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# Magnetoelectric excitation of spin waves in non-uniformly magnetized waveguides

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#### Abstract

We investigate the characteristics of spin waves in ferromagnetic waveguides with non-uniform states of the magnetization. The spin-wave generation is realized via the magnetoelastic effect by applying locally biaxial or shear in-plane strains, as well as via the Oersted field emitted by a wire antenna. Using micromagnetic simulations, we show that both types of excitation field generates quantized width modes with both odd and even mode numbers, with tilted phase fronts. We demonstrate that these effects originate from the average magnetization orientation with respect to the main axes of the magnetic waveguide. Furthermore, it is shown that the excitation efficiency of the second order width mode can even overcome the excitation efficiency of the first width mode. This is traced back to the overlap integral between the mode profile and the distribution of the excitation field. We demonstrate that the relative intensity of the excited width modes can be controlled by the strain state as well as by tuning the dimensions of the excitation area. In addition, we show that the asymmetry in the spin-wave radiation due to the chirality of the Oersted field emitted by inductive antennas is removed by using a magnetoelectric excitation mechanism.

Keywords: spin waves, magnetoelectric effect, quantized spin-wave width modes

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#### I. INTRODUCTION

Spintronic devices based on spin waves have great potential for ultralow power computing technologies that may complement the current complementary metal-oxide-semiconductor (CMOS) technology in future technology nodes. When using spin waves as information carriers, the information can be encoded in the amplitude and/or the phase of the wave. Especially the phase coding has been proposed since wave interference can be used to design majority gates that are advantageous for logic circuit design, but are costly to be realised in CMOS [1–8]. Therefore, it can be envisaged that a hybrid spin-waveCMOS technology may reduce power and area consumption per computing throughput with respect to CMOS alone.

For the successful realization of a competitive hybrid spin-waveCMOS technology, spin wave devices need to be miniaturized down to the nanoscale to achieve a high density of logic functions in the circuit. Yet, scaling magnetic waveguides into the nanoscale leads to higher aspect ratios and introduces stronger anisotropy. For a magnetic bias field transverse to the waveguide as commonly employed in spin wave devices this results in an increasingly nonuniform internal effective magnetic field and consequently in a non-uniform magnetization state [9, 10]. To design magnonic devices at the nanoscale, it is thus crucial to understand how these non-uniformities affect the spin wave generation and propagation behavior.

A key challenge of hybrid spin-waveCMOS circuits is the efficiency of the transduction mechanism between electronic and spintronic parts of the circuit. Different spin wave excitation mechanisms have been proposed, including excitation by inductive antennas [11–14], spin transfer torques [15], or spin orbit torques [16, 17]. All of these coupling schemes are based on electric currents to generate spin waves and hence are neither scalable nor energy efficient. Recently, the magnetoelectric (MEL) cell has been proposed as a novel excitation structure [6, 18]. This element combines the piezoelectric and magnetoelastic effect to excite spin waves by application of a voltage instead of a current. Although it has been shown by experiments [18, 19] and micromagnetic modelling [20] that the MEL effect can excite spin waves, a detailed understanding of spin wave excitation by this effect in nanoscale waveguides is still lacking. In this paper, we investigate by means of micromagnetic simulations how dynamic strain states couple to non-uniformly magnetized waveguides and generate spin waves. The propagation characteristics of spin waves excited by both magnetoelectric



FIG. 1. Sketch of the waveguide geometry with arrows representing the equilibrium magnetization and the out-of-plane component of the magnetization color encoded. Two types of transducers are investigated: excitation with inductive antenna (a) and with magnetoelectric cell (b). Magnetization components  $m_x$ ,  $m_y$  and  $m_z$  in the equilibrium state along the width of waveguide (c).

effect and inductive antenna are further analyzed and compared.

### **II. SYSTEM CONFIGURATION**

The structure under study consists of a CoFeB magnetic conduit with length of 10  $\mu$ m, width of 200 nm and thickness of 10 nm and typical magnetic parameters:  $M_s = 1.25 \times 10^6$  A/m as saturation magnetization [21], an exchange constant of  $A_{ex} = 1.89 \times 10^{-11}$  J/m<sup>3</sup> [22], and a Gilbert damping of  $\alpha = 0.004$ . The damping constant is smoothly increased near the waveguide ends to prevent reflection. The CoFeB is assumed to be polycrystalline, and thus, the magnetocrystalline anisotropy is neglected. A sketch of the geometry is shown in Figure 1(a-b).

A bias magnetic field is applied in-plane transverse to the longitudinal direction of the waveguide. In this way, the bias field counteracts the demagnetization field which tries to align the magnetization in the long direction of the waveguide. The amplitude of the external field is set to 50 mT which results in a magnetization state that is not completely saturated along the external field direction. Thus, the magnetization orientation varies along the width of the waveguide because of the non-uniformity of the demagnetization field. The magnetization components along the width are shown in Figure 1(c) which represents clearly non-uniform orientation of the magnetization.

Two types of transducers are considered to excite spin waves: inductive antenna excitation and magnetoelectric excitation. For the inductive antenna excitation, a current line of width 50 nm is placed on top of the waveguide as shown in Figure 1(a). Oscillating current in this line generates an oscillating Oersted field which generates spin waves in the magnetic conduit.

A second approach for the excitation of spin waves is based on a MEL cell as shown in Figure 1(b). In this case, a piezoelectric material is placed on top of the magnetic waveguide which consist of magnetostrictive CoFeB. When a voltage is applied to the piezoelectric material, a strain is induced inside the piezoelectric and consequently also inside the magnetic waveguide. This strain inside the waveguide couples to the magnetization via the magnetoelastic interaction and is magnetically represented by the magnetoelastic field [23].

$$\mathbf{H}_{mel} = \frac{-2}{\mu_0 M_s} \begin{pmatrix} B_1 \epsilon_{xx} m_x + B_2 (\epsilon_{xy} m_y + \epsilon_{zx} m_z) \\ B_1 \epsilon_{yy} m_y + B_2 (\epsilon_{xy} m_x + \epsilon_{yz} m_z) \\ B_1 \epsilon_{zz} m_z + B_2 (\epsilon_{zx} m_x + \epsilon_{yz} m_y) \end{pmatrix}$$
(1)

Here,  $B_1$  and  $B_2$  are the magnetoelastic coupling constants,  $m_i$  are the normalized magnetization components and  $\epsilon_{ij}$  are the strain components from the strain tensor.

Equation (1) indicates that the MEL excitation field depends on both the strain state and the magnetization. Therefore, the MEL excitation field becomes non-uniform because the waveguide is non-uniformly magnetized. This is in contrast with the Oersted field which is independent of the waveguide properties, and thus can be assumed to be uniform in thin waveguides. Hence, in this paper, the spin waves are excited by a non-uniform MEL field or by a uniform Oersted field.

As previously demonstrated for an in-plane magnetized system, the biaxial and shear strain states are more efficient to excite spin waves than a uniaxial strain state [20]. Therefore, in this work, only the biaxial and shear strain states are used to assess the influence of the strain components on the spin wave properties.

$$\hat{\epsilon}_{biax} = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \hat{\epsilon}_{shear} = \begin{pmatrix} \epsilon_{xx} & \epsilon_{xy} & 0 \\ \epsilon_{xy} & \epsilon_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
(2)

The magnetization dynamics is simulated using the object-oriented-micromagnetic-

framework (OOMMF) [24] with the YY\_mel module included to compute the magnetoelastic field [25]. The magnetic waveguide is implemented as a mesh with cell size of 5 nm x 5 nm x 5 nm. A uniform strain distribution is assumed in the excitation region and isotropic magnetoelastic coupling constants  $B_1 = B_2 = 8.85$  J/m<sup>3</sup> have been considered, which is appropriate for polycrystalline CoFeB films [26].

#### III. SPIN WAVE MODES

The excitation and propagation characteristics of spin waves were studied in detail for different excitation frequencies. For example, the spin wave profiles generated by magnetoelastic effect at 10 GHz, 14 GHz, and 16.5 GHz are shown in Fig. 2(a-c). The dynamic magnetization profiles show that the spin-wave phase front is tilted with respect the propagation direction. This means, the phase front of the mode is not any more perpendicular to the propagation direction of the wave. Additionally, the dynamic magnetization profiles at different frequencies suggest the excitation of different propagating quantized width modes.

To identify the different spin wave modes for every frequency, a spatial Fast Fourier Transform (FFT) is performed along the length of the waveguide. The results are shown in Figure 2(d-f). At 10 GHz, only the first order width mode  $n_1$  is present, with a wavevector of  $k(n_1) = 40 \text{ rad}/\mu\text{m}$ . At 14 GHz, both  $n_1$  and  $n_2$  are present with wavenumbers  $k(n_1) = 54 \text{ rad}/\mu\text{m}$  and  $k(n_2) = 65 \text{ rad}/\mu\text{m}$ , respectively. To note that the intensity of the second order width mode is much higher than the intensity of the first order width mode, case that is not possible with antenna excitation in the Damon-Eshbach (DE) and backward volume wave (BVW) geometry. At 16.5 GHz, the third order width mode  $n_3$  appears and the three modes correspond to wavenumbers  $k(n_1) = 79 \text{ rad}/\mu\text{m}$ ,  $k(n_2) = 72 \text{ rad}/\mu\text{m}$  and  $k(n_3) = 50 \text{ rad}/\mu\text{m}$ .

It is also noted that the spin wave intensity at both edges along the waveguide is not diminishing towards zero. This originates from dipolar pinning near the edges and results in an effective waveguide width which is larger than the real width of the waveguide [27]. This effect becomes even more pronounced in narrow waveguides.

In addition, the spin wave dispersion relations for the whole excitation spectra are extracted from micromagnetic simulations and shown in Fig. 3. These are obtained by applying an excitation pulse of 20 ps duration, and performing a two dimensional Fourier transform



FIG. 2. (a-c) Snapshots images of the magnetization oscillation pattern for different excitation frequencies: 10, 14 and 16.5 GHz, respectively. (d-f) Spin-wave wavenumber distribution across the waveguide width computed by the Fourier transform in space of the z-component of the magnetization after 7 ns of continuous MEL shear excitation (10 mV) at the three excitation frequencies: 10, 14 and 16.5 GHz, respectively.

of the magnetization in space (longitudinal direction) and in time. The solid lines and color plot correspond respectively to spin wave dispersion relations originating from spin waves excited by a shear MEL pulse and an Oersted field pulse. Both excitation fields result in exactly the same dispersion relations.

The phase tilting and the strong excitation of the second order width mode can be attributed to: i) the nature of the MEL excitation field, ii) the non-uniformity of the magnetization, or, iii) the average magnetization orientation which is not anymore along one of the principal axes of the waveguide. To find the real physical origin, different excitation fields and magnetization states are used in the simulations.

From Eq. 1 and 2 it is seen that the biaxial and shear strain generate different nonuniform excitation fields depending on the magnetization orientation. To test the first hypothesis, the results of the three excitation mechanism are compared: biaxial, shear and uniform Oersted field. Virtually, no difference was seen for the spin-wave mode behavior,



FIG. 3. Spin wave dispersion relations for a non-uniformly magnetized waveguide. The color map corresponds to the dispersion relations of spin waves excited by an inductive antenna whereas the lines correspond to the dispersion relations of spin waves excited by a MEL shear excitation.

no change in the dispersion relations nor in the mode profiles of the spin waves. All three excitation mechanism generate modes with tilted phase profile and higher intensity of the second order width mode as compared to the first one. Therefore, the excitation mechanism has no influence on the characteristics of the spin waves.

To determine the influence of the non-uniformity of the magnetization, an artificial waveguide with uniform magnetization oriented under an angle  $\theta$  with the longitudinal direction is investigated. The angle  $\theta$  is set to the average angle over the width of the waveguide:  $\theta = \arctan(\tilde{m}_y/\tilde{m}_x) = 35^\circ$  with  $\tilde{m}_y$  and  $\tilde{m}_x$  the average magnetization components over the waveguide width. The same procedure was used to calculate the dispersion relations and mode profiles and again identical results as in Figure 2 and 3 are obtained. Thus, the non-uniformity of the magnetization lies also not at the origin of the identified behavior.

The higher amplitude of the second mode as compared to the first mode and their tilted phase fronts could also be a consequence of the average magnetization orientation which is not along one of the principal axes of the waveguide. Subsequently, waveguides with uniform magnetization orientation with  $\theta = 0^{\circ}$  or  $\theta = 90^{\circ}$  have been considered in the simulations. In these cases, no tilt of the phase front is seen, and the spin-wave modes with an even mode number are absent. Therefore, the average orientation of the magnetization determines the spin-wave dispersion relations and their corresponding mode profiles. The rotation of the phase front and the mode profile is thus attributed to the average orientation of the equilibrium magnetization which is not aligned with one of the principal axes of the waveguide, as can be seen from Figure 1(c).

Due to the off-axis average magnetization orientation, the dynamic dipolar field becomes anisotropic over the width of the waveguide. At the start of the transient regime, this dynamic field has different amplitude at both edges of the waveguide. Different amplitude of the dynamic field results in different amplitude of the effective field at both edges and thus different precession speeds of the magnetization at both edges. Hence, in the transient regime, phase differences are introduced between both edges until a steady state phase difference is reached. This constant phase difference at both edges in steady state explains the rotation of the phase front.

### IV. MEL EXCITATION EFFICIENCY

As previously explained, the excitation field has no influence on the dispersion relations and mode profiles. Nevertheless, different types of strain distributions (e.g. uniaxial, biaxial or shear strain) result in different excitation efficiencies of different modes. The excitation efficiency of a specific mode n,  $A_n$ , is proportional to the overlap in space between the excitation field  $\mathbf{H}_{exc}$  and the mode profile of that specific mode  $\mathbf{m}_n$  [10]:

$$A_n \propto \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mathbf{H}_{exc}(x, y, z) \cdot \mathbf{m}_n(x, y, z) dx dy dz \right|$$
(3)

The generation of spin wave modes with even mode numbers can be explained by the overlap integral. When the magnetization is along one of the principal axes of the waveguide, the phase front is perpendicular to the propagation direction. In this case, the mode profile of even modes is antisymmetric over the width which results in a zero net overlap integral with a symmetric excitation field. Hence, it is impossible to excite even modes with a symmetric excitation field. Hence, it is even modes here, the magnetization is not any more along one of the principal axes. This results in a rotated phase front and altered mode profiles. Therefore, the antisymmetric profile over the width of even modes is lifted and consequently the net overlap integral is different from zero. Therefore, the existence of both even and odd modes becomes possible in waveguides with average magnetization orientation not along one of the principal axes.

Besides the influence of the mode profile, also the excitation field has an influence on the excitation efficiencies. When using the Oersted excitation field, a uniform field over the width can be assumed. Hence, the excitation field reduces to a constant in the overlap integral. This is not the case for the MEL excitation field. As seen in equation (1), the MEL field is dependent on both the strain and magnetization inside the waveguide. Consequently, if the strain or magnetization inside the waveguide is non-uniform, also the excitation field becomes non-uniform over the width. Therefore, the excitation efficiency of the different spin-wave modes is changing depending on the transducer type.

To illustrate the influence of the MEL excitation field on the excitation efficiency, the biaxial and shear MEL excitation are compared with each other. For both cases, the spin-wave intensity is calculated along the length of the waveguide at a frequency of 12.5 GHz. The result is shown in Figure 4(a) where the grey and red curve, respectively, correspond to the spin-wave intensity for a biaxial and shear excitation field. To note that the excitation region (50 x 200 nm<sup>2</sup>) and voltage (0.01 V) were kept the same for the two strain configurations.

The spin-wave intensity on a logarithmic scale is described by:

$$\log\left(I_n(x)\right) = \log(I_{0n}) - \frac{x}{\delta_n} \tag{4}$$

with  $\delta_n$  the mean free path of mode n. Therefore, every region with a different slope in Fig. 4(a) corresponds to a different mode. Two regions with different slope are identified for both excitation fields, suggesting the generation of two spin-wave modes with different mean free path. The slope of the intensity profile (i.e. negative inverse of mean free path) extracted for mode  $n_1$  and mode  $n_2$  at 12.5 GHz are equal to  $\delta_1 = 4.64 \ \mu m$  and  $\delta_2 =$ 0.88  $\mu m$ , respectively. This difference originates from the group velocity which is also mode dependent. The mean free path is equal to  $\delta = v_g \tau$  with  $v_g$  the group velocity and  $\tau$  the lifetime of the spin wave. The lifetime can be approximated as the same for the two modes whereas the group velocity is strongly differs for the two modes. The group velocities of the different modes are derived from the dispersion relations ( $v_g = \partial \omega / \partial k$ ) and are shown in Fig. 4(b). At 12.5 GHz, the wavenumbers for the modes  $n_1$  and  $n_2$  are  $k_{n1} = 57 \ rad/\mu m$ and  $k_{n2} = 22 \ rad/\mu m$ , respectively, and the associated group velocities  $v_g(n_1) = 1.03 \ \mu m/ns$ and  $v_g(n_2) = 0.25 \ \mu m/ns$ . Since  $v_g(n_2) < v_g(n_1)$  it is expected that  $n_2$  will attenuate faster. This result is confirmed by the intensity curves shown in Fig. 4(a), and can be clearly seen in



FIG. 4. Spin wave intensity along the propagation length for different excitation fields and different transducer areas (a). Group velocity of  $n_1$  and  $n_2$  spin-wave modes as a function of the wavenumber (b). Snapshots of the  $m_z$ -component of the magnetization at 12.5 GHz and MEL excitation voltage 0.01 V with a transducer length of 200 nm and 20 nm in respectively (c) and (d).

the magnetization oscillation pattern displayed in Fig. 4(c). The  $n_2$  mode is dominant close to the excitation region and decays rather strong with the propagation distance, whereas the  $n_1$  mode is visible for longer distances.

Since the width modes are excited with different efficiency and they travel with different group velocities, there will be a point in the waveguide where the intensity of the two modes will equate, after which the intensity of the modes will interchange. For example, for mode  $n_1$  and mode  $n_2$ , this becomes:

$$I_1(X_{tr}) = I_2(X_{tr}) \Rightarrow X_{tr} = \frac{\delta_1 \delta_2}{\delta_1 - \delta_2} \log\left(\frac{I_{02}}{I_{01}}\right)$$
(5)

According to Eq. (5), this transition point can be related to the relative excitation efficiency of mode  $n_1$  and mode  $n_2$ . The further the transition point, the higher relative excitation efficiency  $n_2/n_1$ . Hence, the distance between the excitation region and the transition point holds information on the relative excitation efficiencies of the two different modes.

From Fig. 4(a) it is clear that the second order width mode is more efficiently excited

than the first order width mode for both strain states. This behavior originates from the average magnetization orientation which alters the mode profile. In all cases, the excitation field is symmetric over the width of the waveguide. Hence, the largest overlap integral is obtained if the sign of the dynamic magnetization is everywhere the same in a line over the width. However, if the dynamic magnetization profile consists of a partly positive and a partly negative amplitude over the width, then the net overlap integral reduces. As can be seen from the mode profiles at 10 GHz and 14 GHz (see Fig. 2), mode  $n_2$  has larger areas where the sign is the same over the width. Hence, mode  $n_2$  is more efficiently excited than mode  $n_1$  for a symmetric excitation field. This means that wire antenna excitation also excites mode  $n_2$  more efficiently than mode  $n_1$  for this geometry.

From Fig. 4(a), it is also seen that the transition point is further away from the excitation region for the shear strain than for the biaxial strain. According to Eq. (5), this means that the MEL shear excitation field excites more efficiently mode  $n_2$  than mode  $n_1$  as compared to the biaxial excitation field. The difference between the biaxial and shear excitation field originates from their non-uniform amplitude profile over the width. The strain state inside the excitation region is in both cases assumed to be uniform, however, the magnetization orientation is not. Consequently, this non-uniformity of the magnetization orientation also makes the MEL excitation field non-uniform over the width.

The shear excitation field has maximum amplitude near the edges and minimum amplitude in the middle whereas the biaxial excitation field has a maximum amplitude in the middle and minimum near the edges. On the other hand, the first (second) order mode has highest (lowest) amplitude in the middle and lowest (highest) towards the edges. Therefore, the shear excitation field overlaps more with the second order width mode than the biaxial excitation field which results in a higher excitation efficiency. The opposite is true for the first order width mode. Thus, by altering the strain components, it becomes possible to play with the relative excitation efficiency between the different spin wave modes if they are excited with a MEL excitation field.

Furthermore, from Eq. (3) it is seen that the excitation efficiency depends on the spatial overlap between the excitation field and the mode profile. Therefore, it is expected that changing the area or the geometry of the transducer will change the excitation efficiency.

To illustrate this, we performed additional simulations considering an excitation area of  $50 \ge 20 \text{ nm}^2$  and a frequency of 12.5 GHz. The intensity along the length of the waveguide is

plotted in Fig. 4(a). In this case the mode  $n_2$  is nearly not present, as can be seen in Fig. 4(d), where only  $n_1$  mode is clearly visible. The second order width mode has low amplitude in the middle of the waveguide, therefore, the overlap integral between the excitation field and the mode profile of  $n_2$  is thus nearly zero. However, the mode  $n_1$  can be excited as described by the overlap integral (Eq. (3)). Hence, a mode selective spin-wave excitation can additionally be achieved by tuning the area of the magnetoelectric cell.

It is well known that the non-reciprocal propagation character of the magnetostatic surface waves is enhanced by the chirality of the Oersted field emitted by an inductive wire antenna [11]. However, this chirality is removed when strain excitation fields are used due to symmetry reasons (see Eq. 1), therefore, a symmetric radiation pattern is expected.

To illustrate this, spin waves excited by an Oersted field created by a wire and a magnetoelectric field are compared with each other. The waveguide thickness is set to 40 nm to make sure the anti-symmetry is visible (if present). The spin wave intensity over the length of the waveguide is calculated and plotted together with the mode profile in Fig. 5. It is clearly seen that the Oersted field generates propagating spin waves in both directions, but



FIG. 5. Spin-wave intensity along the propagation length over the waveguide for antenna and shear strain excitation at a frequency of 11 GHz(a). Snapshots images of the  $m_z$ -component of the magnetization for antenna and shear strain excitation in (b) and (c) respectively. The Oersted field has amplitude of 10 A/m and the voltage for the MEL excitation is 0.01 V.

with different intensities, whereas the MEL equally radiates in both directions. To note that the mode profile is the same for the two types of excitation mechanisms: the Oersted field and the strain induced magnetic field.

#### V. CONCLUSION

In summary, we analyzed the excitation of spin waves via the magnetoelastic effect by applying locally biaxial or shear in-plane strains, and we studied their propagation characteristics in non-uniformly magnetized metallic waveguides. We show that both types of strain induced fields generate quantized width modes with both odd and even mode numbers. Furthermore, all excited modes showed a tilted phase front with respect to the propagation direction. We demonstrated that these effects originate from the orientation of the average magnetization with respect to the main axes of the magnetic waveguide. In addition, it is shown that the excitation efficiency of the second order width mode can overcome the efficiency of the first width mode. This is traced back to the rotation of the phase front which affects the mode profile and consequently also the excitation efficiency via the overlap integral between the mode profile and the distribution of the excitation field. We demonstrated that the relative intensity of the excited width modes can be controlled by the strain state as well as by tuning the dimensions of the excitation area. These characteristics were further compared to the classical excitation of spin waves via the Oersted field emitted by a wire antenna. We show that the two excitation mechanisms generate spin waves with similar behavior. However, the asymmetry in the spin-wave radiation due to the chirality of the Oersted field is removed by using a magnetoelectric excitation mechanism.

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