Nanoimaging of Ultrashort Magnon Emission by Ferromagnetic Grating Couplers at GHz Frequencies

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ABSTRACT: On-chip signal processing at microwave frequencies is key for modern mobile communication. When one aims at small footprints, low power consumption, reprogrammable filters, and delay lines, magnons in low-damping ferrimagnets offer great promise. Ferromagnetic grating couplers have been reported to be specifically useful as microwave-to-magnon transducers. However, their interconversion efficiency is unknown and real-space measurements of the emitted magnon wavelengths have not yet been accomplished. Here, we image with subwavelength spatial resolution the magnon emission process into ferrimagnetic yttrium iron garnet (YIG) at frequencies up to 8 GHz. We evidence propagating magnons of a wavelength of 98.7 nm underneath the gratings, which enter the YIG without a phase jump. Counterintuitively, the magnons exhibit an even increased amplitude in YIG, which is unexpected and due to a further wavelength conversion process. Our results are of key importance for magnonic components, which efficiently control microwave signals on the nanoscale.

KEYWORDS: magnonics, nanomagnetism, spin waves, magnetization dynamics, microwave transducer, grating coupler

Magnons allow for information transfer via angular momentum propagation instead of moving electric charges. Hence, magnons attract attention for future low-power computing applications, circumventing the Joule heating which limits the clock-frequency of conventional electronics. In ferro- and ferrimagnetic materials magnons occur in the frequency regime from GHz to THz, which becomes more and more important for high-speed wireless data transfer. The wavelength of magnons is several orders of magnitude smaller than that of electromagnetic waves of the same frequency. Going beyond surface acoustic waves (SAWs), magnons allow one to significantly shrink microwave components and perform analog signal processing like bandpass-filtering, multiplexing, phase-shifting, directional coupling, and buffering on the nanoscale instead of micrometer scale. Unlike SAWs, the resonance frequency of magnons is easily tunable by the application of magnetic field or by a reprogrammed magnetic configuration. Consequently, to harness the full potential of magnons, one needs an efficient microwave-to-magnon transducer that supports many frequency bands as well as a significant wavelength down-conversion. Coplanar waveguides (CPWs) on top of magnetic thin films excite magnons over a broad frequency range. However, their wavelengths are about twice the width of the CPW signal line, restricting the accessible wave vector regime in both thin yttrium iron garnet (YIG) films and along nanosized YIG magnon conduits. To overcome this restriction and excite spin waves (SWs) with a wavelength much smaller than the size of the CPW is the subject of intense research. Recently ultrashort SWs (magnons) were emitted by nanoscale spin textures which were irradiated by microwave fields. Such spin textures required metallic multilayer stacks which are generally prone to large magnon damping, however. Magnonic grating couplers (GCs) are particularly promising as they can both be integrated on low-damping magnetic media like YIG and cover large surface areas to obtain sufficient microwave coupling. For a GC, periodic lattices of nanomagnets with a lattice constant are introduced between CPW and magnonic circuit. All-electrical spin wave spectroscopy (AESWS) showed additional high-frequency magnon modes when a GC was present, but their wavelengths and amplitudes were not quantified due to technical restrictions.

In this work we report real-space measurements of short-wave magnons in thin YIG emitted by GCs consisting of arrays of nanostripes. Using time-resolved scanning transmission X-ray microscopy (TR-STXM) we measure...
their wavelengths, amplitudes, and phases at different GHz frequencies. Our data evidence that magnons are of ultrashort wavelength and propagate underneath the gratings. This observation is in contrast to ref 29 where it was argued that GC modes were standing waves. At the boundary between the GC and bare YIG we discover a frequency-dependent wavelength conversion, which was not yet anticipated. This discovery is highly relevant for applications where a specific wavelength in a magnonic waveguide is required. Although wavelength conversion implied a change of wave impedance at the interface, strikingly magnons were emitted from the GC generated around the CPW by an applied microwave current into the bare YIG without a noticeable phase shift or backscattering (amplitude reduction). For some modes their wavelengths, amplitudes, and phases at different x coordinates as indicated in (b). For x = 0 μm (orange) and 10 μm (green), two maxima at 7.5 mT and at 13 mT are observed matching magnons with wave vectors 2k + k1 and 2G − k1. The reduced signal strength detected at x = −10 μm (blue) is attributed to nonreciprocity. At 7.5 mT (13 mT) the wavelength underneath the gratings amounted to 98.7 nm (101.2 nm) and in the bare YIG to λ = 104.0 nm (104.5 nm). (e) Static and (f) dynamic contrast as well as (g) time evolution of the dynamic magnetization plotted as line profiles at the interface between GC and bare YIG at 7.5 mT. We observe plane-wave magnon emission with propagating wave fronts (indicated by black dashed line) both underneath the GC and in the bare YIG.

Figure 1. Real space imaging of a grating coupler mode. (a) SEM and (b) static X-ray transmission image of sample1a. Bright stripes in (a) represent the Py grating. Light gray regions in (b) on the left and right (high transmission) correspond to the bare YIG. The Py grating underneath the CPW creates locally dark stripes. (c) Sketch of the experimental configuration. (d) Field-dependent magnon amplitudes for 8.07 GHz measured at three different x coordinates as indicated in (b). For x = 0 μm (orange) and 10 μm (green), two maxima at 7.5 mT and at 13 mT are observed matching magnons with wave vectors 2k + k1 and 2G − k1. The reduced signal strength detected at x = −10 μm (blue) is attributed to nonreciprocity. At 7.5 mT (13 mT) the wavelength underneath the gratings amounted to 98.7 nm (101.2 nm) and in the bare YIG to λ = 104.0 nm (104.5 nm). (e) Static and (f) dynamic contrast as well as (g) time evolution of the dynamic magnetization plotted as line profiles at the interface between GC and bare YIG at 7.5 mT. We observe plane-wave magnon emission with propagating wave fronts (indicated by black dashed line) both underneath the GC and in the bare YIG.

We prepared nominally identical GC samples for STXM (sample1a, sample1b) and AESWS (sample2) measurements (Supporting Information (SI), Methods S1.1). Figure 1a shows a scanning electron microscope (SEM) image of sample1a. Figure 1b displays its corresponding X-ray transmission image. The bare YIG film, the CPW, and the GC can be distinguished due to different X-ray transmission signals. Figure 1c shows a sketch of the STXM experiment. The GC consisted of 20 nm thick Py (Ni81Fe19) stripes fabricated directly on a 100 nm thick YIG film. The Py stripes had a width of wpy = 100 nm and a length of 25 μm and were arranged with a lattice constant of a = 200 nm in periodic arrays with a total width of wGC = 10 μm. CPWs out of 5 nm thick Ti and 110 nm thick Cu were patterned collinearly aligned on top of the Py grating. The width of the signal and ground lines of the CPW amounted to 2.1 μm and the gap width to 1.4 μm, resulting in a total width of 9.1 μm, which was slightly smaller than wGC. Fourier analysis of the simulated magnetic field profile hrf generated around the CPW by an applied microwave current i rf (Figure S1) showed a major peak for the transferred wave vector at k1 = 0.85 rad μm−1 (Figure S1). We applied a continuous microwave signal at 8.07 GHz and varied the magnetic field pointing parallel to the CPW in a stepwise manner. Using TR-STXM with circular dichroism contrast, we measured phase-coherently the dynamic out-of-plane magnetic component of the YIG film m ̃(x,y,t) (SI Methods S1.2). We probed three different measurement windows (300 nm × 100 nm) placed at x = −10 μm (left of the CPW), x = 10 μm (right of the CPW), and x = 0 μm below the signal line as indicated in Figure 1b. In Figure 1d extracted amplitudes of ̃m are shown (SI Methods S1.3). For the windows at x = 0 and 10 μm a clear SW signal with two maxima at 7.5 mT and at 13 mT is apparent. We attribute the two peaks to magnons excited with a wave vector of 2G + k1 and 2G − k1, respectively, as further substantiated below. G = 2π/a denotes the reciprocal lattice vector of the grating.
vector of the grating. At the window left of the CPW \((x = -10 \mu m)\) the recorded amplitudes are close to the noise floor. Consequently, there is a strong nonreciprocity of SW emission, favoring the \(+x\) direction. Large nonreciprocity of GC modes was recently modeled by Chen et al.\textsuperscript{33} and was attributed to the dipolar coupling between a ferromagnetic grating and the YIG film.

To study the SW emission process in detail, we focus on the interface region between the GC and bare YIG in the direction of large emission as depicted in Figure 1e. For clarity we introduce the coordinate \(x'\) for which \(x' = 0 \mu m\) resides at the right outer edge of the GC indicated by a yellow dashed line in Figure 1b and 1e. At \(\mu_H = 7.5 \text{ mT}\) we find plane-wave SWs propagating in the \(+x\)-direction (Figure 1f). Sinusoidal fitting of \(n_x\) over 10 periods provides a wavelength of \(\lambda = (98.7 \pm 0.4) \text{ nm}\) in the region covered by the grating and of \((104.0 \pm 0.2) \text{ nm}\) in the bare YIG. Analogously for \(\mu_H = 13 \text{ mT}\), we find \(\lambda = (101.2 \pm 0.1) \text{ nm}\) and \(\lambda = (104.5 \pm 0.1) \text{ nm}\), respectively (not shown). We note that the wavelength found underneath the grating for \(\mu_H = 7.5 \text{ mT}\) and 13 mT, which are the two field values where maximum SW emission was found in Figure 1d, agree very well with the values \(2\pi/(2G + k_x) = 98.7 \text{ nm}\) and \(2\pi/(2G - k_x) = 101.4 \text{ nm}\) expected by theory.\textsuperscript{27} Thus, our measurements agree with the Bloch theorem for coherent waves applied to the periodic lattice of the GC. Propagating into the bare YIG, the SWs undergo a slight wavelength conversion process. In Figure 1g the time evolution of the dynamic magnetization plotted as line profiles at the boundary between GC and bare YIG is depicted. The absence of a phase jump at \(x' = 0 \mu m\) and the almost constant amplitude indicate a transmission coefficient of close to one from the grating into bare YIG. We observe a propagating wavefront (indicated by black dashed line) both underneath the GC and in the bare YIG. In the literature standing waves were assumed underneath the grating.\textsuperscript{29} We do not confirm the assumption. We explain the propagating character underneath the GC by the nonreciprocal excitation and apparently vanishingly small back-reflection at the boundary. We note that we still detected plane wave fronts at a measurement area located at \(x = 15 \mu m\), i.e., \(10 \mu m\) away from the GC (Figure S2). The magnons with \(\lambda \approx 99 \text{ nm}\) possess a wavelength which is 375000 times smaller than the one of the free-space electromagnetic wave at 8.07 GHz and almost 3 orders of magnitude smaller than \(2\pi/k_x\) given by the geometrical size of the CPW.

To allow for comparison of our GC with existing literature data and to show the correspondence between microscopic STXM data and conventional AESWS, we studied SW propagation all-electrically using a nominally identical sample featuring two CPWs as sketched in Figure 2a. The center-to-center distance between CPW1 and CPW2 in sample2 amounted to 35 \(\mu m\), i.e., there was a 25 \(\mu m\) wide region of bare YIG between CPW1 and CPW2. The two CPWs were connected to the ports of a vector network analyzer (VNA) and scattering parameters were measured (SI Methods S1.4).

Figure 2 shows the magnitude of the forward transmission coefficient S21 that was measured between CPW1 and CPW2 as a function of magnetic field applied in parallel to the CPW. For this configuration the observed signal originated from magnons which were excited at CPW1, propagated in the bare YIG, and were detected at CPW2. In the spectra several high-frequency modes were present which were not observable with bare CPWs\textsuperscript{34} (cf. Figure S3). We highlight two closely spaced branches in Figure 2b which cross 8.07 GHz near 10 mT (orange encircled). These branches reflect \(2G \pm k_x\) modes discussed in the previous section. To substantiate the allocation we show the calculated field dependence (SI Methods S1.5) of a mode with \(k = 2G\) (broken line) in Figure 2b. Using the formalism of ref 35, \(G\) and 3G modes can be identified in the spectrum as well (further purple dashed lines in Figure 2b). The 3G mode corresponds to SWs with a wavelength of \(\lambda = 67 \text{ nm}\) underneath the GC. Further observed GC mode branches agree well with the formalism\textsuperscript{32} when we assume an additional quantization along the film thickness. The modes of G+PSSW1 and 2G+PSSW1 are especially apparent, where PSSW1 denotes to the first perpendicular standing spin wave (PSSW) of the YIG film. We attribute the excitation of PSSW1 modes to direct exchange coupling of the Py grating to the YIG film. Pronounced excitations of PSSWs
were recently reported for heterostructures consisting of a ferromagnetic layer and a YIG film. To compare transmission amplitudes, we show in Figure 2c Mag(S21) obtained on sample 2 (black line) at 11 mT and Mag(S21) of a reference sample (green line) with CPWs without GCs (details and field-dependent spectra are displayed in Figure S3). For sample 2, 1G and 2G peaks are clearly visible. For the reference sample without GCs we did not resolve a high-frequency mode above 3 GHz at 11 mT.

In the following we discuss the observed wavelength conversion for different excitation frequencies at the GC/YIG interface. Figure 3 shows a static X-ray transmission image and corresponding snapshots of the dynamic magnetization when a microwave frequency of 3.43 GHz was applied to the CPW. Peaks in emission were observed at 8 mT and 10 mT. By analyzing the wavelength in the region underneath the GC, the two excitation peaks can be attributed to the wave vectors $G + k$ and $G - k$ with a wavelength of about 200 nm. Surprisingly, the wavelength of the magnons transmitted with high efficiency into the bare YIG amounts to about 250 nm, i.e., it is increased by 25%. A similar increase was observed with a second sample (Figure S4) as well as for the opposite field direction measured at larger field magnitude and frequency (Figure S5). We find that the conversion is more pronounced at G1 than at G2. We conclude that the effect is dipolar in nature. We speculate that the Py grating decreases the dynamic demagnetization field in the underlying YIG in the out-of-plane direction, shifting the dispersion of Damon–Eshbach (DE) modes to lower frequencies.

We further analyze the amplitude change of 1G magnons crossing the interface between the GC and bare YIG. Figure 3d shows line profiles of the signal amplitudes for seven time slices during one period at 3.43 GHz and 10 mT averaged along y-direction in the 1 μm wide region indicated by a blue-dashed line in Figure 3b. Sinusoidal fitting of $\tilde{m}_z$ in the region of the GC and the bare YIG (solid orange and green lines, respectively, in Figure 3d) shows that the wavelength expands from (209 ± 5) nm to (276 ± 3) nm as discussed above. We extrapolate both fits into the direct transition region (dashed lines in Figure 3d). It is apparent that the change in wavelength occurs on a small length scale of about 100 nm. In Figure 3e we depict the time-dependent amplitudes of $\tilde{m}_z$ in both regions extracted from the fits for each time slice. Intriguingly, the amplitude in the bare YIG (green symbols) is larger than underneath the GC (yellow symbols) for all times sampled. The ratio of the average amplitudes in the respective regions amounts to $A_{YIG}/A_{GC} = 1.28 ± 0.04$. As the signal is normalized to the absolute photon flux at any given position, the larger magnon amplitude in YIG is not due to a reduced X-ray absorption outside the gratings. At first sight, the increased amplitude of the wave emitted into YIG is counterintuitive and might indicate a transmission coefficient across the boundary of more than one. A more detailed analysis shows, however, that the change in amplitude can be attributed to energy flux conservation in a dispersive medium. The energy transported by a wave is proportional to the product of the square of the oscillation amplitude $A^2$ and the group velocity $v_g$. Using the formalism of ref 35 and considering the different wavelengths in the GC and YIG, we find $v_{gYIG}/v_{gGC} = 1.38$, i.e., the group velocity is larger underneath the GC compared to bare YIG. Assuming energy conservation, the ratio of the average amplitudes should read $A_{YIG}/A_{GC} = \sqrt{v_{gYIG}/v_{gGC}} = 1.18$.

Consequently an increased amplitude is indeed expected for the bare YIG. The measured ratio is even larger. We note that $v_{gGC}$ was calculated from the dispersion relation of bare YIG35 and might be underestimated. Increased group velocities were recently reported by An et al. for Py/YIG bilayer systems.38

In Figure 3d the propagating character of wave fronts is prominent in the region of the GC similar to the 2G mode shown in Figure 1g. Still, a small oscillation of $\tilde{m}_z$ amplitudes for different time slices is visible in Figure 3e (orange symbols). This oscillation in the GC region can be consistently modeled by assuming partially standing waves following the formula $\tilde{A}(t) = A\sqrt{1 + \Gamma^2 + 2i\cos(2\omega t)}$, where $\Gamma$ takes into account the relative amplitude of a counter-propagating wave in the $-x$ direction.36 By fitting (dashed line Figure 3e), we obtain a small value $\Gamma = 0.14 ± 0.03$. The origin of a wave propagating in the $-x$ direction can either be due to the

![Figure 3. Wavelengths and amplitudes conversion observed for the 1G mode. (a) Static and (b) dynamic X-ray transmission images at 3.43 GHz taken at the interface (yellow dashed line) between the GC region (left) and bare YIG (right) for decreasing magnetic field. (c) Wavelengths extracted underneath the grating (orange) and in the bare YIG regions (green). (d) Local amplitudes $\tilde{m}_z$ (black dots) evaluated at 3.43 GHz and 10 mT in the region marked by the blue-dashed line in (b). We display different time slices. The signal is fitted with a sinusoidal time dependence for the region of the GC (solid orange line) and bare YIG (solid green line) separately. The dashed lines extrapolate the respective fits. (e) Amplitudes of the fitting functions indicate larger signals in the bare YIG (green dots) than in the GC (orange dots). The orange (green) dashed line shows a fit of the time-dependent amplitudes considering a partially standing wave in the GC (bare YIG).](image-url)
excitation of \(-2G\) in the GC or some weak back-reflection at the interface. The amplitudes detected in bare YIG (green symbols in Figure 3) also vary slightly with time (\(\Gamma = 0.07 \pm 0.02\)). The tiny variation could indicate that the magnons in YIG experience some reflection at a position remote from the CPW. We speculate that the focused ion beam etching process for the 50 \(\mu\)m \(\times\) 50 \(\mu\)m large X-ray transmission window has caused a small step in the YIG thickness from the backside. Assuming a concomitant change in the spin-wave dispersion relation, one could explain weak backscattering.

To conclude, enhanced magnon emission was found when the wave vector underneath the grating coupler matched the reciprocal lattice vector \(G\) or a multiple of it. This was clear evidence of the magnonic grating coupler effect, which had not yet been measured directly. Further, we reported a wavelength conversion when magnons were emitted from the GC. At 2G the wavelength \(\lambda\) expanded by about 5%. This was not anticipated by previous AESWS measurements. Our finding needs to be considered if a specific \(\lambda\) is required. For 1G we evidenced a clearly increased amplitude when a magnon entered bare YIG. Here, the group velocity decreased in the bare YIG and the SW amplitude increased to keep the energy flux constant. This effect might be purposefully employed to induce large amplitudes for read-out by slowing down SWs at specific locations of a magnonic circuit. Encouragingly, our data suggest that magnons efficiently couple out from the GC without significant back-reflection at its boundary to 100 nm thick YIG. Such YIG is commercially available on the wafer scale. At the same time, the GC modes show a huge nonreciprocity, i.e., the energy flows only in one direction (depending on field direction). The nonreciprocity is preferred for transferring a signal between an emitter and a specific receiver. In contrast, a regular SAW device is reciprocal, which leads to a reduction of transmitted power by half, if no special reflectors are used. Combined with the small damping loss of high-quality YIG, we speculate that GCs can be used as multipass high-frequency filters. While SAW filters work with interdigital transducers, where the impedance is optimized for a specific frequency only, magnonic GCs with CPWs can be applied at multiple frequency bands relevant for future telecommunication.

**ASSOCIATED CONTENT**

* Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.0c02645.

Methods; Fourier transform of the spatial profile of the \(x\)-component of the exciting Oersted field of the CPW; snapshot of propagating magnons at \(x = 15\ \mu\)m and 8.07 GHz; spin-wave spectrum of a reference sample without grating couplers; wavelength conversion at 3.43 GHz for sample 1b; and wavelength conversion of G1 mode for \(-25\) mT (PDF)

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**Author Contributions**

D.G., K.B., J.G., and G.S. designed and planned the experiments. K.B. fabricated the samples and conducted AESWS characterization. J.G. prepared the samples for STXM measurements. K.B., J.G., P.C., A.M., J.F., N.T., M.B., and M.W. conducted the STXM measurements. K.B. and D.G. analyzed the data and wrote the manuscript. All authors commented on the manuscript.

**Notes**

The authors declare no competing financial interest. Data can be downloaded from zenodo via https://doi.org/10.5281/zenodo.4001711.

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