Non-resonant wave front reversal of spin waves used for microwave signal processing

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Abstract

It is demonstrated that non-resonant (ωs ≠ ωp/2) wave front reversal (WFR) of spin-wave pulses (carrier frequency ωs) caused by pulsed parametric pumping (carrier frequency ωp) can be effectively used for microwave signal processing. When the spectral width Ωs of the signal is wider than the frequency band Ωp of signal amplification by pumping (Ωs ≫ Ωp), the non-resonant WFR can be used for the analysis of the signal spectrum. In the opposite case (Ωs ≪ Ωp) the non-resonant WFR can be used for active (with amplification) filtering of the input signal.

Some figures in this article are in colour only in the electronic version

The phenomenon of wave front reversal (WFR), wherein a propagating wave packet of a carrier frequency ωs can be reversed by external pumping of a carrier frequency ωp ≈ ωs, is well known in nonlinear optics and acoustics, where it is caused by a four-wave second-order parametric interaction [1]. For spin waves in magnetically ordered substances it is possible to realize WFR in a three-wave parametric process [2, 3] with conservation laws:

ωs + ωi = ωp,

k_s + k_i = k_p,

where k_p, k_s are the carrier wave vectors of the pumping and signal pulses and ω_i and k_i are the carrier frequency and wave vector of the ‘idle’ wave pulse formed as a result of the parametric interaction. When the pumping wave vector is much smaller than the carrier wave vector of the signal (k_p ≪ k_s) the generated ‘idle’ pulse is wave front reversed, i.e. k_i ≈ −k_s.

WFR of microwave spin-wave packets propagating in a thin ferromagnetic film is performed by applying a pulse of electromagnetic parametric pumping to the film [2, 4]. Previously, WFR of spin waves was realized when the pumping frequency was exactly twice as large as the carrier frequency of the incident spin-wave packet, i.e. ωp = 2ωs.

Here, we demonstrate that the phenomenon of non-resonant WFR, where the input signal frequency is not exactly equal to half of the pumping frequency (ωs ≠ ωp/2), opens interesting new possibilities for signal processing in the microwave frequency range. Spectrum analysis of microwave pulses using the non-resonant WFR process can be realized when the spectral width Ω_s = 2π/τ_s of the input signal pulse of duration τ_s is wider than the frequency band Ω_p of the signal amplification by the applied parametric pumping (Ω_s ≫ Ω_p).

In the opposite limiting case, when Ω_s ≪ Ω_p, the non-resonant WFR can be used for active (with amplification) filtering of input microwave signals.

A scheme of the setup used in our experiments is shown in figure 1. The input microwave signal pulse was converted by a microstrip antenna into a packet of dipolar spin waves propagating in a long (20 mm) and narrow (1.8 mm) 5 µm thick waveguide made of a ferrimagnetic yttrium iron garnet (YIG) film epitaxially grown on a gallium gadolinium garnet (GGG) substrate. A bias magnetic field was applied in the plane of the YIG film along the spin-wave propagation direction.
Thus, similar to the earlier experiment [2], the backward volume magnetostatic waves (BVMSW) were excited in the waveguide. The input BVMSW wave packets were excited by microwave pulses of the carrier frequency $\omega_p$, power $P_r = 0.25$ mW and duration varying from $\tau_r = 50$ ns to 100 $\mu$s.

The central part of the YIG waveguide was placed inside an open dielectric resonator (ODR), as is shown in figure 1. The ODR was used for supplying the pumping pulses at a fixed carrier frequency $\omega_p$. The pumping magnetic field was oriented parallel to the bias magnetic field, leading to parallel pumping conditions. Pumping pulses lasting from $\tau_r = 50$ to 500 ns and power of up to 5 W were supplied at time $\tau_d$. The parametric interaction of the signal wave packet with the pumping pulse, which has a carrier frequency close (but not exactly equal) to $\omega_p$, created a wave front-reversed wave packet, propagating in the opposite direction. This wave packet was detected at the input antenna at the time $2\tau_d + \tau_p$ after the input signal was launched. For further details on the setup see [5].

Figure 1. Schematic experimental setup used for the non-resonant WFR investigation. (Colour online.)

The simplified formalism previously developed in [4] was used for the theoretical analysis of the observed non-resonant WFR process. In the framework of this formalism, performed in wave vector space for the case of strong pumping, the $k$-th Fourier component of the front-reversed spin-wave pulse at the time $\tau = 2\tau_d + \tau_p$, when this component has a maximum value, can be approximately evaluated as

$$C_{-k} \approx C_{i0} \cdot \exp \left[ (V_k h_p - \Gamma) \tau_p - \Gamma (2\tau_d + \tau_p) \right] \left( \frac{\Delta \omega_k}{\Omega_p} \right)^2, \quad (2)$$

where $C_{i0}$ is the $k$-th Fourier component of the input (signal) spin-wave pulse, $h_p$ is the amplitude of the pumping magnetic field, $V_k$ is the coefficient of parametric coupling between pumping and spin waves defined in [4], $\Gamma$ is the spin-wave relaxation parameter, $\Delta \omega_k = \omega_k - \omega_p/2$ is the detuning between half of the pumping frequency and the frequency $\omega_k$ of the $k$-th Fourier component of the signal and

$$\Omega_p = \sqrt{2V_k h_p/\tau_p} \quad (3)$$

is the bandwidth of parametric amplification of the signal by pumping (see [4] for details).

It is clear from (2) that the amplitude $C_{-k}$ of the front-reversed spin wave increases with an increase in the pumping magnetic field $h_p$ and is at maximum for $\Delta \omega_k = 0$, which is the case of exact parametric resonance. One can see in (3) that the parametric amplification bandwidth $\Omega_p$ is determined by the pumping pulse amplitude $h_p$ and duration $\tau_p$.

As pointed out above, the analytic expression (2) is approximate, and is applicable only to a qualitative analysis. For a more accurate calculation of the power $P_r$ of the front-reversed output pulse we performed a numerical summation of the Fourier components (2) $P_r(t) = |\sum C_{-k}(t)|^2$, taking into account fast phase oscillation and the accurate dispersion relation for BVMSW [6]. The results of this more accurate approach are shown as theoretical curves in the figures of this paper.

Below, we shall consider two limiting cases of the non-resonant WFR: the broadband input signal case, when $\Omega_s \gg \Omega_p$, and the narrow-band input signal case, when $\Omega_s \ll \Omega_p$.

**Broadband input signal regime, $\Omega_s \gg \Omega_p$**

The spectral picture of the non-resonant WFR in the case of broadband input signal is shown in the inset of figure 2. The parametric amplification bandwidth is narrow (it is equal to the delta function $\delta(\omega - \omega_p/2)$ in the limiting case), thus only one input signal spectral component $C_{i0}$ with the frequency equal to half of the pumping frequency $\omega_p/2$ can be amplified by the pumping. The amplitude of the $C_{-k}$ component in the reversed pulse is proportional to the amplitude of the corresponding component $C_{i0} \mid_{\omega_k = \omega_p/2}$ of the input signal. The process looks like ‘sampling’ of the input signal spectrum $C_{i0}$ by the spectrally narrow pumping, as illustrated in the inset of figure 2. As a result, the spectrum of the input signal can be directly extracted by the non-resonant WFR process. The carrier frequency of the output reversed signal in this case is equal to $\omega_p/2$.

Figure 2. Experimental (symbols) and calculated (line) dependences of the reversed signal power on the input signal frequency in the situation close to the broadband input signal regime ($\Omega_s/\Omega_p \approx 3.5$). Inset: the spectrum of the input signal (left blue line) and the band of parametric amplification (right green line). (Colour online.)

The results of comparison between the experimentally measured (squares) and theoretically calculated (solid line) power of the reversed pulse as a function of the carrier
frequency of the input (signal) wave packet are shown in figure 2 for the case when the signal duration $\tau_s$ was 50 ns, pumping duration $\tau_p$ was 50 ns and the pumping field multiplied with the coupling coefficient was $h_p V_1/2\pi = 5$ MHz. The ratio of the characteristic bandwidths was $\Omega_s/\Omega_p \approx 3.5$, and, therefore, the situation close to the broadband input signal regime of WFR was realized. The bias magnetic field was equal to 1020 Oe, the pumping frequency was $\omega_p/2\pi = 9420$ MHz, the spin-wave relaxation parameter was $\omega_\pi/2\pi = 0.42$ MHz and the delay time between the signal and pumping was $\tau_d = 65$ ns.

It is clear from figure 2 that theory is in excellent agreement with experiment.

We would like to mention that the non-resonant three-wave parametric interaction for the case $\Omega_s \gg \Omega_p$ was undertaken in a recent paper [7]. However, the interaction process used in [7, 8] involves several different spin-wave groups and, as a result, the information about the duration, and shape of the input signal pulse was lost, and the amplitude of the obtained ‘spectrum’ of the input pulse was considerably modified. This is not the case in the results reported here.

Narrow-band input signal regime, $\Omega_s \ll \Omega_p$

The opposite limiting case of a narrow-band input signal regime of WFR is realized when the input signal pulse is sufficiently long (or/and when the pumping pulse is sufficiently short and strong), i.e. when the condition $\Omega_s \ll \Omega_p$ is fulfilled. It is clear that in this case the spectral width of the signal is much smaller than the band of frequencies amplified by pumping (see the inset of figure 3). The amplitude of the reversed pulse is determined by the amplitude of the main harmonic of the input signal, by the detuning ($\omega_s - \omega_p/2$), and by the parametric amplification bandwidth $\Omega_p$.

The measured (symbols) and theoretically calculated (lines) power of the reversed pulse as a function of the carrier frequency of the input signal obtained for two different pumping pulses are compared in figure 3. In both cases the theoretical and experimental curves were normalized by the corresponding maxima of experimentally measured power of the reversed pulse. The duration of the input signal pulse was $\tau_s = 100 \mu s$. The bias magnetic field was 950 Oe and the pumping carrier frequency was $\omega_p/2\pi = 9408$ MHz.

We performed experiments for two pumping amplitudes and durations. In the first case (circles and solid line in figure 3) the duration of the pumping pulse $\tau_p$ was 500 ns and the pumping field multiplied with the coupling coefficient was $h_p V_1/2\pi = 1$ MHz (corresponding to the pumping power of $P_p \approx 8$ mW). The characteristic ratio $\Omega_s/\Omega_p$ was equal to 0.01 for these conditions. In the second case (squares and dashed lines in figure 3) the parameters were $\tau_p = 100$ ns and $h_p V_1/2\pi = 5$ MHz (corresponding to $P_p \approx 200$ mW), and the characteristic ratio $\Omega_s/\Omega_p$ was equal to 0.0025. Thus, a narrow-band input signal regime of the WFR process was realized for both pumping pulses.

The curves presented in figure 3 can be interpreted as the amplitude–frequency characteristics of an active parametric pass-band microwave filter i.e. tunable by a pumping filter with an amplification of the filtered signal. The bandwidth and the gain factor of the filter can be tuned by varying the duration and the power of the applied pumping pulse. Indeed, for the first pumping pulse (circles in figure 3) the pass-band of the active filter at the $-3$ dB level is equal to 6.4 MHz and for the second pumping pulse (squares in the figure) this pass-band is 2.4 MHz. Note that the gain coefficient of the active filter is substantially higher for the first pumping pulse than for the second one, but the curves shown in figure 3 were normalized. It should also be mentioned that in order to achieve good quantitative agreement between the theory and experiment shown in figure 3 it was necessary to perform the full summation of all the Fourier components of the interacting pulses and release the condition of strong pumping. The approximate analytic formula, equation (3), describes the active filtering process only qualitatively. Nevertheless, it correctly predicts the decrease in the filter pass-band with the increase in the power and decrease in duration of the pumping pulse.

In conclusion, we explicitly demonstrated that non-resonant WFR for dipolar spin waves can be effectively used for spectral analysis and active filtering of pulsed microwave signals. We believe that signal processing devices based on parametric interaction of spin waves in magnetic films will find important applications in microwave technology.

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