Intensity enhancement of ferromagnetic resonance modes in exchange coupled magnetic multilayers

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Abstract
In this work, the ferromagnetic resonance characteristics of a NiFeCu/Non-magnetic(NM)/NiFe/ NM/CoFe/NM/Co multilayer is studied from a theoretical point of view, and comparisons with the ferromagnetic resonance of a NiFe/NM/CoFe magnetic bilayer are presented. It is found that the resonance modes of the multilayer tend to be more intense than those of the bilayer for several combinations of applied field and interlayer exchange coupling. Furthermore, rules governing the individual layer contributions to the resonance modes of a exchanged coupled magnetic multilayer are presented, which would apply to any number of layers. These results open the possibility to tailor the resonance frequencies of the multilayer structure by either engineering the interlayer exchange coupling or by applying a perpendicular magnetic field for multiband high frequency magnetic devices.

1. Introduction

High frequency devices are of great importance for applications in areas such as medicine [1–3], microfluidics [4–6], flexible electronics [7–9], and energy harvesting [10–12]. Using magnetic materials as building blocks for these devices allows to reduce their size, taking advantage of their natural resonance in the order of GHz [13, 14], which is typically exploited in areas such as magnonics [15–17] and spintronics [18–20]. In the case of high frequency devices, the use of magnetic materials makes it possible to fabricate micrometer and nanometer devices such as circulators [21, 22], phase shifters [23, 24], filters [25, 26], and frequency sources [27–32]. Another characteristic that makes magnetic thin films attractive for high frequency applications is the possibility to control their magnetic properties with electrical signals, providing a path for adjusting dynamically the behavior of magnetic high frequency devices. For example, in materials with simultaneous ferroelectric and ferromagnetic characteristics (multiferroics) [33–35] it is possible to change the orientation of the magnetization using electric fields [36–38]. These fields also have been used to modify the perpendicular magnetic anisotropy induced at ferromagnet/Oxide or heavy metal interfaces [39–43], inducing magnetization switching [44] and nonlinear ferromagnetic resonance (FMR) [45].

An important requirement for the materials used in these magnetic devices is a high magnetization, which ensures natural resonance modes with high frequency and intensity [46–49]. In some cases, these requirements can also be fulfilled by using structures composed of multiple materials. For example, in a bilayer with an effective ferromagnetic exchange coupling (which tends to align the magnetization of the layers parallel to each other), two resonance modes with distinguishable frequencies are observed: the low frequency acoustic (both layers are in phase) and the high frequency optical (both layers are in antiphase) modes [50, 51]. The acoustic mode is of particular importance, as it has an enhanced intensity due to the additive contribution of each layer to the frequency signal. The optical mode is of interest due to its high frequency, but it is difficult to use in the practice due to its low intensity [52–56]. Using antiferromagnetic exchange coupling (which tends to align the magnetization of the layers antiparallel to each other) enhances greatly the intensity of the high frequency mode, while reducing that of the low frequency one [37, 58], providing a higher working frequency for applications.
sacrificing access to the lower frequency mode. This illustrates that currently it is difficult to obtain multiple high intensity resonance modes using magnetic bilayers due to the intrinsic behavior of the magnetization of these structures. Another option is the use of more than two magnetic thin films, which would allow for more flexibility on their design at the cost of more complexity. These multilayered structures could potentially enable multiple high intensity resonance modes, allowing for multiband high frequency magnetic devices.

In this work, the FMR characteristics of a NiFeCu/Non-magnetic(NM)/NiFe/NM/CoFe/NM/Co multilayer are studied from a theoretical point of view, providing information on the intensities of the different modes and the subtractive and additive contributions of the different layers to each mode. It is also shown how these modes are affected by an external magnetic field and by the effective exchange coupling, showcasing an enhanced stability under external excitations, and an interesting mode interplay for perpendicular fields. Finally, comparisons with a NiFe/NM/CoFe magnetic bilayer are performed to showcase the advantages of the multilayer over more conventional bilayers.

2. System and methods

A scheme of the studied multilayer system is shown in figure 1. The NiFeCu/NM/NiFe/NM/CoFe/NM/Co structure, labeled as 4L, is composed of four separate magnetic materials, which will provide four FMR modes. The gray slabs represent NM separators introduced to control the interlayer exchange coupling between magnetic films. The NiFe/NM/CoFe structure, labeled as 2L, will be used as reference for several of the observed phenomena. This particular combination is chosen so its resonance modes are as intense as possible. Figure 1 also shows the two reference frames used in this work. The layer reference frame (labeled by uppercase X, Y, Z) where the XY plane represents the plane of the layer, and the magnetization reference frame (labeled by lowercase x, y, z) where the z axis is along the equilibrium direction of the magnetization and the y axis lies on the XY plane forming an angle φ with the Y axis. The x axis is perpendicular to both the y and z axes, following a standard right hand rule. Throughout this work the angles θ and φ represent, respectively, the polar and azimuthal angles in the XYZ reference frame.

The FMR of these multilayers is obtained using a model proposed in [54], in which the resonance frequencies $\omega_{\text{res}} = 2\nu_{\text{res}}$ are given by the imaginary eigenvalues of the dynamical matrix

$$D_m = \mu_y \gamma \begin{bmatrix} -H_{j_x} & -H_{j_y} & -H_{j_z} & -H_{j_z} & \cdots \\ H_{i_x} & +H_{i_y} & H_{i_z} & +H_{i_z} & \cdots \\ -H_{j_x} & -H_{j_y} & -H_{j_z} & -H_{j_z} & \cdots \\ H_{i_x} & +H_{i_y} & H_{i_z} & +H_{i_z} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix},$$

(1)

where the fields $H_{i,j}$ depend on the magnetic characteristics of the layers and the equilibrium direction of the magnetization. $\alpha, \beta = x, y, z$ and $i, j$ are the indexes representing each individual layer. $\gamma = 1.76 \times 10^{11} \text{Ts}^{-1}$ is the gyromagnetic ratio.

For each individual layer $i$ with saturation $M_i$, the dynamical fields account for the contributions from the external magnetic field $H$, the uniaxial anisotropy $K_i$, the cubic anisotropy $K''_i$, and the demagnetizing field. They
are given by [59–61]

\[
H_{k,i}^0 = H_K^0 (\mathbf{M}_i^0, \mathbf{H}) + H_K^0 [e_i^L (c_{x i}^L)^2 - (e_i^L)^2] - M_i^0 (\cos \theta_{M_i}^0 - \sin \theta_{M_i}^0)
\]

\[
+ \frac{H_K^c}{8} [C_m(\mathbf{M}_i) + C_P(\mathbf{M}_i)]
\]

\[
H_{k,j}^0 = H_K^0 (\mathbf{M}_i^0, \mathbf{H}) + H_K^0 [e_i^L (c_{x j}^L)^2 - (e_i^L)^2] - M_i^0 \cos \theta_{M_i}^0
\]

\[
+ \frac{H_K^c}{32} [9 + 15 \cos 4\varphi_{M_i} + 16 C_m(\mathbf{M}_i) + C_P(\mathbf{M}_i)]
\]

\[
H_{k,j}^1 = H_{k,j}^1 = H_K^1 (\mathbf{M}_i^1, \mathbf{M}_j^1),
\]

where \(\theta_{M_i}^0, \varphi_{M_i}^0\) define the equilibrium direction of the magnetization of the layer \(i\), given by the vector \(\mathbf{M}_i^0\). \(C_m(\mathbf{A}) \equiv \cos \theta_A \cos \theta_B + \sin \theta_A \sin \theta_B \cos \varphi_{A,B}, C_P(\mathbf{A}) \equiv 2 \theta_A (1 - \cos 4 \varphi_{A,B})\), and \(\theta_A, \varphi_{A,B}\) are the angles defining the direction of the vector \(\mathbf{A}\). \(\varphi_{A,B} \equiv \varphi_A - \varphi_B\).

\(H\) is the magnitude of the applied field, and \(H_K \equiv 2K_i/(\mu_0 M_i^0)\) is the uniaxial anisotropy field. The latter is defined by the uniaxial anisotropy vector \(\mathbf{K}_i = K_i \hat{\mathbf{e}}_{K_i}\), where \(K_i\) is the magnitude of the uniaxial anisotropy, and \(\hat{\mathbf{e}}_{K_i} = e_{K_i}^x \hat{x}_i + e_{K_i}^y \hat{y}_i + e_{K_i}^z \hat{z}_i\) is the direction. Within our formalism, \(\hat{\mathbf{e}}_{K_i}\) is an easy axis for positive \(K_i\). The components of the uniaxial anisotropy vector are calculated using the direction of the magnetization and \(\mathbf{K}_i\), which represent the direction of \(\hat{\mathbf{e}}_{K_i}\). They are given by \(e_{K_i}^x \equiv \cos \theta_{K_i} \sin \varphi_{K_i} - \sin \theta_{K_i} \cos \varphi_{K_i}\), \(e_{K_i}^y \equiv \sin \theta_{K_i} \cos \varphi_{K_i}\), and \(e_{K_i}^z \equiv C_m(\hat{\mathbf{K}}_i, \hat{\mathbf{K}}_j)\). \(H_{K_i} \equiv 2K_i/(\mu_0 M_i^0)\) is the cubic anisotropy field, and \(K_i^c\) is the cubic anisotropy constant. It has easy axes along the \(X, Y\), and \(Z\) directions for positive \(K_i^c\).

The interlayer exchange coupling contributions to the dynamical fields are given by

\[
H_{j,i}^L = H_{j,i}^L = \sum_j \frac{J_{ij}^L}{\mu_0 M_i^0 t_i} C_m(\mathbf{M}_i^0, \mathbf{M}_j^0)
\]

\[
H_{j,i}^{Lj} = -\frac{J_{ij}^{Lj}}{\mu_0 M_i^0 t_i} S_c(\mathbf{M}_i^0, \mathbf{M}_j^0)
\]

\[
H_{j,i}^{Lj} = -\frac{J_{ij}^{Lj}}{\mu_0 M_i^0 t_i} \cos \varphi_{M_i}^0
\]

\[
H_{j,i}^{Lj} = -\frac{J_{ij}^{Lj}}{\mu_0 M_i^0 t_i} \sin \varphi_{M_i}^0
\]

\[
H_{j,i}^{Lj} = \frac{J_{ij}^{Lj}}{\mu_0 M_i^0 t_i} \cos \theta_{M_i}^0 \sin \varphi_{M_i}^0
\]

\[
H_{j,i}^{Lj} = \frac{J_{ij}^{Lj}}{\mu_0 M_i^0 t_i} \sin \theta_{M_i}^0 \cos \varphi_{M_i}^0
\]

(3)

with \(S_c(\mathbf{M}_i^0, \mathbf{M}_j^0) \equiv \sin \theta_{M_i}^0 \sin \theta_{M_j}^0 + \cos \theta_{M_i}^0 \cos \theta_{M_j}^0 \cos \varphi_{M_i}^0\). The summation over \(j\) refers to the neighboring layers \(i + 1\) and \(i - 1\), and \(t_i\) is the thickness of the layer \(i\). \(J_{ij}^L\) is the effective exchange coupling constant between layers \(i\) and \(j\), and is positive for ferromagnetic coupling and negative for antiferromagnetic exchange.

The fields composing the matrix (1) are then given by \(H_{ij} = H_{ij}^L + H_{ij}^H\).

\(\mathbf{M}_i^0\) is obtained by solving numerically the coupled system of dynamical equations given by the Landau–Lifshitz equation

\[
\frac{d\mathbf{M}_i}{dt} = -\mathbf{M}_i \times \mu_0 H_{eff} - g_i \mathbf{M}_i \times \mathbf{M}_i \times \mu_0 H_{eff},
\]

(4)

where \(g_i\) the Gilbert damping parameter of the layer \(i\), is assumed to be small. \(\mu_0 H_{eff} = \partial \mathcal{H}/(V_i \partial \mathbf{M}_i)\) is the effective field of the layer \(i\), and \(\mathcal{H}\) is the Hamiltonian given by

\[
\mathcal{H} = -\sum_i \mu_0 H \cdot \mathbf{M}_i V_i + \frac{K_i}{(M_i^0)^4} \mathbf{M}_i \cdot \hat{\mathbf{e}}_k^2
\]

\[
+ \frac{K_i}{(M_i^0)^4} [(M_i^X)^2(M_i^Y)^2 + (M_i^Y)^2(M_i^Z)^2 + (M_i^Z)^2(M_i^X)^2]
\]

\[
+ \frac{1}{2} \sum_{j,v} \frac{J_{ij}^L}{M_i^0 M_j^0} \mathbf{M}_i \cdot \mathbf{M}_j - \sum_{j,v} \frac{\mu_0}{2} V_i \mathbf{M}_i \cdot \mathbf{N}_v \cdot \mathbf{M}_j
\]

(5)

where each term represents, respectively, the Zeeman energy, the uniaxial anisotropy, the cubic anisotropy, the interlayer exchange coupling, and the dipolar coupling. \(V_i\) is the volume of the layer \(i\), and \(S_v\) is the area of the surface between the layers \(i\) and \(j\). \(M_i^0 \equiv \mathbf{M}_i \cdot \hat{n}_i\), with \(v = X, Y, Z, X, Y, Z\) are the unitary vectors defining the
XYZ reference frame. \( N_{ij} \) is a rank-3 demagnetizing tensor in the XYZ reference frame which relates the shape of the two layers. It becomes the demagnetizing factors of the layer \( i \) when \( i = j \). For thin films all \( N_{ij} \) components are approximately zero, with exception of \( N_{ZZ} = 1 \). This means that the demagnetizing field induces a hard anisotropy axis in the Z direction, or equivalently, an easy isotropic XY plane. The interlayer demagnetizing tensor \((i \neq j)\) for aligned and identical rectangular prisms is given in [63], and a generalization for any pair of rectangular prisms is given in [65]. However, typical multilayer systems have lateral size much larger than the thickness of the layers. In this case, the demagnetizing tensor (with \( i \neq j \)) is very small and thus the interlayer dipolar coupling contribution to the FMR is negligible.

The magnetic susceptibility \( \chi_{\alpha \beta} \) provides information on the intensity of oscillation of the different resonance modes, and in the linear regime is defined as \( m_a = \chi_{\alpha \beta} h_\beta \). It provides the response of the \( \alpha \) component of the dynamical magnetization to a small dynamical field \( h_\beta \) applied in the \( \beta \) direction. It is obtained from the components of the susceptibility tensor

\[
\chi = \begin{bmatrix}
\chi_{xx} & \chi_{xy} & \chi_{xz} \\
\chi_{yx} & \chi_{yy} & \chi_{yz} \\
\chi_{zx} & \chi_{zy} & \chi_{zz}
\end{bmatrix}
\]

(6)

where \( \chi_{\alpha \beta} \) is the response of the \( \alpha \) component of the dynamical magnetization of the layer \( i \) to a small dynamical field applied in the \( \beta \) direction to the layer \( j \). The total susceptibility is obtained by summing over the different combinations of \( \alpha, \beta, i \) and \( j \), and accounting for the orientation of the magnetization of each individual layer.

Assuming all the magnetic moments lie on the XZ plane, it is calculated using

\[
\chi_{xy} = \sum_i \sum_j t^i_j \chi_{y\alpha_i}
\]

where \( t \) is the sum of the thicknesses of all the magnetic materials.

The susceptibility tensor (6) can be obtained by using \( \chi = D^{-1}_x M_T \), where

\[
M_T = \begin{bmatrix}
0 & -M_t^1 & 0 & 0 & \cdots \\
M_t^1 & 0 & 0 & 0 & \cdots \\
0 & 0 & 0 & -M_t^2 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]

(8)

and \( D_x = \frac{i\omega}{\gamma} W + D_m \), \( \omega \) is the angular frequency of the microwave field, and the matrix \( W \) is given by

\[
W = \begin{bmatrix}
1 & g_1 & 0 & 0 & \cdots \\
-g_1 & 1 & 0 & 0 & \cdots \\
0 & 0 & 1 & g_2 & \cdots \\
0 & 0 & -g_2 & 1 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]

(9)

To validate the model, comparisons are performed between theoretical calculations and experimental FMR measurements of a CoFe(12 nm)/NiFeCu(11 nm) bilayer and a single CoFe(12 nm) thin film extracted from [53]. The results are shown in figure 2. The CoFe(12 nm)/NiFeCu(11 nm) bilayer (CoFe(12 nm) thin film) is modeled as a stack of 23 interacting slabs, each 1 nm thick. The data used for these comparisons is \( \mu_0 M_{CoFe} = 1.81 \text{T}, g_{CoFe} = 0.03, \text{exchange stiffness} A_{CoFe} = 2.5 \times 10^{-11} \text{J m}^{-1}, \mu_0 M_{NiFeCu} = 0.36 \text{~T}, \)

\[ g_{NiFeCu} = 0.012, A_{NiFeCu} = 3.5 \times 10^{-12} \text{~J m}^{-1}. \]

The interlayer exchange coupling at the interface is \( J_{\text{interface}} = 11.4 \text{~mJ m}^{-2} \). The exchange interaction between neighboring slabs of the same material is given by \( J_{eff}^i = A_{\text{eff}} f_{\text{lab}}, \) with \( \zeta = \text{CoFe}, \text{NiFeCu}, \) and \( f_{\text{lab}} = 1 \text{~nm}. \)

Figure 2(a) shows the susceptibility as function of the in plane external magnetic field and a fixed microwave field frequency \( f = 14 \text{~GHz} \), and figure 2(b) shows the frequency as function of the field for the high frequency (optical) mode of the bilayer (red curve) and the individual CoFe thin film (black curve). In figure 2(a), theoretical calculations are obtained from (7), while those of figure 2(b) are given by the eigenvalues of (3). In all cases a very good agreement between experiments and theory can be observed.
3. Results and discussion

In this section, the FMR characteristics of the 4L and 2L systems will be studied. The frequencies and mode intensities as function of the external field and the interlayer exchange coupling are presented, and a description of the contribution of individual layers to the resonance modes of the 4L is given. Unless otherwise specified, the physical parameters used in this section are given in table 1.

\[ J_{\text{eff}} = 0.2 \text{ mJ m}^{-2} \] is a typical value for pairs of magnetic layers with Cu or Ru separators \( \sim 1–2 \text{ nm thick} \) \cite{65–69}. It is chosen to be the same at all interfaces for easier interpretation and exploration of the different contributions to the intensity of the resonance modes. Similarly, a standard value of \( g_i = 0.01 \) is used for all layers. The cubic anisotropy of the NiFeCu is on the same order than that of the NiFe \cite{50, 53–54} and thus both are taken equal.

### 3.1. Longitudinal external field

The FMR frequency \( f_{\text{res}} \) as function of the in-plane external field \( H_\parallel \parallel \hat{X} \) is shown in figure 3(a). Solid lines represent the FMR frequencies of the 4L system. Four distinct resonance modes can be observed, one for each layer. Moreover, the FMR frequency increases with \( H_\parallel \). This is expected as the magnetizations of all the layers already lie parallel to the field, and thus increasing \( H_\parallel \) only increases the internal energy of the structure. The dashed lines show the FMR frequencies of the 2L system, and show a similar behavior as the 4L. The main difference is the presence of only two resonance modes: the acoustic and optical modes.

![Figure 3](image_url)

*Figure 3.* Comparisons of theory and experimental data extracted from \cite{53} for a CoFe(12nm)/NiFeCu(11 nm) bilayer (CoFe(12 nm) thin film) modeled as 23(12) exchange interacting slabs, each 1 nm thick. (a) Susceptibility (with a fixed microwave field frequency \( f = 14 \text{ GHz} \)) and (b) frequency as function of in-plane applied field.

### Table 1. Physical parameters of the multilayer system used for calculations of the FMR modes.

| NiFeCu | NiFe | CoFe | Co |
|--------|------|------|----|
| \( M_s (\text{kA m}^{-1}) \) | 500 \cite{53} | 900 \cite{50, 53, 54} | 1810 \cite{50, 53, 54} | 1200 \cite{64} |
| Thickness (nm) | 2 | 2 | 2 | 2 |
| \( J_{\text{eff}} (\text{mJ m}^{-2}) \) | 0.2 \cite{65–69} | 0 | 0 | 410 \cite{64} |
| \( k_i (\text{kJ m}^{-3}) \) | 22 | 22 | 22 | 22 |
| \( g_i \) (Dimensionless) | 0.01 | 0.01 | 0.01 | 0.01 |

With the objective of understanding the observed behavior, the contributions of each individual layer to the intensities of the 4L resonance modes are shown in figure 4. Each mode is 'governed' by a single individual layer.
with the closest natural resonance frequency (resonance frequency in the non-interacting case). For the 4L with longitudinal external field, the governing layer of each mode is ordered upwards by $M_s$ (lowest $M_s$ governs lowest frequency mode, etc.), with the exception of the Co layer which has the highest frequency due to a stronger magnetocrystalline anisotropy.

In the first (lowest frequency) mode, governed by the NiFeCu layer, all the layers have additive contributions, meaning that they precess in-phase with each other. This is the equivalent to the acoustic mode of the 2L multilayer, and arises because an uniform precession is energetically favorable to the ferromagnetic exchange coupling. The second mode, governed by the NiFe, shows that only the NiFeCu contributes in a subtractive way. Thus, an enhanced intensity is obtained because the NiFe, Co and CoFe layers contribute additively. In a bilayer with only NiFe and CoFe thin films, this mode will be equivalent to a low intensity optical mode because both layers would contribute in a subtractive way. In the third mode, governed by CoFe, the CoFe layer is in phase with the Co and the NiFeCu, but in antiphase with the NiFe. Moreover, in the fourth mode governed by the Co, the governing layer is in phase with the NiFe, but in antiphase with the remaining two (not observed clearly in figure 4 due to low intensity contributions of the NiFeCu and NiFe). To explain this pattern, we will use numbers to refer to each layer in the 4L in ascendant order of natural resonance frequency ($1 = \text{NiFeCu}, 2 = \text{NiFe}, 3 = \text{CoFe}, 4 = \text{Co}$). The pattern observed in the third and fourth resonance modes can then be explained as follows:
complex behavior is observed due to non-collinearity contributions that arise in magnetization. For antiferromagnetic coupling with collinear magnetization, similar rules apply:

(i) The governing layer of a mode will always be in phase with layers which govern higher frequency modes, e.g. in the first mode 1 will be in phase with 2, 3, and 4. In the second mode, 2 is in phase with 3 and 4, etc.

(ii) All the layers governing modes with lower frequencies than the current one will be in antiphase with the neighboring (frequency-wise) layers. Thus, in the third mode 3 is in antiphase with 2, and then 2 is in antiphase with 1. Similarly in the fourth mode, 4 is in antiphase with 3, 3 is in antiphase with 2, and 2 is in antiphase with 1.

The same pattern will repeat for any number of layers with ferromagnetic exchange coupling with collinear magnetization. For antiferromagnetic coupling with collinear magnetization, similar rules apply:

(i) The governing layer of a mode will always be in phase with layers which govern lower frequency modes.

(ii) All layers governing a mode of higher frequency than the current mode will be in antiphase with the neighboring (frequency-wise) layers.

Note that non-collinear magnetization states should follow the same basic rules, however in practice a more complex behavior is observed due to non-collinearity contributions that arise in (7) (see [54]).

3.2. Perpendicular field

A similar study is performed with a perpendicular field \( H_\perp \parallel \hat{Z} \). In this case important variations in the governing layers of each resonance are expected, in addition to the appearance of frequency gaps due to the exchange coupling [54, 71]. Figure 5(a) shows the FMR frequency as function of the perpendicular applied field \( \mu_0 H_\perp \). A much more complex behavior than the one shown in figure 3(a) can be observed. All modes have local maxima which can be linked to a local minima of the immediately superior mode. These maxima-minima pairs represent swaps of governing layers, and are marked with open circles for the 4L. Vertical dashed lines represent the approximate values of \( \mu_0 H_\perp \) at which these swaps occur, obtaining seven different field regimes representing different combinations of governing layers and resonance modes, as shown in table 2. Once the field reaches the regime VII with \( \mu_0 H_\perp \geq 2 \). T, the governing layers will have inverted their order (the order went from 1234 in regime I to 4321 in regime VII) and no more changes will be observed. In the VII regime it also can be observed that the sample reached saturation (all magnetizations are aligned in the perpendicular direction, parallel to the field), which can be clearly identified in figure 5(a) when the acoustic 2L mode and the lowest frequency 4L mode reach zero frequency at \( \mu_0 H_\perp = 2.15 \) T. Figure 5(b) shows the equilibrium direction of the magnetization of both the 4L and 2L. It shows that all the magnetizations are aligned in-plane \( (\theta^{m}_m = \pi/2) \) when \( \mu_0 H_\perp = 0 \), and gradually saturate in the perpendicular direction \( (\theta^{m}_m = 0) \) as \( \mu_0 H_\perp \) increases. The layers with lower saturation magnetization tend to reach the perpendicular direction first because of a lower demagnetizing energy.

Figure 5(c) shows the intensity of the different resonance modes in each field regime, and compares them with the intensity of the 2L modes. The field values are specified in the caption of the figure. Higher frequency modes are not shown due to low intensities. In the 4L, the lowest resonance mode (which has uniform precession) has high intensity for all regimes. The second resonance mode can also be observed up to regime III.
with an intensity comparable to those shown in figure 3(b). As the field reaches the regime IV and higher, this mode disappears. In contrast, 2L shows only one relevant resonance mode up to the regime III. When the field transitions from III to IV, the governing layers of the 2L modes are interchanged and both modes disappear. This shows than the 4L structure not only has more high intensity resonance modes, but also their intensity is less affected by an external perpendicular field.

3.3. Interlayer exchange coupling

Figure 6(a) shows the resonance frequency of the 4L and 2L as function of \( J_{\text{eff}} \), with \( \mu_0 H_l = 0.1 \text{ T} \). A complex behavior can be observed between \(-0.2 \text{ mJ/m}^2 < J_{\text{eff}} < -0.05 \text{ mJ/m}^2 \) due to the transition between antiparallel and parallel orientation of the magnetization of the layers (figure 6(b)). In particular the steep changes on the resonance frequencies are due to a ‘spin-flop’ behavior induced by the cubic anisotropy. For ferromagnetic coupling, all layers are parallel to each other and increasing \( J_{\text{eff}} \) increases the frequency of each mode. If \( J_{\text{eff}} \) is very strong, the frequency of the resonance mode with the lowest frequency will stabilize and the multilayer would behave as a single thin film with an effective magnetization. For strong antiferromagnetic coupling all layers are antiparallel to their neighbors, and making \( J_{\text{eff}} \) more negative also increases all frequencies. Similarly a strong enough antiferromagnetic coupling will stabilize the lowest frequency resonance mode, and the multilayer will behave as a ferrimagnet with a different effective magnetization than the one induced by the ferromagnetic coupling. The 2L follows a similar behavior with slight changes in the antiferromagnetic coupling strength necessary to induce an antiparallel configuration.

Figure 6(c) shows the intensity of the resonance modes of the 4L and 2L for several values of \( J_{\text{eff}} \). Note again that the observed peaks have similar intensity to those shown in figure 3(b). The 4L shows multiple high intensity modes for all values of the exchange coupling. In the case of strong ferromagnetic coupling (\( J_{\text{eff}} = 0.5 \text{ mJ/m}^2 \)) there are two modes: a low frequency mode with very high intensity, and a high frequency mode with reduced intensity. As the ferromagnetic coupling decreases a third mode appears, and the frequency of all modes decreases. Comparing the ferromagnetic coupled multilayer to the non-interacting case (\( J_{\text{eff}} = 0 \)), all modes in the former have comparable intensities than those of the latter and higher frequencies. This shows that there is a clear advantage in inducing interlayer exchange coupling, as it allows to increase the frequency modes while maintaining of even increasing their intensity. For example, comparing the second mode of \( J_{\text{eff}} = 0.5 \text{ mJ/m}^2 \) and \( J_{\text{eff}} = 0 \), it is clear that the frequency of the former is almost the triple than that of the latter without an

Table 2. Approximate values of \( \mu_0 H_l \), which define the limits of the different regimes in the 4L multilayer, and governing layers of the different resonance modes (in ascendant order of frequency) for each regime. NiFeCu = 1, NiFe = 2, CoFe = 3, Co = 4.

| Regime | I | II | III | IV | V | VI | VII |
|--------|---|----|-----|----|---|----|-----|
| \( \mu_0 H_l \) (T) | 0 | 0.71 | 0.88 | 1.3 | 1.42 | 1.7 | 2 |
| | 0.71 | 0.88 | 1.3 | 1.42 | 1.7 | 2 | \( \infty \) |
| Order | 1234 | 2134 | 2314 | 3214 | 3241 | 3421 | 4321 |
important lose of intensity. Comparing the modes of the 4L and the 2L with ferromagnetic coupling, it can be observed that the 4L has more modes with equal or higher intensities in all cases. For weak antiferromagnetic coupling \((J_{\text{eff}} = -0.1 \text{ mJ m}^{-2})\), there is an important increase in the intensity of the first resonance mode. This is because the magnetizations are not in either parallel or antiparallel configuration, so the antiphase contributions are less relevant. Additionally, there is a stronger NiFeCu contribution due to the low frequency of the mode. Once the multilayer reaches antiparallel magnetization \((J_{\text{eff}} = -0.3 \text{ and } -0.5 \text{ mJ m}^{-2})\) the lowest frequency mode disappears due to the antiphase contributions, and two high frequency modes with good intensities can be observed. Again, comparing the 4L with the 2L shows that the multilayer has more frequency modes than the bilayer with comparable intensities.

All these results showcase some advantages that multilayered structures composed by four (or more) different magnetic materials have for high frequency applications. In particular they could be used in multiband applications due to the presence of several high intensity resonance modes, with frequencies that can be tailored by external excitations or design parameters without considerably changing their intensities.

4. Conclusions

The FMR of a NiFeCu/NM/NiFe/NM/CoFe/NM/Co (4L) multilayer was studied theoretically, and comparisons with that of a NiFe/NM/CoFe (2L) bilayer have been presented. It was found that the resonance modes of the 4L multilayer tend to be more (or equally) intense than those of the 2L for several combinations of applied field and interlayer exchange coupling. This is due not only to a higher number of resonance modes obtained from the four different magnetic materials in the 4L, but also to an increased robustness of these modes due to the additive and subtractive contributions of each individual layer. It was found that for ferromagnetic exchange coupling, these contributions follow these two rules, which would apply to the resonance modes of any number of layers with collinear magnetization: (i) The governing layer of a mode will always be in phase with layers governing higher frequency modes, and (ii) All the layers governing modes with lower frequencies than the current one will be in antiphase with layers governing the neighboring (frequency-wise) modes. Similar rules are followed for antiferromagnetic exchange coupling: (iii) The governing layer of a mode will always be in phase with layers governing lower frequency modes, and (iv) All the layers governing modes with higher frequencies than the current one will be in antiphase with layers governing the neighboring (frequency-wise) modes.

It is shown that a perpendicular applied field induces seven different resonance regimes differentiated by which layer governs each mode. Moreover, it is observed that the modes of the multilayer are more stable under a perpendicular field than those of the bilayer, always presenting more resonance peaks with equal or higher intensity. Varying the interlayer exchange coupling shows that is possible to control the frequency of the modes in both the 4L and 2L structures. For ferromagnetic coupling, the intensities of these modes remained largely unaffected in the 4L, while the intensity of the high frequency mode of the 2L was reduced. For antiferromagnetic exchange, the lowest frequency peak disappears in both structures, while maintaining a good intensity in the high frequency modes.

These results open the possibility to tailor the resonance frequencies of the 4L structure by either engineering the interlayer exchange coupling or by applying a perpendicular magnetic field without affecting significantly the intensity of the resonance modes, thus allowing multiple and controllable operational modes in GHz magnetic devices.

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