A spin-wave frequency doubler by domain wall oscillation

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We present a new mechanism for spin-wave excitation using a pinned domain wall which is forced to oscillate at its eigenfrequency and radiates spin waves. The domain wall acts as a frequency doubler, as the excited spin waves have twice the frequency of the domain wall oscillation. The investigations have been carried out using micromagnetic simulations and enable the determination of the main characteristics of the excited spin-waves such as frequency, wavelength, and velocity. This behavior is understood by the oscillation in the perpendicular magnetization which shows two anti-nodes oscillating out of phase with respect to each other.

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The dynamic properties of ferromagnetic thin films have attracted much attention recently. In particular, the possibility to create logic circuits harvesting magnetic features such as domain walls [1] and spin waves [2, 3, 4, 5] is in the focus of research activities. Thus, the excitation and propagation of spin waves and their interaction with domain walls is relevant to this research interest.

In this letter a new mechanism for the excitation and manipulation of spin waves is presented. In case when a pinned domain wall is excited by an external field with its eigenfrequency, a ”steady-state” oscillation forms with this eigenfrequency and a distinct amplitude which is determined by the balance between energy dissipation processes due to damping and the external triggering by the applied field. The energy pumped into the system by the external field leads not only to the compensation of the damped oscillation, but also to the radiation of spin waves. It will be shown that the domain wall itself oscillates with the frequency of the externally applied field whereas the spin waves of twice that frequency are allowed to propagate.

To demonstrate the principle of a spin-wave frequency doubler, micromagnetic simulations using the LLG-code [6] were performed. The used material is Ni$_{81}$Fe$_{19}$ and standard values for this material (saturation magnetization $M_s=800$ G, exchange constant $A_{\text{ex}}=1.05$ $\mu$erg/cm$^3$) were used. The sample geometry is presented in Fig. 1(a). A thickness of 5 nm and cell sizes of 10 nm for the x- and y-direction and 5 nm for the z-direction, respectively, have been used. In this configuration the domain wall is pinned at the two sides of the cross section area and therefore cannot move freely. [7] The starting configuration of the structure exhibits a tail-to-tail domain wall and is presented in Fig. 1(a).

The resonant excitation of the domain wall is one of the most efficient means for creating spin waves. To determine this resonance frequency, the complete structure has been excited by a weak magnetic field pulse in x-direction. After performing a fast Fourier transformation (hereafter referred to as FFT), the local resonance frequency for each point of the structure can be obtained. The resonance frequency for the domain wall has been found to be 5 GHz, and this frequency has been used as the excitation frequency for the investigations presented in the following. By exciting the structure with an external magnetic field in x-direction (frequency 5 GHz, amplitude of 10 Oe), the domain wall starts to oscillate and emits spin waves. The amplitude of the external field is much smaller than the depinning field necessary to drive the domain wall out of its original position.

For a consistent study of this motion, the end of the transient phenomenon, i.e. the steady state of motion has to be reached. The oscillating domain wall emits spin waves whose wavelength was determined to be approximately 130 nm. A detailed insight into the observed phenomenon is given in Fig. 1. In this figure, the temporal evolution of all three magnetization components along the x-axis is shown for a fixed y-position in the middle of the structure. The first column shows the first few nanoseconds of the oscillation. The domain wall can be clearly identified in the center of each panel. The externally applied field needs some time to force the wall to oscillate. After this transition which lasts approximately 1.5 ns, a regular oscillation of the wall can clearly be observed. The second column of panels gives an enlarged view of the steady-state oscillation over a duration of 1 ns. It clearly shows that the wall oscillates with a frequency of 5 GHz.

The spin-wave emission in the wider arms can be observed best in the y- and z-component (as defined in Fig. 1), because these directions are perpendicular to
the equilibrium orientation of the magnetization, and are zero in the initial state. In Fig. 1(b) the emission starts with the first movement of the wall as can be seen from the z-component. The m_z-component of the wall changes its sign during the oscillation, as can be seen from the bright and dark areas in the middle of the graph. As the amplitude of the spin waves is small in comparison with the oscillation of the domain wall itself, the spin waves are only weakly visible in Figs. 1(b) and (c).

The velocity of the spin waves emitted from the wall can be calculated using the slope of the straight lines indicated in Fig. 1(d), yielding a value of 1.25 µm/NS. The interference pattern visible in Fig. 1(d) results from spin waves created by the oscillating domain wall that propagate along the arm until the end of the structure, where they are reflected and overlap with the incoming waves.

The frequency of the propagating spin waves can be obtained by a Fourier transform, which yields a value of 10 GHz. Spin waves with the excitation frequency of the external field of 5 GHz cannot propagate since the corresponding wavevector is imaginary due to the confinement of the spin waves by the stripe boundaries.

As mentioned above, the spin-wave emission depends on the oscillation in the m_z-component. This component shows two anti-nodes as can be seen in Fig. 1(c). This slight tilting of the magnetization out of the plane has already been reported for transverse walls. As expected for a driven oscillation at the resonance frequency the m_x- and m_y-components oscillate with a phase shift of nearly π/2 with respect to the externally applied field (see Fig. 2(a)). Unlike these two components, the m_z-component does not follow this phase relation and shows a tilted oscillation curve which is partially in phase with the external field. This behavior is expected as the domain wall has to be driven by the externally applied field and, therefore, its phase shift is fixed to nearly π/2. The domain wall can be monitored best in the m_y-component, which excites the spin waves second harmonics generation in the spin-wave excitation.

Fig. 3 presents an enlarged view of Fig. 1. The characteristic triangular shape of the z-component as presented in Fig. 1(c) can be identified, resulting from the different velocities of the switching of the m_z-component from positive to negative and vice versa. The frequency of this oscillation is still 5 GHz, as one red and blue area represents half a period each. The frequency doubling is clearly visible by the four beams radiated to both sides within one period (i.e. two maxima (dashed) and two minima (dotted)) and shows that the oscillation of the m_z-component is essential for the excitation of the spin waves. The origin of these spin waves are the two oscillating anti-nodes of the oscillation, as can be seen from Fig. 3. The emission of two maxima in the bottom part of the z-component and one maximum in the top part in the case of positive anti-nodes and one minimum in the bottom part and two maxima in the top part for negative anti-nodes within one period can be identified.

The oscillation of both of these points excites a new spin wave wavefront when switching from the positive m_z-component to the negative and vice versa.

Thus, all three components oscillate with the frequency of the external field. As a result of the two anti-nodes in the m_z-component which excite the spin waves by their oscillation, this component oscillates effectively with twice the driving frequency and allows for the excitation and frequency doubling of the waves.

In summary, dynamic micromagnetic simulations reveal the possibility to create spin waves by the excitation of a pinned domain wall with an external magnetic field. The pinning is necessary to drive the excited domain wall back to its equilibrium position. The properties of the created propagating spin waves such as frequency, wavelength, and velocity can be determined from the simulation data. The frequency doubling of the excited spin waves with respect to the externally applied field can be understood by the oscillation of the m_z-component. As this component shows two anti-nodes which are oscillating non-uniformly but each of them with the given frequency, spin-wave wavefronts are created by both of these oscillations and frequency-doubled as two oscillations contribute to it.

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FIG. 1: (color online) a) Starting configuration. The shape anisotropy fixes the magnetization in the arms in the direction of the arms and forms a tail-to-tail domain wall. The magnetization directions are displayed in the color code defined by the color wheel shown in the upright corner. The denomination of the axes is given in the bottom left corner. b-d) x-, y-, and z-components of the magnetization along the x-axis of the system mapped over time at the y-position shown in the cross area. b) Temporal evolution of the system during the first 2.5 ns. The transient phenomenon in the first 1.5 ns as well as the following steady-state oscillation of the domain wall in the middle of the structure can be clearly identified. c) Temporal evolution of the system after the end of the transient phenomenon for a period of 1 ns. The positions of the two anti-nodes in the z-component are marked by the dashed lines on the left hand side. The triangular shape of the domain wall oscillation is noteworthy and marked for two different periods. d) Enlarged view of the arm region of the structure for a duration of 1 ns. The emission of spin waves from the oscillating domain wall and their propagation is shown as well. The slope of the straight lines given here is used to calculate the spin-wave velocity.
FIG. 2: (color online) a) Oscillation of the magnetization components at the point marked in Fig. 1(a) in comparison to the externally applied field. The amplitude of the external field is given on the left hand side whereas the amplitude of the components is shown on the right hand side. As expected for a driven oscillation the phase shift between the driving field and the \( m_x \)- and \( m_y \)-component, respectively, is nearly \( \pi/2 \). The tilted-shaped \( m_z \)-component does not follow this phase relation.

b) \( m_z \)-component taken at the same \( y \)-position but at the \( x \)-positions where the anti-nodes of the oscillation appear. It can be clearly seen that one period of these oscillations shows a slow increase and a fast decrease (dotted curve) or vice versa (dashed curve). Note that the maxima of the dotted curve and the minima of the dashed curve are in phase with the driving oscillation.

FIG. 3: (color online) Enlarged view of \( y \)- and \( z \)-components of the magnetization as presented in Fig. 1. In this case an amplitude of 40 Oe has been taken to clarify the domain wall movement as well as the spin-wave excitation. The lower parts of the figures were digitally enhanced for better visualization. The triangular shape of a full period of the oscillation in the \( z \)-component is clearly visible and marked for one period. Red areas show a positive value of this component, blue areas a negative one. The position of the two anti-nodes can be identified as well as the fast and slow switching leading to the triangular appearance. The excited spin waves are marked by the straight lines as guides to the eye. The dashed lines in the \( z \)-component mark maxima, the dotted lines minima. By comparing the two components and the course of the lines, the spin waves are excited by the oscillation of the anti-nodes as marked by the lines. The fact that two of these points exist and oscillate explains the frequency doubling.