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Invited review

Broadband stripline ferromagnetic resonance spectroscopy of ferromagnetic films, multilayers and nanostructures

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HIGHLIGHTS

- Low-dimensional magnetic systems form the basis of modern spintronics and magnonics.
- We overview the stripline ferromagnetic resonance (FMR) spectroscopy of these materials.
- Experimental FMR results on magnetic multilayers and nanostructures are summarised.
- The impact of microwave eddy currents on the FMR response of these materials is revealed.
- The discussion is supported by results of analytical and numerical modelling.

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ABSTRACT

This paper presents a comprehensive critical overview of fundamental and practical aspects of the modern stripline broadband ferromagnetic resonance (BFMR) spectroscopy largely employed for the characterisation of magnetic low-dimensional systems, such as thin ferro- and ferromagnetic, multiferroic and half-metallic films, multi-layers and nanostructures. These planar materials form the platform of the nascent fields of magnonics and spintronics. Experimental and theoretical results of research on these materials are summarised, along with systematic description of various phenomena associated with the peculiarities of the stripline BFMR, such as the geometry of stripline transducers, the orientation of the static magnetic field, the presence of microwave eddy currents, and the impacts of non-magnetic layers, interfaces and surfaces in the samples. Results from 240 articles, textbooks and technical reports are presented and many practical examples are discussed in detail. This review will be of interest to both general physical audience and specialists conducting research on various aspects of magnetisation dynamics and nanomagnetism.

Contents

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1. Introduction

Much of the modern technology that energises today's society is based on magnetism. Magnets and numerous sophisticated magnetic effects play key roles in computer hard drives, medical equipment, telecommunications systems, data storage, sensors [1], and non-volatile random access memory already used in spaceships [2]. However, modern magnets are not only bulk magnets familiar from high-school physics classes. A large class of magnetic devices is based on low-dimensional systems, such as thin continuous films or complex nano-patterned structures. This is because thin magnetic films and nanostructures may possess very different properties with respect to their counterpart bulk materials, in part due to the presence of surfaces and interfaces. At a film surface (or interface) the symmetry is lower than in the bulk of the film, and the atoms experience a different local environment. When the films are made sufficiently thin, the impact of material boundaries, surfaces and interfaces becomes significant. From the technological perspective this is extremely important because by customising multi-layered thin films and nanostructures it is possible to create materials with unique properties that do not exist in nature.

The study of magnetic thin films has been around for nearly seven decades (see, e.g., [3–10]) and this research direction still remains very active. An important aspect of the current research is the microwave magnetisation dynamics in thin films, multi-layers, and planar nanostructures made from ferromagnetic metallic materials. The interest in these structures is motivated by their potential as a future platform for microwave signal processing [11–16], magnetic logics [17–21], magnetic memory [22–26], sensors [27–31], and other areas of science and technology [1].

Recently, it has been demonstrated that the magnetisation of a magnetic material can be controlled by using electric currents that transport spin angular momentum [32]. A changing magnetisation orientation produces currents that transport spin angular momentum. Understanding how these processes occur reveals the intricate connection between the magnetisation and the spin transport, and lays foundations of a new technology called spintronics. This technology can be used to develop novel devices that generate, store, or processes information via the magnetisation direction (spin orientation in quantum language) [33]. Consequently, there is a huge interest in a number of spintronic effects such as the spin transfer torque, direct and inverse Spin-Hall effects, and spin pumping [33–35]. A deep understanding of physics of these effects is crucial for the development of magnetic random access memory (MRAM), spin-torque MRAM, and spin-torque nano-oscillators [33,34]. The time scale for responses of the aforementioned devices corresponds to the microwave frequency range. These devices are based on continuous thin films or nanostructures consisting of an (often intricate) sequence of thin non-magnetic and ferromagnetic layers. Furthermore, we are now witnessing a huge progress in the microwave quality of half-metallic [36] and ferrimagnetic films [37,38] with thicknesses in the nanometre range. It is highly likely that availability of these new materials will give a new boost to this research direction.

More generally, the advances in the research on magnetisation dynamics and spintronics stem from the progress in nanofabrication and experimental characterisation techniques. One of the key characterisation techniques – the broadband ferromagnetic resonance (FMR) spectroscopy – is the main subject of this review. For several decades the FMR spectrometers have employed a microwave cavity to take a measurement of FMR absorption [39,40]. The importance of the FMR technique has recently skyrocketed thanks to the advent of the broadband stripline FMR (BFMR) spectroscopy. The BFMR allows characterising materials in a broad range of frequencies, often from several hundreds of MHz to 30–40 GHz [41,42]. This allowed significant improvement of accuracy of extraction of material parameters from the raw FMR absorption traces [42].

Furthermore, the Gilbert magnetic damping constant [43] is extracted as a slope of the frequency dependence of the resonance line width. Without BFMR it is difficult to distinguish between the contribution to the resonance linewidth due to the intrinsic damping (given by the value of the Gilbert constant) and extrinsic contributions [44–46]. The high interest in the magnetisation damping originates, for example, from the technological importance of the spin transfer and spin pumping effects (see, e.g., [32–35,41,42,47]). In this case, the Gilbert damping constant affects the critical current needed to switch the magnetisation direction [32,48]. In the case of self-sustained oscillations, the Gilbert damping affects the instability current that confines the regions of microwave emission [49–51].

We also stress the importance of the BFMR spectroscopy in the emerging area of magnetically tuneable microwave meta-materials and sensors of various substances including sensing of gases and nanoparticles. For more information, we refer the interested reader to Refs. [29,52–57] and references therein.