Terahertz-driven ultrafast magnetization dynamics of iron garnets

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Iron garnets ($A_3Fe_5O_{12}$) represent a broad family of ferrimagnets characterized by antiferromagnetic exchange interactions. Their magnetic structure is described by two magnetic sublattices (e.g., in yttrium iron garnet) or three (e.g., in rare-earth garnets). Their magnetic state can be controlled by relatively weak magnetic fields compared to collinear antiferromagnets, yet their eigenfrequencies still reside in the terahertz (THz) range. This provides unique access to the study of ultrafast magnetic dynamics, several distinct features of which are revealed here using THz-pump/infrared-probe spectroscopy.

First, iron garnets can exhibit a magnetic compensation point where the net magnetic moment vanishes. Interestingly, this compensation can occur either between iron sublattices—as seen in gallium-substituted yttrium iron garnet [1]—or between the combined iron sublattice and the rare-earth sublattice, such as in thulium iron garnet [2]. In both cases, THz pulses can resonantly excite the exchange mode, even in the immediate vicinity of the compensation point. Furthermore, high-intense THz pulses can trigger non-linear, off-resonant excitation of the quasi-ferromagnetic mode (typically in the GHz range). In thulium iron garnet, this process has been demonstrated via the Inverse Cotton-Mouton Effect [3].

Second, the strong temperature dependence of sublattice magnetization allows the exchange mode frequency to span an entire octave or more. This exceptional tunability enables precise frequency matching in cavities to realize the recurrent magnon-pumping effect. For instance, a twofold enhancement of the exchange mode amplitude and a fivefold decrease in effective damping have been demonstrated in gadolinium iron garnet (GdIG) [4].

Third, the non-collinear (canted) magnetic phase is a unique feature of ferrimagnets that emerges near the net magnetic moment compensation point. However, magnetization dynamics in this phase—particularly above the critical point—remain poorly understood due to the requirement for high external magnetic fields. By using a 10 T superconducting magnet, we accessed this non-collinear phase in GdIG and probed its dynamics using THz-pump/infrared-probe spectroscopy. Our results indicate that magnetization dynamics are highly sensitive to the net magnetic moment orientation and exhibit a pronounced dependence on both the external magnetic field and temperature.

Across all experiments, the data shows excellent agreement with phenomenological modeling [5]. Ultimately, THz-pump/infrared-probe spectroscopy proves to be a versatile tool for studying ultrafast magnetization dynamics in these complex systems.

[1] E. A. Mashkovich et al., *Terahertz-driven magnetization dynamics of bismuth-substituted yttrium iron-gallium garnet thin film near a compensation point*, Phys. Rev. B **106**, 184425 (2022).
[2] T. G. H. Blank et al., *THz-scale field-induced spin dynamics in ferrimagnetic iron garnets*, Phys. Rev. Lett. **127**, 037203 (2021).
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[4] C. Reinhoffer et al., *Terahertz excitation of exchange mode in a cavity formed by crystal interfaces*, Phys. Rev. B **111**, 184412 (2025).
[5] M. D. Davydova et al., *Ultrafast spin dynamics in ferrimagnets with compensation point*, J. Phys.: Condens. Matter **32**, 01LT01 (2020).