Storage-recovery phenomenon in magnonic crystal

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The phenomenon of wave trapping in an artificial crystal with limited number of periods is demonstrated experimentally using spin waves in a magnonic crystal. The information stored in the crystal is recovered afterwards by parametric amplification of the trapped wave. The storage process is based on the excitation of standing internal crystal modes and differs principally from the well-known phenomenon of deceleration of light in photonic crystals.

The deceleration or even the full stop of light due to the modification of the light dispersion in photonic crystals (PCs) has been a topic of intense experimental and theoretical studies over the last decade [1–4]. A wave of light propagating through a PC couples with the internal standing PC mode and generates a slow light mode. In terms of the dispersion characteristics this means that the slope of the dispersion curve decreases at the edges of the band gaps which results in an extremely small value of the group velocity. It has been demonstrated that the slow light can be used for time-domain processing including buffering (storage and recovery) of optical signals as well as for an enhancement of nonlinear effects due to the spatial compression of optical energy [3, 4].

Magnonic crystals (MCs) are the magnetic counterpart of photonic crystals which operate with spin waves, i.e. the collective oscillations of the spin lattice of a magnetic material [5–13]. A wide range of parameters, which determine the spin-wave characteristics, can be periodically modulated to form the MC. This, as well as the possibility of fast dynamic control of these parameters [14, 15] make MCs promising candidates for the transfer and processing of information in the GHz frequency range. However, in spite of the considerable recent progress in MCs studies, neither spin-wave deceleration nor storage-recovery of a spin-wave carried signal has been demonstrated yet. This may be due to the spin-wave damping which allows fabrication of MCs comprising usually not more than 20 periods (see Ref. [10] and references therein). The small number of periods implies that the slope of MC dispersion does not become zero at the edges of the magnonic band gap in contrast to light dispersion at the edge of photonic gaps. Hence, rather than vanishing, the group velocity of spin waves only slightly decreases at the gap edges. This makes the realization of storing a signal in a MC using the slow spin-wave mode questionable.

As an alternative solution, in this Letter we show that the storage-recovery phenomenon can be successfully realized in an artificial crystal with a limited number of periods by the use of an internal standing mode of the crystal. This mode is excited by the incident spin wave and conserves oscillation energy after the propagating wave has left the MC area. Upon subsequent parametric amplification the internal mode irradiates part of its energy back into the propagating spin wave allowing the coherent restoration of the stored microwave signal. The restoration occurs at the edges of the magnonic crystal band gaps in narrow (1.2 MHz) frequency windows coinciding with the local minima of the spin-wave group velocity.

The magnonic crystal used in our experiment had been produced in the form of a stripe of a low-damping magnetic insulator (5.1 µm-thick yttrium iron garnet (YIG) film) with an array of parallel grooves chemically etched into its surface (see Fig. 1(a)) [11]. The array comprises ten 300 nm-deep and 30 µm-wide grooves placed 270 µm apart (lattice constant a = 300 µm). The bias magnetic field is applied along the stripe in order to arrange conditions for propagation of backward volume magnetostatic spin waves (BVMSW) [16]. These waves were previously found to be excellent signal carriers for one-dimensional magnonic crystals. For example, it has been shown that even small regular distortions of the surface of a mag-
netic film result in the appearance of pronounced rejection bands in the BVMSW frequency spectrum [17]. The waves were excited and detected in the YIG film waveguide using microwave stripline antennas placed at equal distances from both ends of the grooved area and 8 mm apart from each other (Fig. 1(a)). Microwave power of 0.3 mW applied to the input antenna was sufficiently low to avoid any non-linear effects which could potentially influence the input spin wave and storage process. The measured transmission characteristics for the MC along with the one for the reference unstructured YIG waveguide are shown in the Fig. 1(b). Several band gaps where spin waves are not able to propagate are clearly visible.

The amplification of the signals stored in the magnonic crystal was realized by means of pulsed parallel electromagnetic pumping. Quantum-mechanically such a pumping represents a three-particle process [18, 19], in which one photon of the pumping electromagnetic field splits into two magnons having half the pumping frequency and opposite wavevectors. This phenomenon has been successfully used for spin-wave amplification, wavefront reversal, and for the recovery of a microwave signal stored as a thickness spin-wave mode of a ferromagnetic film (see review [16]). In our experiment a pumping microwave magnetic field oriented parallel to the bias magnetic field (see Fig. 1(a)) was concentrated in the grooved area of the YIG stripe by a dielectric resonator [20] having a resonance frequency of 14.424 GHz.

The storage-recovery experiment has been performed in the following way. A 100 ns-long microwave pulse of $f_s = 7.212$ GHz frequency is applied to the input antenna in order to excite a traveling spin-wave packet which propagates toward the output antenna. The time traces of the output signal are shown in Fig. 2(a). First, the output antenna receives a practically rectangular pulse without any delay, caused by a direct electromagnetic leakage from the input antenna at the time $t = 0$. Approximately 0.3 $\mu$s afterwards the pulsed signal was delivered to the output antenna by the traveling packet of the initially excited spin waves. Well after this took place we applied a 10 $\mu$s-long pumping pulse at the frequency of $f_p = 2f_s = 14.424$ GHz. This resulted in the appearance of an additional bell-shaped pulse at the output antenna. This is the restored signal.

The restoration mechanism used in our experiments is very common and has been already used to recover the signals stored in standing thickness spin-wave modes in plane magnetic films [21]. It is based on frequency selective parametric amplification of a stored wave or oscillation, which can have any physical nature. In a frequency degenerated multi-mode system this artificially excited stored mode is amplified simultaneously with modes from the thermal bath. The competitive interaction between these modes and the consequent process of saturation of the parametric amplification are responsible for the restored pulse characteristics. A qualitative analytical theory of the restoration process of this type is given in [22], while a quantitative theory is presented in [23, 24].

The measured and calculated dependencies of the restored signal power $P_R$ and of the recovery time $t_R$ on the pumping power $P_p$ are shown in Fig. 2(b). The presented data have been obtained with a delay between the applications of the input signal and the pump pulse of 0.5 $\mu$s (no qualitative difference was observed when this time delay was varied between 0.4 $\mu$s and 1.4 $\mu$s). The calculation has been performed using the analytical formulas from Ref. [22] for the same parameters (the relaxation frequency of the thermal mode is 3.7 MHz, of the stored mode 4.3 MHz, the difference between the thermal amplitude level $A_T$ and the critical level of amplification saturation $A_C$ is $\ln(A_C/A_T) = 10.25$). It can be seen that the measured and calculated recovery time $t_R$ decreases and the restored signal power $P_R$ increases with an increase in $P_p$. The reason for this behavior is that an increase in pumping power results in a stronger parametric amplification but also results in a faster saturation. The excellent agreement between the theoretical prediction and the experiment gives a solid support to our understanding of the nature of the restoration process in a magnonic crystal.
Completely new and specific for the magnonic crystal is the fact that the standing MC mode, which is used in the experiment for the signal storage, consists of two counter propagating waves with strictly coupled phases. The phase of the wave propagating towards the output antenna \( \varphi_s \) is determined by the phase of an applied microwave signal \( \varphi_p \). The phase of the counter-propagating wave \( \varphi_{-k} \) is also \( \varphi_s \) and is due to the reflection from the Bragg lattice. Importantly, the parallel pumping, as a parametric process, also couples two counter-propagating waves. The sum of the phases of these two modes is defined by the phase of the pump \( \varphi_p = \varphi_{+k} = \varphi_{-k} + \pi/2 \) \[18, 19\]. Thus, the restoration process in a magnonic crystal combines two different mechanisms coupling two counter-propagating waves and the phase conditions for both these mechanisms should be met simultaneously.

As a result the characteristics of the restored pulse must be influenced by the phase shift between the signal wave and the pumping.

Indeed, we have experimentally registered the strong variation in the bias field in this case results in the variation of the spin-wave wavenumber, and therefore Fig. 3(a) is practically a reminiscent copy to Fig. 1(b) where the transmission characteristics of the magnonic crystal is shown for a fixed field. We used the transfer matrix approach \[7, 17\] to model the field dependence of the spin-wave transmission through the magnonic crystal. As seen in Fig. 4(a), the simulated characteristics are in good agreement with the experiment (parameters for the simulations were taken from \[4\]).

We also calculated the spin-wave group velocity \( v_{gr} \) and compared it with the experimental data \[22\]. One clearly sees from Fig. 4(a) that both the measured and the calculated group velocities decrease at the edges of the band gaps where the slope of spin-wave dispersion decreases. This decrease is only up to 15 percent and cannot be used in a slowing down approach to store information for a reasonably long time as in the case of photonic crystals \[4\].

However, as one can see from Fig. 4(c), the maxima of the restored pulse well correlate with the minima of the group velocity. This means that the recovery process and consequently the signal storage are efficient only at the edges of the band gaps \[20\]. It is especially surprising

FIG. 3. (Color online) Dependence of the restored signal power on the input signal phase. The signal and pump generators were locked-in.

FIG. 4. (Color online) (a) Transmission of the spin-wave signal as a function of bias magnetic field (open circles - experiment, line - theory). (b) Dependence of the group velocity \( v_{gr} \) on the field \( H \). The slight decrease in \( v_{gr} \) at the edges of the band gap is visible. (c) Measured restored signal power \( P_R \) as a function of field \( H \). One sees that the restored signal is visible only at the edges of the band gaps.
that the field width of the regions where the restoration takes place (see inset in Fig. 4c) is very narrow (approximately 0.4 Oe) and is comparable with the ferromagnetic resonance linewidth (0.5 Oe in our case). (Please note that the frequency resolution of the experiment is given by the spectral width of the pump signal of 0.1 MHz which corresponds to 0.03 Oe on the bias field scale.)

The appearance of the restored pulse at the band gap edges can be understood in the frame of the proposed model assuming the storage of the spin-wave signal in the internal magnonic crystal mode. The efficiency of the excitation of this mode by the propagating spin wave is of crucial importance. It is clear that this efficiency is determined by the position of the input signal with respect to the MC’s band gaps. When the signal frequency lies between the band gaps no coupling between the standing and the propagating modes exists. In the opposite situation when the signal frequency lies inside of the band gap, the propagating wave will be fully reflected and no storage will occur again (the evanescent wave whose intensity decreases exponential inside the MC area will be formed here). In this case the spin-wave energy leaves the grooved area in a time interval smaller than the ratio of the double MC’s length to the spin-wave group velocity (under conditions of our experiment $\simeq 230$ ns). Therefore, the only possibility to effectively excite the standing MC mode is to tune the propagating wave frequency very close to the edge of the band gap, namely to one of the spin-wave group velocity minima.

Furthermore, the slower the outflow of the spin-wave energy from the area of the parametric amplification (given in general by the spin-wave group velocity) the higher the amplification rate [20]. That is why the amplification of the MC standing wave is maximal for the smallest group velocity of the propagating wave which is responsible for the outflow of the stored energy outside of the magnonic crystal area. This effect contributes additionally to the strong localization of the restored signals at the band gap edges.

In conclusion, we have demonstrated that spin waves can be stored in magnonic crystals. However, the deceleration of the propagating spin wave of up to 15 percent is not high enough for the information storage mechanism used in photonics. In contrary long-time coherent storage has been experimentally realized using the internal standing mode of the magnonic crystal. By means of further phase-sensitive parametric amplification the stored signal was recovered. The maximal recovery time was more than 9 $\mu$s while the propagation time of the spin waves through the sample was only 0.3 $\mu$s. The results presented here provide deeper understanding of the storage-recovery mechanisms in periodic lattices in general. Besides, they point to the potential possibility of utilization of magnonic crystals for buffering or storage of microwave information.

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[25] The group velocity $v_\text{gr}$ has been measured using a network analyzer and the frequency values has been recalculated to the magnetic field. The $v_\text{gr}$ oscillation are due to the beating of the spin-wave signal and the parasitic electromagnetic leakage between the antennas. The calculated $v_\text{gr}$ has been obtained from the phase of the MC transmission matrix. Note that the wave inside of the band gaps is imaginary and the notion of group velocity is not fully applicable to these areas.
[26] We also detect a restored signal at the field around 1850 Oe which is associated with the spin-wave thickness modes [22] and is visible in unstructured YIG film too.