Spin waves in periodic antidot waveguide of complex base

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We consider the planar magnonic waveguide with a periodic sequence of antidots forming zig-zag pattern, where two neighboring antidots are shifted towards the opposite edges of the waveguide. This system has a complex base with two antidots in one unit cell. The Brillouin zone is here two-times narrower than the Brillouin zone for the waveguide without displacement of antidots. We have shown that for dispersion relation folded into narrower Brillouin zone, new frequency gap can be opened and their width can be controlled by the shift of the antidots. We found that, the different strength of spin wave pinning at the edges of the periodic waveguide (and their antidots) determines the dependence of the width of gap on the shift of antidots. For the systems with completely free or ideally pinned magnetization, these dependencies are qualitatively different. We have found an optimum shift of antidot for maximizing the width of the gap for the system with pinned magnetization. More interestingly, we notice that for this kind of geometry of the structure, majority of the modes are doubly degenerate at the edge of Brillouin zone and have a finite group velocity at the very close vicinity of the edge of Brillouin zone, for larger values of antidot shift. This empowers us to design magnonic waveguide to steer the spin waves.

I. INTRODUCTION

The waveguides and transmission lines are important components of radio-frequency [1], photonic/optical [2–4] and magnonic [5–7] integrated systems for data communication and processing. The most obvious role of this element is transmission of signals between different parts of the system. However, the waveguides, in which the coherent waves propagate, are more sophisticated elements. The geometry of the waveguide determines the quantization of the modes (confined in the cross-section of the waveguide) and their dispersion relation (dependence of the eigenfrequency on wave vector) describes the propagative properties. The adjustment of structural parameters of magnonic systems or the application of external bias field allows to tailor and continuously control the properties of the waveguides important for their dynamical characteristics. One can change the number of modes for given frequency (determined by the position of branches of dispersion relation corresponding successive modes) and control their group delay [8, 9] (given by the group velocity – resulting from the slope of dispersion relation). The molding and controlling of phase delay [10, 11] is the main working principle for wave-based logic systems occurred due to the wave interference in the networks of waveguides [12]. In these systems, the difference of phases of the waves at the junction of two waveguides determines the conditions for constructive or destructive interference which corresponds to high or low level of the output signal. The more sophisticated processing of magnonics signals can be achieved in the waveguides with continuously changing width [13], in arrays of coupled waveguides [17] or in the waveguides with dynamically applied periodic magnetic field [14].

In magnonics [15–17], the dynamics of SWs in partially confined geometries (such as waveguides) is much more complicated phenomena than the dynamics of the excitation of different kinds of waves (e.g. electromagnetic waves or elastic waves). It results from the concurrence of two kinds of interactions (dipolar and exchange one). Due to the presence of dipolar interaction, the anisotropic [18] and nonreciprocal [19, 20] SW propagation is quite easily achievable in microstructured magnonic system. The anisotropy of spin propagation controlled by magnetic field can be used to design the magnonic multiplexers [21, 22]. The other advantage of SWs, as a carrier of information, is the smaller size of magnonic structures and devices comparing to their other counterparts operating on the electromagnetic waves of the same frequency. For future applications, particular attention should be paid on magnonic nanostructured systems which are based on the exchange SW of wave length of few nanometers and the frequencies in few tens of GHz range. In this regime, the dipolar interaction is dominated by exchange interaction and, in general, the most of the features of magnonic systems is the same as in rescaled photonic counterparts. However, there are still some fundamental differences between these two media. Some of the most important differences can be listed as follows: (i) SW propagations is limited to the magnetic material only; (ii) boundary conditions for exchange SWs at the interfaces with nonmagnetic media are determined by surface magnetocrystalline anisotropy resulting from the physical and chemical states of the surface. Therefore, the surface anisotropy is an additional factor, to the geometry and to the bulk material parameters, of controlling the SW spectrum in waveguides at the nanoscale.

The waveguides can have different forms. However, in integrated systems, fabricated by top down lithographic techniques, the planar structures are the most common solutions. Therefore, a great interest is focused on pla-
nar magnonic waveguides where in-plane dimensions are much larger than the thickness and in low frequency range so that we can neglect the out-of-plane quantization of SWs. One of the effective ways of tailoring dispersion relation is a periodic modulation of structural or material parameters of the system. The periodicity in magnonic waveguides can be introduced in various ways \[23,24\]. The simplest method, used for patterning of planar waveguides, is to introduce a periodic sequence of antidots \[24\]. For very long waves this procedure can be understood just as a molding of effective material parameters but for the shorter wavelengths, comparable to the period of the structure, the Bragg reflection on periodic pattern results in folding of dispersion relation to the first Brillouin zone (BZ). This effect can lead to the opening of frequency gaps in the SW spectrum of the waveguide. The frequency gaps can be observed easily in lower frequency range where only one mode exists in the whole range of wave number. The folding of dispersion branches results in their crossings and anti-crossings inside BZ. The anti-crossing of modes gives the possibility to open frequency gaps for higher frequencies where many modes may exist. The presence of frequency gaps at desired position having appropriate width is the working principle of spectral filters.

In this study, we will investigate planar magnonic waveguides periodically patterned by the sequence of antidots. Apart from antidot magnonic waveguide with a single ferromagnetic material, waveguides consisting bi-component material, i.e., antidots filled with some other ferromagnetic material with contrasting magnetic parameters also shows a promising band structure with tunable band gap. However, the advantages of magnonic crystal with air holes surrounded by magnetic material over bi-component one can be noted as: (i) larger contrast in magnetic parameters, e.g., saturation magnetization (\(M_s\)) and exchange length (\(l_{ex}\)) helps to obtain band structure with distinctive gaps in the spectrum, (ii) comparatively easier fabrication process, and (iii) cost effective method as only single magnetic material is required.

In dipolar interaction regime, shape of the antidot plays a consequential role because of significant variation in the demagnetizing field in dot and antidot structures. In our case, due to the nanoscale magnonic structures with few nm length scale, exchange interaction dominates over dipolar interaction in the frequency regime of few tens of GHz. For higher SWs frequencies, the shape of the antidot is not very important in reshaping the magnonic band spectrum if the cross-sectional area of antidot remains constant as reported earlier \[24\]. However, on the other hand, this type of system is very sensitive to broken symmetry (shift of the antidot with respect to the centre of the waveguide) \[24\]. Therefore, we are interested in investigating the intriguing role of broken mirror symmetry in this kind of system.

The considered periodic system has a complex base containing two antidots per one period. The antidots of same sizes are distinguished (in one unit cell) by opposite shifts with respect to the long-axis of the waveguide. This procedure allows to introduce structural changes gradually and to transit the system from the case where the complex base is artificial (we have two indistinguishable elements in the base and the assumed periodicity is artificially doubled) to the case where the spatial separation between neighboring antidots is vital. We investigate the impact of this kind of structural changes on the SW spectrum. We paid particular attention on the tunability of the width of the magnonic band gaps and tailoring the group velocity. We check the role of magnetization pinning/depinning \[28\] (on the edges of the waveguide and antidots) on the mentioned dynamical properties. We performed numerical studies of considered structures using two different numerical techniques: plane wave method (PWM) and micromagnetic simulation (MS) to cross-check the outcomes and to obtain the whole set of complementary results – each of those methods has specific advantages and limitations.

The manuscript is organized in the following way. In the next section ‘Structure and Model’, we describe the considered structures of antidot waveguides and discuss the physical models we solved using the numerical calculations. The section ‘Results and Discussion’ contains the outcomes of numerical studies complemented with detailed discussion. In the last section ‘Conclusion’ we summarize our results.

II. STRUCTURE AND MODEL

We study planar quasi one-dimensional (1D) magnonic waveguide with a series of antidots disposed periodically in zig-zag like manner, as shown in Fig. 1. It possesses the form of an infinitely long 1D stripe with thickness equals to 1 nm. Square antidots with sides \(s\) of 6 nm are placed asymmetrically along the waveguide. We keep the width of the waveguide fixed at 45 nm. The distance between the centers of antidots, measured along the waveguide \(a\) was set to 15 nm. The alternative shifts of the antidots towards the edges of waveguide \(w\) transform the system into the periodic waveguide of complex base with two identical antidot in one unit cell (see Fig. 1). We varied the value of \(w\) from 0 nm (complex base is artificial and waveguide possesses exact mirror symmetry with respect to the long-axis of the waveguide) to 18 nm (complex base with two identical elements and broken mirror symmetry) with a regular increment.

The waveguide here is made of Permalloy (Ni_{80}Fe_{20}) with a saturation magnetization \(M_s = 0.8 \times 10^6\) A/m, and an exchange length \(l_{ex} = 5.69\) nm. The value of gyromagnetic ratio \(\gamma = 175.9\) GHz/T was assumed in the calculations. A bias magnetic field of \(\mu_0H_0 = 1\) T is applied along the \(x\) direction to saturate the sample along the stripe length. It is strong enough to fully saturate the magnetization and make collinear alignment of spins near edges of the waveguide. For the geometry considered here, the SWs propagate with the wave vector \(k\) paral-
Gilbert equation:

\[
\frac{dM}{dt} = \gamma \mu_0 M \times H_{\text{eff}} + \frac{\alpha}{M_s} M \times \frac{dM}{dt}
\]

where \( \mathbf{r} \) and \( t \) are position vector and time, respectively. The symbols \( \mu_0 \) and \( \gamma \) denote the free space permeability and gyromagnetic ratio, respectively. There are two torque terms present on the right-hand side of the equation. The first term corresponds to the torque inducing the precessional dynamics of magnetization vector \( \mathbf{M} \) and the second one is responsible for damping process (\( \alpha \) being the Gilbert damping coefficient). Value of \( \alpha \) is neglected in PWM calculations while a very small value of \( \alpha = 0.0001 \) is assumed in MS allowing magnetization precession for a long time. The field \( H_{\text{eff}} \) is the total effective magnetic field which consists of external bias magnetic field \( H_0 \), exchange field \( H_{\text{ex}} = \nabla \cdot E \), and demagnetizing field \( H_{\text{dem}} \). Magnetization as a function of real space and time i.e. \( \mathbf{M}(r,t) \) and as a function of reciprocal space and frequency, i.e. \( \mathbf{M}(k,f) \) are obtained from MS and PWM, respectively. Using MATLAB subroutine program [30], we analyzed the data obtained from OOMMF to get \( \mathbf{M}(k,f) \). The postprocessing method is described elsewhere [27].

Magnetization pinning is observed to play an important role in opening magnonic band gaps in this type of antidot waveguides [28]. In general, intrinsic dipolar pinning due to demagnetizing field at material/air interface affects the SW spectrum in the dipolar regime. On the other hand, the state (pinning) of the Py/air boundary depends on the fabrication process extending over few nm length scale regimes. This type of pinning does not impact much in case of dipolar interaction but critically affects the exchange SWs. Therefore, we assume magnetization pinning of various strengths at Py/air interface in the calculation process. Pinning in OOMMF is introduced by freezing the magnetization direction (along \( x \) direction) over a finite thin area around Py/air interface. We create a mesh in the OOMMF calculation using cell size \( 1.5 \times 1.5 \times 1 \, \text{nm}^3 \) along \( x, y \), and \( z \) direction, respectively. 1D periodic boundary condition was applied along the stripe length and total simulation time was kept at 4 ns in MS for higher frequency resolution. Pinning in PWM process is intrinsic and applied exactly at the interface. In case of MS, the pinning is applied in the edge cell (of finite size). This may affect the results to a small extent. However, both the methods give similar output results as demonstrated in previous studies [27, 28].

III. RESULTS AND DISCUSSION

The periodic displacement of antidots illustrated in Fig. 1 doubles the periodicity of the waveguide to \( 2a \) in reference to the system with antidots placed inline \( (w = 0) \). This doubling of period results in the folding of dispersion relation to one half of its initial width in reciprocal space. In this narrowed BZ, the new magnonic band gaps appear. We trace the opening and gradual widening of these gaps with increasing displacement \( w \) for the system with pinning. In Fig. 2a we plotted the SW dispersion for few values of the displacement \( w \) calculated with the aid of PWM.

The case \( w = 0 \) corresponds to the waveguide with all antidots placed inline and the period equal to \( a \). In the considered (Fig. 2) frequency range \( (40 - 175 \, \text{GHz}) \), we observe two magnonic gaps which already exist in this system. At around 110 GHz, we find a gap resulting from Bragg scattering of the SWs at the edge of first BZ \( (k = \pi/a) \) – marked by the label 'B'. The gap observed at higher frequency \( (\sim 160 \, \text{GHz}) \), denoted by the label 'AC', results from the anticrossing of the dispersion branches originating from the modes of homogeneous waveguide (of the width equal to the distance between the row of antidots and the edge of the patterned waveguide [28]). These dispersion branches are plotted in Fig. 2 by black and gray thick lines. If we artificially double the period to \( 2a \) then we obtain the folded branches of dispersion relation (marked by black dashed and gray dashed lines in Fig. 2a) in narrowed BZ. At the edge of this BZ \( (k = \pi/2a) \), the branches intersect each other. At this point we observe two pairs of degenerate modes. For the pair with positive (negative) group velocity, the phase increases with the increase of the distance along the wire – see corresponding profile of the modes \( 1' \) and \( 2' \) (or \( 3' \) and \( 4' \)) in Fig. 2b. For the folded modes (dashed lines) the direction of increase of the phase is opposite (the profile not shown in Fig. 2b). It is also worth to notice that the SWs in two halves of the waveguide precess only in-phase.

Figure 1. Structure of periodically patterned Ni_{80}Fe_{20} (Py) nanowire with two square antidots in one unit cell. The antidots are alternatively shifted from the long axis of the waveguide (marked by dotted line) towards its edges by the distance \( w \). The period of the structure is a doubled separation between neighboring antidots \( a \), measured along the waveguide. The external magnetic field \( \mu_0 H_0 = 1 \, \text{T} \) is applied along the waveguide.

We performed two different types of numerical calculations namely, finite difference method based MS using OOMMF [29], and PWM using home-built FORTRAN code. Both these methods solve the Landau-Lifshitz-Gilbert equation:
The group velocity of the modes in the range of anti-still grouped in pairs in the system with SW pinning. New gaps, at the frequencies, the waveguide with the antidots placed inline (mode 1 or 3') or out-of-phase (mode 2' or 4').

For non-zero displacement \( w \), we can observe (see Fig. 2) the opening of new magnonic gaps at \( k = \pi/2a \). The new gaps, at the frequencies \( \sim 85 \text{ GHz} \) and \( \sim 150 \text{ GHz} \) become wider with increasing displacement of the antidots. Note that for higher gap at \( 150 \text{ GHz} \), a small displacement such as \( w = 1.5 \text{ nm} \) (blue curves) is not sufficient for opening of gaps, but both the gaps (red bars in Fig. 2) are opened for larger shift of antidots \( w = 3 \text{ nm} \) (red curves). The opening of the gaps partially lifts the degeneracy between the two pairs of modes which cross at \( k = \pi/2a \) (\( w = 0 \), black and gray lines). The modes which anticross at the edge of this BZ \( (k = \pi/2a) \) are still grouped in pairs in the system with SW pinning. The group velocity of the modes in the range of anti-crossing is significantly reduced (the dispersion branches are practically flat in this region). This is also manifested in the profiles of SW amplitudes where such modes (see modes 1, 3, 5, 7 for \( w = 3 \text{ nm} \) in Fig. 2b) have the forms of standing waves with distinctive zig-zag like nodal lines (white areas) and constant phase over the localization areas of SWs.

Figure 3 presents the dispersion relations calculated for the system with SW pinning at the interfaces between magnetic and nonmagnetic material calculated by PWM (red dashed) and by MS (grayscale map in the background). We have selected eight different values of displacement for the antidots as \( w = 1.5, 3, 4.5, 6, 9, 12, 15 \) and 18 nm. In this range \( (1.5 < w < 18 \text{ nm}) \), the antidots are shifted from the positions closer to the center of the waveguide \( (w = 1.5 \text{ nm}) \) to the locations near the edges of the waveguide \( (w = 18 \text{ nm}) \). For the intermediate values of the shift \( w \), say \( 6 < w < 9 \text{ nm} \), the SW has to propagate in meander-like manner. Therefore its scattering is the strongest. This leads to the increase of the width of the gaps and to the reduction of the width of the bands. For smaller values of the shift, where (due to the pinning) the row of antidots almost isolates the SWs in both halves of the waveguide, the modes appear in almost degenerate pairs. For larger shifts of antidots, where the SW can propagate in zig-zag channel between antidots, this degeneracy is significantly lifted except at the edge of BZ \( (k = \pi/2a) \).

The modes at \( k = 0 \) are standing wave modes where the magnetization precess with spatially uniform phase in the distinctive regions which are separated by nodal lines in the spatial profiles of the modes in Fig. 3b, we can see the spots of uniform colors (representing the spatially homogeneous phase) which do not join each other with transient colors. The SW in these regions always precess in-phase or out-of-phase, with respect to each other. This behavior shows non-propagative characters of modes at \( k = 0 \) which is also manifested in the dispersion relation where the dispersion branches become flat at \( k = 0 \). The standing wave modes (with group velocity equal to zero) are also expected at the edge of the BZ where patterns of standing waves result from the interference of counter-propagative waves differing by reciprocal lattice vector. However, in our system we can find the propagating SWs exactly at the edge of the BZ. For larger values of shift of the antidots, the phase changes continuously in wave-like channels and we do not observe nodal lines for amplitude across the waveguide. The corresponding dispersion branches are also tilted at the edge of BZ. Both observations indicate that we should deal with propagating modes at \( k = 0.5\pi/a \). It is also worth to notice that these modes appear at the edge of BZ in doubly degenerate pairs. This degeneracy can be explained by inspection of the spatial profiles of dynamical magnetization. It is known that Bloch function at the edge of BZ flips its phase after translation by one period. In our case, we have to do with the system with complex unit cell containing two antidots in one period. These anti-
Figure 3. (a) Spin wave dispersion relation for different displacements of antidots \( w = 1.5, 3, 4.5, 6, 9, 12, 15, 18 \) nm calculated with the aid of micromagnetic simulation and plane wave method (dashed lines). We assumed the pinning of magnetization at the edges of the waveguide and the antidots. The green and pink bars denote the lowest magnonic gaps resulting from the presence of the complex unit cell. (b) Spatial profiles of two lowest spin wave modes presenting the out-of-plane component of magnetization at the center and at the edge of first Brillouin zone.

dots are placed equidistantly along the waveguide and are shifted by the same distance toward the opposite edges of the waveguide. Due to this symmetry, the phases are supposed to change by \( +\pi/2 \) or \(-\pi/2\) during the translation by each half of period. We observe such behavior in the profiles of the degenerate modes at the boundaries of BZ where the phase increases (or decreases) along the waveguide. The calculations presented in Fig. 3 were
done for the case of magnetization pinning. However, similar degeneracy of modes at the boundary of BZ can be observed in SW dispersion for the system where the magnetization was pinned at the interfaces with nonmagnetic material – see Fig. 4. The modes in each pair are also counter-propagative at $k = 0.5\pi/a$.

In the dispersion relation, we can easily identify the pair of modes which are degenerate and cross each other with non-zero slope at the edge of BZ. By inspecting the profiles of SWs, we noticed that the phase increases in opposite directions along the waveguide for the each of the modes in every such pair (see e.g., the profiles of modes 1 and 2 in Fig. 3b for $w = 9$ and 18). The direction of spatial changes of phase allows us to classify the modes into two groups. The dispersion branches of the modes of the different symmetries (manifested by the opposite directions of the spatial changes of phase) can cross each other whereas those of the same symmetry have to anticross. For the system with magnetization pinning we can observe (see Fig. 3 for $w = 3, 4.5, 6$ nm) that the pairs of modes which were initially degenerate ($w = 0$) in the whole of the BZ (see Fig. 2) cross each other at few additional points in the BZ. For the system with pinned magnetization the anti-crossing is clearly visible between second and third mode (band) for larger values of antidots displacement ($w = 18$ nm) where the splitting in mentioned pair of modes is significant at $k = 0$. This anti-crossing is responsible for keeping the magnonic gap (marked by green bar) opened. The effect of crossing (and anti-crossing) of dispersion branches resulting for the differences (and correspondence) in symmetry of modes is also observed for system with unpinned magnetization (see Fig. 4). We can see that, due to the lack of pinning, the SWs are constrained to a lesser extent which results in the weaker quantization of their modes – we can notice many more modes in the same frequency range, referring to the system with strong pinning (see Fig. 3). Therefore, for the system with considered sizes where the magnetization is unpinned, the anti-crossing is crucial to observe the magnonic gap being opened at all.

The differences between the systems with pinned and unpinned magnetization are the most striking for small values of displacement of antidots. For the system with pinning, the waveguide is artificially split into two half-waveguides by the row of antidots placed in its center. Due to the weak crosstalk between SW in such half-waveguides, the SWs eigenmodes are almost degenerate. We can notice that the lowest dispersion branches appear in overlapping pairs and the profiles of the modes for each of such pairs show that SWs in half-waveguides precesses in-phase or out-of-phase (see Fig. 2 and Fig. 3 for $w = 1.5$ nm). The pinning at the antidots edges at the center of the waveguide enhances the confinement of SWs. When the antidots are shifted towards the edges of the waveguide, the zigzag-like channel between them is opened and eventually its width becomes close to the width of the whole waveguide. Therefore, with the increase in the displacement of the antidots, the constraints for SWs become weaker, the modes are quantized denser in frequency scale and the frequencies of SW modes are shifted gradually downwards. Strikingly, this effect is absent for the system with the magnetization released at the interfaces with nonmagnetic material (see Fig. 4). For this system, the bottom of the lower magnonic band is located approximately at the same frequency, regardless of the displacement of the antidots. Moreover, for the case of unpinned magnetization, the SWs are not separated by the row of antidots even if the antidots are aligned in the center of the waveguide. Thus, we do not observe the overlapped pair of dispersion branches at this system (see Fig. 4).

We will discuss now the dependencies of the widths of the magnonic gaps on the value of the displacement of antidots. We will consider the gaps resulting from the introduction of complex base of unit cell only (i.e., the base containing two elements/antidots in unit cell). Figure 5 presents these dependencies for such gaps marked in Fig. 3 and Fig. 4 by green and pink bars.

The mechanism for the opening of gaps for the system with pinned magnetization was presented in details
Figure 5. Dependence of the width of the first and second magnonic gaps (green and red lines respectively) for the waveguide with pinned magnetization a) and unpinned magnetization b). Dashed and solid lines refer to plane wave method calculations and micromagnetic simulations, respectively.

In discussion referring to Fig. 2. We pointed out that new gaps are opened at the edges of BZ. For the antidots aligned at the center of the waveguide the BZ was artificially reduced and we got the degeneracy of modes (crossing of dispersion branches) at the BZ edges resulting from the folding of dispersion relation. The introduction of displacement of antidots makes the unit cell containing two antidots essentially elementary and enhances the coupling between two halves of the waveguide. This partially lifts the degeneracy of modes, which results in the opening of new magnonic gaps. Note that at the edge of BZ the modes remain doubly degenerate, which results from the symmetry related to the choice of the direction of spatial changes of phase along the waveguide.

In the system where the magnetization is unpinned, the parts of the waveguide on the opposite sides of the sequence of antidots are strongly coupled regardless on the displacement of the antidots. Therefore, we observe the degeneracy at BZ edge, related only to the choice of two equivalent directions of spatial changes of phase. The new magnonic gaps are opened due to anti-crossing of dispersion branches for which the phase increases in the same direction along the waveguide. The gaps discussed here are induced by presence of the unit cell of complex base and disappear when this complexity is artificial, i.e., when there is no displacement of antidots. Both the case of pinned and unpinned magnetization the width of discussed gaps increases for small values of displacement of antidots. However, this increasing trend is not sustained for system with magnetization pinning. For this system, the maximum width is reached for displacement \( w \sim 6 \text{ nm} \) (\( w \sim 10 \text{ nm} \)) for the first (second) magnonic gap – see Fig. 5a. It corresponds to the case when the waveguide is divided by antidots in three sub-waveguides of comparable width. For the system with pinning, the width of the gaps decreases when the antidots start to approach the edges of the waveguide. This behavior can be understood if we notice that, due to pinning, the amplitude of the SW precession decrease gradually in the vicinity of the edges of the waveguide. The location of the antidots in this region will not influence significantly on SW propagation through the waveguide, and therefore, the SW spectrum should become similar to the spectrum of uniform waveguide where the magnonic gaps are not observed. In the waveguide with unpinned magnetization, the amplitude of SWs reaches the largest values at the edges. It explains why the scattering of SWs should be significant and will lead to opening the largest magnonic gaps for the periodic sequence of antidots placed close to the edges of the waveguide.

Next, we drawn attention to the propagative character of the modes at the edges of BZ which was manifested both in the SW mode profiles and the non-zero slope of dispersion branches. To investigate this effect in further details, we numerically calculated the group velocity for the two lowest dispersion branches of the system with pinned magnetization. Figure 6a presents the dependence of the group velocity in this system on the wave number in the first BZ. The thick green lines denote the group velocity for the system where the antidots are aligned in-line at the center of the waveguide with artificially extended unit cell containing two antidots (see Fig. 2 for reference). We can see that the group velocity changes practically linearly from the center to the edge of the BZ, which proves the quadratic dispersion relation, that is a characteristic for the exchange dominated regime. For tiny displacements of antidots the gap is just opened and we observe maximum of dispersion relation (dependence of the frequency on wave number: \( f(k) \)) at the edge of the BZ. As a result, the group velocity \( v_g = \frac{df}{dk} \) drops to zero at \( k = 0.5\pi/a \) but for smaller values of wave number \( k \), the group velocity changes linearly with \( k \). The increase of antidots di-
IV. CONCLUSIONS

In summary, we have systematically investigated the magnonic band structure in a planar magnonic waveguide with periodic modulation of the antidot position across the width of the waveguide. Our study reveals the possibilities to open-up new magnonic band gap and control their position and width in frequency and wavevector domains by the introduction of two antidots in one unit cell (i.e. for the unit cell with complex base). We showed that the folding of the BZ by introducing double periodicity results in anti-crossing of the modes of different symmetry and opening of new magnonic gap. The width of the gap can be controlled by varying the shift of the position of the antidot from the long axis of the waveguide. We investigated the antidot position modulated gap width for both strong SW pinning and ideally unpinned magnetization at the material/air interface. We found a non-monotonic dependence of the gap width on the shift of the position of the antidot in the first case, whereas the gap width increases in a regular manner for the latter case. This is understood in terms of strong (or weak) SW scattering for the antidots shifted close to the edges of the waveguide without (or with pinning). Moreover, we showed that anti-crossing is crucial for opening of magnonic band gap in case of unpinned magnetization where the Bragg scattering is not so strong. Interestingly, we observed a continuous change in phase for the lowest frequency modes at the edge of the BZ as an indication of propagative character. Further in depth investigation reveals that the lowest modes in folded BZ have significantly large group velocity at the edge of the BZ. Strikingly, the group velocity has opposite sign in each degenerated pair of modes at the edge of BZ and can be mold by the mentioned shift of the antidots. Our findings unveil a new way to design the magnonic waveguide with suitable complex base for SW propagation. By designing this kind of nanoscale waveguide structure, we can create and annihilate the magnonic band gap at very high frequency, which is key for the spectral filter application, as well as control the propagation velocity and phase change of SWs, essential for the design of phase shifter and delay generator.

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