Review

Gaspar Armelles* and Alfonso Cebollada*

Active photonic platforms for the mid-infrared to the THz regime using spintronic structures

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Abstract: Spintronics and Photonics constitute separately two disciplines of huge scientific and technological impact. Exploring their conceptual and practical overlap offers vast possibilities of research and a clear scope for the corresponding communities to merge and consider innovative ideas taking advantage of each other's potentials. As an example, here we review the magnetic field modification of the optical response of photonic systems fabricated out of spintronic materials, or in which spintronic components are incorporated. This magnetic actuation is due to the Magneto Refractive Effect (MRE), which accounts for the change in the optical constants of a spintronic system due to the magnetic field induced modification of the electrical resistivity. Due to the direct implication of conduction electrons in this phenomenon, this change in the optical constants covers from the mid-infrared to the THz regime. After introducing the non-expert reader into the spintronic concepts relevant to this work, we then present the MRE exhibited by a variety of spintronic systems, and finally show the different applications of this property in the generation of active spintronic-photonic platforms.

Keywords: active photonics; infrared and THz spectral range; magneto refractive; magnetic fields; metasurfaces; nanostructures; photonics; plasmonics; spintronics.

1 Introduction

The combination of different disciplines that merge to generate added value materials and novel phenomena is a powerful route to face nowadays technological demands of the society. For example, great efforts have been made in

connecting photonics and magnetism and exploring the control of one by the other. Considering the magnetic field control of the optical response of materials, and focusing specifically into achieving active control of photonic devices, the use of an external magnetic field has many advantages: First, no electrical or any other kind of physical contact with the photonic device is needed to apply a magnetic field on it. In addition, since the magnetization reversal processes in ferromagnets is very fast, the time response of the photonic device to the magnetic field will therefore be very short, provided the suitable magnetic component is smartly incorporated in the design. Finally, many practical applications use magnetic fields. To name a few: magnetic separation, levitation or isolation; generation of electrical currents via electromagnetic induction; magnetic focusing and control of charged particle beams; many types of magnetic based sensors; magnetic storage, writing and reading of information ... all of them rely on the magnetic field action. All these examples make us consider that magnetism-related technologies are at a such mature stage that the technological integration of photonic systems with magnetic capabilities is realistic.

On the other hand, even though not considered in the present review, the control of magnetism using light offers also huge potential. For example, plasmon resonance assisted local heating is currently used for the so called Heat Assisted Magnetic Recording. On the other hand, Inverse Faraday Effect allows for direct magnetic writing using light of the adequate state of polarization. Additionally, the availability of ultrafast light sources allows for the subsequent ultrafast switching of magnetic domains.

Focusing on the realization of magnetically active photonic systems, several approaches have already been taken. For example, the so-called magneto photonic crystal structures allow a strong miniaturization of Magneto Optical (MO) components, with applications in information and communication technologies [1]. Another example is the case of Magneto Plasmonic (MP) systems, which combine MO and plasmonic materials, exploiting the synergy of their corresponding functionalities. In this sense, many approaches based on the plasmon enhanced

*Corresponding authors: Gaspar Armelles and Alfonso Cebollada, Instituto de Micro y Nanotecnología, IMN-CNM, CSIC (CEI UAM+CSIC), Isaac Newton, 8. Tres Cantos, 28760, Madrid, Spain, E-mail: gaspar.armelles@csic.es (G. Armelles); alfonso.cebollada@csic.es (A. Cebollada)

MO activity of different MP nanostructures have been considered up to date, showing great potential in sensing and telecom applications in the visible and near-infrared (NIR) ranges [2–6]. Unfortunately, the MO activity of most materials is strongly reduced in the infrared (IR) and lower energies and, if the magnetic field action is desired to modulate nanophotonic platforms in this spectral range, a different magnetic mechanism is needed.

Luckily enough, this mechanism is at hand and is linked to the discipline that has been responsible, for example, of the exponential increase in the last decades in magnetic storage capabilities in hard disk drives (HDD) heads. We are talking about the so-called Spin Electronics or Spintronics, the discipline which for the first time made use of both the charge and spin character of electrons for practical applications (Figure 1). Spintronics took off thanks to the revolutionary discovery by Fert and Grünberg's groups (1988–1989) of the Giant Magneto Resistance (GMR) effect in magnetic multilayers, which demonstrated a very large magnetic field induced change in electrical resistivity of a number of ferromagnetic systems [7, 8]. The technological impact of successive Spintronics breakthroughs into the magnetic storage area has not stopped ever since: inductive heads were substituted in 1991 by those based in the Anisotropic Magneto Resistance or AMR effect; these by GMR heads, introduced in 1997; taken then over by the Tunnel Magneto Resistance (TMR) or TMR based heads, incorporated in 2007. Quantitatively, in this span of time, the impact of Spintronics in this field implied an almost four orders of magnitude increase in the magnetic storage areal density [9]. Foremost academic recognition took place in 2007 with the Nobel Prize in physics awarded to the two GMR discoverers [10–12].

So, how can one then use Spintronics to act on Photonics? A pretty straightforward way to make this happen is actually at hand thanks to the so-called Magneto Refractive Effect (MRE), that describes the change in the refractive index of GMR systems due to magnetic field induced changes in electrical resistivity. The spin-dependent conduction electron transport inherent to GMR manifests directly in the optical properties from the NIR all the way to the THz range, where the contribution to the optical properties of conduction electrons dominate. The MRE was discovered in 1995 by Jacquet and Valet [13] in GMR magnetic multilayers, and since then has been applied for non-contact probing of the magnetotransport properties of a number of materials systems and spintronic devices.

Bearing in mind the great scientific and technological impact that Spintronics and Photonics already offer

Figure 1: Common room for Spintronics and Photonics. These two disciplines overlap in the low frequency range of the electromagnetic spectrum in which both, electrical conductivity and optical properties, rely on conduction electrons and are connected by the Magneto Refractive Effect.

separately, the aim of this review is to describe the current understanding of the potential of their combination in one of the directions previously described. Namely, we will present a detailed description of the spintronic effects on the optical properties of a variety of materials systems, and subsequently of the different approaches and proposals to exploit these effects in modulating or controlling photonic platforms. For this, we will first of all introduce the main spintronic effects, in a clear and concise way that allows the non-expert reader to understand the basic concepts involved. Due to the huge volume of literature published in this field, here we will just mention the pioneering publications where the different spintronic effects were first presented and those which for materials reasons may have a close connection to this review. We will then go into revisiting the main MRE studies in fully metallic, metal-insulator and oxide spintronic systems, as candidates for their possible incorporation as active building blocks in photonic platforms. Finally, the description of a number of these photonic platforms based on spintronic concepts will follow, covering both metal based plasmonic systems and dielectric based photonic structures. We will then summarize, with the main conclusions and the potential perspectives of this novel approach.

2 Brief tutorial on Spintronics

In this section we will present a general outlook of the main magnetotransport effects responsible for the magnetic field induced modification of the optical properties of spintronic systems. A more complete and extended discussion of these magnetotransport phenomena can be found in reviews and books already published on this subject. The effects described in what follows correspond to a large variety of materials: fully metallic, metal-dielectric and oxide-like systems, that therefore offer a wide variety of possibilities in the design of the photonic platforms, either fully made out of them, or into which they can be incorporated.

2.1 Anisotropic Magneto Resistance (AMR)

It has long been recognized that an externally applied magnetic field modifies the electrical properties of ferromagnetic materials. Back in 1856, W. Thompson already observed a magnetic field induced increase (decrease) of the electrical resistivity of iron and nickel when the current was applied parallel (perpendicular) to the direction of the magnetization [14]. This anisotropy in the magneto resistance of ferromagnets was studied in depth by Smit a century later [15], considering both pure ferromagnetic metals and alloys, explaining the difference between the longitudinal and transverse resistivities in base of the spin-orbit interaction. The use of the current term describing this phenomenon (Anisotropic Magneto Resistance - AMR) had to wait till 1975, when McGuire and Potter [16] extended Smit's work. As an example, in Figure 2A we present characteristic curves of the modification of the resistivity of a ferromagnet as a function of the applied magnetic field. As it can be observed, the resistivity depends, on one hand, on the magnetization (M) of the material and, on the other hand, on the orientation of the applied magnetic field with respect to the current. The relative change of the saturated resistivity for the magnetic field applied parallel and perpendicular to the current, $\Delta\rho/\rho = (\rho_{//} - \rho_{\perp})/\rho_{\perp}$, is the AMR ratio. For ferromagnetic metals the highest AMR ratios have been obtained in Ni based alloys, with values around 5% for $\text{Ni}_x\text{Fe}_{1-x}$ ($x \approx 0.9$), around 6% for $\text{Ni}_x\text{Co}_{1-x}$ ($x \approx 0.8$) at room temperature (RT) for bulk samples, and slightly lower values for thin films [16, 17].

2.2 Giant Magneto Resistance (GMR)

Chronologically, the breakthrough following the use of AMR in practical applications was the discovery of the Giant Magnetoresistance (GMR) [7, 8]. First reported for the Fe/Cr/Fe system, large changes of electrical resistivity were observed when switching with a magnetic field the relative orientation of the magnetizations of the individual Fe layers from antiparallel (AP) to parallel (P) states, linked to a high and low electrical resistivity state, respectively. These large changes of the electrical resistivity only occur for specific Cr thickness, for which the adjacent Fe layers are coupled antiparallel. This antiparallel orientation of the magnetization of the adjacent Fe layers can be switched to parallel orientation by the application of a large enough magnetic field (see Figure 2 B). After this discovery, the portfolio of multilayered systems based on different components rapidly expanded. GMR ratios as high as 65% at RT were soon reported in Co/Cu structures for saturation magnetic fields of 10 KOe [18], while ratios of 12% were obtained for $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ structures, but for much lower saturation fields (30 Oe) [19]. A drawback of these multilayered systems is that the thickness of the spacer to get AP configuration may require accuracy at the atomic level. As an alternative, the so-called spin valves [20, 21] utilize two magnetically uncoupled ferromagnetic layers separated by a metallic spacer, one of the layers for example magnetically pinned to an antiferromagnet via exchange bias [22], so that magnetization reversal of the pinned and the unpinned layers occurs at different magnetic fields, controlling with a magnetic field the P and AP states.

Regarding the physical mechanism responsible for GMR, the change in the resistivity of these systems can be understood taking into account that the main scattering mechanisms are spin-conserving and that the electrical conductivity is the sum of the conductivity of majority (spin up) and minority (spin down) electrons (two current model) [23]. In Figure 2B we present a very schematic representation of the Density of States (DOS) for the parallel state (P), split into localized and propagative electrons, as a function of the energy. Due to the exchange interaction, the energy dependence of the DOS of the localized electrons, responsible for the magnetization, is different for spin up ($e \uparrow$) and spin down ($e \downarrow$) electrons. Besides, the localized states of the spin up electrons are nearly all occupied, whereas the spin-down localized states are partially occupied. On the contrary, the DOS of

Figure 2: Four spintronic phenomena leading to MRE. (A) Anisotropic magnetoresistance (AMR): black and green curves represent, respectively, the dependence of electrical resistivity and magnetization on the applied magnetic field for a ferromagnetic layer. The magnetic field varies from positive to negative (dotted lines) or from negative to positive (full lines). (B) Giant magnetoresistance (GMR): Left panel. - black and green curves represent, respectively, the dependence of electrical resistivity and magnetization on the applied magnetic field for a ferromagnetic/non ferromagnetic metallic multilayer. The magnetic field varies from positive to negative (dotted lines) or from negative to positive (full lines). Right panel. - Schematic representation of the Density of States (DOS) of a multilayer in the P state for different types of electrons. (C) Tunnel Magneto Resistance (TMR): Left panel. - Black curves represent the dependence of the tunnel resistivity on the magnetic field, whereas the green, red and blue curves represent the dependence of the total magnetization and the magnetizations of the FM1 (represented in red) and FM2 (represented in blue) layers on the magnetic field, respectively. The insulator spacer layer is represented in grey. The magnetic field is applied in the plane and varies from positive to negative (dotted lines) or from negative to positive (full lines). Right panel. - Schematic representation of the DOS of all the electrons, for the parallel (P) and antiparallel (AP) configurations, for the two ferromagnetic electrodes FM1 and FM2, respectively. The blue (red) regions correspond to the electrons whose spin points to the positive (negative) direction. The blue and red arrows represent the tunnel current of each spin channel. (D) Colossal Magnetoresistance (CMR) (From ref [29], <https://doi.org/10.1103/PhysRevLett.75.3336>, with permission): Left panel. - Resistivity (upper graph) and magnetization (lower graph) as a function of the temperature for different values of the applied magnetic field. The values of the magnetic field in Tesla along with the corresponding line colors are indicated in each graph. Crystal structure of a representative CMR compound.

the propagative electrons, which are responsible for the electric conductivity, is very similar for both spins. At the Fermi energy, the scattering time of these propagative electrons depends on the number of states available for scattering which, due to the occupation of the localized band, is different for the spin up and spin down electrons. As a consequence, a much higher conductivity (and, therefore a low resistivity) for the spin up current than for the spin down current is obtained for the P state. On the other hand, for the AP state the conduction electrons are

indistinguishable, which results in a symmetrization of the available scattering channels and, therefore, an increase of the resistivity.

2.3 Tunnel Magneto Resistance (TMR)

So far, the described AMR and GMR spintronic effects are both spin dependent electron transport properties characteristic of fully metallic systems. Interestingly enough,

this spin dependence of the electron transport manifests also in tunnel junction systems, i.e. metal-insulator-metal structures with a very thin insulator spacer. This was first observed by Tedrow and Meservey in 1971 [24]. Two decades after this discovery, coincident with the Spintronics boom, the study of Magnetic Tunnel Junctions (MTJ), where the metallic electrodes are ferromagnetic, acquired renewed interest. Many groups started then working in this topic, and nowadays MTJs are applied in a wide variety of uses, such as data storage, generation of THz radiation, or other spintronic systems [25].

In an MTJ, the electrical resistivity between the two ferromagnetic electrodes depends dramatically on the relative orientation of their magnetizations (see Figure 2C). Such behavior is due to the magnetization dependence of the tunnel probability between these two electrodes. Generally speaking, when the two metallic electrodes magnetizations are parallel, the majority electrons (spin up) tunnel toward majority electrons (spin up), whereas the minority electrons (spin down) tunnel toward spin minority down electrons (spin down). On the other hand, when the two electrodes magnetizations are oriented antiparallel, the majority electrons of the emitting electrode tunnel toward states which have the same orientation of spin (minority electrons for the receiving electrode), whereas the minority electrons (spin down) tunnel toward majority electrons. As the tunnel current depends on the DOS of the initial and final electrodes, the tunnel current is different for the P and AP relative orientation of the two electrodes magnetizations.

The values of TMR depend on a large variety of parameters, such as the composition, nanostructure and interface quality of both the electrodes and the dielectric barrier. Just to mention, values as high as 400 % at RT and magnetic fields of 200 Oe have been reported for MTJs using $\text{Co}_2\text{FeAl}_{0.5}\text{Si}_{0.5}$ electrodes and MgO barriers [26]. Both the large changes in resistance and the low magnetic fields required made TMR a very promising candidate mechanism for practical applications.

2.4 Colossal Magneto Resistance (CMR)

The last spintronic phenomenon to be considered here, exhibiting huge changes in electrical resistance upon application of a magnetic field, involves neither metal nor metal-insulator materials, but this time pure oxide systems (see Figure 2D). In the time scope of the nineties of the last century, MR values as high as 10^5 % at 77 K were reported in perovskite-like manganite thin films [27]. Obviously these impressive figures, motivating the “colossal”

adjective to the observed MR effect, promised great potential for this kind of systems, opening a new research route for the development of spintronic devices based on these materials. Their magnetotransport behavior and the corresponding interpretation moved away from the other type of MR structures involving pure metallic components. These systems exhibit a combined metal-insulator and ferro-paramagnetic transition, and a complete interpretation of such complex phenomenology lies beyond the present review, addressing the reader to specialized works [28]. As an example, in Figure 2D we present characteristic resistivity curves as a function of the temperature for a Mn-based perovskite oxide ($\text{La}_{0.75}\text{Ca}_{0.25}\text{MnO}_3$) [29]. As it can be observed, starting from low temperatures the resistivity of these materials increases with temperature, with a dramatic jump at a particular temperature, T_s . This large jump happens to be magnetic field dependent, and the relative change of the resistivity with the magnetic field can be huge. This interesting effect has been observed in a variety of oxide compounds and, as mentioned, its origin is related to a ferromagnetic metal - paramagnetic insulator transition. In Figure 2D we also present characteristic curves of the magnetization as a function of temperature for different magnetic fields. There we can see that, for temperatures lower than T_s , where the resistivity is low, the magnetization follows the magnetic field dependence of a ferromagnet, whereas above T_s , where the resistivity is much higher, the magnetization follows the magnetic field dependence of a paramagnet. So far, and even though progress has been made to increase T_s and decrease the required magnetic fields, the results thus obtained are still too low and too high, respectively, for many practical applications.

To conclude this Section 2, we would like to emphasize that there are a pretty large variety of structures and materials combinations which share the common characteristic of providing a change in electrical resistivity under application of a magnetic field. This wide diversity, from a photonic point of view, provides with a huge versatility since a large range of optical constants will be available depending on the selected spintronic material/component.

3 The Magneto Refractive Effect (MRE)

In the preceding section we have discussed the spintronic effects on the DC conductivity; in this section, we will review the optical counterpart of these effects. The linear

optical response of materials can be described either by the dielectric tensor, $\varepsilon(\omega)$ (or complex refractive index, $n + ik$: $\varepsilon = (n + ik)^2$) which relates the electric displacement $D(\omega)$ to the electric field $E(\omega)$: $D(\omega) = \varepsilon(\omega) E(\omega)$, or by the conductivity, $\sigma(\omega)$, which connects the current density, $J(\omega)$, to the electric field: $J(\omega) = \sigma(\omega)E(\omega)$. Both tensors are related: $\varepsilon(\omega) = 1 + i\frac{\sigma(\omega)}{\omega}$, and can be used alternatively. However, the dielectric tensor is normally used to describe the linear optical response in spectral regions, or in materials, where the main contribution to the optical properties comes from electronic interband transitions or phonons such as, for example, in dielectric materials, where the displacement vector plays a major role. On the other hand, the conductivity is preferred in those situations (either materials or spectral regions) where the current density is more appropriate to describe light-matter interaction, like for example in metallic systems. In this context, and due to the different nature of the spintronic materials, both descriptions can be found in the literature and, accordingly, will be used in this review, representing “two sides of the same coin”. Besides, both $\varepsilon(\omega)$ or $\sigma(\omega)$ can be modified by an external stimulus, such as a magnetic field. The first observation of a magnetic field induced modification of the optical response of a ferromagnet goes back to 1877, when John Kerr observed a rotation of the plane of polarization of the light reflected from “the surface of intensely magnetized iron” [30]. Since then, other magnetic field related optical effects have been observed, most of them linked to magnetization induced changes of the dielectric/conductivity tensor. To illustrate it, in Figure 3A we present the effective dielectric tensor of an isotropic ferromagnet fully magnetized along the x direction up to second order in magnetization (M); the same applies for the conductivity tensor, but for the sake of simplicity we focus here on the dielectric tensor. As it can be observed, linear terms with the magnetization appear in the non-diagonal elements of the dielectric tensor. They correspond to the MO activity of the material, and may give rise to changes in the state of polarization or in the intensity of the reflected or transmitted light produced by the magnetic field. In the case of reflected light, these changes correspond to the so-called MO Kerr effect (MOKE), which is widely used as an optical tool for magnetic characterization of ferromagnetic systems. For example, in Figure 3B we present a characteristic MO Kerr effect loop measured in transverse configuration, i.e., magnetic field in the plane and perpendicular to the plane of incidence. As it can be seen, at oblique incidence the magnetic field induced change in the reflected intensity of a p polarized light is proportional to the x component of the magnetization. On the other hand, terms quadratic with the magnetization also appear in the diagonal components

of the dielectric tensor and give rise to a magnetic field dependence which is quadratic with the component of the magnetization (see Figure 3B). They are responsible of magnetic effects such as the Orientational MO Effect (OME), to be commented in the next subsection, and that results in a different optical response for light polarized parallel or perpendicular to the magnetization. Within this category of quadratic terms also falls the MRE, mentioned in the introduction. Jacquet and Valet discovered the MRE in a series of $\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{Co}/\text{Cu}$ GMR multilayers [13], where they realized that the change of resistance intrinsically due to the GMR directly implied a change in the refractive index of the system, change that was more evident in spectral regions where interband transitions were absent (IR region). This was due to the leading role of conduction electrons in defining both the electric transport and optical properties in this spectral range. Not much later, and in the same line, Kubrakov and coworkers theoretically postulated the existence of this “intensity magneto-optical effect” in GMR materials [31]. This discovery set up the connection between Optics and Spintronics and, since then, the MRE has been used to optically probe (therefore without the need of electrical contacts) the magnetotransport properties of a variety of spintronic

Figure 3: Linear and quadratic dependence of magnetization related optical effects. (A) Dielectric tensor of an isotropic ferromagnet fully magnetized along the x direction. M represents the magnetization, and a , b and c are coefficients related to the Magneto Optical (MOE), Magneto Refractive (MRE) and Orientational Magneto Optical (OME) effects, respectively. (B) Reflectivity vs magnetic field curves showing the different magnetic field dependence of the linear (OME) and quadratic (MRE, OME) effects, respectively.

devices and systems as well as to get a deeper understanding of the spin polarized electron properties of ferromagnets [32–43]. As an example in Figure 4 we present curves of magnetic field dependence of the resistivity and the optical response in the aforementioned spectral range for different spintronic systems. In all of them, the two magnitudes (resistivity and optical response) have the

same magnetic field dependence, highlighting the direct connection of MRE with the magnetotransport properties.

In the previous section we have put in evidence the different nature of the mentioned spintronic effects, the materials systems or complex structures exhibiting them, and the corresponding physical mechanisms underlying. This section now will follow a parallel logic, describing the corresponding optical phenomena associated to the spintronic AMR, GMR, TMR and CMR effects.

Figure 4: Magnetic field dependence of magneto-transport and corresponding MRE in different types of spintronic structures. (A) Curves of the relative change of the resistivity (black) and optical transmission at $10.6\ \mu\text{m}$ (red) as a function of the in-plane magnetic field for a $\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{Co}/\text{Cu}$ multilayer. From ref [13], J. C. Jacquet and T. Valet, “A new magneto-optical effect discovered in magnetic multilayers: the magnetorefractive effect,” *Mat. Res. Soc. Symp. Proc.*, vol. 384, 477, 1995, with permission. (B) Curves of the relative change of the resistivity (upper panel) and optical transmission at $5\ \mu\text{m}$ (lower panel) as a function of the in-plane magnetic field for a $\text{Fe}/\text{Cr}/\text{Fe}$ trilayer. From ref [52], <https://doi.org/10.1103/PhysRevB.57.2705>, with permission. (C) Curves of the relative change of the resistivity (black) and IR integral reflectivity (red) as a function of the in-plane magnetic field for a Spin Valve. From M. Vopsaroiu, M. G. Cain, and V. Kuncser, “The integral magnetorefractive effect: a method of probing magneto-resistance,” *J. Appl. Phys.*, vol. 110, p. 056103, 2011, with the permission of AIP Publishing. (D) Curves of the relative change of the resistivity (dots) and reflectivity at $8.84\ \mu\text{m}$ (squares) as a function of the in-plane magnetic field for a $\text{Co}_{43}\text{Al}_{22}\text{O}_{35}$ nanocomposite film. Reprinted by permission from Springer Nature: Springer Nature Physics of the Solid State, Magnetorefractive effect in granular alloys with tunneling magnetoresistance, I. V. Bykov et al, [77], Copyright 2005.

3.1 The MRE for AMR systems: The Orientational Magneto Optic Effect

Interestingly enough, three decades before the advent of Spintronics Krinchik and coworkers discovered what they called the Orientational Magneto-optic Effect (OME). It consisted on a change in intensity of the reflected light off different ferromagnetic metals in the $0.8\text{--}2.5\ \mu\text{m}$ spectral range, which depended on the relative orientation of the magnetization with respect to the light polarization plane [44,45]. This pretty much corresponds to the optical counterpart of the AMR, which accounts for the dependence of the electrical resistivity on the relative orientation of the electrical current and the magnetization. Krinchik’s measurement configuration was basically that of the equatorial (or transverse) Kerr effect but, unlike it, the OME did not change sign when reverting sign of the magnetization. This means it was quadratic instead of linear with respect with the magnetization, as we have shown in the R vs H graph for MRE and OME in Figure 3B. In Krinchik’s work considered spectral range, the main contribution to the optical properties comes from inter-band transitions, and the observed effect was attributed to modification of these transitions, induced by the spin-orbit interaction.

Moving forward to the Spintronics era, the consequences on the optical properties of systems due to the presence of AMR were also studied. In 1999 [46] van Driel and coworkers carried out a systematic investigation measuring the magnetic linear dichroism for IR light in several ferromagnetic alloy films. They attributed the observed difference in transmission between light polarized parallel and perpendicular to the magnetization direction of the films to the AMR. Explored in this case in the $2.5\text{--}20\ \mu\text{m}$ range, again with conduction electrons as main contributors to the optical properties, the observed effect was considered as the analogous to the MRE observed in GMR systems recently discovered, and was interpreted in terms of a Drude-type two current model.

3.2 MRE in GMR systems

Right after its discovery, the number of systems where the presence and optimization of GMR was studied rapidly increased, with a large diversity of proposals in terms of structuring and materials choices. A large variety of works appeared, growing and characterizing multilayers based in the periodic repetition of a bilayer building block (like the Fe/Cr in the pioneering works). Other alternatives were also considered, such as multiple layers of different ferromagnetic materials each with a specific functionality to optimize antiparallel arrangement of the ferromagnets (exchange biased spin valves), or even granular alloys where metallic aggregates of ferromagnetic metals were embedded in a metallic matrix. However, the exploration of the GMR effects on the IR optical properties was limited by the availability in the same laboratory of magneto transport and magnetic characterization techniques, as well as suitable MO setups. In spite of the technical challenge, different groups involved in the growth and study of spintronic systems soon explored the corresponding MRE properties. Apart from the $\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{Co}/\text{Cu}$ multilayers of Jacquet and Valet MRE pioneering work [13], various other systems have been studied in the near and far infrared range, such as Co/Cu [34, 36, 47, 48] and CoFe/Cu multilayers [40, 49, 50, 51]; Fe/Cr structures [52–54];

granularly alloyed CoAg films [32, 33, 55]; or spin valves with CoFe ferromagnetic layers [39, 56, 57]; and others [37, 58]. In nearly all these systems the strength of the magnetic field that is needed to change the relative orientation of the magnetization of the ferromagnetic entities (i.e.: from AP to P states) is in the range of KOe, and the maximum intensity of the magnetic modulation of the IR optical response depends on the material, varying between 0.2 to 7% (see Table 1).

There is experimental evidence of MRE mediated magnetic modulation all the way to the THz regime, where transmission measurements under a magnetic field have been also carried out. In Figure 5 we present a layout of the transmission experiment using a standard THz time-domain spectroscopy arrangement, and the results as a function of the applied magnetic field obtained by Jin and coworkers [42]. As it can be seen, the THz transmitted pulse gradually decreases its amplitude as the magnetic field increases, along with the corresponding increase of the sample conductivity concomitant to the GMR effect. In their work, Jin et al. obtained a magnetic modulation of the transmission as high as a 20% relative change for applied magnetic fields around 1 KOe in NiCoFe/Cu multilayers with GMR values of 20%.

Regarding the physical mechanism responsible for the MRE in GMR systems, and despite the fact that interband

Table 1: MRE intensities in a variety of spintronic structures: Columns from left to right: Type and composition of the structures. Representative values of the magnetic field induced changes of the electrical resistivity. Spectra range of the optical measurements. Absolute value of the maximum of the MRE spectra in transmission ($\Delta T/T$) or reflection ($\Delta R/R$). Characteristic magnetic fields at which the MRE spectra were obtained.

Material GMR-Like	$\Delta\rho/\rho$ (%)	Spectral Range (μm)	$\Delta T/T$ (%)	$\Delta R/R$ (%)	H (Oe)	Ref.
$\text{Ni}_{80}\text{Fe}_{20}/\text{Cu}/\text{Co}$	13.9	2–20	5	-	600	(13)
Co/Cu	50–65	2.5–22.5	-	5.4–7.2	13K–9 K	(34),(47)
CoFe/Cu	13–28.3	1–25	1.5	0.08–1.2	2 K–12 K	(40),(49), (50),(51)
Fe/Cr	3.8–11	2–13	1.1–0.8	0.18–1.8	3.5 K–9 K	(52),(53),(54)
NiCoFe/Cu	20	THz	20	-	1 K	(42)
$\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$	4	2–15	2.8	0.045	30	(61),(63)
CoAg granular	5.5–6.5	2–18.2	1.1	0.75	1.5 K–4 K	(55),(32)
Spin-Valves						
PtMn/CoFe-Ru/Cu/CoFe-Py	7.2	2.5–20	-	1.8	9 K	(56)
FeMn;NiO/Py/Cu	3.6–6.4	2.5–22.5	2–2.5	-	50	(60)
$\text{CoO}_x/\text{Co}/\text{Cu}/\text{Co}/\text{Fe}$	2.2	2.5–25	1.4	-	300	(57)
Granular dielectric TMR-like						
CoFe- Al_2O_3 (HfO_2)	4.3–7.5	2.5–25	-	0.35–0.45	12 K	(70)
CoFe/ Al_2O_3 (MLs)	5.5	2.5–22	-	2.55	4 K	(65),(66)
CoFe-MgF	7.5	2–20	-	1.5	1.7 K	(75)
CoFeZr-SiO ₂	3.5	1.43–20	-	0.1	1.7 K	(76)
Co- Al_2O_3	8	1.43–20	-	0.8	2.2 K	(76)
Fe-SiO _n	1.2	1.43–20	-	0.2	2.2 K	(76)

Figure 5: Terahertz magnetospectroscopy experiment showing 20% magnetic modulation. Schematic of the terahertz magnetospectroscopy experimental setup. The polarization of the electric field of the terahertz pulse and that of the applied magnetic field are in the plane of the sample. Transmitted terahertz pulse as a function of applied magnetic field for a NiCoFe/Cu GMR multilayer. A reduction of the pulse amplitude by 20% is clearly observed (see lower inset). Reprinted by permission from Springer Nature: Springer Nature, Nature Physics, Accessing the fundamentals of magnetotransport in metals with terahertz probes, Zuanming Jin et al, [42] Copyright 2015.

transitions may play a role [48], it has been shown that a good description of the effect can be obtained taking only into account the contributions of conduction electrons. In this context, the conductivity is more suited to describe the linear optical response. Moreover, the contribution of the conduction electrons to the conductivity can be split into two parts, each one corresponding to one of the two spin orientations. Therefore, according to this simple model, when the system is in the parallel configuration (fully magnetized), the conductivity can be expressed as:

$$\sigma_P(\omega) = \frac{\sigma_{\downarrow}(DC)}{(1 + i\omega\tau_{\downarrow})} + \frac{\sigma_{\uparrow}(DC)}{(1 + i\omega\tau_{\uparrow})}$$

$\tau_{\downarrow,\uparrow}$ and $\sigma_{\downarrow,\uparrow}(DC)$ are the spin-dependent electron relaxation times and the dc conductivities for each spin channel. This DC conductivity is related to the electron mass (m) and electron density (n) as: $\sigma_{\downarrow,\uparrow}(DC) = \frac{e^2 n_{\downarrow,\uparrow} \tau_{\downarrow,\uparrow}}{m_{\downarrow,\uparrow}}$. In this approach the spin dependent electron densities, relaxation times and masses can be viewed as “mean”

values and treated as empirical parameters. Depending on the internal structure of the GMR system, granular or multilayered, and on the thickness of the layers, the relationship between these “mean” values and those of constituent materials and interfaces will be different. On the other hand, when the system is in the antiparallel configuration the two types of electrons are indistinguishable and both have the same contribution. In this case the conductivity is simply:

$$\sigma_{AP}(\omega) = \frac{\sigma_{AP}(DC)}{(1 + i\omega\tau_{AP})}$$

$\sigma_{AP}(DC)$ and τ_{AP} are the DC conductivity and relaxation time for the AP configuration, respectively. They can also be treated as empirical parameters. Obviously, the conductivity of the AP and P states must be related, and different approaches have been proposed to connect them, such as to assume equal electron concentration and masses for both spins and correlate the relaxation times of the AP and P states as: $1/\tau_{AP} = (1/2) \cdot (1/\tau_{\uparrow} + 1/\tau_{\downarrow})$, or to express the conductivities of the AP and P states in terms of the conductivities of the spin up and spin down electrons [13, 59–61]. Finally, the differences in the conductivity results in a difference of the optical properties for the two magnetic states of the system.

In terms of practical applications, to maximize the MRE signal along with reducing the required magnetic field is an extremely important added value. In this sense, the use of the $\text{Ni}_x\text{Fe}_{1-x}$ ($x \approx 0.8$) type of alloys is of great convenience due to their very low saturation fields, and multilayers, spin valves and granular systems in which the ferromagnetic component is this material have demonstrated large GMR values at low magnetic fields [19, 20, 21, 62]. With this in mind, and for example using $\text{Ni}_{80}\text{Fe}_{20}$ as the ferromagnetic component, MRE values equivalent to those obtained for high fields in other systems were reported in a series of spin valves by van Driel et al. [60]. As it can be seen in Figure 6, the spectra of the magnetic field modulation of the transmission at normal incidence are presented for two different types of $\text{Ni}_{80}\text{Fe}_{20}$ based exchange-biased spin valves. The difference between these two groups is the antiferromagnetic (AF) exchange biasing layer, which pins the magnetization of the adjacent $\text{Ni}_{80}\text{Fe}_{20}$ layer. In one group this AF layer is metallic ($\text{Fe}_{50}\text{Mn}_{50}$) and it is located at the top of the structure and in the other group it is insulating (NiO) and located at the bottom of the structure. In these structures, the $\text{Ni}_{80}\text{Fe}_{20}$ layer which is not in contact with the AF layer can switch the relative orientation of its magnetization with respect to the pinned $\text{Ni}_{80}\text{Fe}_{20}$ layer, between parallel (P) and antiparallel (AP), giving rise to a change of the in-plane

Figure 6: MRE in two $\text{Ni}_{80}\text{Fe}_{20}$ based types of spin valves. MRE spectra ($\Delta T/T = (T_{AP} - T_P)/T_P$) of unpolarized light at normal incidence of the spin valves schematically represented on the top part of the figure for different values of the Cu layer thickness. The lines are guides to the eye. From ref [60], <https://doi.org/10.1103/PhysRevB.61.15321>, with permission.

resistivity (GMR). The magnetic field needed to produce this switching is approximately 50 Oe. The GMR value depends on the thickness of the non-magnetic Cu layer, and so do the MRE spectra, which also show a tendency to increase their intensities with the increase of the GMR values.

Recently, sizeable MRE values at very low magnetic fields (a few tens of Oe) have been reported in the $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer system [61, 63]. In the upper panel of Figure 7A we show schematics of such multilayer, typically deposited on $\text{CaF}_2(111)$ single crystalline substrates with a Ti seed layer. Accordingly, in the lower panel of Figure 7A we present the magnetic field modulation of the transmission at normal incidence for two $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers with different Au layer thicknesses. The difference in the Au thicknesses results in a difference of the GMR values (4% for 2.3 nm Au, 0.8% for 3.3 nm), with in turns give rise to a difference in the intensity of the magnetically modulated IR signals. However, the effect of this variation in the Au thickness on the optical properties of the multilayer is very small. For example, in the upper panel of Figure 7B we present the effective dielectric constant for the two $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers shown in Figure 7A. As it can be observed the effective dielectric constants are very similar, showing the multilayer with higher amount of Au a more metallic character. However, and in accordance with the MRE spectra, the magnetic modulation of the effective dielectric constant for these two multilayers is very different (lower panel of Figure 7B). In particular, the intensity of such modulation increases as we increase the GMR value of the multilayer. The dots correspond to the experimental data and the lines are fits using the model of

Figure 7: Schematic, MRE spectra, dielectric constant and magnetic modulation of dielectric constant in $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers with different values of GMR. (A) Upper panel. - Schema of the $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer internal structure. Lower panel. - MRE spectra ($\Delta T/T = (T_P - T_{AP})/T_{AP}$) of unpolarized light at normal incidence for two multilayers with different Au thicknesses. (B) Upper panel. - Spectra of the real (full dots) and imaginary (empty dots) parts of the effective dielectric constant of the two multilayers: dots are experimental values and lines theoretical fits. Lower panel. - Spectra of the difference of the dielectric constants, $\Delta\epsilon = \epsilon_P - \epsilon_{AP}$ (full dots: real part; empty dots: imaginary part) for the two multilayers. The dots correspond to experimental values, the red lines represent a theoretical fit for a multilayer with 0.8% GMR, and the gray dashed lines and black lines represent two theoretical simulations for a multilayer with 4% GMR, (see text). Adapted with permission from ref [61], © The Optical Society.

ref 61. Worth to mention is the information that can be extracted from the spectral dependence of the magnetic modulation of the optical properties and, in particular, of the spin up vs. spin down ratio of both, scattering time and electron concentration. For example, in the lower panel of Figure 7B we also present the theoretical changes of the effective dielectric constants for a multilayer with 4% GMR value, but with different relative concentration of spin up and spin down conduction electrons and relaxation times (black lines and gray dashed lines). A change of only 5% in the relative concentration of the conduction electrons, $\Delta n/n = (n_{\downarrow} - n_{\uparrow}) / (n_{\downarrow} + n_{\uparrow})$, gives rise to a strong increase and a red shift of the real part of the dielectric constant, but with similar changes in the imaginary part (gray dashed lines $\Delta n/n = 0$, black lines $\Delta n/n = 5\%$). On the other hand, in this spectral range the changes of the dielectric constants are less sensitive to the differences of the relaxations times between the two spins, which for this specific case are very

similar, 19.6% (gray dashed lines) and 24.5% (black lines), respectively.

3.3 MRE in TMR and nanocomposite systems

Not surprisingly, the interest raised about the MRE in GMR systems occurred again with the discovery of the TMR. This was specially so because magnetic tunnel junctions are extremely delicate devices, very sensitive to statics, and whose cross checking without the need of electrical contacts is a great advantage. To mention a few examples, TMR systems where the MRE has been studied includes: different ferromagnetic continuous layers with spacers like MgO [64], Al₂O₃ [65, 66], or C [67]; a variety of metal-dielectric granular structures such as CoFe and similar ferromagnetic clusters in Al₂O₃, HfO₂, SiO_x or MgO matrices [68–76]; or so-called metal-insulator alloys [77]. As a representative example, in Figure 8 A we present MRE reflectivity spectra corresponding to (CoFe)_x(Al₂O₃)_{1-x} (upper graph) and (CoFe)_x(HfO₂)_{1-x} (lower graph) granular films for different compositions (x). As it can be observed, both compounds show sharp features in the MRE spectra around the frequencies of the longitudinal optical phonon modes of the dielectric matrices [70]. Also in Figure 8B we present experimental (upper graph) and simulated (lower graph) reflectivity and MRE reflectivity spectra of a CoAlO nanocomposite film [77]. As it can be seen, both, reflectivity and MRE spectra, show an oscillatory behavior due interference effects between the film and substrate. A good description of the experimental spectra is obtained assuming that the MRE effect is due to the magnetic field dependence of the tunnel current between adjacent grains, being the tunnel probability between the grains independent on the frequency. Therefore, the magnetic field dependence of the conductivity can be expressed as:

$$\sigma(\omega, H) = \frac{1}{\rho(H)} + i \frac{\omega \epsilon_c}{4\pi}$$

with $\rho(H)$ the DC electric resistivity, which depends on the applied magnetic field. Consequently, the changes in the complex refractive index can be related to the changes in the DC resistivity as follows.

$$\frac{\Delta n}{n} = \frac{\Delta \rho}{\rho} \frac{(k_0/n_0)^2}{1 + (k_0/n_0)^2}$$

$$\frac{\Delta k}{k} = \frac{\Delta \rho}{\rho} \frac{1}{1 + (k_0/n_0)^2}$$

with n_0 , k_0 the refractive index and absorption coefficient at zero field [76] (for simplicity the frequency dependence of n_0 , k_0 has been omitted). This simple model serves also for a qualitative description of other granular systems, but fails at explaining the observed features related to the longitudinal optical modes in CoFe-Al₂O₃, CoFe-HfO₂ granular films or Fe/MgO tunnel junctions, which strongly suggests that the optical vibrational modes of the matrix/spacer layer may also play a role in this magnetic field dependence of the optical response [78]. In fact, this represents a very good example of the complexity of describing MRE effects in TMR-like systems, where tunnel current between adjacent metallic entities may depend of several factors such as the nature of the barrier, the quality and crystallographic orientation of the metal/dielectric interface, etc. In spite of this lack for a simple theoretical interpretation, the TMR values as high as 400% at RT reported in specific systems [26] offer great deal of motivation for further exploring the MRE associated to TMR systems.

Figure 8: MRE spectra for different types of TMR systems. (A) p-polarized MRE spectra ($\Delta R/R = (R_H - R_{H=0})/R_{H=0}$) for (CoFe)_x(Al₂O₃)_{1-x} (upper graph) and (CoFe)_x(HfO₂)_{1-x} (lower graph) granular films with different metallic concentration (x) for H = 12 kOe, Reproduced from ref [70], <https://doi.org/10.1103/PhysRevB.79.144409>, with permission. (B) Experimental (upper graph) and simulated (lower graph) MRE spectra ($\Delta R/R = (R_H - R_{H=0})/R_{H=0}$) and reflectivity R spectra (dashed lines) for a Co_{51.5}Al_{19.5}O₂₉ nanocomposite film obtained with s- and p-polarized light for H = 1600 Oe, Reprinted by permission from Springer Nature: Springer Nature Physics of the Solid State, Magnetorefractive effect in granular alloys with tunneling magnetoresistance, I. V. Bykov et al, [77], Copyright 2005.

3.4 MRE in CMR-like and oxide systems

In connection with the large changes in the resistivity observed in manganites with CMR, magnetic field modulations of the far infrared optical response of the order of 30-50% have been observed at low temperature in a variety of CMR manganites compounds [43, 79]. However, the number of manganites with sizable RT magnetic modulation is much more scarce. For example, a 6% magnetic modulation for a magnetic field of 8 KOe has been obtained in $\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$ [80], whereas values of 15% have been reported for $\text{La}_{0.8}\text{Ag}_{0.1}\text{MnO}_{3+d}$ [81]. On the other hand, the magnetic field induced modifications of the optical properties in CMR oxides involve, not only the change in the conductivity induced by the magnetic field, but also other aspects, such as modifications of the band structure, or the appearance of different magnetic phases within the compound. All these mechanisms make the description of the MRE effect in CMR oxides very challenging. Finally it is worth mentioning that MRE has also been reported in a number of manganite/oxide systems that exhibit CMR in the visible and near-IR NIR [82–88].

4 Photonic structures controlled via MRE

In this final section we are going to present a compilation of the results where spintronic-based systems are utilized to develop a variety of active photonic platforms. Several approaches have been pursued, including their use in granular structures where the granulates themselves are spintronic materials, the use of GMR multilayers as base material to fabricate the building blocks of metasurfaces or, finally, the incorporation of CMR materials into photonic crystals (PC) or hybrid plasmonic structures.

4.1 Spin plasmonics in granular systems

Following their work on plasmonic enhanced THz transmission in random metallic media [89, 90], Elezzabi and co-workers have recently studied the effect that a magnetic field has on the light transmitted through millimeter thick layers of Co microparticles aggregates. They observed a strong dependence of the THz transmission attenuation and delay on the relative orientation of the applied magnetic field and the polarization of the incident light, denoting the effect as Photonic Anisotropic Magnetoresistance (PAM) [91] (see Figure 9 A).

Figure 9: THz spin plasmonics in granular systems. (A) Time domain transmitted THz waveforms through a 2 mm thick sample of $74\ \mu\text{m}$ Co particles for different values of the magnetic field applied parallel (right panel) or perpendicular (left panel) to the polarization of the pulse. From ref [91], <https://doi.org/10.1103/PhysRevLett.96.033903>, with permission. (B) Normalized THz electric field amplitude (left panel) and magnetic field induced delay (right panel) of the THz pulse transmitted through Co particle ensembles having different Au surface coverages versus magnetic field strength for a magnetic field applied parallel to the polarization of the pulse. Au surface coverage: 0% (red diamonds), 35% (blue circles) and 42% (green squares). From ref [93], <https://doi.org/10.1103/PhysRevLett.98.133901>, with permission.

The Photonic Anisotropic Magnetoresistance effect is somehow the equivalent to a plasmon-mediated OME in the THz range, with relative differences of the transmission delays as high as 15% for 1800 Oe. Elezzabi and co-workers latter showed that such asymmetry of the THz transmission and delay could be modified by changing the particle surface morphology and the material (Ni instead of Co) [92], expanding the versatility of this approach. Worth to mention is that in these Ni microparticles aggregates the relative change of the transmitted power induced by the magnetic field can be as high as 20% at 1200 Oe.

These studies have also been extended to assemblies of bimetallic ferromagnetic/non ferromagnetic microparticles [93]. The ferromagnetic microparticles were made of Co, with $74\ \mu\text{m}$ average diameter and were covered with Au layers deposited by sputtering. The number of successive Au deposits on reoriented Co microparticles controlled the full coverage of the Co particles with Au as well as the Au percentage in the final assembly. In these structures, they

observed that the Au coated Co microparticles exhibited an enhancement of the magnetic field controlled attenuation of the THz radiation propagated through the sample (Figure 9 B left panel) as well as an increase of the magnetic field induced delay (Figure 9 B right panel). This effect was attributed to an electromagnetically induced electron spin accumulation in the non-ferromagnetic coating, and were also observed for other bimetallic microparticles [94].

In the same vein, metal-dielectric composites with variable metal volume fraction, have been analyzed. They were obtained by mixing Co and sapphire microparticles in different proportions. In these systems, a magnetic field induced modification of the direction of the propagation of THz pulses was shown [95]. Besides, active plasmonic directional routers and active plasmonic cylindrical lenses where also theoretically explored based on these ensembles of ferromagnetic and dielectric microparticles [96].

Also in the line of this subsection, mention that very recently Bhatta and co-workers [97] were able to synthesize single-domain 8.7 nm size Co nanoparticles. They observed a sharp absorption peak at 280 nm, which they attributed to a spin polarized Plasmon resonance. Spin-polarization transfer [98] and plasmon-induced carrier polarization [99] are two effects that have also been observed in different types of nanocrystals.

4.2 Active IR Spintronic-plasmonic metasurfaces

As mentioned in Section 3.2, $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers present sizeable MRE values at pretty low magnetic fields, and can be deposited using standard thin film techniques, such as thermal evaporation or sputtering, which allow the required control of the individual Au layers' thickness at the atomic level. For example, 4% GMR is achieved for 2.3 nm Au spacer thickness, while it vanishes for 1.9 and 2.6 nm [61].

Based on $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers, magnetic field control of the mid IR response in a variety of metastructures has recently been demonstrated, with predicted perspectives of continuous increased modulation for longer wavelengths [100–102]. Different aspects have actually been considered, such as the magnetic modulation of propagating and localized plasmons, or how the shape and size of the nanostructures affect their performance. In this line, in Figure 10 we show the first example, consisting of an ordered array of circular micrometric holes in an extraordinary optical transmission like fashion fabricated in a $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ GMR multilayer [101]. The ordering and lattice parameter of the array of the holes makes possible

Figure 10: MRE mediated magnetic modulation of propagating plasmons in the mid IR. (A) Normalized transmission spectra at normal incidence for unpolarized light for membranes fabricated on $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayers without GMR (blue line 5 μm period) or with GMR (black line 3.8% GMR and 5 μm period, red line 4.2% GMR and 7 μm period). The spectra show the characteristic Extraordinary Optical transmission (EOT) peaks, linked to the excitation of propagative plasmons. The inset shows an SEM image of a membrane fabricated on a $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer. (B) MRE spectra ($\Delta T/T = (T_P - T_{AP})/T_{AP}$) for the same membranes. The membrane fabricated on the multilayer without GMR shows no signal (blue line), whereas the membranes fabricated on the multilayers with GMR (black and red lines) show derivative like features at the position of the EOT peaks, due to the modulation of propagative plasmons, superimposed to a broad band originated from the multilayer. The inset shows a schema of the membrane with its internal structure.

the excitation of propagating plasmon polaritons at the desired wavelength. Two multilayers (one presenting and one lacking GMR) were patterned with a 5 μm periodicity holes' array. Since, as mentioned before, achieving GMR depends so critically on the Au spacer thickness, this allowed handling multilayers with just minute differences in Au amount (and therefore almost identical $\text{Ni}_{81}\text{Fe}_{19}$ vs Au concentration) but with presence or absence of GMR. A third one, exhibiting GMR, was patterned with a 7 μm periodicity holes' array. In Figure 10 A we present transmission spectra for these three samples, with well-defined peaks well known to be associated to the excitation of propagating plasmons. As it can be seen, the transmission spectra for the two samples with identical periodicity and just slightly different amount of Au was basically the same, while the multilayer patterned with a different periodicity

shows a similar spectral structure but with the peaks shifted. A more systematic analysis [101] reveals the dispersive nature of the excited modes. The results on the magnetic field modulation in these structures are shown in Figure 10 B. As it can be seen, clear derivative-like features appear in the spectral positions corresponding to the resonances of the two structures fabricated out of GMR multilayers. Interestingly enough, no feature whatsoever is observed in the structure lacking GMR. Since the only difference between this structure and the equivalent one was the absence/presence of GMR, this clearly allows concluding that the mechanism underlying this magnetic modulation lies in the GMR, namely in the MRE that carries as a consequence of the spintronic effect the change in the optical constants of the GMR multilayer.

In the second example, a disordered array of rods is considered. Rods are extensively studied as plasmonic nanoantennas and are well known to exhibit strong electric dipolar resonances when excited with the electric field along the main axis. The rods dimensions were chosen to observe the desired electric dipolar resonance in the 2–12 μm range. In Figure 11 A we show the transmission spectra for the electric field polarization along the rods main axis, clearly observing the excitation of the rods localized plasmon resonance, which is characterized by a profound dip in the transmission spectrum. As we increase the rod length, the position of the resonance shifts towards longer wavelengths. Application of magnetic field again gives rise to a clear modulation of this resonance, as it can be seen in Figure 11 B. As in the previous case, a derivative-like spectral feature appears now in the modulation spectra in the wavelength region corresponding to the rod resonance.

Finally, the third system consists of a disordered array of slits [102]. This last example allows exploring additional aspects with respect to the two previous ones. Unlike the ordered circular holes, the disorder arrangement of the slits minimizes the excitation of propagating plasmons and other possible diffraction effects. In addition, its in-plane aspect ratio is such that strong magnetic dipole localized resonances can be excited provided the electric field is perpendicular to the slit main axis. With this in mind, the reflectivity spectra of two arrays with different slit lengths are plotted in Figure 12 A. The expected redshift for the slit resonance upon increasing the slit length is well observed, with also an increase in the intensity of the resonance peak for longer wavelengths, due to the improved coupling of the light with the slit. Finally, the results of the magnetic

Figure 11: MRE mediated magnetic modulation of rods localized plasmons in the mid IR. (A) Transmission spectra for random arrays of rods fabricated on a $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer with 3.8 % GMR, for two different rod lengths 2 μm (black line) and 3 μm (red line), respectively. The rod width is in both cases 0.3 μm . Light is polarized along the rod long axis and the dips in the transmission correspond to the excitation of the rod localized plasmon resonance. The inset shows an SEM image of the 3 μm rod array. (B) MRE spectra ($\Delta T/T = (T_P - T_{AP})/T_{AP}$) for the same rod arrays (black line: 2 μm long rods, red line: 3 μm long rods). Light is polarized along the rod long axis. The spectra show a derivative like features at the position of rod resonances. The inset shows a schema of the $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer rods.

modulation of these resonances are shown in Figure 12 B. As it can be seen, and as already observed in the previous sections, the dip feature in the reflectivity is associated now with a derivative-like feature in the magnetic modulation spectra, its position red shifting and intensity increasing accordingly with the optical part.

From an applied point of view, a very clear practical realization of the spintronic control of resonant antennas as non-volatile optical switches was proposed in 2012 by Ogasawara and co-workers [103]. In their work, they theoretically considered the use of an array of nanoscale dipole antennas composed of Co/Cu GMR multilayers with parallel (P) and antiparallel (AP) magnetization alignments by using a first-principle electronic structure calculation and a finite difference time domain electromagnetic field analysis. They predict changes in the extinction efficiency of more than 40% in the IR region due to AP-P magnetic induced switching.

Figure 12: MRE mediated magnetic modulation of slits localized plasmons in the mid IR. (A) Reflectivity spectra for random arrays of slits fabricated on a $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer with 3.8 % GMR, for two different slit lengths 2 μm (black line) and 3 μm (red line), respectively. The slit width is in both cases 0.3 μm . Light is polarized perpendicular the slit long axis and the dips in the reflectivity correspond to the excitation of the slit localized plasmon resonance. The inset shows an SEM image of the 3 μm slit array. (B) MRE spectra ($\Delta R/R = (R_P - R_{AP})/R_{AP}$) for the same slit arrays (black line: 2 μm slit length, red line: 3 μm slit length). Light is polarized perpendicular to the slit long axis. The spectra show a derivative like feature at the position of slit resonance superimposed to a broad band originated from the multilayer. The inset shows a schema of the slits fabricated on a $\text{Ni}_{81}\text{Fe}_{19}/\text{Au}$ multilayer.

4.3 MRE modulation of fully dielectric photonic systems

So far, in all the structures considered in the previous subsections the spintronic character is introduced via a ferromagnetic metal. Due to this metallic character, the optical response of all these structures involves plasmonic-like excitations, being the magnetic field control induced by the metallic component of the structure. In this section here the spintronic material will be an oxide, with optical properties obviously quite different from those of a metal, difference that should be taken into consideration for the design of the corresponding active photonic structures. In this context, two approaches have been considered to exploit the magnetic field induced changes of the optical response of CMR oxides.

The first approach exploits the dielectric-like character of the CMR oxides integrating them into resonant dielectric structures, such as PC. PC structures, a concept first

developed for dielectric compounds [104, 105], exploit the different optical properties of their constituents to control the flow of light and optical response of system. A smart inclusion of the CMR oxide into the PC structure allows an enhancement of the oxide MRE response and, therefore, a magnetic field control of the optical response of the system, generating the so-called Magneto Photonic crystals [106]. As an example, lanthanum strontium manganese oxide ($\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$) has been proposed as CMR material, exhibiting 6% magneto resistance at RT and 8 KOe magnetic field. The complete proposed structure is a 1D magneto photonic crystal with the following multilayer structure: $(\text{SiO}_2/\text{Ta}_2\text{O}_5)_m/\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3/(\text{Ta}_2\text{O}_5/\text{SiO}_2)_m$. The $\text{SiO}_2/\text{Ta}_2\text{O}_5$ multilayers behave as Bragg mirrors with light localized inside the magnetic active layer. The operating wavelength is determined by the different parameters of the structure. In particular, sharp features with magnetic

Figure 13: MRE modulation in CMR optical platforms. Spectra of the magnetic modulation of the reflectivity in a 1D Magneto Photonic Crystal for two different photonic structures. The dotted curve corresponds to a configuration with Bragg mirrors of different thicknesses ($m=6, n=12$) and the solid curve to a configuration with symmetric Bragg mirrors ($m=n=6$). The active material is a CMR magnesium oxide ($\text{La}_{0.67}\text{Sr}_{0.33}\text{MnO}_3$). Reprinted by permission from Springer Nature: Springer eBook, Nano-Magnetophotonics, Mitsuteru Inoue, Alexander Khanikaev, Alexander Baryshev, Copyright 2009.

modulation of the reflectivity as high as 100%, have been theoretically predicted at 3.5 μm for a symmetric structure ($n = m = 6$), being the thickness of the SiO_2 , Ta_2O_5 , and $\text{La}_{0.67}\text{Sr}_{0.63}\text{MnO}_3$ layers 600 nm, 580 nm, and 300 nm, respectively (see Figure 13) [106–109].

In the second approach [110], noble metals and CMR oxides are combined. In this case the structure sustains plasmon-like excitations, and the magnetic control is induced by the oxide material. The proposed device is based on a periodic structure in which the unit cell consists of two Au stripes separated by a CMR manganese oxide ($\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$) stripe. The whole structure sustains Fano resonances which can be controlled by an external magnetic field. Theoretical calculations show a strong change in the optical response in the 40 to 200 THz range.

At this point, it is worth to mention that the development of CMR based photonic systems is limited by the available materials, and the lack of CMR materials with adequate properties at RT. Besides, the deposition of CMR manganite thin films usually require the use of high temperature processes, which makes their integration into optical systems an issue.

Worth to mention, non-metallic materials susceptible of exhibiting plasmon resonances in the IR [111] can also be considered as useful components in the systems considered in this section.

5 Conclusions and perspectives

Spintronics and Photonics are two fields with tremendous impact in our current lives, with concepts derived from them existing in a wide variety of practical applications. Information and communication society greatly benefit from spintronic and photonic solutions, and many other areas indirectly make use of devices that are result of research in these disciplines. Our current and continuously increasing technological needs make actually very appealing to explore the feasibility and routes to merge Spintronics and Photonics, as they host the potential to generate great added value functions and devices as a result of their interaction. With this in mind, the purpose of this work has been to compile the up-to-date efforts to explore the common spaces for interaction between these two disciplines and in particular how Photonics may benefit from the Spintronics-related structures and phenomena.

In this review we have presented how Spintronics and Photonics interact in the common space offered by the Magneto Refractive Effect (MRE), making it possible to

generate active photonic systems utilizing spintronic mechanisms. For this, we have first introduced the main spintronic phenomena capable of efficiently affecting the optical properties of different photonic platforms. Then, the current understanding of the MRE properties in the different types of spintronic “families” has been detailed. Finally, we have presented the current approaches to achieve active photonic platforms by the use of a spintronic mechanism, covering a wide range of wavelengths. We have also shown the ample variety of materials systems and complex spintronic platforms susceptible of magnetic field modifications of their optical properties. This versatility in types of spintronic materials at hand makes it possible to face the magnetic actuation on photonic platforms of diverse nature, covering from the metallic plasmonic systems, all the way to the dielectric photonic crystals.

The advantages of a magnetic-spintronic actuation are multiple. The external magnetic field acting on the photonic system does not require of any physical contact in the photonic system itself. The magnetic action in the ferromagnetic component and as a consequence in the photonic response is very fast. The different spintronic systems and the so generated photonic platforms demonstrate magnetic actuation of optical properties in a wide variety of ranges, covering from the mid-IR to the THz. Spintronics is deeply incorporated in the manufacturing processes of devices and, even though the very demanding requirements regarding chemical composition, preparation routes or individual layer thickness in the case of multilayered structures, the fabrication techniques to obtain spintronic materials are very well established.

Regarding the perspectives of this intertwined field, we would like to mention that there are several aspects which have not yet been explored. To name a few, the potentiality of OME effect in fabricating optical structures with magnetically induced optical anisotropy, and its use to modulate the polarization state of the light in a wide spectral range. Also, the use of spin-valve structures or magnetic tunnel junctions with high MR values and low operating magnetic fields as building blocks for active metasurfaces. Another area of development is the implementation of resonant spintronic systems for active elements in the THz spectral range, where active devices are very much welcome. High values of magnetic modulation of the optical response in the THz range have been already obtained in GMR multilayers, and the incorporation of such structures into magnetically actuated photonic THz structures is very appealing. Besides, there is also the possibility of exploring new phenomena controlled by both the spintronic nature of the structure and the enhanced optical response such as for example, photonic induced spin

accumulation, already advanced in granular systems. Not to forget is the contribution that this magnetic modulation approach may have in the development of faster and more accurate sensing platforms based for example in plasmonic and photonic transducers in the mid and far infrared range, where most of the molecular vibrational modes are located.

On the other hand, the development of ultrashort laser sources has opened new perspectives to the study of magnetization dynamics and spin polarized transport phenomena [112–116]. In a ferromagnetic layer a femto-second laser pulse is able to trigger spin-polarized currents. These spin current pulses can propagate through ferromagnetic/non ferromagnetic layers and different phenomena have been observed such as, for example, the excitation of high frequency magnetic modes in ferromagnetic films via the Spin Transfer Torque mechanism [117], or the modification of the spin polarization of hot electrons upon interactions with no collinear magnetization at the ferromagnetic/non ferromagnetic interfaces, opening the door to the development of different kinds of ultrafast spintronic devices like spin polarizers and rotators [118]. Besides, if the non-ferromagnetic layer is a metal with a strong spin–orbit coupling, such as Pt or Pd, at the interface between the ferromagnetic and non-ferromagnetic layer, the spin current pulse can be transformed into a transverse charge current via the Inverse Spin Hall Effect, giving rise to the emission of THz electromagnetic pulses. High efficient and broad band THz sources have been already obtained with these metallic spintronic structures [119]. More recently, combining inverse spin Hall effects concepts and an appropriate photonic design, wavelength-selective spin current generation has also been demonstrated in the mid IR region [120].

To finish, up to know there is still very little overlap between Spintronics and Photonics in what refers to research, and much still needs to be done to make this happen. With only a few groups in the world combining both concepts, most materials, characterization techniques, and theoretical tools are not common. But this simply means that there is still much margin for improvement. For example, exploring spintronic platforms susceptible of exhibiting large MRE values while maintaining low working magnetic fields is a line to be considered. For this, it would be necessary to revisit the huge diversity of spintronic materials and devices already existing and explore which could fulfill both requirements. In this sense, the use of low magnetic saturation materials or weakly magnetically coupled elements should be a route to explore into first place. Besides, it has been shown that the MO activity of magnetoplasmonic structures can be enhanced by putting the MO active

material at particular places within the structure [121, 122]. On the other hand, metamaterials structures have shown their ability to design tailored electromagnetic fields in a very wide spectral range [123], and resonant meta-atoms with both plasmonic and (opto)-magnetic functionalities have shown great potential [124]. Therefore, exploring the use of metamaterials to maximize the electromagnetic field at the position of the spintronic component may be a way to further improve the performance of MRE based photonic platforms. In this case, the required external magnetic field can also be reduced via magnetic shape anisotropy of the fabricated structures by favoring specific magnetization reversal directions. All this said, it is our strong belief that incorporating spintronic functionalities into photonic platforms hosts multiple areas of practical applicability with the needed combined efforts of the scientific communities studying these two disciplines.

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