Building Blocks for Magnon Optics: Emission and Conversion of Short Spin Waves

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ABSTRACT: Magnons have proven to be a promising candidate for low-power wave-based computing. The ability to encode information not only in amplitude but also in phase allows for increased data transmission rates. However, efficiently exciting nanoscale spin waves for a functional device requires sophisticated lithography techniques and therefore, remains a challenge. Here, we report on a method to measure the full spin wave isofrequency contour for a given frequency and field. A single antidot within a continuous thin film excites wave vectors along all directions within a single excitation geometry. Varying structural parameters or introducing Dzyaloshinskii–Moriya interaction allows the manipulation and control of the isofrequency contour, which is desirable for the fabrication of future magnonic devices. Additionally, the same antidot structure is utilized as a multipurpose spin wave device. Depending on its position with respect to the microstrip antenna, it can either be an emitter for short spin waves or a directional converter for incoming plane waves. Using simulations we show that such a converter structure is capable of generating a coherent spin wave beam. By introducing a short wavelength spin wave beam into existing magnonic gate logic, it is conceivable to reduce the size of devices to the micrometer scale. This method gives access to short wavelength spin waves to a broad range of magnonic devices without the need for refined sample preparation techniques. The presented toolbox for spin wave manipulation, emission, and conversion is a crucial step for spin wave optics and gate logic.

KEYWORDS: magnonics, spin waves, scanning transmission X-ray microscopy, antidot, reciprocal space, isofrequency contour

The fundamental excitation of a spin precessing around its equilibrium position is known as a magnon, a magnetic quasi-particle. In magnetically ordered materials, the collective excitation of magnons manifests in a wave like behavior frequently called a spin wave. Over the past decade, the corresponding research field of magnonics has established itself as an indispensable part of magnetism research.1 As is often the case in physics, the application of principles known from other disciplines such as quantum mechanics or electronics can result in fascinating phenomena including but not limited to spin wave tunneling,2,3 spin wave manipulation by spin currents,4,5 band gap tuning using magnonic crystals,6–10 and Bose-Einstein condensation of magnons.11,12 Additionally, magnon optics has attracted attention as an interdisciplinary research topic by transferring known optical wave phenomena to spin waves.13–18

The magnon dispersion relation does not only account for the spin wave wavelength but also inherently depends on the respective orientation of magnetization and k-vector.19 Although this makes it practically challenging to control spin waves, it is simultaneously enriching not only from a fundamental but also from an applicational point of view. To unlock the full potential of magnonic devices for applications it is crucial to have full control over the complex magnon dispersion relation. This allows for the development of a comprehensive toolbox of magnonic building blocks such as omnidirectional emitters, directional converters, and guiding channels to have access to for device fabrication. However, even the excitation of spin waves with applicational relevant length scales is challenging.

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There are several different approaches to excite propagating spin waves in magnetic materials. The most conventional method is the excitation by a microstrip antenna\textsuperscript{20,21} or a coplanar waveguide.\textsuperscript{22} Nevertheless, due to the challenges in lithography it is difficult to get sufficient excitation efficiencies for spin waves far below 400 nm.\textsuperscript{23} Another possibility are spin torque devices.\textsuperscript{24} However, these require high current densities and therefore are problematic for real-world applications. The fact that the size of the underlying excitation element needs to be of the order of the spin wavelength creates an additional challenge.

Hence, some approaches to address this challenge exploit sophisticated magnetic textures to generate spin waves,\textsuperscript{25} for example, by vortex core precession.\textsuperscript{26–28} These methods are able to excite spin waves down to 80 nm. Nevertheless, the problem of vortex cores as spin wave emitters lies within the transition from the vortex structure into a continuous thin film while maintaining the omnidirectional character of the spin waves.\textsuperscript{29} Alternative approaches make use of complex sample designs to excite short wavelength spin waves.\textsuperscript{8,29–44} While the excitation mechanism exploited in spin wave grating couplers is able to excite a continuous spectrum of $k$-vectors,\textsuperscript{33} their inherent structure allows for multiple but only discrete directions.\textsuperscript{29} Hence, none of the presented methods is able to excite the full isofrequency contour\textsuperscript{34} due to the directional limitations of the excitation structure which limits their versatility for magnonic applications.

Within the last 70 years, magnetism has always been related to data storage and information technology. Although it is unlikely that magnonic devices will make up a large part of future processors, the integration of a magnonic circuit\textsuperscript{35–37} as a specialized section of a chip is a realistic prospect. An essential task is to identify applications for which wave-based computing can outperform traditional approaches.\textsuperscript{38} Encoding information not only in amplitude but also in phase allows magnonic devices to exploit the fact that multiple wavelengths can coexist at the same frequency potentially allowing for a multiplexing approach in magnonic devices.\textsuperscript{39}

In this work, we present a single magnetic antidot structure as a multipurpose spin wave emitter and converter. We use scanning transmission X-ray microscopy\textsuperscript{39–41} (STXM) and micromagnetic simulations\textsuperscript{32} to demonstrate the possibility to either create omnidirectional spin waves by exciting the antidot directly by a microstrip antenna or to use it as a directional spin wave converter. Although it has been shown that a single antidot is able to convert plane waves into caustic spin waves,\textsuperscript{43–45} it has not been demonstrated experimentally that a single antidot and even more complex structures actually populate all possible $k$-vectors. In fact, different parts of the isofrequency contour can be populated selectively by varying excitation frequency and applied magnetic field.

Concluding from the experimental results, we present a theoretical combination of a guiding channel and a single antidot, which can be utilized as a short spin wave beam generator.\textsuperscript{46–54} We propose these simple structures as versatile and adaptable building blocks for a wide range of spin wave application devices which require spin wave emission of different $k$-vectors, spin wave conversion, or steering around corners.

**RESULTS AND DISCUSSION**

The first part of this section will elaborate on the possibility of using different magnetic structures to excite and measure spin wave $k$-vectors along all directions within a single field geometry and therefore the full isofrequency contour. Additionally, we propose methods to manipulate their intensity distribution and shape. Subsequently, we present measurements of spin wave converter and emitter structures which allow for the generation of short wavelength spin waves without the necessity of sophisticated lithography steps. Micromagnetic simulations reveal the underlying emission and conversion mechanism which gives rise to 100 nm spin waves.

**Measuring Isofrequency Contours. Antidot Structure.** Measuring a full isofrequency contour requires a structure that is able to excite spin waves of all wave vectors. Therefore, we fabricated 50 nm thick permalloy samples with microstrip antennas structured on top. Afterward, two antidots of 800 nm in diameter are milled into the permalloy thin film, one of which is positioned halfway on the microstrip antenna. The other one is positioned 1.6 μm away from it (see Figure 1a). An example for a frequency filtered spin wave measurement of the antidot close to the antenna is shown in Figure 1b. Additionally, three spin wave movies are included in the Supporting Information.

![Figure 1](https://dx.doi.org/10.1021/acsnano.0c07076)

Figure 1. Experimental setup of the antidot sample. (a) Illustration of the sample. The permalloy rectangle (gray) is placed on a X-ray transparent silicon nitride membrane (yellow). A 3 μm wide microstrip antenna (brown) is used to excite spin waves in the sample. Illustration is not to scale. (b) Three-dimensional rendered snapshot of the dynamic spin wave $m_z$ component at 4.71 GHz and 35 mT. The white circle displays the position of the antidot. Below is a 2D representation of the spin wave in which amplitude is represented by brightness, relative phase by color. (c) Reciprocal space representation of the measurement displayed in (b).
To make it easier to distinguish between experimental and simulated results, all experimental figures will be framed by a purple box while simulated results will be displayed in a green box throughout the article. The picture illustrates a 3D rendered snapshot of the \( m_z \) component of the dynamic magnetization. The white circle in the middle denotes the position of the antidot. The colormap positioned below the spin wave is a 2D representation of the spin wave for which relative phase is encoded in color, amplitude in brightness. A reciprocal space representation of the measurement is displayed in Figure 1c. The intensity distribution reveals that although all possible \( k \)-vectors are populated, the spin waves along the backward volume direction are more emphasized. It is clearly visible that a single antidot structure by itself is a working device to excite and measure the full isofrequency contour.

**Magnon Zone Plate.** It is challenging to focus X-rays using conventional single refractive lenses since the refractive index for X-rays in most materials is very close to unity. Therefore, diffractive type optics called Fresnel zone plates are commonly used.\(^{55,14}\) The same effect can also be utilized to focus spin waves.\(^{14}\)

Although an antidot structure is arguably the simplest structure to excite all wave vectors, the full isofrequency contour can also be excited in nontrivial systems, for example, by a hole arrangement corresponding to a 1D Fresnel zone plate. A scanning electron microscope picture of the sample can be seen in Figure 2a. It consists of a magnetic zone plate and a microstrip antenna, which is positioned next to the zones. The illustration includes an example measurement of spin waves being focused by the zone plate.\(^ {14}\)

The reciprocal space representation of two different measurements can be seen in Figure 2b,c. Figure 2b illustrates the isofrequency contour at \( f = 5.65 \text{ GHz} \) and \( B = -36 \text{ mT} \). It is visible that these measurement parameters do not populate the entire isofrequency contour in reciprocal space. In this particular measurement, only waves with a maximum angle of 13° between \( k \)-vector and magnetization could be excited. At this frequency and field combination, pure backward volume spin waves are not detected in the system.

Figure 2c displays the isofrequency contour measured at \( f = 3.59 \text{ GHz} \) and \( B = -14 \text{ mT} \). It can be seen that the full isofrequency contour can be excited in more complex structures as well as in trivial antidot systems. For this particular frequency, backward volume waves can be excited due to multiple wavelengths fitting between the zones. Hence, the system allows for a selective population of the isofrequency contour depending on frequency and applied magnetic field.

On the basis of the isofrequency contour, the effective field acting on the spin waves can be evaluated including all external and internal contributions such as applied, anisotropy, and demagnetizing fields. Because the size and orientation of the contour is very sensitive to changes in the direction and magnitude of the magnetization, it can be an indicator for changes of the magnetization vector within the region of interest. The rotation of the isofrequency contour in Figure 2b...
reveals that the local magnetization is slightly tilted by approximately −5° with respect to a horizontal measurement plane.

Tuning of field and excitation frequency is not the only method for manipulating the size and shape of an isofrequency contour. The Dzyaloshinskii–Moriya interaction (DMI) is an antisymmetric exchange contribution which is well-known for stabilizing chiral spin textures in bulk and multilayer materials. However, its antisymmetric nature also manifests itself in its interaction with magnons. Similar distortions have also been observed for electric fields.

Figure 3 displays simulated isofrequency contours generated by an antidot structure including artificial interfacial DMI. The DMI vector points to out-of-plane with its effective influence on the spin waves along the y-direction. It is very visible that DMI does not only change the size but also the shape of the isofrequency contours. The antisymmetric interaction is reflected by a nonsymmetric distortion in reciprocal space along the k_x-axis, which has been proposed to be a measure for the DMI constant. With increasing DMI, the distortion of the contour gradually increases and hence affects the spin wave propagation in a nonsymmetrical manner. Therefore, wavelength as well as direction of the spin wave can be manipulated by introducing DMI into a material.

Spin Wave Converter and Emitter. Emission and Conversion Mechanism. A close-up view of the antidot sample in Figure 1a is displayed in Figure 4a. In the following, it will be distinguished between spin wave converters and spin wave emitters. Both components differ in their position with respect to the microstrip antenna as well as their functionality in emitting spin waves or converting incoming plane waves. Both antidots are sufficiently separated from each other to avoid interaction. When running a high-frequency current through the microstrip antenna, spin waves are either directly emitted by the emitter or start to propagate from the antenna toward the converter.

In literature, the conversion mechanism has been described as spin wave scattering, or as a consequence of the Schlömann effect which describes the local coupling of an external field to local changes of the effective field. The coupling in in-plane magnetized films results in caustic beams propagating away from the antidot.

The underlying mechanism turns out to be the same for converter and emitter. In both cases, the local effective field changes necessary for spin wave emission are caused by the demagnetizing field of the antidot. For the emitter, the magnetization is excited by the plane wavefront and by the antenna itself. Propagating spin waves are even more amplified in the presence of the antenna. An illustration of the demagnetizing structures responsible for the emission can be found in the Supporting Information.

For the converter, the incoming spin wave mimics the variation of an external field. Hence, the local magnetization starts oscillating subsequently converting the incoming spin waves in wavelength and direction.

The difference is that the effective field variation which is needed to drive the local magnetization is either caused only by the spin waves (converter) or mainly by the antenna (emitter).

Expanding on previous results from others, the high resolution of STXM allows us to resolve these localized edge modes converting the incoming wave, as well as the full spectrum of the outgoing spin waves. In Figure 4b,c, the full spatial spin wave spectrum at an excitation frequency of f = 4.21 GHz and an applied field of B = 25 mT is presented which was obtained from a spatial Fourier transformation. Extending on other spin wave excitation mechanisms, the emitter as well as the converter are capable of exciting all possible k-vectors for a given frequency and field, that is, the full isofrequency contour, characterized by a horizontal eight in reciprocal space.

In the presented case, propagation along x-direction represents backward volume modes while the y-direction denotes Damon-Eshbach geometry. It is visible that converter and emitter spectrum are qualitatively equal with
maximum $k$-vector magnitudes of $|k| = 8.31 \mu m^{-1}$ which corresponds to a wavelength of $\lambda = 120.4$ nm whereas the spin waves directly excited by the antenna have a wavelength of approximately $\lambda = 6 \mu m$. Because both mechanisms excite spin waves in multiple directions, this might be applicable for spin waves multiplexing applications in magnonic devices.39

To showcase the versatility of the presented devices, the spin wave emitter was measured for different excitation frequencies and magnetic fields. The results are presented in Figure 5a. The second of the three panels displays the distribution of $k$-vectors at an excitation frequency of $f = 4.21$ GHz and a magnetic field of $B = 30$ mT. It can be seen that the isofrequency contour is almost collapsed for these excitation parameters. Further decreasing the frequency or increasing the field will cause the isofrequency contour to collapse completely, drastically reducing the excitation efficiency.

As it can be seen in the first and third panel, the isofrequency contour expands when decreasing the magnetic field to $B = 20$ mT or increasing the frequency to $f = 4.71$ GHz. Although the signal-to-noise ratio is slightly worse at higher excitation frequencies due to the synchrotron operation mode, the third panel shows that the spin wave emitter is able to directly excite spin waves with $k$-vector magnitudes of $|k| = 10.02 \mu m^{-1}$ corresponding to a wavelength of $\lambda = 99.8$ nm. It should be mentioned that the creation of these short wavelength spin waves did not rely on sophisticated lithography processes for sample preparation. Although approaches to reduce sample structure sizes to spin wave relevant length scales can be complex and challenging, adding an antidot into a sample is rather straightforward. In this case, the important length scale is not given by the structure itself but by the demagnetizing features.

**Micromagnetic Model.** To complement our findings, we performed micromagnetic simulations of the antidot structures. The simulated results can be seen in Figure 5b. When comparing Figure 5a,b, it is obvious that the experiment is resembled well by the simulations. In particular, for the cases for which the experiment has a high signal-to-noise ratio the results are almost identical. A real space comparison of experiment and simulations can be found in the Supporting Information.

To obtain a deeper insight into the spin wave emission and conversion mechanism, we performed simulations of the antidot at two different positions with respect to the antenna. The right column of Figure 6a,d displays four different snapshots in real space. The position of the microstrip antenna is illustrated in brown with increased transparency close to the antidot to reveal the region of interest. The timestamp of the snapshot is measured with respect to the beginning of the excitation.

Times are chosen such that they display four different states of the system. Figure 6a displays the antidot directly after turning on the excitation where no short wave spin waves are emitted yet. It can be seen that spin waves start to propagate away from the antenna and are slightly scattered by the demagnetizing structure of the antidot resulting in caustic beams. In the second frame (Figure 6b), short wavelength spin waves start to propagate away from the emitter caused by the coupling of the effective field to the demagnetization structures. Natural imperfections in its circularity ensure that small demagnetizing structures are present all around the antidot, even for a much larger antidot structure. This allows for a difference of at least 2 orders of magnitude between structural length scales and spin wave wavelength. Compared to CMOS technology, the smallest element carrying information is therefore not given or limited by the size of the structured element, which allows magnonics to operate far below the limits of lithography.

The third illustration (Figure 6c) displays the system while emitting spin waves in all directions with wavelengths given by frequency and field. Looking at the spatial Fourier transformation displayed left of the three frames, it can be seen that the full isofrequency contour does not appear directly after turning on the excitation. For numerical reasons, it takes

![Figure 5. Comparison between experimental and simulated results. (a) Experimental results for two different magnetic fields and frequencies. With respect to the middle row, the magnetic field is changed when going to the left, and the excitation frequency is adjusted when going to the right. (b) Simulated results of the measurements presented in (a).](image-url)
approximately 6 ns for it to be fully visible in reciprocal space. However, this is not the steady state of the system. Approximately 10 ns after the beginning of the excitation, demagnetizing structures located below the antenna start to oscillate and emit spin waves which are further amplified by the oscillating field. This steady state of the system is shown in Figure 1d. Hence, the simulations reveal that there are two distinct mechanisms emitting short wavelength spin waves: the excitation of localized demagnetizing structures near the antidot and the local resonant oscillation of demagnetizing structures below the antenna. From the simulations, we can conclude that the short wavelength spin waves visible in Figure 1b are mainly caused by these demagnetizing structures below the antenna.

In contrast to the emitter structure, the antenna has been moved 10 μm away from the antidot for the simulations presented in Figure 6e–h. In addition to Figure 4, these simulations further prove that the antidot cannot only be excited by the direct magnetic influence of the antenna but also by incoming propagating spin waves.

Although the 2 ns frame already displays short wavelength spin waves for the emitter, they are hardly visible for the converter which is also reflected by the corresponding illustrations of reciprocal space. This is mainly due to the fact that the spin wave needs to first travel 10 μm, resulting in a time delay compared to the emitting structure. The main difference between simulated emitter and converter can be seen in Figure 6d and Figure 6h. The emitter has a strong tendency toward backward volume spin waves amplified by the presence of the antenna. In contrast, the converter equally excites all k-vectors in reciprocal space. Nevertheless, it is clearly visible that both structures are able to excite the entire iso-frequency contour which allows for the generation of a full spin wave spectrum including very short backward volume modes.

**Spin Wave Beam Generation.** Although it might be interesting for future applications to have multiple wavelengths within one spin wave channel, concepts for spin wave application need a coherent spin wave beam or package. Figure 7 illustrates a possible application for the spin wave converter by showcasing its steering and wavelength reduction capabilities. The following simulation highlights the capabilities of a converter structure as a spin wave beam emitter.

The first graph in Figure 7a displays the position of the snapshots with respect to the beginning of the excitation at \( t = 0 \). Figure 7b–d displays the spin wave \( m_\phi \) component at different points in time. Magnons are excited by an antenna (brown) and start to propagate through a channel of zero...
damping toward the antidot. Low damping can be achieved by using yttrium iron garnet which is widely known to have an exceptionally low damping coefficient for magnons. The light blue region around the channel displays a region of increased damping which can be achieved by covering the magnetic layer with platinum for strong damping enhancement. The different frames illustrate four different states of the system. In Figure 7b, the majority of the plane waves emitted by the antenna are still traveling along the Damon-Eshbach direction toward the antidot. No short wave conversion can be observed at that point in time. In the second frame, the converter starts to emit short wavelength spin waves along the backward volume direction which have only traveled approximately 1.5 μm. In the third frame, the converted backward volume waves have traveled half way into the channel and continue to travel until the system reaches its steady state, displayed in Figure 7e.

As it can be seen from the illustrations the device is not only able to convert the long wavelength Damon-Eshbach spin waves into short wavelength backward volume spin waves but can simultaneously steer the incoming spin waves around a 90° angle converting it into a coherent short wavelength spin wave beam. These two characteristics are of interest for magnonic applications in integrated circuits. It not only allows for easy scalability of spin waves by reducing their size by 2 orders of magnitude but it also enables magnonic devices to function around corners further reducing their potential size. For example, it is conceivable to realize a spin wave majority gate on the scale of a few micrometers using a coherent spin wave beam as input. Moreover, the anisotropic dispersion relation allows the device to work at two different wavelengths while maintaining equal frequencies.

CONCLUSION

Many articles report on various methods for the generation of short wavelength spin waves essential for the scalability of future magnonic devices and circuits. However, most of them require sophisticated structural or magnetic designs to achieve length scales relevant for applications. In this article, we presented a generation technique by means of a simple antidot. The structure can serve as a multipurpose object by either acting as emitter when placed next to a microstrip antenna or as a spin wave converter when positioned several micrometers away from it. We found that the emitter as well as the converter populate the same k-vectors in reciprocal space independent of their position with respect to the antenna, that is, all k-vectors allowed for a certain combination of field and frequency.

By presenting results from a magnetic Fresnel zone plate system, it was shown that also nontrivial systems can be used to measure a full isofrequency contour. Moreover, the system can even be used to selectively excite distinct parts of the isofrequency contour depending on the applied field and frequency. Introducing DMI into the system allows for a nonsymmetric manipulation of reciprocal space. This technique provides a compelling approach to measure all wave vectors of a system within just one excitation geometry and allows for the evaluation of effective field changes caused by demagnetization or anisotropy fields.

Using the emitter as a versatile tool for spin wave generation at various fields and frequencies, it is possible to create backward volume spin waves with wavelengths as small as 100 nm. This limit is not given by the generation mechanism itself but rather by the efficiency of the microstrip antenna at higher frequencies or lower fields. Compared to other generation techniques, a simple antidot is capable of either emitting or...
converting incoming spin waves and reducing their size by approximately 2 orders of magnitude.

By performing micromagnetic simulations, it was confirmed that the obtained reciprocal emission spectra match well with theoretical predictions. Moreover, simulations gave insight into the emission and conversion mechanism, both of which consist of magnetization features being driven into oscillation by either the antenna or the incoming spin wave.

On the basis of the findings of the spin wave converter, we simulated a system to potentially isolate spin wave beams. It could be seen that after 45 ns a continuous beam of small wavelength spin waves was well isolated from plane waves exciting the converter. This concept can be of impact for potential spin wave applications which need to steer spin waves around corners or applications at multiple different wavelengths operating at the same clock frequency. Additionally, a coherent spin wave beam of small wavelength reduces the size of existing magnonic devices down to the few micrometer length scale.

We anticipate that the presented spin wave excitation and conversion method is especially useful for the fabrication of future spin wave devices by achieving application relevant spin wavelength scales without the need for nanometer-sized lithography. It is easily conceivable that the generation of a coherent spin wave beam not only allows for the production of exceptional magnonic devices but also eases the down-scaling of existing magnonic gate logic.

**METHODS**

The permalloy rectangle used as the basis for the antidot structure in this paper were patterned using photolithography and direct laser writing. Photo resists used were LOR 3A and AZ ECI 3027 by MicroChem and MicroChemicals, respectively. The UV exposure was done with KLOE’s Dilas 250 laser writing system. A 100 μm × 200 μm × 50 nm permalloy (Ni₈₀Fe₂₀ Py) thin film was deposited on top of a X-ray transparent silicon nitride membrane Si₃N₄(100 nm)/Si(100). As oxidation protection, a 2 nm thick Al layer was deposited on top of the Py. The 3 μm wide microstrip antenna was fabricated in a second lithography step and consists of 10 nm Cr/180 nm Cu/10 nm Al. The microstructures were deposited with ion beam sputtering and consists of 10 nm Cr/180 nm Cu/10 nm Al. After thin film deposition, a focused ion beam was used to mill two antidots into the permalloy.

An illustration of the antidot sample is shown in Figure 4a.

The zone plate samples consist of 50 nm thick Py with a 5 nm Al capping layer deposited on silicon nitride by evaporation at pressures below 1 × 10⁻⁷ mbar. Zone plate structures were patterned using electron beam lithography. The microstrip antenna was isolated from the magnetic film by depositing 10 nm Al₂O₃ with atomic layer deposition. The 1.6 μm wide antenna consists of 10 nm Cr/150 nm Cu/5 nm Al. An illustration of the zone plate sample can be seen in Figure 2a.

All measurements presented in this article were conducted on a scanning transmission X-ray microscope (STXM) at the MAXYMUS endstation at the BESSY II synchrotron radiation facility in Berlin. STXM allows for high resolution in space (20 nm) as well as time (35 ps). After acquisition, each spin wave movie was filtered in the frequency domain and subsequently transformed into reciprocal space by applying a spatial Fourier transformation. For a comprehensive elaboration on the analysis process, the reader is referred elsewhere.

If not stated differently, simulations without Dzyaloshinskii–Moriya interaction were performed with a saturation magnetization of \( M_s = 5.04 \times 10^5 \) A/m and a damping coefficient \( \alpha = 0.0067 \) both of which were obtained from ferromagnetic resonance measurements. The exchange constant was set to \( A_{ex} = 5.5 \times 10^{-12} \) J/m. To reproduce a continuous thin film we set periodic boundary conditions in \( x- \) and \( y- \) direction. Spin wave interference between the simulation boxes was avoided by gradually increasing the damping coefficient close to the box boarders.

Simulations with Dzyaloshinskii–Moriya interaction were performed with identical simulation parameters but contained an antenna which is able to excite all \( k- \) vectors equally. The damping was set to \( \alpha = 6.0001 \).

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c07076.

Illustration of the \( x- \) and \( y- \) component of the demagnetizing structures obtained from the simulation as well as a real space comparison between experiment and simulation (PDF)

Emitter, \( f = 4.21 \) GHz, \( B = 30 \) mT (AVI)

Emitter, \( f = 4.21 \) GHz, \( B = 25 \) mT (AVI)

Converter, \( f = 4.21 \) GHz, \( B = 25 \) mT (AVI)

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**Notes**

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