Interaction between Magnon Spin and Phonon Spin

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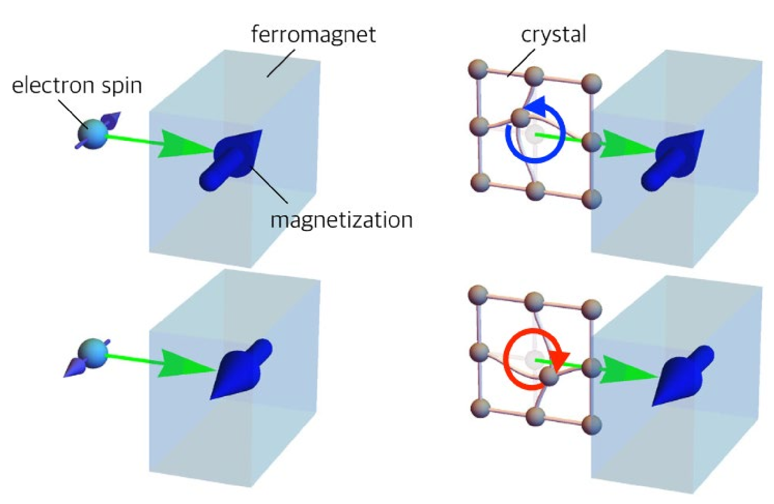
Abstract: Spin is the degree of freedom possessed by both magnons and phonons. Magnon spin comes from the excitation of spin in the magnetic system, while phonon spin comes from the spin angular momentum of the lattice vibration in the elastic system. Spin-spin interaction can reveal the coupling strength in magnon-phonon coupling. In particular, The coupling strength between magnon and surface acoustic waves (SAWs) with transverse spin can be also revealed by the theory of interaction between spin.

Introduction



The lattice dynamics of isotropic elastic medium is dominated by the equation of motion for elastic waves. The magnetization dynamics of ferromagnetic material is dominated by the Landau-Lifshitz-Gilbert (LLG) equation. Magneto-elastic simulation is performed by COMSOL Multiphysics (Finite Elements Method).

$$\rho \frac{d^2\boldsymbol{u}}{dt^2} = (\lambda+\mu)\nabla(\nabla\cdot\boldsymbol{u}) + \mu\nabla^2\boldsymbol{u} + \boldsymbol{f}_{\mathrm{me}}$$

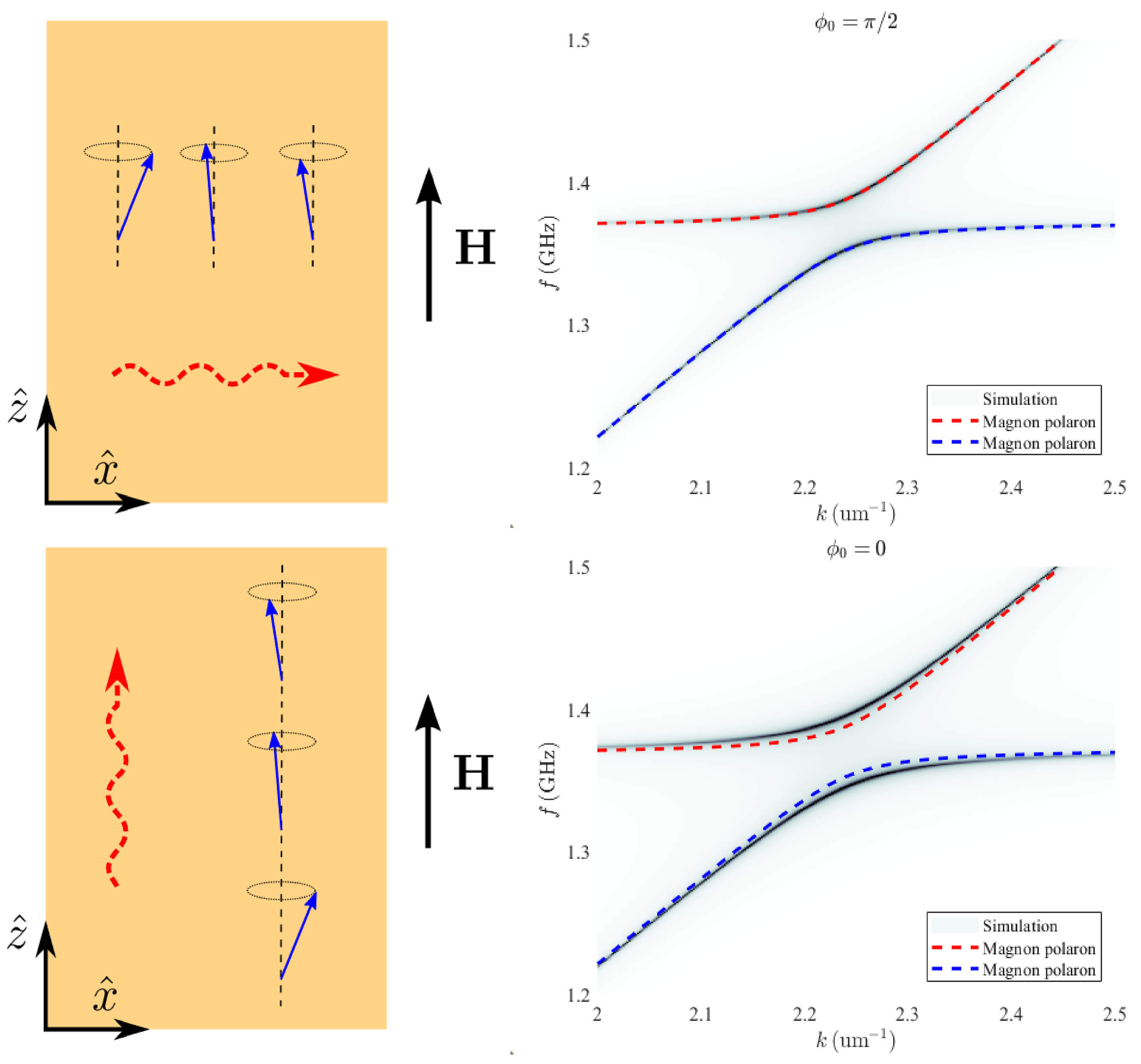
$$\frac{d\boldsymbol{m}}{dt} = -\gamma\boldsymbol{m}\times(\boldsymbol{H}_{\mathrm{eff}}+\boldsymbol{H}_{\mathrm{me}}) + \alpha\boldsymbol{m}\times\frac{d\boldsymbol{m}}{dt}$$

$$\mathcal{H}_{\mathrm{me}}^{\mathrm{cubic}} = b_1\sum_i m_i^2 S_{ii} + b_2\sum_{i\neq j} m_i m_j S_{ij}\,, \qquad i,j = x,y,z$$

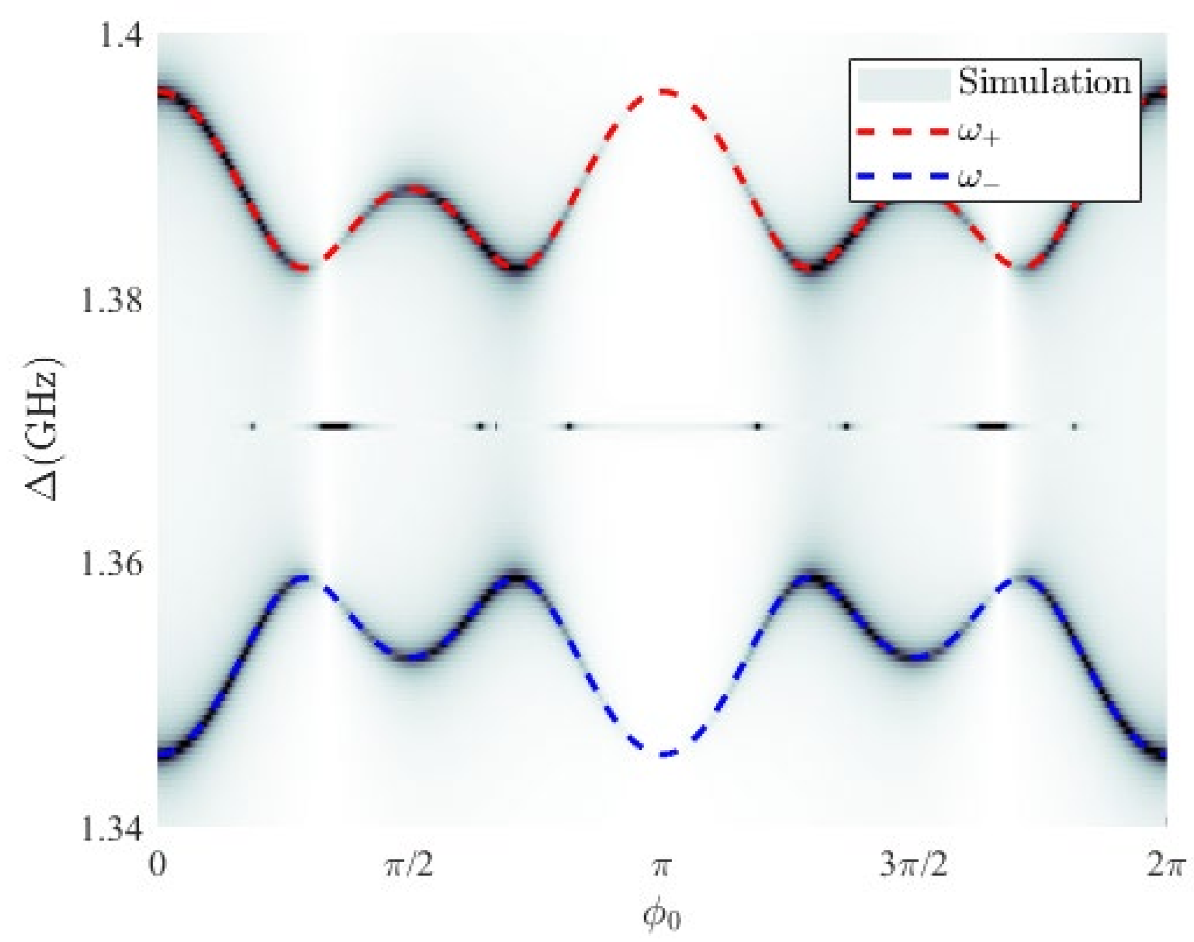
$$\boldsymbol{S}_{\mathrm{p}} = \rho\left(\boldsymbol{u}\times\frac{d\boldsymbol{u}}{dt}\right) \qquad \boldsymbol{S}_{\mathrm{m}} = -2\mu_{\mathrm{B}}\cdot\frac{|\boldsymbol{m_q}|^2}{2M}\boldsymbol{m}_0$$

Circularly Polarized Transverse Wave

Spin wave resonance (SWR) can be excited by circular polarized transverse wave when they have the same wave number with magnetoelastic coupling. The coupling leads to level repulsion in dispersion relation of magnon polaron.



Spin-spin interaction can reveal the coupling strength of the magnon-phonon coupling.

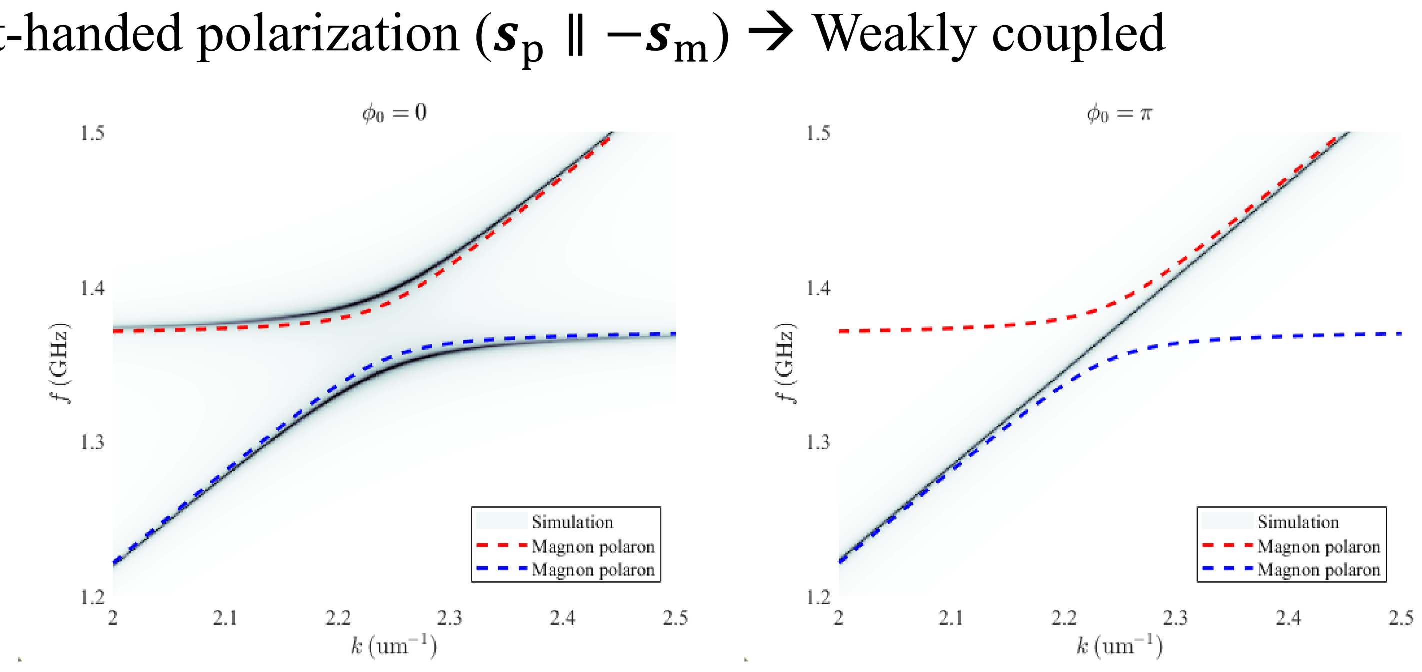


$$\Delta_{\mathrm{t}} = \sqrt{\frac{\gamma b_2^2\omega_r}{c_{\mathrm{t}}^2\rho M\mu_0}\left(4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^4 - 3(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 + 1\right)}$$

$$\omega_{\pm} = \sqrt{\frac{\omega_{\mathrm{p}}^2+\omega_{\mathrm{m}}^2}{2} \pm \sqrt{\left(\frac{\omega_{\mathrm{p}}^2-\omega_{\mathrm{m}}^2}{2}\right)^2 + |\Delta_{\mathrm{t}}|^2}}$$

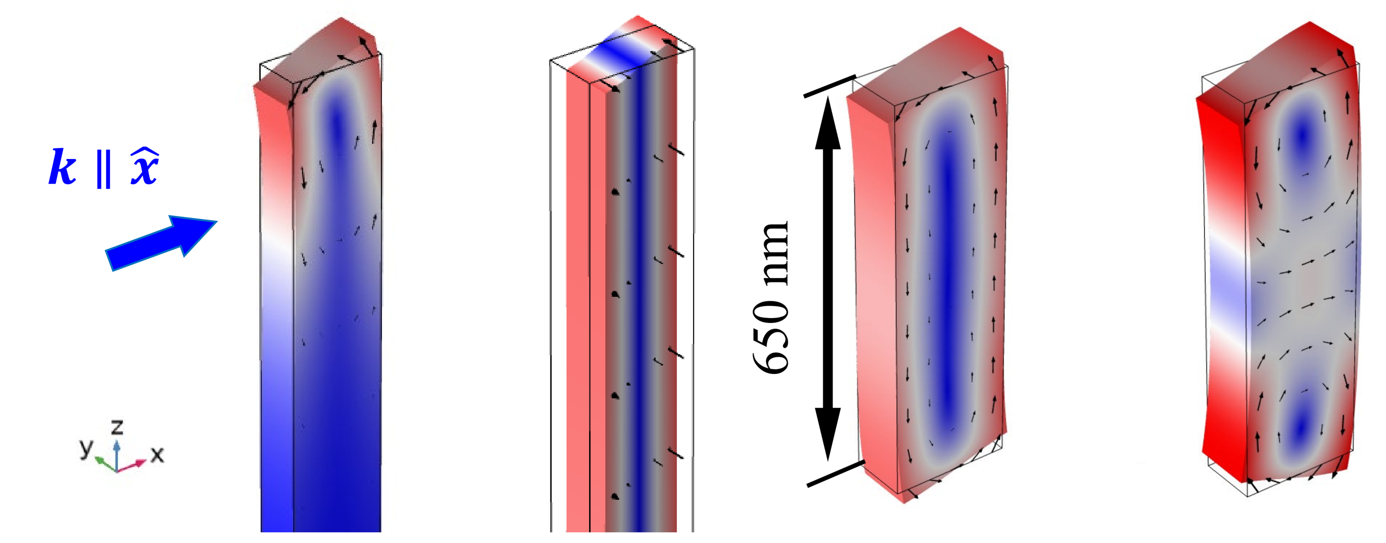
Chiral Coupling

Right-handed polarization ($\boldsymbol{s}_{\mathrm{p}} \parallel \boldsymbol{s}_{\mathrm{m}}$) → Strongly coupled
Left-handed polarization ($\boldsymbol{s}_{\mathrm{p}} \parallel -\boldsymbol{s}_{\mathrm{m}}$) → Weakly coupled



Surface Acoustic Wave

For bounded space, there are many modes of surface acoustic wave. Rayleigh wave and shear-horizontal (SH) wave exist in semi-infinite medium. Lamb wave exists in infinite plate. They have different polarization and dispersion relation from bulk wave.



Spin-spin interaction theory can tell us the coupling strength between magnon and surface phonon.

(a) Rayleigh wave

$$\Delta_{\mathrm{R}} = \frac{c_{\mathrm{R}}}{c_{\mathrm{t}}}\sqrt{\frac{\gamma b_2^2\omega_r}{c_{\mathrm{t}}^2\rho M\mu_0}(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 + \frac{\gamma b_1^2\omega_r}{c_{\mathrm{l}}^2\rho M\mu_0}\left(4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 - 4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^4\right)}$$

(b) SH wave

$$\Delta_{\mathrm{SH}} = \sqrt{\frac{\gamma b_2^2\omega_r}{c_{\mathrm{t}}^2\rho M\mu_0}}|\cos^2 2\phi_0|$$

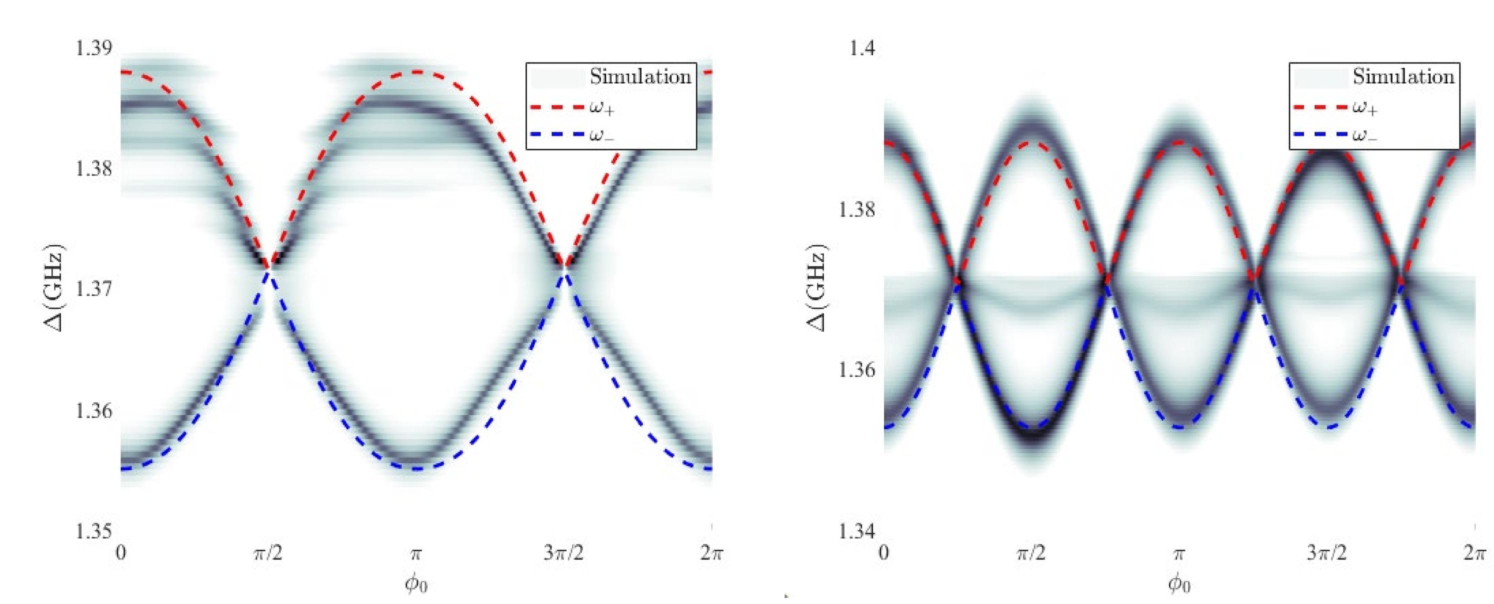
(c) A0 mode of Lamb wave

$$\Delta_{\mathrm{A0}} = \frac{c_{\mathrm{A0}}}{c_{\mathrm{t}}}\sqrt{\frac{\gamma b_2^2\omega_r}{c_{\mathrm{t}}^2\rho M\mu_0}(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 + \frac{\gamma b_1^2\omega_r}{c_{\mathrm{l}}^2\rho M\mu_0}\left(4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 - 4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^4\right)}$$

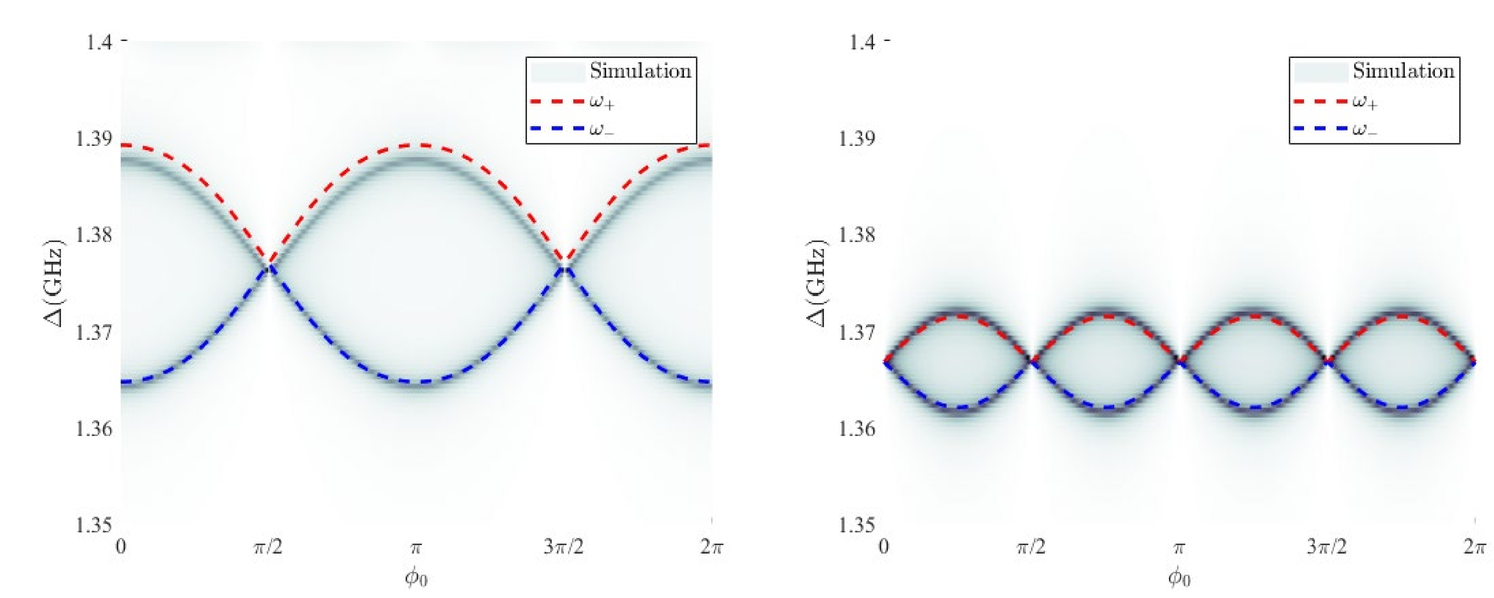
(d) S0 mode of Lamb wave

$$\Delta_{\mathrm{S0}} = \frac{c_{\mathrm{S0}}}{c_{\mathrm{t}}}\sqrt{\frac{\gamma b_1^2\omega_r}{c_{\mathrm{l}}^2\rho M\mu_0}\left(4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^2 - 4(\boldsymbol{s}_{\mathrm{p}}\cdot\boldsymbol{s}_{\mathrm{m}})^4\right)}$$

Rayleigh wave | SH wave



A0 mode of Lamb wave | S0 mode of Lamb wave



Reference

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