The Magnetic Manipulation of Surface Plasmons — Consideration of Possible Technologies

Dave M. Newman, **M. Lesley Wears**, **and Raphael J. Matelon**
School of Engineering, Computing & Mathematics, University of Exeter, Exeter EX4 4QF, UK

Abstract— An as yet unexploited mechanism for producing controlled shifts in the frequency of lightwaves via their temporary conversion to surface plasmons propagating on a ferromagnetic surface or under the action of applied magnetic fields is introduced. Indirect evidence of the observation of this phenomena is presented and the technological possibilities it might offer are explored and discussed.

Interfaces between dielectric and metallic media possessing negative permittivity (ε) can support electromagnetic waves propagating as longitudinal density oscillations in the free-electron plasma at the metallic surface. Like photons, the quanta of these collective excitations remain bosons and are known as surface plasmons. Moreover, under conditions satisfying the relevant conservation laws, photons and plasmons are mutually transformable. Photons incident on a metallic surface may for example be temporarily induced to convert to plasmons that propagate on the surface for a while before their subsequent recovery as photons emitted back into the incident medium. The most exciting and complete confirmation of the nature of this process is evidenced in the work of Altewischer et al. [1] which demonstrated that a photon, having followed a path that includes its conversion to a plasmon and back to a photon, retains entanglement with the twin with which it was originally created in a down-conversion process. The objective here is to draw attention to the potential to exploit this two way conversion process to operate on photons in ways not previously considered.

More than 30 years ago Chiu and Quinn [2] and Nakamura and Paranjape [3] first described theoretically how propagating plasmons undergo frequency shifts when subject to influence by appropriately orientated dc magnetic fields (H) applied orthogonal to the plasmon flux. In more recent times Smolyaninov et al. [4] have interpreted the equations of Chiu and Quinn [2] and Nakamura and Paranjape [3] as describing a second-order mixing process between the ac plasmon field (E_p) and any applied dc magnetic field (H). If $\chi^{(2)}$ is a generalised susceptibility then such mixing processes generate terms of the form $\chi^{(2)}E_p^2H$ in the plasmon field energy density and the breaking of inversion symmetry at the interfaces requisite for the very existence of surface plasmons determines that terms such as $\chi^{(2)}E_p^2$ will always be present.

The plasmon energy and hence frequency consequently acquire a contribution linear in the applied field H which is real and in light of the results of Altewischer et al. [1] transposable to a photon emission field when the plasmon is intercepted by a grating out-coupler. We have obtained strong indirect evidence of the reality of this position by studying plasmon propagation on a nickel surface on which a linear grating with a period of 1.13 µm and depth of 0.7 µm is modulated, as shown schematically in Figure 1, by a shallower structure with an order of magnitude greater periodicity of about 12.5 µm [5].

When this structured surface is illuminated at an angle of incidence (θ_i) of exactly 19.85° by optical radiation with a wavelength of 800 nm and conservation of wavevector is satisfied by the addition of that associated with the 1.13 µm structural periodicity to that of the incident photons, a deep absorption trough is observed as shown on the left of Figure 1 indicating the resonant generation of a flux of forward propagating surface plasmons. Because of the finite spectral width of the incident optical beam, its residual divergence and the inherent error in the periodicity of the 1.13 µm coupling structure this flux consists of plasmons with a narrow spectrum of wavevectors rather than a single identical wavevector and the population of this spectrum is primarily determined by the Gaussian intensity profile of the incident beam. The width of the plasmon spectrum at full width half maximum ΔK_{sp}(FWHM) may be estimated by examination and analysis of the form of the reflectivity trough in Figure 1 to be of the order of $0.35 \times 10^{-3}\,\mathrm{nm}^{-1}$. This plasmon flux subsequently interacts in a much weaker fashion with the longer and shallower periodic structure which re-couples it back to an emissive optical field emerging from the surface at an angle of 77°

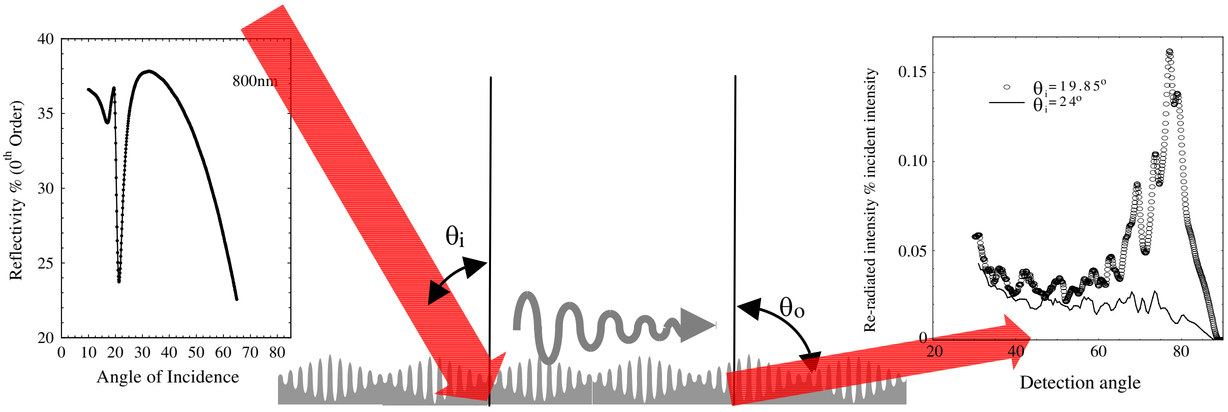

Figure 1: Bi-periodic nickel grating interaction with incident radiation.

as shown on the right of Figure 1. Full Fourier analysis of the surface structure and the diffractive orders and other phenomena it supports shows that the optical beam emerging from the surface at 77° arises solely from plasmons created by the beam incident at 19.85° which having travelled a short distance across the surface are re-coupled out. Fourier analysis of the surface periodicities also yields the width ΔK_{st}(FWHM) of the wavevector spectrum associated with imperfections in the periodicity of the output coupling structure as of the order of $0.24 \times 10^{-3}\,\mathrm{nm}^{-1}$. Any plasmon in the spectrum ΔK_{sp} can re-transform to form part of the well directed, low (∼85 mrad half angle) divergence beam of the optical radiation observed emanating from the surface at 77° if it can make an appropriate exchange of wave-vector with surface structure to satisfy conservation criteria.

Under the action of a magnetic field applied in the plane of the surface and transverse to the plasmon flux the intensity of the optical radiation emitted at 77° is recorded as a linear function of applied magnetic field. This is because as illustrated in Figure 2, the recorded output intensity arises from all possible combinations of wave-vectors in and between the spectra of the plasmons and output coupling structure subject to the constraint of wave-vector conservation $k_{sp}^{i} - k_{st}^{j} = k_{p}^{ij} \sin(\theta_o)$ where k_{sp}^{i} and k_{st}^{j} are respectively specific surface plasmon and structure wave-vectors within the corresponding spectra ΔK_{sp} and ΔK_{st} and $k_{p}^{ij} \sin(\theta_o)$ is the wave-vector of a re-emitted photon.

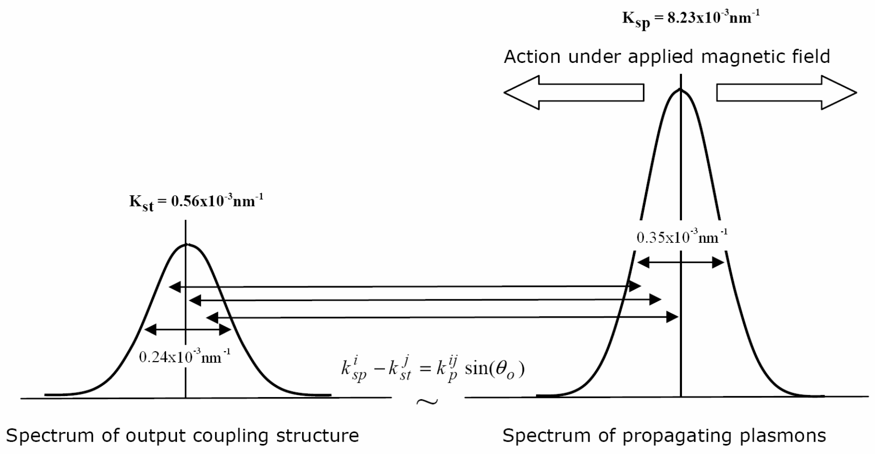

Figure 2: Origin of emission from grating and its magnetic dependency.

Therefore as the applied magnetic field reverses the magnetization of the nickel surface the frequency of the plasmons varies as determined by Nakamura and Paranjape [3] shifting the plasmon spectrum ΔK_{sp} first one way and then the other about its mean position in the absence of an applied field. This effectively "scans" states in the plasmon spectrum across those in the spectrum ΔK_{st} of wavevector states associated with the surface structure, which of course remain unchanged under magnetization reversal, producing the change in emitted intensity as the combinations of k_{sp}^{i} with

k^j_{st} possible under the conservation constraints vary.

Significantly no similar variation in emitted output is recorded when the applied field and hence the nickel magnetization is reversed along a direction collinear with the plasmon flux. A negative result in this configuration also precludes the effects observed in the transverse configuration arising from any conventional magneto-optic effect or resulting from changes in the coupling efficiencies of the input and out couplers as a consequence of magnetization induces changes in permittivity.

In principle we have an as yet unexploited mechanism for the frequency shifting or frequency modulation of optical radiation offering the prospect of new devices and technologies. Theory indicates that frequency shifts of an order relevant to wavelength division multiplexing in optical communications, frequency selection in spectral domain data storage technologies or the novel readout of conventionally recorded magnetic data may all be achievable. Practical realisation of these concepts is however somewhat constrained by the materials available and the strength of the magnetic fields required. Whilst silver and aluminium are the surfaces of choice for the efficient generation and propagation of plasmons the production of frequency shifts significantly greater than about ±2.6 GHz in plasmons propagating on either silver or aluminium is predicted to require the application of localised magnetic fields of magnitudes not easily attainable. However, much greater frequency shifts are predicted for magnetized ferromagnetic surfaces but at the expense of greatly reduced creation and propagation efficiencies. In Nickel the plasmon frequency shift under the action of the internal induction field is calculated to be about ±56 GHz. We have shown that not only do the surfaces of all three of the principle ferromagnetic elements support plasmon creation and propagation but that it is also possible to combine both metallic systems to optimise desired behaviour. Figure 3 for example, shows experimentally that the fields associated with plasmons propagating on thin silver layers deposited on top of a Nickel grating penetrate the Nickel surface to produce enhancement in the magneto-optic behaviour.

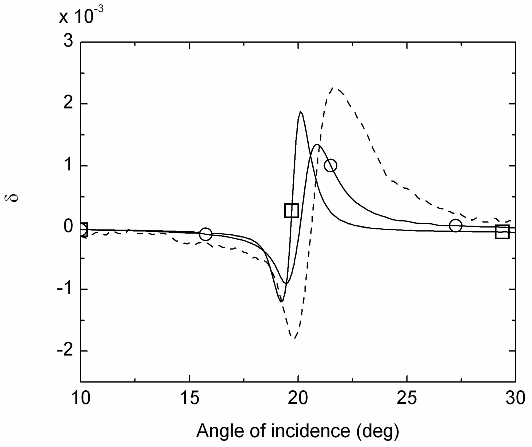

Figure 3: Transverse Kerr effect (δ) measurements *versus* angle of incidence at an optical frequency of 3.66×10^{14} Hz (819 nm) on silver films of different thicknesses (□ 16 nm and ○ 9 nm) supported on a 1200 nm period Ni grating, data for the bare Ni grating is shown for comparison (dotted line).

We explore the potential to create practical and useful devices based on the magnetic manipulation of propagating plasmons by considering the efficiencies of simple structures such as shown in Figure 4 and using the material data in Table 1.

Table 1.

	Wavelength nm	n	k	Propagation length µm	Penetration depth nm
Silver	1442	0.431	8.7	117	26
Nickel	1442	3.25	6.47	5	40

If the structure in Figure 4 is fabricated in silver, the plasmon path between input and output couplers is 30 μm and the angles of incidence, emission and the depths of the grating couplers are chosen to optimize the coupling efficiencies then the frequency of incident radiation can be easily shifted by ±2.6 GHz with an overall efficiency of 65%. This drops to 10% for nickel and requires the path length be reduced to 5 μm but should produce a frequency shift of the order of ±56 GHz, well within the range useful to the telecommunications industry.

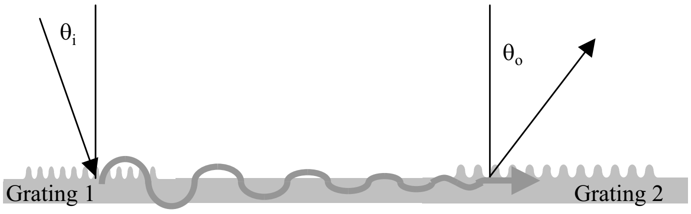

Figure 4: Schematic of simplest possible technologically relevant device.

At first sight it might appear that a similar sort of efficiency (11%) and frequency shift (13 GHz) should also be obtained by passing radiation back and forwards five times through the device fabricated in silver. Unfortunately the effect is reciprocal in nature in the transverse configuration. This concept should however be possible in the configuration in which the magnetic field is applied normal to the surface on which the plasmons propagate when the non reciprocal nature of the predicted interaction also offers the possibility of building novel optical- isolators.

Further calculations indicate that the overall input-output efficiency of devices fabricated in nickel can be dramatically improved whilst retaining much of the frequency shifting power of the ferromagnetic. This is achieved by overcoating them with very thin layers of silver. Plasmon generation efficiencies between 88% and 99.9% are obtained on optimally structured nickel profiles when overcoated with silver films between 5 nm and 15 nm in thickness. Under these circumstances the plasmon continue to interact with the field produced by the nickel since the plasmon penetration depth in silver is considerably less than the thickness of the silver films.

It would appear that devices based on this principle and of real relevance to the telecoms and other optical industries may be possible and certainly at the tens' of micron scale devices such as illustrated schematically below, where the arrows indicate reversible localized fields realized via current elements, could already be fabricated.

Figure 5: Schematics of other possible simple devices. (Left) Separation of information on to two frequency separated channels — depending on direction of field applied to individual arms their output frequency can be up-shifted, down shifted or unchanged with respect to the input. (Right) A device such as might be used to explore plasmon interferometers.

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