Interface magnons with superconducting quantum circuits

Magnon-polaritons from room temperature down to milliKelvin temperature

Martin P. Weides  
Johannes Gutenberg University Mainz, Germany  
and Karlsruhe Institute of Technology (KIT), Germany
Introduction

- Quantum Magnonics

- Superconducting quantum circuits
  - Multi-level spectroscopy, magnetic dipole qubit, high coherence

- Magnonics
  - Classical to quantum
Magnonics: spin waves in nanostructures

Magnon: quantized spin wave excitation

Future information technology
(e.g. spin-torque oscillator, spin-wave propagation control for logic)

Slavin et al., Nat. Nanotech. ’09
Linewidth $\Delta f > 1$ MHz

Vogt et al., Nat. Commun. ’14
Attenuation length $\sim 10$ um

Strong magnon damping: magnon/phonon/electron scattering

Grand challenge:
To understand physics, single magnon information needed!
Status quo

‘Classical measurement’:

- Inelastic scattering (neutron, photon, electron)
- Ferromagnetic resonance

Drawbacks:

- Weakly (not coherent) coupled
- Large flux, small signal (statistics)
- Thermally excited population ($T > 4\text{ K}$)

$$k_B T \gg \hbar \omega_m$$

Difficult to access magnon ground state!
How to probe a single magnon?

- Quantum ground state ($T=10$ mK) $\hbar \omega_m \gg k_B T$
- Ultra-low power spectroscopy, coherent coupling
- How to achieve?

Extend magnon to artificial spin!

\[ |\Psi\rangle = \alpha |\uparrow\rangle + \beta |\downarrow\rangle \]

Access magnon lifetime and coherence via coherent coupling
Coherent coupling requirement

\[ \hat{H} = \hbar \omega_m \hat{a}^{\dagger} \hat{a} + \hbar \omega_q \frac{\hat{\sigma}_z}{2} + \hbar g (\hat{a}^{\dagger} \hat{\sigma}^- + \hat{\sigma}^+ \hat{a}) \]

- **Magnon** \( \frac{1}{T_m} \) < 50 MHz
- **Qubit** \( \frac{1}{T_q} < 1 \text{ MHz} \)
- **Magnon** \( \frac{1}{T_m} \) Ni\(_{80}\)Fe\(_{20}\) < 50 MHz, Y\(_3\)Fe\(_5\)O\(_{12}\) < 5 MHz

Coupling rate \( g \) (\( N \) number of spins in qubit mode volume \( V_0 \))

\[ \frac{g}{2\pi} = \frac{\gamma_e}{2\pi} \sqrt{N} \sqrt{\frac{\mu_0 \hbar \omega_c}{V_0}} > 10 \text{ MHz} \quad \text{(strong coupling)} \]
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**Transmons:** capacitively shunted Josephson junction

→ **Anharmonic oscillator**

\[ L_J(\phi) \propto \frac{1}{I_c \cos \phi} \]

Non-linear, tunable LC oscillator

Magnetic flux \( \Phi \) changes \( L_J(\phi) \)

\[ \omega_{10}(\Phi) = \frac{1}{\sqrt{L_J(\Phi)C}} \]

Two lowest levels \( \rightarrow \) **Bloch sphere**

\[ |\Psi\rangle = \alpha |\uparrow\rangle + \beta |\downarrow\rangle \]
Al, Nb, NbN films
Al-AlO₅-Al tunnel junctions (shadow evaporated)
Lithography, etching (Nanostructure Service Laboratory)

He³/He⁴ dilution fridge (40cm base plate)
18 RF & 24 DC lines, filters, 5 amps
9 quantum chips

Spectroscopy, time-domain setups
Software (simulation, measurement)
QKIT on GitHub
Anharmonic many-level quantum circuit

\[ |\Psi\rangle = \alpha |0\rangle + \beta |1\rangle \]

transmon qubit: weak anharmonicity

Consider higher quantum levels

- efficient & robust quantum gates
- enhanced security of key distribution in quantum cryptography
- quantum simulation

spin-\(\frac{1}{2}\) ↔ two levels
spin-1 ↔ three levels

Fedorov Nat. 481 (2011)  
Bruß PRL 88 (2002)  
Cerf PRL 88 (2002)  
Paraoanu JLTP 175 (2014)
Qubit sample

- microstrip geometry
  - overlap Josephson junction
  - transmon regime: $E_J \gg E_C \Rightarrow \alpha_r \sim 0.05$
- spectroscopic measurements
  - VNA readout tone
  - microwave drive/probe tone

\[
\hat{H} = \hbar \sum_j \omega_j |j\rangle \langle j| + \hbar \omega_r \hat{a}^\dagger \hat{a} + \hbar \sum_{i,j} g_{ij} |i\rangle \langle j| (\hat{a}^\dagger + \hat{a})
\]

Sandberg APL 102 (2013)

Koch PRA 76 (2007)

Blais PRA 69 (2004)
High power spectroscopy

Multi-photon transitions $\frac{1}{j} (|0\rangle \leftrightarrow |j\rangle)$

determine qubit parameter $E_J, E_C$

Koch et al. PRA 2007

Braumüller et al., PRB 2015
Multiphoton dressing – pumping the $|2\rangle$-level

Sweep drive & probe freqs.

\[ \frac{\omega_{3}^{rf}}{2\pi} = (-)330 \text{ MHz} \quad (i) \]
\[ \frac{\omega_{1}^{rf}}{2\pi} = 104 \text{ MHz} \quad (ii) \]

Dynamical coupling of levels by probe tone $\rightarrow$
Autler-Townes doublet like avoided crossing

Braumüller et al., PRB 2015
Transmon qubit

\[ \hat{H} = 4E_C (\hat{n} - n_g)^2 - E_J \cos \hat{\phi} \]

- Operation in phase regime, \( E_J \gg E_C \)

Koch, PRA 76 (2007)

pad geometry → dipole antenna

concentric geometry → reduced radiation/crosstalk

Sandberg, MW, APL 102 (2013)
Geometry of concentric, gradiometric transmon

- Central island and concentric ring electrode, interconnected by two Josephson junctions, $E_J/E_C \sim 120$
- Gradiometric dc-SQUID loop $\rightarrow$ fast frequency control
- Dispersive qubit readout
Main features

- Hybrid coplanar/microstrip design
  - Minimize defect loss at surface and interface oxides

- Straightforward fabrication:
  - Optical lift-off lithography
  - Electron beam lithography, shadow-angle evaporation
Pulsed (time-domain) measurement setup

- **qubit manipulation**
  - DAC
  - I
  - Q
  - LO
  - RF
- **readout**
  - ADC
  - I
  - Q
  - LO

- **300 K**
  - -16 dB
  - DAC
  - 3.4 GHz
- **4 K**
  - -20 dB
  - -10 dB
  - LO
- **0.3 K**
  - -20 dB
  - -20 dB
  - DAC
- **20 mK**
  - -20 dB
  - -20 dB
  - DAC
  - AC
  - sample

**Rabi**

\[ T_1 \]

- \[ (\pi)^x \]
- \[ \Delta t \]
- \[ (\pi)^x \]

**Ramsey**

- \[ \left( \frac{\pi}{2} \right)^x \]
- \[ \Delta t \]
- \[ \left( \frac{\pi}{2} \right)^x \]

**Hahn echo**

- \[ \left( \frac{\pi}{2} \right)^x \]
- \[ \Delta t/2 \]
- \[ (\pi)^x \]
- \[ \Delta t/2 \]
- \[ (\pi)^x \]
Dissipative dynamics

\[ T_1 = 9.1 \mu s \]
\[ T_2 = 10 \mu s \]

\[ \langle \hat{\sigma}_z \rangle \]

\[ \Delta t (\mu s) \]

\[ \Gamma \]

\[ \Gamma^{-1} = 16 \mu s \]
\[ \Gamma^{-1} = 26 \mu s \]
\[ \Gamma^{-1} > 100 \mu s \]

\[ \Rightarrow \Gamma^{-1} = 9 \mu s \]
Qubit coherence – Hahn echo sequence

\[ T_1 = 9.1 \mu s \]

\[ T_2 = 10 \mu s \]

\[ T_2^* = 2.2 \mu s \]
Pulsed measurements – fast control of qubit frequency

\[ \left( \frac{\pi}{2} \right)^x \]

\[ R^z_\varphi \]

\[ \left( \frac{\pi}{2} \right)^x \]

\[ \langle \hat{\sigma}_z \rangle \]

1/65 MHz

\[ \Delta t \text{ (ns)} \]

\[ |0\rangle \quad \rightarrow \quad |0\rangle \]

\[ |0\rangle \quad \rightarrow \quad |1\rangle \]

\[ |0\rangle \quad \rightarrow \quad |0\rangle \]

\[ |0\rangle \quad \rightarrow \quad |1\rangle \]

Braumüller et al., APL (2016)
Fast qubit tuning \rightarrow Full tomographic control

SSB-mixing, shaped
\rightarrow Gate benchmarking
Consider geometric loop inductance

Artificial spin array with non-trivial couplings

→ (analog) spin system simulation

- Good agreement for $L_g = 0.6\text{nH}$

Reiner, Marthaler, Braumüller, MW, et al.
arXiv 1602.05600 (2016)
Quantum SWAP (Qubit-Resonator)

1. Excite qubit off-resonance to resonator
2. Bring on-resonance and hold for $\Delta t$
3. Detune qubit and readout

$\rightarrow$ Quantum-Setup works! DC & RF electronics, pulse shaping, bias tee, software...
$\rightarrow$ Controlled quantum SWAPs (qubit-HO)
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Magnonics
- Classical to quantum
Yttrium iron garnet ($\text{Y}_3\text{Fe}_5\text{O}_{12}$)

- Electrically insulating ferrimagnet
- Empty 4s, half filled 3d orbitals $\rightarrow$ no orbital momentum, $s=5/2$
- Five Fe$^{3+}$ ions per unit cell form sublattices of opposing magnetization $\rightarrow$ approximated as ferromagnet
- Extremely low spin-wave damping spin wave decay length on the order of centimeters
- $T_{\text{Curie}} = 559\text{K}$
- High spin density $\rho = 4.22 \cdot 10^{27} \text{ 1/m}^3$
- Anisotropic, [110]-axis is soft magnetic
Magnons

Quasiparticles, collective excitation of the electrons' spin structure in crystal lattice

Outer magnetic field $H$ removes degeneracy

\[ \mathcal{H} = -\frac{1}{2} J \sum_{i,j} S_i \cdot S_j - g \mu_B \sum_i H \cdot S_i \]

Precessional motion of magnetization $M$, Landau–Lifshitz eq.

\[ \frac{dM}{dt} = -\gamma M \times H_{\text{eff}} - \lambda M \times (M \times H_{\text{eff}}) \]

$k=0 \rightarrow$ precessing macrospin with Kittel resonance frequency

\[ f = \frac{\gamma}{2\pi} B \]
Spin waves affect static and dynamic magnetization

**Spin wave**: spin-lattice excitation in magnetically ordered material
Harmonic variation ([wavelength](#) \( \lambda \)) in phase of precession of adjacent spins about the local magnetization direction (parallel to magnetic field \( B \))

**Single magnon** = \( \pi \) flip (i.e. 180° rotation) of a single spin
Saturation magnetization \( M_S \)

Change in static magnetization: \( \Delta M_Z = M_S(1 - \cos \theta) \)
\( \theta \) notional precessional angle of spins about magnetization direction

AC magnetization perturbation (vector rotating at magnon frequency \( \omega \))
\( \Delta M_{AC} = M_S \sin \theta \) in-plane perpendicular to \( \Delta M_Z \).

For small \( \theta \):
- Reduction in static magnetization \( \Delta M_Z \approx M_S \theta^2/2 \)
- Increase in dynamic magnetization \( \Delta M_{AC} = M_S \theta \)
Magnon-Cavity experiments (incomplete...)  
Since 2014 rapid growth of publications

- Tabuchi et al. PRL 2014  
  *Hybridizing Ferromagnetic Magnons and Microwave Photons in the Quantum Limit*

- Zhang et al. PRL 2014  
  *Strongly Coupled Magnons and Cavity Microwave Photons*

- Goryachev et al. PR Applied 2014  
  *High-Cooperativity Cavity QED with Magnons at Microwave Frequencies*

- Cao et al. PRB 2015  
  *Exchange magnon-polaritons in microwave cavities*

- Zhang et al. NPJ 2015  
  *Cavity quantum electrodynamics with ferromagnetic magnons in a small yttrium-iron-garnet sphere*

- Tabuchi et al. Science 2015  
  *Coherent coupling between a ferromagnetic magnon and a superconducting qubit*

- Bourhill et al. arXiv 2016  
  *Ultra-High Cooperativity Interactions between Magnons and Resonant Photons in a YIG sphere*
3d cavity resonator

Magnetic field distribution

1\textsuperscript{st} mode

2\textsuperscript{nd} mode

YIG sphere

Marcel Langer BA thesis KIT (2015)
3d cavity-Kittel mode (YIG) → strong coupling

Two setups
(classical and quantum)

- 4 to 300 K
- Up to Tesla-fields
- Extend to thin films

- Few/ single magnon excitations (mK)
- Linewidth and noise
- Extend to qubit
Temperature dependence down to 5K

Reducing temperature
- Coupling strength $g$ increases
- Resonant magnetic field decreases

Reentrant cavity, see Goryachev et al. PR Applied 2014
Approaching quantum: magnon-polaritons at 500mK

Extraction from fit

$\kappa_{in} = 65$ kHz
$\kappa_{m} = 2.4$ MHz
$\kappa_{r} = 0.9$ MHz
$g = 27.8$ MHz

Non-uniform modes visible
Coupling qubit to magnon

resonator  magnonic medium
\[ \omega_r \] \[ \omega_m \]

+ qubit readout resonator (not shown)

Straightforward:
coupling via 3d cavity (modes for coupling, Q-readout)

Tabuchi et al., Science 2015
Transmon qubit coupled to 3d cavity

3d cavity: quantized field suppresses radiative loss
low $E$-fields and weak coupling to surface TLSs

→ Long coherence $T_1 \approx 15 \, \mu s$, $T_2 \approx 16 \, \mu s$, $T_2^* \approx 30 \, \mu s$
Hybrid quantum systems

- Magnon-polaritons from RT → 0.5K
- YIG sphere and thin films
- Spectroscopy and pulsed measurement setup ready

Dry 10mK fridge (July `16)
QKIT framework - an extension to qtlab written in python

Open-source measurement software QKIT [https://github.com/qkitgroup/qkit](https://github.com/qkitgroup/qkit)

- Collection of ipython notebooks for measurement and data analysis
- hdf5 based data storage of 1,2 and 3d data
- 1 and 2d data viewer
- Extended and maintained drivers for low and high frequency electronics
- Large parts of the framework can be used independently of qtlab
- Classes for data fitting, e.g. of microwave resonator data. This includes also a robust circle fit algorithm (Probst et al. Rev. Sci. Instrum. 86, 024706 (2015))
Team

BA
Oliver Hahn
Moritz Kappeler
Tomislav Piskor

MA
Julius Krause
Lukas Grünhaupt
Yannick Schön
Patrick Winkel
Max Zanner

PhD
Jochen Braumüller
Marco Pfirrmann
Steffen Schlör
Andre Schneider
Ping Yang

Technician
Lucas Radtke

Scientists
Hannes Rotzinger
Sasha Lukashenko
Alexey Ustinov

@JGU Mainz
Isabelle Boventer
Mathias Kläui

- 10+μs coherence in 2d and 3d qubits
- Multi-photon dressing, Autler-Townes doublets
- Qubit with anisotropic magnetic dipole moment
- Strong coupling btw. YIG and cavity
- Goal: quantum sensor for magnons
Thank you for your attention