Spin-wave self-modulation instability in a perpendicularly magnetized magnonic crystal

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Abstract. Self-modulation instability of microwave spin waves monochromatically excited in a periodic magnetic film structure, a magnonic crystal, has been observed. The phenomena occurs only at the frequencies corresponding to the band gaps of the spin-wave spectrum of the magnonic crystal. Depending on the frequency within the band gap the nonlinear waveforms have a shape of bright or dark pulses.

1. Introduction

During last years a great attention has been given to the study of tunable materials [1] both for their properties and for the high number of potential applications. Magnonic crystals (MCs) are new class of tunable materials with the periodically modulated magnetic properties where spin waves (SW) can propagate [2-5]. Reviving interest to such structures is stimulated by fundamental and applied researches. In particular, the periodic magnetic waveguides were used for development of the tunable resonators and filters, signal-to-noise-enhances, logic elements, sensors and other [6-13]. Microwave properties of such structures can be tuned in a wide frequency range with magnetic field. Most attention was given to study the linear properties of MCs and possibilities of their reconfiguration [2, 14]. However, the magnonic crystals produced from the ferrite films may demonstrate strong nonlinearity for high spin wave power [7].

The phenomenon of modulation instability that appears due to four-wave parametric process is typical of many nonlinear media (see, e.g.,[15]). The modulation instability is commonly classified by two types, spontaneous and induced instability [15, 16]. Induced instability arise from the interaction of two initial monochromatic signals owing to nonlinearity of the medium. Spontaneous modulation instability (called also “self-modulation instability”) appears due to the decay of an initial monochromatic signal into waves with close wave numbers. As is known, both types of modulation instability can lead to the formation of envelope solitons.

In this work, we report the first experimental study of self-modulation spin-wave instability in perpendicularly magnetized magnonic crystals.
2. Experimental investigation

The magnonic crystal was fabricated from an yttrium-iron garnet (YIG) film with chemical etching. The fabricated sample of the magnonic crystal had a width of 2 mm and a length of 30 mm. The YIG film with thickness of 9 µm and saturation magnetization of 1750 Gs was grown by liquid-phase epitaxy on a gadolinium-gallium garnet substrate. The half-width ΔH of the ferromagnetic resonance curve of the YIG film was 0.55 Oe measured for the frequency of 4500 MHz. The film had free surface spins. It was confirmed with preliminary experimental research using the methods of magnetic well and spin-wave spectroscopy [17-20].

To avoid possible unwanted reflected spin waves, the edges of the MC were cut at an angle less than 45°. The experimental periodic structure had a period Λ of 400 µm, a groove length of 50 µm, and a groove depth of 1.5 µm.

A delay line structure was used for the measurements. Spin waves were excited and received using short-circuited input and output microstrip antennas having a length of 2 mm and a width of 50 µm. The distance between the antennas was 5.2 mm. Thus, there were 13 periods of the structure between the transmitting and receiving antennas. The experimental device was placed between poles of an electric magnet generating a uniform magnetic field with strength of 3050 Oe. The field was directed perpendicular to the plane of the magnonic crystal. Such mutual orientation of the field and the propagation direction of spin waves corresponds to the excitation of forward volume spin waves in the magnonic crystal. For this magnetic field direction, the nonlinear self-interaction coefficient N is positive.

The experiment was carried out in several stages. First, the transmission characteristics of spin waves in a knowingly linear regime of their excitation and propagation were studied. The measured amplitude–frequency characteristic is shown by solid lines in figure 1. As is seen, the spin-wave spectrum of the magnonic crystal has pass bands and stop bands (band gaps) with strong group velocity dispersion and high damping of spin waves. The stop bands are formed due to Bragg resonances.

The numerical calculation of the amplitude–frequency characteristic was performed with the use of the method similar to that described in [17, 18], i.e., in terms of the transmission matrix. The calculation did not take into account the losses for the excitation and reception of the spin waves. Nevertheless, the plots indicate good quantitative agreement between measured and calculated frequencies of the stop bands.

![Graph](image)

**Figure 1.** The experimental (solid line) and theoretical (dotted line) transmission characteristics of magnonic crystal. Dashed line shows the frequency dependence of the spin-wave dispersion coefficient near the frequency of the first Bragg resonance.
At the second stage of the experiments we studied the possibility of the emergence of self-modulation instability of the spin-waves propagating in the magnonic crystal. We measured the spectra and envelopes of the output microwave signal under the systematic variation of the power and frequency of the input monochromatic signal. The results show that the spin-wave instability in the magnonic crystal emerged in a threshold manner at $P_{in} = 18$ dBm for frequencies within high-frequency slope of the stop band. For these parameters, low-amplitude satellites emerged in the spectrum of the output signal. The amplitude of these frequency harmonics increased and the spectrum was enriched with an increase in the input power. The frequency region of the self-modulation instability was also broadened.

![Figure 2](image-url)

**Figure 2.** Frequency spectra (left) and the respective envelopes (right) of the output signal measured for various frequencies of input microwave signal: (a) $f_{in} = 3680$ MHz, (b) $f_{in} = 3681$ MHz, (c) $f_{in} = 3682$ MHz.
The shape of output waveform depends not only on the power, but also on the frequency of the input microwave signal. Figure 2 exemplifies the frequency spectra (left panel) and the corresponding envelopes of the output microwave signal (right panel) measured for frequencies near the first Bragg resonance for $P_{in} = 20 \text{ dBm}$.

Figure 2.a shows the measured results for the frequency of the input signal of $f_{in}=3680 \text{ MHz}$ and negative dispersion coefficient (see point 1 on figure 1). In this case the output bright pulses were observed. This agrees with the theoretical concepts of the Lighthill criterion for solitons ($D\cdot N<0$) [14]. In the region where the dispersion coefficient changes its sign (see point 2 on figure 1) the pairs of bright and dark pulses were observed (see figure 2.b). For areas with a positive dispersion coefficient (see point 3 on figure 1) and $D\cdot N>0$ the formation of dark pulses was observed as is shown in figure 2.c.

It should be mentioned that the self-modulation instability was observed also near the second and the third stop bands of the magnonic crystal. Outside the stop bands, i.e., in the regions where the dispersion coefficient is low, the inherent modulation instability was not observed in the entire power range of the experimental setup.

3. Conclusions

In conclusion, self-modulation spin-wave instability in a magnonic crystal has been studied for the first time. The formation of periodic bright and dark spin-wave envelope soliton trains has been detected at the edges of stop bands.

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References

[1] Ye Z. G. 2008 Handbook of advanced dielectric, piezoelectric and ferroelectric materials: Synthesis, properties and applications (Elsevier).
[2] Vogel M, Chumak A V, Waller E H, Langner T, Vasyuchka V I, Hillebrands B, Freymann G 2015 Nature Physics 11 487–491
[3] Kruglyak V V, Demokritov S O, Grundler D 2010 J. Phys. D: Appl. Phys. 43 264001
[4] Nikitov S A, Tailhades Ph, Tsai C S 2001 JMMM 236 320-330
[5] Ustinov A B, Grigorieva N Y, Kalinikos B A 2008 JETP Lett. 88(1) 31–35
[6] Gouzerha J, Stashkevich A A, Kovshikov N G, Matyshev V V, Desvignesa J M 1991 JMMM 101(1) 189-190
[7] Ustinov A B, Drozdovskii A V, Kalinikos B A 2010 Appl. Phys. Lett. 96 142513
[8] Grishin S V, Beginin E N, Dulin Y V, Nikitov S A, Sharaevskii Y P 2012 Tech. Phys.Lett. 38(7) 638-641
[9] Zhu Y, Chi K H, Tsai C S 2014 Appl. Phys. Lett. 105 022411
[10] Grishin S V, Beginin E N, Sharaevskii Yu P, Nikitov S A 2013 Appl. Phys. Lett. 103 022408
[11] Grishin S V, Beginin E N, Morozova M A, Sharaevskii Yu P, Nikitov S A 2014 J. Appl. Phys. 115 053908
[12] Inoue M, Baryshev A, Takagi H, Lim P B, Hatafuku K 2011 Appl. Phys. Lett. 98 132511
[13] Kryshtal R G, Medved A V 2012 Appl. Phys. Lett. 100 192410
[14] Nikitin A A, Ustinov A B, Semenov A A, Chumak A V, Serga A A, Vasyuchka V I, Hillebrands B 2015 Appl. Phys. Lett. 106(10) 102405
[15] Remoissenet M 1996 *Waves Called Solitons: Concepts and experiments* (Springer-Verlag, Berlin).

[16] Kivshar Y S, Agrawal G 2003 *Optical solitons: from fibers to photonic crystals* (Academic press).

[17] Soohoo R F, 1965 *Thin Magnetic Films* (Harper and Row).

[18] Gurevich A G, Melkov G A, 1996 *Magnetization oscillations and waves* (CRC press).

[19] Kalinikos B A, Kovshikov N G, Kolodin P A, and Panchurin I P 1985 *Electronn. Tekn. Ser. Elektr. SVCh* **10** 53

[20] Kalinikos B A, Slavin A N, 1986 *J. Phys. C: Solid State Phys.* **19** 7013

[21] Seshadri S R 1986 *J. Appl. Phys.* **60** 1758

[22] Chumak A V, Serga A A, Wolff S, Hillebrands B, Kostylev M P 2009 *Appl. Phys. Lett.* **94** 172511