THz near-field Faraday imaging in hybrid metamaterials

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Abstract: We report on direct measurements of the magnetic near-field of metamaterial split ring resonators at terahertz frequencies using a magnetic field sensitive material. Specifically, planar split ring resonators are fabricated on a single magneto-optically active terbium gallium garnet crystal. Normally incident terahertz radiation couples to the resonator inducing a magnetic dipole oscillating perpendicular to the crystal surface. Faraday rotation of the polarisation of a near-infrared probe beam directly measures the magnetic near-field with 100 femtosecond temporal resolution and (λ/200) spatial resolution. Numerical simulations suggest that the magnetic field can be enhanced in the plane of the resonator by as much as a factor of 200 compared to the incident field strength. Our results provide a route towards hybrid devices for dynamic magneto-active control of light such as isolators, and highlight the utility of split ring resonators as compact probes of magnetic phenomena in condensed matter.

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References and links
1. Introduction

Metamaterials - artificially structured composites - provide a design-based approach to create novel electromagnetic functionality. This functionality spans the spectrum from the microwave through the visible with examples including cloaking and superlensing. The induced magnetic dipoles in subwavelength “atoms” comprising such metamaterials (MMs) have played a crucial role in these advances with the magnetic response encoded in an effective bulk magnetic permeability. The split ring resonator (SRR) is the canonical subwavelength resonant magnetic “atom”. SRRs are fabricated from high conductivity metals such as gold where incident electromagnetic radiation drives a circulating current. This current is the origin of the induced magnetic dipole which, importantly, exhibits a resonant response that is determined by the loop inductance and gap capacitance as depicted in Fig. 1(a). For example, if the incident magnetic field is perpendicular to the plane of the SRR, this will generate a magnetic dipole that is also perpendicular to the SRR plane. This resonant response leads to a negative magnetic permeability in the vicinity of the resonance frequency [1]. An electric field parallel to the arm with the gap will also induce a magnetic dipole.

The single SRR (sSRR) in Fig. 1(a) is but one of a myriad design possibilities for subwavelength magnetically active resonators. For example, Fig. 1(b) depicts a double SRR (dSRR) which is simply two sSRRs placed back-to-back. Electric field excitation drives counter circulating currents resulting in two oppositely directed magnetic dipoles. Thus, the magnetic dipoles cancel and the bulk effective response of an array of dSRRs is described by an effective electric permittivity, if the distance between two resonators is large enough, to avoid coupling between the resonators. In short, the magnetic fields associated with these magnetic dipoles are of opposite sign, originate from a subwavelength area, and thus largely cancel in the far field. In fact, for both sSRRs and dSRRs, the near-field magnetic distribution is expected to be quite complex. Deep subwavelength measurements of the magnetic near-field with high spatial resolution can shed light on the strength and distribution of the local magnetic field. Although it is possible to calculate the magnetic near-field from measurements of the electric near-field [2–4], such bypass introduces noise and inaccuracy. In addition, calculation of the magnetic near-
field requires two measurements, namely that of \( E_x \) and \( E_y \) to extract the magnetic field using Faraday's law \( \vec{V} \times \vec{E} = -\partial \vec{B}/\partial t \). At optical wavelengths, only indirect measurements of the magnetic near-field have been reported [5], or of the amplitude of the magnetic field [6], or only of its polarization [7]. At microwave frequencies, only simple microstrip lines have been investigated [8] while no direct measurements have been reported at THz frequencies.

2. Technique

We directly measure the magnetic field of SRRs that are resonant at terahertz frequencies. This is accomplished using near-field terahertz time domain spectroscopy (THz-TDS) as depicted in Fig. 1(c). Faraday polarisation rotation of the probe beam results from the induced magnetic field of SRRs that have been deposited on terbium gallium garnet (TGG). TGG is a magneto-optic crystal providing a linear Faraday rotation, that is, a rotation of the plane of polarisation of an optical beam linearly proportional to the strength of an external magnetic-field pointing in the optical beam propagation direction. TGG doesn’t show any second order electro-optic effects and it is generally used as a polarisation rotator or isolator. In combination with THz-TDS, TGG (Verdet constant of 60 radT\(^{-1}\)m\(^{-1}\) at 800 nm) has previously been used to measure the free-space time-dependent magnetic field component parallel to a probe beam [9]. Adapting this technique allows us to measure the two-dimensional spatial distribution of the magnetic near-field which strongly varies in a small region of space of only several tens of micrometers, more than two order smaller than the wavelength of the THz light.

These hybrid devices have been constructed using sSRR and dSRR resonators (as in Fig. 1(a) and 1(b)) [10–12]. Similar SRRs had their electric near-field measured in the infrared [13, 14] and at terahertz frequencies [4, 15]. Schematic diagrams of these resonators are shown next to Table 1 which details the dimensions and simulated resonance frequencies of the SRRs. The resonance frequency given in the table is the resonance frequency of the resonator on TGG, not the resonance frequency of a resonator in free space. The presence of TGG lowers the resonance frequency. Before fabrication, we first deposit a reflective coating for the 800 nm beam consisting of 130 nm of SiO\(_2\) and 300 nm of Ge on top of a 1 mm thick (111) TGG crystal.

In our first experiment, a single-cycle, broadband THz pulse propagating in the \( \hat{z} \)-direction with an electric field polarisation in the \( \hat{y} \)-direction, as defined in Table 1, is incident on a single resonator. The single-cycle, broadband (0 - 3 THz) THz pulse is generated using a Ti:sapphire laser producing 15 fs pulses, which are focused on the surface of a semi-insulating GaAs crystal biased with a 50 kHz, ±400 V square wave. A silicon hyper-hemispherical lens is glued on the back of the crystal to collimate the emitted THz radiation. The THz beam is then further collimated and refocused using gold-plated parabolic mirrors [16].

The THz beam at focus covers a larger area than that of a single resonator. At the same time, a synchronized, femtosecond probe laser pulse propagating in the (−\( \hat{z} \))-direction is focused in the crystal to an approximately 5 \( \mu \)m diameter spot immediately below the structure, using a reflective objective. The Ge/SiO\(_2\) reflection coating on the crystal reflects the probe beam. The (111) orientation of the TGG crystal ensures that the probe pulse will only experience a Faraday rotation by a magnetic field component \( H_z \) aligned with the propagation direction of the probe beam. This means that the setup is blind to both the incident magnetic field, polarised in the \( \hat{z} \)-direction, and any other magnetic field in the \( \hat{y} \)-direction. In practice, no change in probe polarisation was detected in the absence of the metallic split-ring resonators. Therefore, we can safely assume that the probe beam polarisation will be linearly rotated only in the presence of a
Table 1. Summary of different single split resonators and the double split resonator simulated and measured in the near-field with the parameters indicated in the drawings on the right side.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Arm length (L) (µm)</th>
<th>Arm width (t) (µm)</th>
<th>Gap width (g) (µm)</th>
<th>Resonance Frequency Simulated (THz)</th>
<th>Resonance Frequency Measured (THz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sSRR-1</td>
<td>90</td>
<td>10</td>
<td>5</td>
<td>0.155</td>
<td>0.166</td>
</tr>
<tr>
<td>sSRR-2</td>
<td>90</td>
<td>15</td>
<td>15</td>
<td>0.185</td>
<td>0.181</td>
</tr>
<tr>
<td>sSRR-3</td>
<td>70</td>
<td>10</td>
<td>10</td>
<td>0.224</td>
<td>0.250</td>
</tr>
<tr>
<td>dSRR-1</td>
<td>90</td>
<td>10</td>
<td>5</td>
<td>0.170</td>
<td>0.174</td>
</tr>
</tbody>
</table>

longitudinal magnetic field \(H_z\) inside the crystal. A differential detector, combined with a \(\lambda/2\) wave plate and a Wollaston prism measures this rotation [17]. A half-wave plate is required here to balance the differential detector rather than the standard quarter-wave plate used in electro-optic detection, because the Faraday Effect rotates the linear polarization of the probe beam which otherwise remains linearly polarized.

The THz magnetic near-field as a function of time is obtained by optically and rapidly delaying the probe pulse via the optical delay stage, with respect to the THz pulse while measuring the Faraday rotation. This technique measures the field and thus both the amplitude and the phase of the magnetic near-field are obtained. Because the signal is weak, the time-dependent signal at a single position is an average over 200000 temporal scans and was obtained in less than an hour time. To measure the two-dimensional spatial distribution of the magnetic near-field, the sample is raster scanned in the \(xy\)-plane. The temporal average scan number is reduced to 10000 per pixel for the 2D-scan. A typical, 25 ps long scan of the THz magnetic near-field was obtained by stitching two partially overlapping 15 ps long scans together.

3. Single split ring resonator

3.1. Single point measurements

Figure 1(a) shows a drawing of the sSRR patterned on the TGG crystal. The incident electric field is polarised along the \(\hat{y}\)-axis, parallel to the arm containing the gap of the resonator. The sSRR covers an area of 90 µm by 90 µm, the width of each arm is 10 µm and the gap is 5 µm wide as shown in Table 1. In Fig. 2(a) we plot the measured magnetic near-field \(H_z(t)\) induced by the incident electric field at a single fixed position inside the sample sSRR-1, indicated by a cross in the insert of Fig. 2(a). To confirm that we measure the magnetic field induced by the structure, the structure is rotated by 180° around the \(z\)-axis. The incident electric field being unchanged, this should reverse the direction of the current and thus reverse the direction of the magnetic near-field vector. Indeed, the figure shows that the measured \(H_z(t)\) is opposite in sign compared to the previous measurement confirming that we indeed measure the magnetic near-field.

The oscillations found in the two time traces indicate that the structure behaves like a resonator. Time traces of the magnetic near-field of two other sSRRs with dimensions shown in Table 1 have also been measured. The spectral content of the three measured magnetic field
Fig. 1. Design of the (a) single split ring resonator (sSRR) and of the (b) double split ring resonator (dSRR). The incident THz electric-field (blue) is polarised parallel across the gap. It generates current flowing in the arms of the resonator, leading to a single magnetic dipole (green) for the sSRR and two magnetic dipoles of inverse polarisation for the dSRR. (c) Rotation of the probe polarisation due to the magnetic near-field present inside the TGG crystal. (d) Cross sectional view of the structure indicating different layers and the geometry of the beams.
Fig. 2. (a) Measurement of the time dependent out-of-plane magnetic near-field $H_z(t)$, induced by the electric field incident for the two different orientations of the sSRR shown in the insets. Measurements are taken at the positions indicated by the crosses. (b) Amplitude spectra calculated from the time-dependent magnetic field $H_z(t)$ for the three different sSRR with dimensions given in Table 1. (c) Calculated surface current density at the resonance and two dimensional spatial distribution of the calculated amplitude d) and phase e) of $H_z$ at the crystal surface at the resonance frequency of 166 GHz. One can see the 180° phase difference between the fields on the inside and outside of the structure.

time traces, obtained by fast-Fourier transforming these traces, is shown in Fig. 2(b). Each sSRR shows a single large peak in its frequency spectrum, which corresponds to the strong oscillations observed in the time trace of the magnetic near-field. The peak frequency for the three different sSRRs are 0.155, 0.185, and 0.224 THz, respectively. These resonances correspond to the ones found in far-field transmission measurements of the LC response of arrays made of similar SRRs [10]. The peak frequency is a clear function of the sSRR dimensions: the smallest resonator (sSRR-3) exhibits the highest resonance frequency at 0.224 THz. To confirm that the measured peak frequencies correspond to the resonance frequencies of the SRRs, we have performed finite integration technique (FIT) simulations on these structures using CST Microwave Studio®, a commercial software package. The gold layer was taken as a perfect conductor, which is a reasonable assumption at THz frequencies. The reflective layers were neglected. The index of refraction of the TGG crystal at THz frequency was taken to be 3.75, equal to the value that we have measured. The peak positions calculated by the FIT simulations are at frequencies of 0.166, 0.181, and 0.250 THz respectively, which agrees well with the experimental values. Figure 2(c) shows the calculated surface current densities at the resonance frequency (166 GHz) of the sSRR-1 sample. When the single split-ring resonator is excited with an incident electromagnetic wave, a spatially circulating and temporally oscillating electric current is induced in
the metallic ring. One can see that the strongest current is inside the long arm of the structure, and that it is particularly strong near the corner. This can be understood intuitively: the electrons flowing through the arm would prefer to take the shortest path, i.e. hugging the bend, resulting in a stronger current at the inside of the corner. This current creates a time-dependent magnetic field, which is oriented normal to that plane, i.e. along the z-axis. It corresponds to the field component that we measure in our magneto-optical detection setup.

### 3.2. Two dimensional distribution

We have also measured the two-dimensional spatial distribution of the magnetic near-field $H_z$ at the resonance frequency. These 2D measurements give information about the distribution of the field inside and outside the ring. As we can see in the measurement in Fig. 3, the field is only measurable inside the resonator and within our measurement accuracy no field was measured at positions outside the sSRR. The strongest field is measured in a region opposite the gap, close to the long arm. Both observations can be understood by the fact that the current is stronger in the long arm than in the arm containing the gap. This leads to a stronger magnetic near-field near the long arm, on the inside of the ring. This is supported by the calculations shown in Fig. 2(d) and 2(e) where we plot the calculated amplitude and phase of $H_z$ in the plane below the structure at the resonance frequency. Interestingly, these calculations predict a 200 times stronger magnetic field near the corner, close to the long arm, compared to the incident magnetic field strength.

The calculated 2D magnetic field distribution plotted in Fig. 2(d), however, differs from the measured 2D distribution. In the calculation, the field is strongly localized near the long arm, whereas the magnetic field has expanded to fill the resonator in the measurement. To better understand the discrepancy between experiment and simulation, we have calculated 2D spatial distributions of the magnetic near-field inside the TGG crystal at four different distances from the surface at $z = 0$, -10, -20 and -30 µm. These results are shown in Fig. 3 along with the measurement. In both cases, the total area covered is 130 µm by 130 µm.

Although the field is mainly concentrated near the edge of the metal at the plane $z = 0$, it gradually changes into an uniform distribution when the distance $z$ to the structure increases. One can see that the measurement resembles the calculation for a distance between 10 to 20 µm from the surface. This shows that we measure directly in the near-field, at a distance much smaller than the size of the object. We reach a spatial resolution of about 10 µm, much smaller than the 1.88 mm vacuum wavelength that corresponds to the resonance frequency of 0.16 THz. This corresponds to a value of about $\lambda/200$ in free space, nearly two orders of magnitude below the diffraction limit, approaching $\lambda/50$ when considering the wavelength inside the TGG crystal.

As the simulations also show, the longitudinal component of the magnetic field amplitude decreases rapidly with distance from the surface but at 30 µm below it, the calculated magnetic field strength is still 11 times larger than the incident field strength. At the average depth where we measure the magnetic field, the calculated enhancement explains why we are able to measure the magnetic near-field at all, despite the fact that we sample the field in a very small volume only.

In principle, our measurement method doesn’t sample the field at a single depth only but, it integrates the field over the entire length of the crystal. To understand why we observe a magnetic field distribution at an effective depth of 10-20 µm, we plot in Fig. 4(a), the calculated magnetic field component $H_z$, as a function of depth $z$ inside the crystal at the location indicated by the cross in the figure. The figure shows that as we move away from the surface the magnetic field decays rapidly over a distance of about 30 µm and becomes negligibly small at larger distances. The largest contribution to the signal, therefore, comes from a region of space less
Fig. 3. Measured (left) and calculated (right) two-dimensional spatial distributions of the magnetic near-field $H_z$ at the resonance frequency of sample sSRR-1: for $z = 0, -10, -20$ and -30 $\mu$m. The 2D measurement agrees mostly with the calculated spatial distributions between 10 and 20 $\mu$m below the surface.

Fig. 4. (a) Magnitude of the magnetic near-field, $H_z$, inside the TGG crystal, vs. distance to the structure at the surface. The line has been taken below the cross indicated in the drawing. (b) Two dimensional spatial distribution of magnetic near-field after integration from $z = 0$ to $z = -300$ $\mu$m inside the crystal. The magnetic field distribution matches exactly to the distribution calculated at $z = -20$ $\mu$m distance, shown in Fig. 3.

than about 30 $\mu$m away from the surface. In Fig. 4(b), we plot the two-dimensional distribution of the field calculated by integrating the field along the length of the crystal at each point. Clearly, this calculation strongly resembles both the measured distribution and the calculated one for a depth of 20 $\mu$m.
4. Double split ring resonator

Additionally, we have performed measurements on a double split ring resonator (dSRR). This sample, dSRR-1, is composed of two sSRRs sharing a middle arm; the dimensions and drawings are shown in Table 1. When the THz electric field is polarised parallel to the gaps along the $\hat{y}$-axis it generates at one moment in time, a clockwise running current in the left ring and a counterclockwise running current in the right ring. Some time later, the situation reverses since the currents oscillate in time. Due to the opposite directions of the currents, we have at a moment of time a magnetic-field component pointing down into the plane in the left ring, while in the right ring it is pointing up. This means that we have time-dependent magnetic fields of opposite direction in a deep subwavelength sized region of space, which thus more or less cancel in the far-field. We note that only near-field measurements are capable of discerning these fields.

4.1. Single point measurements

Figure 5(a) shows a measurement of the time-dependent magnetic near-field $H_z(t)$ of the dSRR structure at two different locations indicated by two crosses in the insert of Fig. 5(a): one inside the left ring and the other inside the right ring. In both measurements, the presence of long-lasting temporal oscillations indicate that the structure has a well defined resonance. The two
time traces of the magnetic near-fields are opposite in sign for the two locations. This means that the component of the magnetic near-field $H_z(t)$ points into the plane for the left ring, and out of plane for the right ring. The spectrum of $|H_z|$, calculated from the time-domain measurement is plotted in Fig. 5(b) and shows a strong peak at 0.17 THz. The resonance frequency was calculated again via FIT simulations, and was found to be 0.174 THz, in good agreement with the experiment.

The current in the dSRR in the central arm is larger than the current in a sSRR and distributed uniformly across its width, because the current is fed by two identical resonators rather than just one. The presence of the magnetic field is mainly due to this high current flowing in the middle arm, along the $\hat{y}$-direction as shown in Fig. 5(c). This creates a magnetic near-field with field lines describing roughly circles around the arm as schematically shown in the insert of Fig. 5(b).

4.2. Two dimensional distribution

The two-dimensional spatial distribution of the magnetic near-field component $H_z$, below the dSRR at the resonance frequency of 0.17 THz is shown in Fig. 6. The total area covered is 140 $\mu$m by 140 $\mu$m. The measurement shows that there is little or no field $H_z$ outside the structure and at the location of the middle arm. In the contrast, a field $H_z$ is present in the left and right ring and is strongest in the area of the dSRR near the middle arm. Due to the structure of the resonator, clockwise and anti-clockwise oscillating currents exist in the left and the right ring and therefore the magnetic fields $H_z$ in both resonators are opposite in direction. The change of sign of the magnetic near-field component, from positive (red) to negative (blue) occurs within 10-15 $\mu$m, a distance two orders of magnitude smaller than the vacuum wavelength of 1.7 mm. This is also shown in Fig. 5(d) and 5(e) where we plot the calculated amplitude and phase of $H_z$ in the plane below the dSRR structure at the resonance frequency.

As in the case of the sSRR, for DSRR also, the measured 2D distribution of the magnetic near-field doesn’t match the 2D distribution calculated at $z = 0$. To understand this difference, Fig. 6 shows the calculated spatial distribution of the magnetic near-field inside the crystal at various distances from the crystal surface at $z = 0$ (at the surface), -10, -20 and -30 $\mu$m. The calculated field distribution at $z = 0$, shows inside each ring a distribution resembling the one of the sSSR, and the field is mainly concentrated along both sides of the middle arm of the structure. As $z$ increases, it gradually expands and fills up the resonator. The measurement resembles the calculation for a distance between 10 to 20 $\mu$m, confirming again that we are probing the magnetic-field in the near-field at an average distance of 10-20 $\mu$m from the structure. Moreover, as we move away from crystal surface, the magnitude of the magnetic near-field deceases. At $z = 0$, the magnetic near-field $H_z$ is 155 times stronger than the incident magnetic field, while at 30 $\mu$m distance from the crystal surface, the strength of the calculated $H_z$ is still 8 times stronger than the incident magnetic field.

5. Conclusion

While our MM/TGG magneto-active devices have enabled direct imaging of the magnetic field with a resolution of $\lambda/200$, numerous other possibilities are worthy of detailed exploration. This includes further optimization of the response to create compact devices such as dynamic Faraday isolators. In addition, SRRs provide a unique pathway to locally excite magnetic materials with well-defined high frequency fields to interrogate, for example, magnetic field induced switching or control of ferromagnets initiated by an applied picosecond electric field - that is, creating dynamic magneto-electric materials. This is essentially what we have accomplished at a basic level with our MM/TGG: it is the incident electric field which induces the SRR magnetic dipole that, in turn, induces the TGG Faraday rotation at near-infrared frequencies.

Finally, recent advances in generating high-field THz pulses will be of interest for magnetic
Fig. 6. Measured (left) and calculated (right) two-dimensional spatial distributions of the magnetic near-field $H_z$ at the resonance frequency of sample dSRR-1: for $z = 0, -10, -20$ and -30 $\mu$m. The 2D measurement agrees mostly with the calculated spatial distributions between 10 and 20 $\mu$m below the surface.

structures similar to what we have presented [19]. For example, an incident THz pulse with a peak electric field of 1 MV/cm has a corresponding peak magnetic field of 0.3 Tesla. A field enhancement of 200 suggested by our numerical calculation would correspond to a local magnetic field of 60 Tesla of picosecond duration in the plane of the SRRs, sufficient to interrogate the dynamic magnetic properties of numerous materials.

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