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Green's function theory of ferromagnetic resonance in magnetic superlattices with damping

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ABSTRACT

We explore a quantum Green's-function method to study the resonance absorption of magnetic materials. The relationship between the resonance magnon (spin wave) density and the resonance frequency of a superlattice consisting of two magnetic layers with damping and antiferromagnetic interlayer exchange coupling is studied. The effects of temperature, interlayer coupling, anisotropy, external magnetic field and damping on the the resonance frequency and resonance magnon density are investigated. The resonance excitation probability for a magnon is proportional to the resonance magnon density. In the classic methods, the imaginary part of magnetic permeability represents the resonance absorption in magnetic materials. In the quantum approach, the resonance magnon density can be used to estimate the strength of the resonance absorption. In the present work, a quantum approach is developed to study resonance absorption of magnetic materials and the results show the method to obtain a magnetic multilayered materials with both high resonance frequency and high resonance absorption.

1. Introduction

Nowadays, a high permeability of magnetic materials at high frequency is a requirement for electromagnetic interference suppressors, microtransformers, etc. [1–4]. This is because electromagnetic interference (EMI) between microwave and electric devices (LSI, CPU, etc.) has become a serious problem [5]. However, the enhancement of the resonance frequency of bulk magnetic materials is limited due to Snoek's limit [6]. Magnetic thin films or multilayer materials are expected to extend Snoek's limit and have high permeability in the GHz frequency range [7–13]. Wang et al. have studied Ni–Fe/Fe–Co–N/Ni–Fe multilayer films, in which the real permeability is 1000–1400 at frequencies up to about 1.2 GHz, and the imaginary permeability peaks at about 1.5 GHz, which corresponds to the ferromagnetic resonance (FMR) frequency [7]. Ni–Zn–Co ferrite films have been deposited by the spin-spray ferrite plating method at a low temperature of 90 °C. The complex permeability was measured in the range 20 MHz–3 GHz and a large imaginary part of the permeability $\mu'' > 30$ at 3 GHz has been found [11]. The static and high-frequency magnetic properties of $(Co_{90}Nb_{10}/Ta)n$ multilayers have been investigated [13]. The results show that the in-plane uniaxial magnetic anisotropy fields can be adjusted from 12 to 520 Oe only by decreasing the thickness of Ta interlayers from 8.0 to 1.8 nm. As a consequence, the resonance frequencies of the multilayers increases from 1.4 to 6.5 GHz, while the permeability decreases quickly [13]. As mentioned above, some magnetic multi-layer films have higher permeability but lower resonance frequency, while others have higher resonance frequency but lower permeability. There exists a trade-off between permeability and resonance frequency [14,15]. Therefore it is a challenge for research scientists to realize a film with resonance frequency beyond 5 GHz, which simultaneously has sufficiently high static permeability [16]. Both the permeability and the resonance frequency of stripe-domain-ferrite doped CoFe thin films are enhanced by using a Ta buffer layer, which suggests that the employment of Ta buffer layers may be useful in the realization of magnetic thin films with high permeability in the GHz frequency range [17].

In order to understand the mechanisms of high resonance frequency and high permeability of magnetic multilayers, many theoretical studies have been performed [18–31]. Walser et al. use a shape-dependent form of Snoek relation to show that the geometry of soft-FM objects can be chosen to maximize their linear susceptibilities at microwave frequencies [18]. Stamps et al. have provided a calculation method of the magnetic permeability in very thin FM film with imperfections using an effective-medium approach [19]. Suhl has shown that the basic dissipation mechanisms may be roughly divided into direct relaxation to the

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lattice and indirect relaxation via excitation of many magnetic modes [21]. The formalism for transmission of normally incident electromagnetic radiation through a finite superlattice of alternating magnetic and non-magnetic layers has been presented and the transmission and reflection coefficients are expressed in terms of the transfer matrix for propagation across a unit cell of the superlattice [22]. Prominent features are seen related to resonances in the magnetic permeability and to the stop bands of the Bloch waves of the superlattice [22]. By means of Landau–Lifshitz theory, an analytic calculation of the frequency dependence of the complex permeability of thin soft FM films with in-plane anisotropy has been performed [23]. The influence of intrinsic parameters of the thin films, such as saturation magnetization, anisotropy field and the damping parameter, on the spectra has been discussed. The benefit of using ferromagnetic resonance (FMR) to study exchange-coupled magnetic films has been demonstrated. Structurally well-defined trilayer systems consisting of two ultrathin magnetic films (Ni or Co) separated by a non-magnetic Cu spacer layer have been examined. The experimental results on positions, intensities and line widths of resonance peaks have been compared to results of a theory which uses a continuum approach in the framework of the Landau–Lifshitz equation of motion [26,27]. Based on the Landau–Lifshitz equation and on Maxwell's equations, the permeability and microwave properties of FM trilayers with in-plane uniaxial anisotropy have been investigated [28,29]. Various effects of geometry on the magnetic properties at microwave frequencies (about 20 GHz) have been systematically studied for micro- and nano-structured FM thin films with fourfold in-plane magnetic anisotropy by using micromagnetic simulations. The permeability and the resonance frequency are found to scale well with the structural parameter w/t (w is the lateral pattern size and t the film thickness) for pattern sizes that differ by an order of magnitude [31].

Up till present, in theoretical work, mainly the classical method of the Landau–Lifshitz equation (or based on the Landau–Lifshitz equation) has been used, while quantum methods have seldom been used. It is worthwhile to develop some quantum methods to study the microwave properties of magnetic multilayer films. Using the generalized Anderson–Callen approximation and the RPA decoupling procedure, Schwieger et al. have studied the resonance frequency and resonance field in a FM monolayer and a system of two coupled layers, but the resonance intensity is not considered [32,33]. In our previous work [34], only the resonance frequency of two-layer and three-layer FM superlattices has been studied, using Callen's Green function method, also without studying the resonance intensity. The intensity of the resonance line is proportional to the square of the overall transversal component of the magnetization. In other words, the intensity of the resonance corresponding to a given nth spin-wave mode is directly proportional to the squared sum of its amplitudes across the bilayer film [35]. The magnon-resonance spectra in a FM film have been investigated using the quantum theory, in which the quantum jump probability represents the resonance-absorption intensity [36]. In [35] and [36], effects of damping and temperature are not considered. The magnon density is an important measure for the excitation probability of a magnon in a magnetic material. The magnon density of states for spin-1/2 Heisenberg ferromagnets has been calculated by means of the quantum Green-function method [37,38]. The magnon density perpendicular to the superlattice plane of one-dimensional magnonic crystals has been studied [39], without including the effect of damping.

In the present work, for the first time, the resonance magnon density will be used to estimate the strength of the resonance absorption, because the resonance excitation probability of a magnon is proportional to the resonance magnon density. We attempt to study the relationship between the resonance intensity and the resonance frequency of a magnetic multi-layer surperlattice with damping by means of a quantum method. We will use Callen's Green's function method, the Tyablikov decoupling approximation and the Anderson–Callen decoupling approximation to study the resonance frequency and use the imaginary part of the Green's function to calculate the resonance magnon density in a two- layer magnetic superlattice with antiferromagnetic (AFM) interlayer coupling. In order to consider the damping factor, we introduce the imaginary frequency in the Green's function. We investigate the effects of temperature, interlayer coupling, anisotropy, external magnetic field and imaginary frequency (damping)

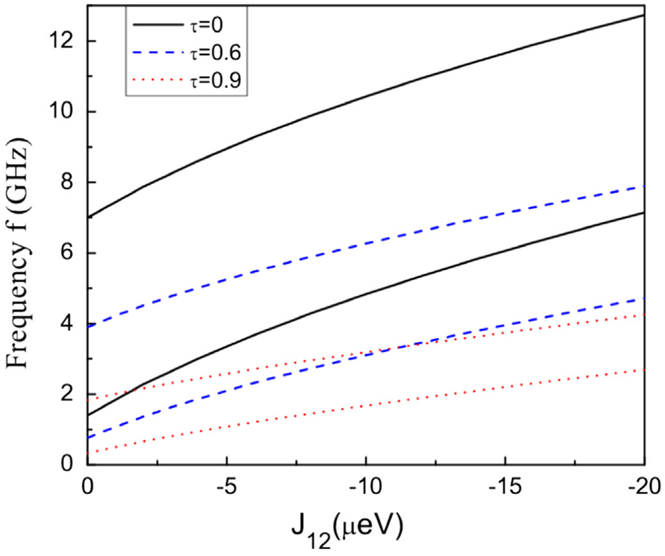

Fig. 1. (Color on-line) Dependence of the resonance frequency of a two-layer magnetic superlattice with $D_1=5$ μ_BkG and $D_2=1$ μ_BkG on the AFM interlayer exchange coupling J_{12} and at reduced temperature $\tau=T/T_c=0$, 0.6 and 0.9 (solid black, dashed blue and dotted red lines, respectively) and zero magnetic field. The value of T_C is the value at zero interlayer exchange coupling J_{12}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

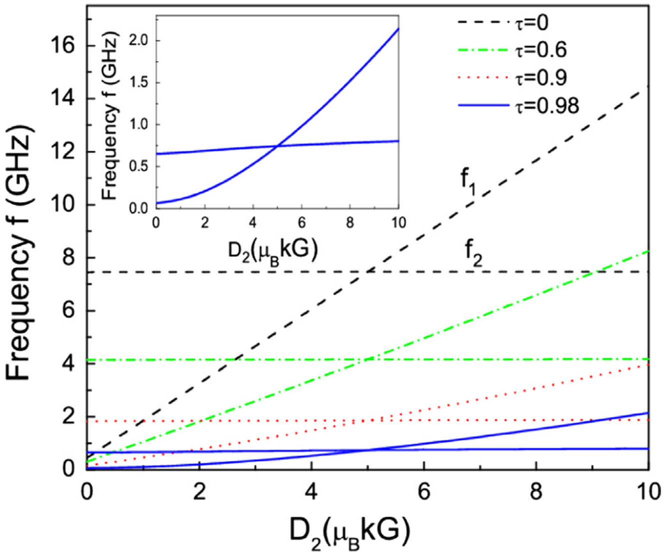

Fig. 2. (Color on-line) Dependence of the resonance frequency of a two-layer magnetic superlattice with $J_{12}=-1$ μeV and $D_1=5$ μ_BkG on the anisotropy D_2 at reduced temperatures $\tau=T/T_c=0$, 0.6, 0.9 and 0.98 (dashed black, dashed-dotted green, dotted red and solid blue lines, respectively) and at $B=0$. The inset shows the detailed situation for $\tau=0.98$. The value of T_C is the value at zero anisotropy D_2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)