Bidirectional conversion between microwave and light via ferromagnetic magnons

Koji Usami

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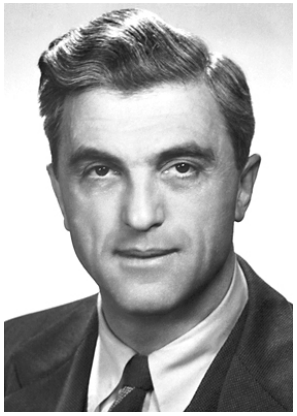
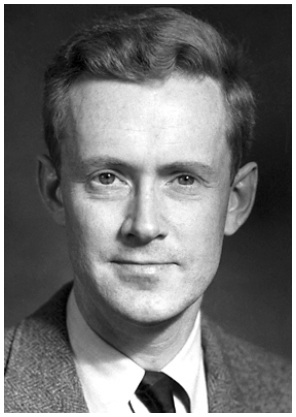
University of Tokyo

Why microwave-light converter ?

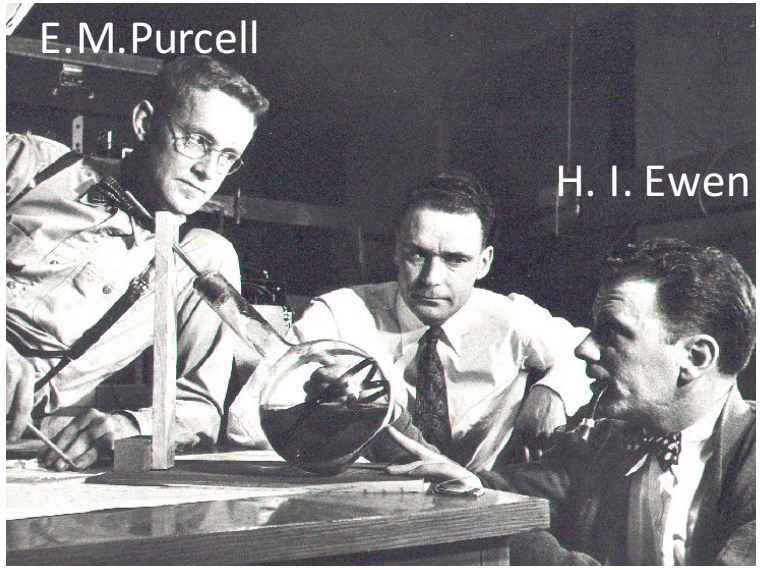
Important microwave signals

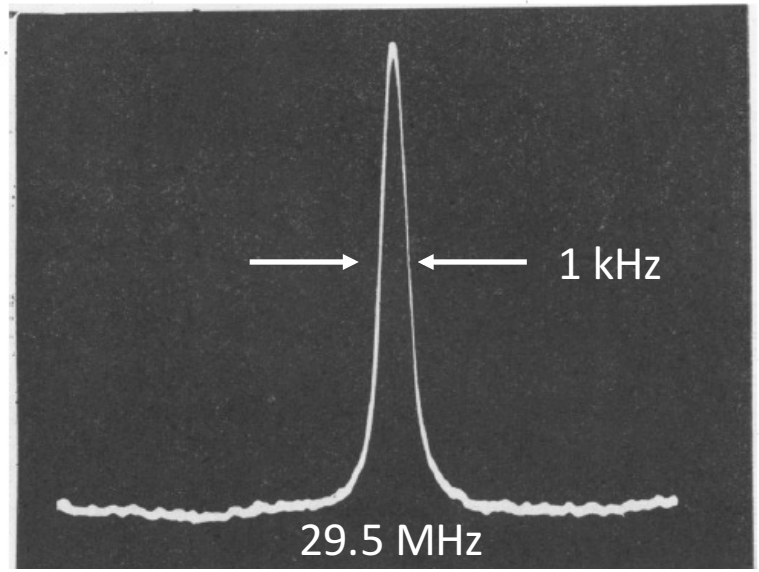


Felix Bloch



E. M. Purcell



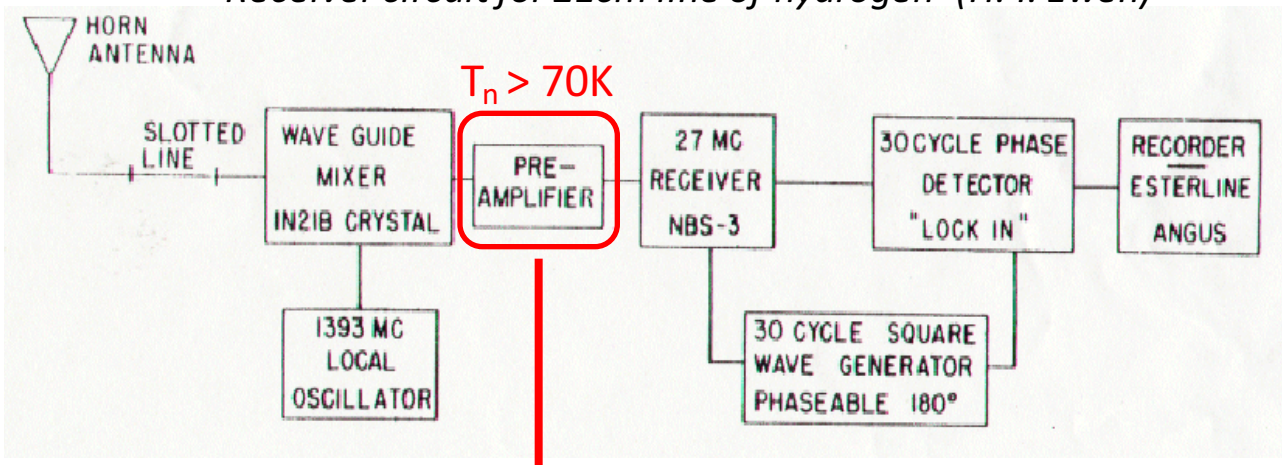


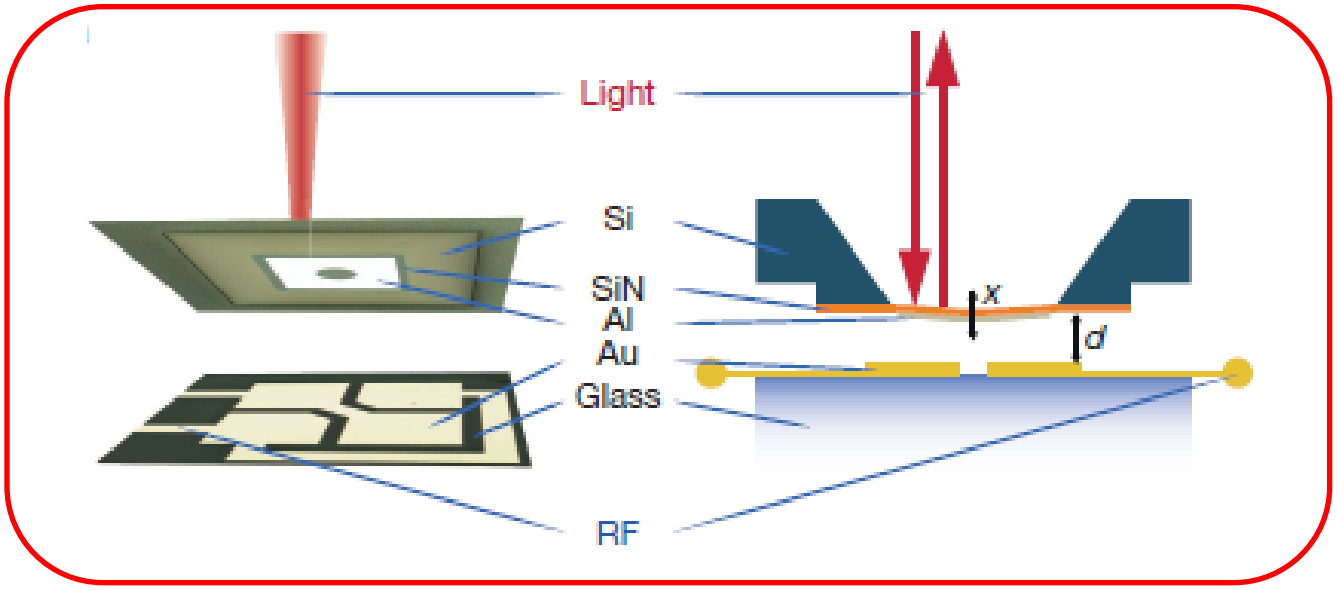
Condensed matter (NMR)

Astronomy (21cm line of H)

Quantum-noise-limited MW amplifier

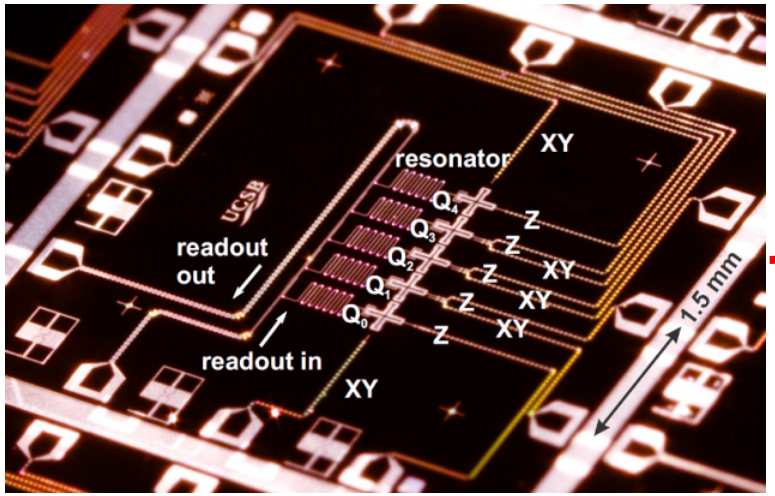
Receiver circuit for 21cm line of hydrogen (H. I. Ewen)



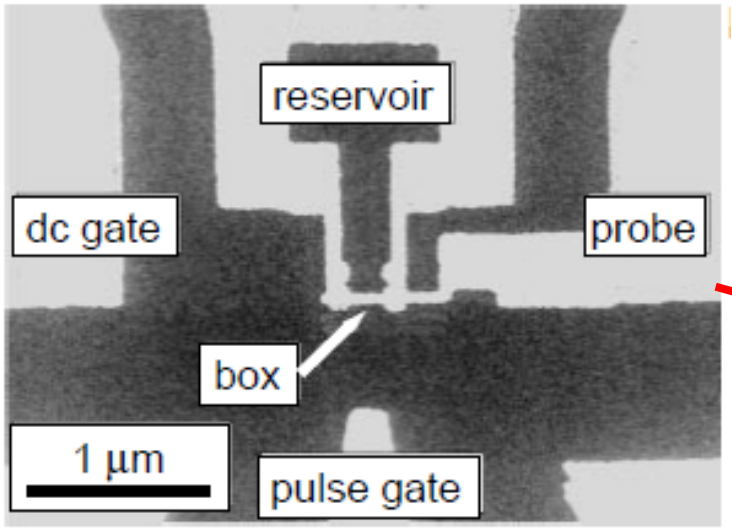


T. Bagci *et al.,* Nature **507,** 81 (2014).

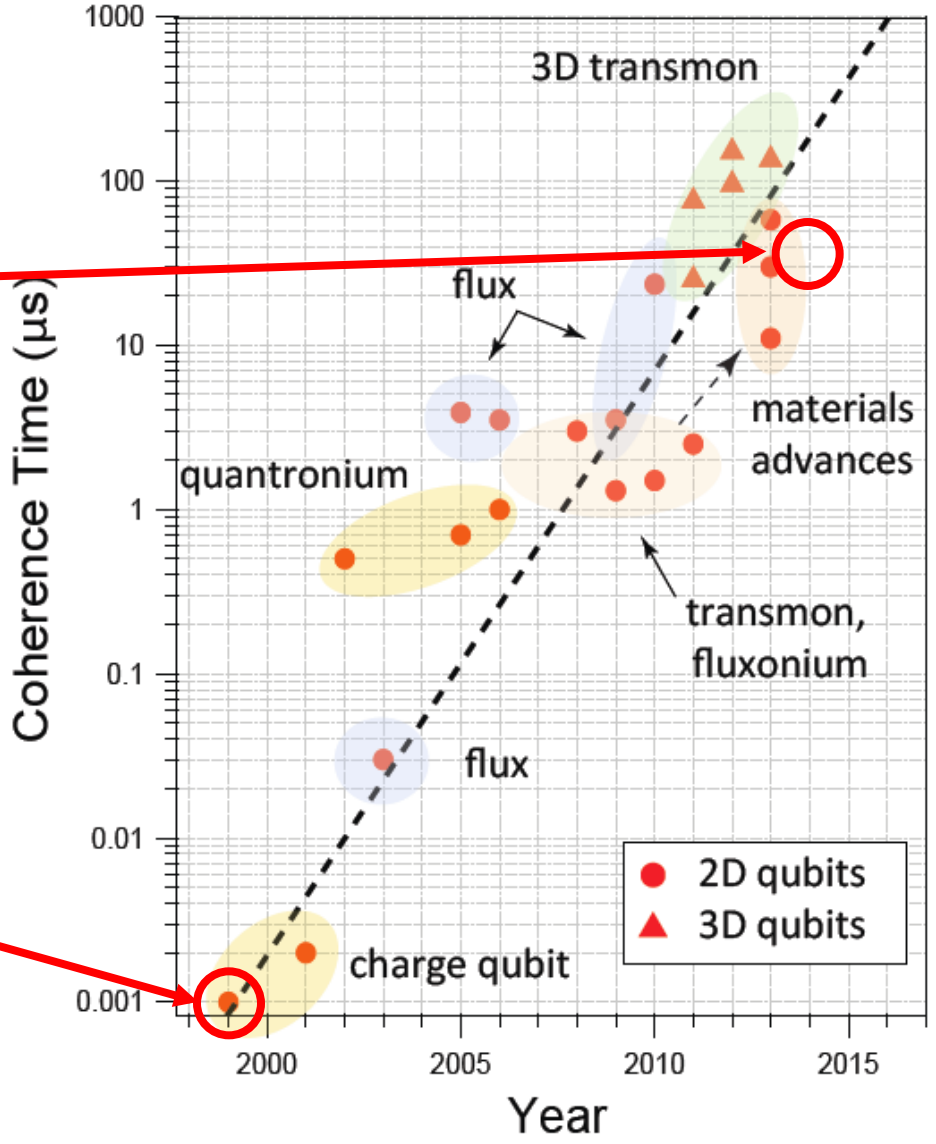
Superconducting quantum circuits



R. Barends et al. Nature **508,** 500 (2014).



Y. Nakamura et al. Nature **398,** 786 (1999).

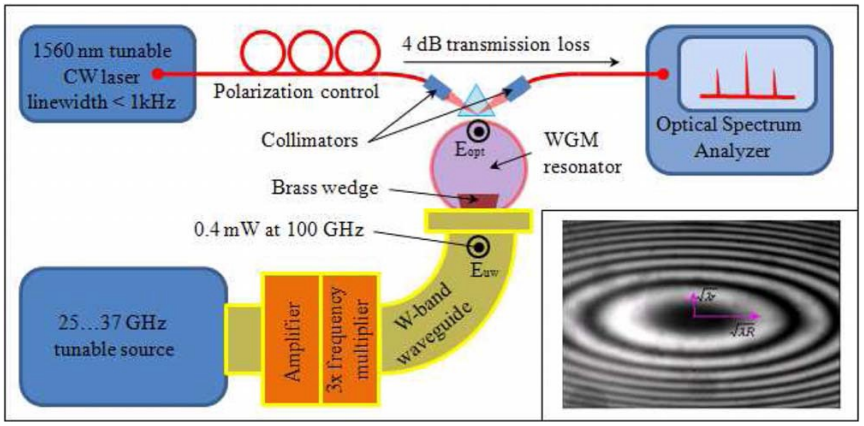


Courtesy of W. Oliver and P. Welander

Architecture

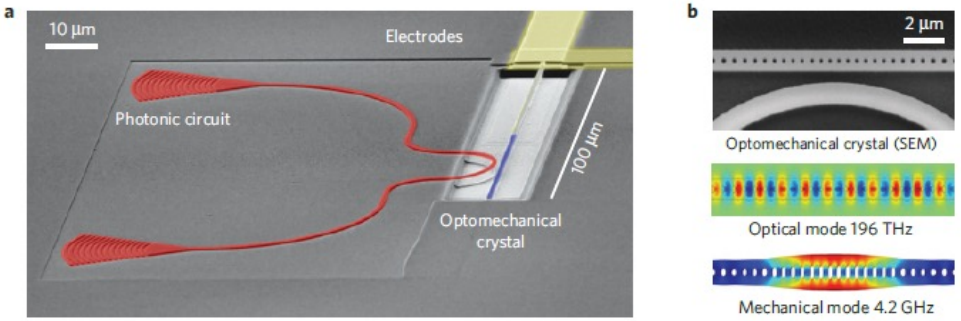
Candidates

Electro-optic modulators



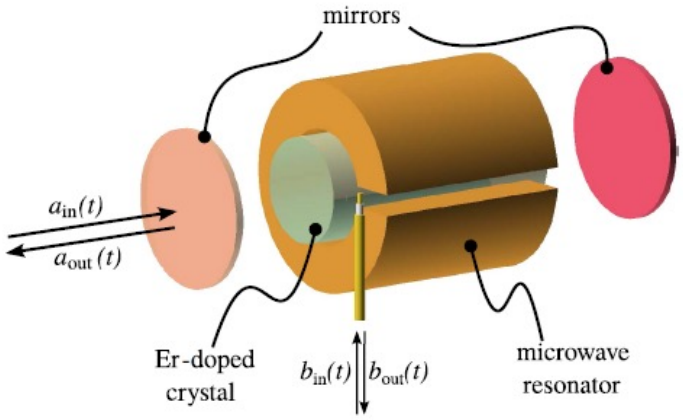
D.V. Strekalov *et al.,* Opt. Lett. **34,** 713 (2009)

Nano-mechanics

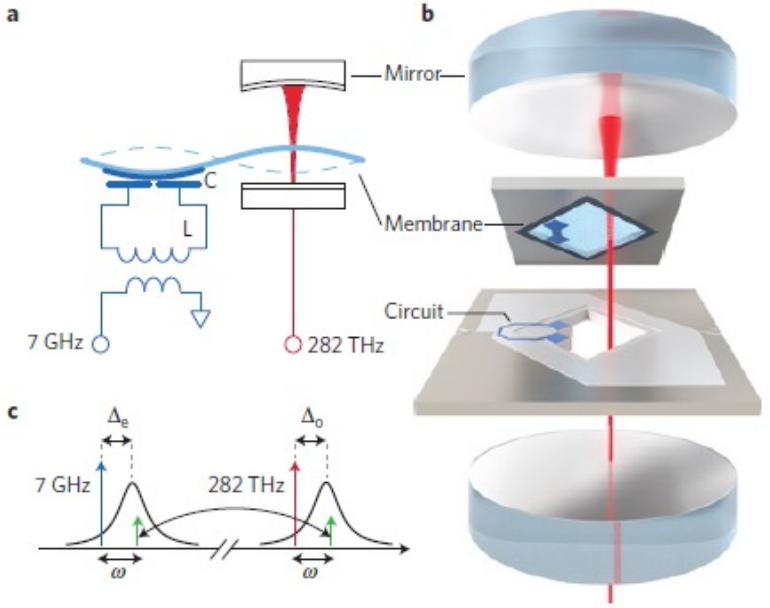


J. Bochmann *et al.,* Nature Phys. **9,** 712 (2013)

Magneto-optic modulators

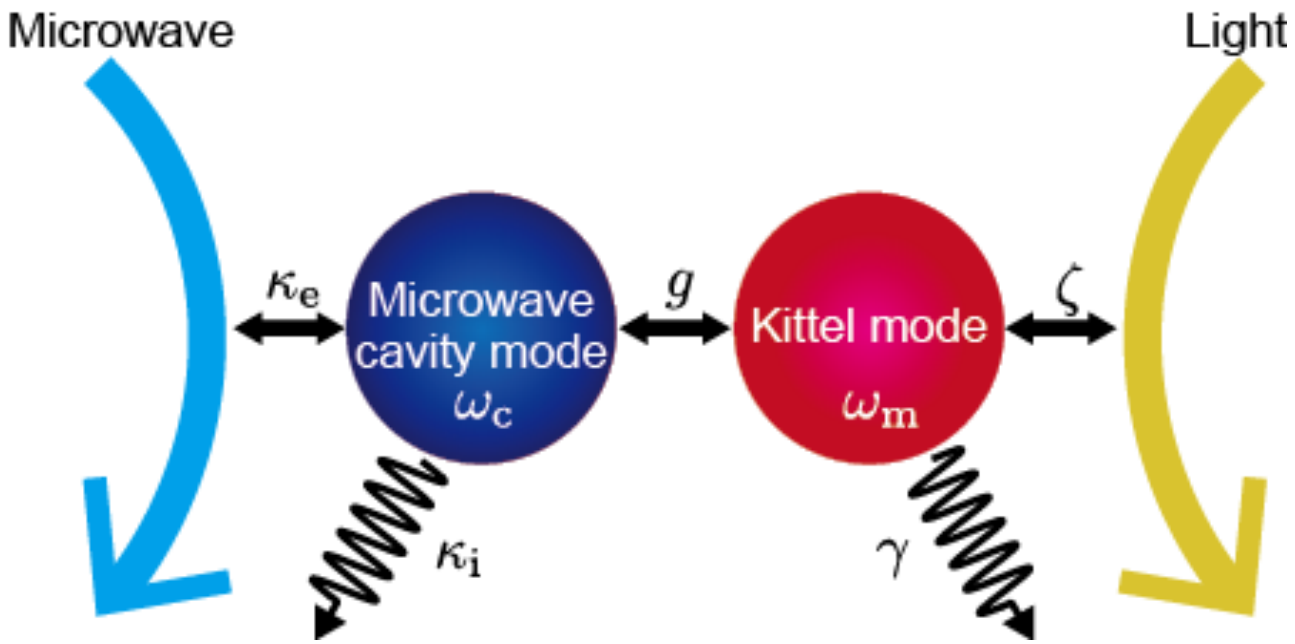


L.A. Williamson *et al.,* Phys. Rev. Lett. **113,** 203601 (2014)

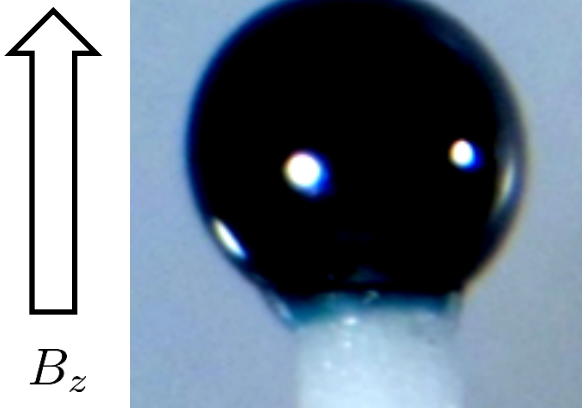


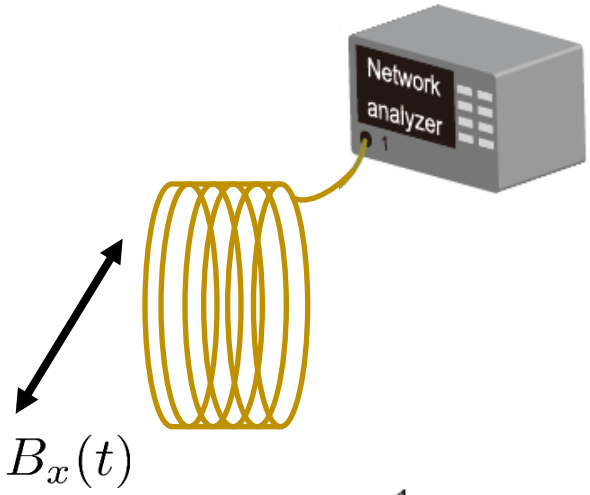
R. W. Andrews *et al.,* Nature Phys. **10,** 321 (2014)

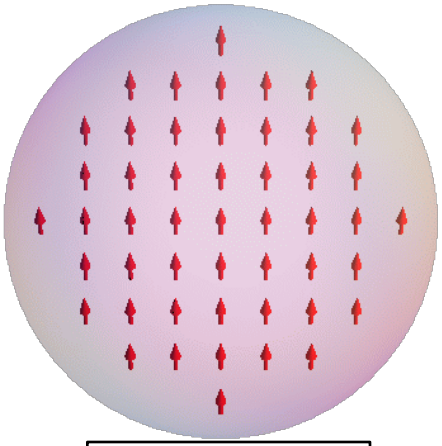
Magnon-based converter



YIG, Kittel mode, and FMR



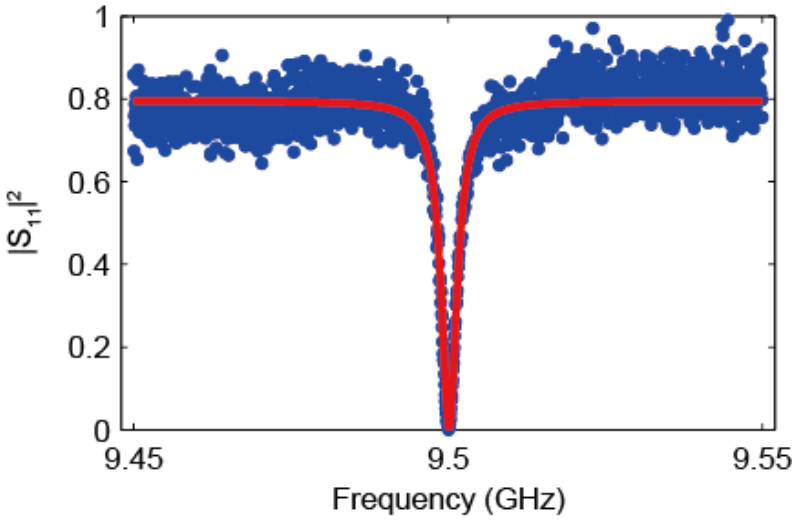




Kittel mode

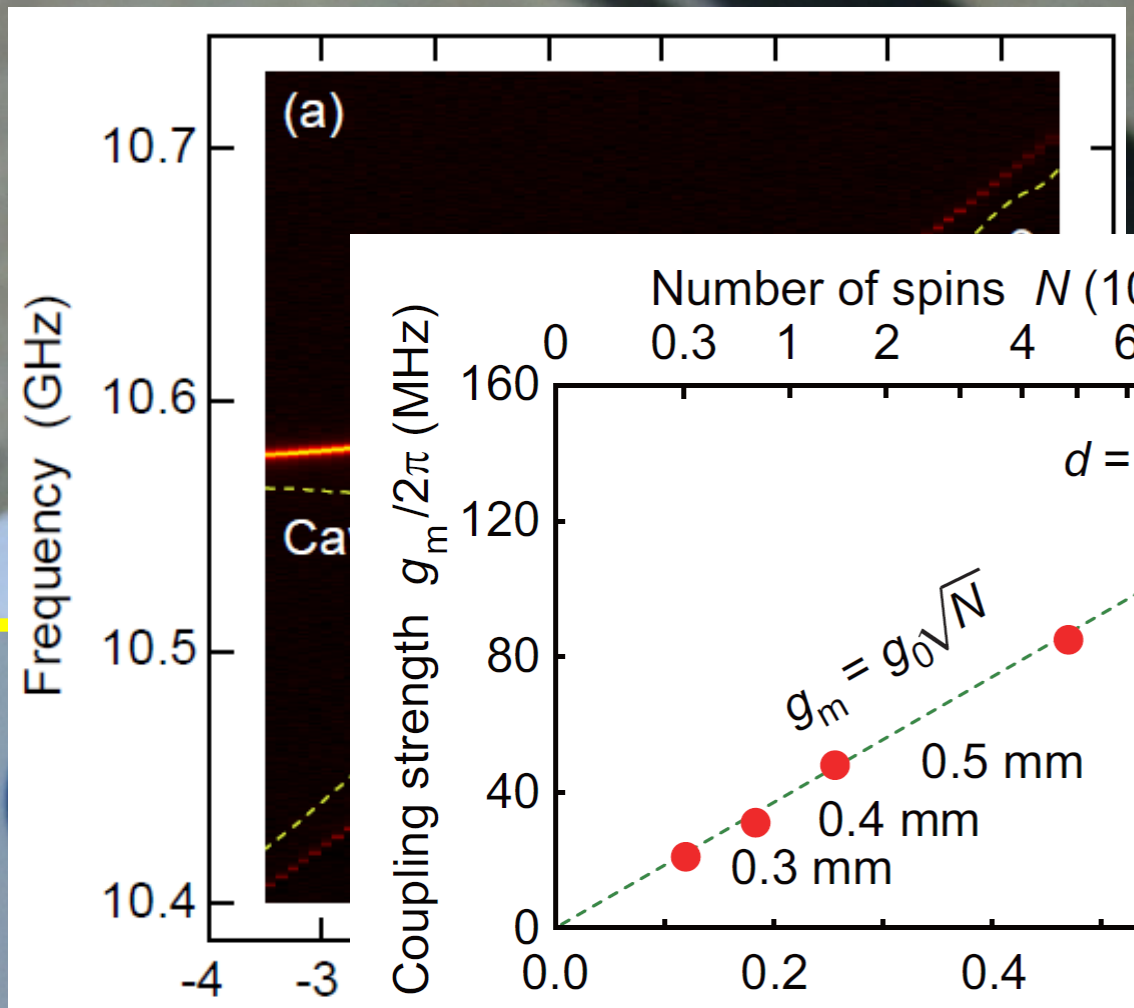
Yttrium Iron Garnet (YIG)

- Insulator
- High spin density: $2 \times 10^{22}\ \mathrm{cm}^{-3}$
- Large Verdet constant: $4.2\ \mathrm{radian/cm}$



Ferromagnetic resonance (FMR)

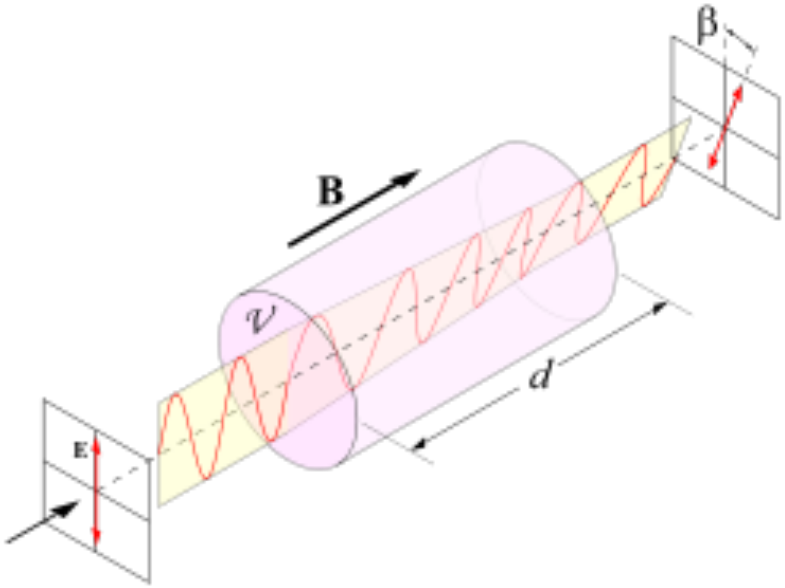
With microwave cavity



Y. Tabuchi *et al.,* Phys. Rev. Lett. **113,** 083603 (2014)

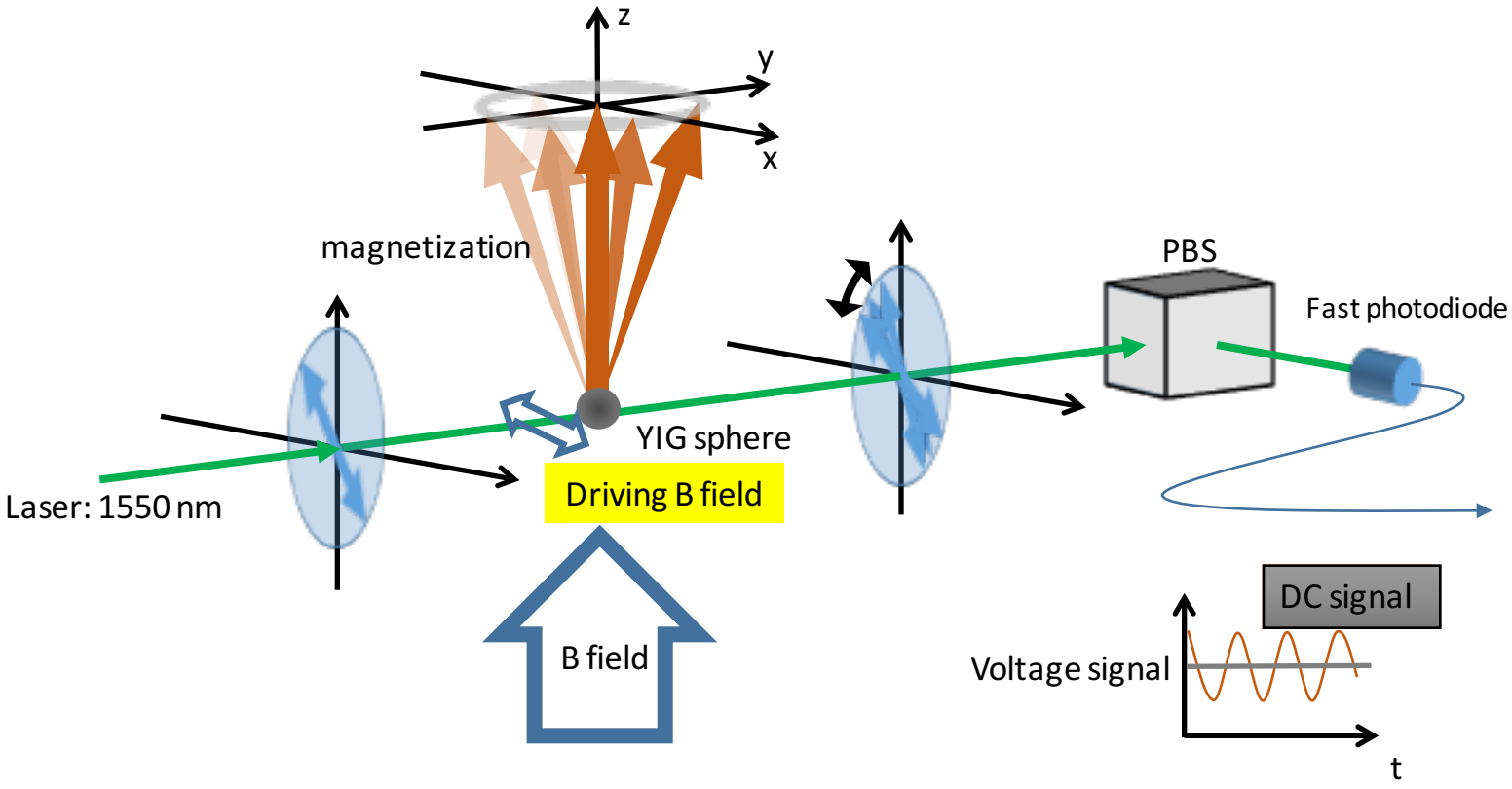
Magnon - light coupling

Michael Faraday

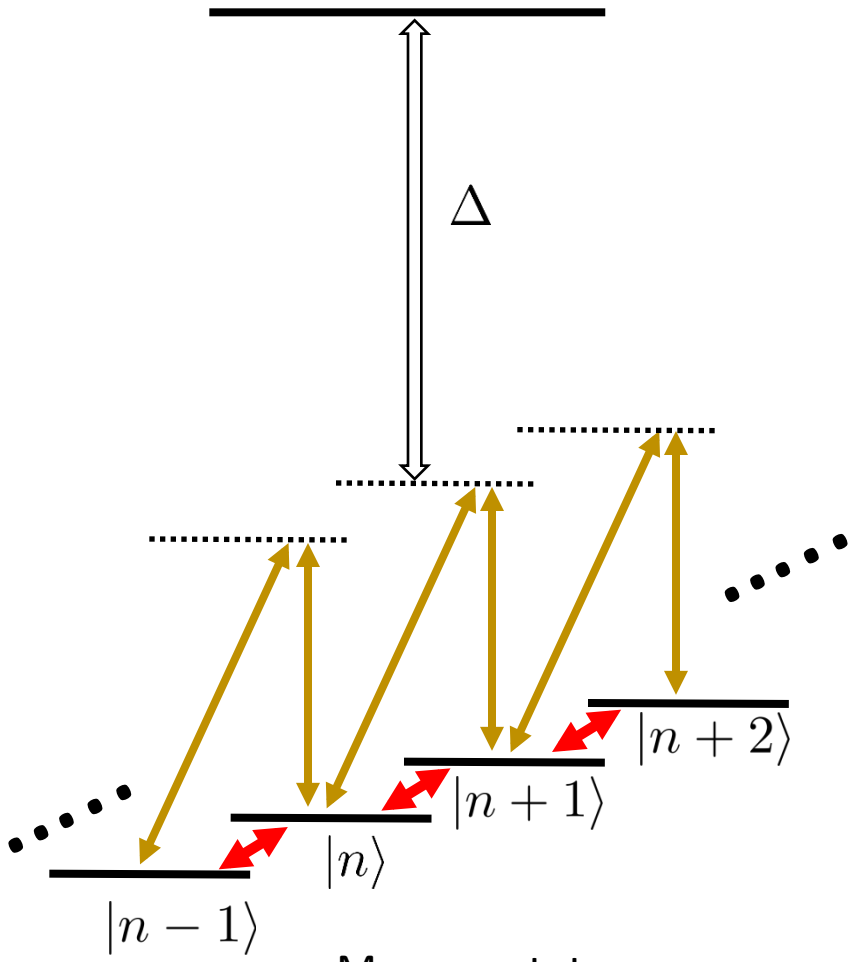


Faraday effect

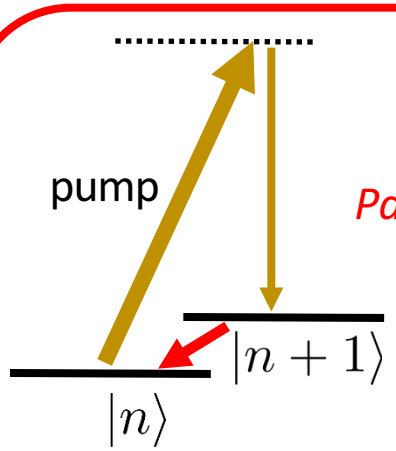
AC Faraday effect



Spin-Raman effect

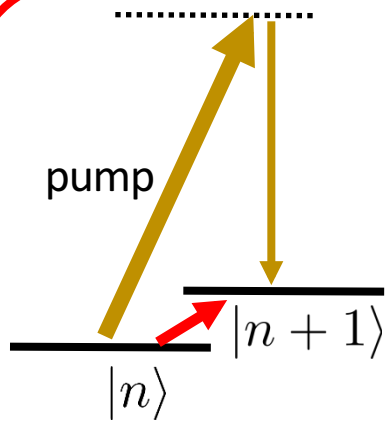


Magnon states



Parametric amplification :

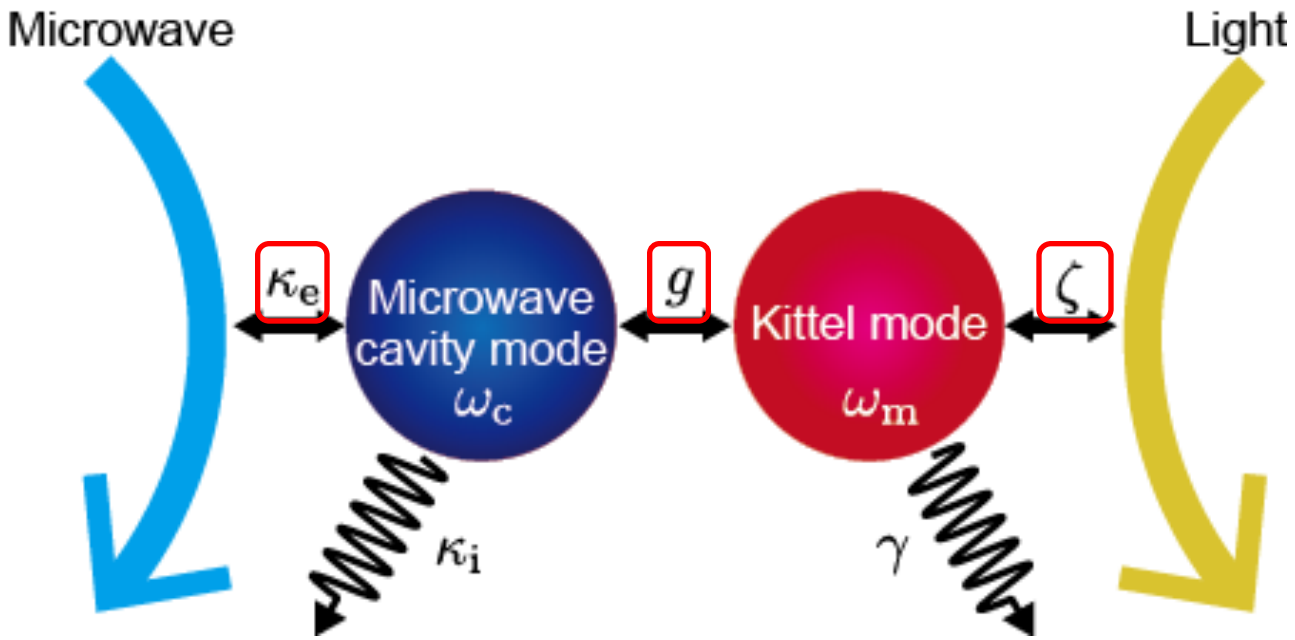
$$H_{PA} = -i\hbar\sqrt{\zeta}\int_{-\infty}^{\infty} d\omega \left(\hat{c}^{\dagger}\hat{b}_i(\omega)^{\dagger} - \hat{c}\hat{b}_i(\omega)\right)$$



Beam splitter :

$$H_{BS} = -i\hbar\sqrt{\zeta}\int_{-\infty}^{\infty} d\omega \left(\hat{c}^{\dagger}\hat{b}_i(\omega) - \hat{c}\hat{b}_i(\omega)^{\dagger}\right)$$

Converter architecture



Hamiltonian:

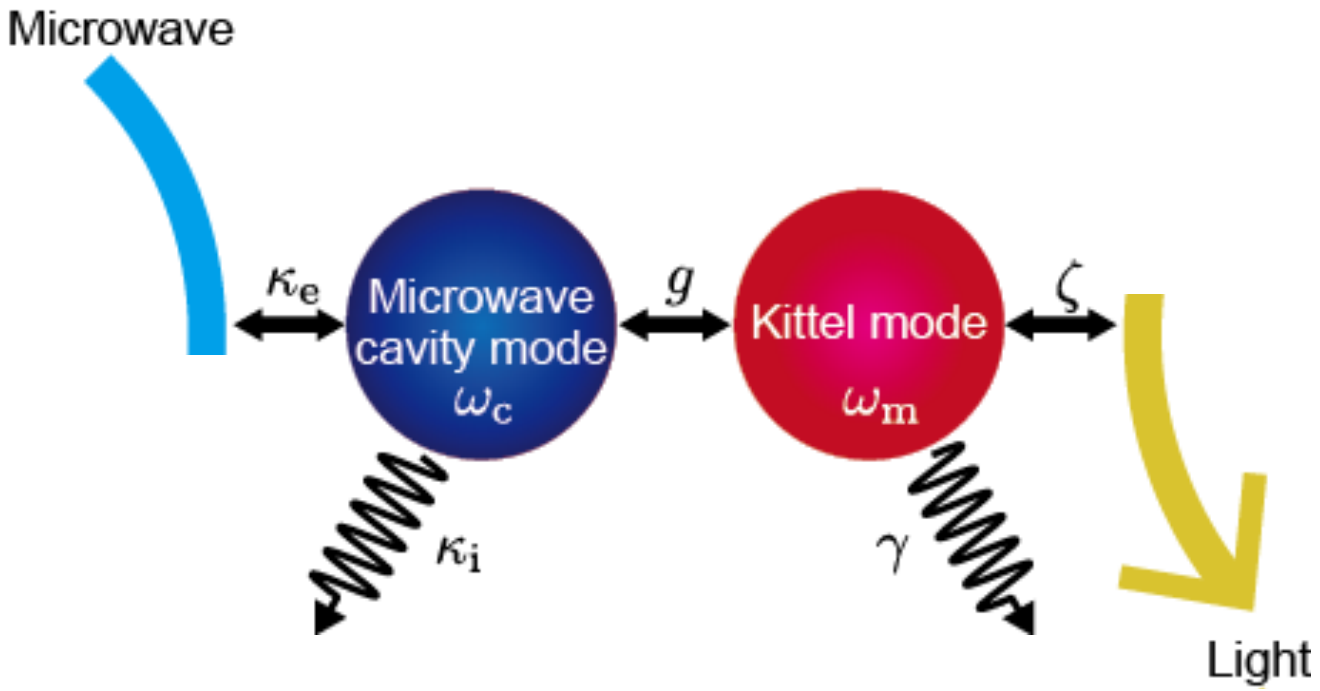
MW cavity Kittel mode

$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{c}^\dagger \hat{c} + \hbar g \left(\hat{a}^\dagger \hat{c} + \hat{c}^\dagger \hat{a}\right)$$ → MW cavity-magnon

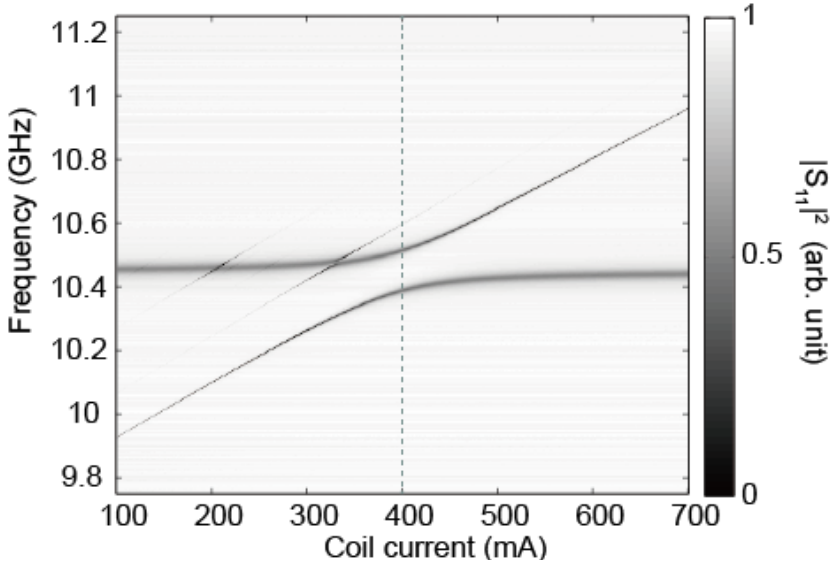
$$-i\hbar\sqrt{\kappa_e}\int_{-\infty}^{\infty}\left(\hat{a}^\dagger \hat{a}_i(\omega) - \hat{a}\hat{a}_i^\dagger(\omega)\right)$$ → itinerant MW – MW cavity

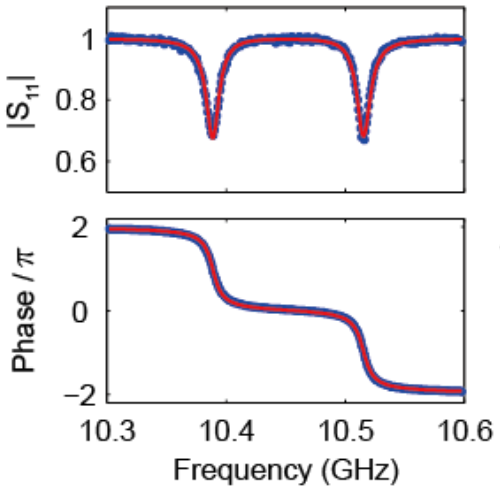
$$-i\hbar\sqrt{\zeta}\int_{-\infty}^{\infty}\left(\hat{c}^\dagger \hat{b}_i(\omega) - \hat{c}\hat{b}_i^\dagger(\omega)\right)$$ → magnon – itinerant light

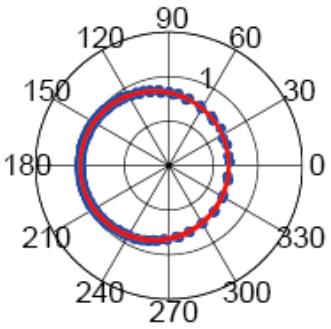
From microwave to light

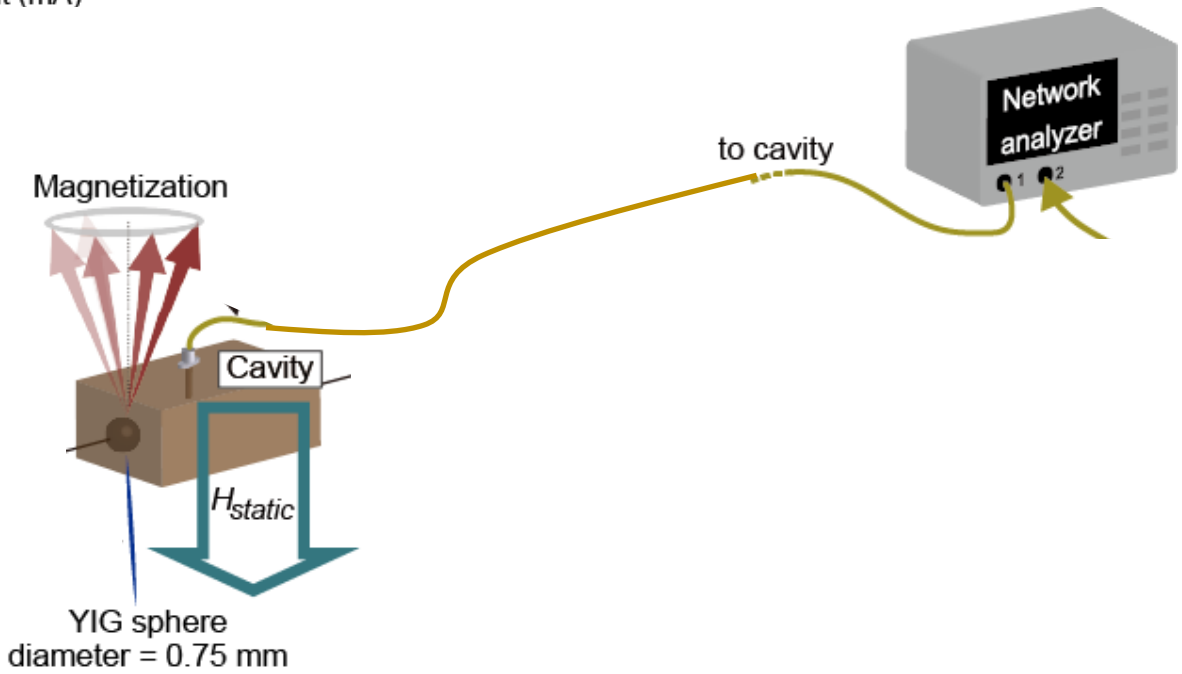


Coherent conversions

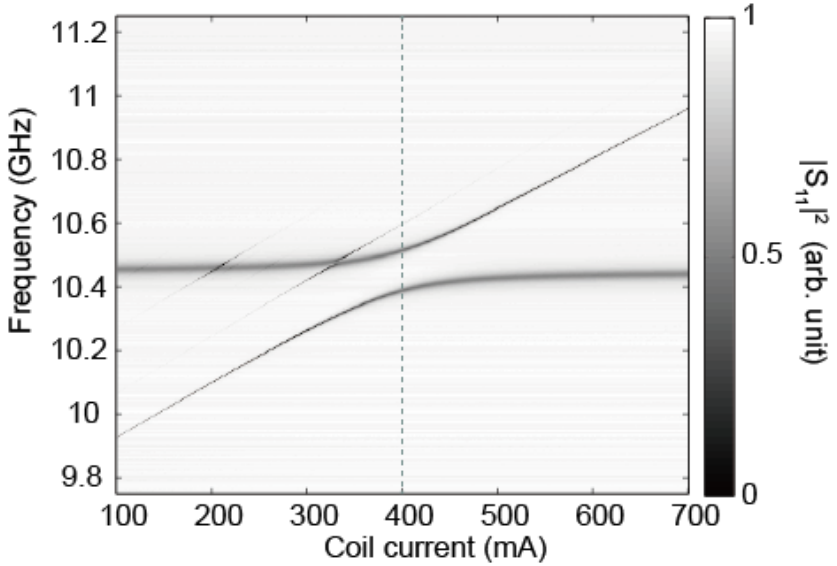


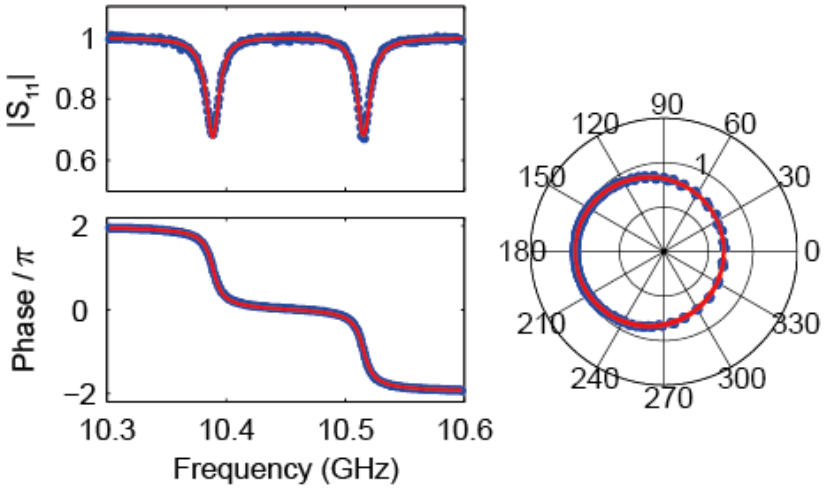


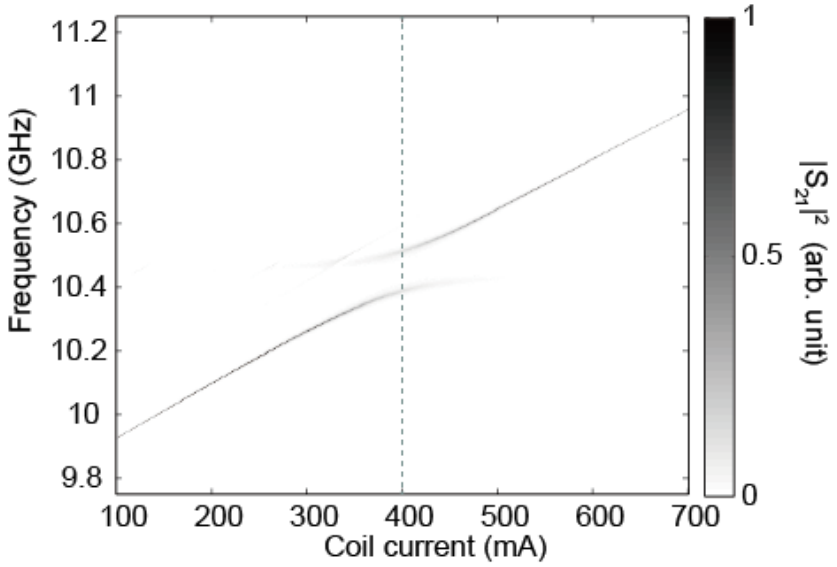




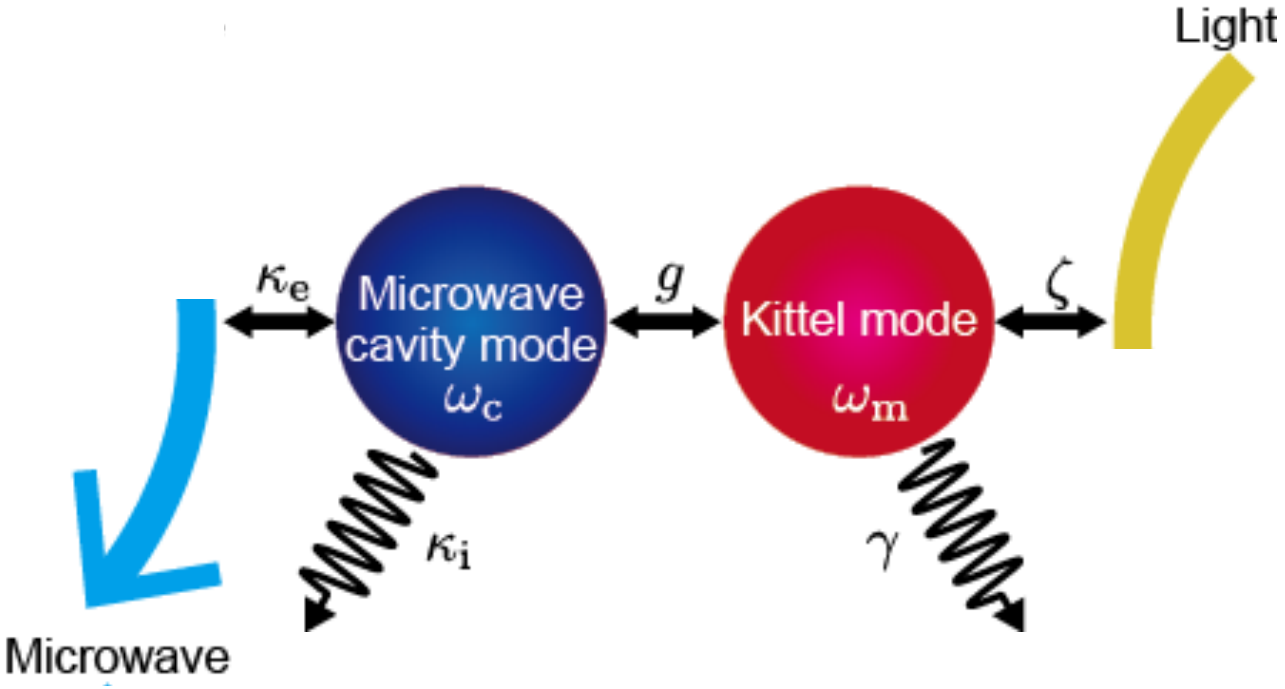
Coherent conversions



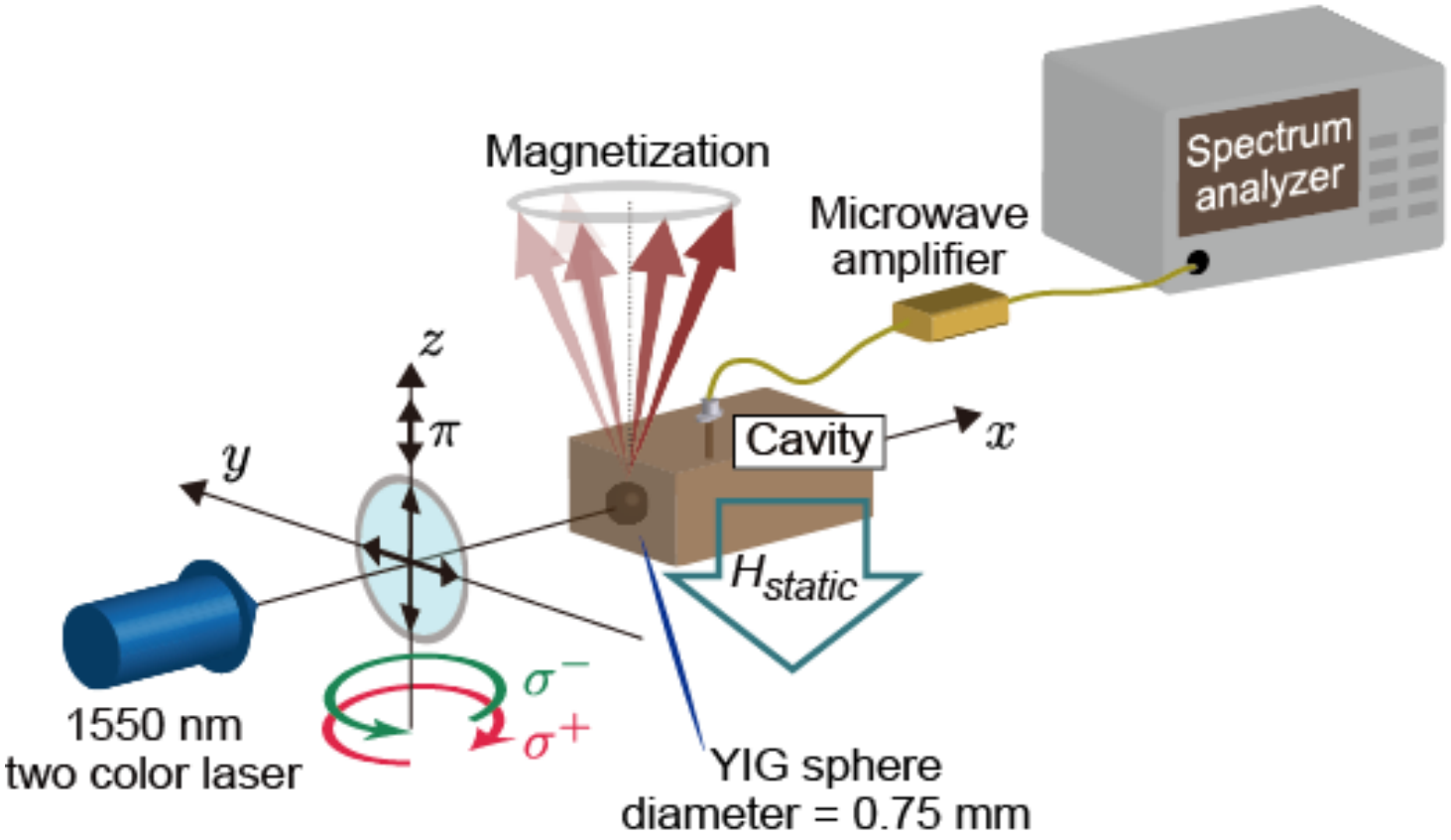




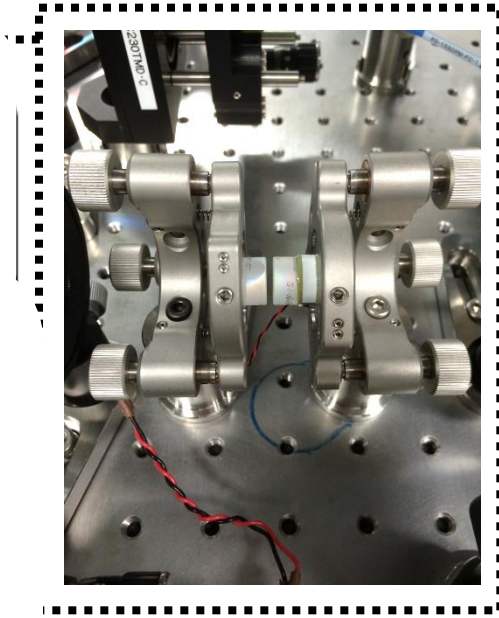
From light to microwave

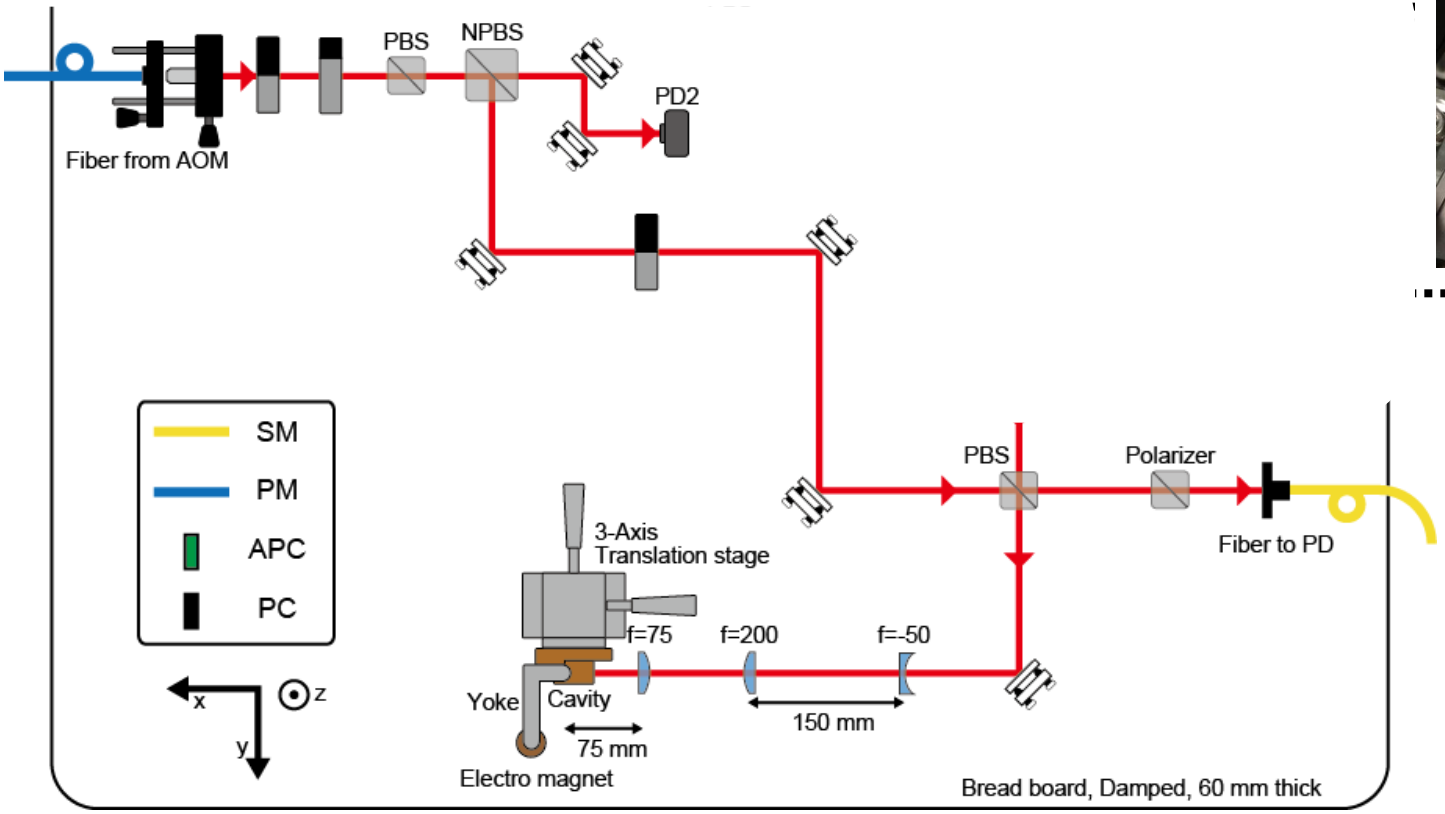


Experimental setup

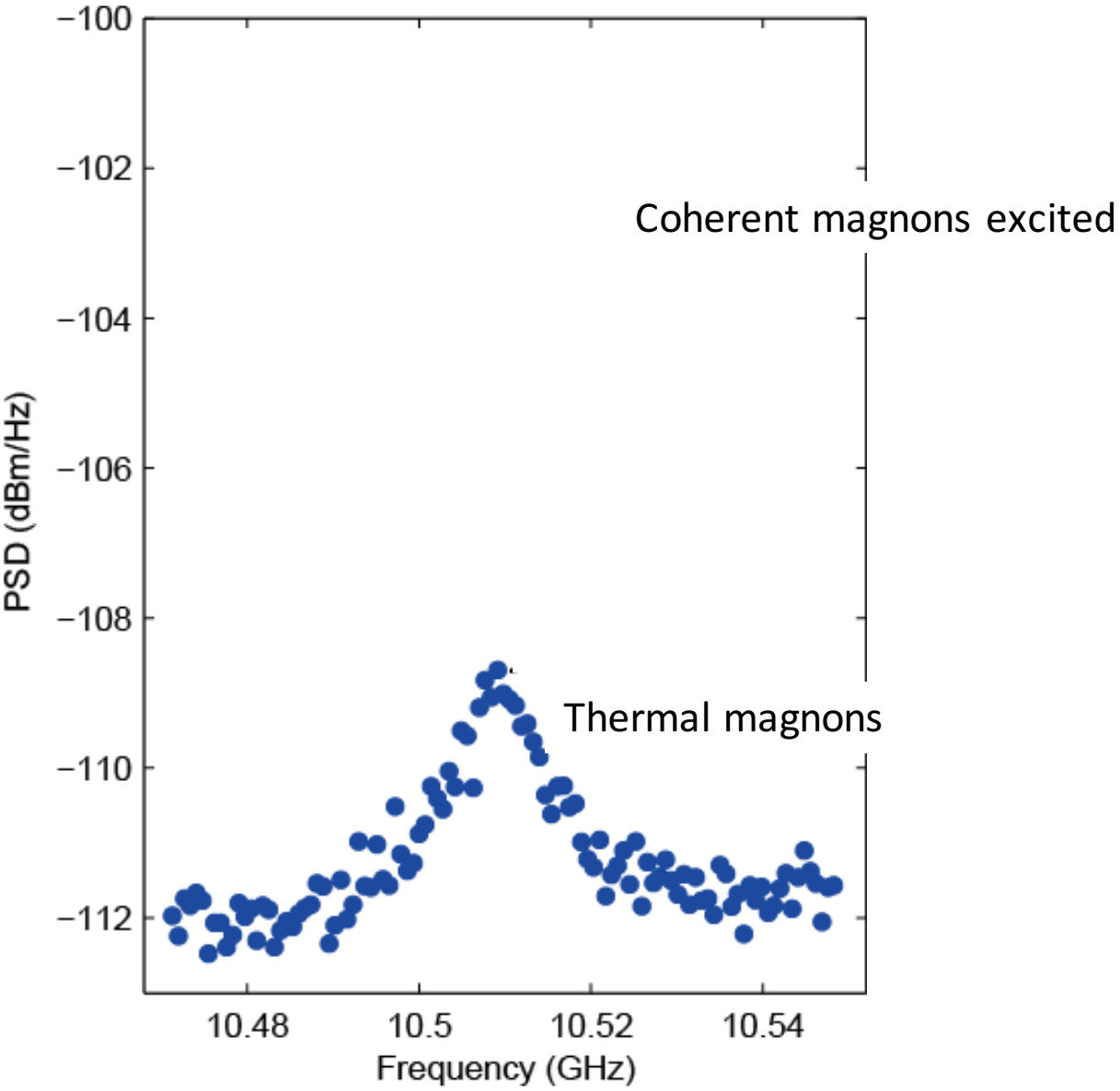


Experimental setup

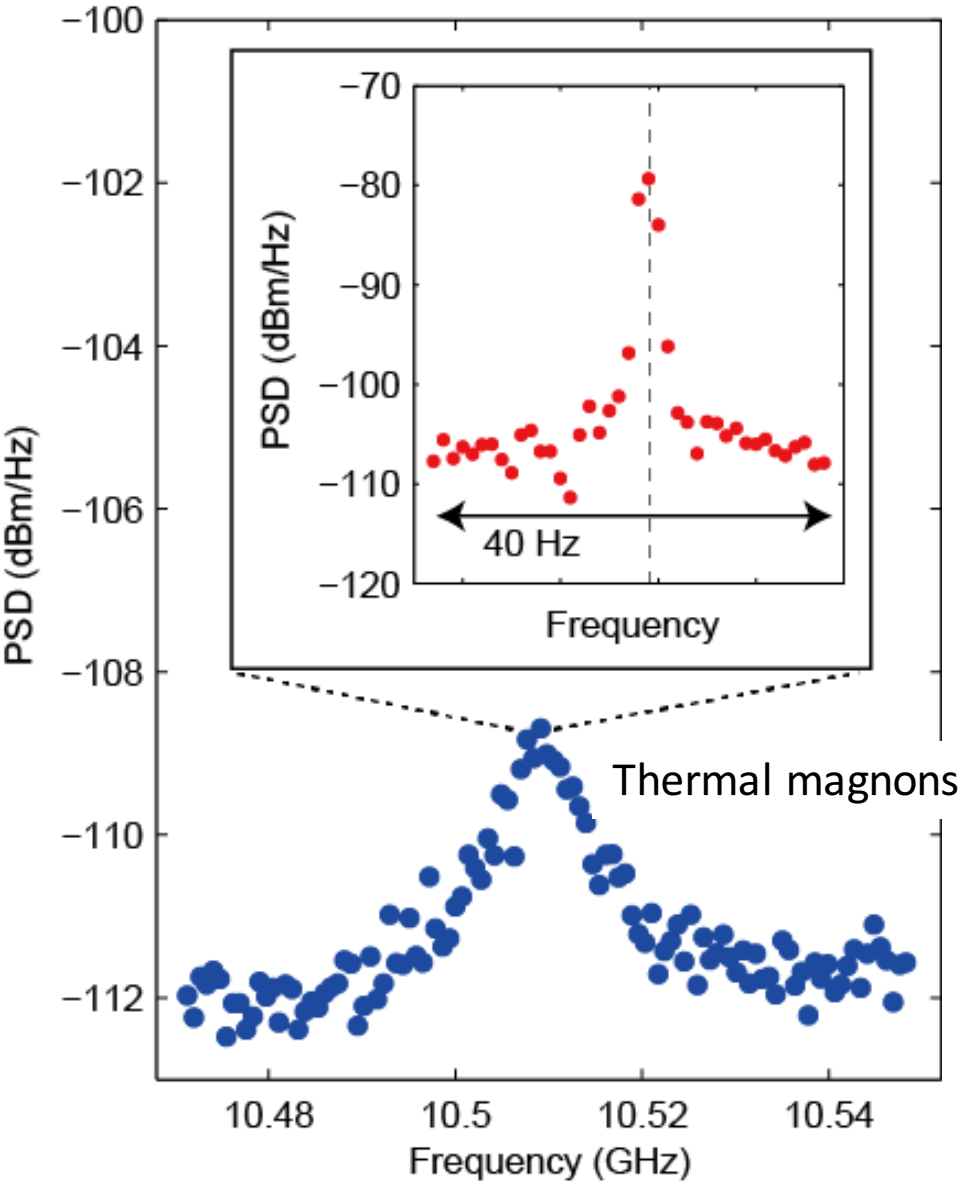


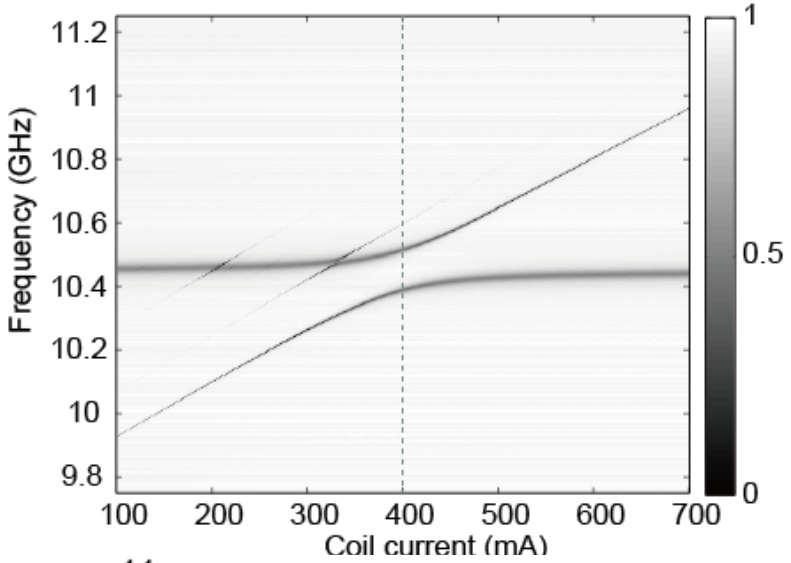


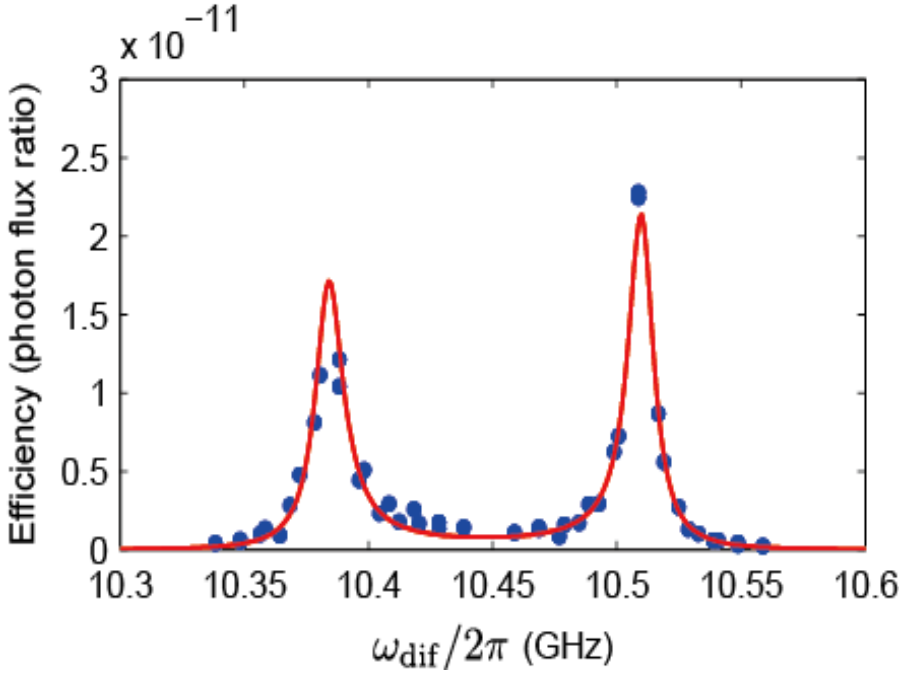
Coherent conversions



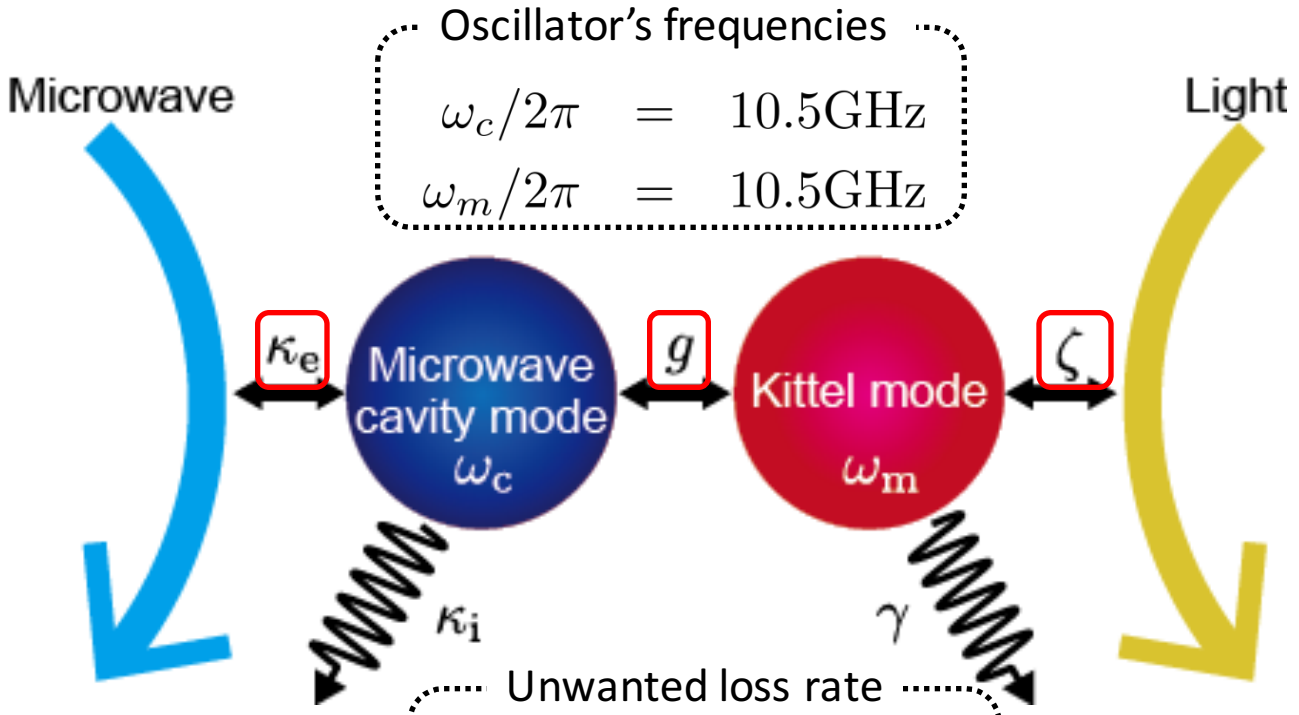
Coherent conversions







Converter performance



Important parameters

$\kappa_e/2\pi = 24.5\text{GHz}$

$g/2\pi = 63.4\text{GHz}$

$\zeta/2\pi = 0.4\text{mHz}$

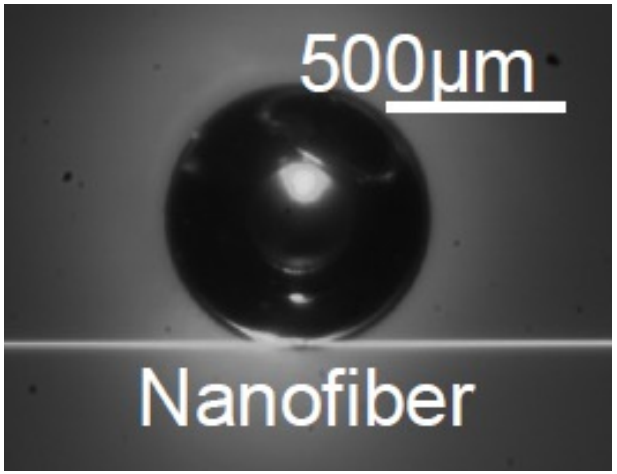
$$\mathcal{C} = \frac{4g^2}{(\kappa_e + \kappa_i)\,\gamma} > 1 \quad \Rightarrow \quad \eta \approx \frac{\kappa_e \zeta}{g^2}$$

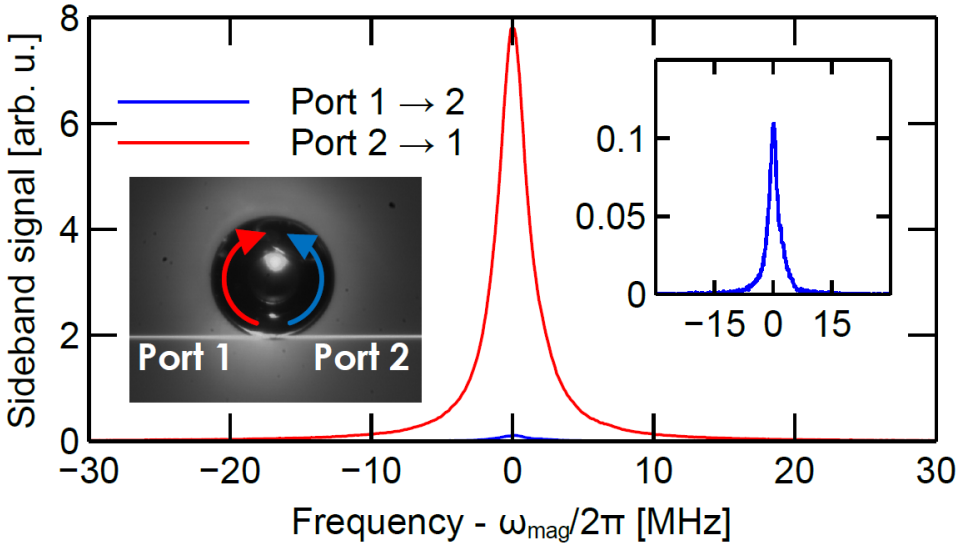
Conversion efficiency:

Prospect and summary

Prospects

Optical Cavity



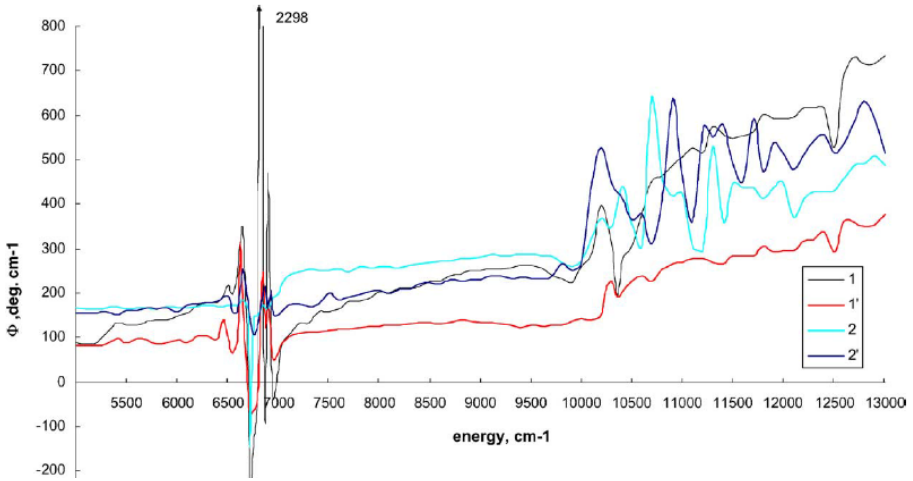


Spin-orbit coupled light + T-inversion broken spin

Poster by Alto Osada!

Other materials

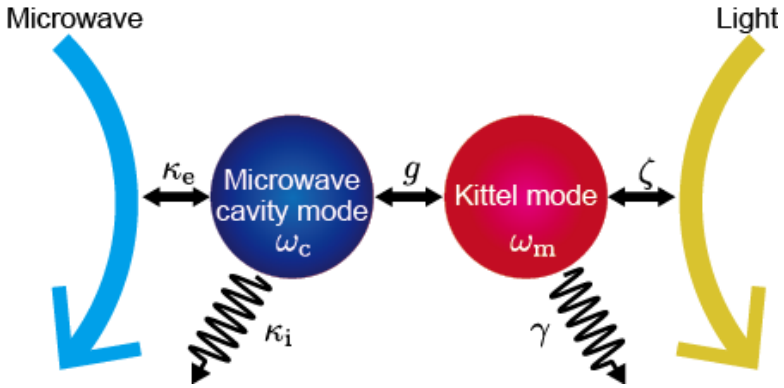
e.g.) Er - YIG



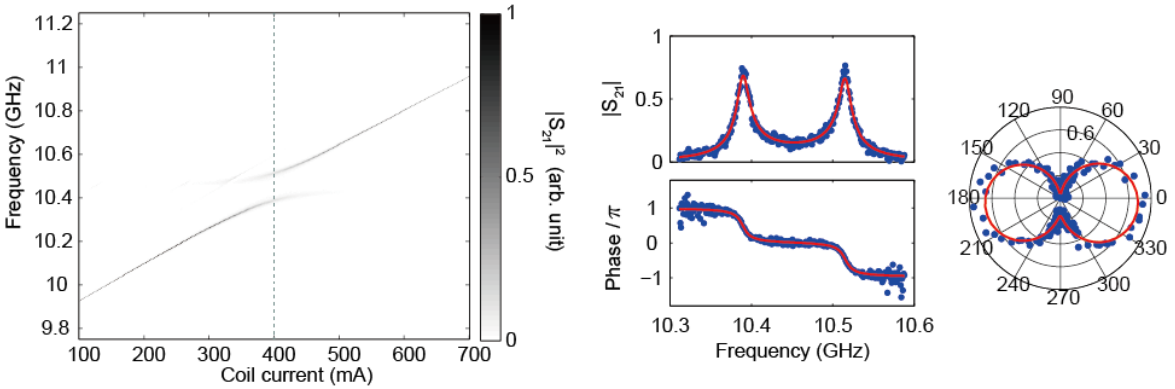
N.I.Tsidaeva, J.Alloy.Compd. **374,** 160 (2004)

Summary

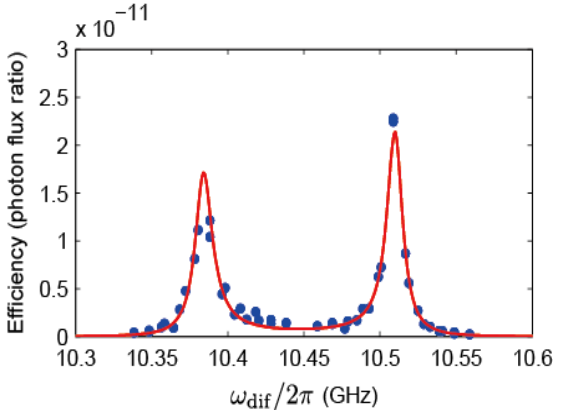
- Introducing magnon-based microwave-light converter



- Coherent conversion from microwave to light

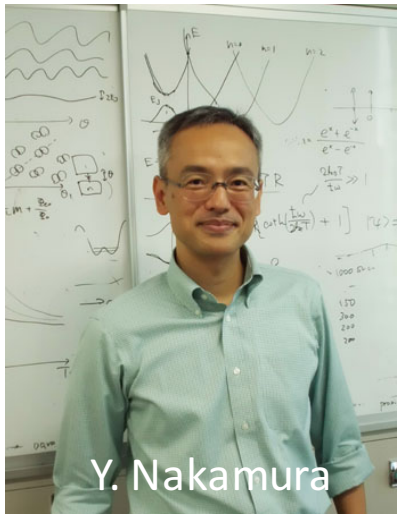


- Successful conversion from light to microwave



R. Hisatomi *et al.,* in preparation.

The team



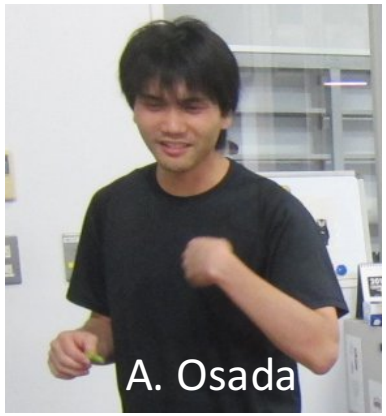
Superconducting Qubit

Microwave photon

ferro-magnets

Magnons

Poster PS26!



Optical photons