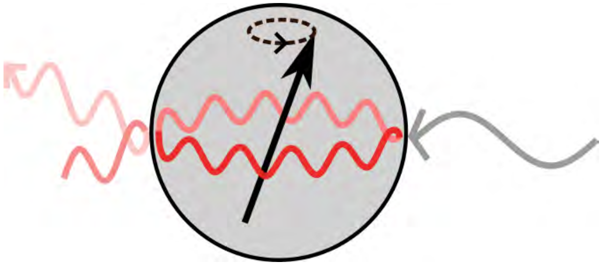
Triple-resonant Brillouin light scattering in magneto-optical resonators



James Haigh, Andrew Ramsay
Hitachi Cambridge Laboratory

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Cavendish Laboratory, University of Cambridge

UNIVERSITY OF CAMBRIDGE

HITACHI
Inspire the Next

Contents

- **Introduction**
  - Microwaves
  - Optics

- **Brillouin light scattering in YIG spheres**
  - experiments
  - Towards larger coupling.

Introduction

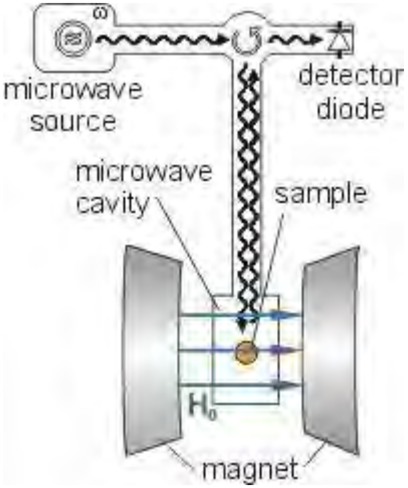
- Often optics/microwaves are used as probes of magnet properties/dynamics.

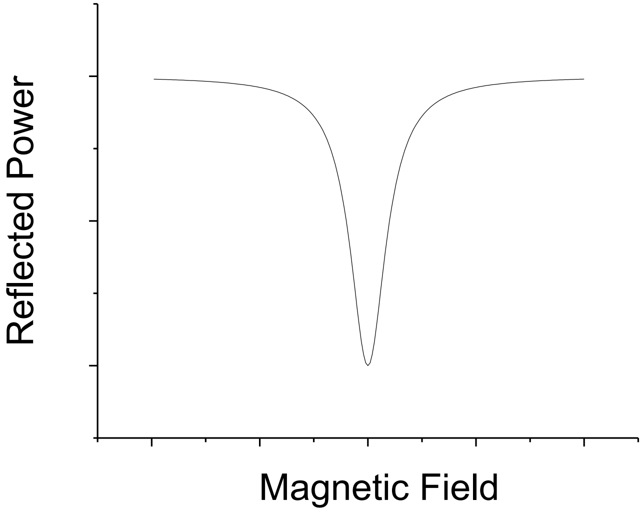
- Can there be some situation in which modification is stronger, and dynamics have to be consider equally?

  - Ferromagnetic resonance
  - Brillouin light scattering

Microwave cavities and magnets

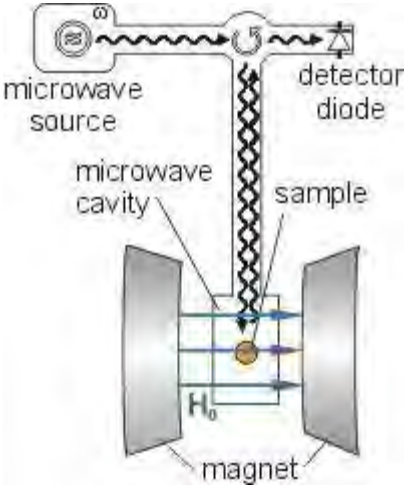
Traditional cavity FMR





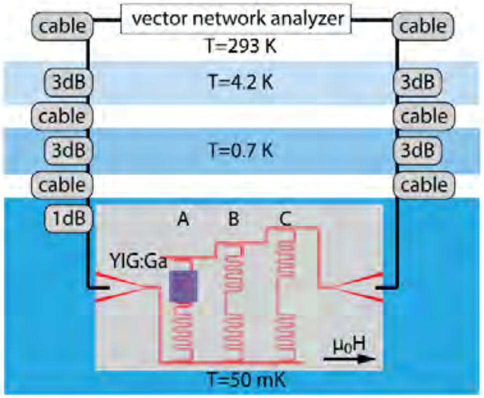
Microwave cavities and magnets

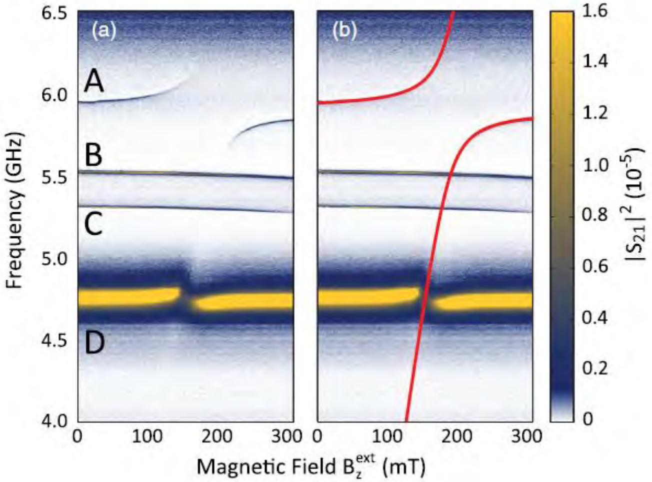
Traditional cavity FMR



High Cooperativity in Coupled Microwave Resonator Ferrimagnetic Insulator Hybrids

Hans Huebl,[1,*] Christoph W. Zollitsch,[1] Johannes Lotze,[1] Fredrik Hocke,[1] Moritz Greifenstein,[1] Achim Marx,[1] Rudolf Gross,[1,2] and Sebastian T. B. Goennenwein[1]

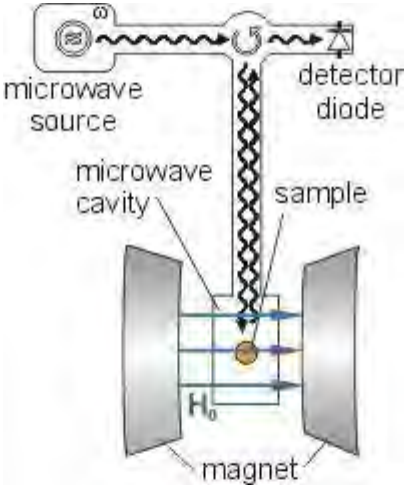


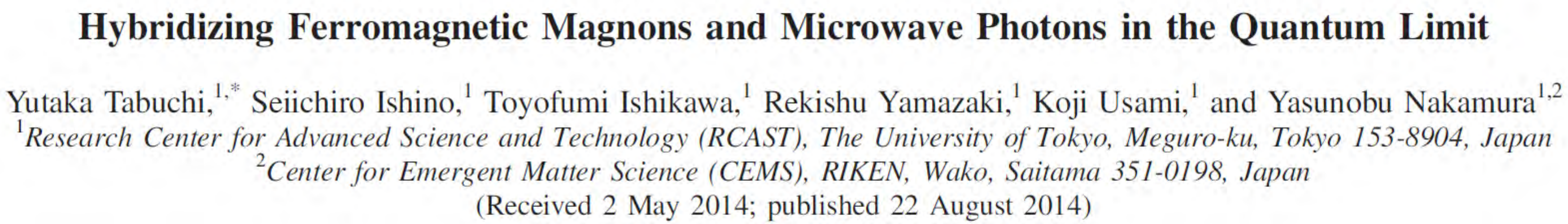


PhysRevLett.111.127003

Microwave cavities and magnets

Traditional cavity FMR

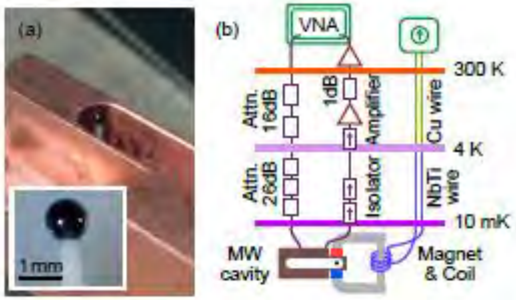


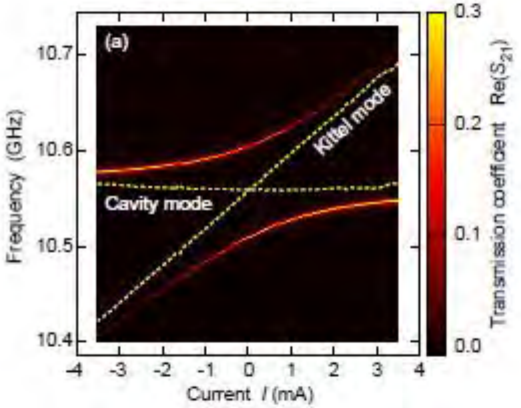


Hybridizing Ferromagnetic Magnons and Microwave Photons in the Quantum Limit

Yutaka Tabuchi,[1,*] Seiichiro Ishino,[1] Toyofumi Ishikawa,[1] Rekishu Yamazaki,[1] Koji Usami,[1] and Yasunobu Nakamura[1,2]
[1]*Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan*
[2]*Center for Emergent Matter Science (CEMS), RIKEN, Wako, Saitama 351-0198, Japan*

(Received 2 May 2014; published 22 August 2014)





PhysRevLett.113.083603

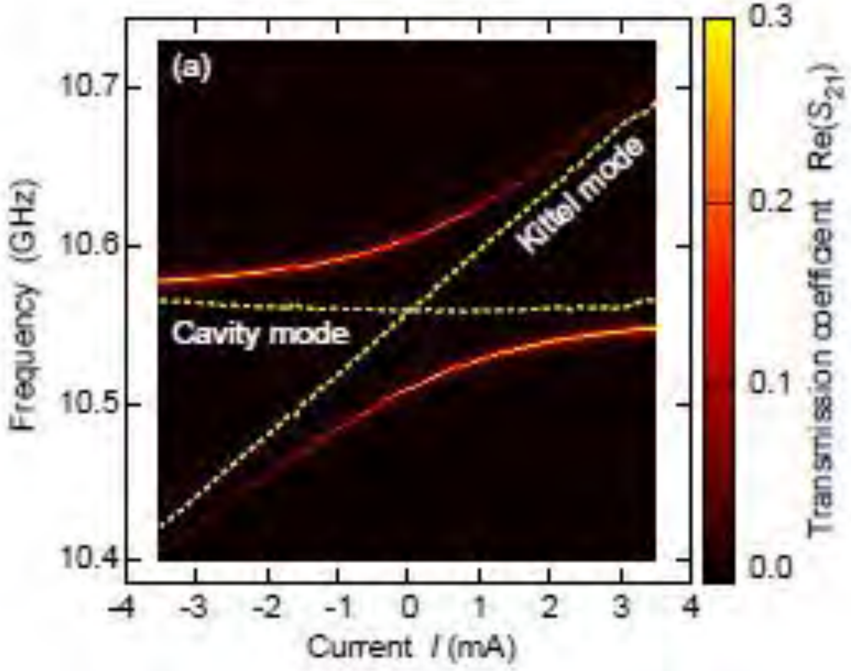
Microwave cavities and magnets

coupling rate

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

magnetic dissipation rate

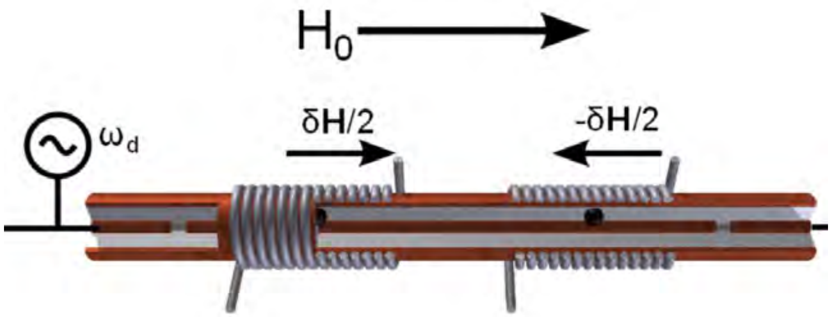
cavity dissipation rate



PhysRevLett.111.127003

PhysRevLett.113.083603

Microwave cavities and magnets

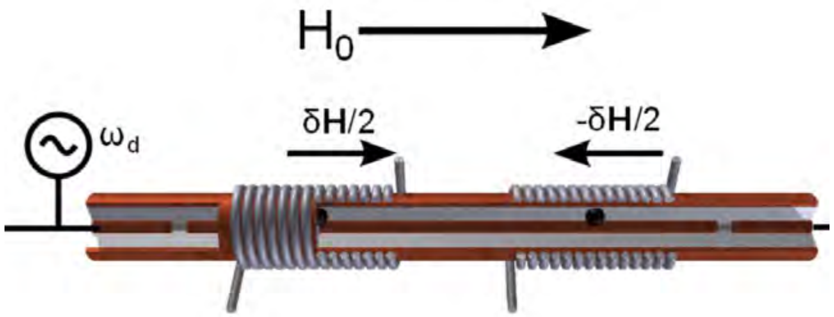


Cavity-mediated coherent coupling of magnetic moments

N. J. Lambert, J. A. Haigh, S. Langenfeld, A. C. Doherty, and A. J. Ferguson

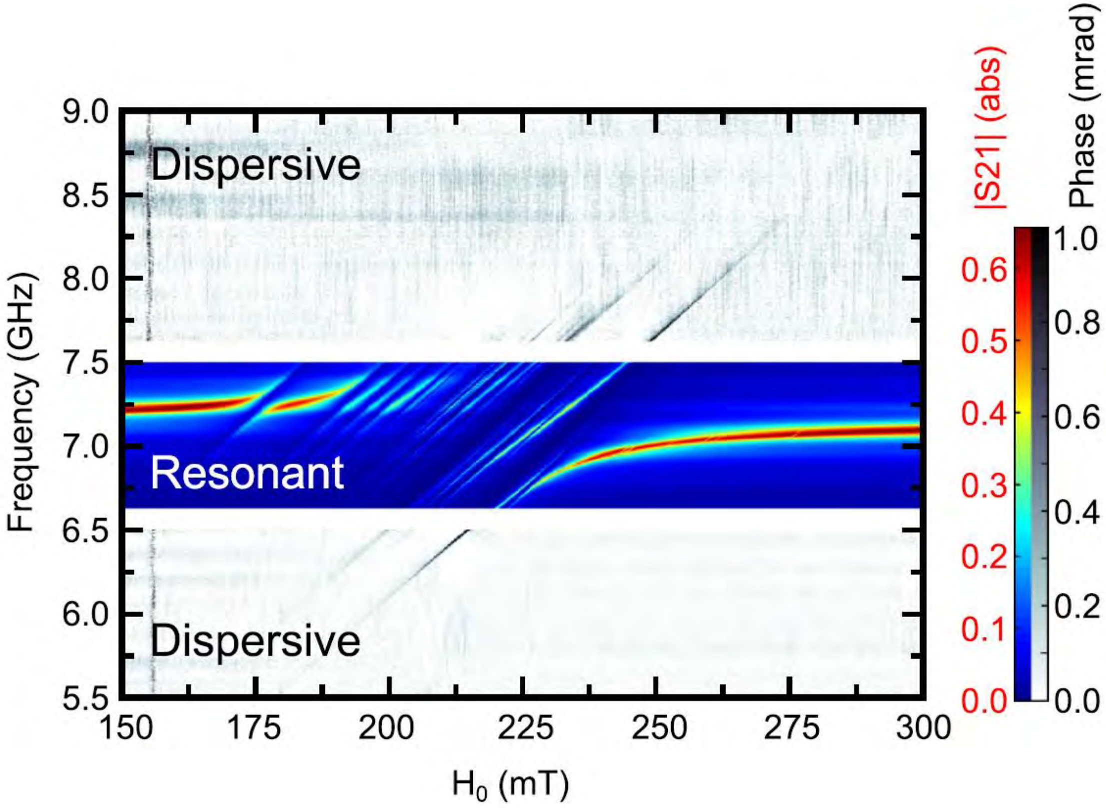
PhysRevA.93.021803

Microwave cavities and magnets



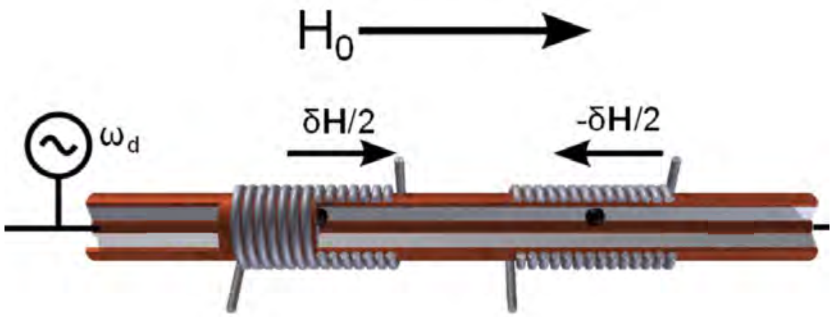
Cavity-mediated coherent coupling of magnetic moments

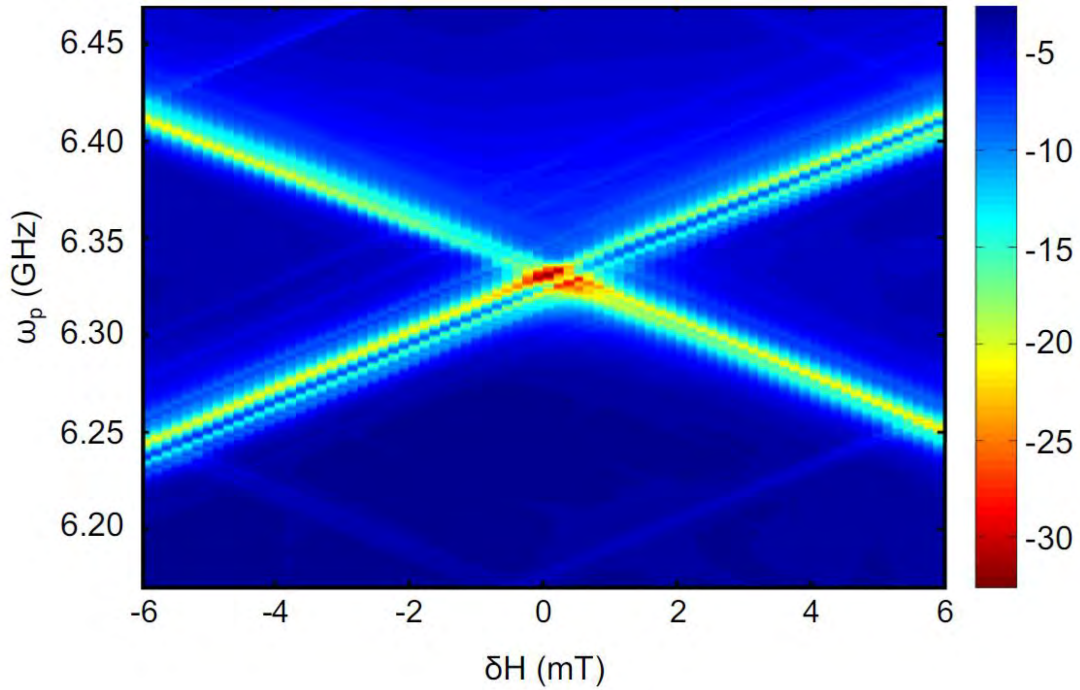
N. J. Lambert, J. A. Haigh, S. Langenfeld, A. C. Doherty, and A. J. Ferguson



PhysRevA.93.021803

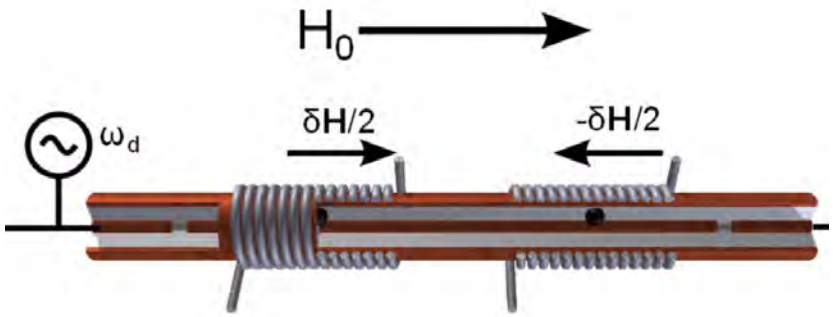
Microwave cavities and magnets



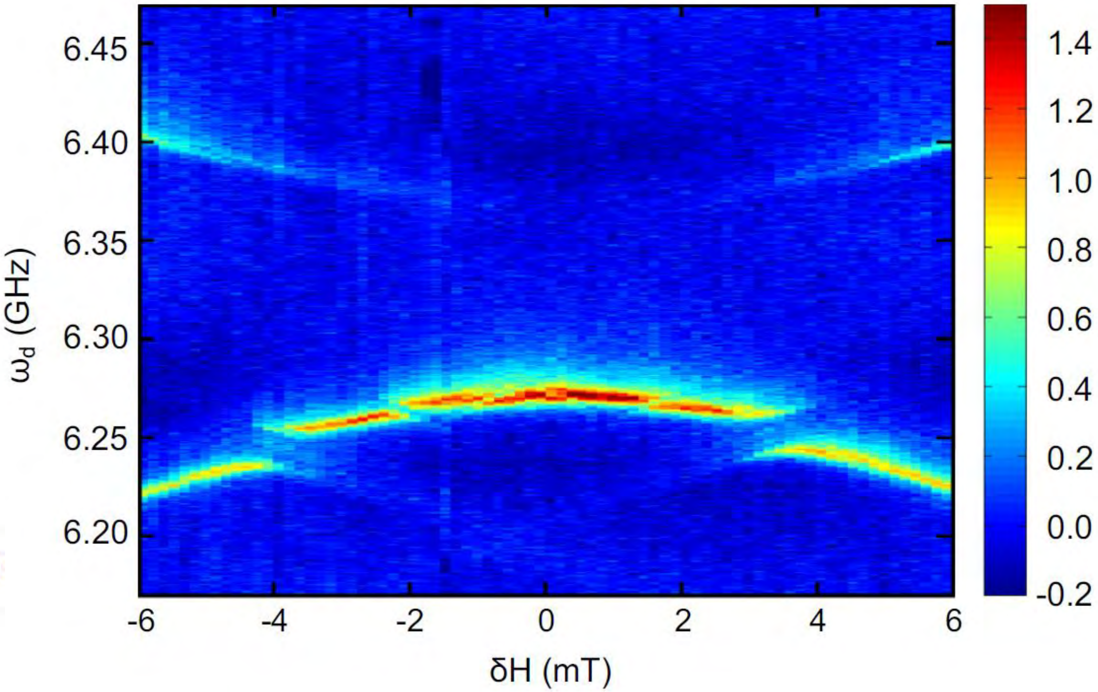


PhysRevA.93021803

Microwave cavities and magnets



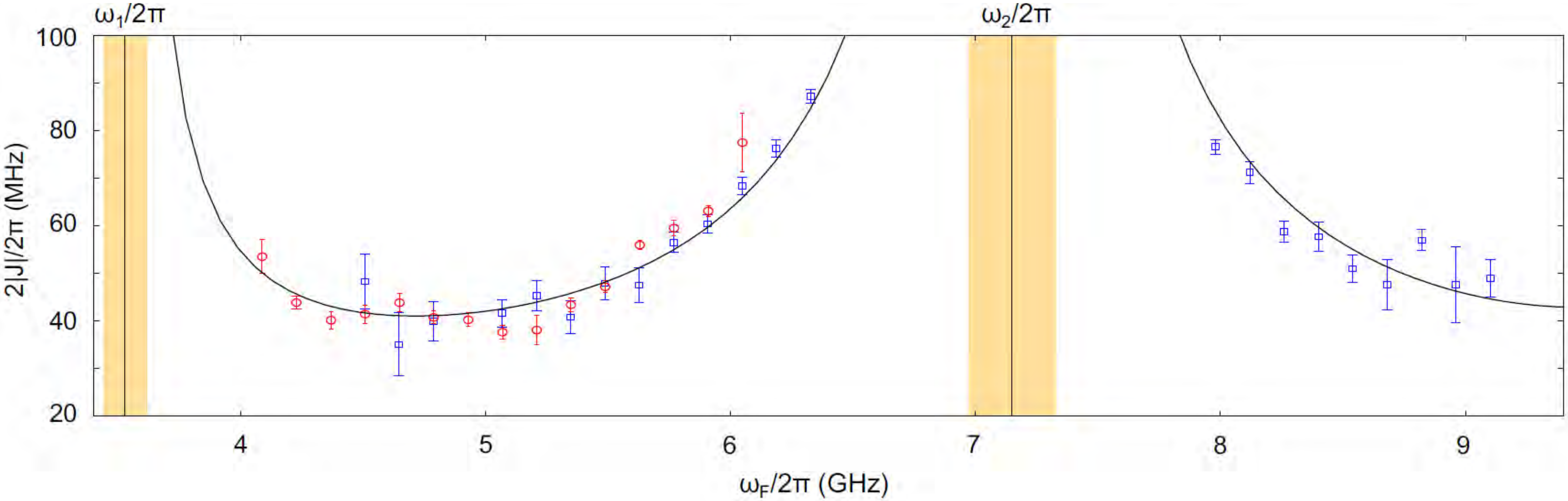
$\omega_c \approx 7.3$ GHz



$$\pm\frac{2g_0^2}{\hbar\Delta}(S_{1x}S_{2x}+S_{1y}S_{2y})$$

PhysRevA.93021803

Microwave cavities and magnets



$$\pm\frac{2g_0^2}{\hbar\Delta}(S_{1x}S_{2x}+S_{1y}S_{2y})$$

Spatially separated magnetic moments may be passively coupled over a long range via the modes of an electromagnetic cavity.

PhysRevA.93.021803

What about optics?

Brillouin light scattering from magnons

S.O. Demokritov et al. / Physics Reports 348 (2001) 441–489

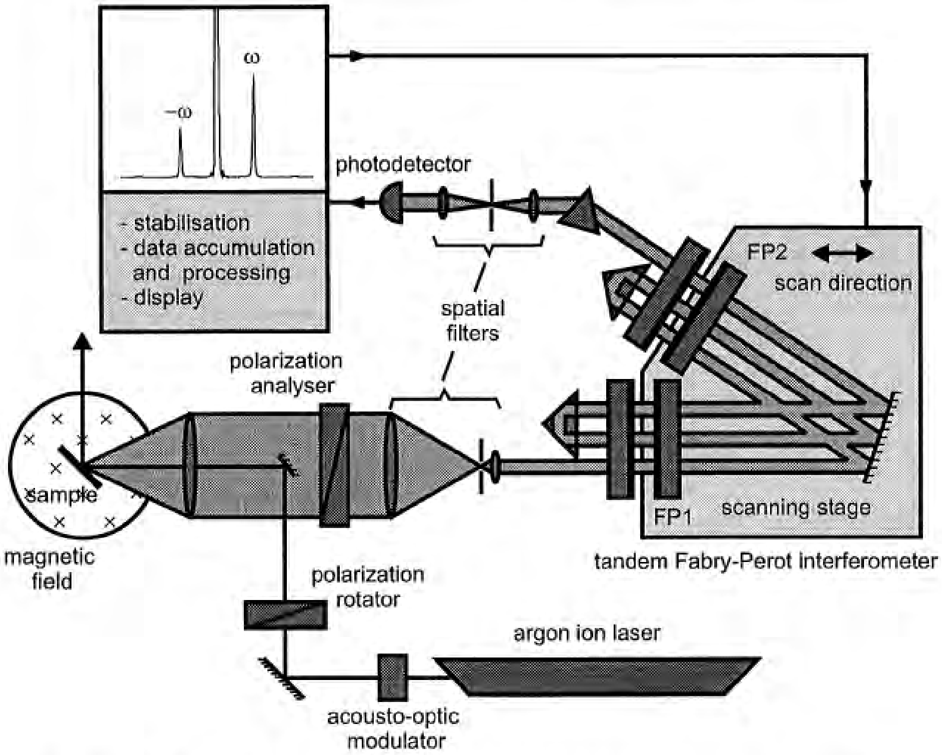


Fig. 8. Schematic view of the Brillouin light scattering setup in the backscattering geometry used for investigation of spin waves in laterally patterned structures. The transferred wavevector is changed by changing the angle between the sample surface and the incident laser beam.

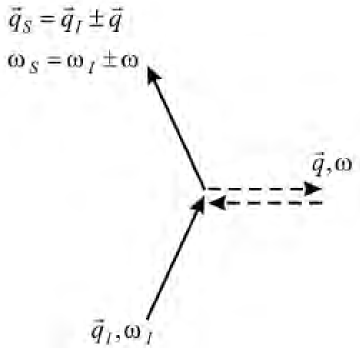
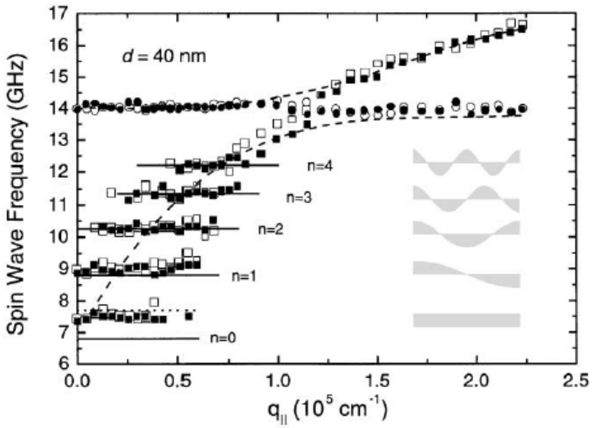
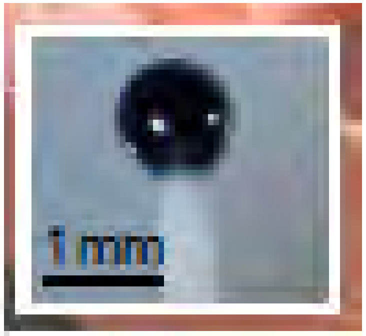


Fig. 4. Scattering process of photons from spin wave excitations.

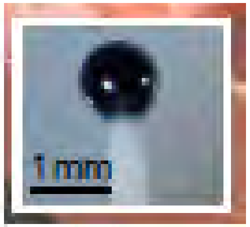


S.O. Demokritov et al. / Physics Reports 348 (2001) 441–489

Optical cavities and magnets

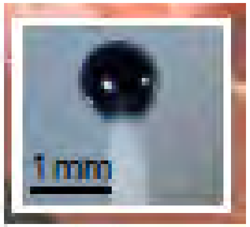


Optical cavities and magnets



built in optical cavity ✓

Optical cavities and magnets



built in optical cavity ✓

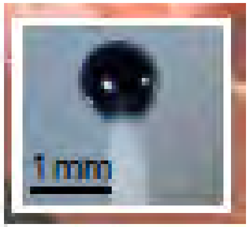
magneto-optical coupling ✓

$$\varepsilon_{ij} = \varepsilon_{ij}^{(0)} + \underbrace{K_{ijk}}_{\text{Faraday}} M_k + \underbrace{G_{ijkl}}_{\text{Voigt (Cotton-Mouton)}} M_k M_l$$

Faraday

Voigt
(Cotton-Mouton)

Optical cavities and magnets



Optomagnonic Whispering Gallery Microresonators
X. Zhang et al. PRL **117**, 123605 (2016)

Cavity Optomagnonics with Spin-Orbit Coupled Photons
A. Osada et al. PRL 116, 223601 (2016)

Magneto-optical coupling in whispering-gallery-mode resonators
PRA **92**, 063845 (2015)

built in optical cavity ✓

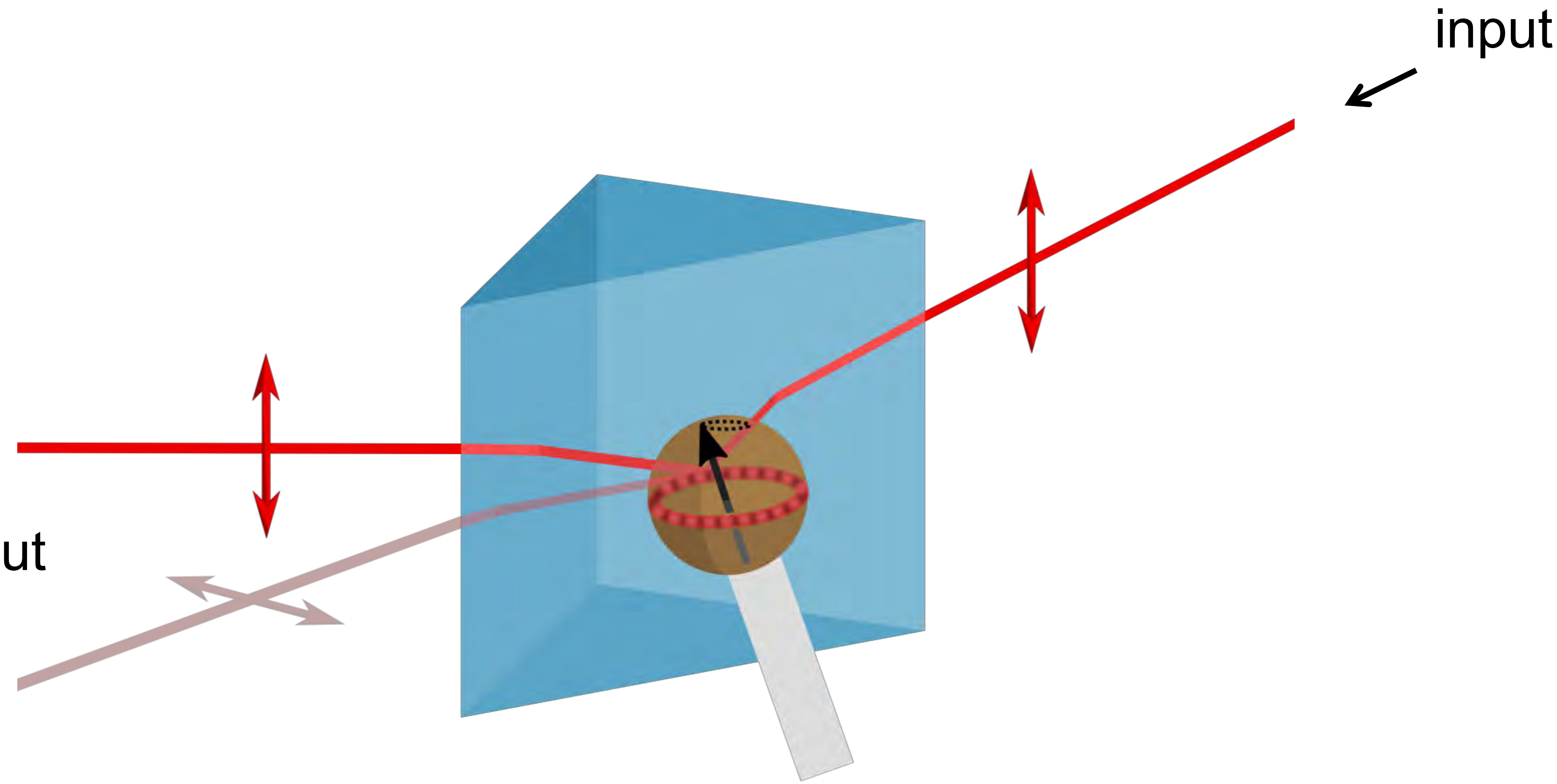
magneto-optical coupling ✓

$$\varepsilon_{ij} = \varepsilon_{ij}^{(0)} + K_{ijk}M_k + G_{ijkl}M_kM_l$$

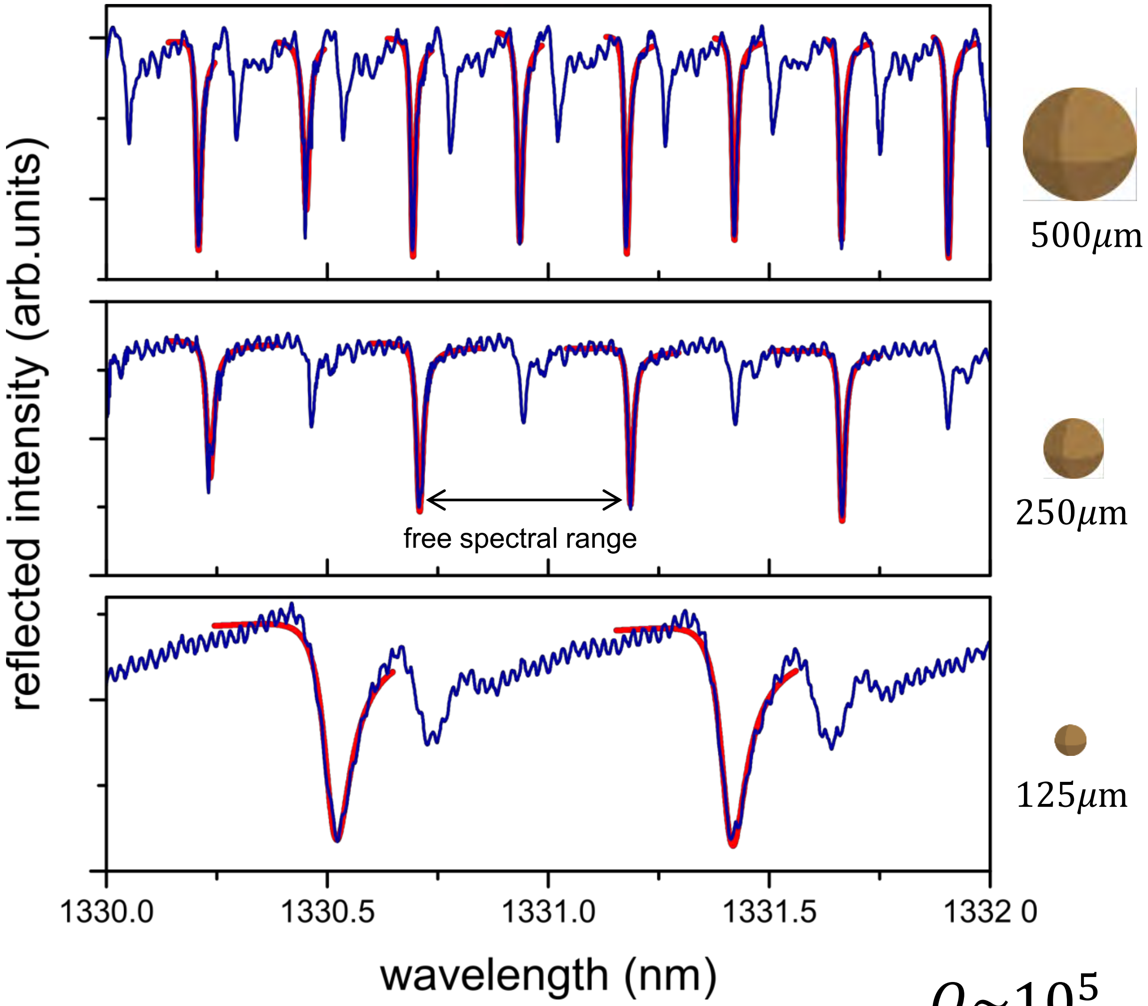
Faraday

Voigt
(Cotton-Mouton)

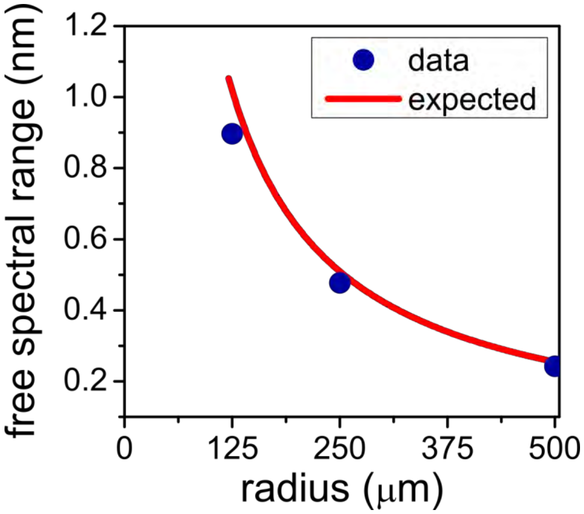
Optical modes in YIG spheres

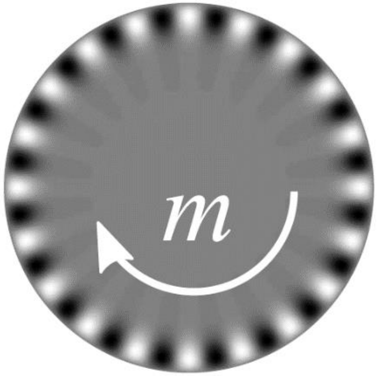


Optical mode identification

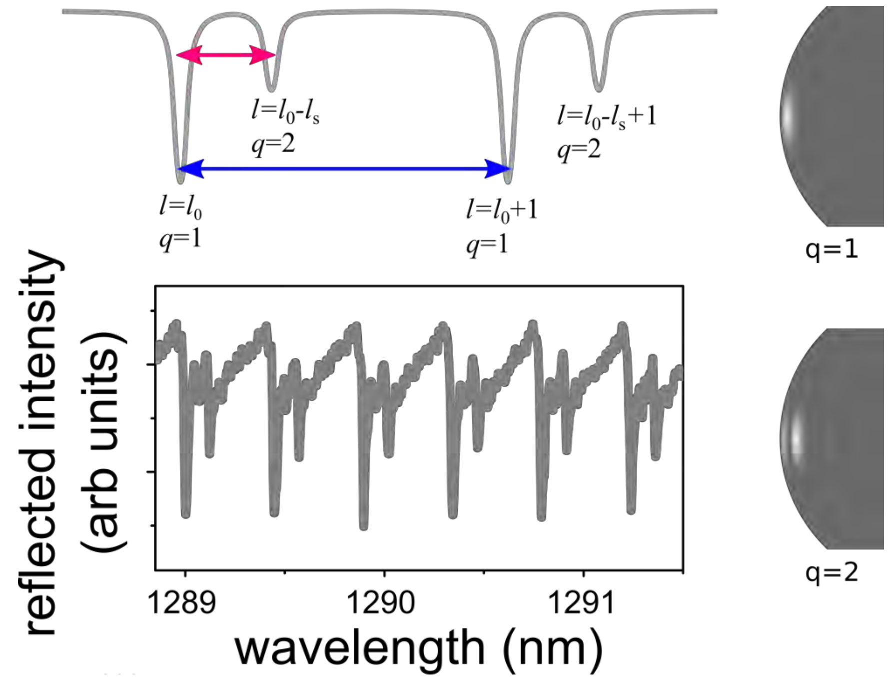


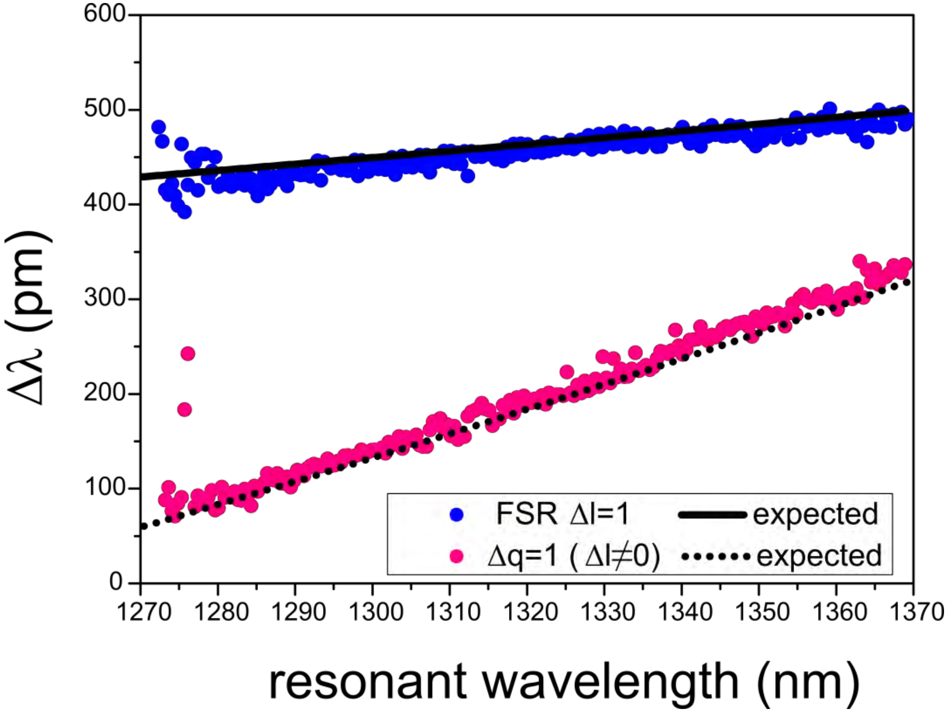
$Q \sim 10^5$





Optical mode identification

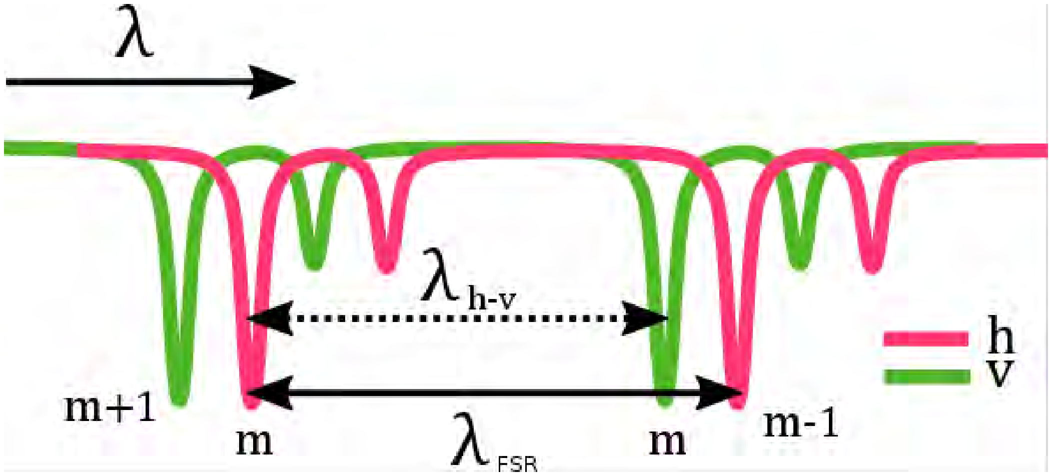




$$l \approx 3000,\ \Delta l_{\Delta q} = 20$$

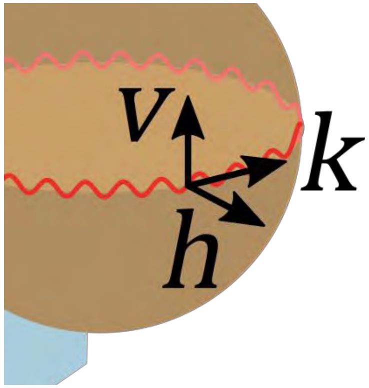
G. Schunk *et al.*, "*Identifying modes of large whispering-gallery mode resonators from the spectrum and emission pattern*," *Optics Express* **22** 30795 (2014).

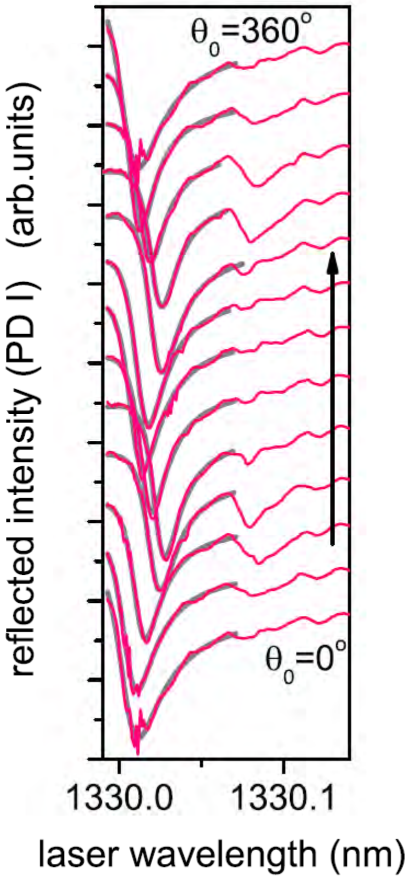
Optical mode identification: *v-h* (TE –TM) splitting

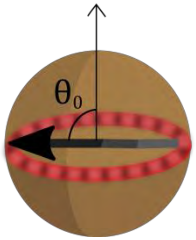


$$\lambda_{h-v} = \lambda_{FSR}\frac{\sqrt{n_{YIG}^2-1}}{n_{YIG}}$$
$$= 0.9\ \lambda_{FSR}$$

~7 GHz







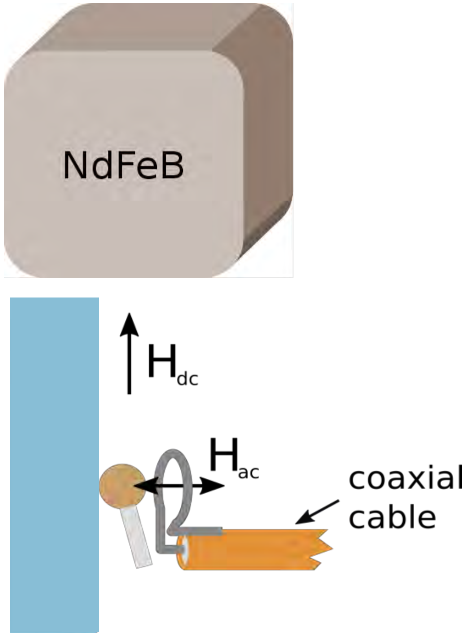
G. Schunk *et al.*, “*Identifying modes of large whispering-gallery mode resonators from the spectrum and emission pattern*,” *Optics Express* **22** 30795 (2014).

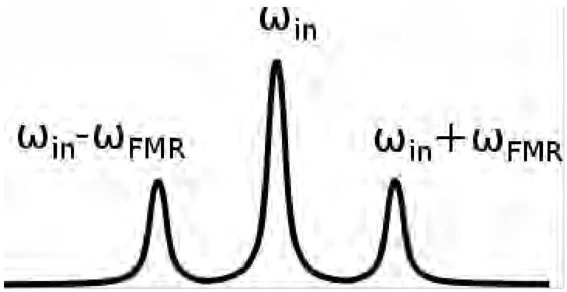
Optical mode identification

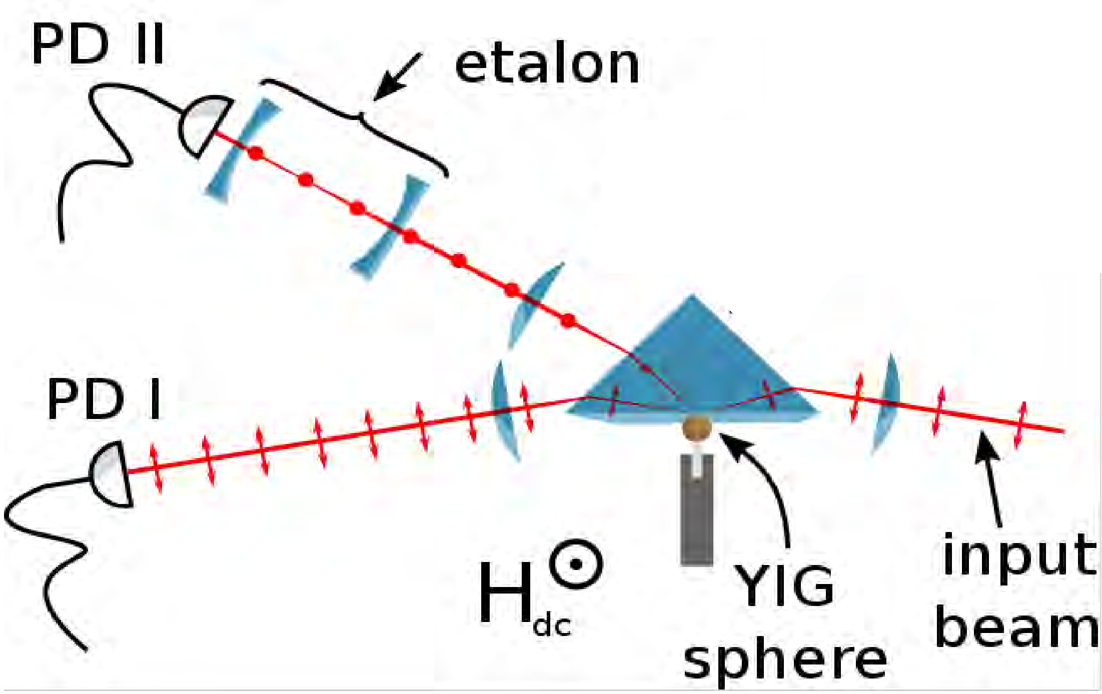
Summary:

- Optical modes can be identified.
- *h*-*v* splitting is comparable to typical FMR frequencies (for $\Delta m = 1$) for 1 mm sphere.

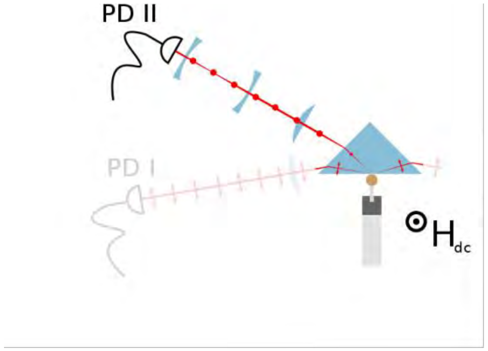
Setup for measuring Brillouin scattering



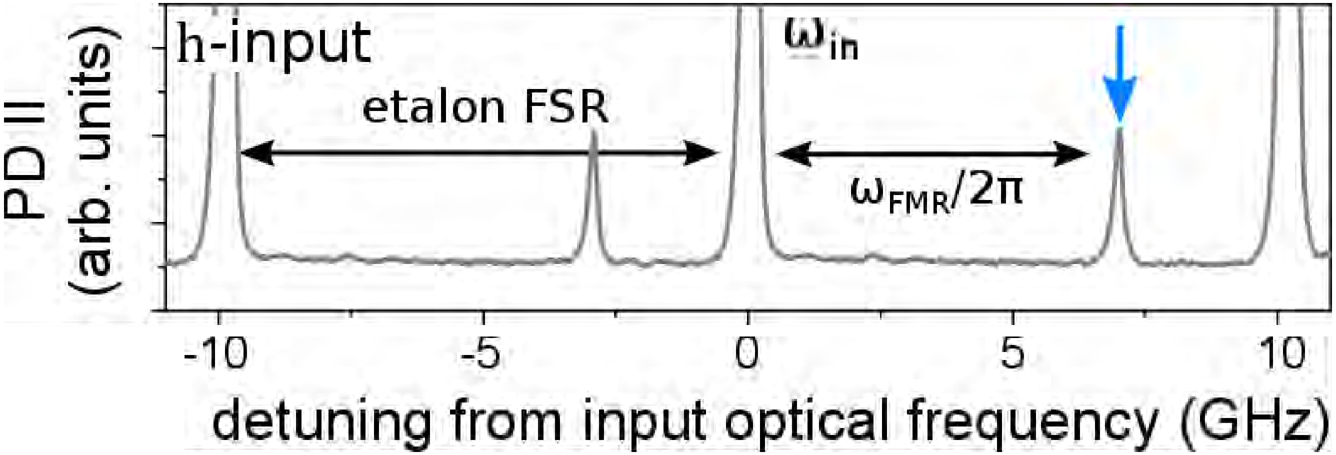


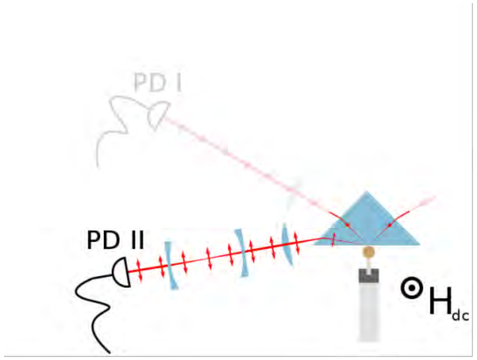


Measurement of Brillouin scattering due to driven FMR

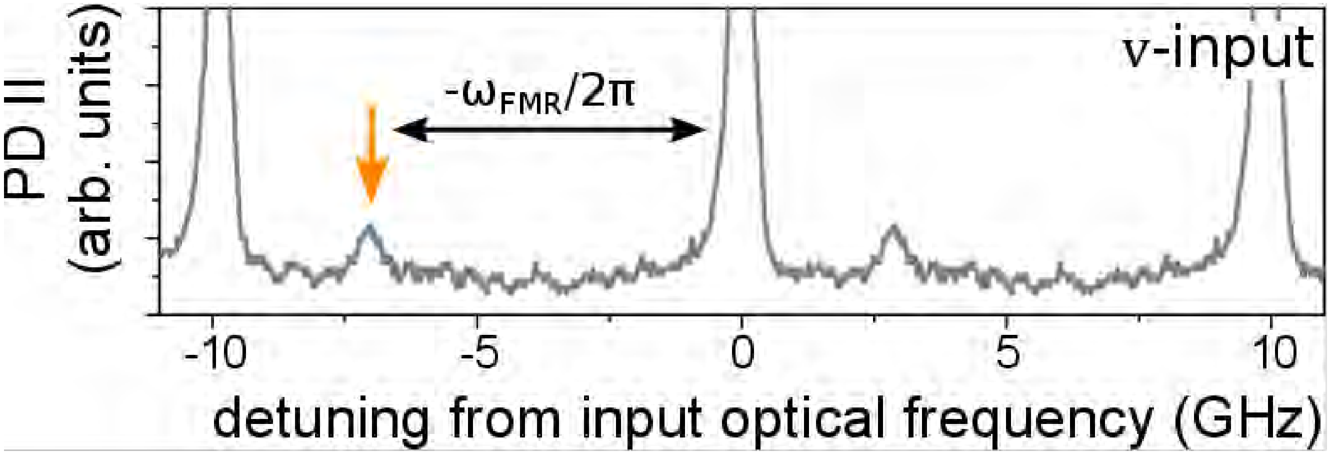


anti-Stokes

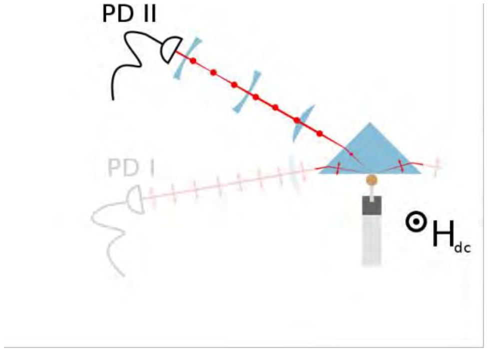


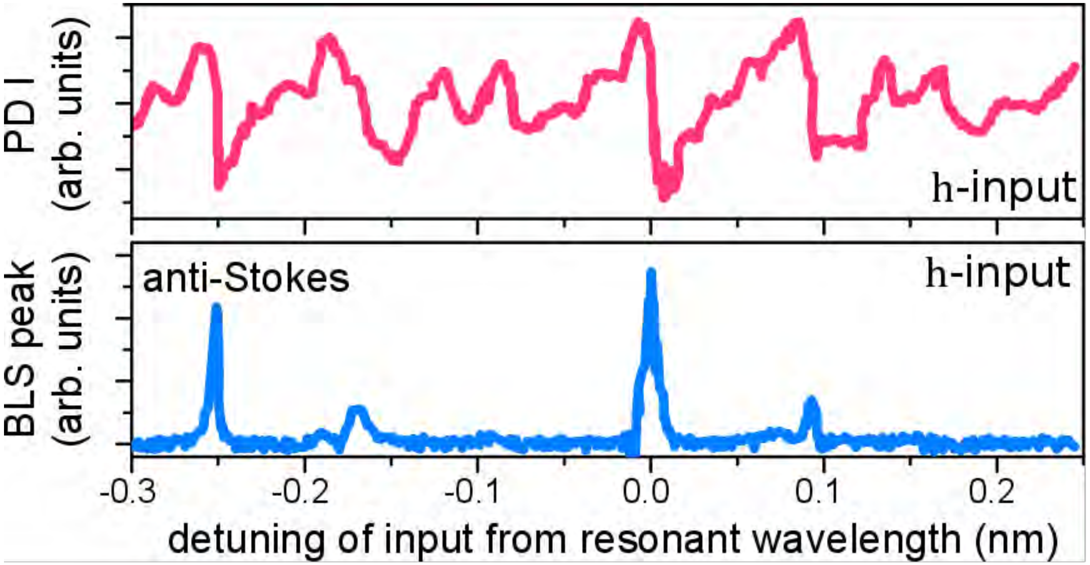


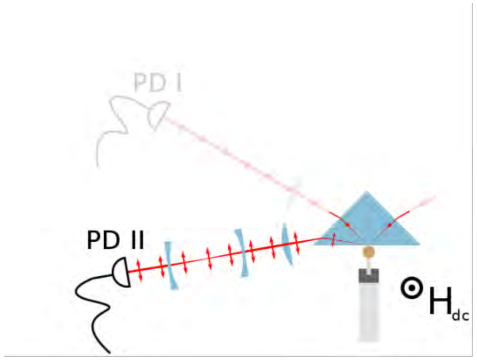
Stokes

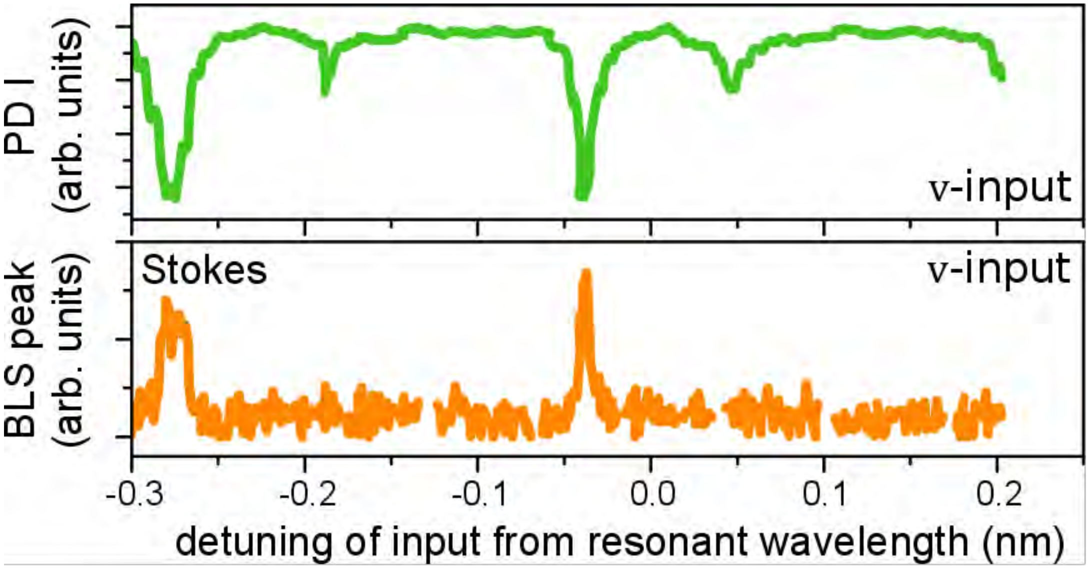


Input wavelength dependence of BLS

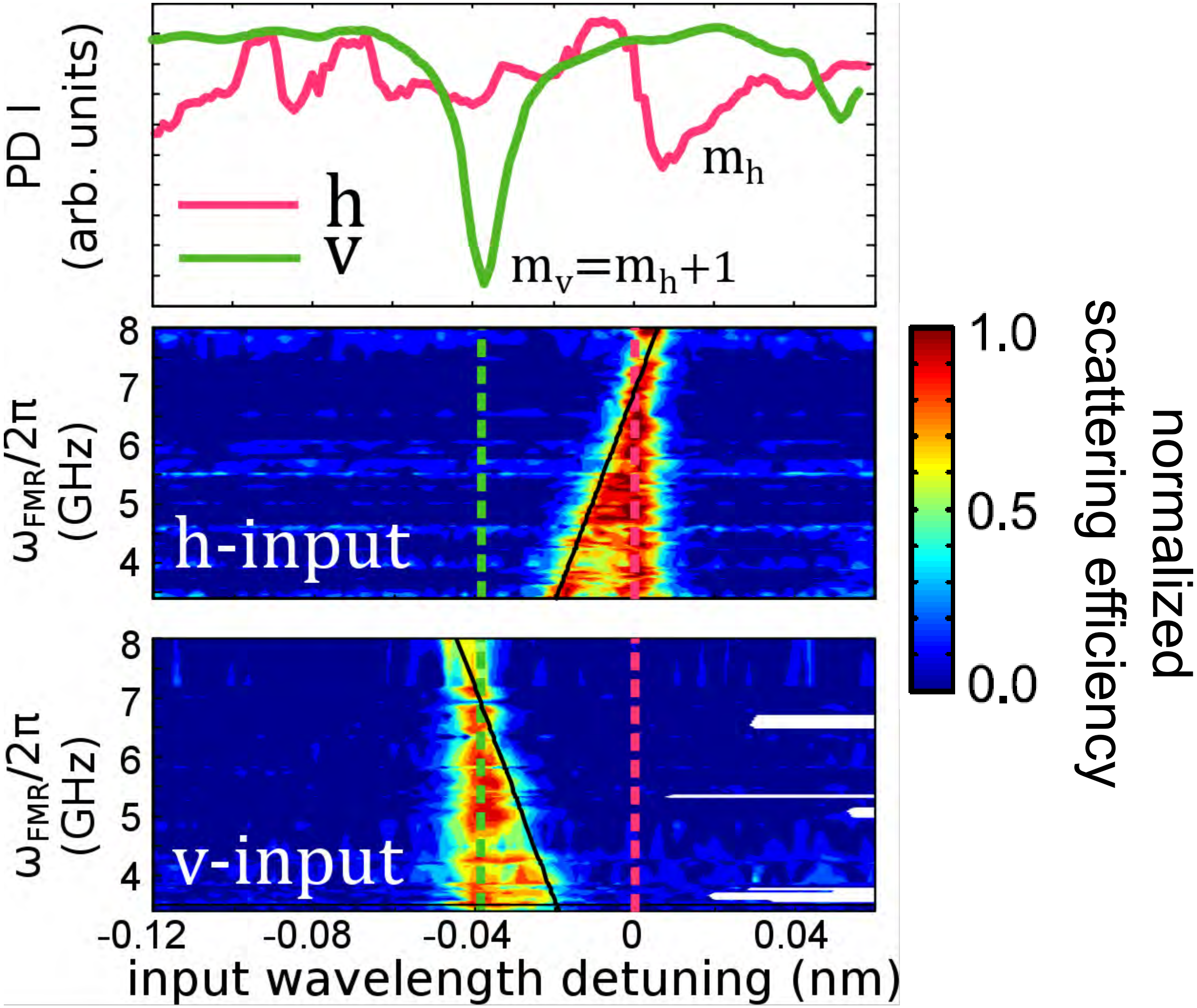






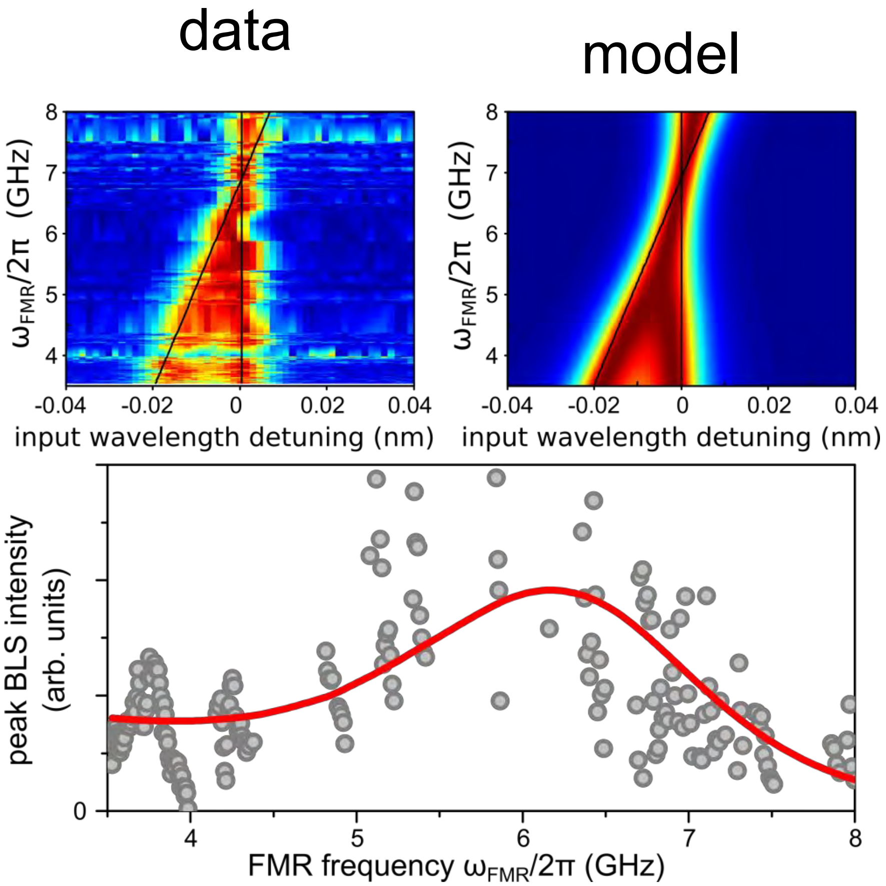


FMR frequency dependence of BLS



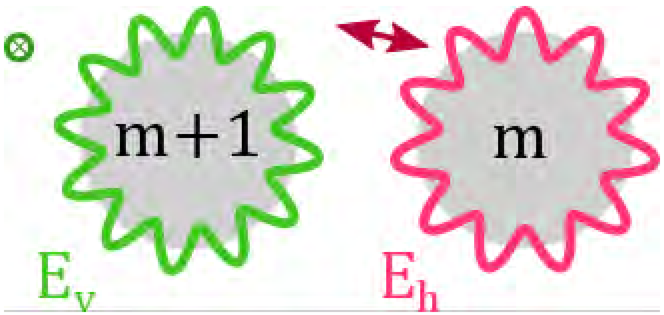
Resonant enhancement into and out-of WGMs

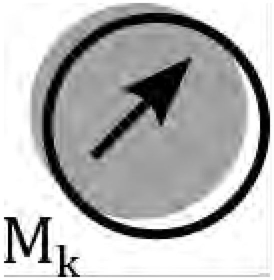
Triple resonant Brillouin scattering



$$|\langle \hat{d}_v \rangle|^2 = \frac{4\bar{G}^2 |\bar{m}_{\mathrm{in}}|^2 \kappa_v |\bar{a}_{\mathrm{in}}|^2 / \Gamma}{\left[\frac{\kappa_h^2}{4} + (\omega_h - \omega_L)^2\right]\left[\frac{\kappa_v^2}{4} + (\omega_{\mathrm{FMR}} - \omega_v + \omega_L)^2\right]}$$

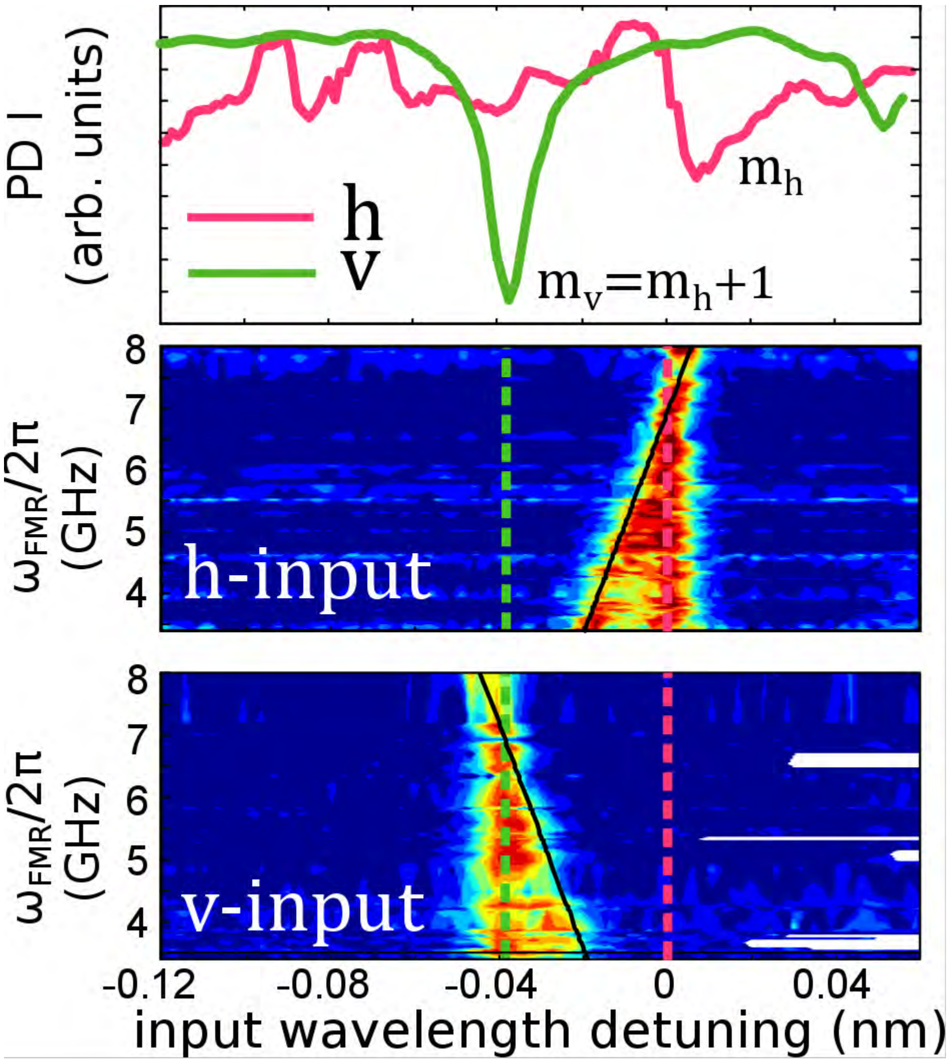
Selection rule due to angular momentum conservation





$$M_k \cdot E_v \times E_h^*$$

$$e^{-i\phi} \qquad e^{-im_v\phi} \qquad e^{im_h\phi}$$



magnet mode identification

Summary:

- can enhance Brillouin light scattering through the optical cavity modes
- triple resonance condition results in single side-band selection.
- maybe it is possible to explore similar physics as in opto-mechanics

Cooperativity?

coupling rate

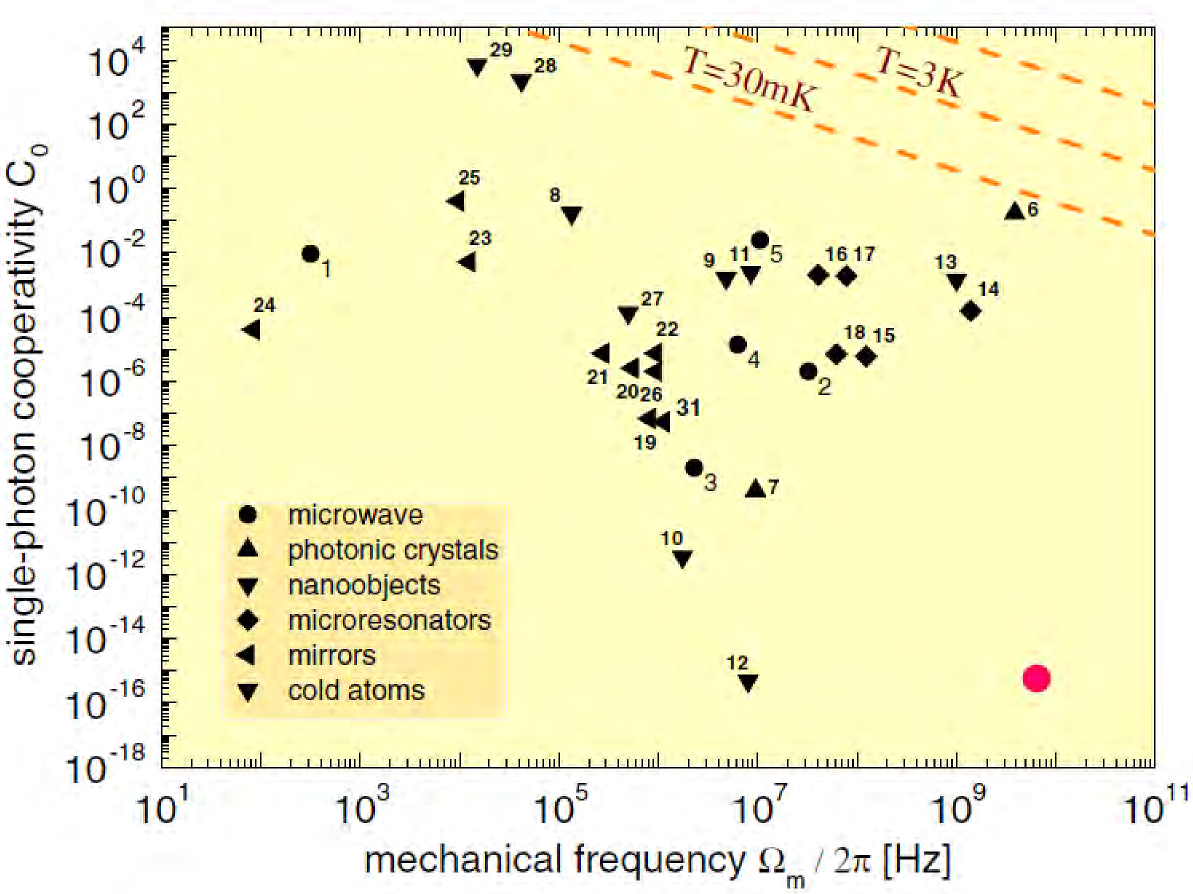
$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

optical dissipation rate

magnet dissipation rate

Comparison with opto-mechanics

Single photon cooperativity



$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, “Cavity optomechanics,” *Rev. Mod. Phys.* **86** 1391 (2014)

Future improvements

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

optical dissipation rate κ

Essentially a material parameter: see Q for different diameter yig spheres

Different materials?

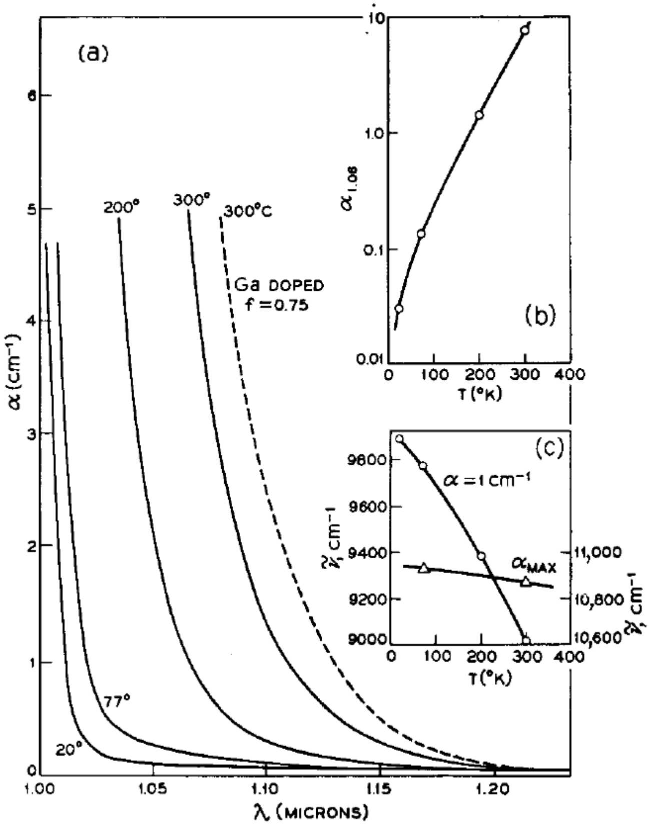


FIG. 7. Absorption of YIG at various temperatures. (a) Details of the absorption for 3-mm thick sample. (b) Absorption coefficient vs temperature for a wavelength of 1.06 μ. (c) Frequency vs temperature for $\alpha = 1$ and for the first absorption maximum due to the ferric ion.

“Effect of Impurities on the Optical Properties of Yttrium Iron Garnet,” *Journal of Applied Physics* **38** 1038 (1967).

Future improvements

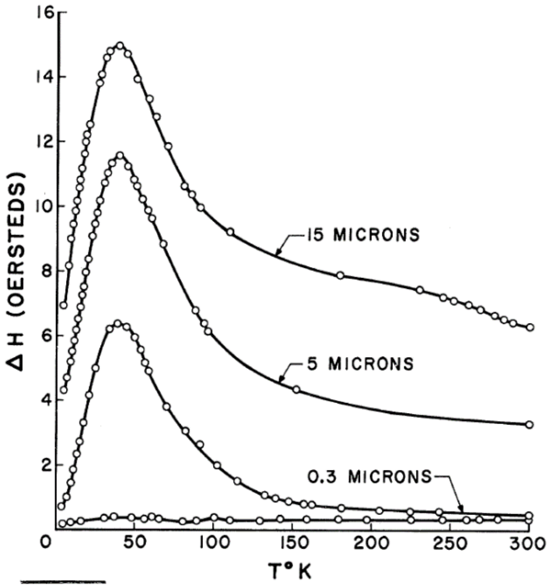
$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

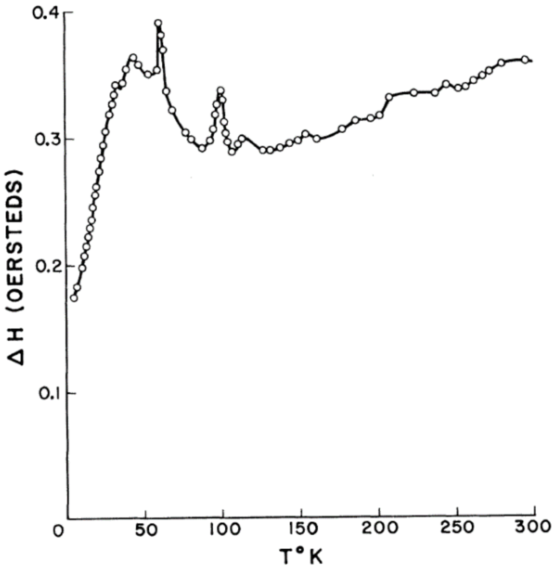
magnet dissipation rate Γ

Essentially a material parameter – much work on optimising this parameter for rf filters etc.

Different contributions:

-surface defects ->two-magnon scattering





=> Decreasing temperature doesn't make much difference

E. G. Spencer, R. C. LeCraw, and A. M. Clogston, "Low-Temperature Line-Width Maximum in Yttrium Iron Garnet," *Phys. Rev. Lett.* **3** 32 (1959)

Future improvements

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

coupling rate

$g_0 =$ 1 Hz

$$g_0 = \frac{\mathcal{V}c'}{4}\sqrt{\frac{1}{N_{\text{spins}}}}$$

$\mathcal{V}$ is Verdet constant: material parameter
c' is speed of light in YIG: material parameter

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, “Coupled spin-light dynamics in cavity optomagnonics,” *PRA* **94** 033821 (2016).

C. Leycuras, H. L. Gall, J. Desvignes, M. Guillot, and A. Marchand, “Magnetic and magneto-optical properties of a cerium YIG single crystal,” *IEEE Transactions on Magnetics* **21** 1662 (1985).

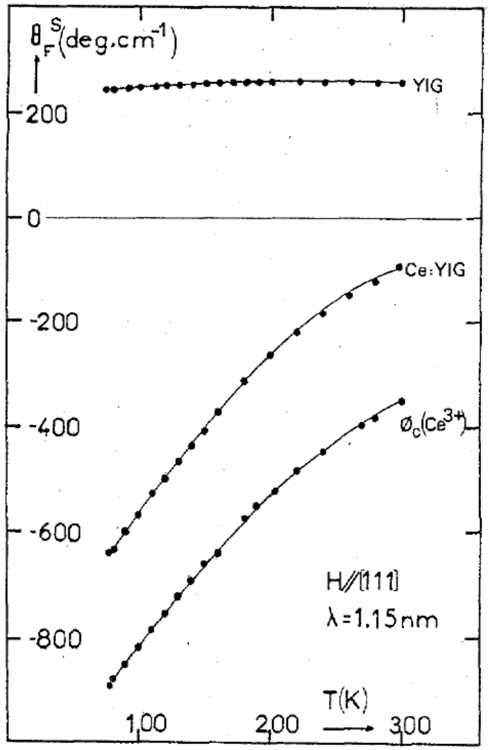


Fig. 4
Thermal evolution of the spontaneous Faraday rotation of Ce$_{0.06}$: YIG, pure YIG and cerium contribution.

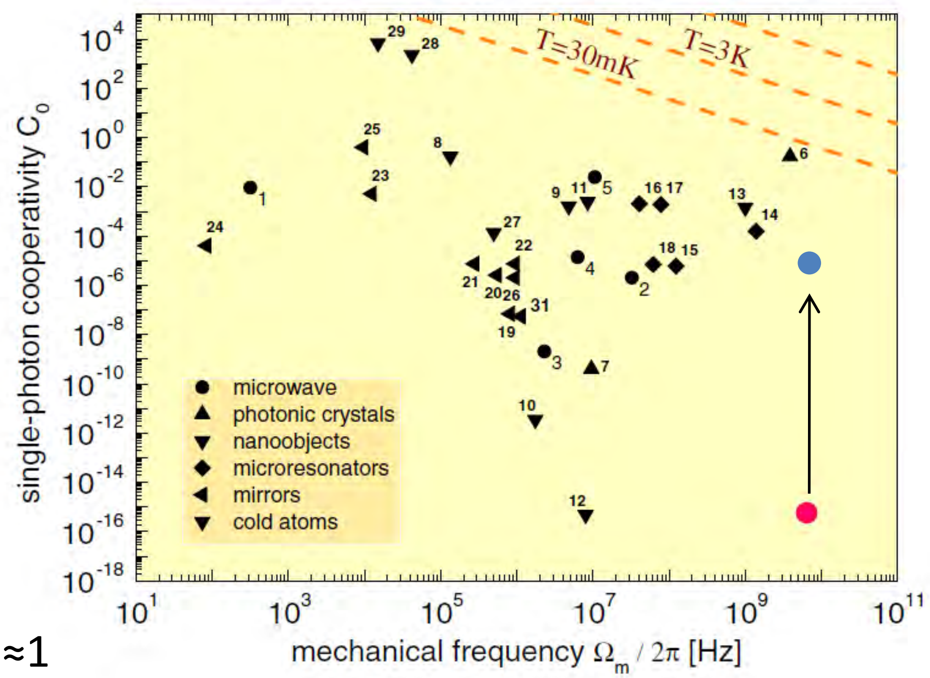
Is it possible to get to an interesting regime?

$$C_0 = \frac{4g_0^2}{\kappa\Gamma}$$

- Volume decrease gives factor 10^5 in coupling constant $g_0 = 0.1$ MHz (currently 1 Hz).
- Decrease in magnetic linewidth gives factor 10
- Decrease in internal optical dissipation doesn't seem to matter as the maximum Q is about the same.

$\Rightarrow$ At most 10^{11} increase in cooperativity.

$$C_0 = \frac{g_0^2}{\kappa\Gamma}$$



=> With optical pumping, in principle ≈1

Conclusions

- can couple to optical WGMs in magnetic YIG spheres
- can enhance Brillouin light scattering through the optical cavity modes
- triple resonance condition results in single side-band selection.

- maybe it is possible to explore similar physics as in opto-mechanics
- a long way to go before achieving comparable cooperativity

J. A. Haigh, S. Langenfeld, N. J. Lambert, J. J. Baumberg, A. J. Ramsay, A. Nunnenkamp, and A. J. Ferguson., "*Magneto-optical coupling in whispering-gallery-mode resonators*," PRA **92** 063845 (2015).
J. A. Haigh, A. Nunnenkamp, A. J. Ramsay, and A. J. Ferguson, "Triple-Resonant Brillouin Light Scattering in Magneto-Optical Cavities," PRL **117** 133602 (2016).