Electrical excitation and detection of magnetic dynamics with impedance matching

D. Fang, T. Skinner, H. Kurebayashi, R. P. Campion, B. L. Gallagher, and A. J. Ferguson

1Hitachi Cambridge Laboratory, Cambridge CB3 0HE, United Kingdom
2Cavendish Laboratory, University of Cambridge, CB3 0HE, United Kingdom
3School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom
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Motivated by the prospects of increased measurement bandwidth, improved signal to noise ratio and access to the full complex magnetic susceptibility we develop a technique to extract microwave voltages from our high resistance (∼10 kΩ) (Ga,Mn)As microbars. We drive magnetization precession with microwave frequency current, using a mechanism that relies on the spin orbit interaction. A capacitively coupled λ/2 microstrip resonator is employed as an impedance matching network, enabling us to measure the microwave voltage generated during magnetisation precession.

Magneto-resistance effects displayed by ferromagnets and ferromagnetic devices enable the observation of precessing magnetization. A direct-current passed through the sample results in a oscillating voltage due to the oscillating magneto-resistance. Alternatively if a microwave frequency current is passed through the sample, the sample itself can be used as a rectifier: the oscillating magneto-resistance multiplied by the oscillating current yields a time-independent voltage. It is straightforward to extract the microwave voltage in the case of samples with a resistance of about 50 Ω, however significantly higher (or lower) resistance samples suffer from an impedance mismatch problem. In this Letter we demonstrate a simple impedance matching technique that can be used to extract this microwave voltage from high-resistance samples. We use a λ/2 microstrip resonator to impedance match a ~10 kΩ sample towards 50 Ω at frequency of 7 GHz. We are motivated to access the microwave frequency voltage because of the advantages it confers over the dc rectification signal, in the following we list a few. The measurement bandwidth is determined by the Q-factor of the resonator, giving 350 MHz bandwidth rather than the ~kHz offered by rectification; the use of low noise microwave amplifiers enables an improved signal to noise ratio; the microwave voltage allows access to the real and imaginary parts of the complex susceptibility; and the microwave voltage is ideally suited to studying the bias dependence of spin transfer torques. Finally, we anticipate that the study of the microwave voltage in thin film ferromagnetic layers will lead to the discovery of new phenomena in magnetisation dynamics.

We use normal-metal λ/2 resonators but note that high quality factor superconducting resonators have been widely used in radio-astronomy and condensed matter physics over the past decade. These superconducting resonators have been used for sensitive detection of x-rays, read-out of superconducting qubits and double quantum dots and are also of interest for high-sensitivity electron spin resonance.

Passing an electrical current thorough the dilute magnetic semiconductor (Ga,Mn)As generates an effective magnetic field. The origin is the combination of spin accumulation due to the spin-orbit coupled bandstructure (the inverse spin galvanic effect) and the exchange coupling between the carriers and the local moments. As this is a bandstructure effect, the direction of the current induced field depends on the current direction with respect to the crystal (fig. 1(a)). We use a sample in the [010] direction producing an in-plane field nearly parallel to the current direction (fig. 1(b)). For typical samples the magnitude of the current induced field is 1 mT/10⁶ Acm⁻². The current induced field provides a convenient way of driving ferromagnetic resonance (FMR) and the oscillating magnetic field (B₁eʲωt) can be in the range 1 μT - 1 mT.

Due to the anisotropic magneto-resistance the sample resistance depends on the in-plane angle between the current and magnetisation (θ) as follows: R = R₀ + ΔRsin²θ (fig. 1(c)). During precession θ varies, leading to a time-dependent change in resistance, δR(t) = (ΔRm_y(t)sin 2θ) / m_y(t), where m_y(t) is the y-component of the magnetization. By solving the Landau-Lifshitz-Gilbert equation, m(t) can be related to B₁(t) by a susceptibility tensor (m(t) = (χ + jχ')B₁(t)). If B₁eʲωt is along the bar, as for our [010] samples, then we can consider the following individual components of the susceptibility: χ_y (an anti-symmetric Lorentzian) and χ_y' (a symmetric Lorentzian) and χ_y'' (a symmetric Lorentzian). In the co-ordinates we use, x is along the average magnetisation direction, so the y-component of B₁(t) is −B₁(t)sin θ. If there is a microwave frequency current I₁eʲωt through the bar, in phase with B₁(t), a time independent voltage V_dc results from Ohm’s law:

\[ V_{dc} = \frac{-\Delta RI_y B_1 \sin \theta \sin 2\theta}{2m_y} \] (1)

This leads to the anti-symmetric Lorentzian lineshape (fig. 1(d)). A symmetric Lorentzian component is also present in the signal indicating a component of B₁(t) out of plane, or a phase shift between B₁(t) and I₁(t). In the case of a dc current I₀ through the bar a microwave voltage V_c(t) results at the precession frequency:

\[ V_c = \frac{-\Delta RI_y B_1 \sin \theta \sin 2\theta}{2m_y} \]
V_ω(t) = \frac{-\Delta RI_0(\chi_{yy} + j\chi_{yr})B_1 \sin \theta \sin 2\theta e^{j2\pi f t}}{m_s} \tag{2}

V_ω(t) has been studied in low-resistance spin-valve structures \[H \parallel \hat{B}\], and provides the most straightforward approach to measuring the bias dependence of current-induced torques. Unlike V_{dc}, it contains information about the full complex susceptibility rather than just the real part. Some impedance matching approach must be taken to extract this signal from our samples. The voltage reflection coefficient between a 10 kΩ sample and a 50 Ω coaxial cable, \[\Gamma = \frac{R - R_0}{R + R_0} = 0.995\] so only 1 % \((1 - \Gamma^2)\) of the incident microwave power is transmitted to the cable from our device. Of course, the same impedance mismatch problem occurs when trying to drive a microwave current through the sample. To quantify this, we measured the increase in V_{dc} when impedance matching is used. We expect a 100-fold increase in V_{dc} (since V_{dc} \propto I_0^2) however, due to losses in our resonator, a 48-fold increase was observed.

Now we describe our implementation of the λ/2 impedance matching network. A Z_0=50 Ω microstrip
resonator is patterned on a low-loss printed circuit board (PCB) (fig. 2(a)). The resonator is excited through a 4-finger interdigitated capacitor and the thin film ferromagnetic sample is wire-bonded between the resonator and the ground-plane. When driven at its fundamental frequency, there is a node of electric field at the centre-point of the resonator. This enables the simple incorporation of a bias-tee [23], a wire bond ($\approx 5$ mm) is made to the centre-point and then attached to our dc circuitry. The bias-tee is observed to have negligible effect on the microwave properties of the resonator and we measure $> 18$ dB isolation between the resonator input and the bias-tee connection. To reduce radiation losses the PCB is placed in a copper enclosure.

The impedance of the resistively-loaded resonator is described by the following expression, where $l$ is the resonator length, $v_p = \omega/k$ is the phase velocity, R is the sample resistance and $C_k$ the coupling capacitance:

$$Z(\omega) = \frac{1}{j\omega C_k} + Z_0 \frac{R + jZ_0 \tan(\frac{\omega l}{v_p})}{Z_0 + jR \tan(\frac{\omega l}{v_p})}$$  \hspace{1cm} (3)$$

Simplifying equation 1, it may be seen that the $\lambda/2$ resonator is equivalent to a parallel circuit [24], the sample resistance (R) in parallel with a capacitance ($C = \frac{1}{2\pi f L}$) and inductance ($L = \frac{1}{\omega^2 C}$) (fig. 2(b)). The resonant frequency of the unloaded circuit is given by $\omega_0^2 = 1/LC$. A frequency of 7 GHz gives values of $C = 0.71\mu F$ and $L = 0.73\mu H$. At resonance, the impedance of the capacitatively driven parallel resonant circuit remains real:

$$Z(\omega_0) \approx \frac{1}{R_0^2 C_k^2}$$  \hspace{1cm} (4)$$

The circuit acts to invert the impedance of the resistor: $Z(\omega_0) \propto 1/R$. Also notice the $1/C_k^2$ dependence, the coupling capacitance is used to define the matching resistance. Taking the expected values of $L$ and $C$ for our resonator and a realistic value for the coupling capacitance, $C_k = 30\mu F$, we show how the load resistance affects the reflection coefficient (fig. 2(c)). The load resistance is matched when $\Gamma = 0$, occurring for a resistance of $\approx 10\Omega$.

The frequency response of our resonator with and without the sample attached is shown (fig. 2(d)). With no sample attached, the reflection coefficient $\Gamma_S \approx 0$ at resonance indicative that the sample is close to perfectly impedance matched. With no sample attached $\Gamma_{NS} \approx 0.8$ showing that conductor and dielectric losses are also contributing to, but not dominating, power loss in the resonator. These reflection coefficients help us calibrate the microwave current in the sample. Using a calibrated microwave diode we determine that the power reaching the sample is $P_{in} = -5\text{ dBm (320} \mu\text{W)}$. Equating the power dissipated in the sample ($((1 - \Gamma_S^2 - \Gamma_{NS}^2))P_{in} \approx 0.36P_{in}$) to $I_f^2R/2$ we find that $I_f = 160 \mu A$, giving a peak current density of $1.6 \times 10^5 \text{ Acm}^{-2}$.

In order to detect $V_\omega(t)$ we perform microwave reflectometry. We drive the resonator close to its resonant frequency, using a directional coupler to separate the incident and reflected signals (fig. 2(a)). The reflected signal is detected using an I-Q mixer, which enables the in-phase (I) and quadrature (Q) components of the reflected microwave signal to be detected with respect to the mixer’s local oscillator (LO). The microwave frequency is adjusted to bring the I-component exactly in-phase with the local oscillator. Any $V_\omega(t)$ generated by the sample will be superposed on the much larger reflected signal. In order to determine the contribution of $V_\omega(t)$ we perform a lock-in experiment, low-frequency ($\sim 44\text{ kHz}$) pulse modulating the current through the sample and detecting the mixer outputs with a pair of
lock-in amplifiers. Finally we extract the $I(V_{\omega, t})$ and $Q$ components of the microwave voltage at the sample $(V_{\omega, q})$.

The resulting signals are shown in figure 3(a). Since the sample is $\lambda/2$ away from the coupling capacitor the microwave current in the sample is nearly in phase with the reflected microwave signal. This means that the $I$ channel has the form of $\chi_{yy}$, giving an anti-symmetric Lorentzian similar to the rectification measurement. Correspondingly the $Q$-component gives follows the form of $\chi_{yy}$ and can be fitted to a Lorentzian. By dividing the maximum of $V_{\omega, q}$ by $I_0$ we find the amplitude of the oscillating resistance during magnetisation precession to be $\delta R = 4 \text{ m}\Omega$. Using the in-plane AMR, measured at 1.1 % for a similar sample at 30 K ($\Delta R = 100 \text{ m}\Omega$), we deduce an in-plane cone angle ($\approx \sqrt{\Delta R/\Delta R}$) of 0.4 degrees. As the magnitude of $I_0$ is increased so does the amplitude of $V_{\omega, t}(t)$ (fig. 3(b)), from equation 2 we expect that $V_{\omega, q}(t) \propto I_0$ and this is indeed observed (fig. 3(c)). The amplitude of $V_{\omega}$ should also be proportional to $B_1$, and in our case $B_1$ is a current induced effective magnetic field proportional to $I_1$. Hence we expect, and observe, that $V_{\omega, q}(t) \propto I_1$ (fig. 3(d)).

We described how the capacitatively coupled $\lambda/2$ microstrip resonator enables the extraction of the microwave voltage generated by magnetisation precession in high resistance samples. This simple impedance transformer could also be applied to quantum circuits where the microwave conductance is of interest \cite{25} and used as alternative to other transmission line matching techniques \cite{26, 27}.

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\* Electronic address: ajf1006@cam.ac.uk

[1] A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, Nature 438, 339 (2005).

[2] H. J. Juretschke, J. Appl. Phys. 31, 1401 (1960).

[3] M. V. Costache, S. M. Watts, M. Sladkov, C. H. van der Wal, and B. J. van Wees, Appl. Phys. Lett. 89, 232115 (2006).

[4] N. Mecking, Y. S. Gui, and C.-M. Hu, Phys. Rev. B 76, 224430 (2007).

[5] J. C. Sankey, P. M. Braganca, A. G. F. Garcia, I. N. Krivorotov, R. A. Buhrman, and D. C. Ralph, Phys. Rev. Lett. 98, 227601 (2006).

[6] A. Yamaguchi, K. Motoi, A. Hirohata, H. Miyajima, Y. Miyashita, and Y. Sanada, Phys. Rev. B 78, 104401 (2008).

[7] L. Xue, C. Wang, Y.-T. Cui, J. A. Katine, R. A. Buhrman, and D. C. Ralph, Appl. Phys. Lett. 101, 022417 (2012).

[8] L. Frunzio, A. Wallraff, D. Schuster, J. Majer, and R. Schoelkopf, IEEE transactions on applied superconductivity 15, 860 (2005).

[9] M. Goppl, A. Fragner, M. Baur, R. Bianchetti, S. Filipp, J. M. Fink, P. J. Leek, G. Puebla, L. Steffen, and A. Wallraff, J. Appl. Phys. 104, 113904 (2008).

[10] B. A. Mazin, P. K. Day, H. G. LeDuc, A. Vayonakis, and J. Zmuidzinas, Proc. SPIE 4849, 283 (2002).

[11] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Kumar, S. M. Girvin, and R. J. Schoelkopf, Nature 431, 162 (2004).

[12] T. Frey, P. J. Leek, M. Beck, A. Blais, T. Ihn, K. Ensslin, and A. Wallraff, Appl. Phys. Lett. 108, 046807 (2012).

[13] D. I. Schuster, A. P. Sears, E. Ginossar, L. DiCarlo, L. Frunzio, J. J. L. Morton, H. Wu, G. A. D. Briggs, B. B. Buckley, D. D. Awschalom, and R. J. Schoelkopf, Phys. Rev. Lett. 105, 140501 (2010).

[14] Y. Kubo, F. R. Ong, P. Bertet, V. J. D. Vion, D. Zheng, A. Dréau, J.-F. Roch, A. Aufeves, F. Jelezko, J. Wrachtrup, M. F. Barthe, P. Bergonzo, and D. Esteve, Phys. Rev. Lett. 105, 140502 (2010).

[15] H. Wu, R. E. George, J. H. Wiesen, K. Mølmer, D. I. Schuster, R. J. Schoelkopf, K. M. Itoh, A. Ardana, J. J. L. Morton, and G. A. D. Briggs, Phys. Rev. Lett. 105, 140503 (2010).

[16] T. Jungwirth, J. Sinova, J. Mašek, J. Kučera, and A. H. MacDonald, Rev. Mod. Phys. 78, 809 (2006).

[17] L. Garate and A. H. MacDonald, Phys. Rev. B 80, 134403 (2009).

[18] A. Manchon and S. Zhang, Phys. Rev. B 79, 094422 (2009).

[19] A. Chernyshov, M. Overby, X. Liu, J. K. Furdyna, Y. Lyanda-Geller, and L. P. K rohinson, Nature Phys. 5, 656 (2009).

[20] M. Endo, F. Matsukura, and H. Ohno, Appl. Phys. Lett. 97, 222501 (2010).

[21] D. Fang, H. Kurebayashi, J. Wunderlich, K. Vyborny, L. P. Zarro, R. P. Campion, A. Casiraghi, B. L. Gallagher, T. Jungwirth, and A. J. Ferguson, Nature Nanotech. 6, 413 (2011).

[22] V. M. Edelstein, Solid State Commun. 73, 233 (1990).

[23] F. Chen, A. J. Sirois, R. W. Simmonds, and A. J. Rimberg, Appl. Phys. Lett. 98, 132509 (2011).

[24] D. M. Pozar, Microwave engineering (Wiley, 2005).

[25] J. Gabelli, G. Feve, J.-M. Berroir, B. Placais, A. Caravella, B. Etienne, Y. Jin, and D. C. Glattli, Science 313, 499 (2006).

[26] S. Hellmuller, M. Pikulski, T. Muller, B. Kung, G. Puebla-Hellmann, A. Wallraff, M. Beck, K. Ensslin, and T. Ihn, Appl. Phys. Lett. 101, 042112 (2012).

[27] G. Puebla-Hellmann and A. Wallraff, Appl. Phys. Lett. 101, 053108 (2012).