Optical control of magnetism in complex oxides: A new frontier

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The manipulation of spin is a central concept in the field of spintronics. Among several methods, the light control of magnetism (or magneto-optics) has a unique versatility, since it can stimulate a wide range of interactions [1]. The light-magnetism interactions were first considered in the definition of the Faraday effect, in 1845; moreover, they have been taken into account in another milestone work by Stanciu et al. [2]. These authors demonstrated that the magnetization of the ferromagnetic alloy GdFeCo can be switched up or down by changing the circular direction (left or right) of a laser light. Impressively, the laser pulses required to switch the magnetization direction were only 40 fs long, enhancing the efficiency of ultrafast magnetic data storage. This discovery boosted wide range of studies on magneto-optical manipulation and its application on a variety of magnetic textures [3]. Indeed, the optical switching of magnetization has been achieved in both natural and synthetic ferrimagnetic alloys [4] and, recently, also in ferromagnetic metals [5].

While the aforementioned studies have focused mainly on magnetic metallic alloys, the magneto-optical effects in complex oxides has been emerging exponentially in recent years. Compared to metallic alloys, complex oxides feature highly entangled interactions between spin, charge, lattice, and orbital degrees of freedom, resulting in many interesting properties (Figure 1) [6]. The light-spin interactions in such materials are often coupled to the electric and structural or-

ders, providing a new territory to explore magneto-optical effects. A remarkable example is the optical switching of antiferromagnetism in the multiferroic material TbMnO₃ [7]: at low temperatures, the antiferromagnetic ordering induces spontaneously a ferroelectric polarization, resulting in a strong coupling between the magnetic and ferroelectric orders. Light illumination can transiently heat up the sample, destroying the magnetic and electric orders near the surface area. After this transient heating, the surface area will experience a stray electric field produced by the unheated region underneath and re-orient its ferroelectric polarization by 180°. Consequently, the direction of the antiferromagnetic vector will also flip by 180°, resulting in a reversible switching of the magnetic order. The inherent coupling in complex oxides provides a brand new platform for the control of multiple ferroic orders and domain structures by laser light [8].

An intriguing aspect of complex oxides is represented by the close energetics of their different electronic and magnetic phases, which can coexist within wide temperature and spatial ranges [9]. A notable example is phase separation in La_{0.325}Pr_{0.3}Ca_{0.375}MnO₃ system, where mesoscopic domains of the ferromagnetic metal and antiferromagnetic insulators coexist [10]. Lin et al. [10] have demonstrated that a laser light can twist the balance between two distinct phases, inducing critical fluctuations and phase transitions; such effects are greatly enhanced when the size of the material is at hundreds of nanometers, demonstrating the possibility of

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light-controlled magnetic and electronic switching at small length scales.

The above examples have shown the powerfulness of the optical tuning of magnetism applied to complex oxides; however, many questions still need to be answered. For example, it would be interesting to assess whether light illumination can create new and foreign magnetic states or textures. The close energetics that occur in correlated oxides indicate that multiple magnetic orders can be metastable and vulnerable to light illumination. The recent discovery of an unexpected third magnetic state in phase-separated manganites under light illumination has offered an early glimpse into this matter (Figure 1) [11].

From a technological point of view, a major goal would be the light-induction of magnetic switching at room-temperature. Materials exhibiting at the same time robust ferromagnetic and ferroelectric orders at such temperatures are rare. Magneto-electric interfaces can represent a solution: these heterostructures consist of magnetic and ferroelectric materials that, at room-temperature, present coupled magnetism and ferroelectricity at their interface [12]. An interesting aspect to investigate, in this context, would be the eventual influence of light illumination on the magnetic and ferroelectric orders via interfacial coupling (Figure 1). Wan et al. [13] have suggested that an antiferromagnetic BiFeO_3 layer can modulate the magnetization precession of ferromagnetic $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ via interfacial effects, suggesting

the feasibility of interface-induced magneto-optical manipulations via similar approaches.

Last but not the least, it would be interesting to use a focused light beam at room-temperature to perform optical writing on complex oxides (Figure 1). A similar approach was successfully applied to a LAO/STO interface: the local metallic or insulating state could be written at the nanoscale using an electric field (by force microscope) [14]. This kind of “freestyle” vectorial magnetic writing, which employs a focused laser beam, can be highly attractive for the design of local spin-based logic circuits and transistors. The incorporation of pure spin-current operations, whenever possible, will allow the production of highly energy-efficient architectures for next-generation electronic devices.

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Figure 1 (Color online) Magneto-optical phenomena in complex oxides. Left: optical control of the magneto-electric interfaces; bottom: light-induced new magnetic states at the domain edges in phase-separated manganites [11]; right: optical writing and lithography of the magnetic states.

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