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Non-linear optics and magneto-optics on nano-structured interfaces

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ABSTRACT The behaviour of the reflectivity and Kerr magneto-optic effects in the non-linear second-harmonic (SH) field diffracted from nano-scale structured ferromagnetic interfaces is reported. Measurements are made in both the linear and non-linear fields at two different fundamental wavelengths (1064 nm and 800 nm) and their associated harmonics. Resonant behaviour observed as a function of angle of incidence is identified with surface-plasmon production that is known to intensify the local field within the interface. Radiation incident at angles of incidence that optimise coupling to the electron plasma produces an increase in the SH field radiated in the vicinity of those angles. Similarly, at those angles of incidence where radiation at the SH wavelengths (532 nm and 400 nm) couples optimally to the electron plasma, troughs are seen in the angular spectrum of the generated SH radiation. Kerr magneto-optic measurements taken in both the linear field and the SH field both show very significant enhancement at angles meeting the plasma-resonance condition. The totality of experimental data presented allows the conclusion that intensification of the interface electric field due to plasmon creation enhances not only the SH reflection coefficient, as was already known, but also the magneto-optic reflection coefficients in both linear and SH fields.

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1 Introduction

The interfaces of many recording materials such as patterned magnetic recording media currently being studied as a route to overcoming the superparamagnetic limit and the physical data pattern on certain optical disks have a regular physical relief structure. Interfaces having such a structure can exhibit optical phenomena in addition to simple diffraction. Under appropriate conditions, the structure can make possible the transference of energy from incident radiation to plasmons created within the surface. This phenomenon most commonly recorded as a sharp resonant suppression of the reflected radiation also produces an intensification [1] of the local field in the region of the interface. At high incident intensities it may therefore also be observed as a peak in the production of second-harmonic (SH) radiation. The intensification of the field in the interface effectively enhances the SH reflection coefficient.

In recent work [2] we demonstrated that magneto-optic (MO) effects, and in particular the transverse Kerr effect, are also enhanced in the presence of resonant plasmon creation on structured surfaces. Although similar results have been previously reported [3–5] and extensively analysed, they were obtained from smooth multi-layer films using the Kretschmann–Raether configuration to couple incident radiation to surface-plasmon modes. However, whereas structure-mediated coupling readily lends itself to practical exploitation (see for example the work of Tominaga et al. [6], who reported the observation of a plasmon-augmented readout signal from a phase-change optical disk media using a near-field super-resolution structure), exploiting the Kretschmann–Raether configuration in a similar manner is not so simple and remains seemingly unexplored.

At the time of [2], however, the precise mechanism responsible for the enhancement observed in the fractional change in reflectivity under magnetisation reversal (δ) was unclear. The experimental data was insufficient to determine whether the enhancement observed arose solely as a consequence of the reduction in the normal reflected component of the incident radiation or whether field intensification actually enhanced the magneto-optic reflection coefficients (r_{pp}, r_{ps}). The purpose of the work described in this report is to address these issues by extension of these earlier measurements to include optical and magneto-optical measurements taken in the SH field.

2 Experimental methodology

All of the results taken for this report were obtained from a nickel diffraction grating consisting of small section cut from an optical disk ‘mother’. Over the area of the incident beam this sample presented an essentially linear aspect with a pitch of 1200 nm and a depth of 70 nm. Reflectance and magneto-optical measurements in the linear optical field were taken over the wavelength range 415 nm to 1064 nm on fully automated equipment with an angular resolution of 0.01°. For clarity, results are presented only at the fundamental wavelengths of the lasers used for the SH measurements and their harmonics. Similarly, results presented are

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in all cases confined to measurements made in the zeroth (0th)-reflected order.

Measurements of the SH reflectance (R_{SHG}) and the fractional intensity change in the SH field under magnetisation reversal in the transverse Kerr configuration (δ_{SHG}) were taken using both YAG ($\lambda = 1064$ nm) and Ti-sapphire ($\lambda = 800$ nm) lasers. Although detection schemes appropriate to the different emission characteristics of these sources were used, the greater data-collection efficiency of the Ti-sapphire laser running at 250 kHz as compared to the 10 Hz of the YAG laser is reflected in the quality of the non-linear MO results obtained. In both the SH experiments the angular precision achieved is much less than in the linear experiments.

3 Results

3.1 *Optical results*

In Fig. 1 the angular reflectance spectra of the grating are shown at the fundamental and SH wavelengths of the YAG and Ti-sapphire lasers. (The curve shown for 415 nm represents the closest practical approach to 400 nm with the broadband source and wavelength-selection equipment used for these measurements in the linear field.)

Simple theory gives the angle of incidence (ϑ) at which optimum coupling of incident radiation to surface plasmons will occur as

$$\sin\vartheta = \left[\frac{\varepsilon_1(\omega)}{1+\varepsilon_1(\omega)}\right]^{\frac{1}{2}} - \frac{m\lambda}{d}\,, \tag{1}$$

where d is the grating period, λ the incident wavelength and $\varepsilon_1(\omega)$ the real part of the optical permittivity. Using accepted values for the optical constants of bulk nickel [7] in the above allows the troughs observed around 7°, 22°, 39° and 51° at wavelengths of 1064 nm, 800 nm, 532 nm and 415 nm respectively to be positively identified with 1st-order plasmons ($m = 1$). The weaker features seen at the same wavelengths near angles of 50°, 17°, 11° and 24° are likewise determined to be associated with 2nd-order plasmon processes ($m = 2$).

With such clear evidence of plasmon production it is anticipated that intensification of the field that accompanies such processes would produce significant enhancement of the SH output when the YAG and Ti-sapphire lasers are incident at angles of 7° and 22° respectively. Figure 2 shows the SH output recorded at 532 nm (top) and at 400 nm (bottom); the expected enhancement is clearly visible in both cases. Moreover at 532 nm it is also possible to discern evidence of enhancement around 50° due to the weak 2nd-order processes, but at 400 nm the angular resolution is such that the enhancement observed at around 22° results from the merging of 1st- and 2nd-order processes. Note also in Fig. 2 the re-absorption of SH radiation at angles of incidence where radiation at wavelengths of 532 nm and 400 nm optimally couples into 1st-order

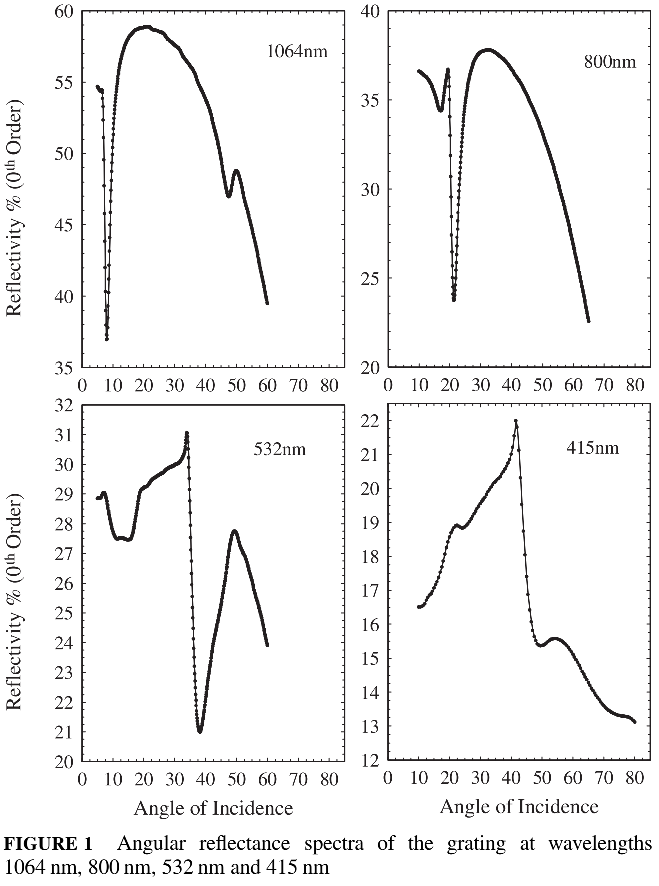

FIGURE 1 Angular reflectance spectra of the grating at wavelengths 1064 nm, 800 nm, 532 nm and 415 nm

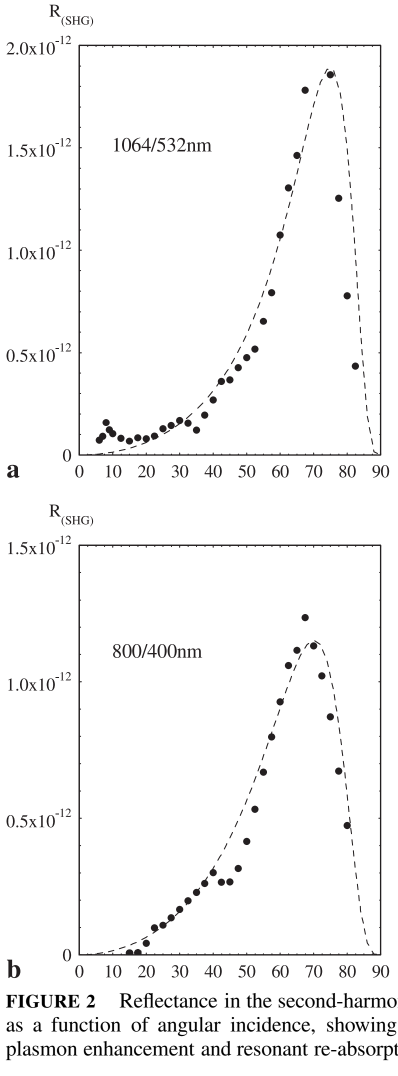

FIGURE 2 Reflectance in the second-harmonic field (532 nm and 400 nm) as a function of angular incidence, showing fine structure resulting from plasmon enhancement and resonant re-absorption

plasmons (see Fig. 1). The dotted line scaled to the experimental data in both graphs is calculated using the simple theory of Jha [8] for a specular nickel surface.

3.2 *Magneto-optical results*

Magneto-optical measurements made in the regions of optimum plasmon creation also exhibit dramatic enhancement. Figure 3 shows results obtained in the transverse Kerr configuration for the linear reflected field at the four wavelengths of interest. At the longer wavelengths of 1064 nm and 800 nm enhancement occurs where specular in-plane magneto-optical effects tend to zero. Similar behaviour is also observed in the longitudinal configuration. This same type of behaviour is then carried over to magneto-optic measurements made in the SH field as shown in Fig. 4. The behaviour at both SH wavelengths is seen to be broadly the same, with the enhancement peaks occurring at those angles where the fundamental wavelength is optimally coupled to the electron plasma.

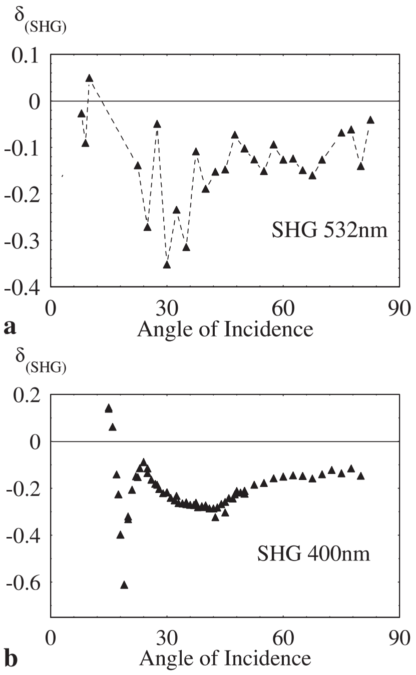

FIGURE 4 Transverse Kerr measurements in the non-linear optical fields (532 nm and 400 nm), showing the impact of plasmon enhancement

The more definitive results obtained at 400 nm are largely a consequence of the near-optimum coupling obtained at 800 nm and the practical difficulty of accessing angles of incidence less than 10° in the second-harmonic experiments. Kirilyuk et al. [9] have recently reported evidence of resonance behaviour in non-linear magneto-optic measurements from structure observed using a sum-frequency generation technique. Comparison of these results with the present work is however difficult as they are presented as a function of wavelength rather than angle of incidence. As a general point note that, as is usually found, the magneto-optic measurements made in the SH field are some two orders of magnitude greater than those taken in the linear field.

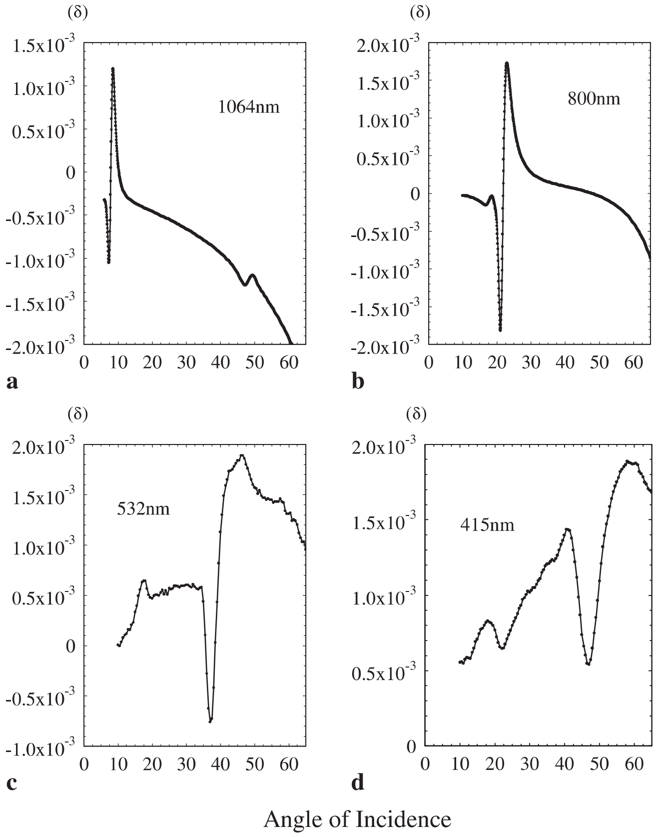

FIGURE 3 Transverse Kerr measurements in the linear optical field as a function of angle of incidence, showing the impact of plasmon enhancement

4 Discussion and conclusion

In the linear reflected field the enhancement in the fractional intensity change on magnetisation reversal (δ) occurs at the point where the normal reflected component goes to a minimum. It is therefore not immediately clear whether the enhancement observed in (δ) is simply a consequence of the

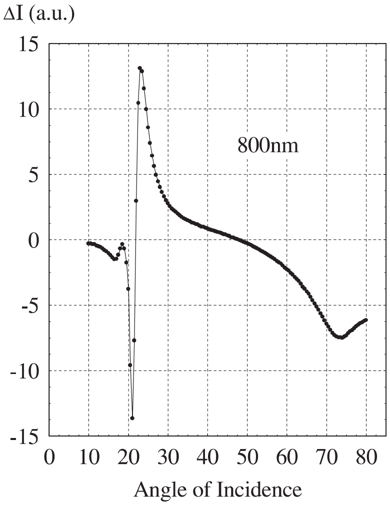

FIGURE 5 Intensity change on magnetisation reversal in the linear optical field at 800 nm in the transverse configuration as a function of angle of incidence

fall in the normal component. Conversely, the same magneto-optic measurements made in the SH field exhibit enhancement where the normal reflected SH component increases. This strongly suggests that field intensification occurring as a consequence of resonant plasmon creation actually increases the magneto-optic reflection coefficient. The latest results shown in Fig. 5 confirm this. An ac technique is used where a continuous light source (800 nm) and a modulated magnetic field are applied to the sample in the transverse configuration. The ac signal detected in the linear reflected field (ΔI) then represents twice the generated magneto-optical component and is increased in the vicinity of plasmon creation. In addition, the sign change in (ΔI) and (δ) (Fig. 3) at angles where suppression due to surface plasmons is a maximum indicates a 180° phase shift in the generated magneto-optical component.

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