Propagation of Spin-Wave Packets in Individual Nanosized Yttrium Iron Garnet Magnonic Conduits

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ABSTRACT: Modern-day CMOS-based computation technology is reaching its fundamental limitations. The emerging field of magnonics, which utilizes spin waves for data transport and processing, proposes a promising path to overcome these limitations. Different devices have been demonstrated recently on the macro- and microscale, but the feasibility of the magnonics approach essentially relies on the scalability of the structure feature size down to the extent of a few 10 nm, which are typical sizes for the established CMOS technology. Here, we present a study of propagating spin-wave packets in individual yttrium iron garnet (YIG) conduits with lateral dimensions down to 50 nm. Space and time-resolved microfocused Brillouin-light-scattering (BLS) spectroscopy is used to characterize the YIG nanostructures and measure the spin-wave decay length and group velocity directly. The revealed magnon transport at the scale comparable to the scale of CMOS proves the general feasibility of magnon-based data processing.

KEYWORDS: spin waves, magnonics, spintronics, magnetic nanostructures, yttrium iron garnet, beyond-CMOS

The further scaling of CMOS-based computation technologies is increasingly costly and challenging due to several fundamental constrains, which arise from both technological and physical limitations. To allow for further progress, the field of spintronics aims to complement CMOS by taking advantage of the spin degree of freedom to generate and control charge currents. However, a different approach to tackle these challenges and avoid electric currents can be found in the field of magnonics, which proposes a wave-based logic for more-than-Moore computing by utilizing spin waves to carry the information instead of electrons. The phase of a spin wave offers an additional degree of freedom enabling efficient computing concepts, which typically rely on the interference of coherent spin waves. In addition, spin waves possess readily accessible nonlinear phenomena that can be utilized to perform logic operations and to realize novel computing devices. A variety of spin-wave-based devices has already been realized on the macro- and microscale, pushing partially into the nanoscale with structure sizes of a few 100 nm extent. However, a significant milestone on the path toward the development of magnonic circuits is the final advance to the sub-100 nm scale. In particular, yttrium iron garnet (YIG), the go-to material of magnonics, which provides the lowest known spin-wave damping, is lacking this push to the nanoscale due to its complicated crystallographic structure featuring a unit cell size of 1.2376 nm. Recently, we reported on the fabrication of sub-100 nm wide YIG nanostructures and the investigation of the uniform precession mode in them, developing an extended theoretical model describing the spin-wave dispersion in nanostructures, which takes an unpinning of the lateral mode profile for small aspect ratios into account. Nevertheless, neither propagating spin waves, which allow for the transport of information, nor the impact of the structuring process on their propagation have yet been investigated in structures of sub-100 nm lateral sizes.

In this Letter, we report on the investigation of propagating spin waves in individual YIG magnonic conduits with lateral sizes down to 50 nm. Spin waves are excited continuously or pulsed using a microantenna, and microfocused Brillouin-light-scattering (BLS) spectroscopy is employed to directly measure the spin-wave decay length and group velocity. Considering a potential application in magnonic circuits, the investigations are performed in the backward-volume (BV) geometry, which corresponds to the natural self-magnetized state of such a conduit to avoid the necessity of large bias magnetic fields. The results are compared to the theoretical predictions based on the extended model of the spin-wave dispersion in nanostructures. The measured spin-wave decay length is found to be in agreement with this theory, indicating only a moderate influence of the nanostructuring process on the YIG...
parameters. Moreover, the decay length in the smallest investigated structure is twice as large as the expected theoretical value of the excited dipolar spin waves, assuming a possible contribution of short-wavelength exchange waves to the detected BLS signal.

As a basis for the structuring procedure, a thin lanthanum-doped (111) YIG film with a thickness of \( t = 44 \) nm is used, which is grown on top of a 500 \( \mu \)m thick (111) gadolinium gallium garnet (GGG) substrate by liquid phase epitaxy (LPE). An analysis and in-detail discussion of the structural properties of similar pure YIG films are provided in ref 26, while the lanthanum doping, which further reduces the lattice mismatch, is discussed in ref 25. Moreover, a characterization by stripline vector-network-analyzer ferromagnetic resonance (VNA-FMR) spectroscopy is performed to obtain the fundamental magnetic properties. For the theoretical description of the system, the BV geometry spin-wave dispersion has to be considered:

\[
\omega = \sqrt{\left(\omega_\text{ex} + (\kappa_2^2 K^2 + \kappa_1^2 S^2)\omega_\text{ex}\right) \times \left(\omega_\text{ex} + (\kappa_2^2 K^2 + K^2)\omega_\text{ex}\right)}
\]

(1)

where \( \omega_\text{ex} = \gamma \mu_0 M_0 \), \( \alpha = \gamma B = \gamma H_\text{ext} \) due to a negligible demagnetization along the \( x \)-direction and \( \lambda = \sqrt{\frac{3A_{\text{xx}}}{\mu_0 M_0^2}} \) with the exchange constant \( A_{\text{xx}} \) and the vacuum permeability \( \mu_0 \).

Moreover, \( F_\text{ex} \) and \( F_\text{int} \) denote the dynamic demagnetization tensor components out-of-plane (\( z \)-direction) and in-plane perpendicular to the waveguide (\( y \)-direction), and \( K = k_z^2 + k_x^2 + k_y^2 \) is the total wavevector. In a confined system, the phenomenon of pinning takes place caused by the dipolar interaction, which can be taken into account by introducing an effective width \( \omega_\text{eff} > \omega \) of the structure. Thus, considering only the fundamental width mode, \( k_y \) can be written as \( k_y = \frac{\omega}{\omega_\text{eff}} \). For a decreasing structure size, the contribution of the...
exchange interaction will increase and eventually dominate over the dipolar interaction. This will lead to an effective unpinning of the system described by the fact that \( \omega_{\text{eff}} \to \infty \), beyond this so-called unpinning threshold, as it is shown in Figure S3. A comprehensive description of this matter was recently given in ref 24. It should be noted that, since the thickness of the investigated film is very small, the modes are always unpinned in the z-direction, hence \( k_z = \frac{p\pi}{L} \).

Here, \( p \) denotes the mode number of these so-called perpendicular standing spin-wave (PSSW) modes. To summarize

\[
K^2 = k_z^2 + \left( \frac{p\pi}{\omega_{\text{eff}}} \right)^2 + \left( \frac{p\pi}{\tau} \right)^2
\]

(2)

The experimental investigation of the spin-wave dynamics is carried out using microfocused BLS by focusing a laser beam on top of the waveguides and analyzing the inelastically scattered light, while a small external magnetic field \( \mu_0H_{\text{ext}} \) is applied in the x-direction parallel to the long axis of the waveguide (BV geometry). Frequency, spatial, and time-resolved measurements of the spin-wave intensity are performed\textsuperscript{32} as it is schematically illustrated in Figure 1A.

Since BLS is also sensitive to incoherent magnons, the thermal population of the magnon dispersion can be measured. Figure 2A shows such an exemplary measurement for a YIG waveguide of \( w = 1000 \) nm. Two peaks are detected, which correspond to the fundamental waveguide mode and the first PSSW mode. Performing a field-dependent measurement and using eq 1 to fit the frequency of the PSSW mode intensity maximum, with the approximation of \( k_z = 0 \), gives access to the exchange constant \( A_{\perp} \) as a fitting parameter. The results presented in Figure 2B show no significant dependency on the structure width, which indicates an insignificant influence of the nanostructuring process. An average exchange constant of \( A_{\perp} = (4.22 \pm 0.21) \times 10^{-11} \) J m\(^{-1} \) can be extracted, which is within the typical range for YIG.\textsuperscript{33,34} In addition, a decline of the PSSW mode intensity is observed, which denies the extraction of the PSSW mode frequency below a width of \( w = 200 \) nm, which is further discussed in Supporting Information.

Using the extracted exchange constant, the dispersion of the fundamental mode can be calculated based on eq 1, as it is exemplarily shown in Figure 1B for the investigated waveguides with a respective width of \( w = 1000, 300, \) and 50 nm. Furthermore, the expected group velocity \( v_g \) can be calculated as the derivative of the dispersion, and moreover, assuming an unchanged Gilbert damping constant, the expected decay length \( \lambda_D \) can be derived. An overview for different investigated structure widths is given in Figure S5. In the following, these theoretical predictions are compared to the experimentally measured spin-wave spectra.

To acquire the respective spin-wave spectrum for each structure width, an RF current is applied to the CPW antenna to excite spin waves. Using microfocused BLS, the spin-wave intensity is measured in the center of the waveguide close to the edge of the CPW. Sweeping the applied RF frequency \( f_{\text{exc}} \) yields the spectrum, as it is exemplarily shown in Figure 3A–C (solid black lines) for structure widths \( w = 1000, 300, \) and 50 nm. The theoretical spin-wave spectrum (dashed black lines in Figure 3A–C) is calculated from the excitation efficiency of the CPW antenna (Figure S5) and the spin-wave dispersion. For larger structure sizes, a good qualitative agreement between theory and experiment is found. However, a frequency shift is observed, which increases for decreasing structure sizes (see Figure S9) to approximately 200 MHz for the smallest structures. A potential cause for this shift can be found in the increasing influence of laser heating for decreasing structure sizes. The influence of the structuring process cannot be excluded either. Additionally, in Figure 3C, an unexpectedly broad spectrum is observed. This is an indicator for nonlinear behavior of the spin waves and the appearance of a nonlinear shift due to a high magnon density, which would also lead to a downshift of the measured spectrum (see Supporting Information).\textsuperscript{9,35–37}

In the following, the decay length \( \lambda_D \) is extracted from the experiment. This parameter is crucial considering any application of spin waves, since it defines the range of information transport and determines the energy consumption of devices.

Depending on the chosen excitation frequency and the excited mode, the decay length might vary due to a change in group velocity and lifetime. To select the frequency which possesses the largest decay length, a second spectrum (Figure 3A–C, solid red line) is acquired in a certain set distance to the edge of the CPW antenna. The intensity maximum of this spectrum is shifted to the frequency of the wave, which has the best trade-off between velocity and propagation losses and, thus, the largest decay length within the accessible excitation regime. This frequency \( f_{\text{exp}} \) marked by a vertical dashed black line in Figure 3A–C, is used for further investigation. A
spatially resolved 2D-scan across and along the waveguide is performed, while spin waves with \( \lambda_D \) are continuously excited. Integrating the measured intensity across the width results in the decay graphs shown in Figure 3D–F. To describe the observed decrease, an exponential decay according to

\[
I(x) = I_1 \exp\left(\frac{2x}{\lambda_D}\right) + I_0
\]

(3)
can be fitted. Here, \( I_1 \) denotes the initial intensity, \( x \) the position along the waveguide, and \( I_0 \) the offset intensity due to the background of thermal spin waves. The results are displayed in Figure 3D–F. For \( w = 1000 \text{ nm} \), the decay length is found to be \( \lambda_D = (12.0 \pm 1.2) \mu \text{m} \). For smaller structure widths, a decrease to \( \lambda_D = (4.6 \pm 1.1) \mu \text{m} \) for \( w = 300 \text{ nm} \) down to \( \lambda_D = (1.8 \pm 0.4) \mu \text{m} \) for \( w = 50 \text{ nm} \) is observed. The appearance of nonlinear effects, as seen in Figure 3C, might influence these measurements. This is due to the fact that they constitute an additional loss channel for the initial spin wave; hence, the presented results can be understood as a lower limit estimation. In fact, the observed decay lengths already fulfill the fundamental requirement regarding the realization of nanoscaled magnonic logic circuits, which is the information conservation on the length scale of the respective logic gate. Moreover, the potential circuit complexity, which can be defined as the decay length over the feature size \( R_{\text{PCC}} = \lambda_D/w \), increases from \( R_{\text{PCC}} = 12 \) for \( w = 1000 \text{ nm} \) to \( R_{\text{PCC}} = 36 \) for \( w = 50 \text{ nm} \) (see Figure 3D,F and Figure S10). Hence, with a decreasing structure size, more advanced logic operations can be achieved without the need for intermediate amplification of the spin waves.

In the following, the measured decay lengths are compared to the theoretical expectation. The experimental results for all investigated structure widths are shown in Figure 4A (black dots) and confirm the observed decline of the decay length. One can calculate the theoretical expectation (see Figures S5 and S7) under the assumption that the total line width remained unchanged during the structuring process as follows:

\[
\lambda_D = \tau \nu_g
\]

(4)

with

\[
\nu_g = \frac{\partial \omega}{\partial k_x} \quad \text{and}
\]

\[
\tau^{-1} = \left(\alpha \omega + \frac{\gamma \mu_B \Delta H_D}{2}\right) \frac{\partial \omega}{\partial \omega_H}
\]

(5)

(6)

For further comparison, the maximum of the theoretically expected decay length, within the accessible wavevector excitation regime, is extracted and plotted in Figure 4A (red dots solid line). The theoretical values describe the results reasonably well but are slightly smaller than the experimental data for larger structure widths above \( w = 1000 \text{ nm} \). This discrepancy might be caused by the determination of the initial Gilbert damping parameter. Since the used method essentially probes a large sample area, also, inhomogeneities are included, which might lead to an overestimation of the damping, whereas a local measurement in a nanostructure yields a damping value closer to the real intrinsic value.\(^{19} \) Furthermore, the experimental data shows a quasi-saturation level below \( w = 100 \text{ nm} \), whereas the theory decreases monotonously. A careful analysis has to be made to exclude that the observed saturation level is a measurement artifact, since the direct excitation by the CPW antennas far field can mimic an exponential decay. This influence is ruled out by theoretical estimations as
of their propagation, the wavevector of the observed waves is shifted to the exchange regime, which would result in an increased group velocity. This can be caused by a frequency downshift of the dispersion due to laser heating, whereas two-magnon scattering provides the mechanism to transform the wavevector, while the frequency of the spin wave is conserved. An exemplary calculation for \( w = 50 \text{ nm} \) shows that only a small frequency shift of 28 MHz is necessary to cause a wavevector transformation from 2.62 rad/\( \mu \text{m} \) to 10.5 rad/\( \mu \text{m} \) (transformation of the wavelength from 2.4 \( \mu \text{m} \) to 600 nm), which corresponds to the observed group velocity. Nevertheless, these measurements are ultimately proving the propagation of spin waves in these nanoconduits, since any kind of direct excitation of the CPW antenna is immediately separated by the time resolution.

To conclude, we presented a study of the propagation of spin-wave packets in individual magnonic conduits with lateral dimensions down to 50 nm. Space and time-resolved microfocused Brillouin-light-scattering spectroscopy was used to extract the exchange constant and directly measure the spin-wave decay length and group velocity. The decrease of the decay length in dependency of the conduit width theoretically predicted by ref 24 was proven experimentally showing a decrease from \( \lambda_D = (12.0 \pm 1.2) \mu \text{m} \) for \( w = 1000 \text{ nm} \) down to \( \lambda_D = (1.8 \pm 0.4) \mu \text{m} \) for \( w = 50 \text{ nm} \), which indicates only a moderate influence of the structuring process on the YIG parameters. The decrease is caused by a successive flattening of the dipolar branch of the spin-wave dispersion, due to the interplay of the in-plane and out-of-plane demagnetization tensor components leading from an elliptical to a circular spin precession when approaching an aspect ratio of 1. In spite of the drop in the free path, the potential circuit complexity increases by a factor of 3 from \( R_{\text{PCC}} = 12 \) to \( R_{\text{PCC}} = 36 \), rendering nanowaveguides more attractive for the construction of magnonic circuits. Surprisingly, the measured free path in a 50 nm wide waveguide is two times larger than the expected theoretical value of \( \lambda_D = 0.97 \mu \text{m} \), which is, however, in agreement with the unexpectedly high spin-wave group velocity obtained from direct measurements. This indicates that fast exchange-dominated spin waves of short wavelengths down to 600 nm are responsible for the transfer of energy in the smallest waveguides rather than long-wavelength dipolar waves. The presented demonstration of spin-wave propagation on the nanoscale, comparable to the scale of modern CMOS, is a significant milestone on the way toward the development of novel magnonic circuits.

**Methods. Sample Fabrication.** A 44 nm thin lanthanum-doped LPE grown (111) YIG film on a 500 \( \mu \text{m} \) thick (111)-oriented GGG substrate was used for the fabrication of the nanostructures. Prior to the structuring process, the sample was cleaned by means of an ultrasonic bath in acetone and isopropanol. Afterward, an oxygen plasma treatment was used to remove any organic residuals. Ti/Au (20 nm/40 nm) alignment marker and structure labels were fabricated utilizing a lift-off technique with electron beam (E-beam) lithography and E-beam physical vapor deposition. YIG waveguides of 60 \( \mu \text{m} \) in length with tapered ends and widths of \( w = 5 \mu \text{m} \), 3 \( \mu \text{m} \), 2 \( \mu \text{m} \), 1 \( \mu \text{m} \), 900 nm, 800 nm, 700 nm, 600 nm, 500 nm, 400 nm, 300 nm, 200 nm, 100 nm, 90 nm, 80 nm, 70 nm, 60 nm, and 50 nm were fabricated using a hard mask ion beam milling procedure. This procedure was based on a Cr/Ti stack of 30 nm/15 nm thickness as the hard mask and successive Ar\(^+\) ion milling under 20\(^\circ\), 70\(^\circ\), and 20\(^\circ\) incident angles with respect to

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**Figure 4.** Measured decay length and group velocity in dependency of the structure width. (A) The observed decay length decreases with decreasing structure width. Comparing to theoretical calculations, a reasonable agreement is found, which indicates an intrinsic origin, found to be the group velocity, rather than a loss of quality during the structuring process. (B) This is verified by confirming the theoretical expectations for the group velocity by employing time-resolved microfocused BLS.
the film normal. An additional in-detail description is given in Supporting Information. In a final step, ground—signal—ground (GSG) CPW antennas were structured on top of the waveguides made from Ti/Au (10 nm/80 nm). The respective width of the GSG lines is 400 nm–600 nm–400 nm, with a G–S center-to-center distance of 1.1 μm. Additional information on the antenna field distribution is given in Supporting Information.38,39

Microfocused BLS Spectroscopy. The sample is placed in between the poles of a large electromagnet to provide a variable and spatially homogeneous magnetic field. A continuous-wave single-frequency laser operating at 457 nm is focused through the substrate of the sample on the respective structure to be investigated using a compensating microscope objective (magnification 100×, numerical aperture NA = 0.85). The effective laser spot size is approximately 300 nm, and the effective laser power on the sample is 2 mW. The influence of the applied laser power is discussed in Supporting Information.38 Analyzing the inelastically scattered light using a multipass tandem Fabry–Perot interferometer and a single photon detector yields the frequency shift of the light and, thus, due to momentum and energy conversation, the frequency of the magnons. The measured BLS intensity is proportional to the spin-wave intensity, and in-plane spin-wave wavevectors up to 24 rad/μm can be detected. For the measurement of the thermal population, the absolute frequency resolution is 150 MHz. A piezoelectric driven nanopositioning stage allows for spatially resolved scans by moving the sample with respect to the objective and, in addition, is used to realize an optical stabilization to compensate thermal drifts. Furthermore, using a pulse generator allows for the synchronization of the microwave excitation source and the detector output and, thus, allows for time-resolved measurements.

■ ASSOCIATED CONTENT

+ Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acs.nanolett.0c00657.

Additional figures, experimental details, and theoretical calculations; VNA-FMR characterization of the YIG film in use; detailed description and depiction of the nanostructuring procedure; the calculated inverse effective width; comparison of thermal BLS spectra for different waveguide widths and degradation of the first PSSW mode intensity; theoretical calculations and underlying equations of the spin-wave dispersion; calculation of the antennas far field; discussion of the spin-wave lifetime in nanoconductors; theoretical calculation and discussion of the nonlinear coefficient T_2; the frequency mismatch of the measured and calculated spin-wave spectra; definition of the potential circuit complexity; description of the time-resolved group velocity measurements and exemplary measurement for w = 1000 nm; influence of the applied laser power (PDF)

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Author Contributions

C.D. fabricated the used YIG film. B.H., B.L., A.M.F., D.B., and S.S. carried out the nanostructuring of the sample. B.L. and B.H. acquired the SEM micrographs. M.S. and B.H. prepared the measurement setup, and B.H. conducted all VNA-FMR and BLS measurements and carried out the evaluation. B.H. and Q.W. performed all theoretical calculations. B.H. drafted the manuscript with the help of A.V.C., T.B., and P.P. The study was supervised by A.V.C., T.B., and P.P. All authors contributed to the scientific discussion and commented on the manuscript.

Notes

The authors declare no competing financial interest.
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