A current-controlled, dynamic magnonic crystal

A V Chumak, T Neumann, A A Serga, B Hillebrands and M P Kostylev

Fachbereich Physik and Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany
School of Physics, University of Western Australia, Crawley, Western Australia 6009, Australia

E-mail: neumannt@physik.uni-kl.de

Received 16 July 2009, in final form 17 July 2009
Published 23 September 2009
Online at stacks.iop.org/JPhysD/42/205005

Abstract

We present a current-controlled magnonic crystal consisting of a ferrite film in which spin waves propagate and a set of parallel, periodically spaced, current conducting stripes placed close to the film surface. The current flow causes a sine-like variation of the film’s internal magnetic field, which can be modulated by changing the amount of current. Transmission measurements reveal a single, pronounced rejection band. With increasing current strength the rejection band depth and its width increase strongly. Moreover, it is possible to switch the artificial, periodic structure on and off, so that the waveguide makes a transition from full rejection to full transmission within less than 50 ns. Numerical simulations confirm the experimental results and show that the spin-wave propagation in the crystal can be effectively described as a scattering process in the first Born approximation. Three ways to increase the reflection efficiency of the magnonic crystal are identified: an increased number of periods, an increased lattice constant and a decreased spacing between the current carrying structure and the waveguide.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Spin waves in magnetic materials attract special attention because of their potential application as information carriers in signal processing devices. Digital logic devices [1–3] as well as devices for analog signal processing [4–6] can be fabricated based on spin waves. It has been shown that relaxation, one of the main obstacles for the application of spin waves, can be overcome by means of parametric amplification [6, 7]. Spin waves in magnetic materials are also interesting from a fundamental point of view. They provide a model system to study nonlinear effects such as soliton and bullet formation [8–10], to investigate the emergence of chaotic behaviour [11] and the interaction between discrete modes in a multimodal system.

A major advantage of the spin-wave system is its rich spectrum which can be modified in different manners. Magnonic crystals constitute one such possibility. Magnonic crystals [12–19] are defined as artificial media with a spatially periodic variation of some of their magnetic parameters. As such, they constitute a research field which connects fundamental physics with application.

Magnonic crystals are the analogue to photonic crystals [20], but instead of light they operate with spin waves. Compared with uniform media, magnonic crystals exhibit considerably modified spectra of spin-wave excitations which contain features such as full band gaps where spin waves are not allowed to propagate.

These rejection bands can be used to design microwave filters [12, 15]. In addition, promising functionalities arise if the characteristics of the magnonic crystal can be controlled dynamically on a time scale faster than the spin-wave relaxation time: the possibility to switch a stop band on and off immediately offers a method to trap and release a spin-wave packet. This can be exploited for instance in information storage.

Here, we present such a dynamic magnonic crystal. It is based on an yttrium iron garnet (YIG) waveguide placed in a periodically varying, dynamically controllable magnetic field. The magnetic field is created by the superposition of
a spatially homogeneous bias magnetic field $H_{bias}$ with the localized Oersted fields $H_{Oe}$ of a set of current conducting stripes placed in a meander-type geometry close to the YIG film surface [21] as shown in figure 1. By controlling the direct current flowing through the array the field modulation is adjusted and the spin-wave transmission can be changed from full transmission to a transmission showing a distinct, 30 MHz wide stop band. The dynamic controllability constitutes a major difference to previous realizations of magnonic crystals with a periodically varying magnetic field [22] or a corrugated surface [15, 16, 23]. It is the analogue to dynamic photonic crystals [24].

Previous studies focused on the interaction of propagating spin-wave packets with the Oersted field of a single current carrying wire or a set of two wires at most [25–29]. It was shown that the spin-wave transmission can be effectively changed by varying the value of the direct current. However, the appearance of a pronounced frequency stop band, for which spin-wave transmission is prohibited (while it remains almost unaffected outside the band), is only observed for a larger number of conducting stripes. Numerical simulations show that this is related to the change in the Fourier spectrum of the internal magnetic field, which becomes narrower as the number of periods increases.

2. Experimental results

A sketch of the experimental section is shown in figure 1. It consisted of a 5 µm thick YIG film which was epitaxially grown on a gallium gadolinium substrate. A bias magnetic field of 1600 Oe was applied along the YIG waveguide so that the conditions for the propagation of backward volume magnetostatic waves (BVMSWs) [30] are given.

To achieve a periodic modulation of the magnetic field an array of connected, parallel conducting stripes was designed. The array structure was patterned by means of photolithography on an aluminium nitride substrate with high thermal conductivity in order to avoid heating. The structure consists of 40 conducting stripes of 75 µm width and 10 µm height with 75 µm spacing in between. Overall, the structure is 5.925 mm long.

The conducting array was placed above the YIG film in such a way that the stripes ran perpendicularly to the spin-wave waveguide, as sketched in figure 1. When a current $I$ is applied to the periodic array, a magnetic Oersted field is produced. In the first approximation this field is oriented parallel or antiparallel to the bias magnetic field $H_{bias}$.

In the experiment the individual conducting stripes of the array were connected in series to form a meander structure [21] where the current in neighbouring stripes flows in opposite directions (see figure 1). In this way, a one-dimensional magnonic crystal with a lattice constant $a = 300$ µm and a number of periods $n = 20$ was achieved.

We remark that another possible configuration would have all stripes connected in parallel resulting in the currents flowing in the same directions. In this configuration all Oersted fields would have identical orientation. This is an advantage since previous studies have shown the existence of two physically different regimes for the different field orientations: when the Oersted field decreases the internal field one implements the spin-wave tunnelling regime [26]. When the internal field is locally increased the conditions for resonant spin-wave scattering [27] can be fulfilled for which the spin-wave transmission depends non-monotonically on the applied current and exhibits a strong frequency dependence [28].

However, the meander structure is more practical: (i) it produces a much stronger field modulation because the in-plane components of the Oersted fields for neighbouring conducting stripes are oriented in opposite directions. (ii) As a consequence, the individual stripes can be placed closer together which is important if the design is to be downscaled for nano-sized applications. (iii) The meander structure ensures that the magnetic field averaged over the structure remains constant for any current magnitude.

Two microstrip antennas were placed symmetrically one in front and another one behind the periodic array (see figure 1) in order to excite and detect BVMSWs. The distance between the antennas was 8 mm, which resulted in a 1 mm wide gap between the antennas and the conducting structure. A network analyzer connected to the input and the output antenna was used to measure the spin-wave transmission characteristics.

In order to minimize the electromagnetic coupling between the current carrying, metallic array and the spin waves, a 100 µm thick SiO$_2$ spacer was placed between the YIG film and the array. Without such a spacer, the metallic stripes of the conducting array act as antennas which pick up the propagating spin waves and transmit their energy as electromagnetic waves to the other conducting stripes nearby. These in turn excite spin waves which then continue to propagate in the film and may be picked up again by other parts of the array. Overall, this process disturbs the spin-wave propagation strongly so that the usual transmission characteristics known for BVMSWs are modified even if no current is applied to the conducting array [31]. In order to avoid these problems, the mentioned SiO$_2$ spacer was
Spin-wave transmission characteristics introduced [32]. Note that the spin-wave dipole field decays exponentially with the distance from the film surface while the Oersted field around the conducting stripes scales with the inverse distance between the wire and the film surface. The distance of 100 µm between the array structure and the film surface proved to be large enough to avoid any disturbance of the spin-wave propagation by the meander-like conductor, but is still small enough to ensure an efficient modulation of the magnetic field in the film by the current field.

We remark that we tried to reduce the electromagnetic microwave coupling by placing a grounded metal shield between the current carrying array structure and the YIG film. However, this approach did not prove to be effective, as the metal plate introduced a strong disturbance to the BVMSW transmission.

The experimental results for the spin-wave transmission are shown in figure 2. In panel (a), the transmission characteristics obtained without current are shown. As can be seen, they agree well with the characteristics generally expected for BVMSWs: with increasing frequency the transmission increases steadily due to the change in antenna excitation and detection efficiencies. The minimal transmission losses of about 35 dB are determined by the spin-wave excitation/detection efficiency of the microwave antennas as well as by the spin-wave relaxation parameter of the ferrite film. The ferromagnetic resonance frequency $f_{\text{FMR}} \approx 6550$ MHz limits the transmission curve towards higher frequencies.

The undisturbed transmission characteristics are included in panels (b)–(d) as dotted curves, for comparison.

Figure 2(b) shows that the application of a current $I = 0.25$ A to the structure results in the appearance of a pronounced rejection band at a frequency $f_g \approx 6510$ MHz, where the transmission of spin waves is prohibited. This rejection band is already noticeable for currents as small as 80 mA. An increase in the current from this level leads to a rapid increase in the rejection band depth until it reaches the low-signal limit of the dynamic range for the experimental setup at $I = 0.25$ A. The dynamic range is determined mainly by the direct electromagnetic leakage between the input and output microstrip antennas and limits the detection to approximately $-65$ dB. Therefore, a further increase in the applied current above 0.25 A results only in a pronounced broadening of the rejection band (see figures 2(c) and (d)).

In order to determine the time scale on which the designed magnonic crystal can be modulated, a cw-microwave signal with a carrier frequency $f = f_g$ inside the rejection band was applied to the input antenna. The continuous spin-wave signal picked up at the output antenna without applied current is shown as a dashed line in figure 3(a). Next, a current $I = 0.5$ A was sent to the conducting array in the form of a 200 ns long pulse (figure 3(b)). The resulting modulation of the transmitted spin-wave signal is shown in figure 3(a) as a solid line.

Indeed, the spin-wave transmission is effectively suppressed by the current pulse.

The suppression starts with a time delay of 70 ns after the current pulse is switched. The reason for the delay is twofold: first, there is a gap of 1 mm between the current array constituting the magnonic crystal and the output antenna used to detect the spin-wave signal. With a group velocity of $2.6$ cm $\mu$s$^{-1}$, it takes the spin waves 40 ns to pass this gap. Secondly, it must be assumed that spin waves which are inside the array structure at the time when the current is switched on can still partially pass through the magnetic field inhomogeneities and are detected. This accounts for the remaining delay of 30 ns. This means that spin waves which are no more than 1 mm (or three periods of the conducting array) away from the edge of the crystal can (partially) reach the output antenna.

The transition from full transmission to full rejection takes approximately 50 ns. As the magnonic crystal is switched on, a certain part of the spin waves is trapped inside the structure. There, it is continuously reflected and dissipates. The incident spin waves from the input antenna are reflected back from the front edge of the array structure and cannot contribute to the spin-wave energy inside the structure.
Thus, after 200 ns when the magnonic crystal is switched off the spin waves stored inside the crystal have dissipated. The restored signal received at the output antenna is therefore delayed by 270 ns with respect to the switching of the current. This is close to the propagation time of the spin waves between the front edge of the magnonic crystal and output antenna (≈310–40 ns).

Note, that according to the above discussed, simplified model the sum of delays (70 and 270 ns) should correspond to the propagation time of the spin waves in the waveguide. The difference of 30 ns can be either due to the switching time of the magnonic crystal or a slightly asymmetric placement of the array structure between the antennas.

### 3. Numerical simulations

We performed numerical simulations in order to confirm the experimental results. In particular, the simulations were aimed at clarifying the influence of the limited number of magnetic field modulations which constitute the magnonic crystal. Note that due to the meander-like structure of the conducting array, it takes two conducting stripes to create a single crystal period.

From the Landau–Lifshitz equation one can arrive at

\[ m = \chi \cdot h \]

which connects the dynamic magnetization \( m \) via the magnetic susceptibility \( \chi \) with the dynamic magnetic field \( h \). In the low wavenumber limit we can neglect the exchange interaction and consider only two fields which contribute to \( h \). The first one is caused by the dipole field of dynamic magnetization. The corresponding relation can be expressed with the help of Green’s function, which is derived from the magnetostatic Maxwell equations

\[ h_{\text{dipol}} = 4\pi \int G(r, r') m(r') \, dr'. \]

The second contribution stems from the external microwave signal, whose magnetic field is used to excite the spin waves.

To simulate the magnonic crystal performance a one-dimensional approach is sufficient since we consider BVMSWs. If we denote by \( z \) the direction of the applied, bias magnetic field and by \( x \) the out-of-plane direction, we can derive from the above relations the central equation which was used for the simulations

\[ \chi(z, \omega, I)^{-1} m_x(z) = 4\pi \int G_{x}(z, z') m_x(z') \, dz' = A \delta(z - z_0). \quad (1) \]

Here \( m_x(z) \) describes the \( x \)-component of the dynamic magnetization for which the equation has to be solved. The term on the right side contains the excitation source, i.e. the field of the microstrip input antenna, which is assumed to be located at \( z_0 \). Details on the model can be found in [27]. The main difference to the referenced publication is the expression for the inhomogeneous, external magnetic field. It is composed of the bias field \( H_{\text{bias}} \) and the superposed Oersted field \( H_{\text{Oe}} \) of the periodic array, which is the sum of the fields of 2\( n \) parallel conducting stripes (see appendix). The field \( H = H_{\text{bias}} + H_{\text{Oe}} \) enters into the magnetic susceptibility \( \chi \) together with the spin-wave damping.

We numerically solved the integral equation (1) on a lattice of step size 5 \( \mu \)m with the \( \chi \) profile determined by (A1) in the appendix. Green’s function of the dipole field was averaged over the steps of the integration lattice. In addition, the dynamic magnetization \( m_x(z) \) was assumed to be constant over each lattice step. This assumption is valid as long as the step size of the chosen lattice is small compared with the wavelength of the considered spin waves. As a consequence, the integral equation was transformed into a set of linear equations, which can be solved with conventional mathematical toolkits.

The simulations were carried out with material parameters \( 4\pi M_s = 1750 \, \text{G} \) for the saturation magnetization and damping \( \Gamma / (2\pi) = 0.56 \, \text{MHz} \). In order to obtain the measured frequency of ferromagnetic resonance, the bias magnetic field was taken as \( H_{\text{bias}} = 1625 \, \text{Oe} \). The deviation from the experimentally measured, external field by 25 Oe accounts for the otherwise neglected crystalline anisotropy.

The proposed model does not take into account the energy transformation by the microwave antennas adequately. In order to compensate for this deficiency, the calculated transmission coefficients were multiplied with the transmission characteristics which were experimentally measured without applied current. This allows us to compare the numerical simulations with the experimental data.

The obtained results are plotted in panels (b)–(d) of figure 2 as dashed lines. In order to take into account the dynamic range of the setup, the rejection bands were cut off at −65 dB. Overall, the agreement with the experimental data is excellent, especially if we keep in mind that the anisotropy field represents the only fit parameter in our model.
The corresponding currents increase with decreasing structure is essential. periods are necessary to ensure a desired functionality of the will always be limited in size. Hence, the question how many will be infinite. However, in practical applications, the crystals for theoretical considerations, magnonic crystals are usually considered to determine the dependence of the rejection band parameters on the design of the magnonic crystal. For theoretical some aspects are noteworthy. Firstly, the width of the rejection band significantly decreases as the number of periods increases. Secondly, the centre frequency of the frequency band slightly shifts. Thirdly, looking at the frequencies above the main rejection band, a series of minima and maxima is seen. To explain these features, consider the spin-wave scattering on the field inhomogeneity in the first Born approximation as it has been proposed in [27]. In this approximation, the reflection coefficient for a wave with wavenumber $k$ incident on the periodic, conducting array is proportional to the Fourier component of the magnetic inhomogeneity with Fourier wavenumber $2k$. Consequently, a short magnonic crystal with a small periodicity and therefore a wide Fourier spectrum exhibits a relatively wide rejection band. As the periodicity increases and the Fourier spectrum of the inhomogeneity narrows, the rejection band grows smaller. A close analysis of the Fourier spectrum for the magnetic field inhomogeneity reveals the full extent of the agreement between the numerically calculated transmission coefficients and the Fourier components which are included in figure 4(b). As can be seen, all mentioned features are mirrored in the Fourier spectrum of the field inhomogeneity: the change in band width, the shift in central frequency as well as the side bands.

The validity of the first Born approximation is a consequence of the comparatively low current-induced field modulation. As evident from table 1, the prediction that twice the wavevector of the incident wave coincides with the Fourier vector of the field inhomogeneity is correct for $n \geq 4$. For lower $n$ the higher applied currents lead to corrections which are not included in the first Born approximation.

Note that the Fourier spectrum of the field inhomogeneity transforms into two single peaks at $\pm 2\pi/a$ as the number of periods is increased and the inhomogeneity profile grows more and more sine-like. This is already evident from the inset of figure 4(b) for $n = 20$. It is the reason for the existence of a single rejection band in the low-current-limit where the first Born approximation holds.

Let us now turn to the current required to achieve a certain rejection band width. The corresponding dependence for

### Table 1. Frequencies in the main rejection band which exhibit the minimal transmission with corresponding wavevectors and wavelength for different numbers of periods. A single period of the crystal corresponds in all cases to 300 $\mu$m. The last row shows the wavevector associated with the peak in the Fourier spectrum of the magnetic field distribution for comparison.

| Number $n$ of periods | 2   | 3   | 4   | 5   | 10  | 20  |
|-----------------------|-----|-----|-----|-----|-----|-----|
| Frequency (MHz)       | 6517| 6516| 6515| 6514| 6513| 6513|
| Wavelength ($\mu$m)   | 663 | 642 | 626 | 617 | 604 | 601 |
| Wavevector (cm$^{-1}$) | 95  | 98  | 100 | 102 | 104 | 105 |
| Fourier vector (cm$^{-1}$) | 173 | 191 | 199 | 204 | 207 | 209 |

Figure 4. (a) Numerically simulated frequency rejection bands for different numbers $n$ of magnetic field periods. The currents differ for different $n$ in order to achieve the same depth of the rejection band. (b) One side of the Fourier spectrum calculated for the magnetic field inhomogeneity as given by equation (A1). The inset shows the complete Fourier spectrum for $n = 20$ which exhibits two distinct peaks at $k = \pm 209$ cm$^{-1}$. (Colour online.)

The calculated transmission characteristics reproduce well the three main features observed in the experiment: (i) a pronounced rejection band centred at $f_{\text{gap}} = 6510$ MHz which increases in width as the current is increased, (ii) a slight decrease in the transmission for frequencies above the rejection band and (iii) an almost unaltered transmission for frequencies below the rejection band.

In fact, the simulation revealed a second, weak rejection band at $f = 6469$ MHz which is visible only for the largest, applied current in figure 2. In the experimental data, it cannot be distinguished due to the noise level.

The same calculations were carried out using different numbers $n$ of periods. Such calculations are relevant to determine the dependence of the rejection band parameters on the design of the magnonic crystal. For theoretical considerations, magnonic crystals are usually considered to be infinite. However, in practical applications, the crystals will always be limited in size. Hence, the question how many periods are necessary to ensure a desired functionality of the structure is essential.

Figure 4(a) shows the calculated transmission characteristics for different $n$. In the simulations, the current values were intentionally chosen to give the same depth of $-10$ dB. The corresponding currents increase with decreasing $n$. This dependence is discussed below. As can be seen, each of the transmission characteristics contains a rejection band. Several aspects are noteworthy. Firstly, the width of the rejection band significantly decreases as the number of periods increases. Secondly, the centre frequency of the frequency band slightly shifts. Thirdly, looking at the frequencies above the main rejection band, a series of minima and maxima is seen.
different numbers $n$ is plotted in figure 5(a). The rejection band width is measured at a transmission level of $-10\,\text{dB}$ which corresponds to a 10% transmission of the original signal power. Again, the experimental data agree well with the simulations. Above a certain minimal current, which depends on the number of crystal periods, the rejection band width increases monotonically. For high enough currents a linear dependence between necessary current and number of crystal periods can be approximated by $n \cdot I = \text{const}$. The rejection band of $\leq -10\,\text{dB}$ is achieved. (Colour online.)

Figure 5 relates the minimal current, which is required for a $-10\,\text{dB}$ deep rejection band, to the number $n$ of periods. Clearly, a lower $n$ requires a higher current. The dependence between necessary current and number of crystal periods can be approximated by $n \sim 1/I$ for low currents. This is in accordance with the derived formula for the Fourier transform of the magnetic field (A2). It suggests that the Fourier amplitude (which is proportional to the reflected spin-wave amplitude) at the frequency $f_{\text{exp}}$, is (i) proportional to the applied current, (ii) proportional to the number of periods $n$, (iii) exponentially decreases with increasing spacing $s$ between current array and waveguide. As a consequence, if the current is lowered, the reflection efficiency of the magnonic crystal can be kept constant if simultaneously either the number of periods is increased in such a way that $n \cdot I = \text{const}$ holds or the spacing $s$ between the current carrying wires and the waveguide is decreased so that $\exp(-ks) \cdot I$ remains unchanged for the wavevector $k$ in the rejection band. Note that the wavenumber is also a possible parameter to tune the crystal efficiency. As seen from (A2) it enters into the Fourier amplitude of the field (and therefore the reflected amplitude) as $\exp(-ks)/k$. Therefore, a higher lattice constant, which results in a lower wavenumber of the primarily reflected spin wave can be advantageous, even though the longer crystal leads to a more pronounced dissipation of the spin-wave energy during the propagation.

4. Discussion and conclusions

In this paper we have presented a magnonic crystal design based on a current conducting array which consists of periodically spaced, parallel stripes connected in series which are located close to a ferrite spin-wave waveguide. The current-induced, spatial variation of the field inside the YIG film results in a pronounced modification of spin-wave dispersion which leads to the appearance of spin-wave rejection bands.

Measurements and simulations indicate that for all practical purposes only one rejection band needs to be considered. This constitutes a major difference to other realizations of magnonic crystals consisting, for example, of an array of grooves on the YIG film surface [15, 23] where multiple rejection bands are formed. The presence of only one rejection band is an advantage for applications in microwave filter devices.

Another positive aspect of the presented crystal is that practically no losses occur for frequencies outside the main stop band with increasing current (see figures 2(c) and (d)). In the magnonic crystal which is based on surface grooves [15, 23] such an undesired increase in parasitic losses in the transmission bands was observed for larger groove depths.

The main advantage of a current-based magnonic crystal is its dynamic controllability. We have shown that the crystal can be switched from full transmission to full rejection with a transition time of less than 50 ns. This is a necessary condition for energy storage inside the crystal structure. Moreover, by adjusting the current the rejection band width can be tuned. This was experimentally shown for a magnonic crystal with 20 periods, where the dependence of the rejection band width on the current was found to be nearly linear in the range from 5 to 30 MHz. Numerical simulations confirmed these observations.

The number of periods in the magnonic crystal is a crucial control parameter. It influences the Fourier spectrum of the internal magnetic field, and thus the depth and the width of the rejection band. In fact, if the variation of the internal magnetic field is small, the first Born approximation for the scattering of the spin waves on the magnetic inhomogeneities holds and the rejection band frequency and width can be estimated directly from the Fourier spectrum of the magnetic field.

For possible applications, it is desirable to increase the efficiency of the magnonic crystal. The simulations have shown that this is principally possible by increasing the number of crystal periods. However, an increased
number of periods translates into a longer crystal and a longer propagation distance for the spin-wave pulse. Without additional amplification, it is therefore not possible to reduce the current arbitrarily. The same holds for an increase in the period \( l \) which leads to a lower \( k \) with potentially higher reflected amplitude for the same current. Another possibility to decrease the required current would be to decrease the distance between array structure and waveguide. From the Fourier analysis of the magnetic field it is evident that the current depends exponentially on this spacing (as long as the assumptions of the model are valid). The problem, which this approach faces, is the electromagnetic coupling of the spin waves to the array of metallic wires.

Acknowledgments

Financial support by the DFG project SE 1771/1-1, the Matcor Graduate School of Excellence, the Australian Research Council, and the University of Western Australia is acknowledged. Special acknowledgments go to the Nano+Bio Center, TU Kaiserslautern. The authors thank Professor B A Kalinikos for helpful discussions. TN would like to thank especially Robert L. Stamps and the University of Western Australia for their assistance during his research stay.

Appendix A. Oersted field of a conducting array of stripes

In order to calculate the Oersted field of the conducting array we consider a single conducting stripe first. The component of the Oersted field in the direction of the bias field is then given (in CGS) by

\[
H_{\text{stripe}, z}(z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{-I(x-x')(z-z')}{5(x-x')^2 + (z-z')^2} \, dx \, dx' \, dz' = \frac{I(x-x')}{10 \cdot w \cdot h} \left( \log((z-z')^2 + (x-x')^2) + ((x-x')^2 - (z-z')^2) \times \arctan \left( \frac{z-z'}{x-x'} \right) \right)_{x=-w}^{x=w} \, dz'.
\]

The constants encode the geometric dimensions of the section and are explained in figure A1.

Adding up the fields of the different current conducting stripes, we obtain the field of the conducting array as a function of the number of array periods \( n \):

\[
H_{\text{Oe}, z}(z) = \sum_{l \leq j < 2n} \sum_{l} (-1)^j H_{\text{stripe}, z}(z - (j + 0.5 - n) \cdot l).
\]

(A1)

For the theoretical analysis it is interesting to consider the Fourier transform of this field. If we neglect the height \( h \) of the conducting array and the thickness \( w \) of the waveguide, which are both small compared with the distance \( s \) between the waveguide and the conducting array, the formula for the Oersted field of a single stripe simplifies to

\[
H'_{\text{stripe}, z}(z) = \frac{I}{5} \arctan \left( \frac{z-z'}{s} \right)_{z=z'/s}. \]

The Fourier transform \( \mathcal{F}(H_{\text{Oe}, z}(k)) \) for the corresponding overall Oersted field is given by the analytical expression

\[
\mathcal{F}(H_{\text{Oe}, z}(k)) = \frac{4 \pi I}{5} e^{-|k|} \sin \left( \frac{|k|}{2} \right) \sum_{j=1}^{n} (-1)^{j+1} \sin((2j - 1)k). \]

This can be evaluated at the wavenumber \( k_{\text{gap}} = 2\pi/a \) associated with the magnonic crystal of period \( a = 4l \):

\[
\mathcal{F}(H_{\text{Oe}, z}) \left( \frac{2\pi}{4l} \right) = \frac{4 \pi n I}{5} e^{-\frac{2\pi}{4l}} \sin \left( \frac{\pi}{4} \right). \quad (A2)
\]

References

[1] Schneider T, Serga A A, Leven B, Hillebrands B, Stamps R L and Kostylev M P 2008 Appl. Phys. Lett. 92 022505
[2] Lee K and Kim S 2008 J. Appl. Phys. 104 053909
[3] Kostylev M P, Schneider T, Serga A A and Hillebrands B 2008 J. Nanoelectron. Optoelectron. 3 69
[4] Adam J D 1988 Proc. IEEE 76 159
[5] Kobljanjskyj Yu V, Melkov G A, Serga A A, Tiberkevich V S and Slavin A N 2002 Appl. Phys. Lett. 81 1645
[6] Serga A A, Chumak A V, Andre A, Melkov G A, Slavin A N, Demokritov S O and Hillebrands B 2007 Phys. Rev. Lett. 99 227202
[7] Schiömann E, Green J J and Milano U 1960 J. Appl. Phys. 31 3868
[8] Kalinikos B A, Kovshiko N G and Slavin A N 1983 JETP Lett. 38 413
[9] Demokritov S O, Serga A A, Demidov V E, Hillebrands B, Kostylev M P and Kalinikos B A 2003 Nature 426 159
[10] Serga A A, Kostylev M P and Hillebrands B 2008 Phys. Rev. Lett. 101 137204
[11] Hagerstrom A M, Tong W, Wu M, Kalinikos B A and Eykhol R 2009 Phys. Rev. Lett. 102 207202
[12] Reed K W, Owens J M and Carter R L 1985 Circuits Syst. Signal Process. 4 157
[13] Gulyaev Yu V, Nikitov S A, Zhivotovskii L V, Klimov A A, Tailhades Ph, Presmanes L, Boningue C, Tsai C S, Vysotskii S L and Filimonov Yu A 2003 JETP Lett. 77 567
[14] Kostylev M P, Schrader P, Stamps R L, Gubbiotti G, Carlotti G, Adeeyea A O, Goolaup S and Singh N 2008 Appl. Phys. Lett. 92 132504
[15] Chumak A V, Serga A A, Hillebrands B and Kostylev M P 2008 Appl. Phys. Lett. 93 022508
[16] Chumak A V, Serga A A, Wolff S, Hillebrands B, and Kostylev M P 2009 Appl. Phys. Lett. 94 172511
[17] Wang Z K, Zhang V L, Lim H S, Ng S C, Kuok M H, Jain S and Adeyeye A O 2009 Appl. Phys. Lett. 94 083112
[18] Sykes C G, Adam J D and Collins J H 1976 Appl. Phys. Lett. 29 388
[19] Gubbiotti G, Tacchi S, Carliotti G, Singh N, Goolaup S, Adeyeye A O and Kostylev M P 2007 Appl. Phys. Lett. 90 092503
[20] Krauss T F, De La Rue R M and Brand S 1996 Nature 383 699
[21] Myasoedov A N and Fetisov Y K 1989 Sov. Phys. Tech. Phys. 34 666
[22] Voronenko A V, Gerus S V and Haritonov V D 1988 Sov. Phys. J. 31 76
[23] Chumak A V, Serga A A, Wolff S, Hillebrands B and Kostylev M P 2009 J. Appl. Phys. 105 083906
[24] Tanaka Y, Upham J, Nagashima T, Sugiyama T, Asano T and Noda S 2007 Nature Mater. 6 862
[25] Serga A A, Neumann T, Chumak A V and Hillebrands B 2009 Appl. Phys. Lett. 94 112501
[26] Demokritov S O, Serga A A, André A, Demidov V E, Kostylev M P and Hillebrands B 2004 Phys. Rev. Lett. 93 047201
[27] Kostylev M P, Serga A A, Schneider T, Neumann T, Leven B, Hillebrands B and Stamps R L 2007 Phys. Rev. B 76 184419
[28] Neumann T, Serga A A, Hillebrands B and Kostylev M P 2009 Appl. Phys. Lett. 94 042503
[29] Hansen U-H, Gatzen M, Demidov V E and Demokritov S O 2007 Phys. Rev. Lett. 99 127204
[30] Damon R W and Eshbach J R 1961 J. Phys. Chem. Solids 19 308
[31] Fetisov Y K, Ostrovskaya N V and Popkov A F 1996 J. Appl. Phys. 79 5730
[32] Kalinikos B A 2007 private discussion
[33] Tiberkevich V 2009 private discussion