PHOTONICS INSIGHTS

Universal orthoferrites and orthoferrites as a universe

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It is hard to imagine, but such an exotic and little-known material as rare-earth orthoferrite can rightfully be called a source of inspiration for many generations of scientists in magnetism during the last 60 years. Orthoferrites host antiferromagnetism, the Dzyaloshinkskii–Moryia interaction, magnetoelectricity[1], multiferroicity[2], and bubble domains, which are often seen as a prototype of topologically protected spin textures. Orthoferrites are characterized by very strong magneto-optical[3] and magneto-acoustic effects[4], THz frequencies of spin resonances[5], and record high domain-wall velocities[6]. Practically all of these phenomena and effects were once or still are a subject of intense research interest in magnetism, and rare-earth orthoferrites can be seen as a universal playground material to discover and explore the hottest topics of modern magnetism. It is thus not surprising that also newly emerging fields chose orthoferrites as a model material. It was exactly the case in 2004, when the very first experiments on laser-induced spin dynamics in orthoferrites[7] revealed a plethora of opportunities for experimental research in, at that time, the young, but already rapidly developing field of ultrafast magnetism[8]. The paper "THz spin dynamics in rare-earth orthoferrites" by X. Li *et al.* reviews nearly 20 years of history of ultrafast magnetism in orthoferrites.

Orthoferrites $RFeO_3$ (R = La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y) belong to the class of antiferromagnets. The materials have an orthorhombic structure with a space group *Pbnm*. The spins of Fe^{3+} ions are aligned in a regular pattern with neighboring spins pointing in opposite directions. Due to the Dzyaloshinskii–Moriya interaction and despite the antiferromagnetic coupling, the spins are canted for about 1 deg from the purely antiferromagnetic orientations and result in a net magnetization. Although the magnetization is small, the magneto-optical Faraday effects in orthoferrites are huge, so that the rotation strikes the imagination (3000 deg/cm). Many orthoferrites undergo spin-reorientation phase transitions, which were intensively studied in the Soviet Union. The theory of phase transitions was developed and published decades ago in Russian literature[9,10], but, unfortunately, not translated and thus not known to a broad public. Rare-earth orthochromites $RCrO_3$ and orthocobaltites $RCoO_3$ are far less explored materials whose properties, however, are expected to be very similar to those of orthoferrites.

Ultrafast magnetism is a rapidly developing research field that explores spin dynamics in ferro-, ferri-, and antiferromagnetic media excited by ultrashort (sub-100 ps) stimuli. Such stimuli bring media into a strongly non-equilibrium state, where the conventional description of magnetic phenomena in terms of equilibrium thermodynamics is no longer valid, conventional approximations fail, and the triggered magnetization dynamics can become counterintuitive. Apart from a purely fundamental interest, one should not forget that nowadays, in information technologies reorientation and rotation of spins in a magnet by 180 deg correspond to writing of a single magnetic bit. Hence ultrafast magnetism challenges the fundamental and practical limits on the speed and energy dissipations of writing of a single magnetic bit[11].

In 2004, it was realized that orthoferrites offer a very appealing playground to search for the fastest possible spin reorientation[7]. For instance, to reorient spins in the fastest and least dissipative way, it is very natural to employ spin resonances. The period of the resonance will practically define the time scale of the fastest spin reorientation. In orthoferrites, the frequencies of spin resonances are in the THz domain. Hence, potentially, orthoferrites can be used as a storage medium to facilitate writing and rewriting of magnetic bits at the scale of ps and at the unprecedentedly high rate of Tb/s. Magnetic anisotropy in most orthoferrites is strongly temperature dependent. Increasing the lattice temperature by just a few Kelvins can result in dramatic changes of spin structure leading, in particular, to reorientation of spins by 90 deg. Using a femtosecond laser pulse as an ultrafast heater, one can initiate the spin-reorientation phase transition and thus launch large amplitude THz spin dynamics. Although THz spin dynamics in orthoferrites was studied using frequency-resolved techniques long before 2004[5], the demonstration of ultrafast dynamics of spins in $TmFeO_3$ initiated a plethora of experimental studies of the spin dynamics using time-resolved methods.

The review "Terahertz spin dynamics in rare-earth orthoferrites" by X. Li *et al.*[12] is an overarching review of the progress in the field of experimental studies of ultrafast spin dynamics in

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rare-earth orthoferrites achieved with the help of time-resolved techniques. Although for many decades orthoferrites were not considered to have high potential to be applied in modern technologies, recently, these materials have started to attract attention in the fields of antiferromagnetic spintronics and magnonics. Interestingly, the studies of THz spin dynamics also demonstrated the potential of rare-earth orthoferrites in fundamental research of fields fairly distant from magnetism such as nonlinear phononics, cavity quantum materials, ultrastrong light–matter coupling, and even quantum optics.

The list of research fields where orthoferrites offer a playground is by far not complete, and it seems that a new wave of interest in these materials is about to come. Recently, it was proposed that the traditional classification of magnetic materials on ferro- and antiferromagnets is incomplete and self-contradicting. This apparent contradiction can be resolved by establishing a third distinct magnetic phase, dubbed altermagnetism[13]. One of the most appealing properties of altermagnets is their ability to host quasi-particles for which spin and wave vectors are mutually locked, and hence their currents must be spin polarized. Although the field of altermagnetism has just been born, it is already clear that orthoferrites are altermagnets. Hence rare-earth orthoferrites keep confirming the reputation of a universal playground material to discover and explore the hottest topics of modern magnetism. It can also be said that orthoferrites are a universe where many more discoveries are still to be made.

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