Observation of phonon modes in a chiral spin soliton lattice

DMI-2021

Yusuke Shimamoto*[1], Y. Matsushima[1], T. Hasegawa[1], Y. Kousaka[1]
I. Proskurin[2], F. J. T. Goncalves[3], Y. Togawa[1]

(1) Osaka Prefecture University, Osaka, Japan
(2) University of Manitoba, Winnipeg, Canada
(3) Helmholtz Zentrum Dresden Rossendorf, Dresden, Germany

*y-shimamoto-spin@pe.osakafu-u.ac.jp

☆ Summary

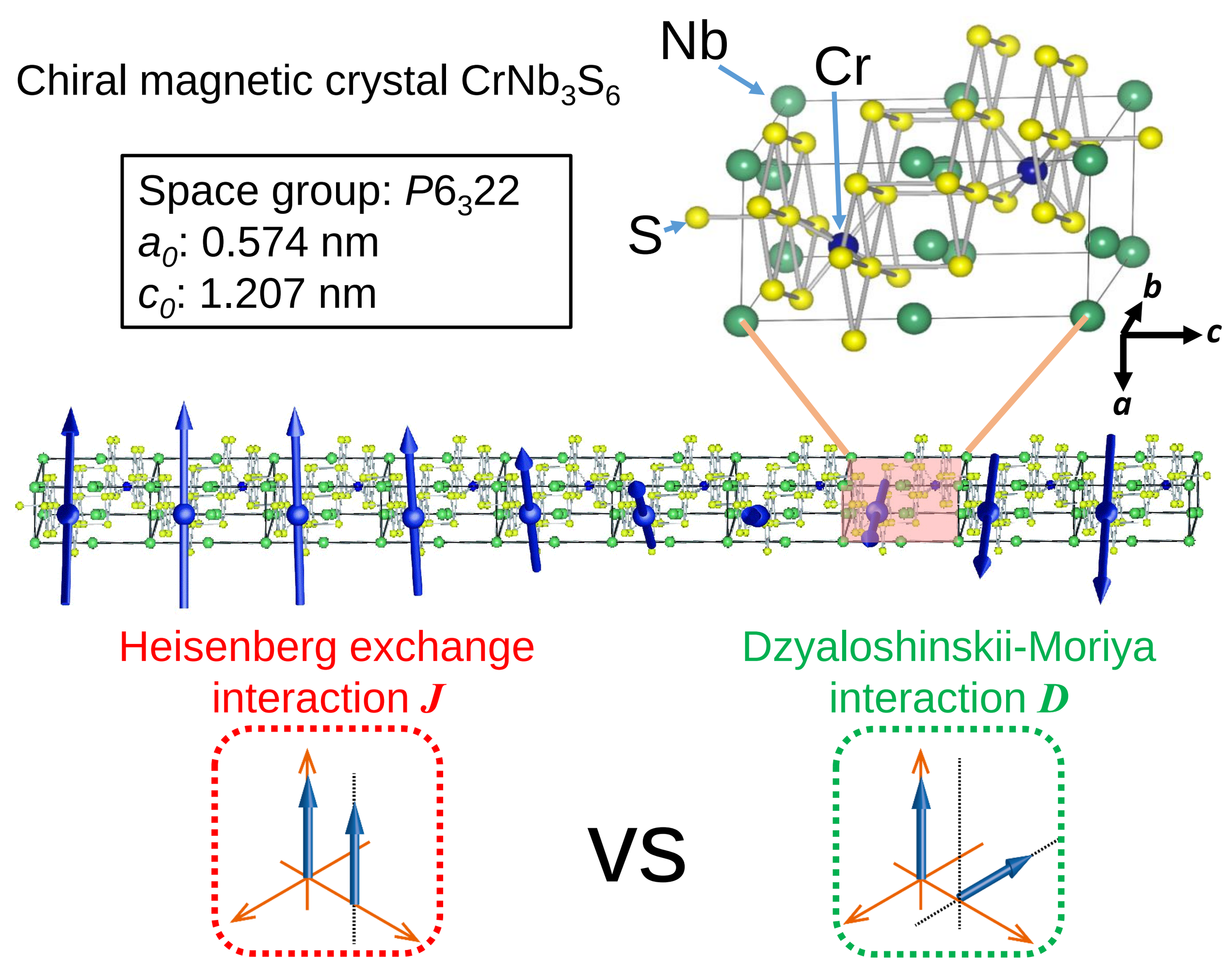
- We report experimental results of the magnetic resonance of a chiral spin soliton lattice (CSL) in bulk single crystal of monoaxial chiral helimagnet $CrNb_3S_6$.
- We observed a lowest frequency mode and three higher order modes between 16 and 40 GHz.
- The frequency of all resonance modes converged at a critical field due to a increase of the CSL period concurrently with decrease of the size of the Brillouin zone in spin-wave band.
- Experimental data were fitted to analytical solution of band problem of the one-dimensional chiral sine-Gordon model and we evaluated Dzyaloshinskii-Moriya interaction as 2.88 K in the crystal.

Introduction and Experimental details

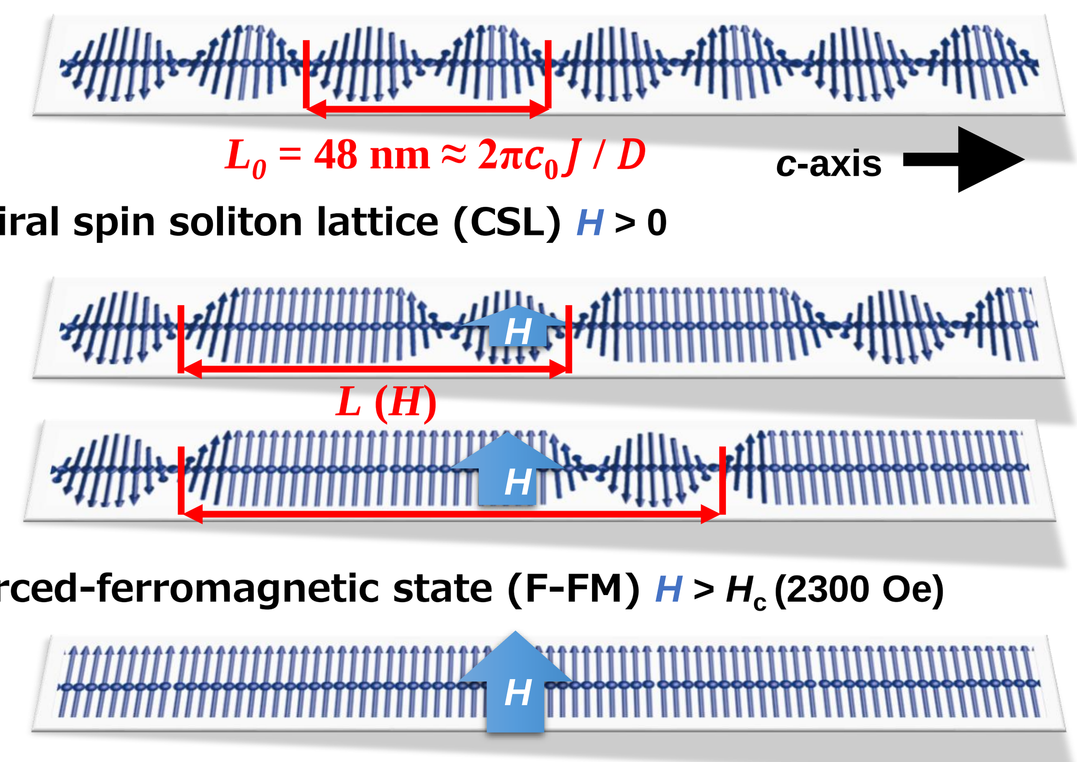
Chiral spin soliton lattice (CSL)

Chiral magnetic crystal $CrNb_3S_6$

Space group: $P6_322$
a_0: 0.574 nm
c_0: 1.207 nm



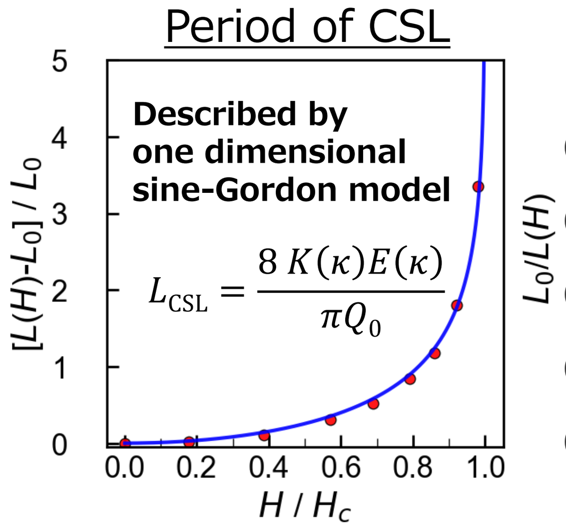
Chiral helimagnetic order $H = 0$ $T_c \sim 130$ K



Chiral spin soliton lattice (CSL) $H > 0$

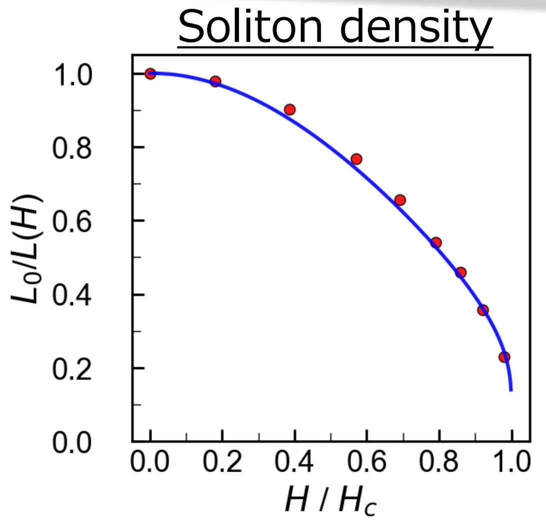
Forced-ferromagnetic state (F-FM) $H > H_c$ (2300 Oe)

Period of CSL



$$L_{CSL} = \frac{8K(\kappa)E(\kappa)}{\pi Q_0}$$

Soliton density

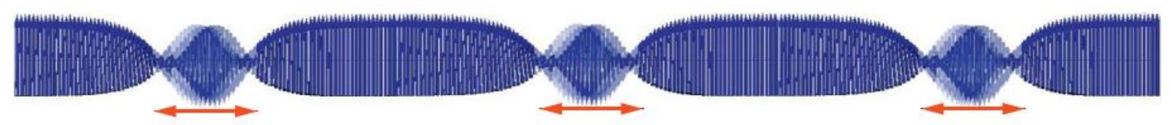


I. E. Dzyaloshinsky, Sov. Phys. JETP **19**, 960 (1964).
Y. Togawa *et al*., Phys. Rev. Lett. **108**, 107202 (2012).

The CSL can be regarded as a magnetic superlattice with tunable periodicity.

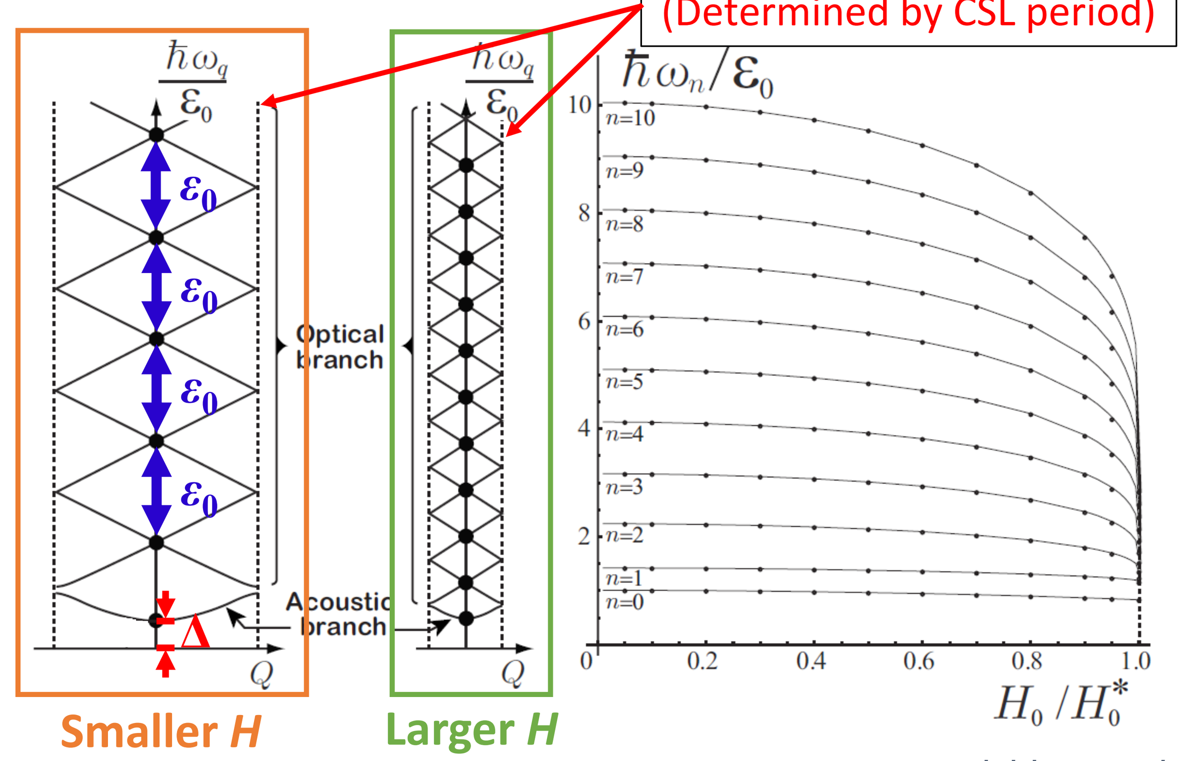
Elementary excitation of CSL

➢ Phonon-like excitation of CSL (Vibration of magnetic superlattice)



Spin-wave dispersion of CSL

Brillouin Zone boundaries (Determined by CSL period)

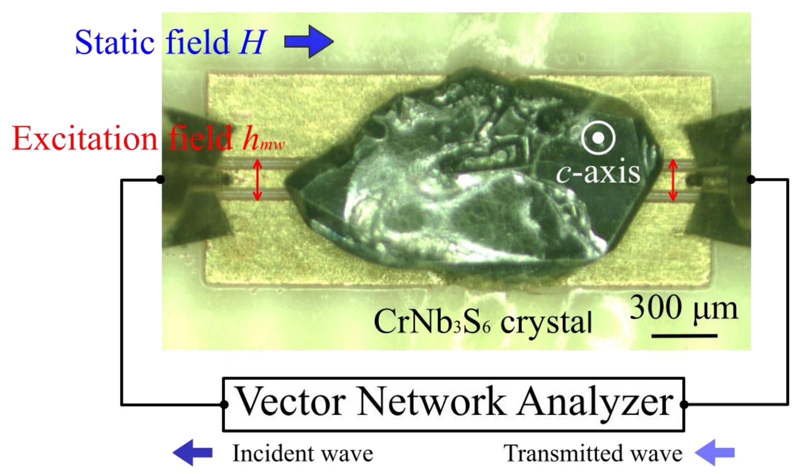


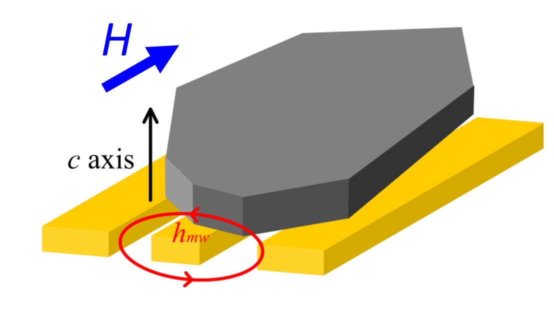
$$\varepsilon_0 \approx \frac{DS^2}{2} \qquad \Delta \approx \frac{D^2S^2}{2J}$$

J. Kishine *et al*, Phys. Rev. B 79, 220405(R) (2009).

Measurement

Vector Network Analyzer and coplanar waveguide (VNA-FMR)

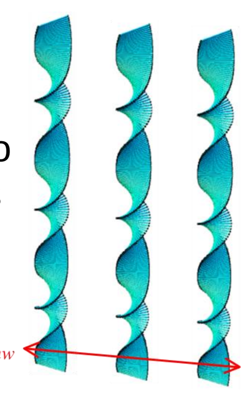


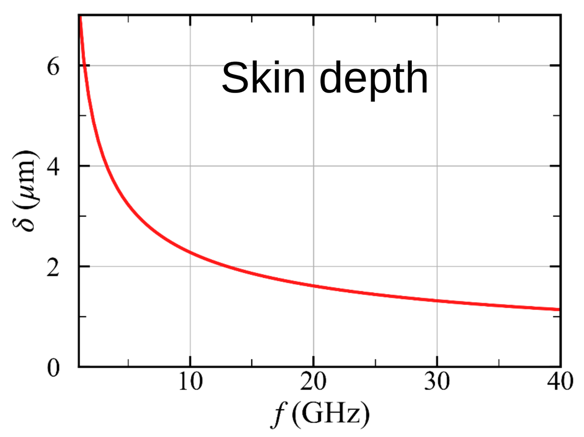


$t \approx 100$ μm (Soliton number ~ 2000)

Temperature : 100 K
Field sweep : +200 to -200 mT (Above H_c)
Frequency range : 1 ~ 40 GHz
Power intensity : 1 dBm

Excitation field perpendicular to *c* axis oscillates the CSL locally near surface.





Skin depth $\delta = \sqrt{\frac{\rho}{\pi f \mu}} \approx 1.8$ μm (Soliton number ~ 40)

Permeability $\mu = 1.42 \times 10^{-5}$ H/m

(Evaluated by magnetization measurement)

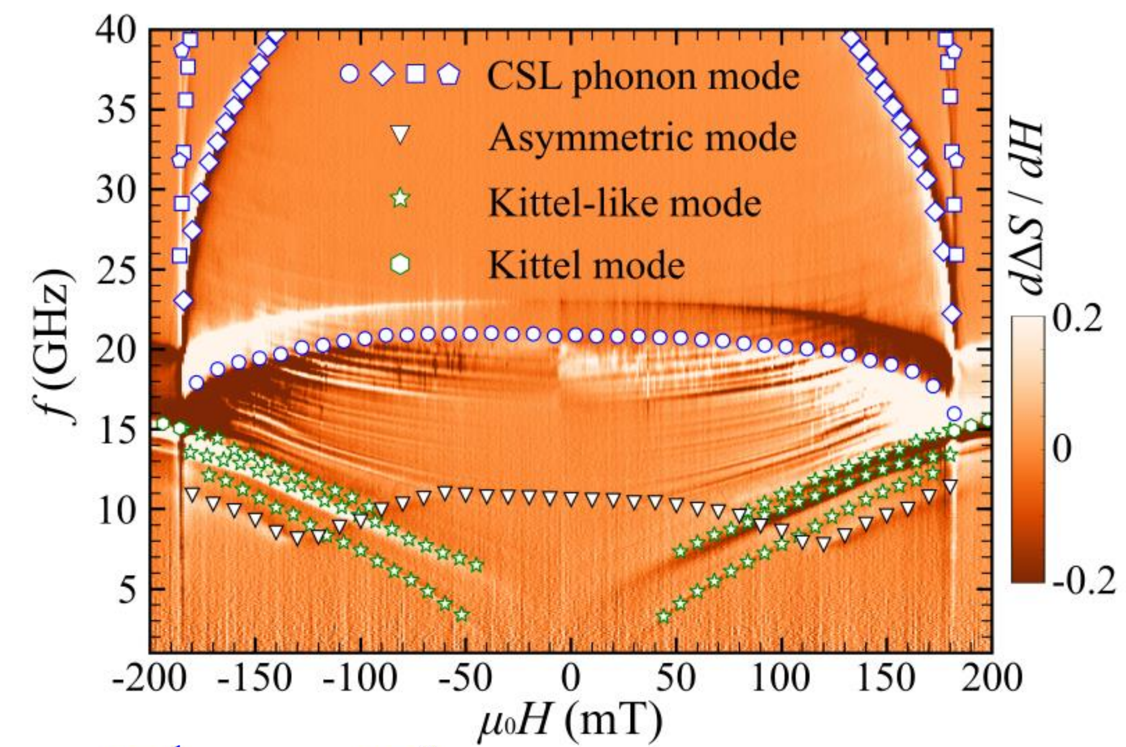
Resistivity $\rho = 2.32 \times 10^{-6}$ (Ω・m)

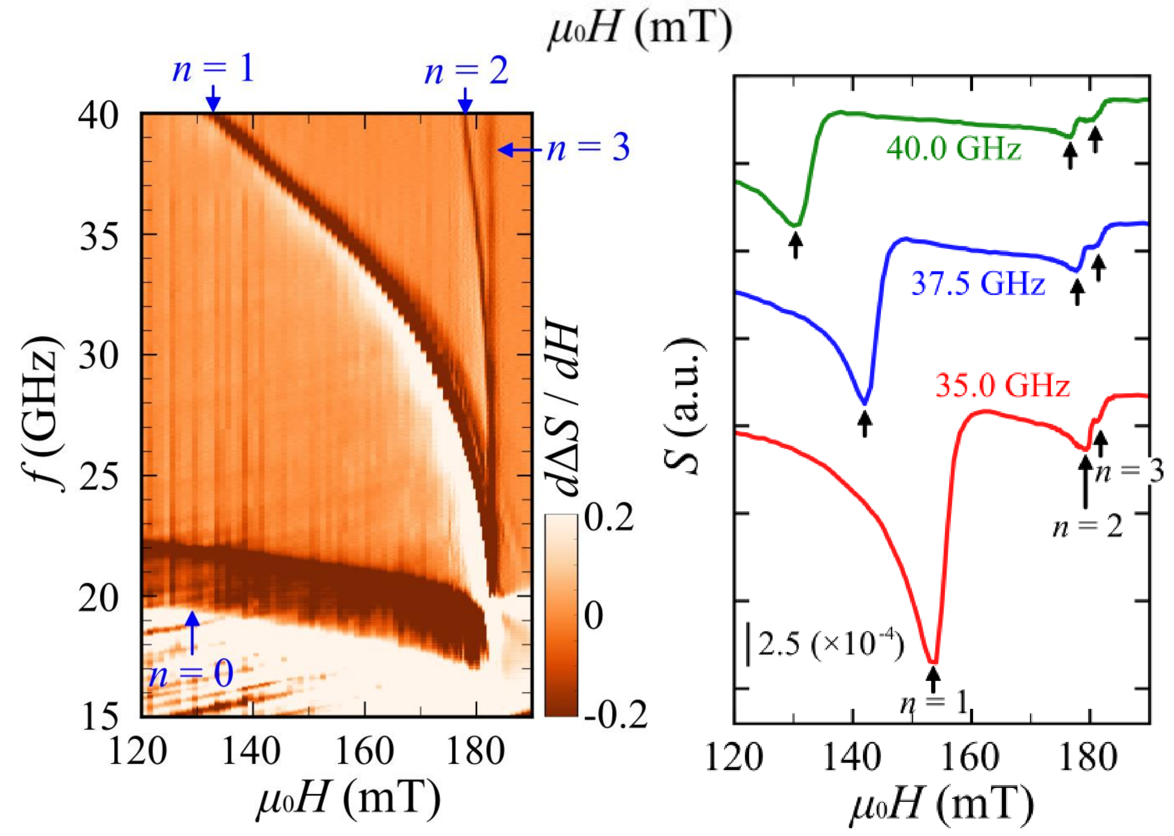
Y. Togawa *et al*., PRB. **92**, 220412(R) (2015).

Main Results and Discussions

Experimental data

Field dependence of magnetic resonance in CSL

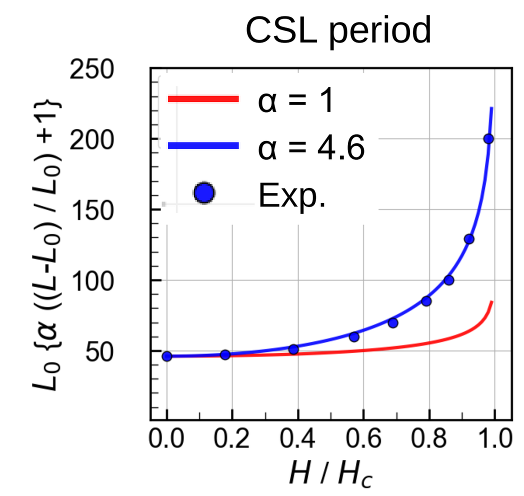




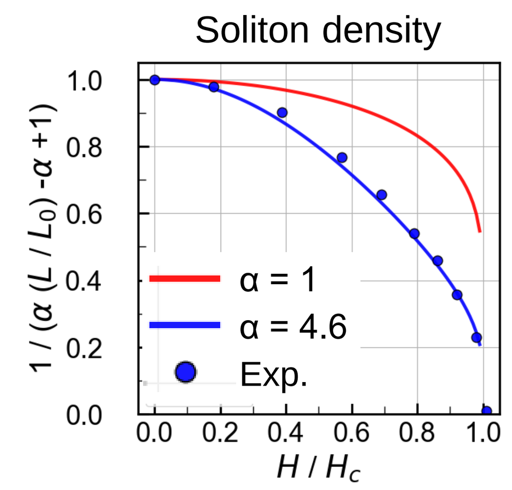
☐ Multiple resonance modes (n = 0, 1, 2, 3) up to 40 GHz.

Field dependence of CSL period

Non-trivial coefficient α appears in the H dependence of CSL period (Direct observation using Lorenz microscopy)



$$L_0\{\alpha\frac{L(H)-L_0}{L_0}+1\}$$



$$\frac{1}{\alpha\frac{L(H)}{L_0}-\alpha+1}$$

Data fitting

Theoretical equation (derived by sine-Goldon model)

$$\Omega_n = \frac{1}{k\,\mathrm{sn}(V_n,\ 1-k^2)} \approx \frac{2\pi}{L}n$$

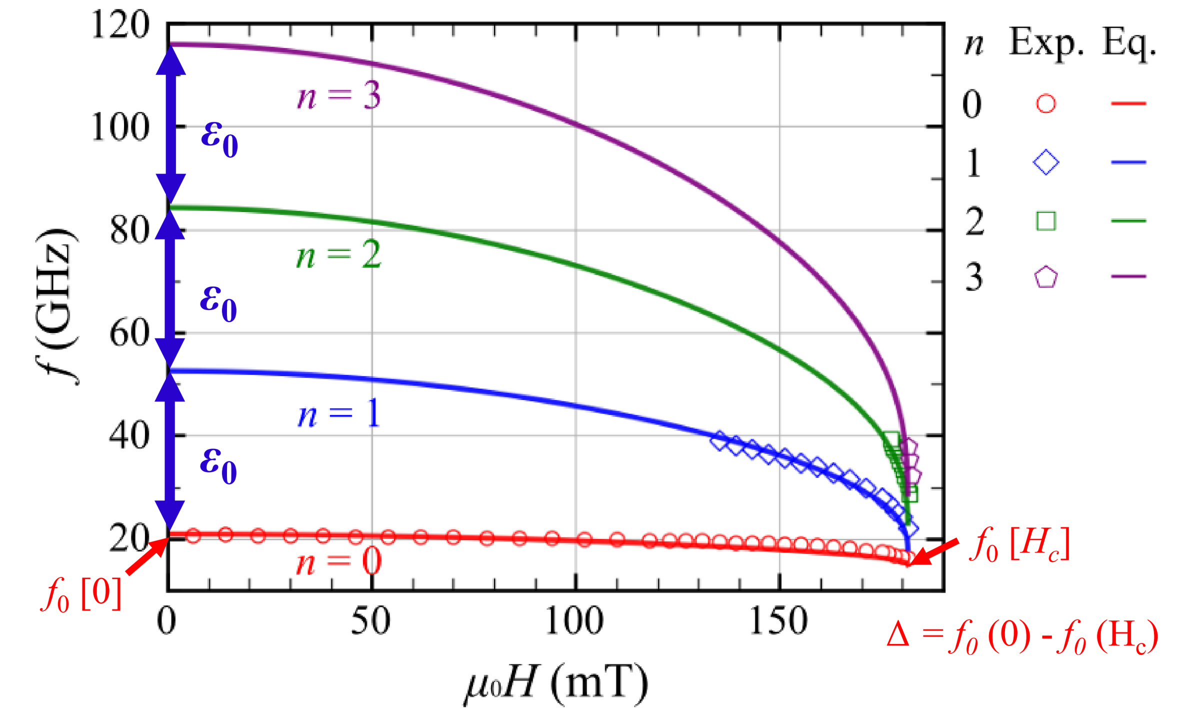
sn : Jacobi elliptic functions
k : elliptic modulus

V. V. Kiselev and A. A. Raskovalov, J. Exp. Theor. Phys. 116, 272 (2013).

Equation for fitting

$$f_n(H) = \frac{\beta\Omega_n[0]}{\alpha\frac{\Omega_n[0]}{\Omega_n} - \alpha + 1} - \gamma$$

parameters
$\alpha = 2.1$
$\beta = 5.9$
$\gamma = 15.0$ GHz



☐ Good agreement between theory and experiment

Meanings of parameters

α: field dependence of the CSL (see left in detail)

β: magnitude of Dzyaloshinskii-Moriya interaction (energy gap ε_0 at $H = 0$)

Energy gap $\varepsilon_0 = 31.2$ GHz → $\varepsilon_0 \approx \frac{DS^2}{2}$ → $D = 2.88$ K

γ: frequency at the convergence points of CSL phonon (frequency at critical field f_0 [H_c])

Finite frequency-gap for $n = 0$ mode

➢ (In experiment) $\Delta = f_0(0) - f_0(H_c) = 5.9$ GHz

➢ (In theory) $\Delta \approx \frac{D^2S^2}{2J}$

If $D = 2.88$ K and $D / J = 0.16$ $\Delta = 5.0$ GHz

☐ Good agreement