Compact tunable YIG-based RF resonators

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We report on the design, fabrication, and characterization of compact tunable yttrium iron garnet (YIG) based RF resonators based on µm-sized spin-wave cavities. Inductive antennas with both ladder and meander configurations were used as transducers between spin waves and RF signals. The excitation of ferromagnetic resonance and standing spin waves in the YIG cavities led to sharp resonances with quality factors up to 350. The observed spectra were in excellent agreement with a model based on the spin-wave dispersion relations in YIG, showing a high magnetic field tunability of about 29 MHz/mT.

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Yttrium iron garnet (YIG, Y₃Fe₅O₁₂) radiofrequency (RF) resonators based on YIG spheres are a well-established technology and are employed in a broad range of applications, including RF filters and oscillators. These technologies benefit from the low intrinsic magnetic loss of YIG, leading to quality ($Q$) factors of up to several thousand. Moreover, the resonance frequency of filters and oscillators can be tuned over a wide frequency by means of an applied magnetic field. Yet, YIG spheres have mm-scale diameters and require even larger transducers for input and output RF signals in addition to the system to apply magnetic fields.

More recently, the development of thin film deposition techniques, in particular liquid phase epitaxy (LPE), has led to an increased interest in planar YIG resonators. This has resulted in considerable reduction of size and form factor, culminating in $Q$ factors reaching several thousand for groove-based cavities. However, the area of such devices was still in the square mm range, with YIG thicknesses of several µm, and usually operating in a flip-chip configuration.

In the last decade, the field of magnonics has seen tremendous progress and spin-wave devices have been miniaturized to µm and sub-µm dimensions. Nonetheless, while YIG micro- and nanostructures have been studied intensively in recent years, the miniaturization of YIG-based filters and resonators to sub-mm dimensions has received little attention so far. Here, we report on the fabrication and characterization of YIG thin film RF resonators that are based on spin-wave cavities with µm lateral dimensions. This approach allows for a compact device design, with $Q$ factors of up to 350 and large magnetic field tunability. A model of the spin-wave dispersion relations of the structures is in excellent agreement with the observed resonator spectra. These results show such devices are promising to reduce the footprint of YIG-based filters, while maintaining high $Q$ factors and tunable electrical output.

The devices were based on 800 nm thick (111) YIG films (Innovent Technologieentwicklung, Jena, Germany) deposited by LPE on (111) gadolinium gallium garnet (GGG) substrates. The films showed low Gilbert damping of $\alpha \approx 1 \times 10^{-4}$. A combination of e-beam lithography, wet etching, and lift-off was used for device fabrication. The spin-wave cavities were microfabricated by wet etching ($\text{H}_3\text{PO}_4$, 130°C) using a SiO₂ hardmask. After planarization by spin-on carbon, the 100 nm thick Au antenna transducers were defined by a lift-off process.
Figure 1(a) depicts a schematic of a YIG cavity resonator. Spin-wave cavity modes (dashed lines) are excited inside the cavity by inductive antennas. Two distinct types of antennas were used in this study: meander and ladder structures [Fig. 1(b)]. Both meander and ladder antennas consisted each of \( N \) identical wires [\( N = 4 \) in Fig. 1(b)] with a width of 1 µm and a pitch of 2 µm. Figure 1(c) shows an optical micrograph of processed device including a meander antenna. The dashed red line indicates the region where the YIG cavity (8 × 32 µm²) is located. The difference between the two types of antennas lies in the direction of the RF current: while in ladder antennas, currents in wires flow in the same direction with the same phase, currents in adjacent meander antenna wires have a phase shift of \( \pi \), i.e. they flow in opposite directions. Hence, local magnetic fields are always in the same direction for ladder antennas but alternating for meander antennas.

The RF response of the devices was assessed by measuring the RF reflection (\( S_{11} \)-parameter) using a Keysight E8363B network analyzer (input RF power −17 dBm) at frequencies between 10 MHz and 15 GHz. During the measurements, an external magnetic field of \( \mu_0 H_{\text{ext}} = 145 \) mT was applied along the antenna wires [see Fig. 1(c)]. Figure 2(a) shows as
FIG. 2. RF characteristics of YIG cavity resonators with ladder antennas for different cavity heights $h$ and constant width $w = 16 \, \mu m$. (a) Measured magnitude of the $S_{11}$-parameter vs. frequency. (b) Smith chart representation of the RF measurements matched to a 50 Ohm impedance ($f = 10$ MHz to 15 GHz). In all cases, $\mu_0 H_{\text{ext}} = 145$ mT.

An example the return loss of three ladder-antenna resonators ($N = 8$) with different cavity heights ($w = 16 \, \mu m$) after de-embedding the contact pad parasitics. Sharp resonances are observed at frequencies between 6.1 and 6.2 GHz, followed by a series of weaker resonances at higher frequencies. A Smith chart representation of the device impedances is shown in Fig. 2(b). The intrinsic $Q$ factor of these devices varied between about 200 and 350, which was obtained for the largest device. The RF absorption by the YIG cavity increased with $h$ due to the increasing magnetic cavity volume.
FIG. 3. RF characteristics of YIG cavity resonators (16 × 32 µm² cavity size) with (a) ladder and (c) meander antennas. (b) schematic representation of the studied devices (top) and the generated external magnetic field (bottom). Dispersion relations for the resonators with (d) ladder and (f) meander antennas, with DE (solid lines), BV (dashed lines), and excited cavity modes (stars). \( \mu_0 H_{\text{ext}} = 145 \) and 164 mT for ladder and meander antenna resonators, respectively. (e) Excitation spectrum for ladder (blue line) and meander antennas (red line).

We now discuss in more detail the different resonance spectra for devices including both ladder and meander antennas. Resonator spectra are shown in Figs. 3(a) and 3(c) for ladder \( (\mu_0 H_{\text{ext}} = 145 \text{ mT}) \) and meander \( (\mu_0 H_{\text{ext}} = 163 \text{ mT}) \) antennas, respectively. The cavity area was 16 × 32 µm² in both cases and all applied magnetic fields were sufficient to saturate the magnetization. In addition to the main resonance, the spectra showed several additional weaker resonances that are well separated in the case of the ladder antenna. This behavior can be understood by considering the spin-wave dispersion relations in the YIG cavity. In this geometry, two types of spin-wave modes can be generated: (i) backward...
volume (BV) modes with the wavevector parallel to $H_{ext}$; and (ii) Damon-Eshbach (DE) modes with the wavevector perpendicular to $H_{ext}$. The corresponding dispersion relations (saturation magnetization $M_s = 130$ kA/m, exchange constant $A = 3.5$ pJ/m, $\alpha = 1 \times 10^{-4}$) are represented in Figs. 3(d) and 3(f) for the two devices and $\mu_0 H_{ext} = 145$ mT and 163 mT, respectively. The dashed and solid lines represent dispersion relations for propagating BV and DE spin waves, respectively.

In a cavity, the boundary conditions impose that the wavenumber can only assume discrete values of $k = n\pi/L$ with $n$ the mode number and $L$ the cavity length. The resulting discrete spectra are shown as stars in Figs. 3(d) and 3(f). Note that for a rectangular cavity, the effective cavity lengths for BV (here $L_{BV} = 32$ µm) and DE modes (here $L_{DE} = 16$ µm) are not equal.

A comparison with the experimental spectra in Figs. 3(a) and (c) shows excellent agreement with the frequencies of both BV and DE spin-wave cavity modes. Further insight into the excited resonances, their relative amplitudes, and the dependence on the antenna design can be gained by considering the excitation efficiency of a spin-wave (cavity) mode, which is given by

$$\Gamma_n \propto \left| \int_V \mathbf{H}_{RF}(x) \cdot \mathbf{m}(x) \, dV \right|, \quad (1)$$

with $\mathbf{H}_{RF}$ the magnetic excitation field, $\mathbf{m}(x)$ the dynamic magnetization of the spin-wave mode, and $V$ the cavity volume. In wavevector space, the excitation efficiency is thus given by a Fourier transform of the magnetic excitation field. To a first approximation, the magnetic field underneath an antenna wire with width $d$ can be written as $H_{RF} \approx \pm I_{RF}/2d$ in the wire region and 0 outside, as shown in Fig. 3(b) for both ladder and meander antennas. Here, $I_{RF}$ is the RF current.

The resulting spatial Fourier spectra of the excitation fields transverse to the wires are shown in Fig. 3(e) for both ladder and meander antennas ($N = 8$). This geometry corresponds to the excitation of DE spin-wave cavity modes. The spectra show that ladder antennas efficiently excite DE cavity modes with smaller wavenumbers $k$ (larger wavelengths) but cannot excite high-$k$ modes. A similar result is found for the Fourier transform along the wires of the ladder antenna (not shown), which couple to BV cavity modes. As a result, the main resonance in the experimental spectrum in Fig. 3(a) can be attributed to a superposition of the DE and BV ferromagnetic resonances—which are nondegenerate due to the finite dimensions of the rectangular YIG cavity—and the first BV spin-wave cavity mode.
FIG. 4. Tunability of YIG cavity resonators. Resonance frequency vs. external magnetic field for resonators (16 × 32 µm² cavity) with ladder and meander antennas, as indicated. The solid lines represent best linear fits to the data.

Additional resonances at lower frequency correspond to higher order BV spin-wave modes, whereas only one DE mode was clearly observed at higher frequencies. Note that due to symmetry reasons, only odd BV cavity modes can be excited.

By contrast, meander antennas preferentially excite DE cavity modes with larger wavenumbers around a maximum determined by the wire pitch. Moreover, due to the opposite directions of the magnetic fields underneath adjacent wires, the meander antenna cannot excite BV modes since the average magnetic field transverse to the wires is zero. Therefore, the spectrum consists of DE modes with increasing mode number \( n \) until the dispersion relation becomes flat at high \( k \). The main resonance in the spectrum in Fig. 3(c) thus consists of a superposition of a large number of BV cavity modes with nearly continuous \( k \). As a result, the \( Q \) factor of the main resonance is lower for meander antennas than for ladder antennas. Note that the \( Q \) factor of resonators with meander antennas can be optimized by reducing the wire pitch, which reduces the excitation of DE cavity modes with low wavenumbers.

One of the key advantages of YIG resonators is their tunability by a magnetic field. This is illustrated in Fig. 4, which shows the dependence of the measured main resonance frequency on the applied magnetic field for ladder and meander antennas. In both cases, the dependence in the studied magnetic field range was linear with slopes of 29.3 MHz/mT (ladder) and 28.0 MHz/mT (meander). The tunability was very similar to that of devices.
FIG. 5. RF characteristics of YIG cavity resonators with ladder antennas for different cavity dimensions. (a) Different cavity widths $w$ for constant antenna wire density ($N = w/2 \mu m$) and cavity height ($h = 40 \mu m$). (b) Different cavity heights for constant cavity width ($w = 16 \mu m$, $N = 8$). In all cases, $\mu_0 H_{ext} = 145$ mT.

Based on bulk YIG,[50,51] demonstrating the device miniaturization does not affect tunability. The slight dependence of the tunability on the antenna design can be attributed to the different magnetic field dependence of the relevant spin-wave cavity modes.

These results indicate that ladder antennas lead to a better-defined device response with a sequence of well-marked and sharp resonances. In the following, we focus on the signal optimization of ladder structures. Figure 5(a) shows the frequency response of resonators with identical antenna wire width ($1 \mu m$) and pitch ($2 \mu m$), identical cavity height $h = 40 \mu m$, but different cavity width $w$. Maintaining a constant wire density for increasing $w$ was achieved by setting the number of wires in each resonator to $N = w/2 \mu m$. In this case, increasing $w$ leads to two competing effects: (i) an increase of the magnetic volume and
transducer size; and (ii) the redistribution of the total current in an increasing number of parallel wires, which lowers the RF magnetic field underneath each individual wire. Whereas (i) increases the RF absorption by the cavity, (ii) reduces the external excitation. Both effects tend to compete with each other and, as a result, an optimum width of $w = 16 \, \mu m$ ($N = 8$) was observed, as shown in Fig. 5(a). As expected, the separation between adjacent DE cavity modes decreased for larger $w$ and several peaks became superimposed for the largest cavity. Narrower cavities also showed reduced resonator $Q$ factors, possibly due to edge effects or processing imperfections.

The effect of varying the cavity height $h$ is illustrated in Fig. 5(b). In this case, longer antennas overlap with a larger magnetic volume without reducing the driving RF magnetic field, leading to increased RF absorption by the longer YIG cavity. Thus, the strongest RF absorption was obtained for the largest studied cavity with $h = 256 \, \mu m$, in keeping with the results in Fig. 2(a). The main resonance frequency increased with $h$ in agreement with the change of the dispersion relation as a function of the cavity length (not shown).

In conclusion, we have studied the characteristics of RF resonators based on YIG cavities with areas down to $128 \, \mu m^2 \approx 10^{-4} \, \text{mm}^2$. Both ladder- and meander-type antennas were used as transducers between the RF and spin-wave domains. The resonators showed $Q$ factors up to 350, depending on the YIG cavity dimensions, and a magnetic field tunability of about $29 \, \text{MHz/mT}$. The observed frequency dependence of the resonators was in excellent agreement with the spin-wave dispersion relations in YIG, indicating that the different transducers excited distinctly different cavity modes. While ladder antennas mainly coupled to ferromagnetic resonance, meander antennas excited standing spin-wave modes with large wavevectors. The results show that $\mu m$-sized YIG resonators may find applications in future miniaturized magnetically tunable RF filters. The small device size and form factor of the resonators are particularly promising for future integrated systems in a package combining different RF components.

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