Nanomagnonic devices based on the spin-transfer torque

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Magnonics is based on signal transmission and processing by spin waves (or their quanta, called magnons) propagating in a magnetic medium. In the same way as nanoplasmonics makes use of metallic nanostructures to confine and guide optical-frequency plasmon-polaritons, nanomagnonics uses nanoscale magnetic waveguides to control the propagation of spin waves. Recent advances in the physics of nanomagnetism, such as the discovery of spin-transfer torque, have created possibilities for nanomagnonics. In particular, it was recently demonstrated that nancontact spin-torque devices can radiate spin waves, serving as local nanoscale sources of signals for magnonic applications. However, the integration of spin-torque sources with nanoscale magnetic waveguides, which is necessary for the implementation of integrated magnonic circuits, has not been achieved to date. Here, we suggest and experimentally demonstrate a new approach to this integration, utilizing dipolar field-induced magnonic nanowaveguides. The waveguides exhibit good spectral matching with spin-torque nano-oscillators and enable efficient directional transmission of spin waves. Our results provide a practical route for the implementation of integrated magnonic circuits utilizing spin transfer.

Recent experimental studies of spin-transfer torque nano-oscillators (STNOs) have used advanced magneto-optical microscopy techniques to demonstrate that these devices can convert the energy of direct electrical current into propagating spin waves (magnons), which are radiated into the surrounding magnetic film and can be used for the transmission and processing of high-frequency signals on the nanoscale. These results have provided a proof-of-principle demonstration of the possibility to utilize STNOs as nanoscale emitters for magnonic applications.

Every signal-processing technology based on propagating waves requires sources of waves and also waveguiding structures capable of directional signal transmission. Recent studies of the propagation and control of spin waves in microscopic magnetic waveguides have demonstrated the feasibility of transmission and processing of signals carried by spin waves in nanoscale structures. However, the studied devices have relied on conventional inductive spin-wave sources, which are not suitable for integration into nanostructures. This obstacle can be removed by integrating STNO-based sources into magnonic circuits. Although this route seems to be straightforward, it has proven difficult to achieve frequency matching of STNOs with the propagating modes of waveguides, because the nonlinear properties of STNOs result in oscillation at frequencies shifted with respect to the characteristic frequencies of propagating spin waves.

Here, we experimentally demonstrate that efficient matching between magnetic waveguides and STNOs can be achieved by taking advantage of the dipolar magnetic field of the magnetic nanowires producing one-dimensional propagating modes that are spectrally matched with the STNO. We show that magnonic nanowaveguides based on this principle can be easily integrated with STNOs, providing the possibility for directional transfer of the energy of spin waves generated by the spin-torque effect. Our results demonstrate that efficient spin-wave emission by an STNO and its directional transmission can be achieved by straightforward modification that does not require large out-of-plane magnetic fields or increased currents to operate the STNO. Moreover, we show that our approach results in an increased group velocity compared to that typical for spin waves propagating in extended films, resulting in a significant increase of the spin-wave propagation length.

Figure 1a presents the layout of the studied device. A point-contact STNO is comprised of a Cu(4)/Co80Fe20(4)Au(150) multilayer (numbers in parentheses are thicknesses in nanometres) shaped into an elliptical nanopillar with dimensions of 120 nm × 40 nm, which is fabricated on top of an extended 5-nm-thick Permalloy (Py) film. The nanopillar is located at a distance of 200 nm from the edge of the top device electrode, providing optical access to the Py film for magneto-optical measurements. The device also includes a 5-nm-thick and 200-nm-wide Co80Fe20 nanowire below the Py film. The edge of the nanowire is located at a distance of 150 nm from the centre of the nanopillar. The device is magnetized by a static magnetic field applied in the plane of the Py film, perpendicular to the CoFe nanowire.

Figure 1b,c presents the characteristics of the oscillation of the STNO, as determined by standard electronic spectroscopy measurements. The static field was set at 900 Oe, and d.c. current flowed through the nanocontact from the CoFe nanopillar to the extended Py layer. Above the onset current of ~3.5 mA, the spectral characteristics of auto-oscillations exhibit a smooth dependence on current, indicating a single-mode operation of the STNO. The frequency of the microwave signal is twice the expected frequency of the magnetization oscillation. Accordingly, this signal can be attributed to the second harmonic of the STNO.

The magnetization dynamics excited by the spin-transfer torque was directly imaged by microfocus Brillouin light scattering (BLS) spectroscopy. The probing laser light was focused into a diffraction-limited spot on the surface of the Py film, and the spectrally resolved signal—proportional to the local intensity of the dynamic magnetization—was detected. Figure 2a presents representative BLS spectra recorded with the probing laser spot positioned above the CoFe nanowire. The inset to Fig. 2a shows that the frequency of the BLS peaks (symbols) is exactly equal to half the frequency of the electronically detected spectral peaks (curve), confirming that the latter represents a second-harmonic response.
obtained at current–frequency coordinates. The data in c4 (black), 5 (blue), 6 (red) and 7 mA (purple). PSD, power spectral density.

induced oscillations of the STNO measured by a spectrum analyser at nanometres. Inset: SEM micrograph of the sample.

Numbers in parentheses indicate the thicknesses of the layers in Figure 1 | Schematic of the experiment and electronic characterization of STNOs. a Layout of the studied devices. \( H_0 \) is the static magnetic field. Inset: SEM micrograph of the sample. b Spectra of the current-induced oscillations of the STNO measured by a spectrum analyser at different driving d.c. currents. The data were acquired at currents of 4 (black), 5 (blue), 6 (red) and 7 mA (purple). PSD, power spectral density. c Logarithmic-scale colour map of the PSD of the electrical signal generated by the STNO in current-frequency coordinates. The data in b and c were obtained at \( H_0 = 900 \) Oe.

Although the BLS spectra acquired above the CoFe nanowire clearly show the signals resulting from the STNO oscillation, no such signals were detected away from the nanowire. This observation, together with other spatial characteristics of the signal (discussed in detail in the following), indicates that spin waves generated by the STNO efficiently propagate along the CoFe nanowire, but their radiation into the free Py film is inefficient. This can be attributed to the mismatch between the magnon spectrum of the free Py film and the frequency of the auto-oscillations\(^1\), which is attributed to the mismatch between the magnon spectrum of the free Py film and the frequency of the auto-oscillations\(^1\), which is eliminated in the area above the CoFe nanowire. The spectral characteristics of magnons in the free Py film and in the region of the CoFe nanowire can be determined experimentally by recording the BLS spectra of thermally excited magnons in the absence of d.c. current (Fig. 2b). These data show that the range of the oscillation frequencies of the STNO (hatched region) is shifted significantly below the magnon frequencies in free Py film. In contrast, the magnon spectrum in the region of the CoFe nanowire extends to lower frequencies and clearly overlaps with the spectrum of auto-oscillations.

To understand the mechanisms controlling the magnon spectrum, one has to consider the effects of the dipolar field of the CoFe nanowire on the internal field in the magnetic layers. The distribution of the internal field in the Py film through the section perpendicular to the nanowire obtained from the micromagnetic simulations is shown in Fig. 2c. These results show that the internal field is significantly reduced in the magnetic film in the region of the CoFe nanowire (hatched region) compared to its magnitude away from the nanowire, which is simply equal to the applied field \( H_0 = 900 \) Oe (horizontal dashed line). The reduction of the internal field results in a lowering of the local magnon spectrum, creating a one-dimensional channel with allowed magnon frequencies below the bottom of the spectrum in the free Py film, similar to the one-dimensional channel with allowed magnon frequencies below the bottom of the spectrum in the free Py film. The reduction of the internal field results in a lowering of the local magnon spectrum, creating a one-dimensional channel with allowed magnon frequencies below the bottom of the spectrum in the free Py film, similar to the one-dimensional channel with allowed magnon frequencies below the bottom of the spectrum in the free Py film. Thus, the static-field channel induced by the CoFe nanowire plays the role of a compound dipolar magnon waveguide formed by the strongly exchange-coupled bilayer of the CoFe nanowire and the Py film on top of it. In contrast to the isotropically...
radiated spin waves\(^{10}\), only the intrinsic relaxation is expected to contribute to the spatial decay of spin waves propagating in the nanowaveguide, without additional decay associated with the spreading of the wavefront.

The measured propagation characteristics of spin waves in the nanowaveguide are shown in Fig. 3. Figure 3a shows the normalized spatial map of the BLS intensity, which is proportional to the local spin-wave intensity. The map was recorded at a constant d.c. current of 5 mA by rastering the probing laser spot over a 1.6 \( \mu \text{m} \times 1.6 \mu \text{m} \) area with a step size of 100 nm. To highlight the transverse profile of the propagating wave, the spatial decay in the direction of propagation was compensated by normalizing the signal with the integral of the transverse intensity profile. The map exhibits a simple exponential spatial decay in the direction of the static magnetic field in the free Py film (line). The frequency range of the magnetic oscillations generated by the STNO is indicated by a hatched region. Inset: normalized profile of spin-wave intensity in the section transverse to the nanowaveguide. Symbols are experimental data; curve is a fit by the Gaussian function (symbols, log-linear scale). The line shows the result of fitting the normalized profile of spin-wave intensity in the section transverse to the nanowaveguide. Symbols are experimental data; curve is a fit by the Gaussian function (inset). Dependence of w on the propagation coordinate. Symbols are experimental data; horizontal line is the mean value.

The BLS intensity integrated over the transverse section of the map exhibits a simple exponential spatial decay in the direction of propagation (shown on the logarithmic scale in Fig. 3b). We define the propagation length \( L \) as the distance over which the wave amplitude decreases by a factor of e. By fitting the data of Fig. 3b with the function \( \exp(-2y/L) \), we obtain \( L = 1.3 \mu \text{m} \). We note that this value is close to the best spin-wave propagation characteristics obtained in low-loss Py films with comparable thickness, despite the higher dynamical losses expected due to the stronger damping in CoFe.

By analysing the transverse cross-sections of the BLS intensity map (Fig. 3c), we determined the transverse full-width at half-maximum (FWHM) \( w \) of the spin-wave intensity distribution for different positions along the waveguide. The obtained value \( w = 320 \text{ nm} \) is independent of the propagation coordinate (Fig. 3d), which confirms that the spin wave is efficiently localized in the waveguide and does not spread out in the process of propagation. We note that the measured spatial profile (Fig. 3c) represents a convolution of the actual profile of the spin-wave intensity with the distribution of intensity in the diffraction-limited probing light spot, which has an estimated diameter of 250 nm. The value \( w = 320 \text{ nm} \) is therefore in reasonable agreement with the measured waveguide width of 200 nm (Fig. 1a, inset).

To gain further insight into the spin-wave propagation in the field-induced nanowaveguide, we performed additional micromagnetic simulations. Figure 4a shows the obtained dispersion spectrum of the fundamental waveguide mode (symbols), as well as the dispersion spectrum calculated for the free Py film using analytical theory\(^{10}\) (solid curve). The results of these calculations support our experimental findings: the dispersion curve for the free Py film starts at 8.4 GHz, whereas the waveguide mode starts at a much lower frequency and spectrally overlaps with the...
auto-oscillations induced in the STNO (hatched region), in agreement with the experimentally determined BLS spectra of thermally excited magnons (Fig. 2b). Micromagnetic simulations also provide insight into the spatial characteristics of the excited waveguide mode on length scales below the resolution limit of our experimental technique. The inset to Fig. 4a shows the distribution of the spin-wave intensity in the direction transverse to the waveguide. The calculated profile exhibits two maxima close to the edges of the waveguide and a minimum at the centre, consistent with the characteristics of the propagating edge mode. The difference between the calculated profile and that shown in Fig. 3c is explained by the limited experimental spatial resolution, which does not allow the two maxima at the edges of the nanowaveguide to be resolved. Nevertheless, the symmetry of the measured profile with respect to the waveguide axis allows one to conclude that the intensities of the two maxima are approximately the same.

Simulations also allow us to estimate the propagation characteristics of the excited mode. In particular, the propagation length is given by the product of the relaxation time and the group velocity, the latter determined by the slope of the dispersion curve. Propagating edge modes are generally characterized by large group velocities, resulting in an increased propagation length. This can be clearly seen from the data of Fig. 4a: the slope of the edge-mode dispersion is significantly larger than that of the spin waves in the free Py film. Correspondingly, the calculated spatial decay of the waveguide mode (squares in Fig. 4b) is significantly slower than that of the spin waves in the free Py film (inverted triangles in Fig. 4b). Figure 4b (triangles) also shows the decay curve calculated for the edge mode in an isolated CoFe nanowire. These results demonstrate that, in addition to the increased group velocity of the edge mode, the spin-wave decay characteristics of the composite Py/CoFe nanowaveguide significantly benefit from the low dynamic damping of the Py layer.

Note that the suggested magnonic system operates at moderate in-plane static magnetic fields and is compatible with the previously demonstrated spin-wave control methods. For example, one can easily implement control of spin-wave propagation by using magnetic fields created by the underlying control lines or by varying the demagnetizing fields using a variable-width waveguide. Finally, we discuss the power transmission between the STNO and the nanowaveguide. This is mediated by the dynamic dipolar fields generated due to the magnetization oscillations in the STNO point-contact area and depends on the distance between the waveguide and the STNO. In our test system, the distance of 150 nm gives a transmission efficiency of ~2%, which is comparable, for example, with the typical outcoupling in lasers. On the one hand, the coupling can be increased by reducing this distance. On the other hand, losses associated with the spin-wave radiation will result in an increase in the driving current required to operate the STNO.

In conclusion, we have experimentally demonstrated a new approach to efficient integration of spin-torque sources of propagating spin waves with nanoscale magnonic waveguides. Our approach enables local excitation and directional transmission of spin waves generated by the spin-torque devices. A significant reduction of the spatial decay of the propagating spin wave is achieved by eliminating the spreading of the wavefront and as a result of the increased group velocity of the excited spin waves. Our results provide a simple and efficient route for the implementation of next-generation magnonic devices, integrating nanoscale sources of signals based on the spin-torque mechanism and their processing via waveguiding structures.

Methods

Sample fabrication. The samples were fabricated on (0001)-oriented sapphire substrates purchased from MTI Corporation (www.mtitl.com). Before sample fabrication, the substrates were cleaned and annealed at 1,300 °C, resulting in an atomically flat surface by atomic force microscopy. Gold electrodes patterned into microwave striplines were fabricated on the substrates by photolithography and thermal evaporation. A Cu(40)Co(20)Fe(5)Au(2) multilayer (numbers in parentheses are thicknesses in nanometres) was subsequently deposited by high-vacuum magnetron sputtering in a vacuum chamber with a base pressure of 3 × 10⁻⁷ Pa. Using ultrahigh purity Ar gas at 5 × 10⁻⁵ Pa, a 200-nm-wide Au(19) strip serving as a mask to define the nanowaveguide was then fabricated on the multilayer by electron-beam lithography and thermal evaporation. Argon ion milling was used to remove Au and CoFe everywhere except for the area protected by the mask, where only the Au(2) cap and 1 nm of CoFe were removed. Multilayer Ni₈₀Fe₂₀(5)/Cu(4)/CoFe(5)/Au(5) serving as the STNO stack was subsequently deposited by sputtering, without breaking the vacuum. An elliptical contact with dimensions of 120 nm × 40 nm was defined on the multilayer by electron-beam lithography and evaporation of a 50-nm-thick Au mask. The long axis of the elliptical contact was oriented at 45° to the axis of the nanowaveguide to provide a non-zero angle between the magnetizations of the structured CoFe(4) spin polarizer and the extended Py(5) film for giant magnetoresistance measurements with the static field oriented perpendicular to the waveguide axis. Argon ion milling was used to remove part of the multilayer down to the surface of the Ni₈₀Fe₂₀ everywhere except for the area protected by the Al mask. A Si₃N₄(30) layer was deposited by radiofrequency sputtering without breaking the vacuum, to isolate the multilayer and protect the NiFe from oxidation. The Al mask was then removed by a combination of Ar ion milling and etching in KOH:H₂O solution. Finally, a 150-nm-thick Au electrode was deposited on top. After the fabrication, the samples were characterized by scanning electron microscopy with a spatial resolution of 2.5 nm (SEM, Zeiss 1540 XB CrossBeam) to determine the precise width of the nanowaveguide and confirm its position with respect to the rest of the device.

Measurements. The samples were soldered into a holder that provided optical access for the BLS measurements, as well as microstrip for the broadband electronic measurements. The sample leads were connected through a bias-tee to a current source and a spectrum analyser (N9030A, Agilent Technologies) via a broadband amplifier. All measurements were performed at room temperature. The frequency-dependent gain of the amplifier, as well as the microwave losses in the cables and the sample leads, were determined with a calibrated microwave generator and a power meter. The measured microwave signals were corrected for these gains/losses after subtracting the background determined at I = 0. Microlens BLS measurements were performed by focusing light produced by a continuous-wave single-frequency laser operating at a wavelength of 532 nm into a diffraction-limited spot. The light scattered from magnetic excitations was analysed by a six-pass Fabry–Perot interferometer FFP-1 (JRS Scientific Instruments) to obtain information about the BLS intensity, which is proportional to the intensity of spin waves at the location of the focal spot. By rastering the probing spot over the surface of the sample using a closed-loop piezo-scanner, two-dimensional maps of the spin-wave intensity were recorded with a resolution of 250 nm. The positioning system was stabilized by custom-designed active feedback, providing long-term spatial stability better than 50 nm.

Micromagnetic simulations. Simulations were performed using the object oriented micromagnetic framework OOMMF (http://math.nist.gov/oommf). The computational domain was discretized into 5 × 5 × 5 nm³ cells. The values of the saturation magnetization for the Py and CoFe (0.9 and 1.4 kG, respectively) were determined from the BLS measurements of thermally excited spin waves. Standard Gilbert damping constants of 0.008 and 0.015, respectively, were used for these materials.

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References


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Author contributions
S.U. suggested the idea for the experiment and fabricated the samples. V.E.D. and H.U. performed measurements and data analysis. T.Ke. and T.Ku. performed micromagnetic simulations. J.L. and G.W. performed sample characterization. S.O.D. formulated the experimental approach and performed the general supervision of the study. All authors co-wrote the manuscript.

Additional information
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Competing financial interests
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