Spin transport in a charge current induced magnon Bose-Einstein condensate at room temperature

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Bose-Einstein condensation (BEC) describes a state of matter in which identical particles with integer angular momentum (bosons) occupy a collective quantum state [1, 2]. BEC is at the heart of many macroscopic quantum phenomena, including superfluidity [3], the condensation of diluted gas systems [4] as well as of bosonic excitations in solid-state systems [5–8]. Most importantly, BEC is the key prerequisite for dissipationless transport phenomena, forming the basis for quantum technologies on many levels. The magnetic analogon, the magnon BEC, is particularly appealing for applications, as it can emerge at room temperature [8]. However, transport phenomena within the magnon condensate or the generation of a critical magnon density by DC charge currents have only been considered theoretically [9–11]. Here, we demonstrate the realization of magnon BEC using a DC magnetotransport scheme and study its room temperature magnon conductivity. Above a critical magnon density, the magnon conductivity increases by almost two orders of magnitude, indicating dissipationless magnon transport, i.e. the realization of spin superfluidity [12]. Our results demonstrate an all-electrical approach for the investigation of spin transport in a magnon condensate. The regime of dissipationless magnon transport paves the way for phenomena equivalent to Josephson effects in superconductivity and will be of key relevance for future (quantum) magnonic devices.

The phenomenon of BEC is inherently connected to the quantum statistics of bosons. When lowering the temperature at constant boson density, the chemical potential \( \mu \) approaches the energy of the ground state and the latter becomes macroscopically populated. Considering bosonic excitations in a solid, such as phonons or magnons, BEC cannot be realized in a thermal equilibrium situation, since the boson number is not conserved (\( \mu = 0 \)). The boson number rather decreases with decreasing temperature as, loosely speaking, the excitations freeze out. Continuous generation of excitations by external pumping, however, results in a steady-state non-equilibrium situation with finite \( \mu \) [13, 14]. Such driven BEC has been reported for many systems such as excitons [5], phonons [6], photons [7] and magnons [8]. For the latter, BEC was achieved using a two-magnon excitation scheme followed by a thermal relaxation of the magnons into the ground state [8]. Recently, Bender et al. [9] suggested the creation of magnon BEC by injection of a DC spin current into a magnetic material, resulting in a steady-state non-equilibrium with finite magnon chemical potential \( \mu_m \) [14]. When \( \mu_m \) exceeds a critical value, the ground state becomes macroscopically populated and BEC is achieved. In our corresponding experiments [15], we realize spin current injection into a magnetic insulator (MI) via the spin Hall effect (SHE) [16, 17] by driving a charge current \( I_{dc} \) through a heavy metal (HM) strip in contact with the MI. As a result, a spin chemical potential \( \mu_s = \frac{e\hbar I_{dc}}{c\sigma_s} \tanh (\eta) \) [14, 18, 19] builds up at the HM/MI interface, leading to a non-equilibrium magnon density in the MI. Here, \( e \) is the elementary charge, \( w \) denotes the width of the HM strip, \( \sigma_s \) and \( \sigma_{SH} \) are the electric conductivity and the spin Hall angle of the HM. Moreover, \( \eta = H_{HM}/(2\sigma_s) \) is the ratio of the thickness of the HM strip \( t_{HM} \) and its spin diffusion length \( l_s \). Since \( \mu_m \) is expected to grow with \( \mu_s \), we can tune \( \mu_m \) by varying \( I_{dc} \). Adopting the model in Ref. [9] to our experimental configuration, the criteria for the formation of magnon BEC as well as the swelling instability (the spin wave analogon of lasing [20]) within the DC pumped magnon condensate are given by

\[
\mu_{BEC/SW} = \left(1 + \frac{\alpha_{eff}}{c \cdot \alpha_{sp}} \right) \left[ \hbar \gamma \mu_0 \left( H + \frac{M_s}{2} \right) \right].
\]

Here, \( \mu_s = \mu_{BEC} \) (i.e. \( I_{dc} = I_{BEC} \)) corresponds to the critical spin chemical potential (current) for the formation of magnon BEC with \( c = 2 \), while \( \mu_s = \mu_{SW} \) (i.e. \( I_{dc} = I_{SW} \)) corresponds to the swelling instability with \( c = 1 \). Furthermore, \( \alpha_{eff} \) is an effective damping parameter (see SI), \( \alpha_{sp} \) is the spin pumping induced damping enhancement of the MI, \( \hbar \) is the reduced Planck constant, \( \gamma \) is the gyromagnetic ratio and \( \mu_0 \) is the vacuum permeability. The criteria further depend on the external magnetic field \( H \) and the saturation magnetization \( M_s \). As magnon BEC represents a state of coherent magnetization precession, it resembles the classical phenomenon of spin torque oscillators [21]. Here, the threshold criterion is determined by the frequency linewidth

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(damping rate) of the ferromagnetic resonance (FMR) transition. As detailed in the SI, we find full equivalence of the DC current pumped magnon swasing criterion [9] (\(\mu_{SW}\) in Eq. (1)) and the DC current threshold for spin torque auto-oscillations, which is the classical description of swasing.

In this letter, we report on magnon transport properties across the phase transition of a DC pumped magnon Bose-Einstein condensate formed in the ferrimagnetic insulator yttrium iron garnet (YIG). Within the swasing phase of the magnon condensate, we find an increased magnon conductivity by almost two orders of magnitude, indicating dissipationless transport of magnons.

The principle of our magnon conductance measurement is inspired by recent DC magnetotransport experiments that infer magnon properties in YIG [14, 15, 22–26]. Here, magnons are injected from a Pt strip (injector) into the YIG by a low-frequency (13 Hz) charge current \(I_{ac}\) (see Fig. 1a) and the SHE in Pt. The diffusion and, hence, the conductivity of these magnons is quantified by electrically measuring the magnon density below a second Pt strip (detector) as a voltage signal \(V_{ac}\) exploiting the inverse SHE. Cornelissen et al. [27] demonstrated that the magnon conductivity measured in such an arrangement can be controlled by a DC charge current \(I_{dc}\) applied to a third (modulator) strip placed in between injector and detector. In a simple picture, \(I_{dc}\) controls the magnon density below the modulator and thereby alters the magnon conductivity.

In contrast to Ref. [27], we here focus on the non-linear regime of this magnon conductance. Our physical picture of the magnon transport beneath the modulator is condensed in Fig. 1: For \(I_{dc} = 0\) (panel b), the magnon density \(\n_{ac}\) from the injector decays exponentially (orange solid line). For \(I_{dc} = I_{BEC}\) (panel c), the magnon density generated by the modulator is sufficient to support the formation of magnon BEC. Due to the strong increase in magnon density for \(I_{dc} \gtrsim I_{BEC}\), the magnon conductivity is enhanced, which results in an increased \(V_{ac}\) at the detector. For \(I_{dc} = I_{SW}\) (panel d), the swasing threshold of the magnon BEC state is reached, the magnon lifetime diverges and a macroscopic excitation is generated. In this swasing state, the magnon damping is completely compensated by the DC pumping and dissipationless transport ensues.

To investigate the magnon propagation in the YIG for different modulator currents \(I_{dc}\) and to test the criteria set in Eq. (1), we measure \(V_{ac}\) as a function of the magnetic field orientation \(\varphi\) with a fixed magnetic field strength of \(\mu_0H = 50\) mT at a temperature \(T = 280\) K. The result is shown in Fig. 2, where the black data points show the characteristic (\(\cos^2\varphi\)) modulation expected for magnon transport between injector and detector for \(I_{dc} = 0\), resulting from the variation of the magnon injection with \(\varphi\) with maxima expected for \(H\) perpendicular to \(I_{ac}\) (\(\varphi = -180^\circ, 0^\circ, 180^\circ\)) [15, 22]. Interestingly, a significant enhancement of the magnon transport signal is observed at \(\varphi = \pm 180^\circ\) in Fig. 2a for \(I_{dc} > 0\). This can be understood by a magnon accumulation underneath the modulator, which increases the magnon conductivity and results in a larger \(V_{ac}\). In the same way, a decrease of \(V_{ac}\) is expected for \(\varphi = 0^\circ\) due to the magnon depletion obtained in this configuration.
However, this is counterbalanced by thermally injected magnons present due to Joule heating of the modulator strip. Figure 2b shows the measurement for the inverted DC current direction ($I_{dc} < 0$). Here, we observe the expected $180^\circ$ shifted case: an enhancement for $\varphi = 0^\circ$ and no significant change for $\pm 180^\circ$. This behaviour is consistent with an accumulation of magnons for the given current and magnetic field direction.

For a quantitative analysis of the data presented in Fig. 2, we extract the amplitudes $A(\mu_0 H)$ and $A(-\mu_0 H)$ as a function of $I_{dc}$ for various magnetic field amplitudes $H$ (see Fig. 3). In the low bias regime ($|I_{dc}| < 0.4mA$), the $A(I_{dc})$ curves can be modeled by a superposition of a linear and quadratic dependence as already reported by Cornelissen et al. [27] (see SI). However, we observe a two orders of magnitude improved control of the magnon conductivity compared to Ref. [27]. This is in agreement with the predicted magnetic layer thickness dependence of the modulation efficiency [27]. A quantitative comparison to the model of Ref. [27] is shown in the SI. In addition, and most importantly, we see a pronounced deviation from the linear in $I_{dc}$ transport modulation [27] for large $I_{dc}$. This manifests itself by a shoulder in the $A(I_{dc})$ curves for $I_{dc} > 0.5$ mA (marked by black triangles).

We now focus on the magnon transport properties, i.e. the magnon resistance $R_{YIG}$. To this end, we evaluate the magnon resistance measured between injector and detector as a function of the modulator current. As explained in detail in the methods, the spin resistance in YIG can be directly deduced from the magnon transport amplitudes $A$ plotted in Fig. 3 [14]. However, $A$ contains contributions from thermal (quadratic in $I_{dc}$) as well as SHE induced injection effects (linear in $I_{dc}$). We correct for both of those contributions, leading to the $R_{YIG}^s(I_{dc})$ dependence shown in Fig. 4a (details are given in the SI). Thus, $R_{YIG}^s(I_{dc})$ enables us to evidence the impact on magnon transport stemming solely from magnon BEC and swasing. For $I_{dc} < 0.4$ mA, we observe a constant $R_{YIG}^s$. At the characteristic current $I_{BEC}$, the magnon resistance $R_{YIG}^s$ starts to drop rapidly by $0.13 \, \Omega$ and saturates at a finite value above the second characteristic current $I_{SW}$. Here, we define $I_{BEC}$ as the current at which $R_{YIG}^s$ drops by $10\%$ compared to the constant resistance observed for small $I_{dc}$. $I_{SW}$ is taken at the current level where $R_{YIG}^s$ reaches its minimum value.

In Fig. 4b, the experimentally determined critical currents $I_{BEC}$ and $I_{SW}$ are plotted as a function of the applied magnetic field. For $I_{BEC}$ ($I_{SW}$), we observe a critical current around $0.45$ mA ($0.6$ mA) for $\mu_0 H < 50$ mT and both critical currents increase with the applied magnetic field strength for $\mu_0 H > 50$ mT. We can understand this behaviour quantitatively by solving the aforementioned condition $\mu_s = \mu_{BEC}$ ($\mu_s = \mu_{SW}$) for $I_{dc}$. Using the values $\sigma_e = 1.74 \times 10^6 / \Omega m$, $\sigma_{SH} = 0.11$, $l_s = 1.5$ nm, $w = 500$ nm and $\Delta_{PE} = 3.5$ nm to calculate $\mu_s$, we find excellent quantitative agreement of model and experimental data for both $I_{SW}$ (spheres and red line) and $I_{BEC}$ (stars and blue line). The characteristic parameters $\alpha_{eff}$ and $\alpha_{SW}$ entering Eq. (1) are determined independently using ferromagnetic resonance experiments presented in the SI. We want to emphasize that the magnetic field dependence of $I_{SW}$ is identical to the critical current dependence for auto-oscillations in spin Hall nano-oscillators [21] (see SI). It is remarkable that we observe the spin torque auto-oscillations without any patterning of the YIG. The geometrical confinement required for stable spin torque oscillations is rather de-
transport properties. In stark contrast to the reduction in spin resistance induced by ferromagnetic resonance, which is associated with linear SHE and thermal magnon injection effects (see SI), a very steep decrease of $R_{YIG}$ for $I_{BEC} < I_{dc} < I_{SW}$ is evident. The reduction of $R_{YIG}$ by 0.13 $\Omega$ is compatible with a vanishing magnon resistivity underneath the modulator strip. The right $y$-axis shows the critical chemical potentials $\mu_{BEC/SW}$ from Eq. (1) (solid red and blue lines).

The spin resistance data (Fig. 4a) also allows us to roughly estimate the condensate resistance within the swasing phase. Assuming a serial resistor network model [14] (see SI), and zero magnon resistance underneath the modulator strip, we expect $R_{YIG} = 0.19 \Omega$ for $I_{dc} > I_{SW}$, which is in excellent agreement with our data shown in Fig. 4a. We can further roughly estimate the spin resistivity $\rho_{YIG}^s$ for the swasing magnon condensate and obtain 8.16 n$\Omega$ m, which is almost two orders of magnitude smaller than the spin resistivity in the normal state (0.54 $\mu$ $\Omega$ m) (see SI). Thus, the observed spin resistance shows similarities to the sudden electrical resistance drop of a superconductor at the superconducting phase transition. Our data therefore provides evidence for the presence of a magnon BEC state with vanishing spin resistivity, which is also known as spin superfluidity [10–12, 28]. The observation of a magnon conductivity change in the BEC swasing regime warrants the question how a coherent magnetization precession induced by ferromagnetic resonance affects the transport properties. In stark contrast to the reduction of spin resistance due to the formation of the BEC, we find an increase of spin resistance when coherently driving the YIG magnetization by a low power microwave magnetic field (see SI) [29]. This demonstrates that the effective compensation of magnetic damping in the BEC phase is responsible for the formation of the superfluid - and not the coherent magnetization precession.

The excellent quantitative agreement between our experimental data and the model predicting BEC/swasing by DC spin current injection into magnetic insulators by Bender et al. [9] strongly suggests the formation of BEC in the YIG thin film. This transition from a classical magnon gas into a collective quantum state can also be independently estimated by comparing the thermal de Broglie wavelength $\Lambda$ with the mean (magnon) particle distance $a$. While for $a \gg $ $\Lambda$ the particles form a classical gas, a degenerate quantum gas is obtained for $a \lesssim $ $\Lambda$. We estimate the induced magnon density $n_m$ via spin-orbit torque, as pursued in this experiment, to be $10^{23}$/cm$^3$ for $I_{dc} = 0.8$ mA (see SI). In comparison, the thermal magnon de Broglie wavelength at room temperature is $\sim$ 2 nm, which exceeds the mean particle separation $a \approx n_m^{-1/3} \approx 0.2$ nm by an order of magnitude (see SI). Thus, even this simple estimate strongly supports the formation of a magnon Bose-Einstein condensate.

In summary, we find ultra-low magnon resistance indicating superfluid spin transport through the swasing phase of a DC pumped magnon condensate. Here, BEC is created by employing spin-orbit torque mediated spin current injection in a YIG/Pt heterostructure. We find excellent quantitative agreement between our experimental data and the theoretically predicted threshold conditions for the transition into magnon BEC and the swasing instability of the magnon BEC [9]. This work lays the foundation for experiments ranging from zero-resistance magnon transport to physics equivalent to the Josephson effects in superconductivity [10, 30]. Eventually, it even has the potential to make a significant impact on modern day magnon based (quantum) devices.

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AUTHOR CONTRIBUTIONS

T.W., M.A., L.L. and N.V. carried out the experiments and evaluated the data. T.W. fabricated the sample. S.G. performed the thin film growth. H.H., M.A. and R.G. supervised the project. T.W., M.A., M.W., R.G., H.H. and S.G. interpreted the results. T.W., M.A., M.W. and H.H. prepared the manuscript and figures with the assistance of all authors.
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METHODS

Sample preparation

The 13.4 nm thick, single crystalline (100)-oriented yttrium iron garnet (Y₃Fe₅O₁₂, YIG) film was grown via pulsed laser deposition at the Walther-Meißner-Institute on a gadolinium gallium garnet (Gd₃Ga₅O₁₂, GGG) substrate using a substrate temperature of 450 °C, an oxygen pressure of 25 µbar, a laser fluence at the target of 2.0 J/cm² and a laser frequency of 10 Hz. The YIG film exhibits a saturation magnetization of 140 mT and a Gilbert damping of 2 × 10⁻³. The 3.5 nm thick Pt strips were deposited on the YIG thin film by DC sputtering and were patterned by e-beam lithography: the strips have an edge-to-edge separation of d = 400 nm and a width of w = 500 nm. Subsequently, Ti/Al layers of 5/50 nm were deposited on the film by DC sputtering and patterned into leads for the Pt strips to contact the device electrically. A low frequency (f = 13.131 Hz) AC current I_{ac} of 50 µA is fed through the injector with a Keithley 2400 Sourcemeter to control the magnon chemical potential. The use of this lock-in detection technique is essential to distinguish between magnons stemming from the DC driven modulator and the AC driven injector [23, 27].

YIG spin resistance

The spin resistance R_{YIG} in YIG was determined by adopting an equivalent spin-resistor model [14]:

$$R_{YIG} = \frac{R_{Pt}}{\eta_s} - (2R_{int}^e + 2R_{Pt}^e),$$  \hspace{1cm} (2)

where $R_{Pt}^e = l_s/(\sigma_A \int \tanh(t_{Pt}/l_s))$ is the spin resistance of the Pt strip and $R_{int}^e = 1/(g_A \int)$ the interface spin resistance. We will neglect the last two terms in Eq. (2) (i.e. the interface and Pt spin resistances), since these are three orders of magnitude smaller than the first term. $\eta_s$ denotes the spin transfer efficiency from injector to detector and reads

$$\eta_s = \frac{t_{Pt}}{l_s^2} \frac{A_{corr}}{I_{ac} R_{det}} \frac{(e^{t_{Pt}/l_s} + 1)(e^{2t_{Pt}/l_s} + 1)}{(e^{t_{Pt}/l_s} - 1)^3}$$  \hspace{1cm} (3)

with $R_{det}$ the electrical resistance of the Pt detector strip. In order to isolate the effect of the magnon BEC on the spin resistance, we use the corrected voltage amplitudes $A_{corr}$ (see SI) of the magnon transport signal for the calculation of $\eta_s$ and eventually of $R_{YIG}$. 

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