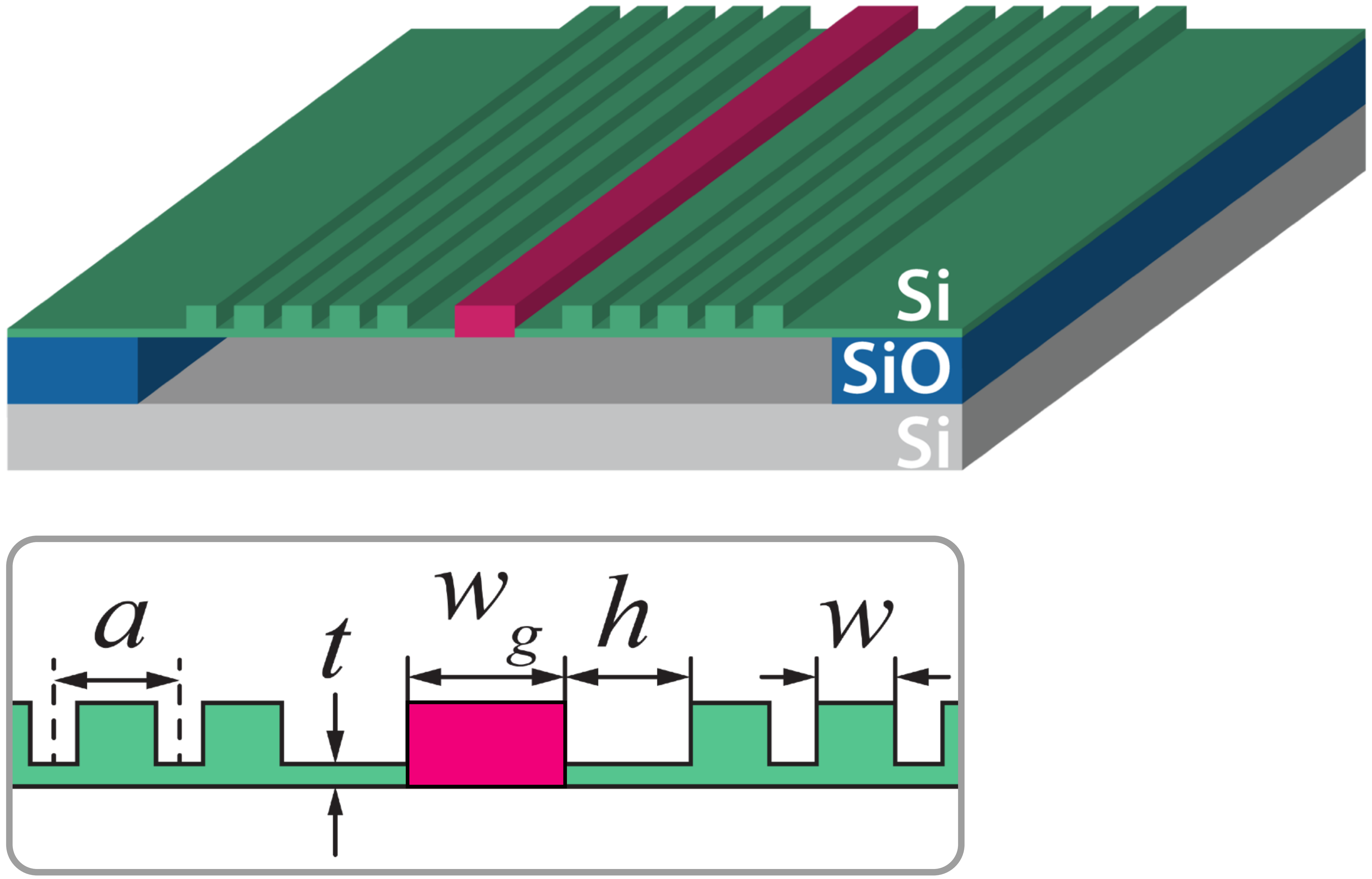

waveguide core

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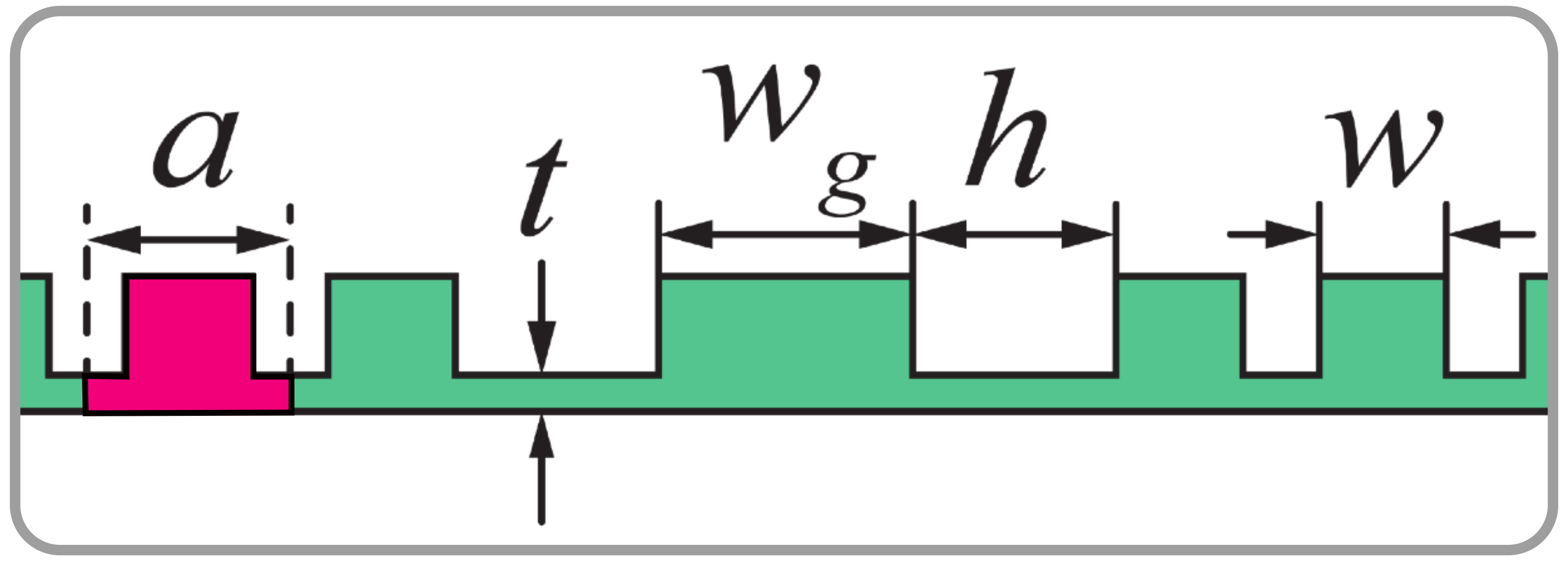
Waveguide Design



phonic crystal

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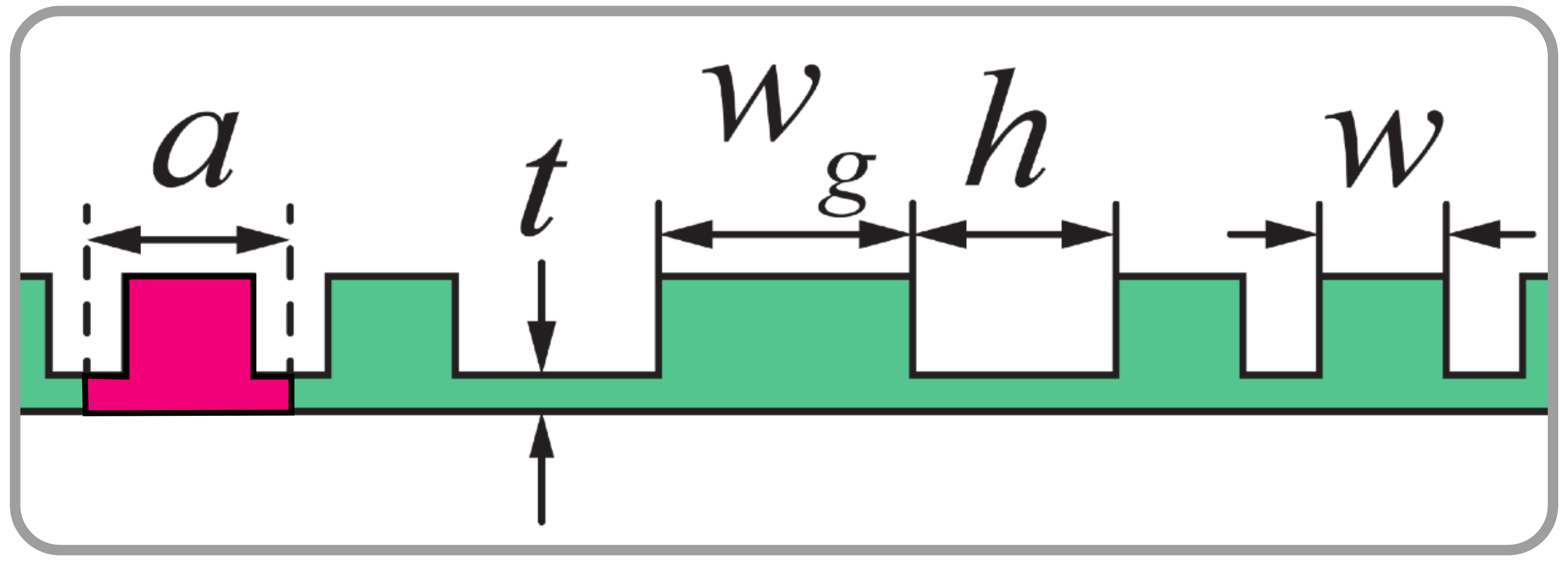
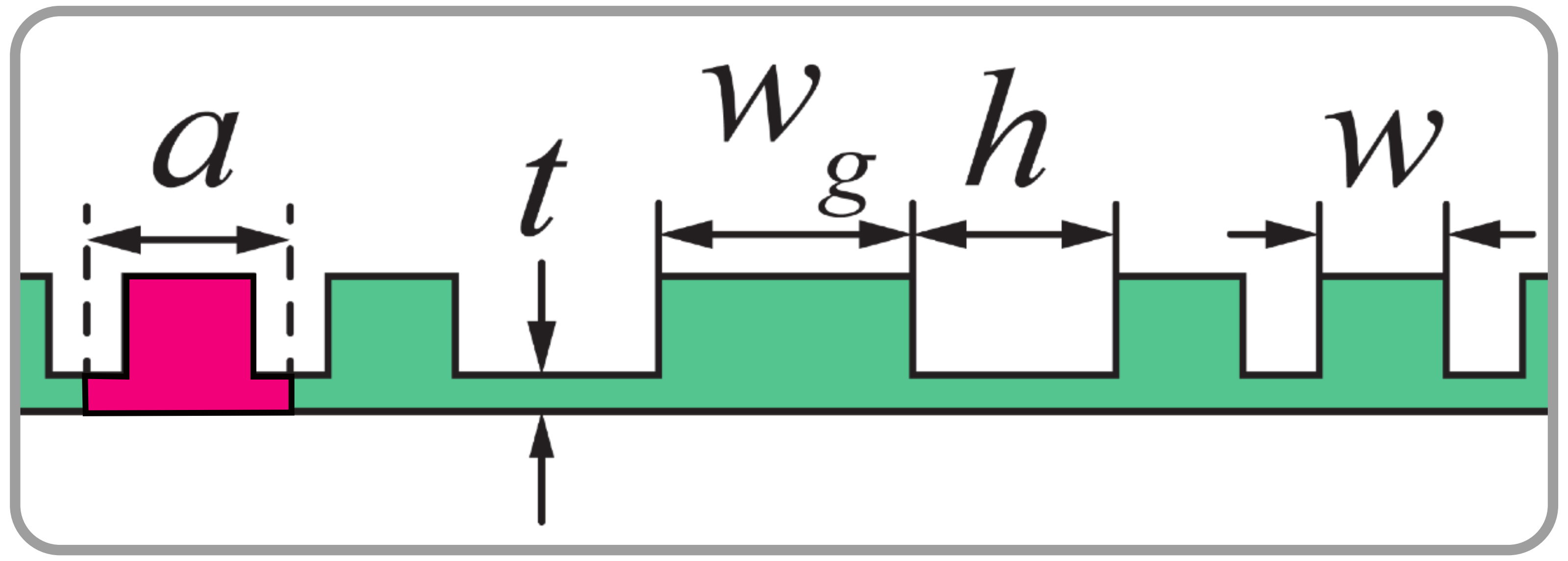
Waveguide Design



phononic crystal

✓ Homogenous mechanical confinement
- Suitable to deal with traveling phonons

Waveguide Design



phononic crystal

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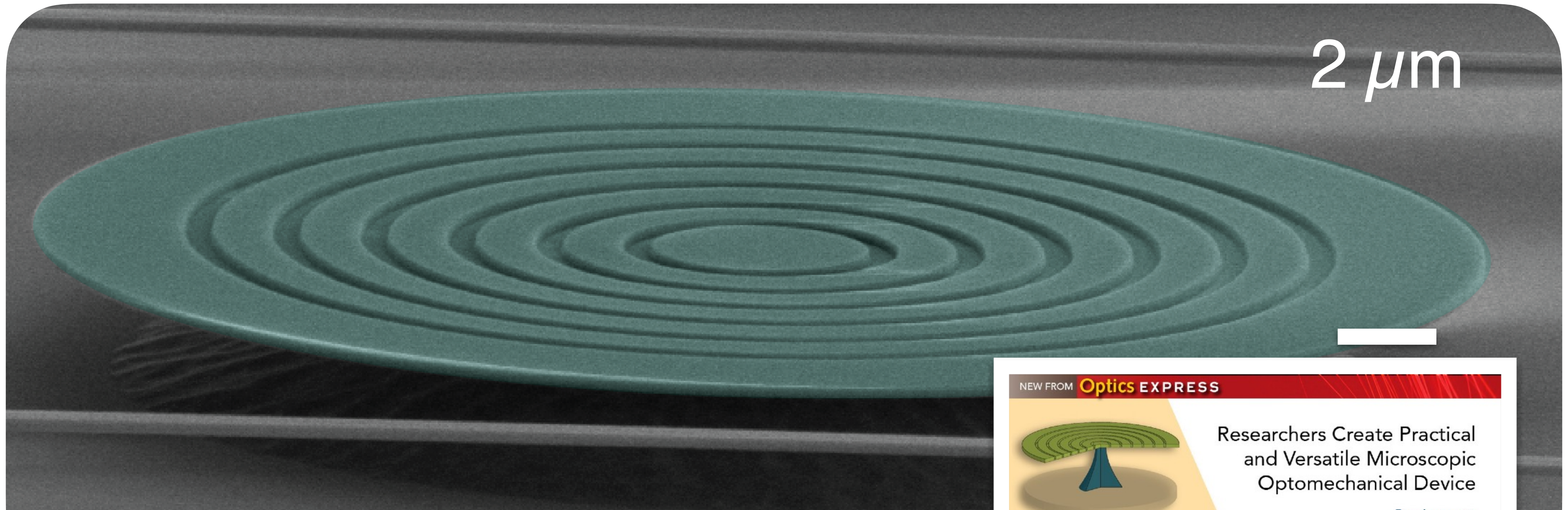
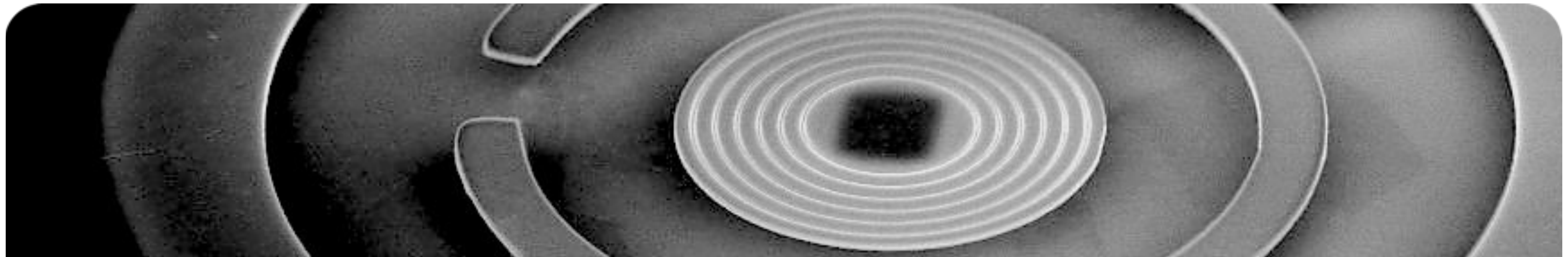


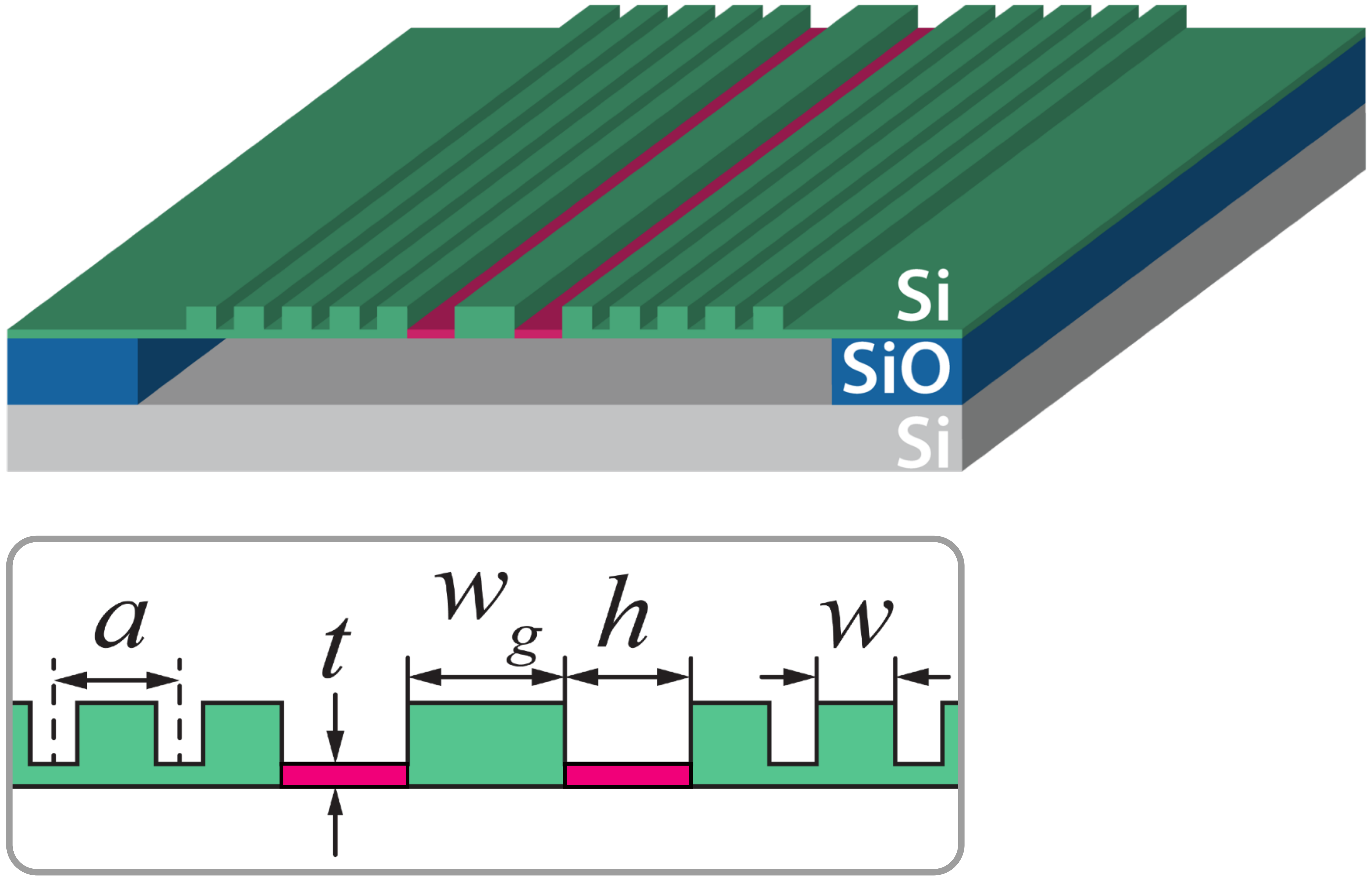
Santos, F.G. et al ,Optics Express, **25**, 508 (2017)



C. Carvalho, N. et al. APL Photonics 6, 016104 (2021).

Zurita, R. O., et al. **Opt. Express** 29, 1736 (2021).

Waveguide Design



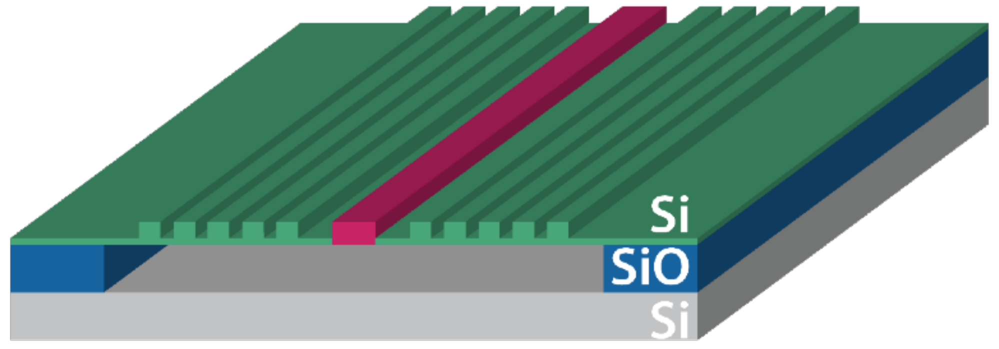
waveguide core support

✓ Homogenous mechanical confinement
- Suitable to deal with traveling phonons

Zurita, R. O., et al. **Opt. Express** 29, 1736 (2021).

DOI: 10.5281/zenodo.4148337

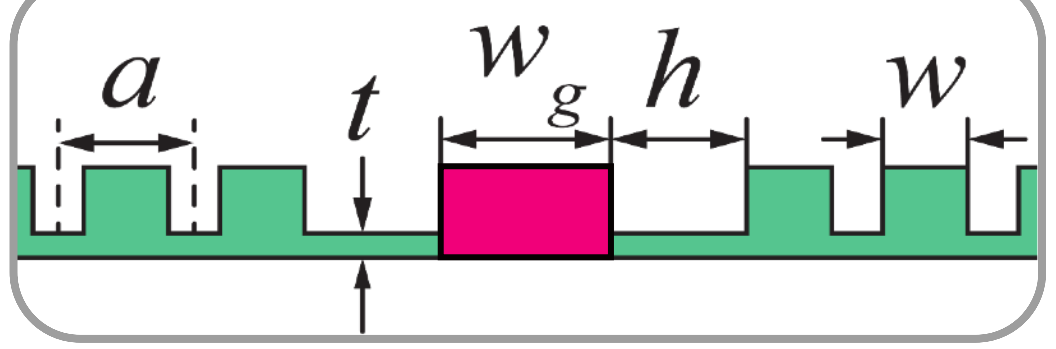
Waveguide Design Process: Core



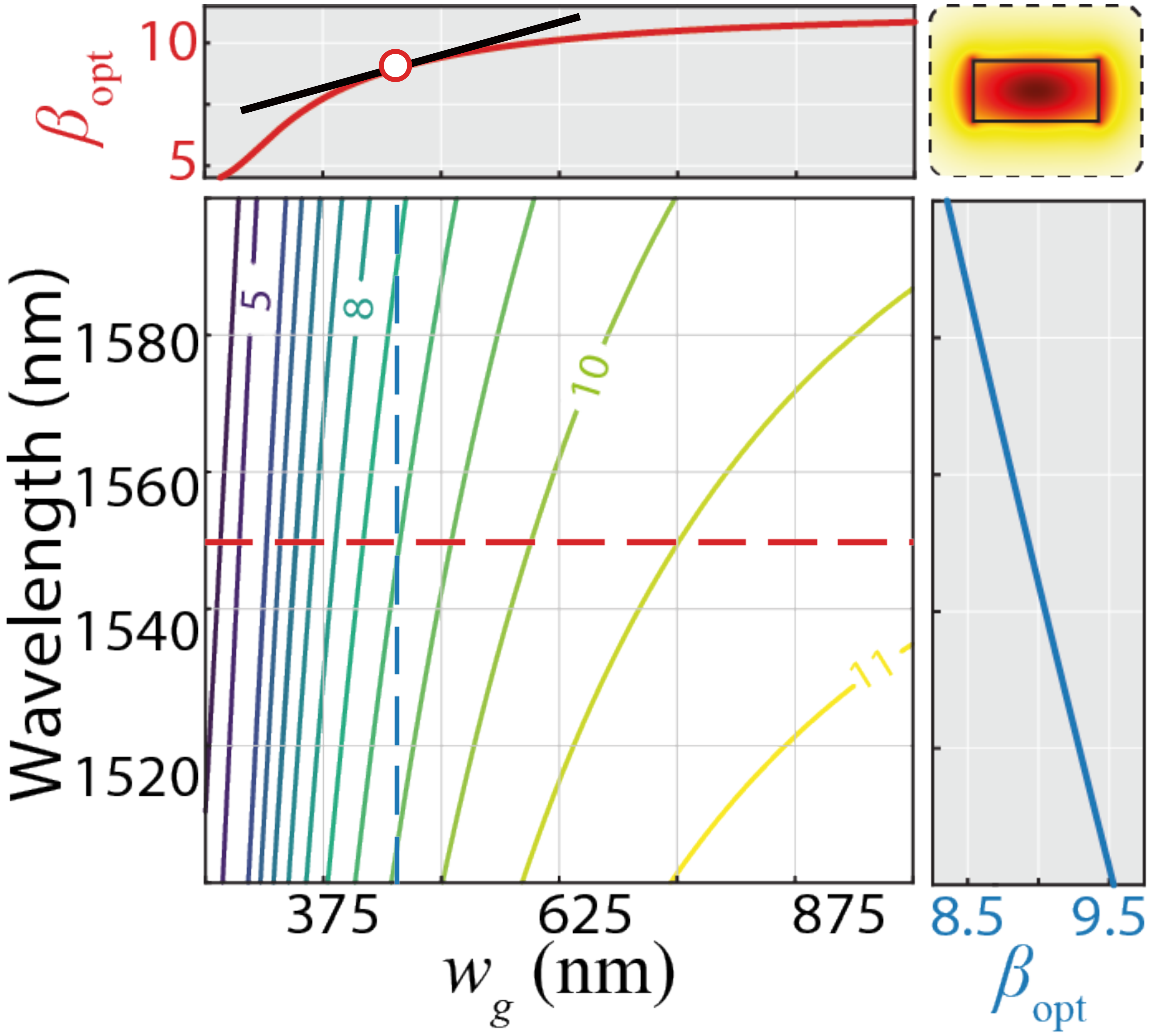
waveguide core

phononic crystal

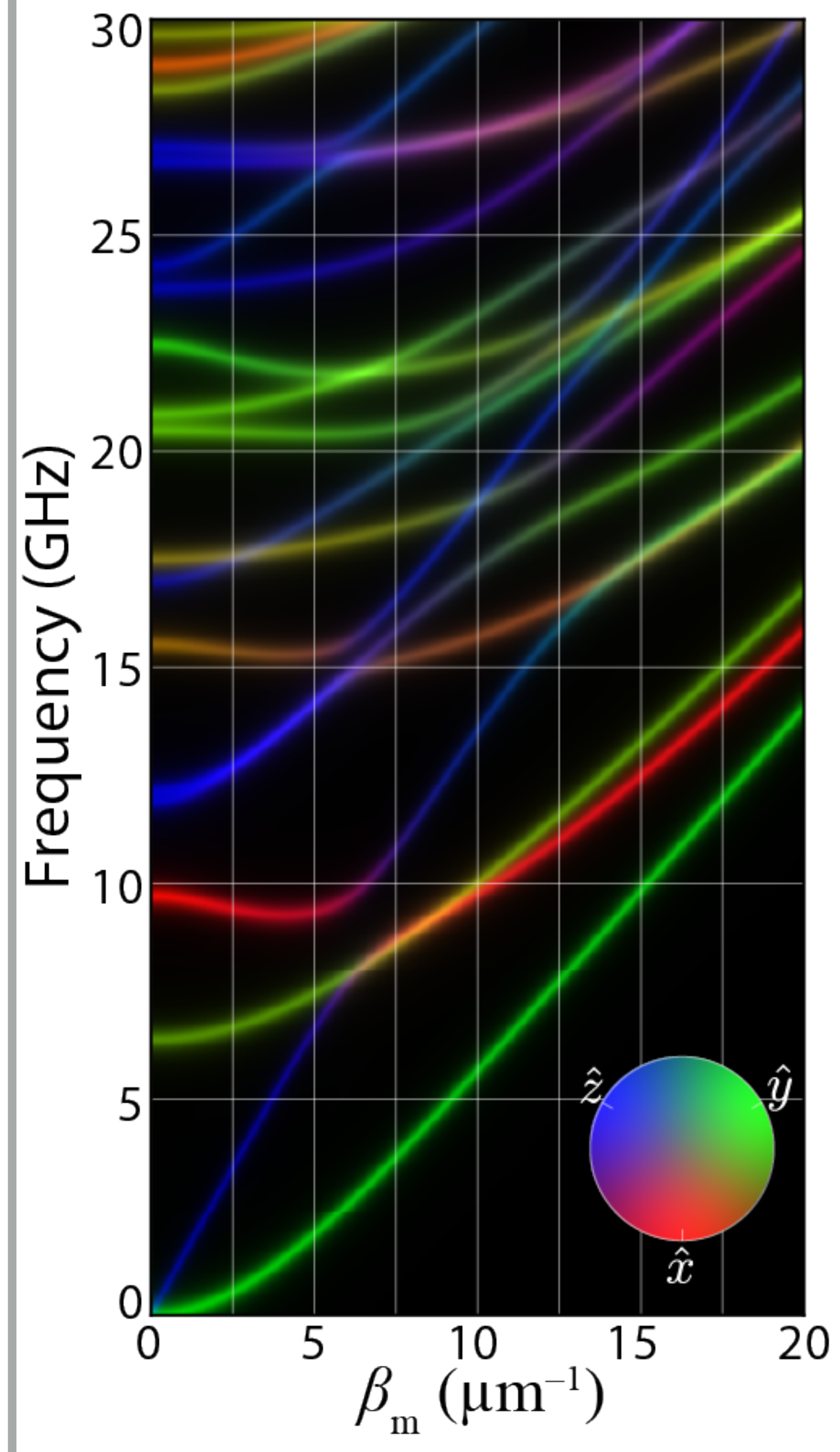
waveguide core support



Optical Domain



Mechanical Domain



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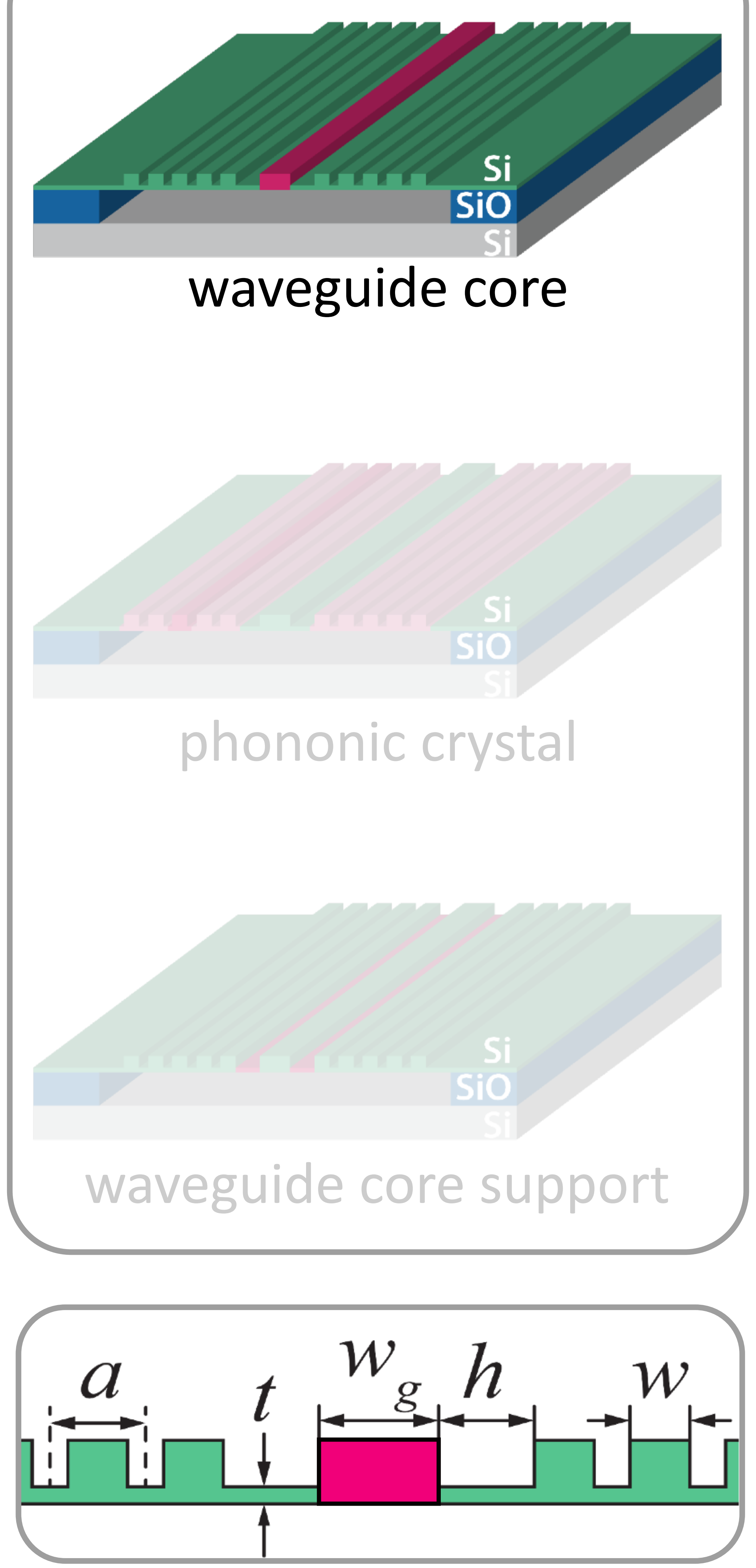
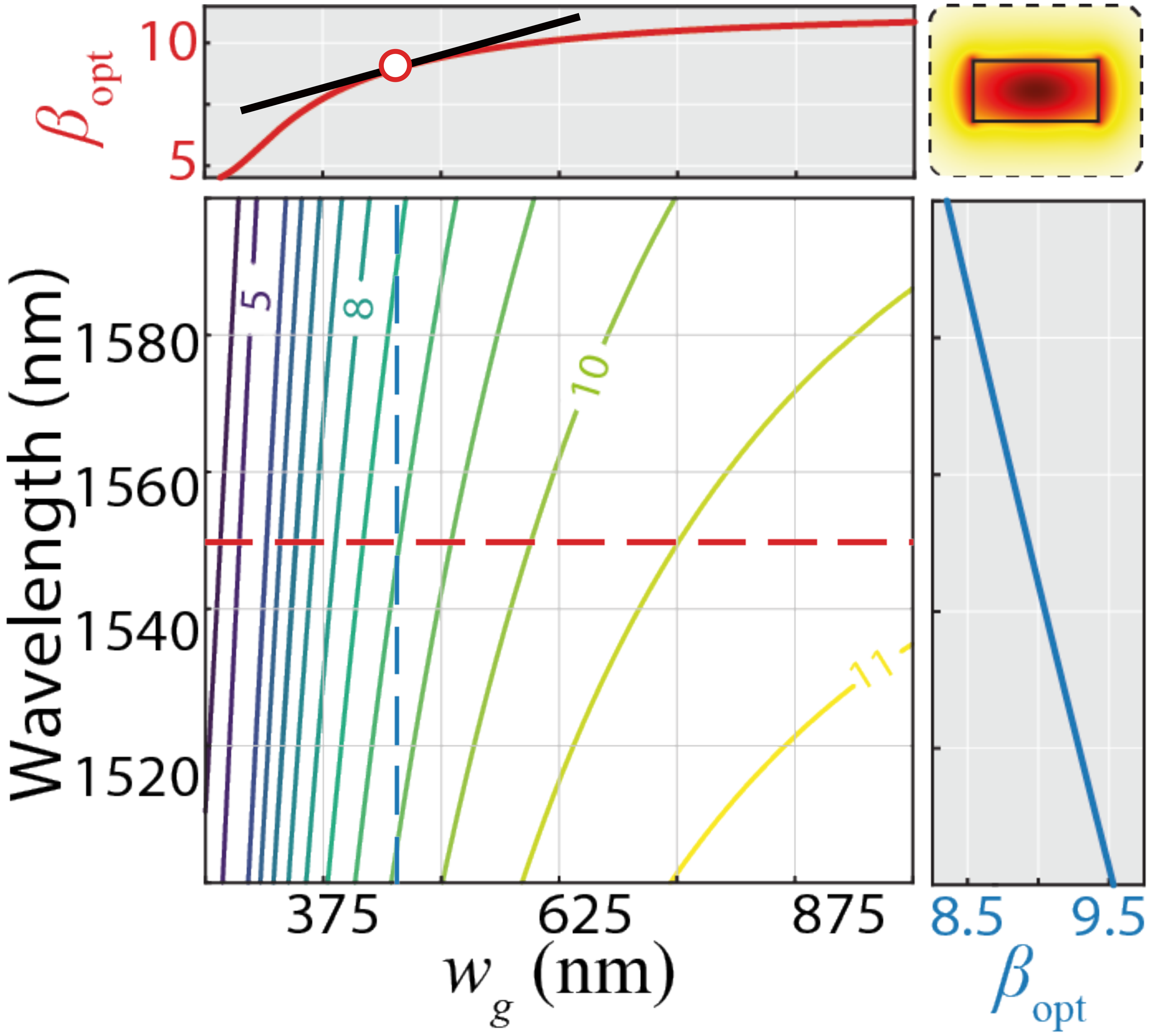
Waveguide Design Process: Core



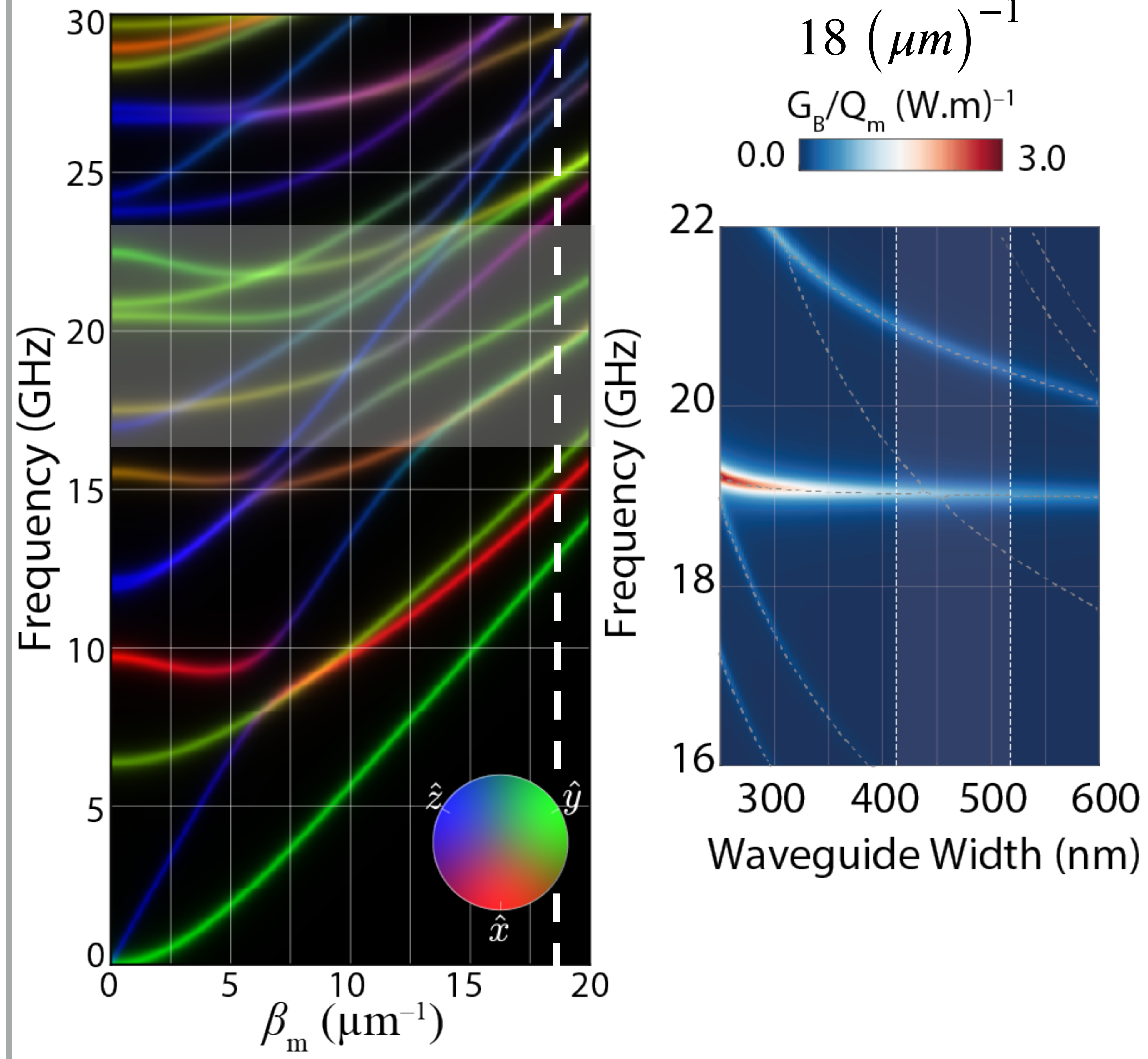
Optical Domain



Mechanical Domain

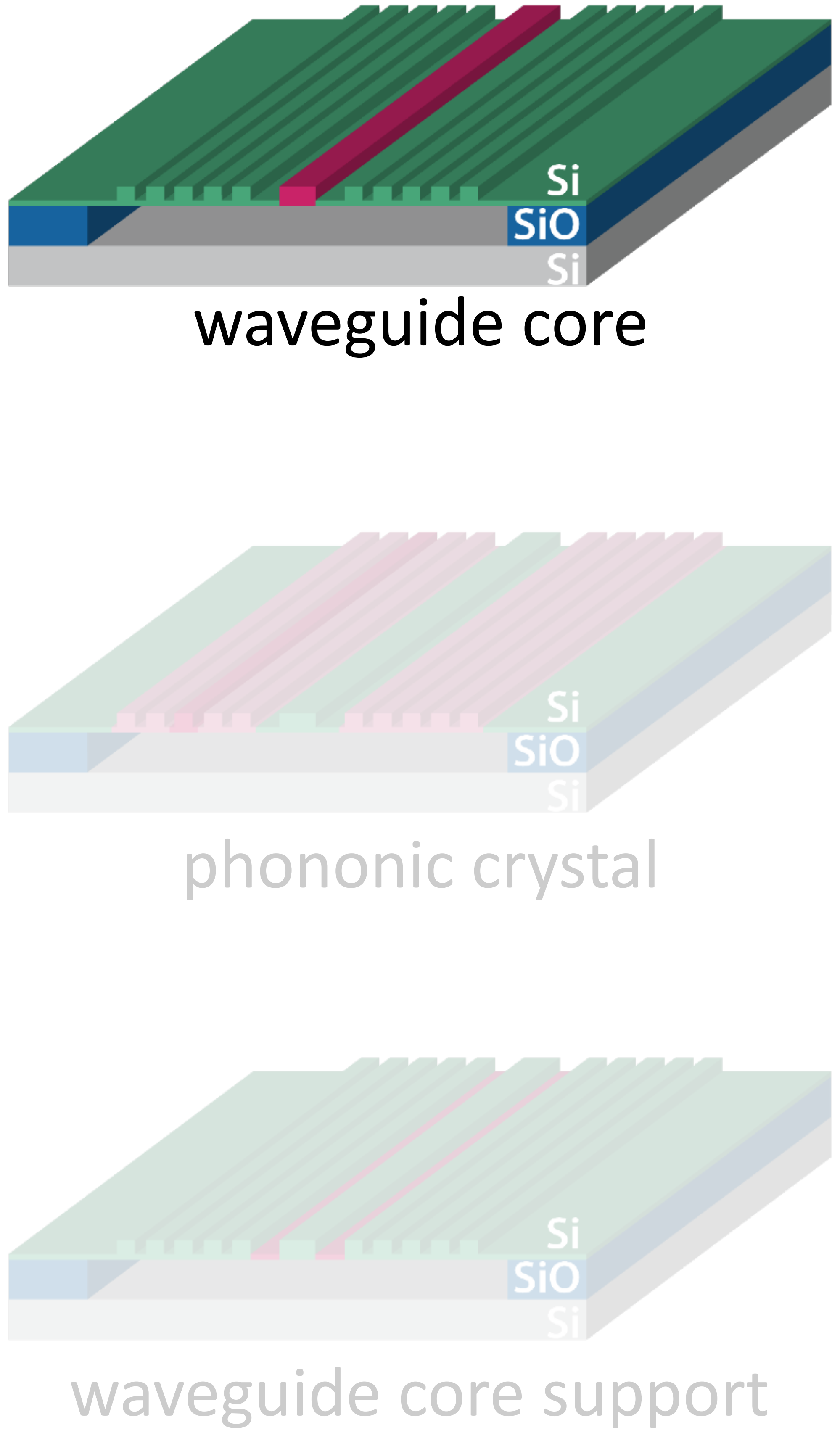
Coupling factor map @

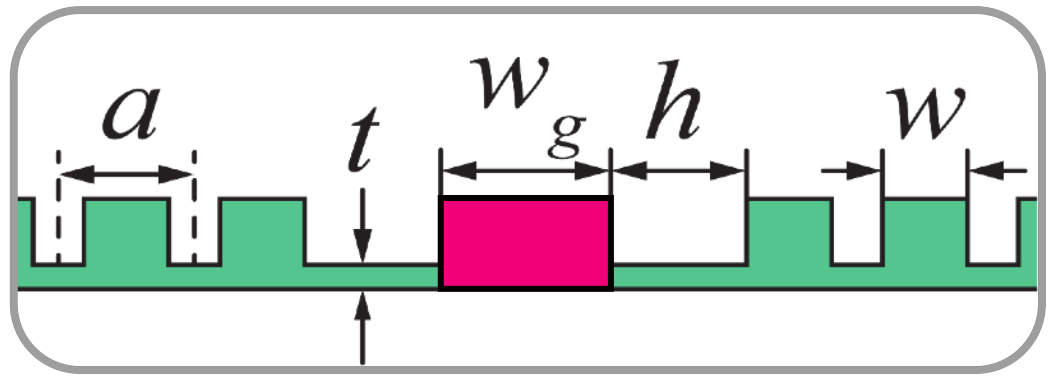
$18\ (\mu m)^{-1}$



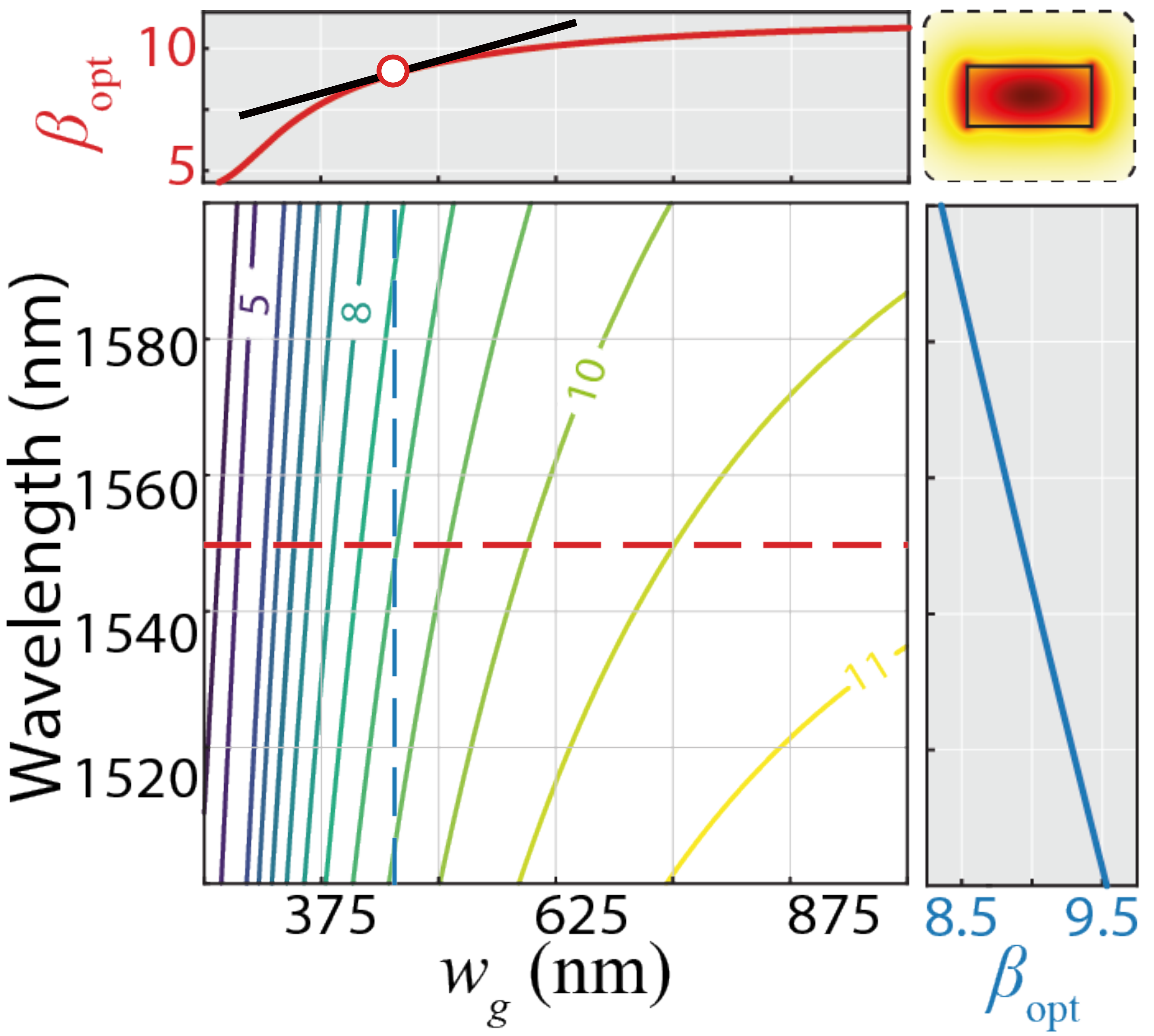
DOI: 10.5281/zenodo.4148337

Waveguide Design Process: Core

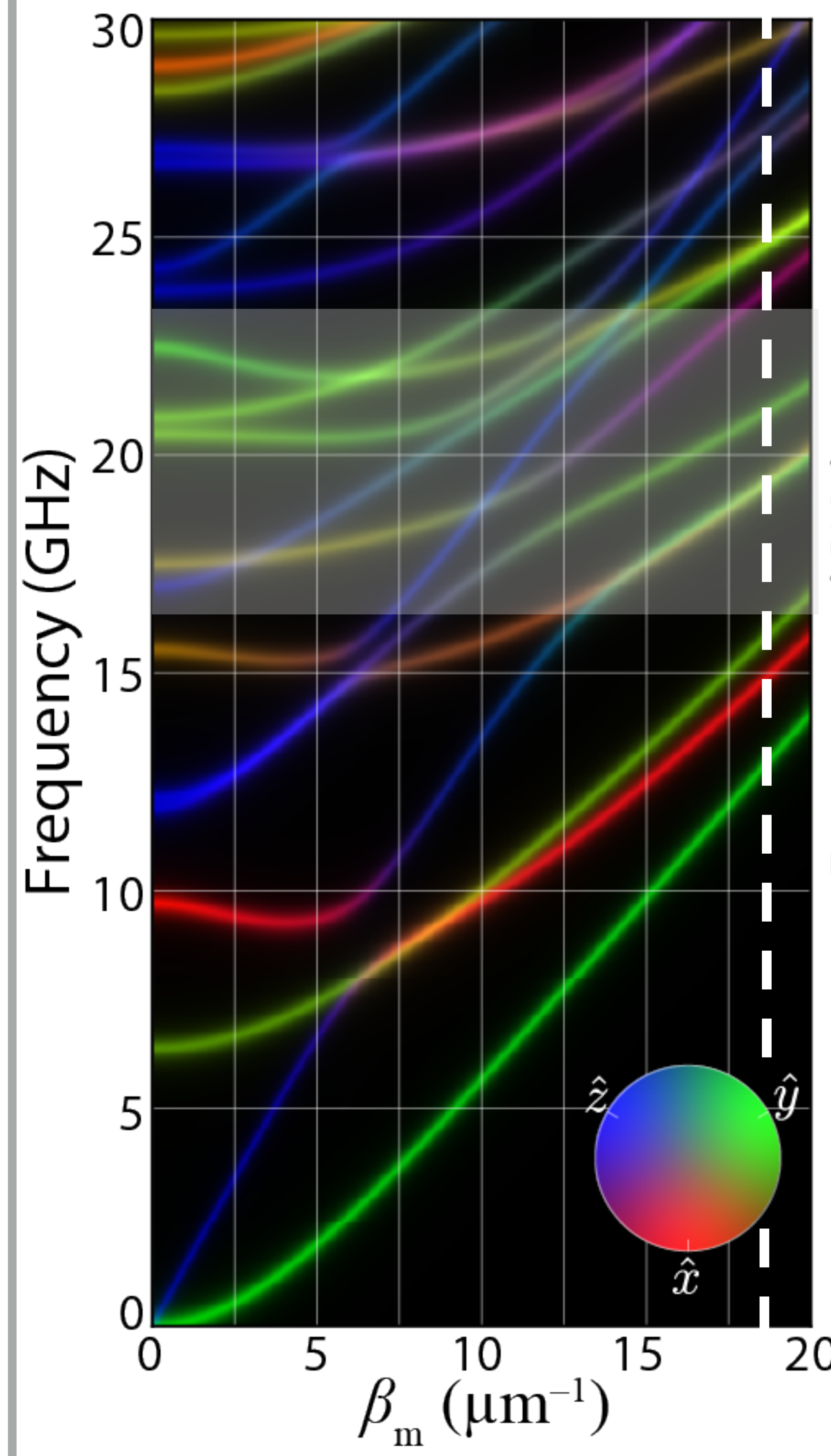




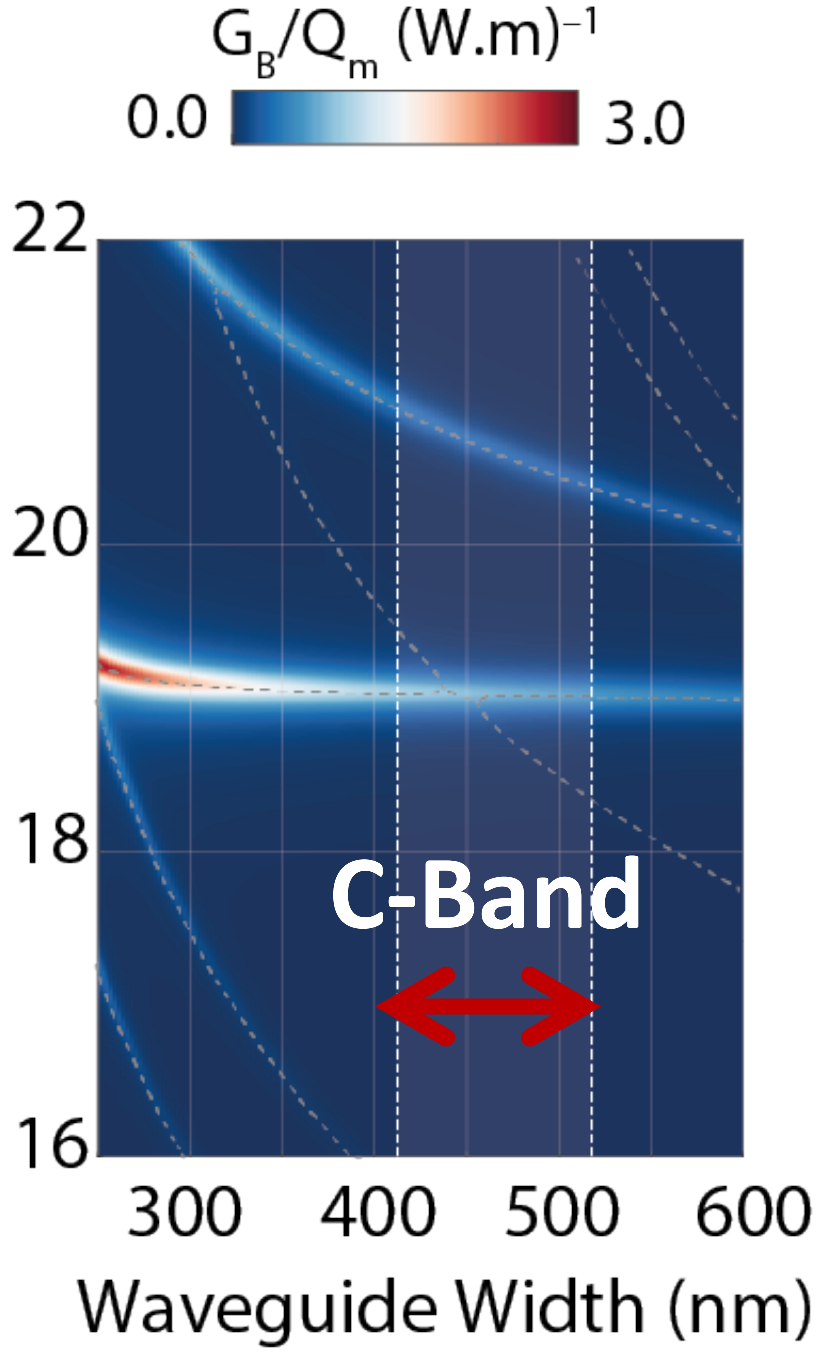
Optical Domain



Mechanical Domain

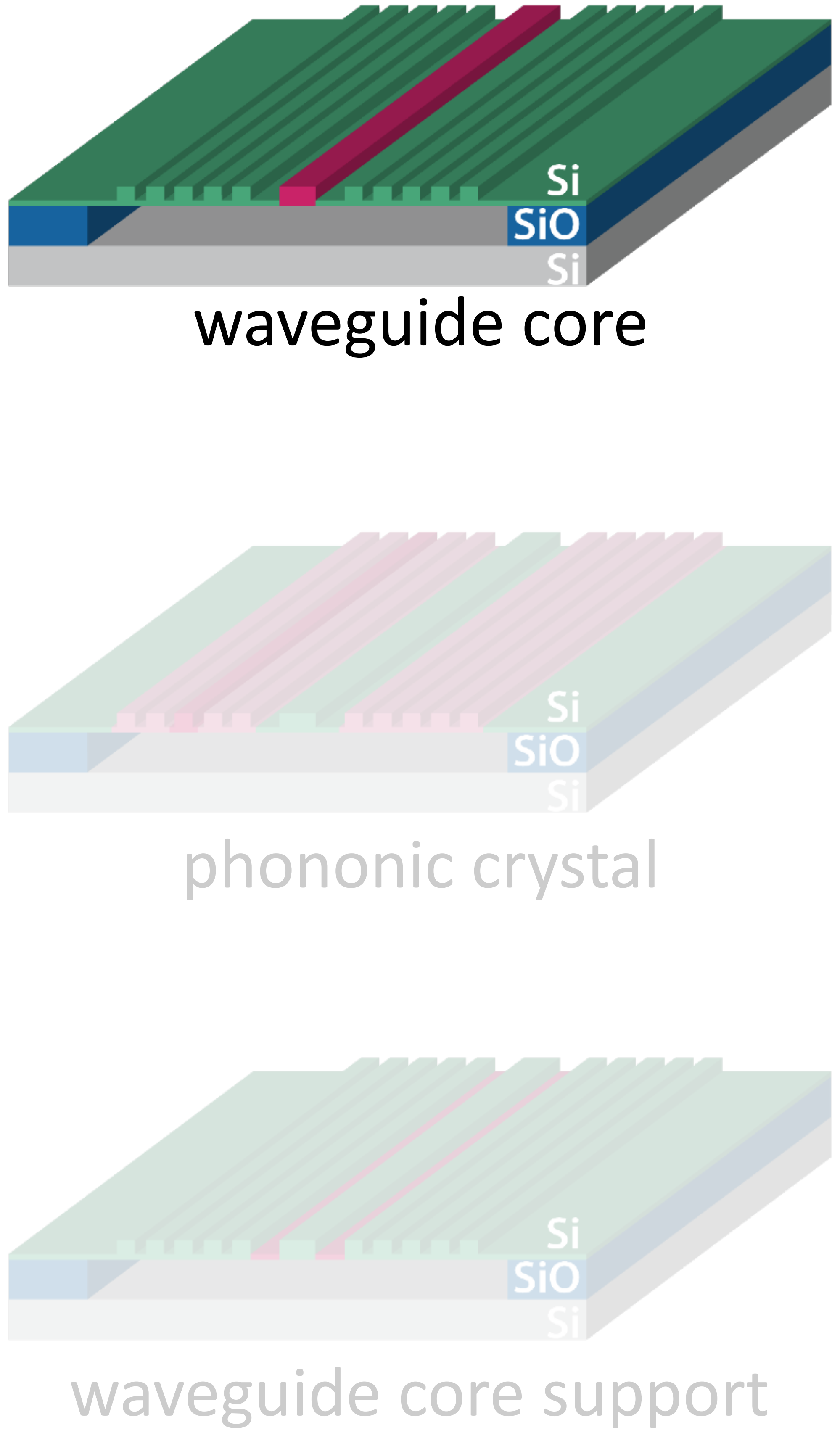


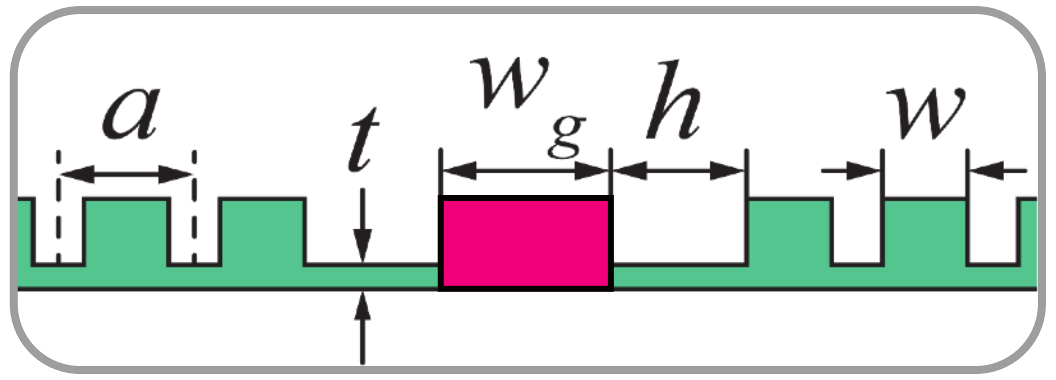
Coupling factor map @ $18\ (\mu m)^{-1}$



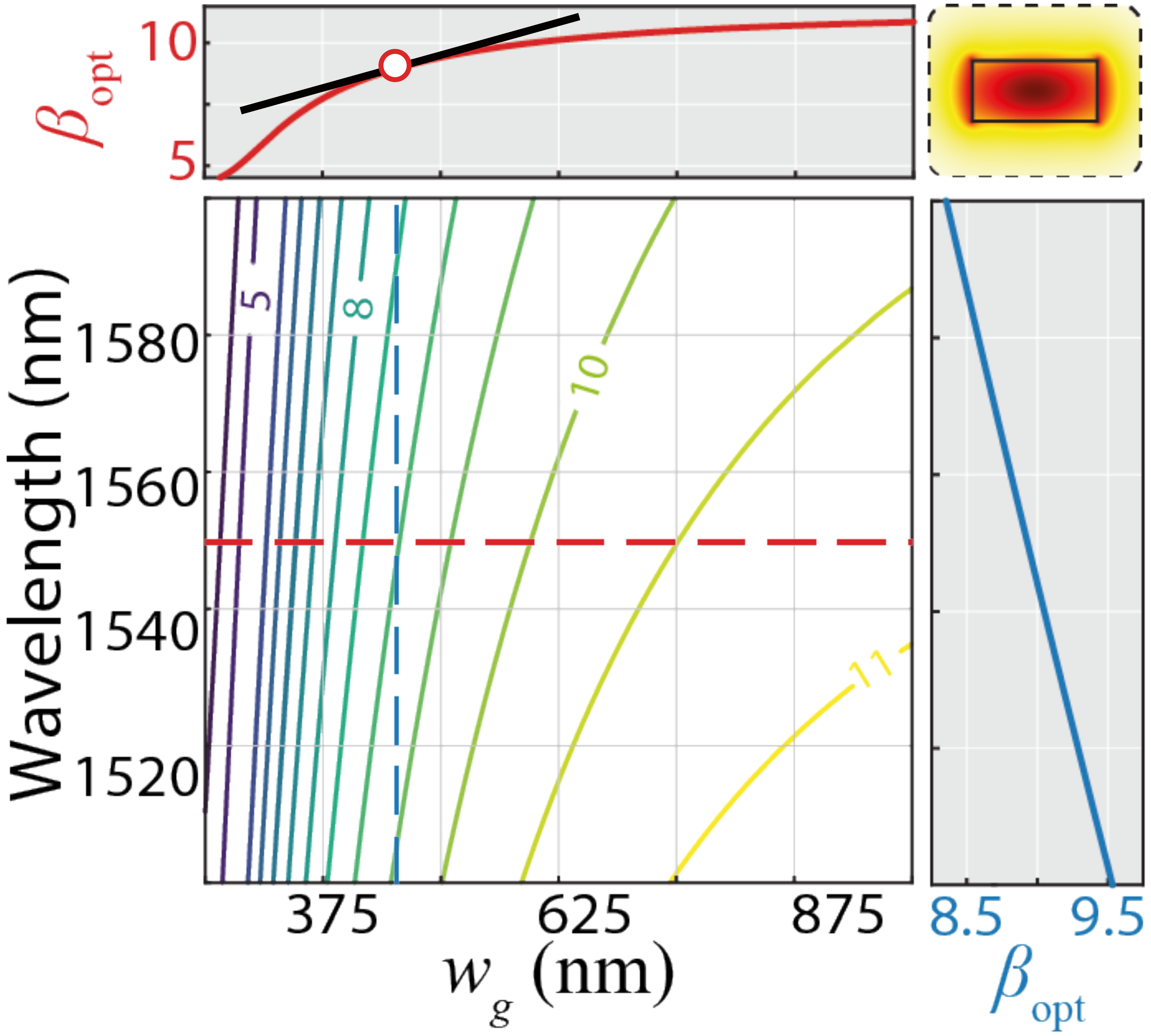
DOI: 10.5281/zenodo.4148337

Waveguide Design Process: Core

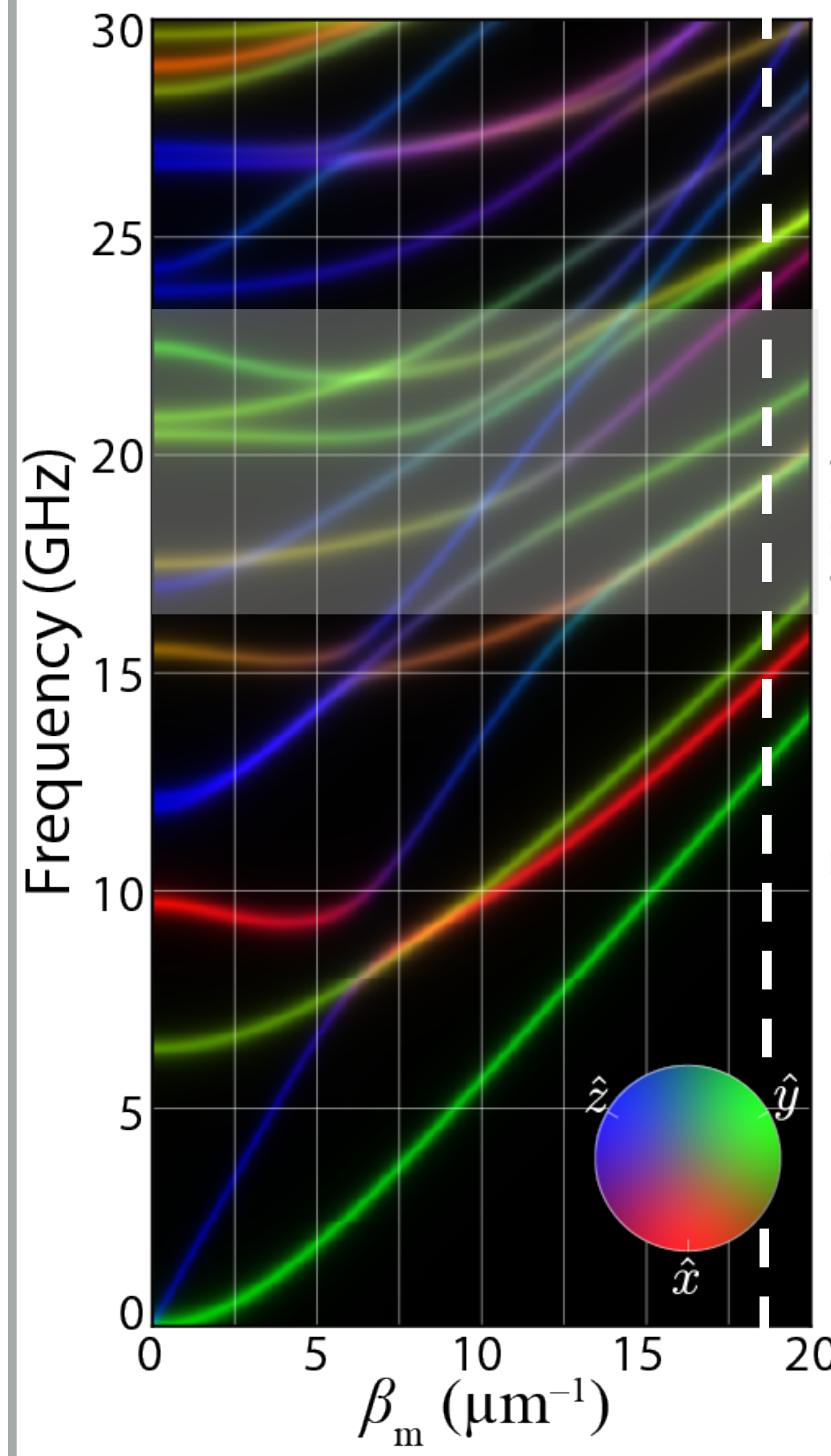




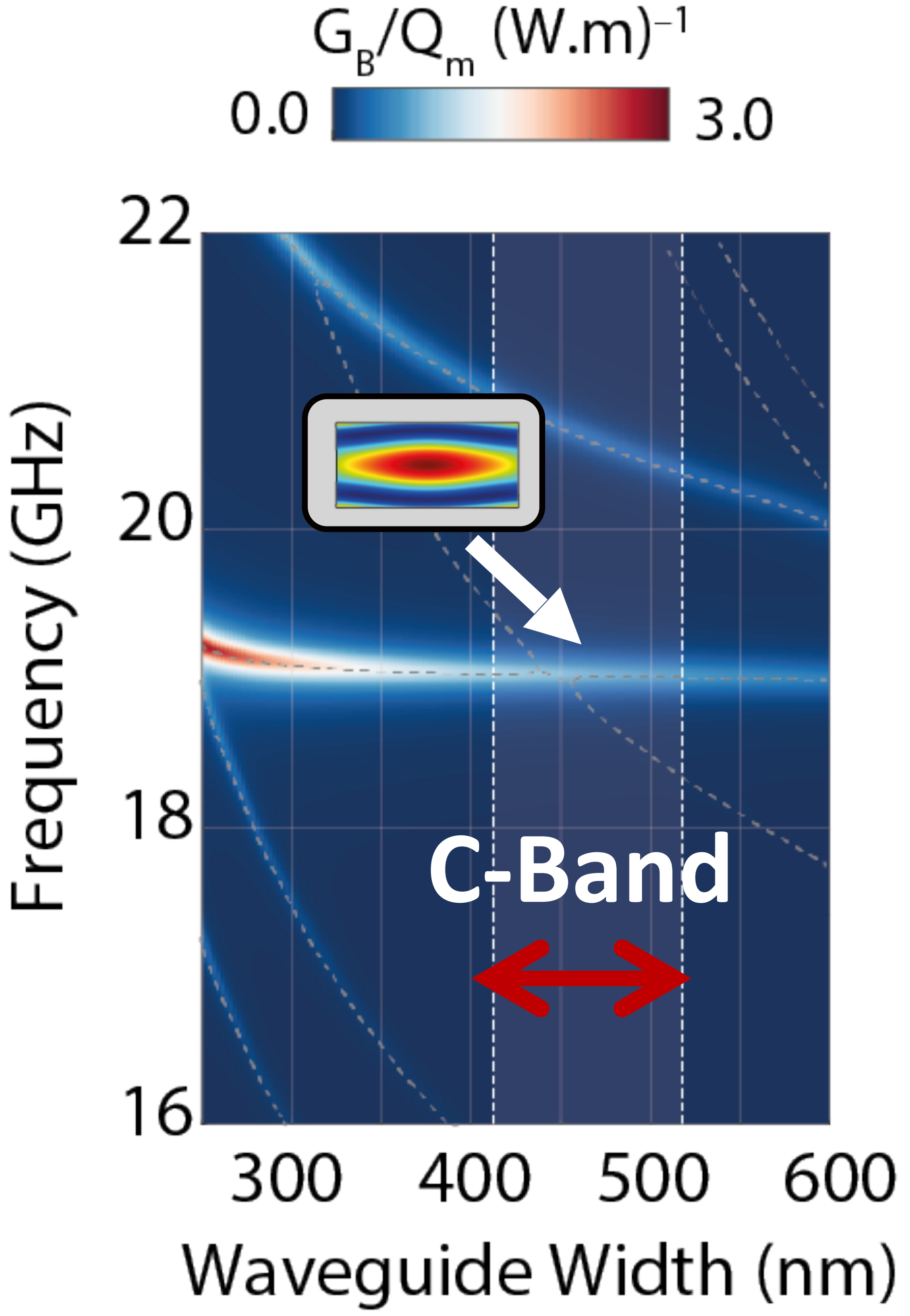
Optical Domain



Mechanical Domain

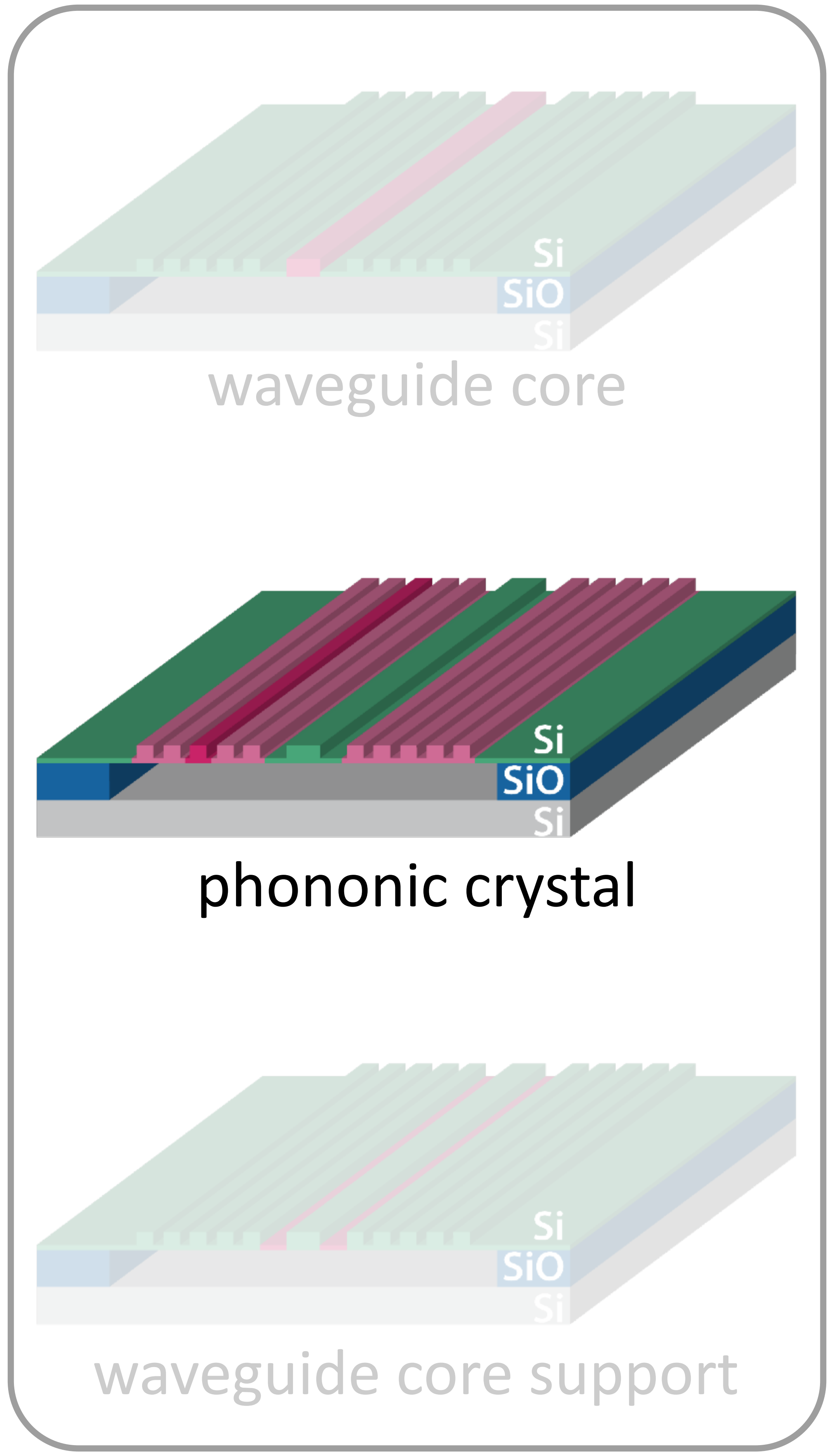


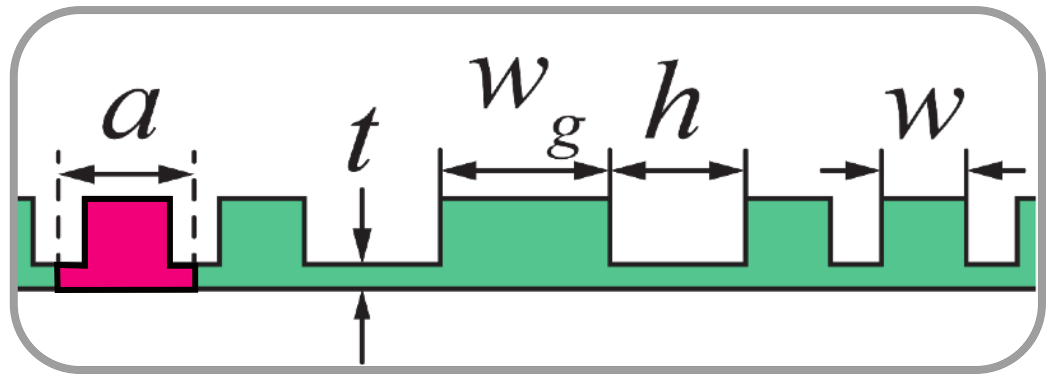
Coupling factor map @ $18\ (\mu m)^{-1}$



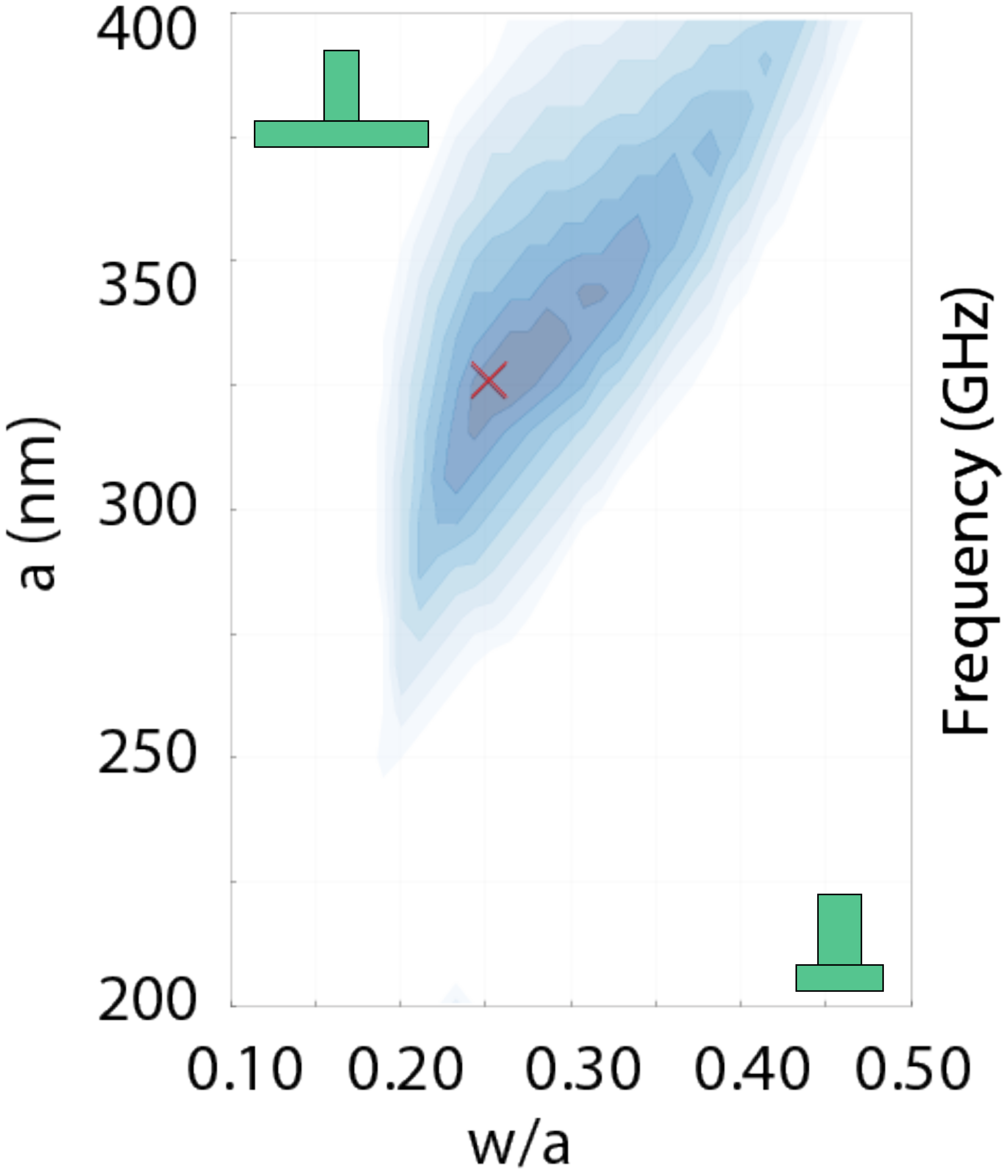
DOI: 10.5281/zenodo.4148337

Waveguide Design Process: PhnC

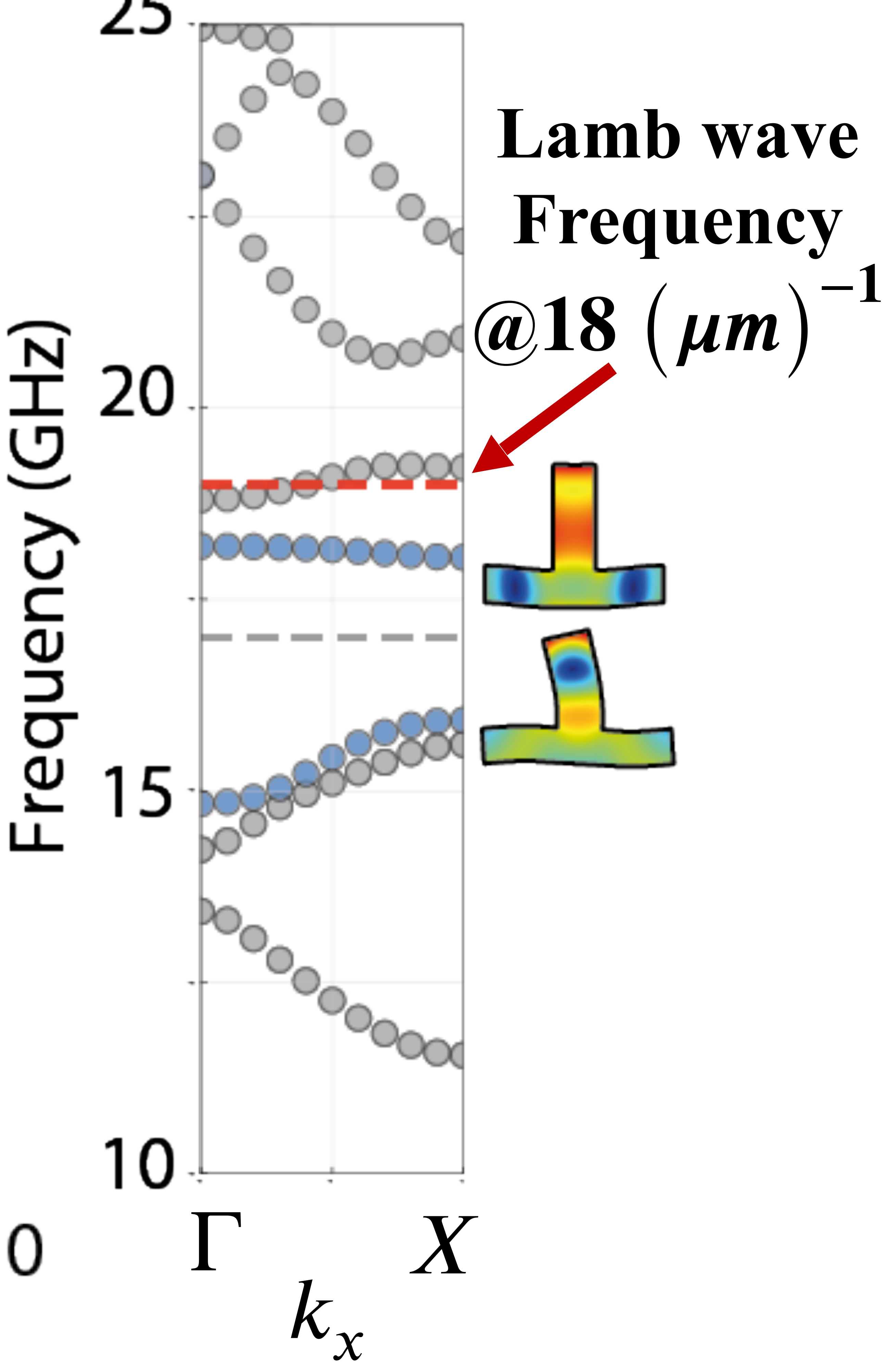




PhnC Parameters map

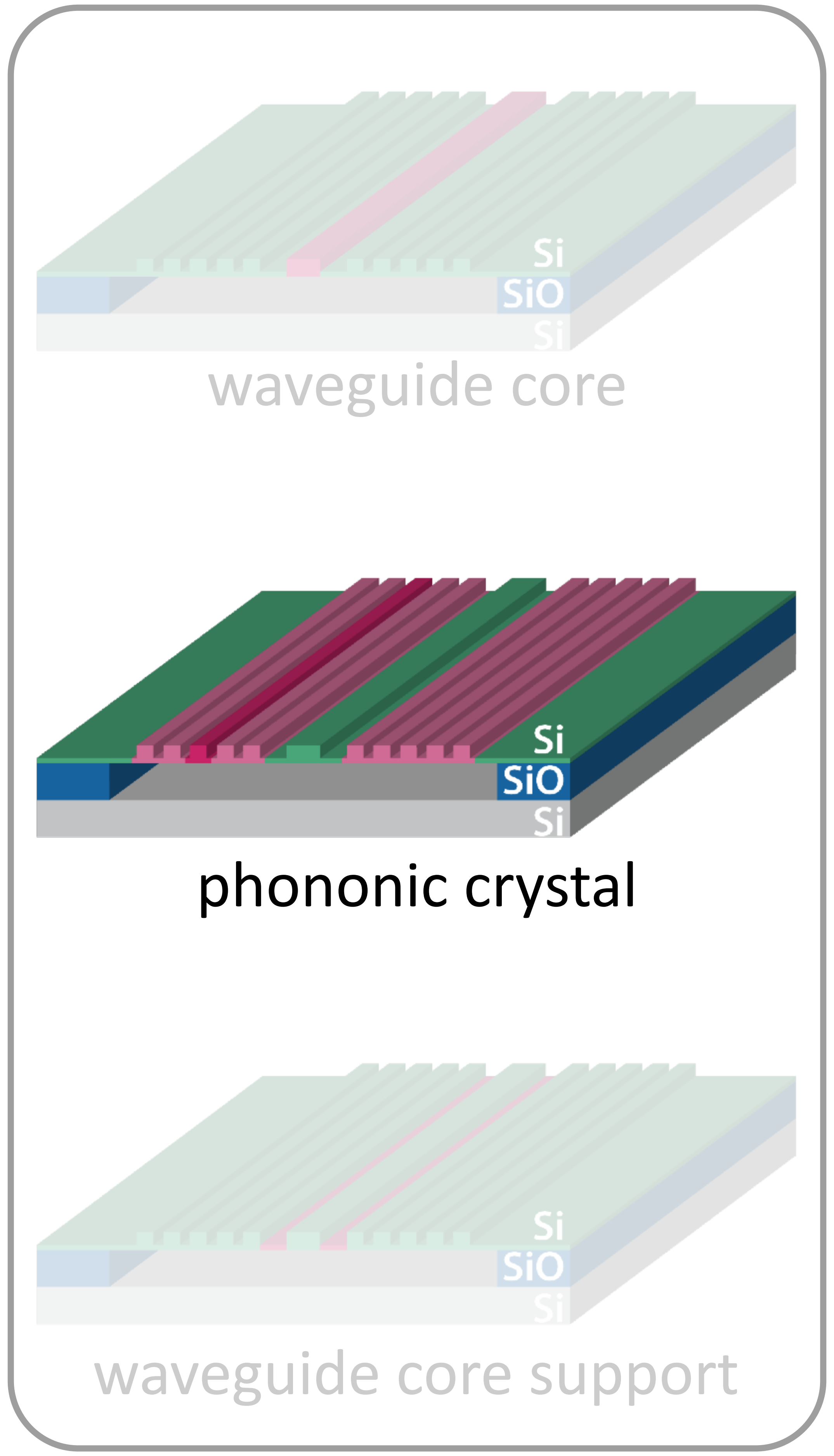


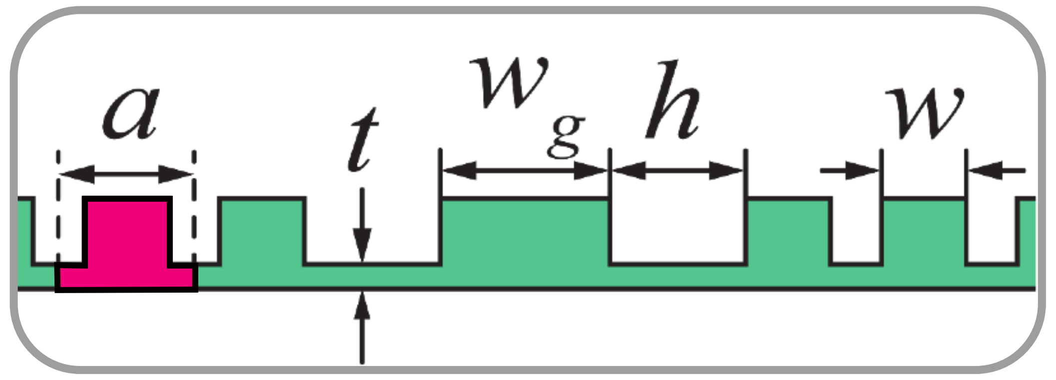
Band diagram @18 $(\mu m)^{-1}$

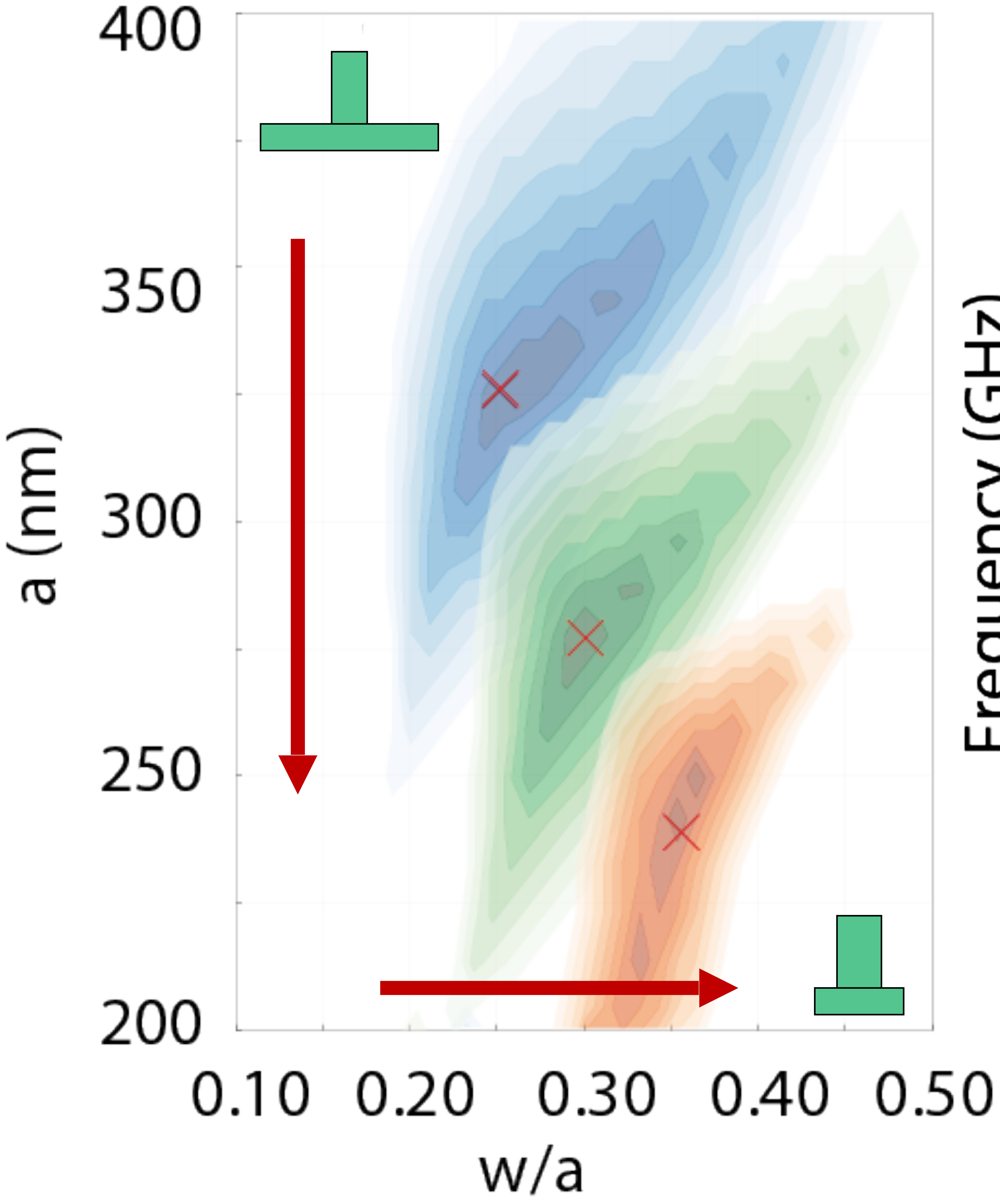


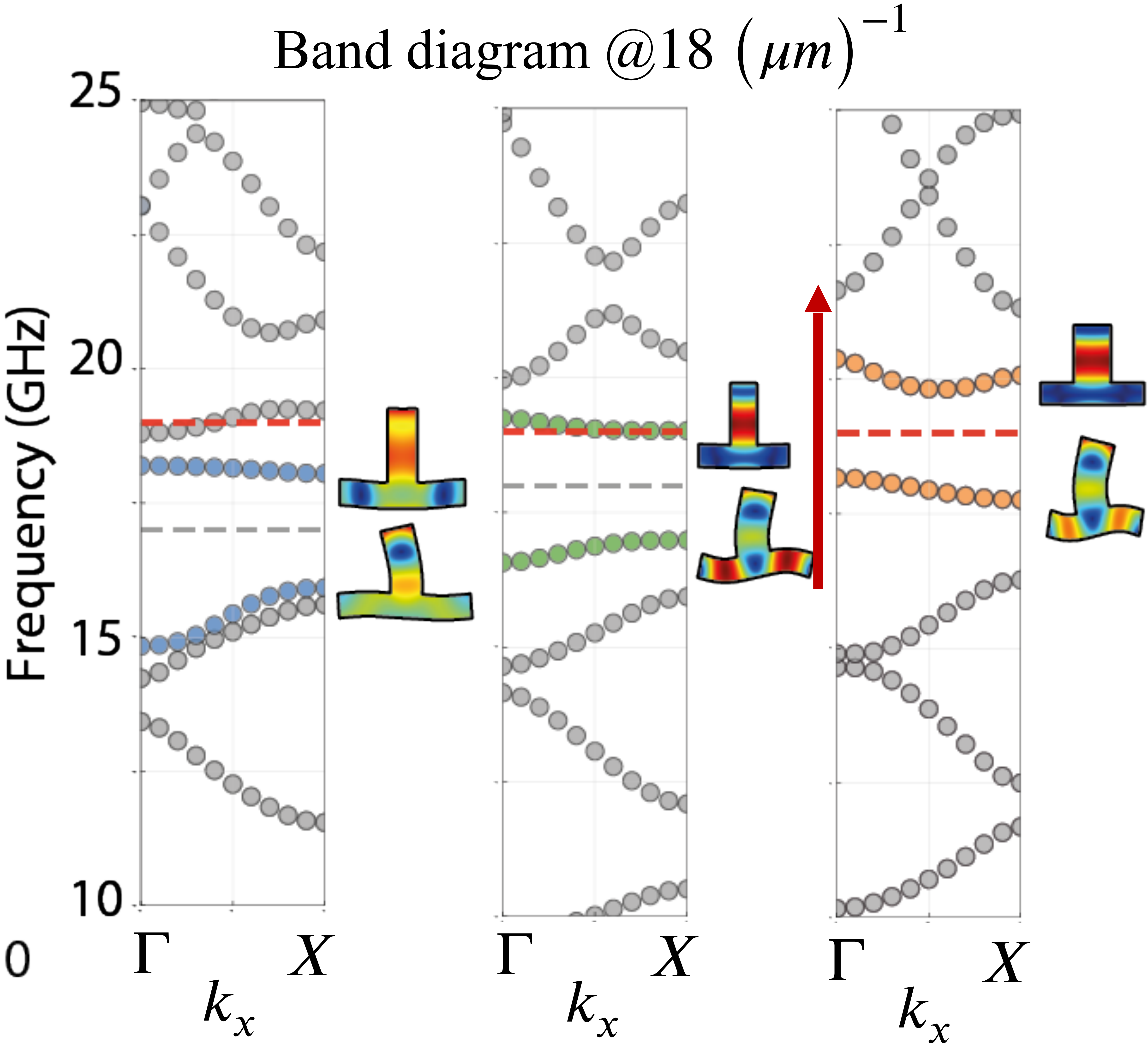
DOI: 10.5281/zenodo.4148337

Waveguide Design Process: PhnC



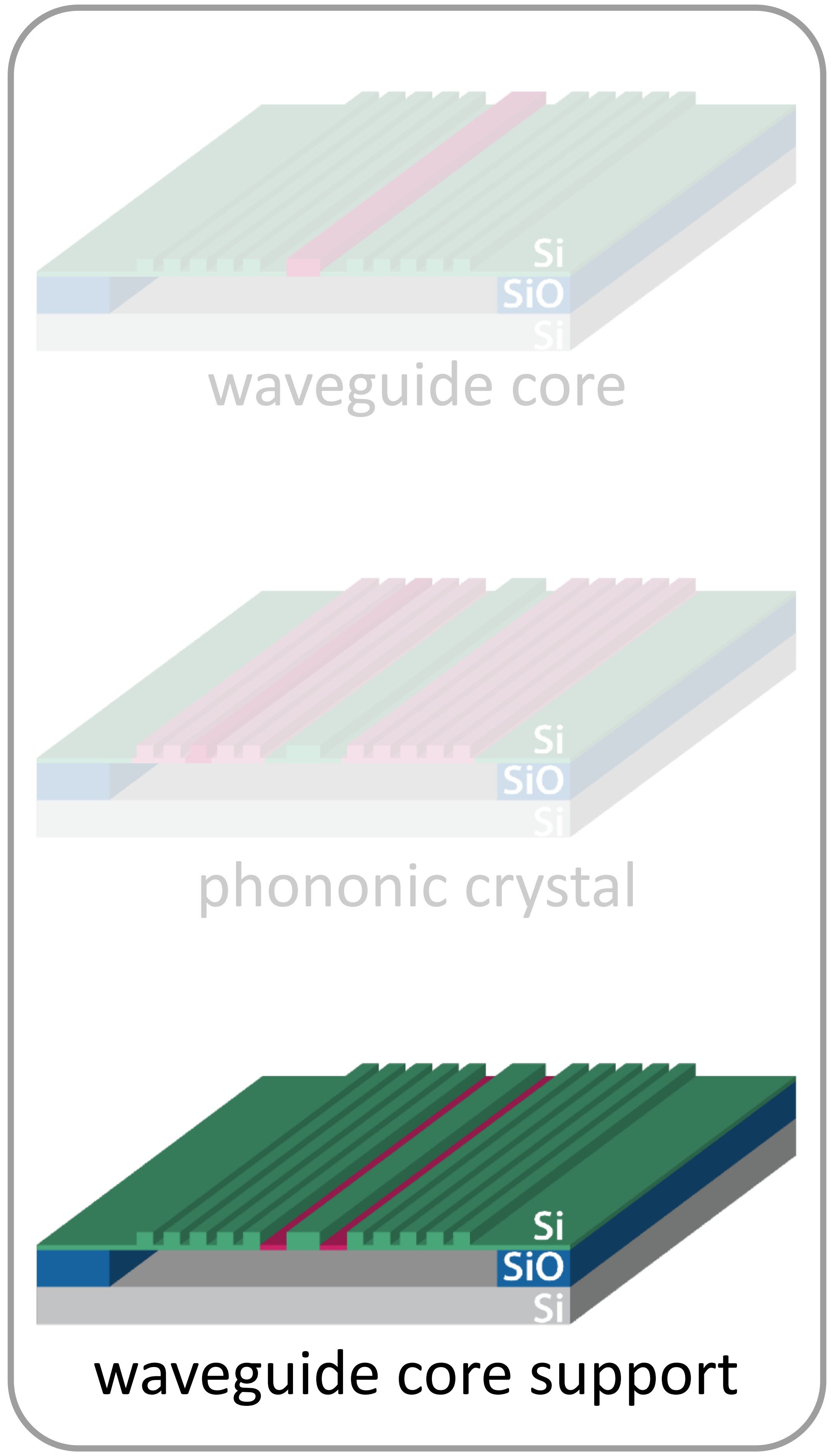


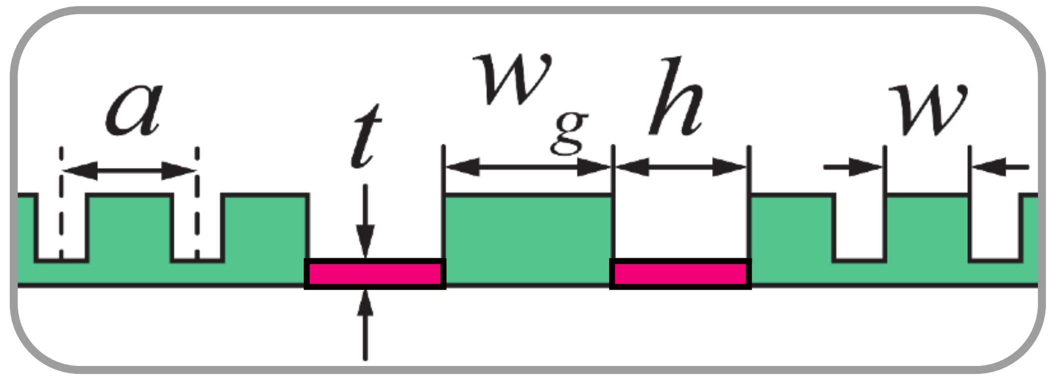




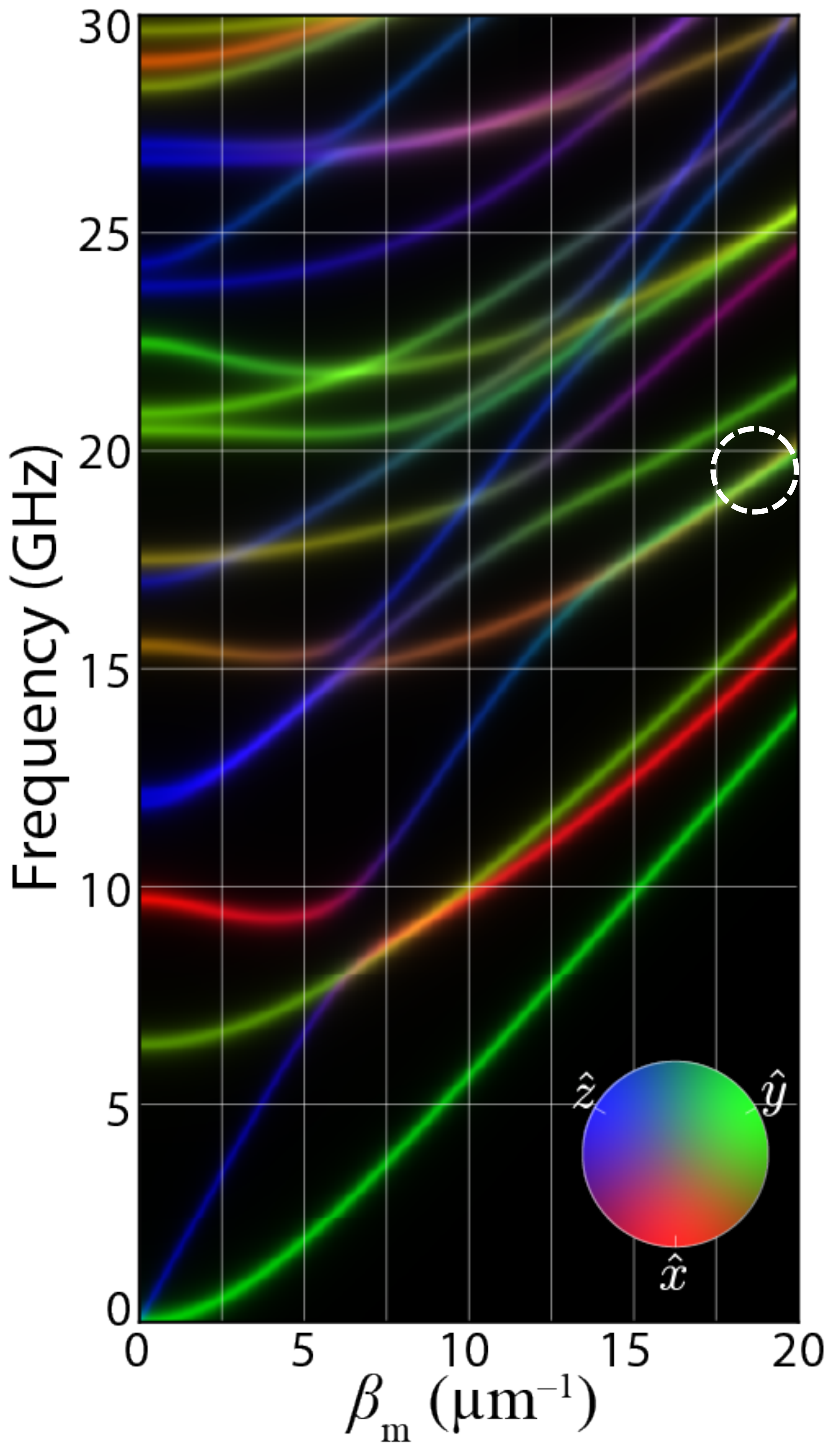
DOI: 10.5281/zenodo.4148337

Waveguide Design Process: Core support

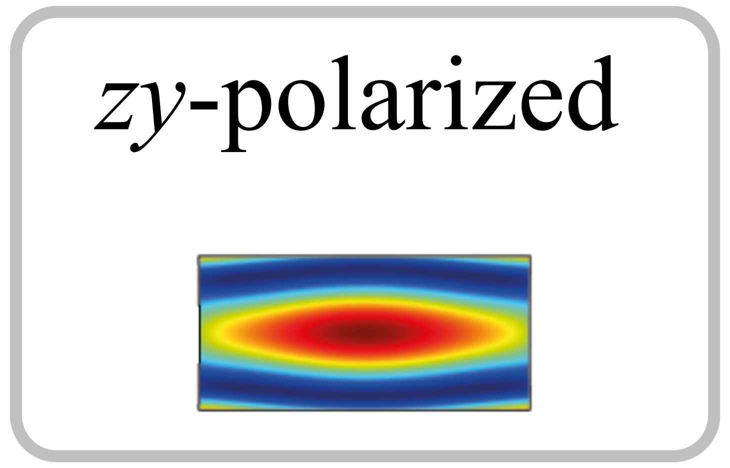




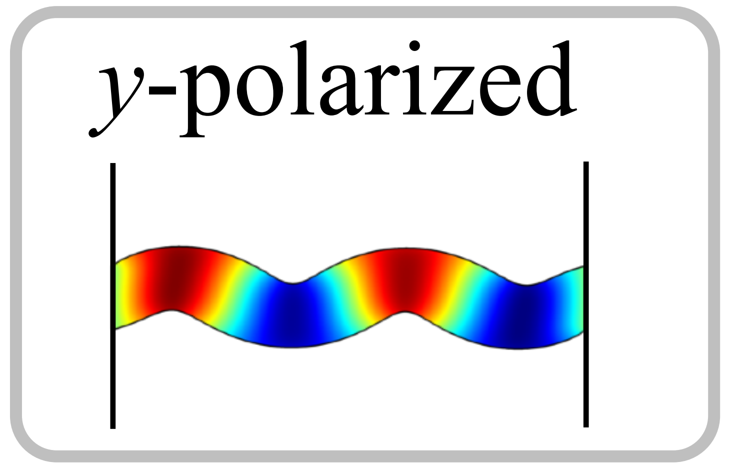
Core mechanical dispersion

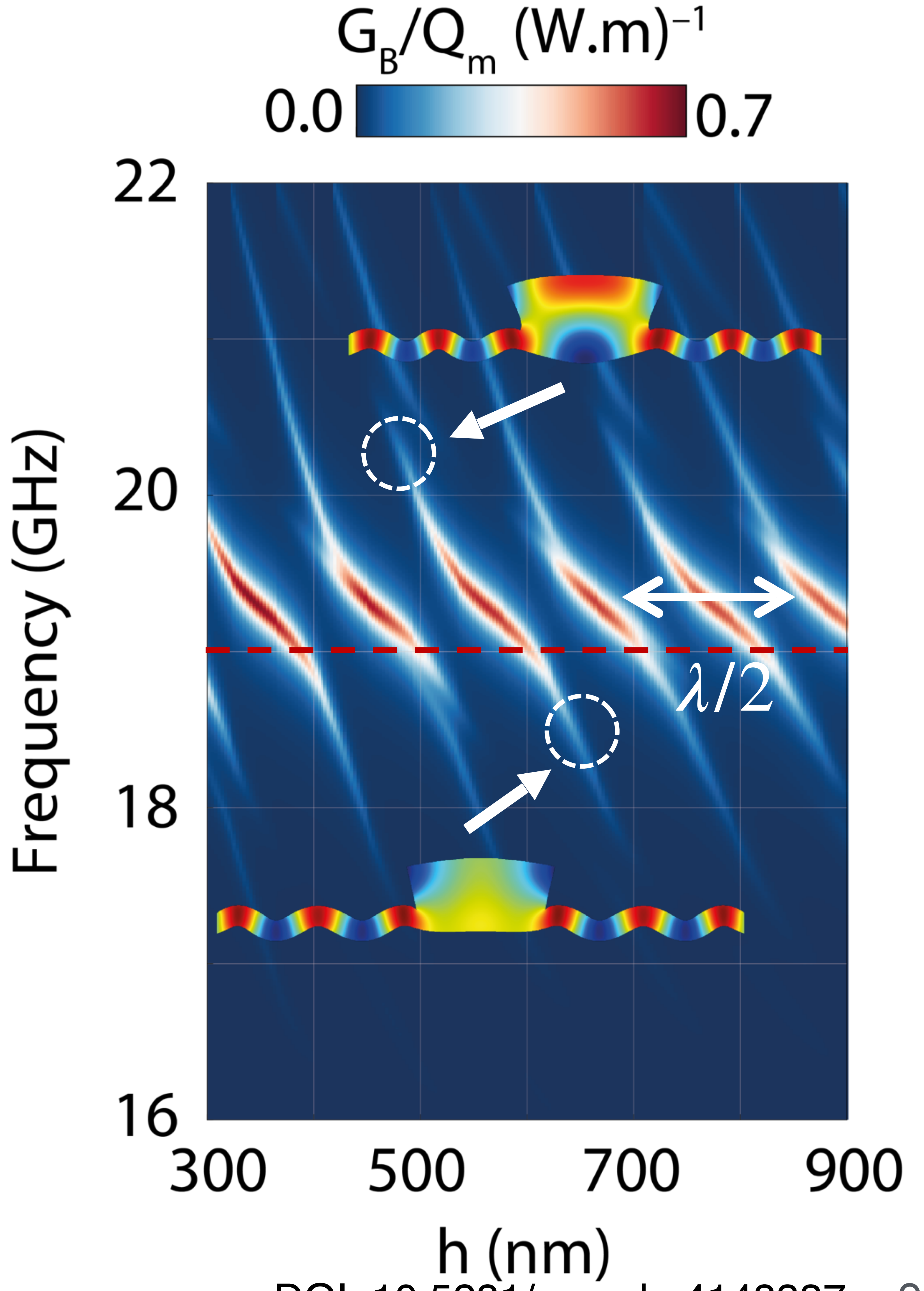


Waveguide Mode



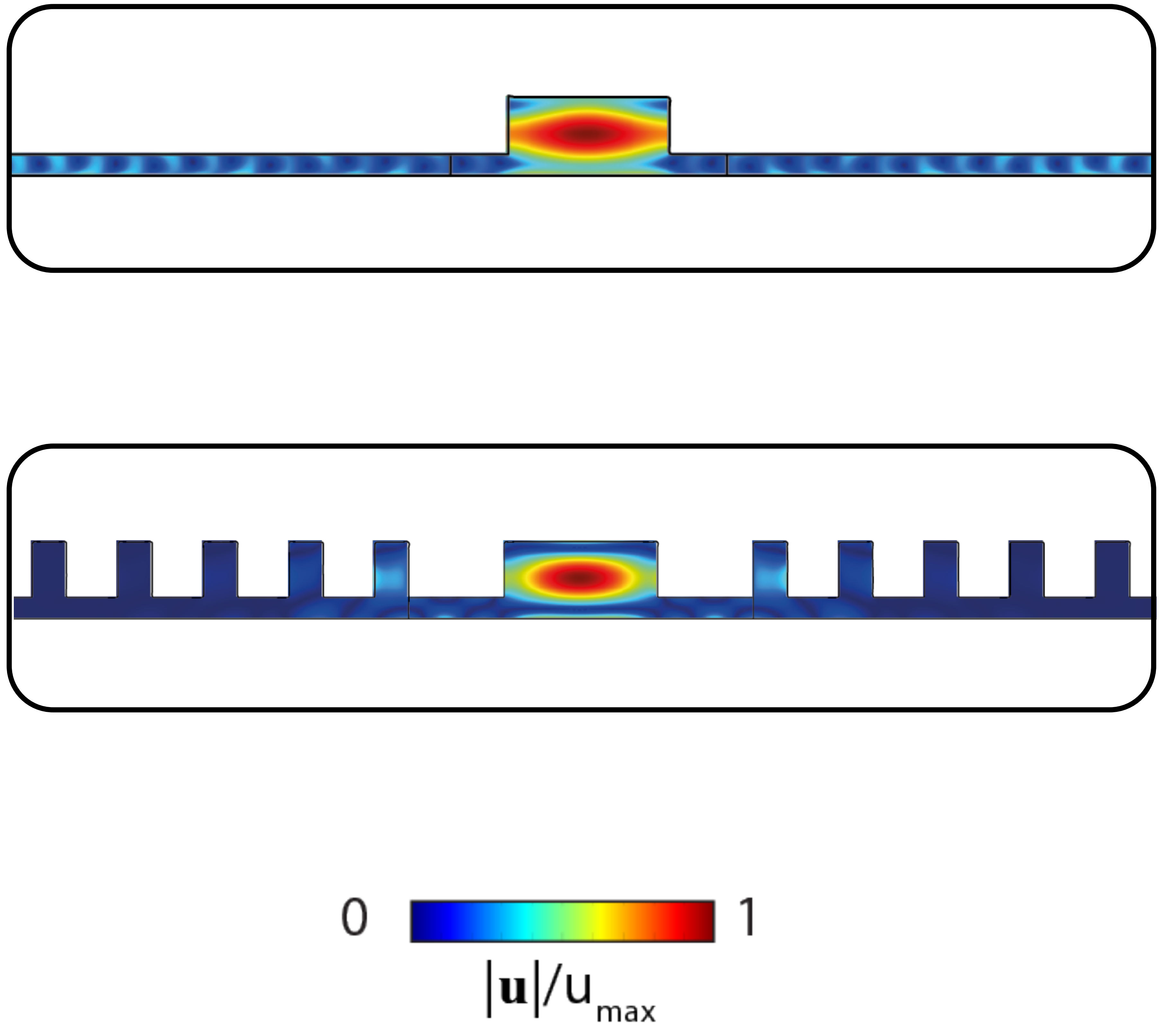
Support Mode

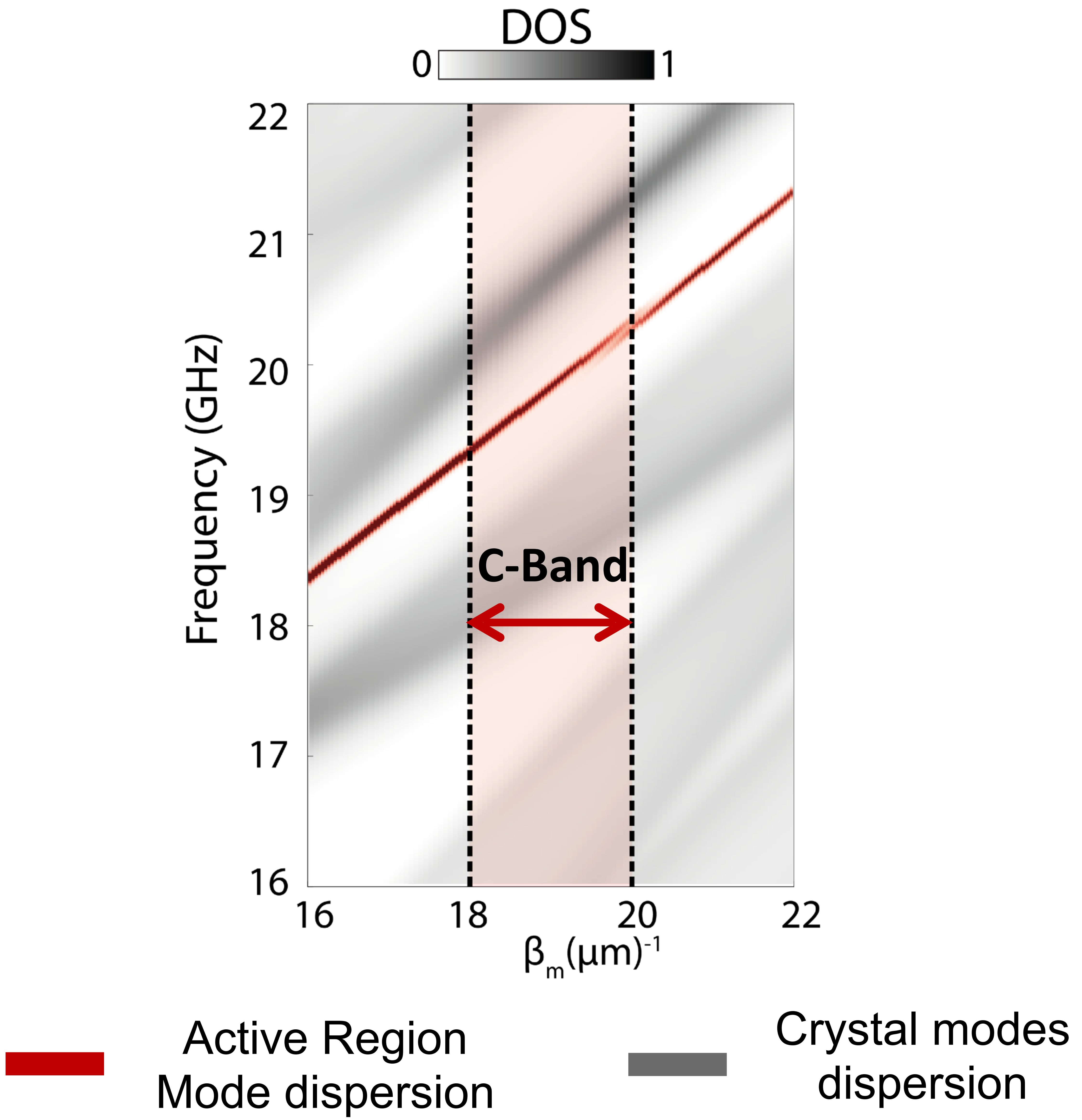




DOI: 10.5281/zenodo.4148337

Discussion





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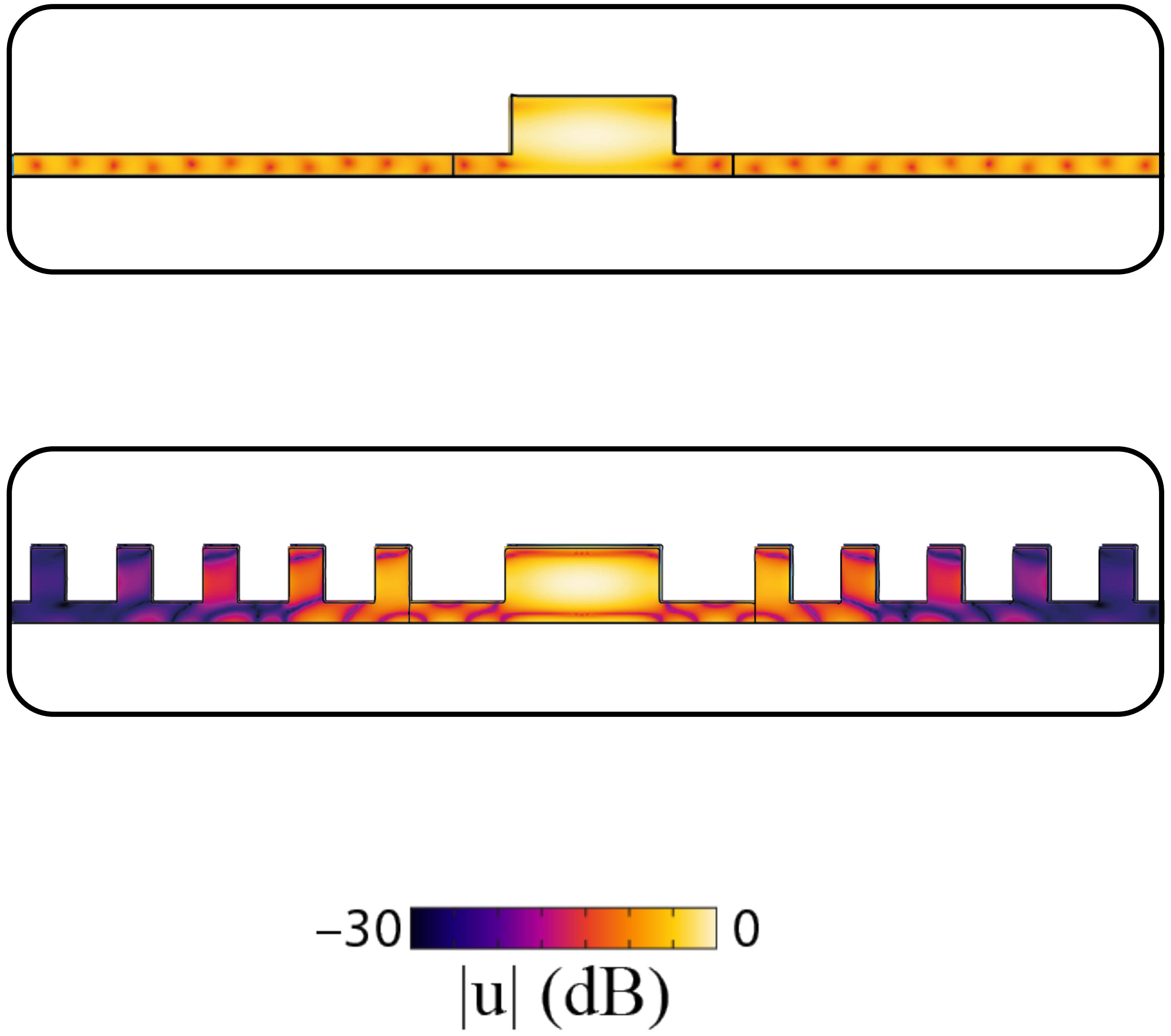
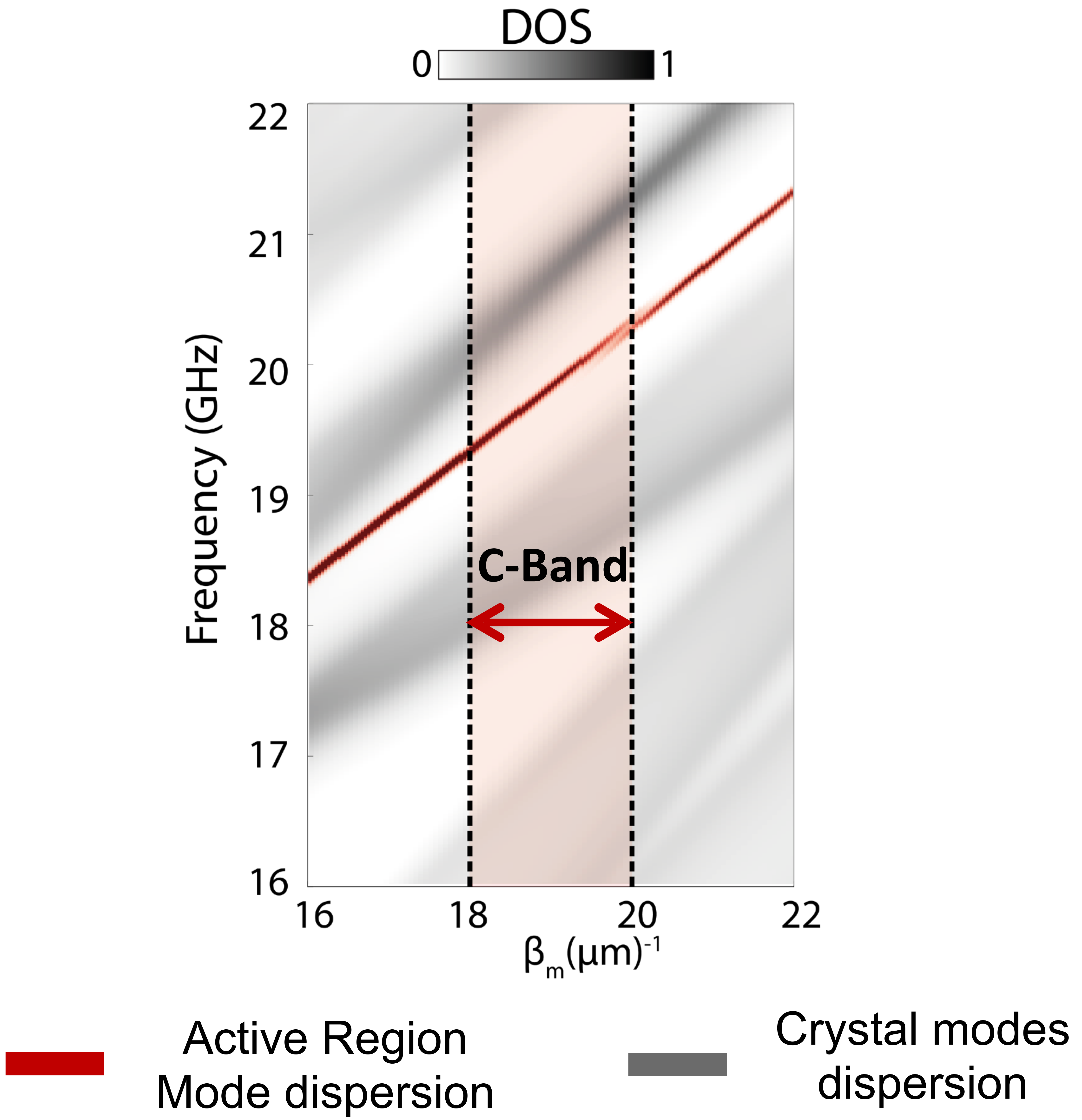
Discussion





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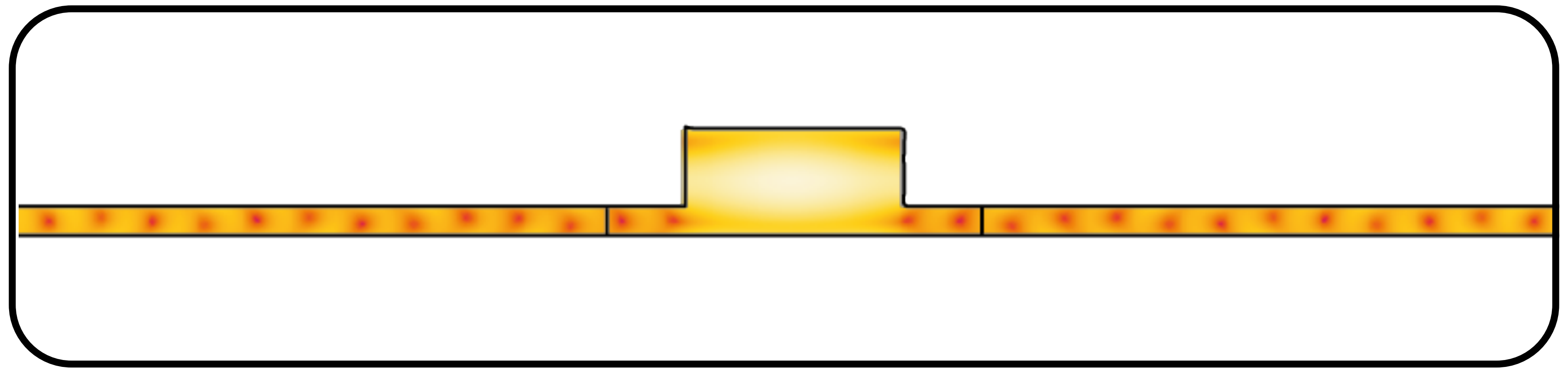
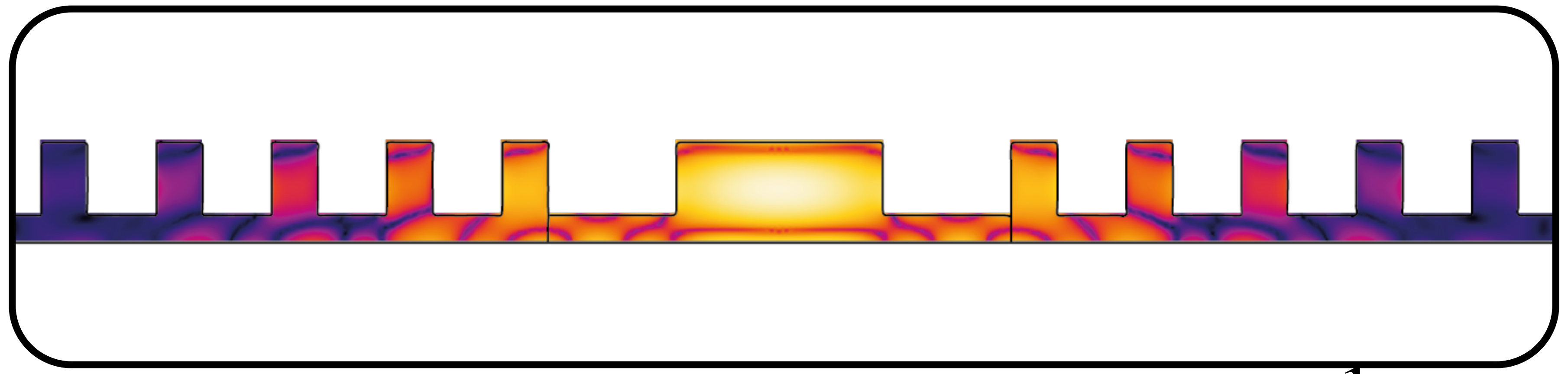
Discussion

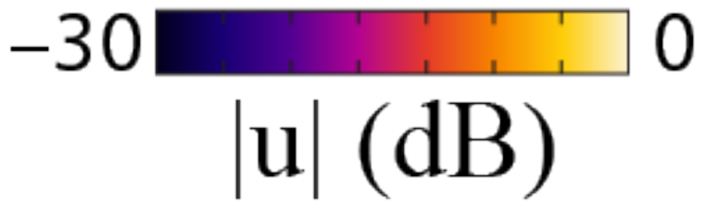
Mechanical Confinement:
$\approx 4 \times$ Larger Gain

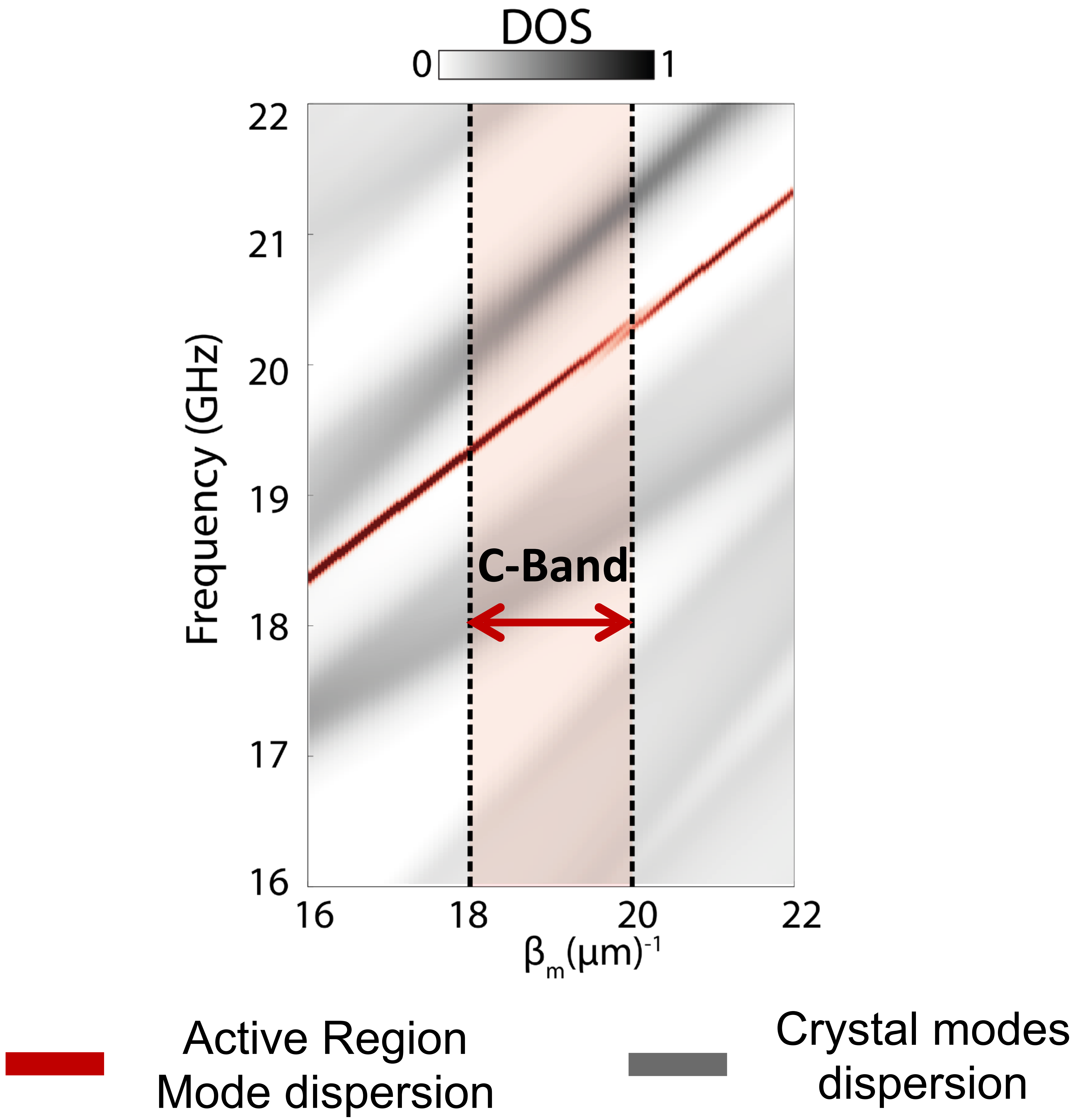


$$G_B/Q_m = 0.15\ (W.m)^{-1}$$



$$G_B/Q_m = 0.55\ (W.m)^{-1}$$





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Discussion

Mechanical Confinement:
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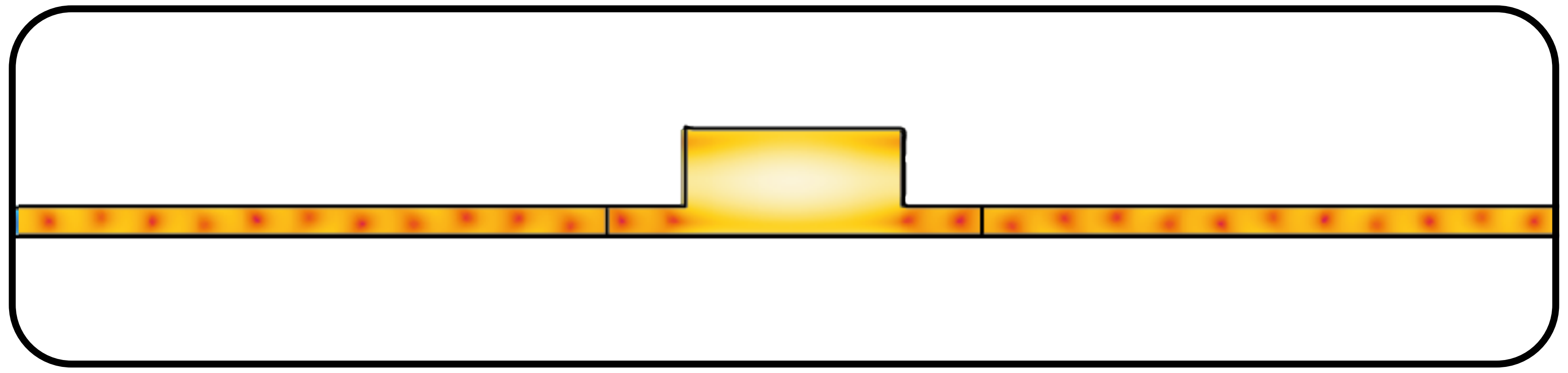

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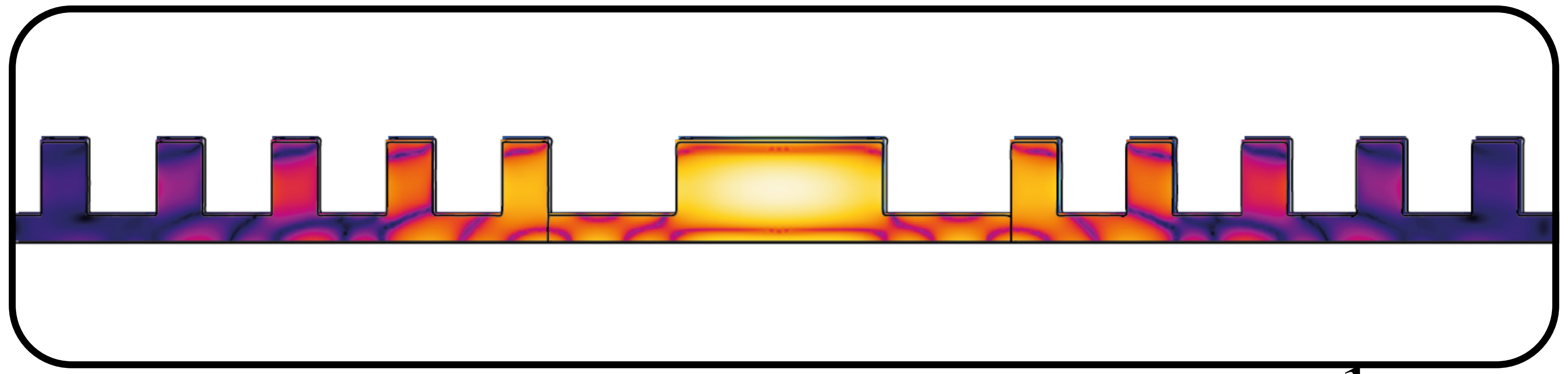
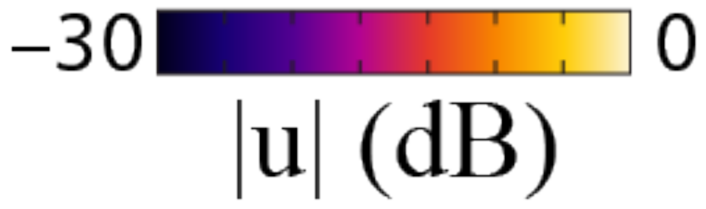
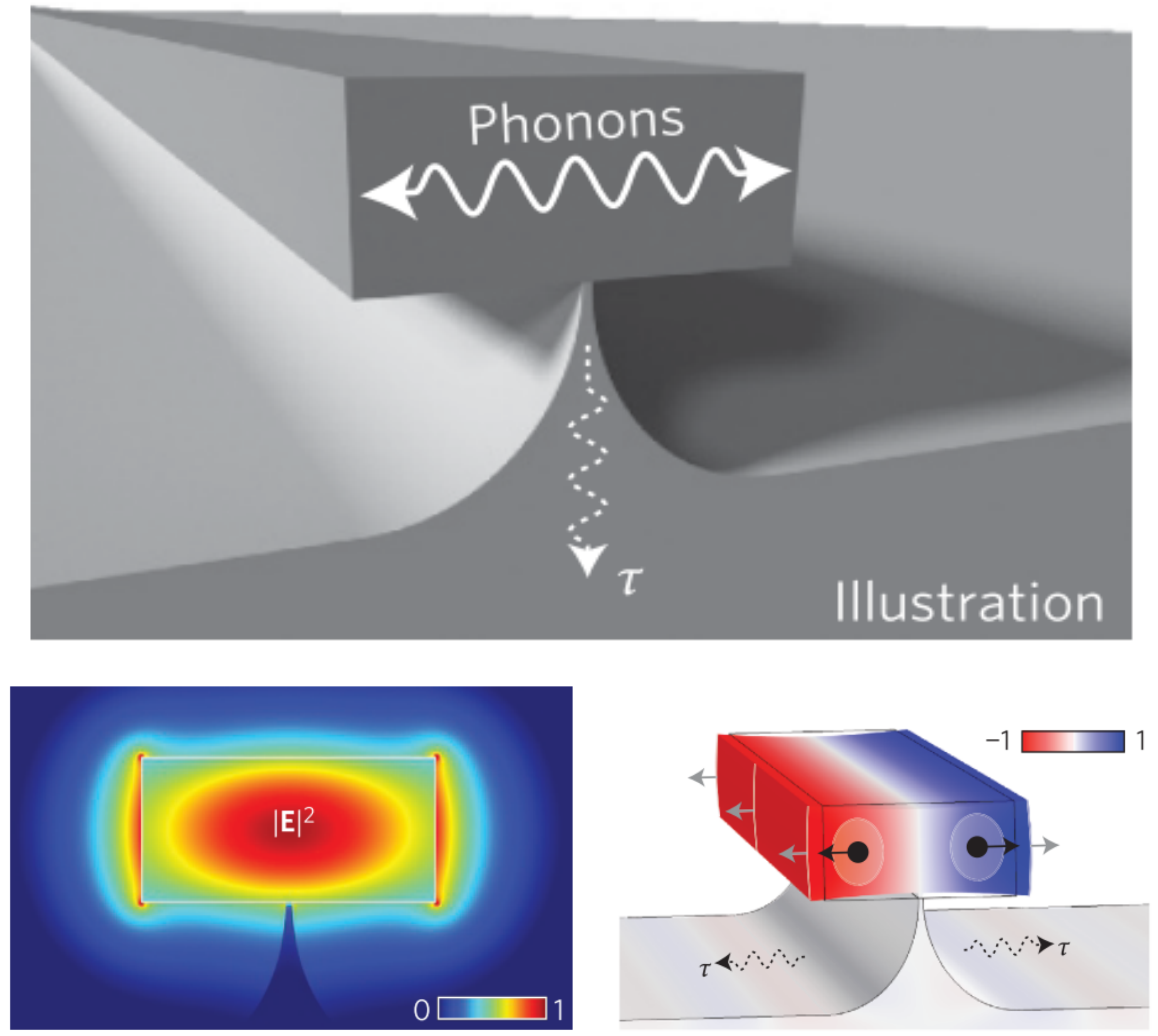


$$G_B/Q_m = 0.55\ (W.m)^{-1}$$





$G_B/Q_m = 12.\ (W.m)^{-1}$ (FW)

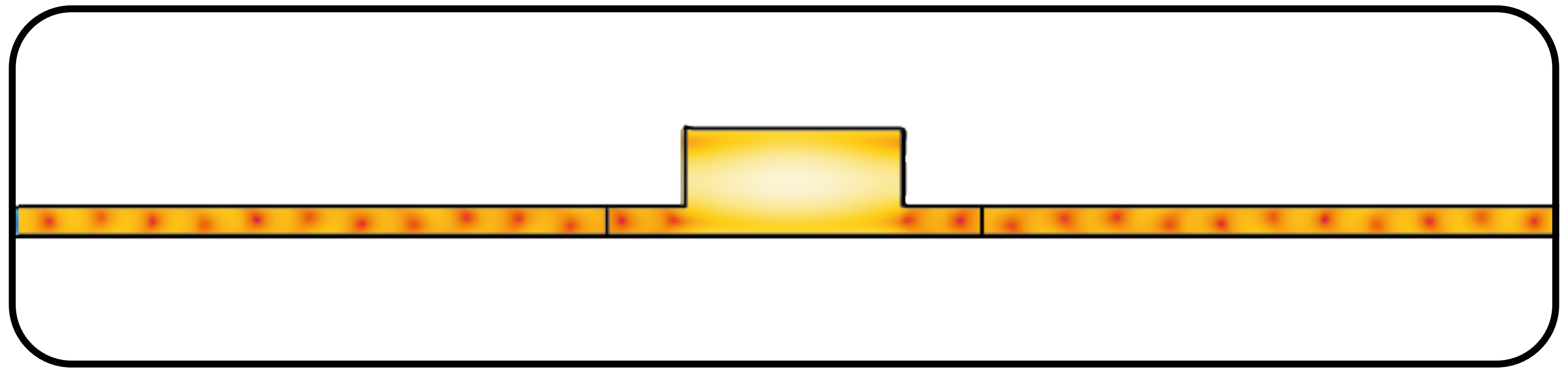
$\boldsymbol{G_B/Q_m = 0.4\ (W.m)^{-1}}$ **(BW)**

R. Van Laer et. al, Nat .Phot. **9**, (2015)

DOI: 10.5281/zenodo.4148337

Discussion

Mechanical Confinement: $\approx 4\times$ Larger Gain



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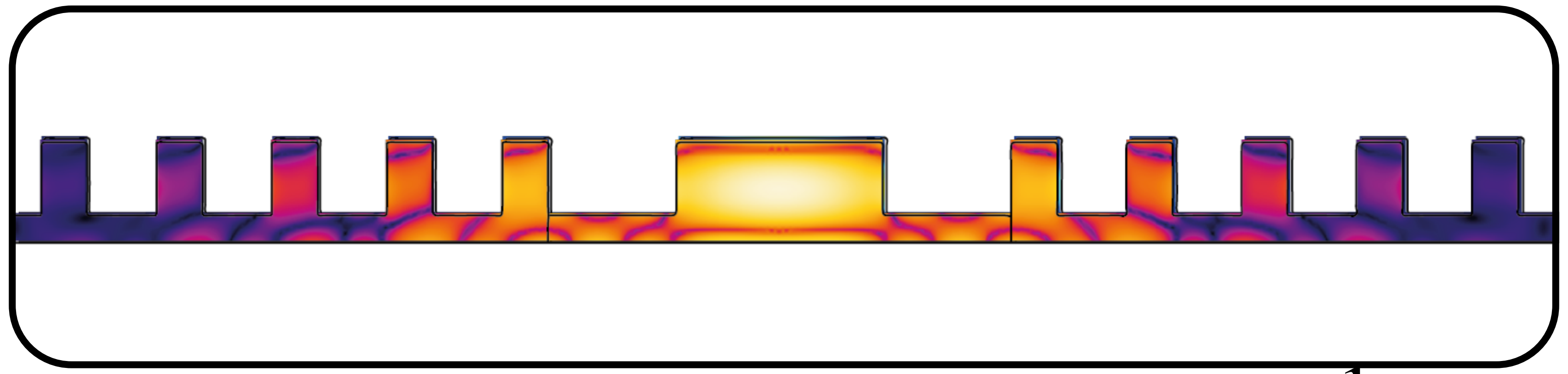
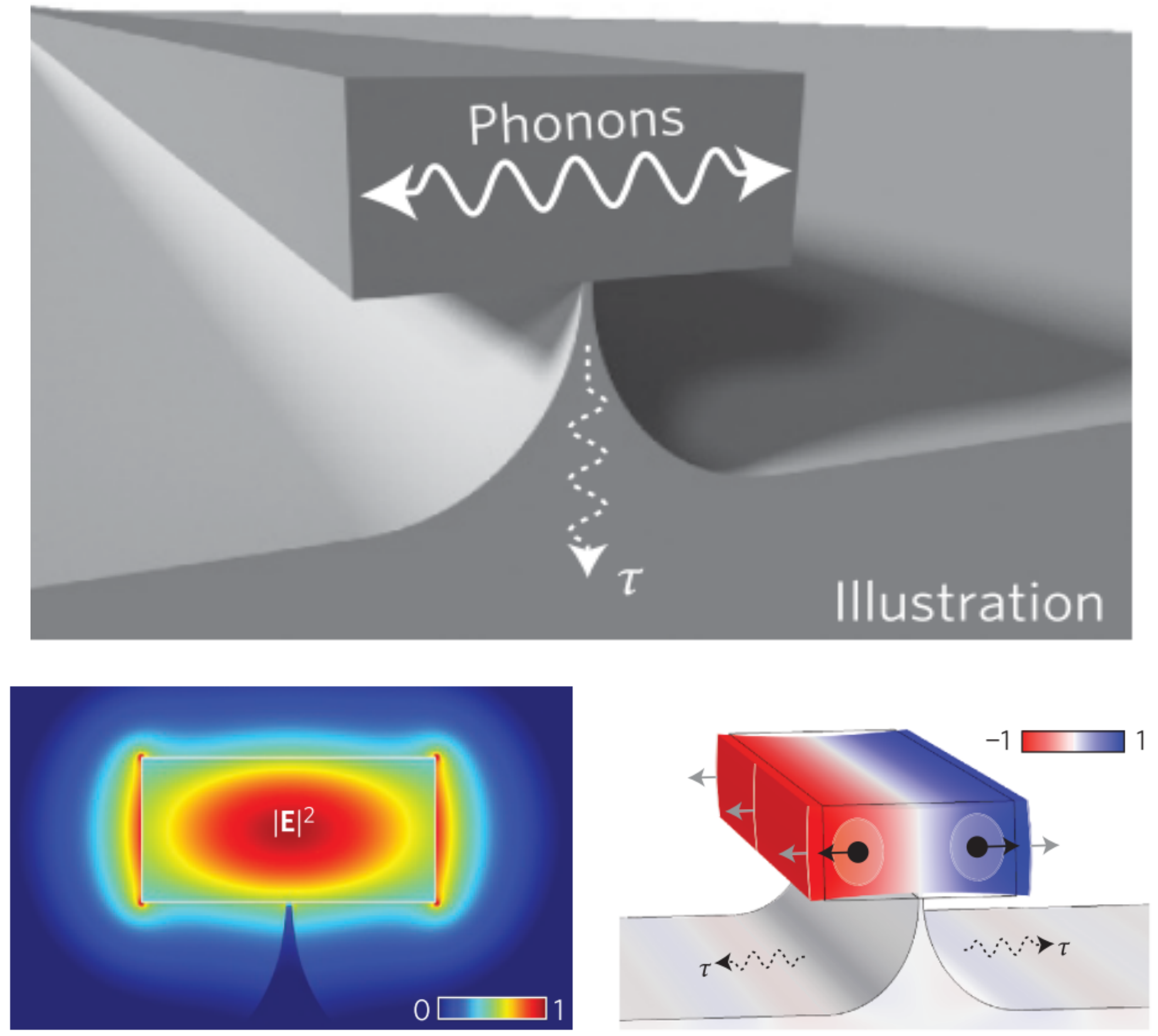


$$G_B/Q_m = 0.55\ (W.m)^{-1}$$



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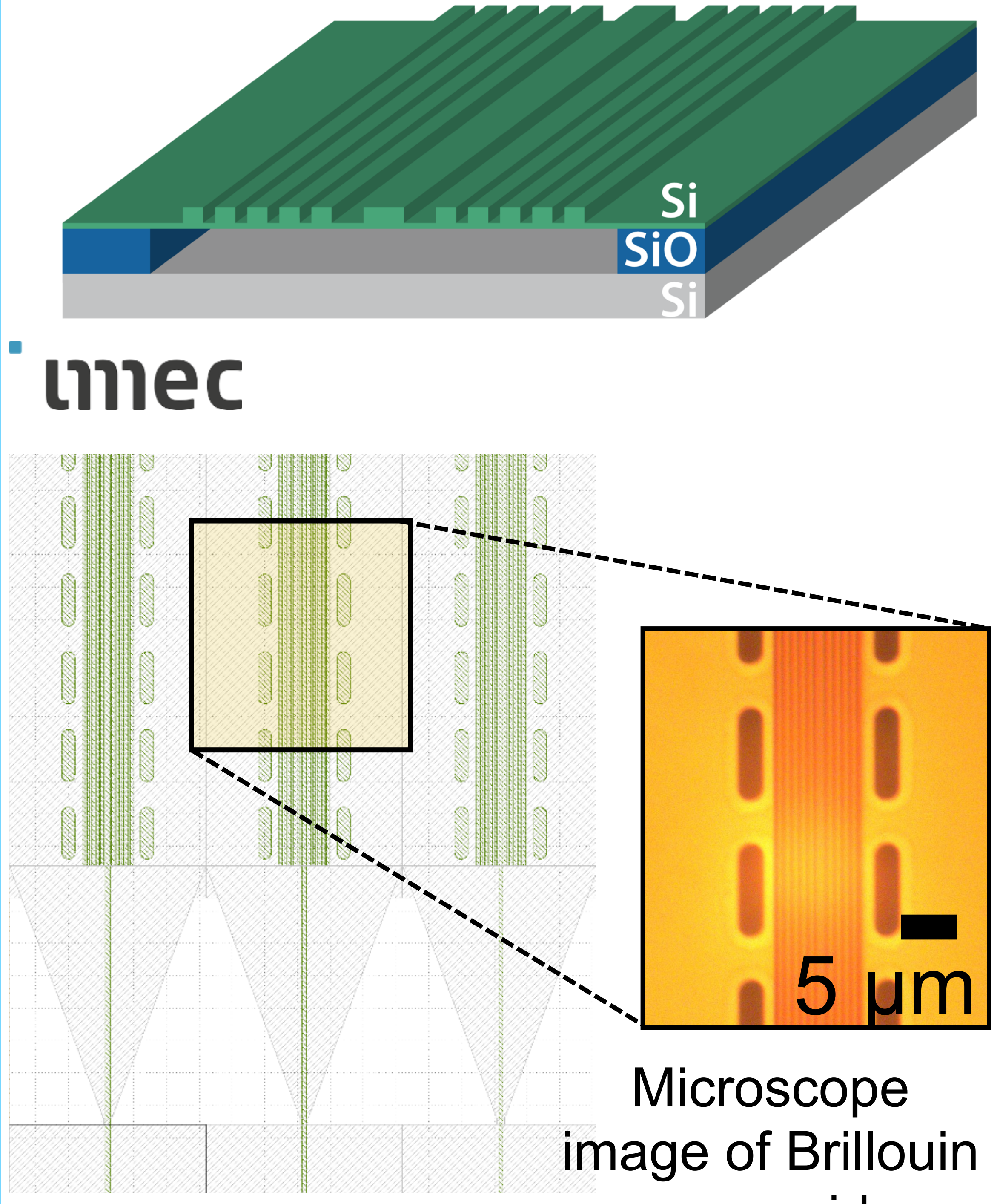
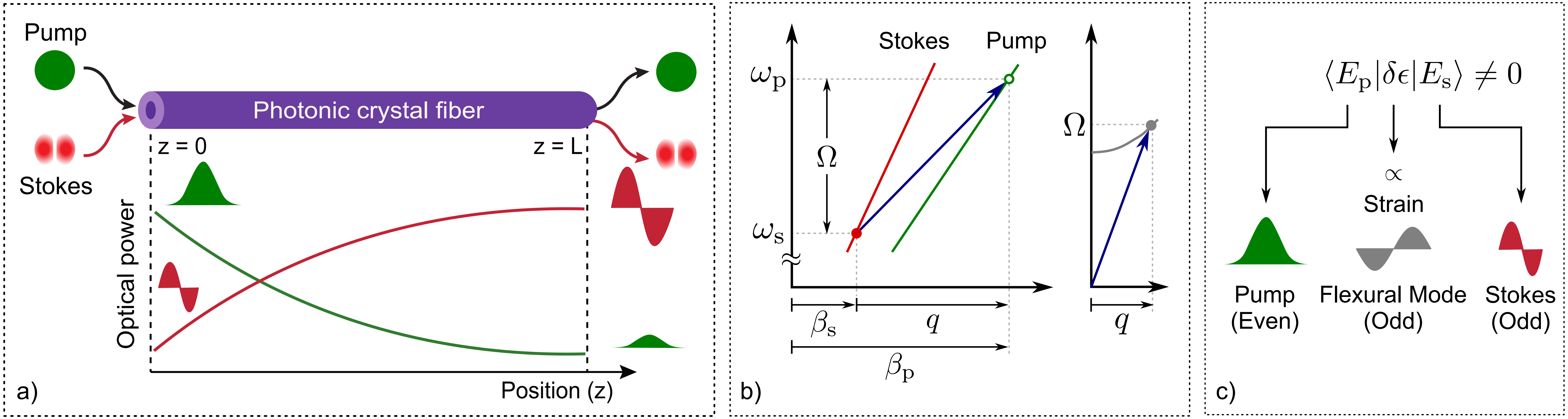


Microscope image of Brillouin waveguide

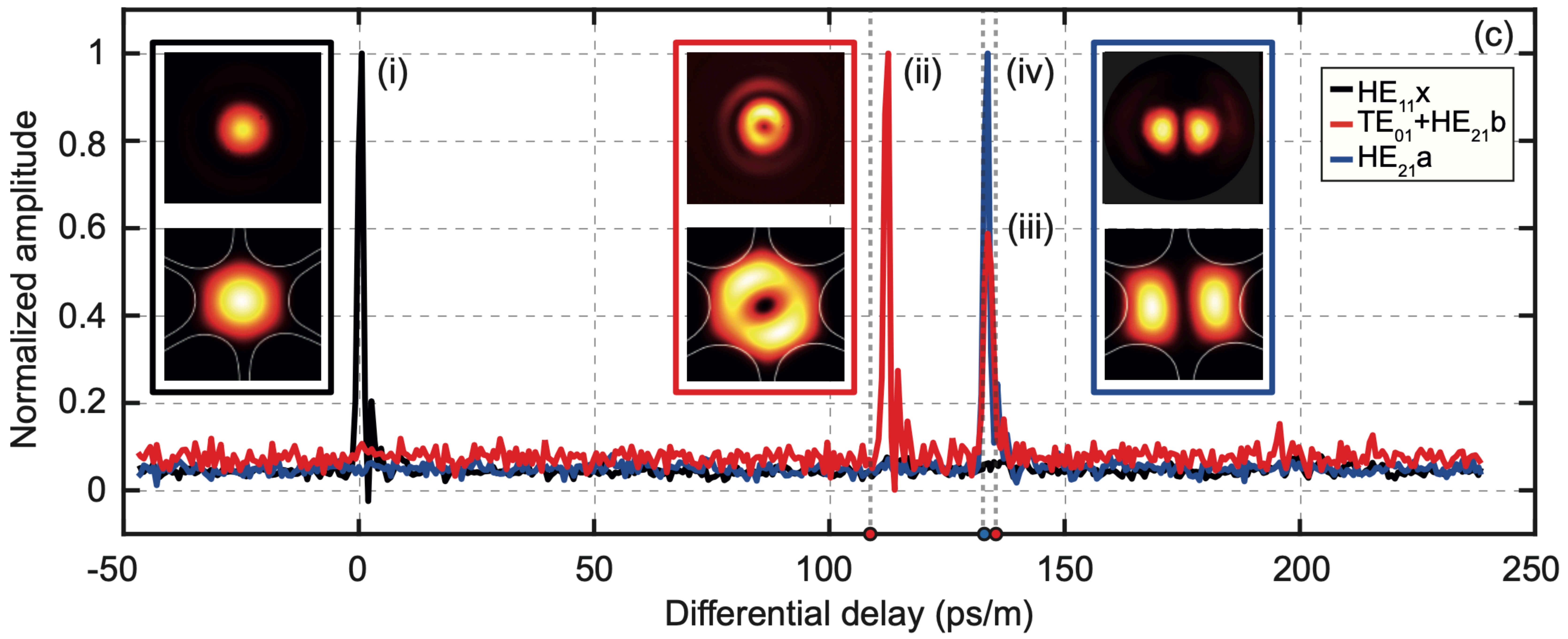
DOI: 10.5281/zenodo.4148337

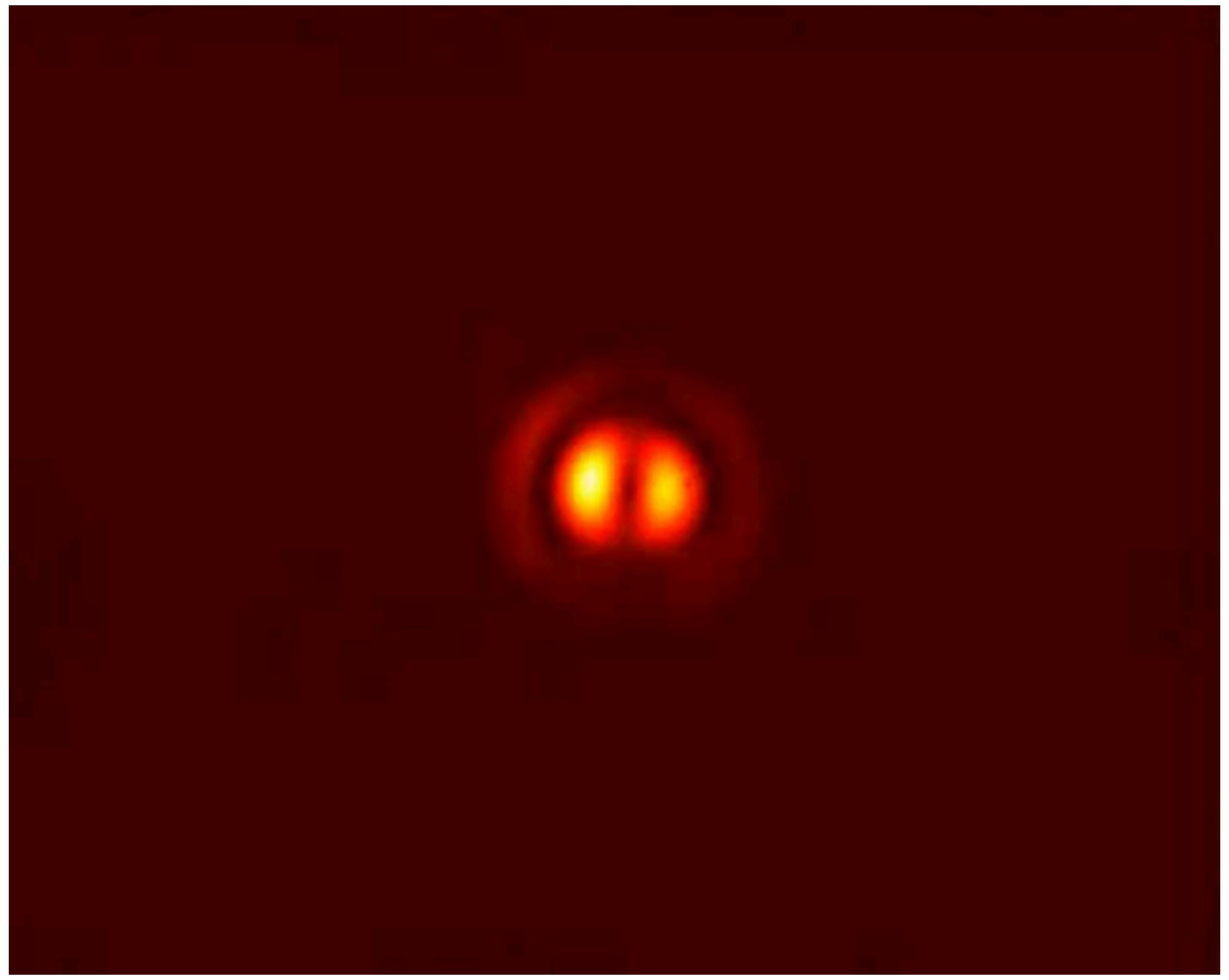
SBS Mode-converter



Jarschel, P. F. et al.**APL Photonics** 6, 036108 (2021).

SBS Mode-converter





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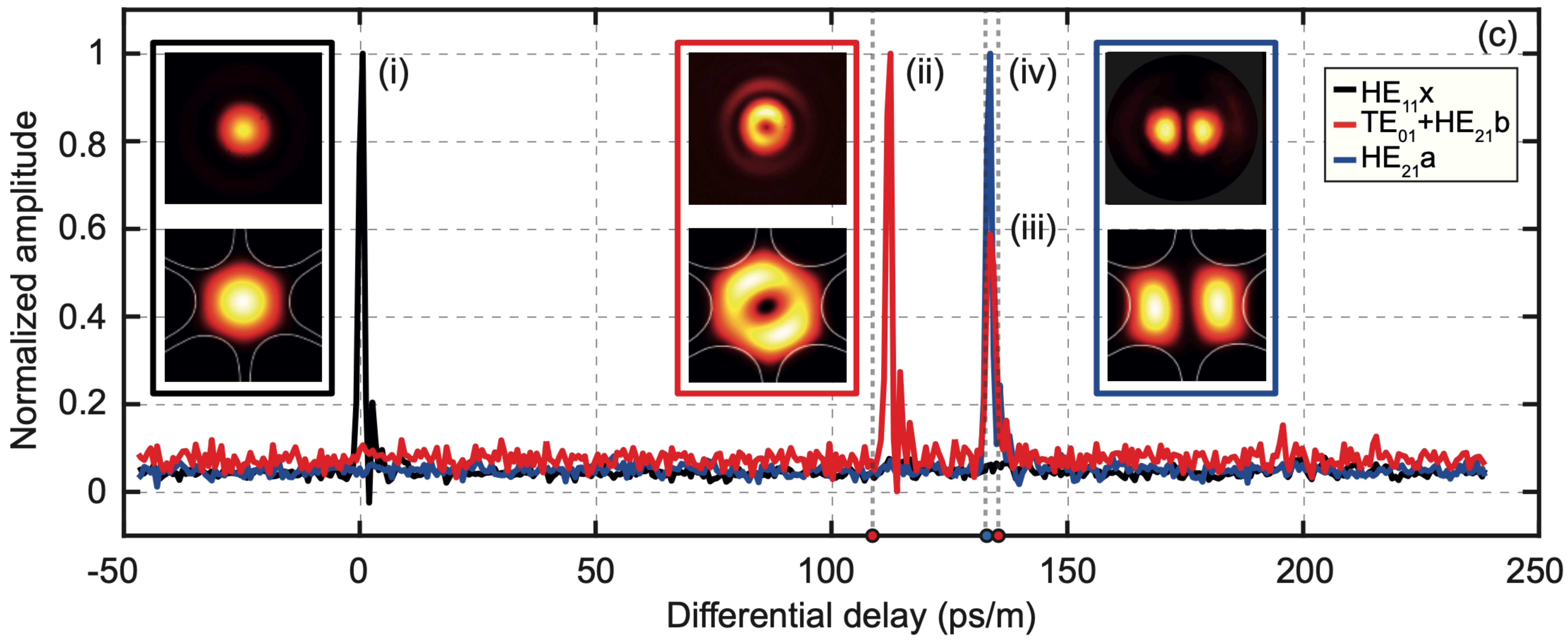
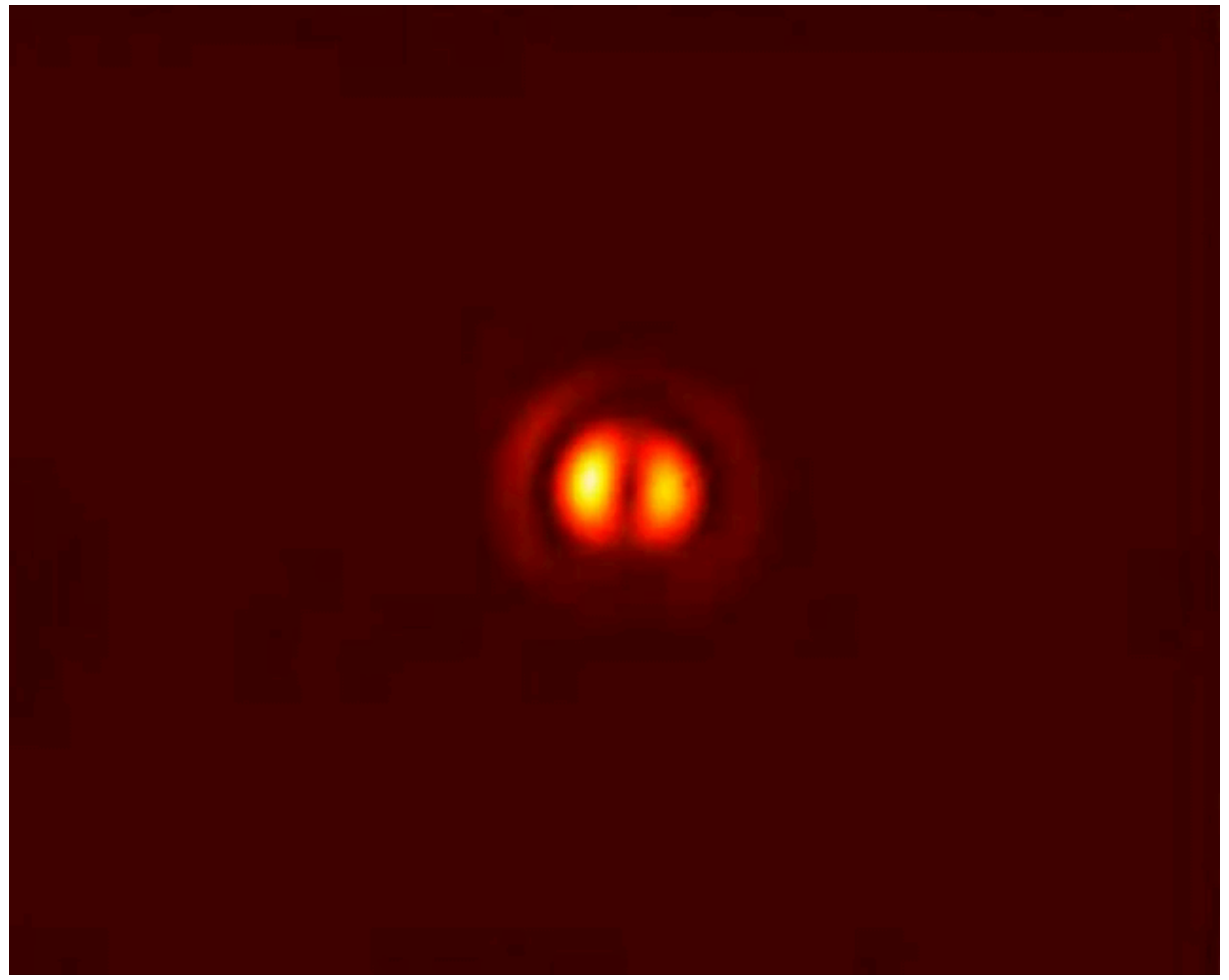
SBS Mode-converter





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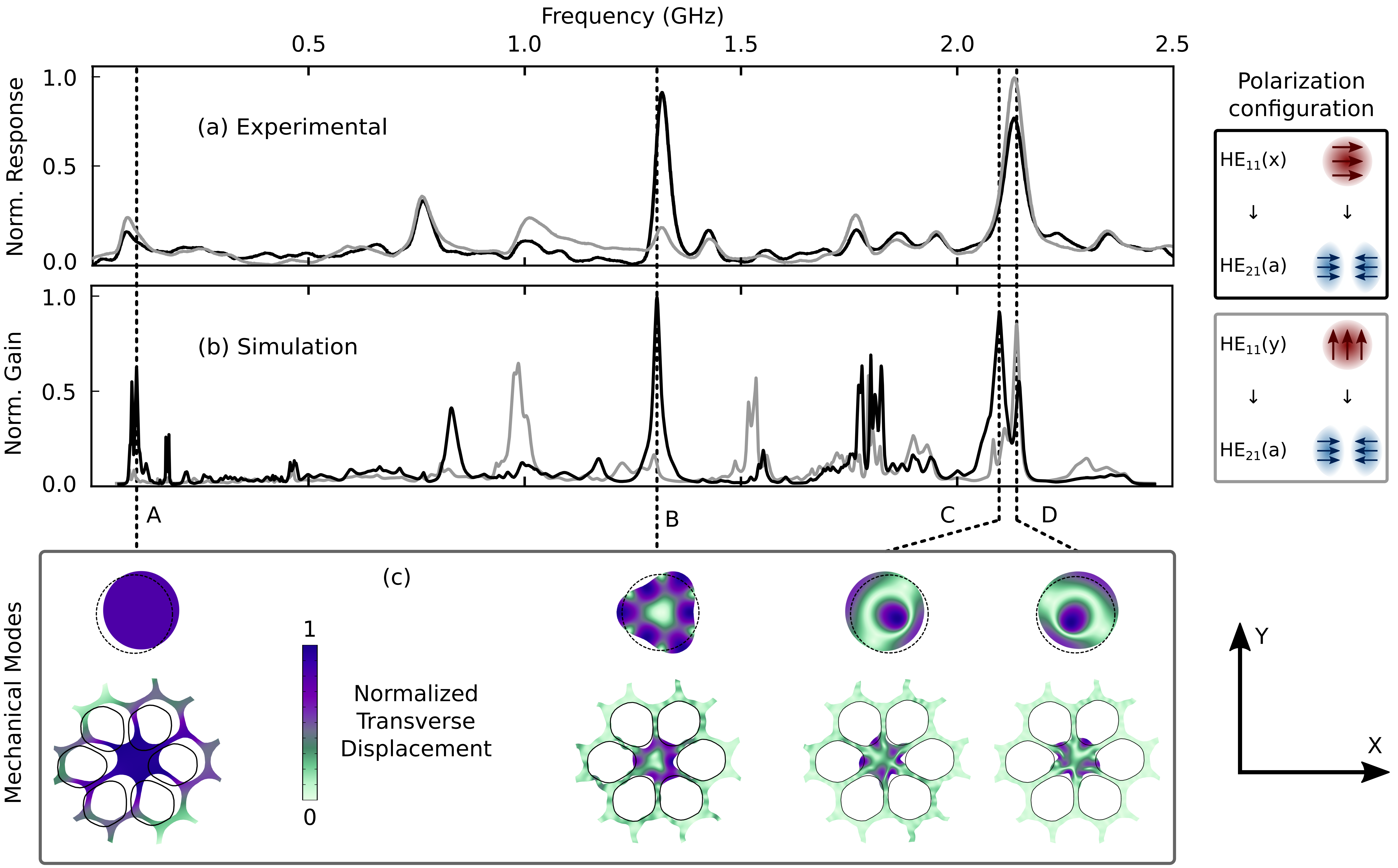
SBS Mode-converter



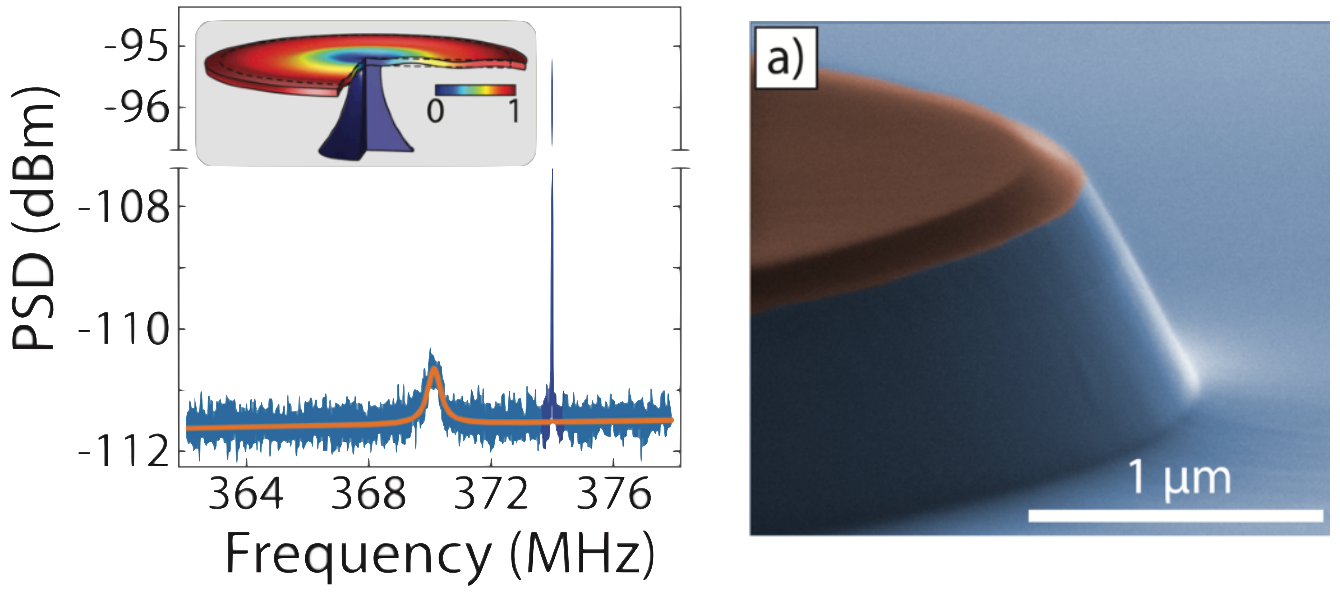
Jarschel, P. F. et al.**APL Photonics** 6, 036108 (2021).

Outline

- Introduction to Brillouin Scattering
- Mechanical modes
- Optical modes
- Harnessing Brillouin interaction
- Optomechanical cavities
- Final remarks

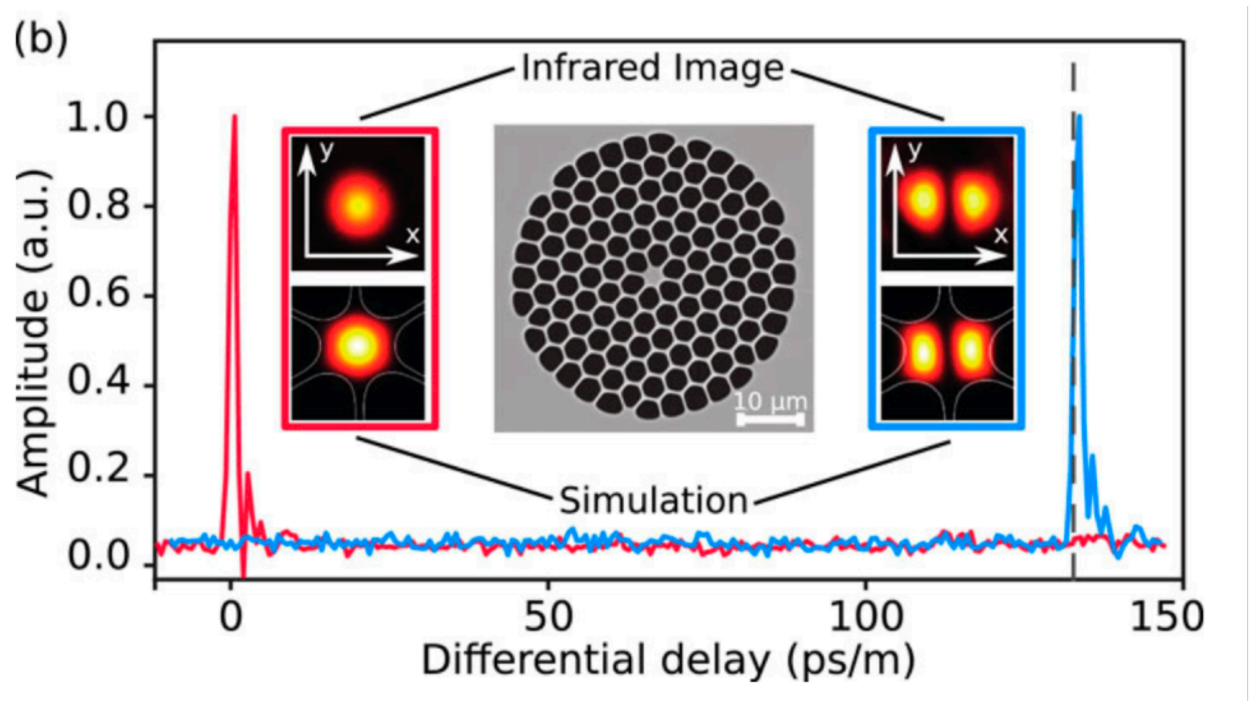
Optomechanical possibilities

GaAs Optomechanics



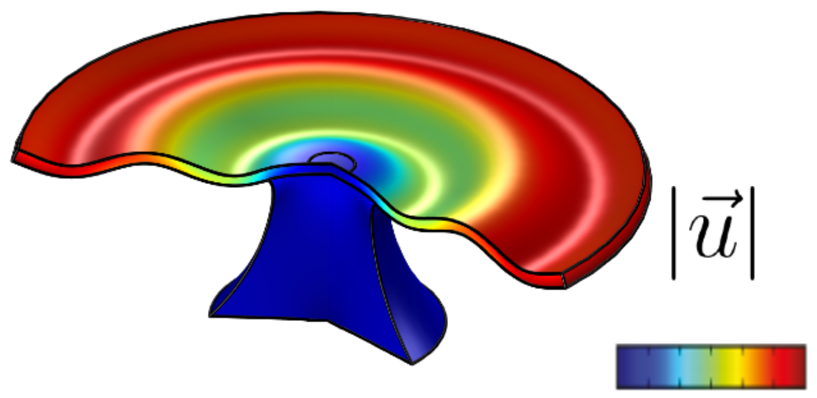
Opt. Mat. Express, **10**, 57 (2020)

Optomechanical mode converter

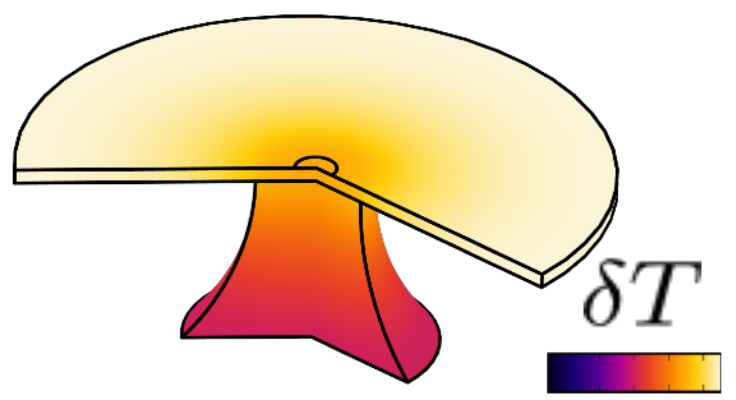


Jarschel et al, APL Photonics 6, 036108 (2021)

Photo-Thermal Forces

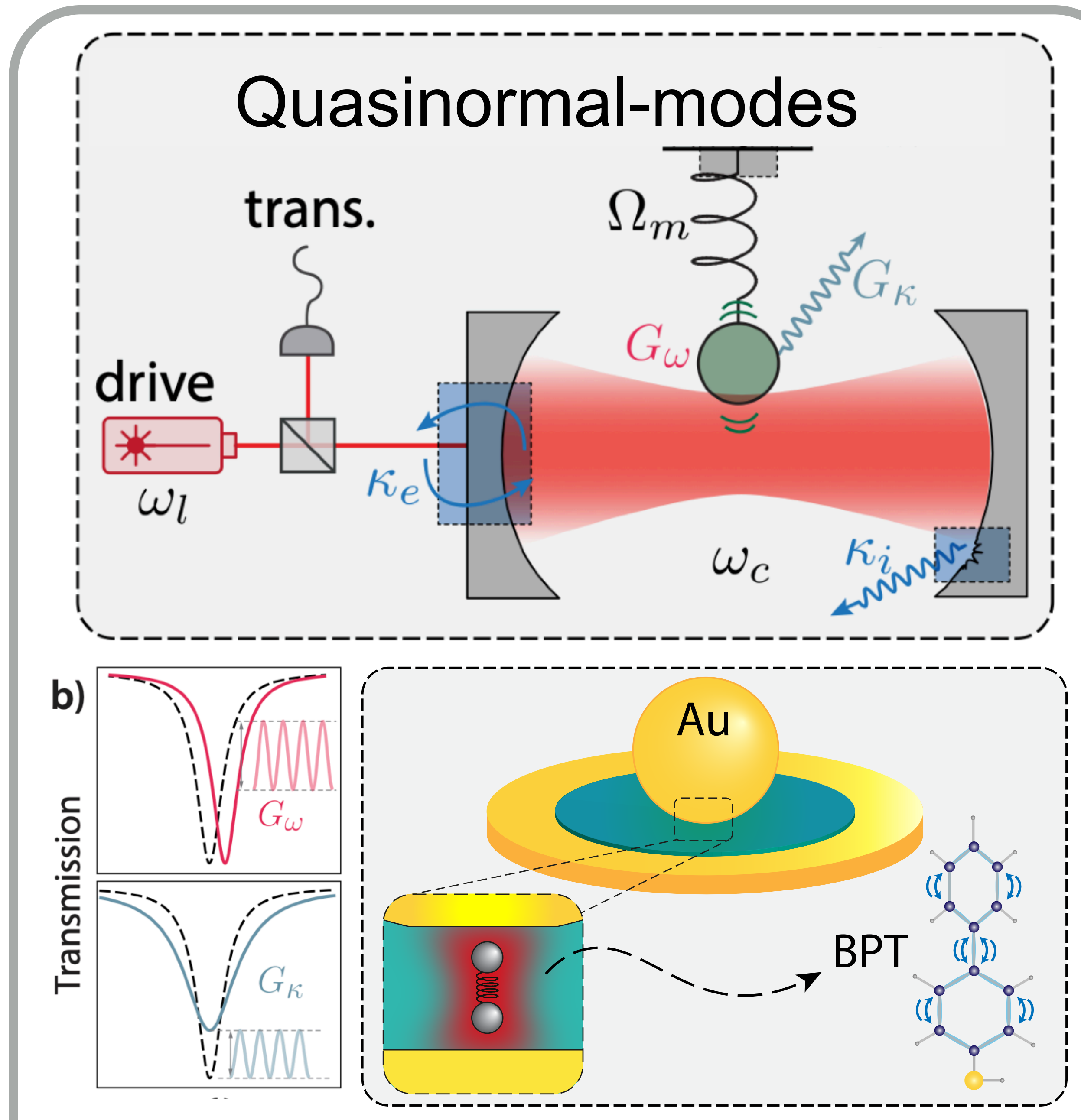


$$S^{\theta} = \boldsymbol{\alpha}\delta T(\vec{r}, t)$$



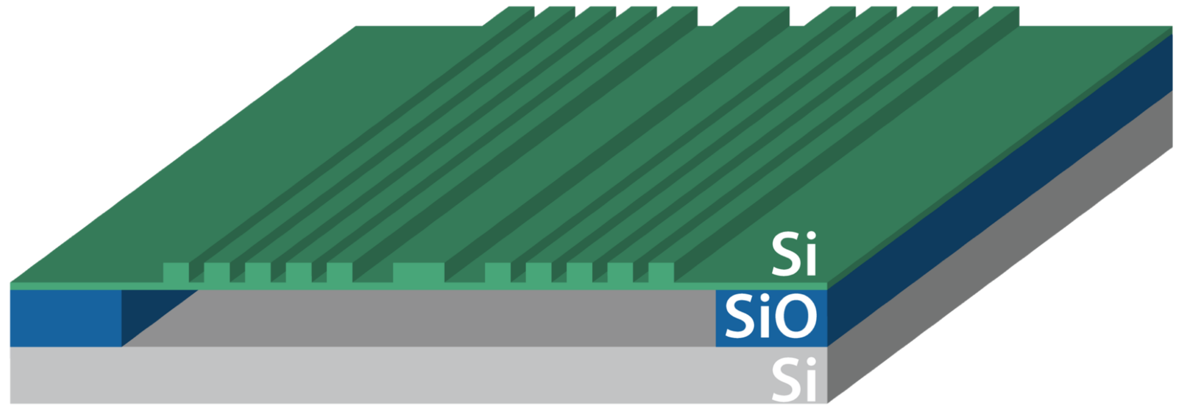
APL Photonics **6** (8), 086101

Quasinormal-modes



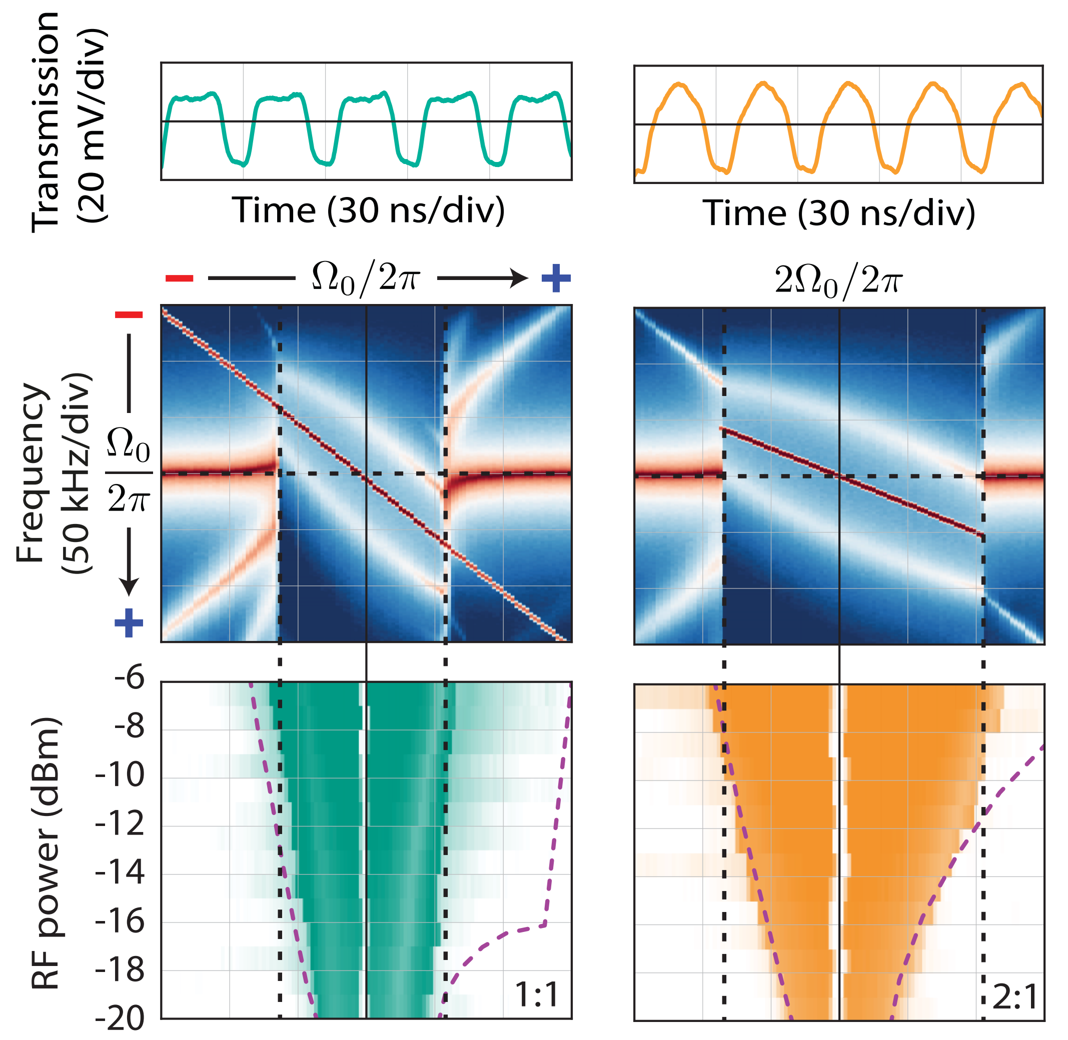
PRL **125**, 233601 (2020)

Strong Confined Brillouin



Optics express **29**, 1736-1748 (2021)

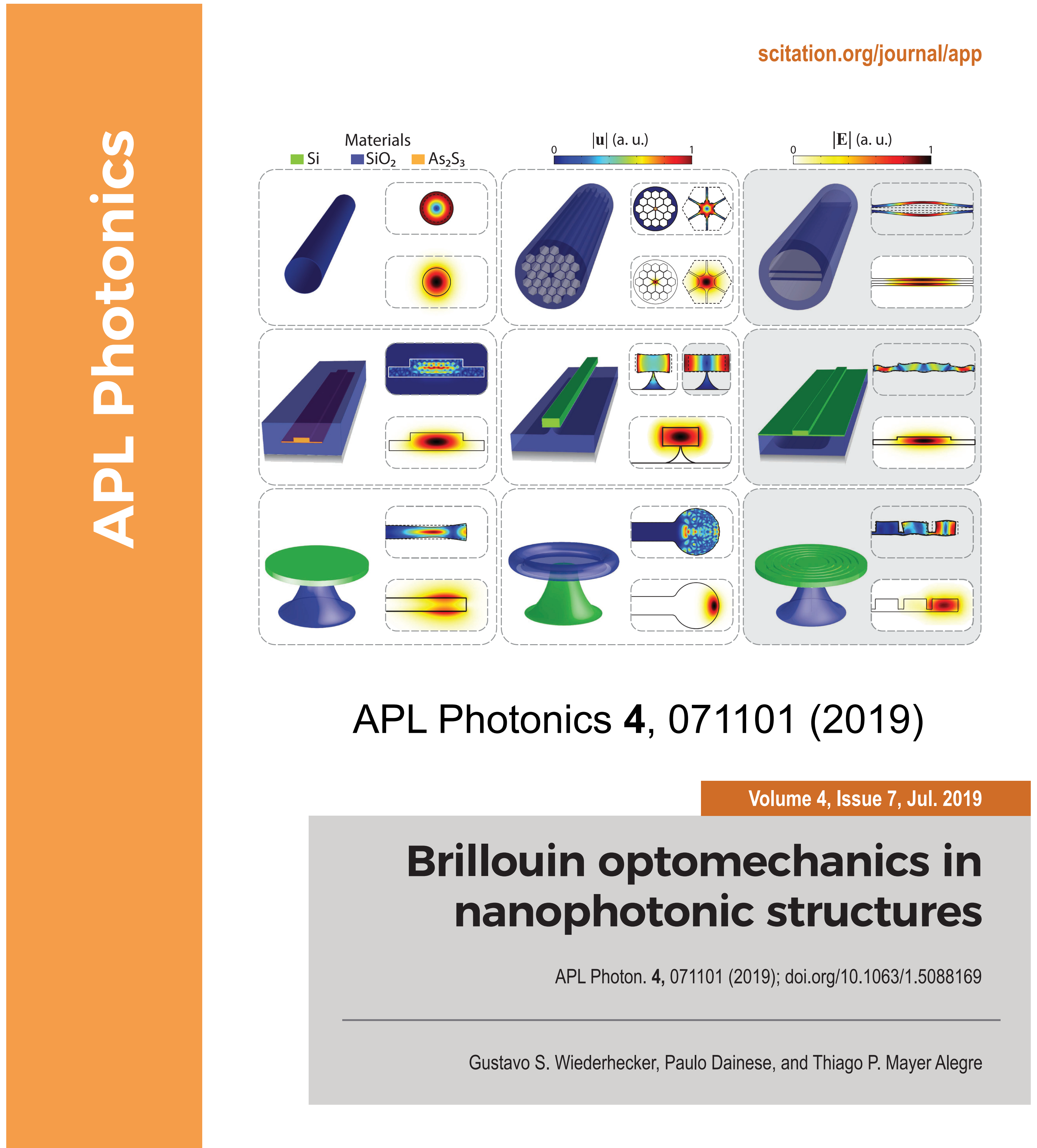
Optomechanical synchronization



Nat Commun **12,** 5625 (2021).

Conclusions & Outlook

- Fundamental and technological challenges
- Bridge radio and optical frequencies
- Nonlinear optical interactions to write and read information (including quantum)
- Interface with molecular vibration
- OM cavities and waveguides based on active materials

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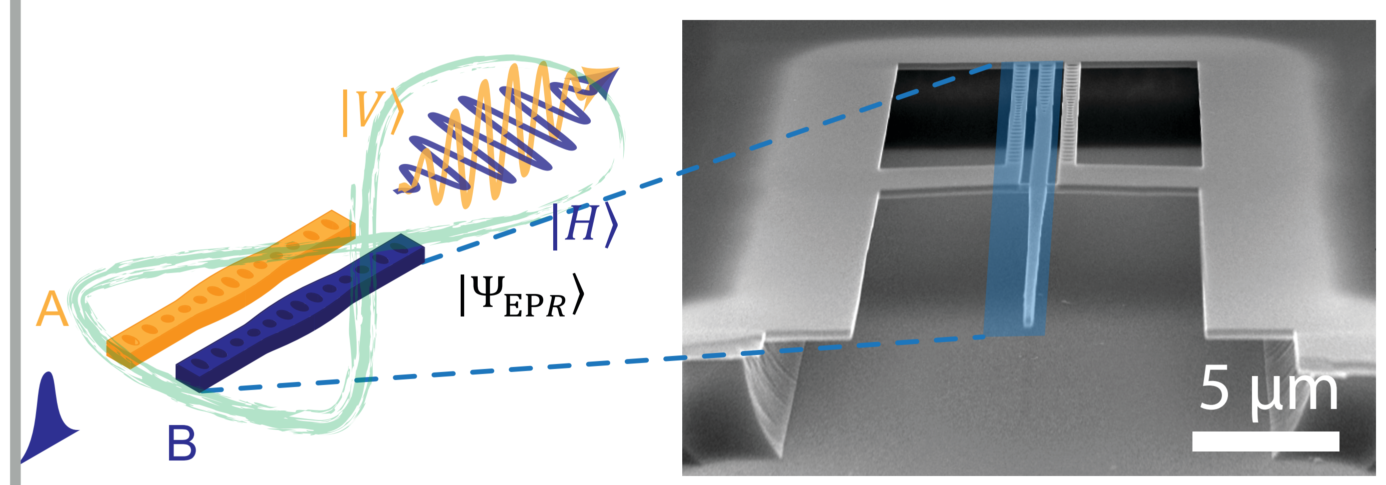
Conclusions & Outlook

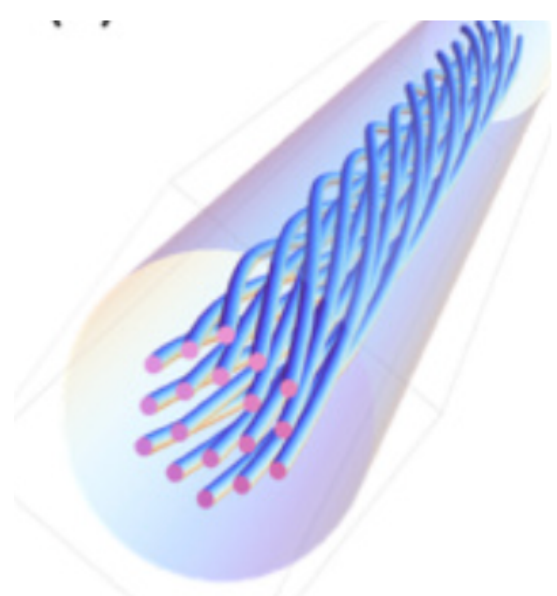
- Fundamental and technological challenges
- Bridge radio and optical frequencies
- Nonlinear optical interactions to write and read information (including quantum)
- Interface with molecular vibration
- OM cavities and waveguides based on active materials

Optomechanical quantum teleportation



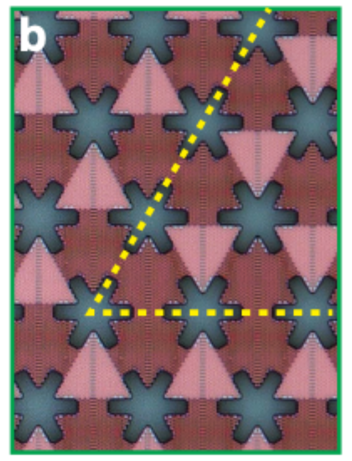
Fiaschi, et al. Nature Photonics 15, 817-821 (2021)

Chiral interaction

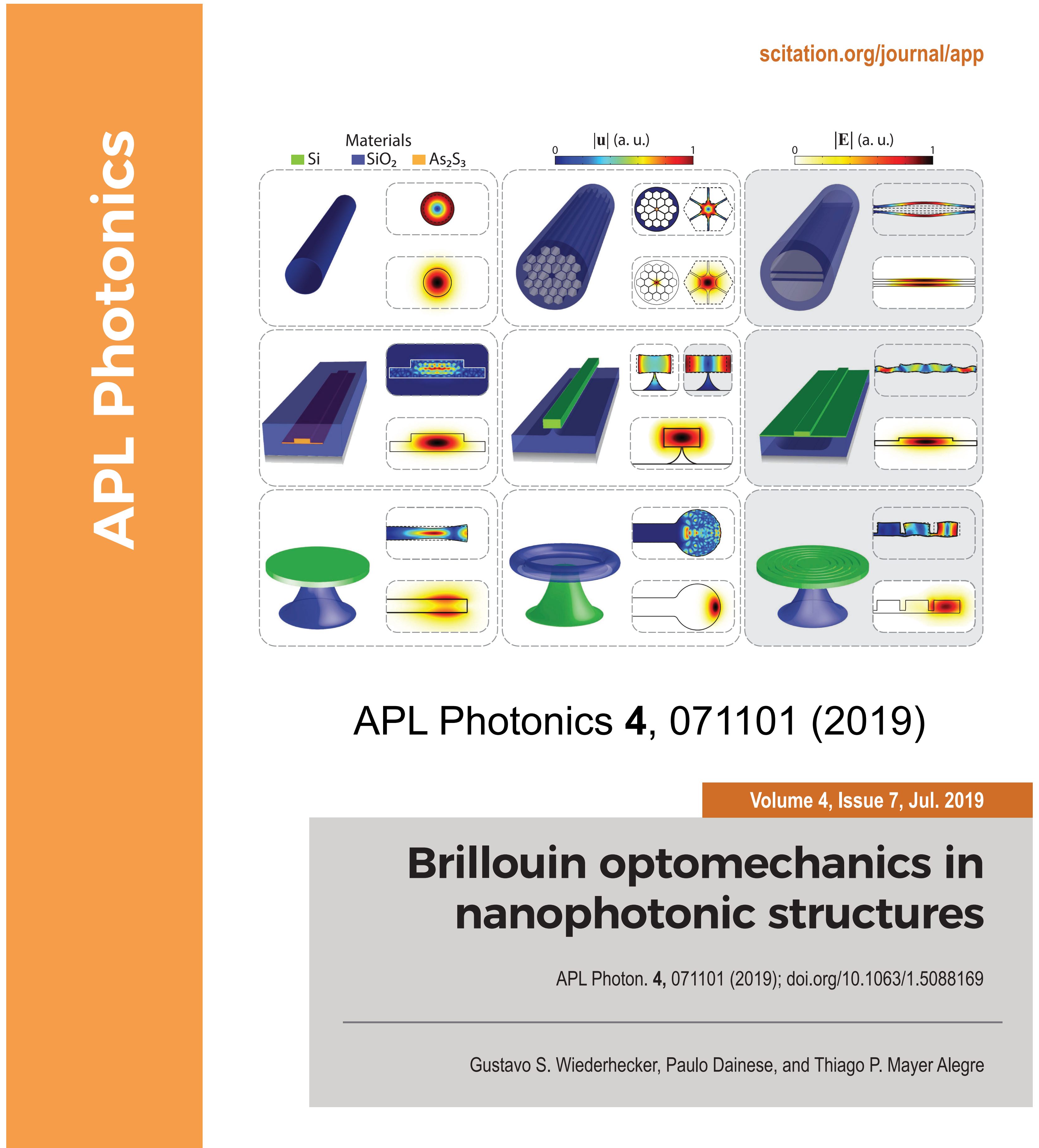


Xinglin Zeng, Photon. Res. 10, 711-718 (2022)

Topological transport



Ren et al, arXiv:2009.06174 (2021)



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The man-powered machine learning

Linear Optomechanics
- Displacement detection
- Optical Spring
- Cooling & Amplification
- Two-tone drive: "Optomechanically induced transparency"
- Ground state cooling
- State transfer, pulsed operation
- Wavelength conversion
- Radiation Pressure Shot Noise
- Squeezing of Light
- Squeezing of Mechanics
- Light-Mechanics Entanglement
- Accelerometers
- Single-quadrature detection, Wigner density
- Optomechanics with an active medium
- Measure gravity or other small forces
- Mechanics-Mechanics entanglement
- Pulsed measurement
- Quantum Feedback
- Rotational Optomechanics

Multimode
- Mechanical information processing
- Bandstructure in arrays
- Synchronization/patterns in arrays
- Transport & pulses in arrays

Nonlinear Optomechanics
- Self-induced mechanical oscillations
- Attractor diagram?
- Synchronization of oscillations
- Chaos

○ White: yet unknown challenges/goals

Nonlinear Quantum Optomechanics
- QND Phonon number detection
- Phonon shot noise
- Photon blockade
- Optomechanical "which-way" experiment
- Nonclassical mechanical q. states
- Nonlinear OMIT
- Noncl. via Conditional Detection
- Single-photon sources
- Coupling to other two-level systems
- Optomechanical Matter-Wave Interferometry

Florian Marquardt, 2014

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https://www.iphd.tec.br

https://zenodo.org/communities/lpd-nanophotonics/

10.5281/zenodo.4148337

10.5281/zenodo.1971811

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How it is actually done?