Nonlinear Microwave Devices Based on Magnonic Crystals

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Abstract

A novel multifunctional nonlinear microwave spin-wave device utilizing a YIG-film magnonic crystal have been designed, fabricated and tested. A principle of operation of the device is based on a nonlinear frequency shift and a nonlinear damping of the carrier spin waves propagating in the magnonic crystal. The device performs several functions of microwave signal processing, namely, enhancement of signal-to-noise ratio and limiting or suppression of high-power signals.

1. Introduction

Periodic magnetic film structures fabricated from high-quality epitaxial yttrium iron garnet (YIG) films could find application for development of spin-wave (SW) devices for microwave signal processing [1]. In recent years there is a strong renewed interest to such structures that is stimulated by fundamental and applied investigations. Artificially created periodic magnetic film structures, which are often called as magnonic crystals (see e.g. [2-4] and literature therein) may be considered as a class of metamaterials. Such metamaterials can be left to stand too long in a wide frequency range of the magnetic field.A survey of the state-of-the-art of SW devices shows that a wide variety of linear SW devices based on both regular and periodic YIG film waveguides have been designed and investigated during the past three decades or so (see e.g. [5,6]). In particular, the periodic waveguides were used for development of resonators, filters, delay lines, and directional couplers [7,8]. In contrast, nonlinear SW devices have been developed using regular waveguides only [5-10]. In this paper we present a novel nonlinear microwave magnonic device which performs several functions of microwave signal processing, namely, enhancement of signal-to-noise ratio, limiting or suppression of high-power signals, and power-dependent phase shift.

2. Design and Fabrication

The one-dimensional magnonic crystal was fabricated from a regular 12 μm thick, 2 mm wide, and 30 mm long YIG film waveguide by chemical etching the grooves on the film surface. The initial waveguides were cut from a lager single-crystal YIG film grown on 500 μm thick gadolinium gallium garnet (GGG) substrate.

The waveguides were tested with the “magnetic well” setup which provided the local nondestructive monitoring of the magnetic-film magnetic properties. The high-quality YIG-film waveguide which demonstrated the narrowest ferromagnetic resonance line-width of 0.6 Oe at 4.5 GHz and homogeneous magnetic characteristics in the film plane was chosen for the further fabrication of the magnonic crystal. A conventional ultraviolet photolithography was used to form the mask on the YIG-film surface. Then hot 160 °C orthophosphoric acid was used to etch the grooves in the unprotected areas of the film surface.

The grooves were etched along the full length of the YIG-film waveguide. They were transversely oriented with respect to the long side of the waveguide. The grooves had a depth of 2 μm, a width of 50 μm, and a spatial period of 400 μm. In other words, the magnonic crystal lattice constant was 400 μm.

Two 50 μm wide and 2 mm long short circuited microstrip transducers were used to excite and to detect spin waves in the magnonic crystal (see Fig. 1(a)). The distance between the transducers was 7.6 mm. They were fed by the microstrip transmission lines of 50 Ω characteristic impedance. The microstrip structure was fabricated on 500 μm thick alumina substrate by conventional photolithography.

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Another side of the substrate was grounded. Note that the distance between the transducers was chosen to be divisible by the groove spatial period. Therefore, the microstrip transducers were positioned in the middle between the grooves and 19 grooves were situated between the transducers. The magnonic crystal was magnetized by a spatially-uniform external magnetic field directed in the plane of the YIG/GGG structure along the grooves so as to provide a condition for propagation of the magnetostatic surface spin waves.

3. Results and Discussion

Fig. 1(b) shows fragments of two typical amplitude-frequency characteristic (AFC) of the device. They were measured for the bias magnetic field $H = 1210$ Oe for the relatively low input microwave power of 0.5 mW corresponding to linear SW propagation, and for the relatively high power of 90 mW. The well-pronounced dips in the characteristics correspond to the stop-bands for the microwave signals transmission. For the particular device design the strong signal attenuation was observed for the second and the third stop-bands. The central frequencies of the experimental stop-bands measured in the linear device operating regime were in good agreement with a theory described in [11]. Frequency width Δf_S of the stop-bands measured at the level of -3 dB was about 6 MHz. An increase in the input power led to the shift of the AFC toward the lower frequencies and to the rise in the insertion loss within pass-bands due to the stable nonlinear effects. In particular, for $P_{in} = 0.5$ mW the center frequency of the second stop-band was $f_1 = 5464.5$ MHz and for $P_{in} = 90$ mW the center frequency was shifted to $f_2 = 5460.2$ MHz.

Fig. 1(c) shows by dots the experimental frequency shift of the second stop-band as a function of the input microwave power. A linear fitting of the data is given by a solid line. A slope of the dependence was found to be $N_P=4.7\times10^{-2}$ MHz/mW. It is clear that the nonlinear frequency shift was $\Delta f_{NL} = 4.3$ MHz for $P_{in} = 90$ mW, the value higher than $\Delta f_S/2$. Therefore, at the particular driving frequency f_1 the stop-band-like behavior was changed by the pass-band-like behavior with the increase in the power level. In contrast, at the frequency f_2 the pass-band-like behavior was changed by the stop-band-like behavior.

The above described behavior of the AFC allows one to realize different functions of microwave signal processing by choosing the carrier microwave signal frequency. Thus, the device performs the function of signal-to-noise ratio enhancement at f_1, whereas the device performs the function of high-power signal suppression at f_2. The experimental transmission characteristics corresponding to these operating regimes are shown in Fig. 2.

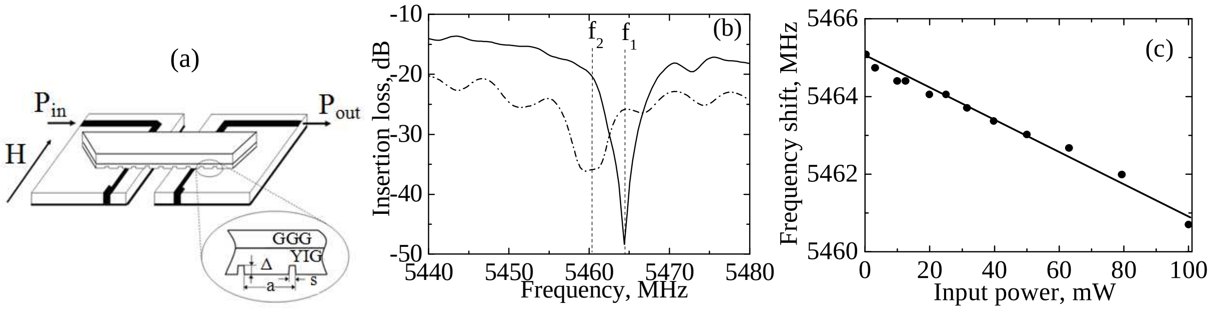

Fig. 1: (a) Scheme of the experimental sample (b) Fragments of the amplitude-frequency characteristics of the nonlinear magnonic device measured for input microwave powers of 0.5 mW and 90 mW. (c) Nonlinear frequency shift as a function of input power measured for the second stop-band.

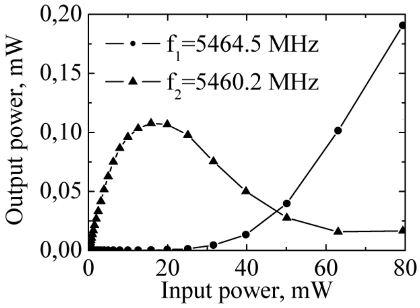

Fig. 2: Transmission characteristics of the magnonic device measured for the carrier frequencies of f_1 and f_2.

4. Conclusion

A novel multifunctional nonlinear magnonic device has been designed and its performance characteristics have been experimentally tested. The device performs several functions depending on the carrier frequency of the input microwave signal. The device could be used in various microwave systems as a signal-to-noise enhancer or a power limiter.

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References

[1] B. A. Kalinikos, *Dipole-exchange spin-wave spectrum of magnetic films*, in *Linear and nonlinear spin waves in magnetic films and superlattices*, edited by M. G. Cottam, Singapore: World Scientific Publishing Co., 1994.

[2] S. A. Nikitov, Ph. Tailhades, and C. S. Tsai, Spin waves in periodic magnetic structures – magnonic crystal, *Journal of Magnetism and Magnetic Materials*, vol. 236, pp. 320–330, 2001

[3] H. Puszkarski and M. Krawczyk, Plane-wave theory of three-dimensional magnonic crystals, *Physical Review B*, vol. 77, p. 054437, 2008.

[4] A. D. Karenowska, A. V. Chumak, A. A. Serga, J. F. Gregg, and B. Hillebrands, Magnonic crystal based forced dominant wavenumber selection in a spin-wave active ring, *Applied Physics Letters*, vol. **96**, p. 082505, 2010.

[5] J. D. Adam, L. E. Davis, G. F. Dionne, E. F. Schloemann, and S. N. Stitzer, Ferrite deices and materials, *IEEE Trans. Microwave Theory and Techniques*, vol. 50, pp. 721–737, 2002.

[6] W. S. Ishak, Magnetostatic wave technology: A review, *Proc. of the IEEE*, vol. 76, pp. 171–187, 1988.

[7] J. P. Castera and P. Hartemann, Adjustable magnetostatic surface wave multistrip directional coupler, *Electronic Letters*, vol. 16, pp. 195–196, 1980.

[8] B. Ustinov and B. A. Kalinikos, The power-dependent switching of microwave signals in a ferrite-film nonlinear directional coupler, *Applied Physics Letters*, vol. 89, p. 172511, 2006.

[9] B. Ustinov and B. A. Kalinikos, Ferrite-film nonlinear spin wave interferometer and its application for power-selective suppression of pulsed microwave signals, *Applied Physics Letters*, vol. 90, p. 252510, 2007.

[10] E. N. Beginin, S. V. Grishin, and Yu. P. Sharaevsky, Generation of a stationary train of chaotic soliton-like microwave pulses in self-oscillating ring systems with a ferromagnetic thin film, *JETP Letters*, vol. 88, pp. 647–650, 2008.

[11] K.-S. Lee, D.-S. Han, and S.-K. Kim, Physical origin and generic control of magnonic band gaps of dipole-exchange spin waves in width-modulated nanostrip waveguides, *Physical Review Letters*, vol. 102, p. 127202, 2009.