Electrically driven magnetic antenna based on multiferroic composites

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Received 6 October 2016, revised 13 December 2016
Accepted for publication 22 December 2016
Published 27 January 2017

Abstract
We suggest and demonstrate via large scale numerical simulations an electrically operated spin-wave inducer based on composite multiferroic junctions. Specifically, we consider an interfacially coupled ferromagnetic/ferroelectric structure that emits controllably spin waves in the ferromagnets if the ferroelectric polarization is poled by an external electric field. The roles of geometry and material properties are discussed.

Keywords: spintronics, magnetic antenna, multiferroics, magnetoelectric effect

(Some figures may appear in colour only in the online journal)

1. Introduction
Spin-wave excitation and manipulation is an important sub-field of spintronics dubbed magnonics, which is also of relevance to spin-wave-based computing and communication devices [1–4]. To effectively excite and manipulate the magnonic spin current, various methods are proposed and experimentally tested, such as microwave field and spin polarized current [4–6]. However, high power dissipation and scaling issues are serious drawbacks. Recent electric-field-induced spin-wave generation using multiferroic systems points to promising directions [7].

Multiferroics [8–11] have multiple coupled ferroic orders such as ferroelectric (FE), and/or ferroelastic, and/or ferromagnetic (FM) orders and hence may respond to a variety of external probes which opens the way for qualitatively new applications. Here we will be dealing with magnetoelectric composites, i.e. FE/FM heterostructures [12–15]. In principle the underlying idea includes also strain-based magnetoelectrically coupled structures, albeit detailed numerical simulations as those presented here are necessary to estimate the relevance of the associated effects. Generally, composite FE/FM are most interesting, as in these materials the interfacial magnetoelectric coupling turned out to be quite sizable even at room temperature, as evidenced by numerous studies [16–18, 21]. Experimental verification and a direct observation of the ME coupling was reported recently for Co/BaTiO3-interfaces [19] and Co92Zr8/PMN-PT-films [20]. Several coupling mechanisms are discussed in the literatures. For example, for strain-induced magnetoelectric (ME) coupled FE/FM structure, the strain due to e.g. lattice mismatch between the FE and FM can strongly influence the magnetic properties like magnetic anisotropy in the FM layer [13, 22, 23]. For charge-mediated ME coupling when the FM is metallic, the uncompensated charge at the edge of the FE are balanced by the itinerant electrons in the FM, which in turn are spin-polarized and also coupled via the exchange interaction to the net FM magnetization [16, 20, 21, 25]. Generally, several coupling mechanisms are operational at the same time. Via experimental arrangement one may gain insight into their relative strengths. For example, in the experiments on polycrystalline, several-dozens-nm thick Co deposited on single crystal BaTiO3 [19], the main contribution is shown to be provided by the charge-mediated ME coupling (similar findings have been reported for multiferroic Co/P vinylidene fluoride-trifluoroethylene [24]).

In this paper we will simply assume the existence of the ME coupling (using previous knowledge) and study the consequences therefore, such as spin-wave emission via electric
stimulations. In turn the properties of these spin waves carry some footprints of the underlying ME coupling. We assume that an external electric field induced a FE polarization quench due to the magnetoelectric coupling is shown on the left (2 nm-thick, grey color). The area where the induced spin waves are analyzed is in the middle (400 nm-area).

Figure 1. Schematics of the considered two-dimensional $3000 \times 30 \times 10$ nm$^3$-structure. The area corresponding to the magnetization quench due to the magnetoelectric coupling is shown on the left (2 nm-thick, grey color). The area where the induced spin waves are analyzed is in the middle (400 nm-area).

2. Origin of the quenched magnetization

To be specific, we employ the results of [25], where layers of BaTiO$_3$ were grown on 3 MLs of Fe(001). The authors report on two remarkable observations: the magnetic moment is induced in the initially non-magnetic TiO$_2$ layer closest to Fe and when the FE polarization is switched, the induced magnetic moment changes by approximately $\Delta \mu_{\text{TiO}_2} = 0.4\mu_B$. We start with figure 4 of [25], which shows the $ab\ initio$-calculations of the layer resolved magnetic moments (red symbols). Assuming the exchange interaction to be a direct one and ferromagnetic between the induced and the magnetic moments in the first monolayer of iron from the interface, one can estimate the total change of the interfacial magnetization as $\Delta M_{\text{TiO}_2}(P_1 - P_f) = \Delta \mu_{\text{TiO}_2} V_{\text{TiO}_2} \approx 0.46 \times 10^9$ A m$^{-1}$, where $V_{\text{TiO}_2} = (2 \times 10^{-10})$ m$^3$. Now from figure 3 of [25] we estimate the quenched length near the Fe-interface to be $d \approx 2A$. This allows estimating (the relative to the saturation magnetization at $T = 0$ K) the quench of the interfacial magnetization to be around $\Delta M_{\text{TiO}_2}(P_1 - P_f)/M_s = 27\%$. Switching of the FE polarization quenches the interfacial magnetization and excites so propagating spin waves.

Although the experiment [25] provides important quantitative estimates regarding the strength of the magnetoelectric effect, it contains little or no information on the spatial alignment of the magnetization near the interface. To the best of our knowledge, the authors are not aware of any experimental evidence for the FM order in the vicinity of the interface for such a structure. Nevertheless, in the recent study [21] a theory elucidating the spin alignment near the FE/FM-interface was proposed. According to the suggested mechanism, an interfacial spiral spin density extending over the spin diffusion length in the ferromagnet functionalizes the interface for the electric control. Taking the Fe/BaTiO$_3$-interface as an example with the spin diffusion length around 8 nm in Fe [26], we conclude that the spin spiral ordering is highly localized when thinking of FM extensions up to several hundred nanometers.

3. Results of numerical simulations

We first consider a magnetic nanostripe with 3000 nm in length (along the $x$ direction), 30 nm width and with 10 nm thickness (figure 1). The spin wave is excited at the left boundary, since the contact of the FM with the FE driven by an E-field leads to a quenched magnetization. In principle we can also model the FE dynamics in the presence of the strong driving E-field, as done in our previous studies, for the purpose of the present study doing this is not necessary (the spin dynamics is much slower than the interfacial transient electric dipole switching). Poling the FE part results in a quenched magnetization at the boundary in the form $M_{\text{TiO}_2}^{\text{real}}(t) = M_s - b M_s [1 + \sin(\omega t)]$, where $\omega/(2\pi) = 50$ GHz is taken ($b$ is a constant).

We note that the parameter $b$ characterizes the strength of the quench of the magnetization that occurs at the ferroelectric–ferromagnetic interface due to the switching of the ferroelectric polarization. Thus, the upper limit of $b$ is $b = \Delta M_{\text{TiO}_2}(P_1 - P_f)/2M_s$. The angular frequency of the quenched magnetization is defined by the frequency of the time-dependent electric field that switches the ferroelectric polarization $P_1 \leftrightarrow P_f$.

In general, the direction of the quenched magnetization is determined by demagnetizing fields which give rise to slightly tilted magnetic moments at the boundary. In the following, to examine the influence of dynamics in the quenched region, we contrast two situations: when the amplitude of the saturation magnetization is steered, (a) fixed quench case: direction of the magnetization vector is fixed and (b) free quenched case: direction of the magnetization vector is free. Experimentally interesting is to consider the relevant and realistic case of a free quenched magnetization. A fixed quench case delivers information on whether a fixed quench of magnetization can excite spin waves or not. Further on, we will analyze the spin-wave spectrum in the 400 nm-area (figure 1), which is far enough away from both edges to exclude boundaries effects.

The modeling proceeds within the micromagnetic framework using the $\text{mumax}^3$-simulation package [27] with the cell size $2 \times 2 \times 10$ nm$^3$ and the material parameters related to the bulk iron: the saturation magnetization $M_s = 1.7 \times 10^6$ A m$^{-1}$, the exchange stiffness constant $A = 2.3 \times 10^{-11}$ J m$^{-1}$, the anisotropy constant $K = 4.8 \times 10^4$ J m$^{-3}$ with the easy axis aligned along the $x$-direction [28] (since spin waves are low energy magnonic excitations, we neglect the second constant $K_2$ of the (cubic) anisotropy). The damping parameter is taken as a maximum value calculated via $ab\ initio$ $\alpha = 0.01$ [29].
To assess and remove possible numerical spurious effects, such as the choice of the initial state and boundary conditions, we start with the randomly chosen magnetic state. However, we propagate the magnetization within the time interval \( \tau = 200 \text{ ns} \) that exceeds the relaxation time of the homogeneously magnetized FM \( \text{Fe}_{63} \). Then the Fourier analysis is performed only for the last 40 ns and this naturally excludes the memory effect related to the initial state.

The frequency domain relevant to the spin wave can be roughly estimated from the energy gap in the dispersion relation. A precise expression for the finite size bulk system reads [30, 31]:

\[
\omega^2_{\omega} = \omega_H^2 + \omega_m k_x^2 + \omega_m P(k_d) k_x^2, \quad k^2 = k_x^2 + k_y^2 + k_z^2.
\]

Here \( P(k_d) = 1 - [1 - \exp(-k_d)] / (k_d) \) and we introduce the following notations: \( \omega_H = \gamma H_\text{in} \) where \( H_\text{in} \) is the internal magnetic field consisting from the magnetocrystalline anisotropy and static demagnetization fields, \( \omega_m = \gamma M_s, a = 2A / (\mu_0 M_s^2) \) and the spin-wave vector \( k^2 = k_x^2 + k_y^2 + k_z^2 \) is quantized along the y axis \( k_{y,n} = (n + 1) \pi / w_0 \). For the dipolar pinning boundary condition [32], \( w_d \) is supposed to be \( w_d = w d(p) / \{ d(p) - 2 \} \), where \( d(p) = 2\pi (1 + 2n(1/p)) \) is the effective pinning parameter, \( p = t / w \) and \( t, w \) are the thickness and width of the nanostripe. The cutoff frequency is of the order \( \omega_{\text{cut}} = 32 \text{ GHz} \). In the following, we will consider frequencies above this threshold value.

In our simulations time-dependent magnetization is steered homogeneously along the y-direction in the vicinity of the FE/FM interface. This mimics the cooperative effect of the ME coupling and FE polarization driven via the external electric field. The equilibrium spin-wave profile 400 nm in length (figure 2), shows gradual decay of the amplitude away from the FE/FM interface. We clearly see an alternation between maximum and minimum values of the longitudinal magnetization along both \( x \)- and \( y \)-directions (\( n = 1 \) mode). The observed magnetic texture can be explained qualitatively in terms of the noncollinear magnetic order formed in the vicinity of the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case. Obviously steering of the interface magnetization \( \Delta M_{\text{TiO}_2} \) modifies magnetic order at the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case. Obviously steering of the interface magnetization \( \Delta M_{\text{TiO}_2} \) modifies magnetic order at the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case. Obviously steering of the interface magnetization \( \Delta M_{\text{TiO}_2} \) modifies magnetic order at the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case. Obviously steering of the interface magnetization \( \Delta M_{\text{TiO}_2} \) modifies magnetic order at the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case. Obviously steering of the interface magnetization \( \Delta M_{\text{TiO}_2} \) modifies magnetic order at the FE/FM interface. A noncollinear magnetic order occurs due to the dipole–dipole interaction at the FE/FM boundary and enhances at elevated saturation magnetization. The reduction of the saturation magnetization leads to a collinear magnetic order. Our calculations show (not presented here) that the dipole–dipole reservoir dominates over the exchange energy when the saturation magnetization is large, a small saturation magnetization corresponds to the opposite case.
the spin waves. Hence, the features of the emitted spin waves may yield information on the interfacial coupling mechanism, e.g. whether this coupling induces interfacial spin noncollinearity [21] which is essential for the spin-wave emission.

The excitation mechanism of the \( n = 1 \) spin wave is as follows: in the upper part of the FE/FM interface, magnetization is slightly tilted down with respect to the reference direction \( x \), while in the bottom part of the FE/FM interface, magnetization is slightly tilted up, as shown in figure 1. With a decrease of \( M_s \) noncollinear order transforms into collinear. Changes in the upper and lower parts of the FE/FM interface are opposite to each other. Time-dependent \( M_{t\text{TiO}_2}(t) \) induces the out-of-plane magnetization oscillations in both upper and lower parts of the quenched area, while the spin-wave amplitude is zero in the center \( (n = 1 \) mode spin wave). Besides, the spectrum of the spin waves is monochromatic and contains only main frequency 50 GHz for both fixed and free magnetization at the left edge (not shown here). No spin waves with other frequencies are excited.

Evidently the spin-wave excitation mechanism is related to the noncollinearity. To manipulate noncollinearity and hence manipulate the excited spin wave, we suggest a different geometry (figure 3), in which the \( M \)-quenched area is broader than the width of the FM stripe. In contrast to the asymmetric noncollinearity, now the noncollinearity along the \( y \) axis is almost uniform and the excited spin wave is uniform as well \( (n = 0 \) spin wave). Besides, the spectrum of the spin waves is monochromatic and contains only main frequency 50 GHz for both fixed and free magnetization at the left edge (not shown here). No spin waves with other frequencies are excited.

For further optimization of the nanostructure’s geometry and hence noncollinearity, we explore the dependence of the amplitude of the spin waves (or the strength of the equivalent magnetic field) on the geometry of the quenched area (figure 6). Here, demagnetizing fields play the major role, therefore, if the magnetization direction is free, for significantly high lengths and widths one observes an enhancement of the spin waves’ amplitude. Clearly, not the width of the quenched area, but the length of it is more significant (see the points for free magnetization, red points in figure 6).

A strong quench (larger \( b \)) increases the amplitude of the excited spin waves because of the larger amount of the energy pumped into the system. The same effect is achieved by the thickness of the quenched area. An increase of the length \( l_0 \) also increases the number of excited magnetic moments and the amount of the pumped energy. An increase of the width \( w_0 \) presents however no advantage. Because of the geometry of...
the system, part of the energy is not further transmitted and is wasted.

It is noteworthy that the only \( n = 0 \) spin waves are excited for these geometries here. In addition to the quenched magnetization we also inspected the effect of the decaying magnetization at the Fe/FM-interface described in [21]. To perform this, the area with the quenched magnetization was modeled according to \( M(x,t) = \left[ M_S - b M_0 \right] \left[ 1 + \sin(\omega t) \right] \exp(-x/l) \), where \( \gamma = 8 \) nm is of the order of the spin-diffusion length in Fe. The calculations revealed no sizable changes both for the spin-wave spectrum containing the original frequency 50 GHz only.

Our simulations apply to other frequencies, not only 50 GHz. For \( w_0 = 210 \) nm and \( l_0 = 2 \) nm, the excited spin-wave amplitude as a function of the frequency is shown in figure 7, where \( b = 0.003 \) and the quenched part is fixed. Spin waves having frequencies lower than 28 GHz are prohibited to propagate in the nanostrip, which is in a reasonably good agreement with the estimation of the threshold cutoff frequency (32 GHz). By comparing figure 7 with the local microwave field-induced frequency spectrum (not shown here), we find the magnetization excitation effect with \( b = 0.003 \) is equivalent to that of the local microwave field with an amplitude of 1 mT.

4. Summary

Summarizing, in a multiferroic composite consisting of a ferroelectric coupled to a ferromagnetic stripe poling the ferroelectric polarization leads to spin-wave emission in the ferromagnetic part provided the interfacial magnetoelectric coupling results in an interfacial non-collinear spin order in the ferromagnet. Such coupling mechanisms have indeed been reported theoretically and experimentally [20, 21]. Performing large scale micro magnetic simulations for realistic material parameters we demonstrated how the features of the generated spin waves depend on a geometry of the stripe and the coupling at the interface.

Acknowledgments

Financial support by the Deutsche Forschungsgemeinschaft (DFG) through SFB 762 is gratefully acknowledged.

Guang-hua Guo acknowledges financial support from National Natural Science Foundation of China under Grants No. 11674400 and No. 11374373.

References

[1] Chumak A V, Vasyuchka V I, Serga A A and Hillebrands B 2015Nat. Phys. 11453
[2] Lenk B, Ulrichs H, Garbs F and Mnzenberg M 2011Phys. Rep. 507107
[3] Kruglyak V V, Demokritov S O and Grundler D 2010 J. Phys. D: Appl. Phys. 43 264001
[4] Serga A A, Chumak A V and Hillebrands B 2010 J. Phys. D: Appl. Phys. 43 264002
[5] Kiselev S I, Sankey J C, Krivorotov I N, Emley N C, Schoelkopf R J, Buhrman R A and Ralph D C 2003Nature 425380
[6] Lee K J, Deac A, Redon O, Nozieres J-P and Dieny B 2004Nat. Mater. 3877
[7] Cherepov S et al 2014 Appl. Phys. Lett. 104 082403
[8] Fiebig M 2005 J. Phys. D: Appl. Phys. 38 R123
[9] Eerenstein W, Mathur N D and Scott J F 2006Nature 442759
[10] Ramesh R and Spaldin N A 2007 Nat. Mater. 621
[11] Velev J P, Jaswal S S and Tsymbal E Y 2011Phil. Trans. R. Soc. A 3693069
[12] Nozaki T et al 2012 Nat. Phys. 8491
[13] Valencia S et al 2011Nat. Mater. 10753
[14] Pantel D, Goetze S, Hesse D and Alexe M 2012 Nat. Mater. 11289
[15] Vaz C A F 2012 J. Phys.: Condens. Matter 24 333201
[16] Duan C-G, Jaswal S S and Tsymbal E Y 2006Phys. Rev. Lett. 97 047201
[17] Rondonelli J M, Stengel M and Spaldin N A 2008 Nat. Nanotechnol. 346
[18] Cai T, Ju S, Lee J, Sai N, Demkov A A, Niu Q, Li Z, Shi J and Wang E 2009Phys. Rev. B 80 140415
[19] Jedecry N, von Bardeleben H J, Badjeck V, Demaille D, Stanescu D, Magnan H and Barbier A 2013Phys. Rev. B 88 121409
[20] Jia C-L, Wang F, Jiang C, Berakdar J and Xue D 2015Sci. Rep. 5 11111
[21] Jia C-L, Wei T-L, Jiang C-J, Xue D-S, Sukhov A and Berakdar J 2014 Phys. Rev. B 90 054423
[22] Sahoo S, Polisetty S, Duan C-G, Jaswal S S and Tsymbal E Y 2007Phys. Rev. B 76 092108
[23] Jia C-L, Sukhov A, Horley P P and Berakdar J 2012Europhys. Lett. 99 17004
[24] Mardana A, Ducharme S and Adenwalla S 2011Nano Lett. 11 3862
[25] Meyerheim H L, Klimenta F, Ernst A, Mohseni K, Ostanin S, Fechner M, Parihar S, Maznichenko I V, Mertig I and Kirschner J 2011 Phys. Rev. B 83 054423
[26] Bass J and Pratt W P Jr 2007 J. Phys.: Condens. Matter 19 183201
[27] Vansteenkiste A, Leliært J, Dvornik M, Helsen M, Garcia-Sanchez F and Van Waeyenberge B 2014 AIP Adv. 4 107133
[28] Coey J M D 2010 Magnetism and Magnetic Materials (New York: Cambridge University Press)
[29] Gilmore K, Idzerda Y U and Stiles M D 2007Phys. Rev. Lett. 99 024204
[30] Choi S, Lee K-S, Guslienko K Y and Kim S-K 2007Phys. Rev. Lett. 98 087205
[31] Guslienko K Y, Chantrell R W and Slavin A N 2003Phys. Rev. B 68 024422
[32] Guslienko K Y and Slavin A N 2005Phys. Rev. B 72 014463