Performance characteristics of bistable active ring resonators based on ferrite films

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Abstract. A bistability phenomenon in a ring resonator consisting of a delay line on surface spin waves and a microwave amplifier has been experimentally investigated. It is shown that an enhancement of the gain coefficient above a specified value provides an appearance of a hysteresis at the resonator transmission characteristic. A frequency range of the bistability broadens due to an increase of the gain coefficient as well as the external magnetic field. While the value of the gain is limited from above by a transition of the ring into a self-oscillating regime, an increase in the magnetic field from 1150 Oe up to 3150 Oe provides an expansion of the frequency range of the hysteresis from 77 kHz to 185 kHz.

1. Introduction
Phenomenon of bistability of oscillations is known for a long time. It is observed in microwave magnetic [1-6], spintronic [7-9], magnetoelectric [10-13], microwave photonic [14, 15], optical [16-18], and other devices [19, 20]. In particular, microwave bistability was studied in details for magnetic oscillations in magnetic film resonators [1-9]. It is shown recently that the bistability phenomenon exists also in active ring resonators (ARRs) based on magnetic films [21]. The active ring operates below self-generation threshold as a resonator [22-24]. Thus, in the work [21] the experiments were carried out for the forward-volume spin waves which propagate in perpendicularly magnetized films and demonstrate a relatively strong nonlinearity and a positive nonlinear frequency shift. Above the self-generation threshold the active ring can generate a continuous wave microwave signal [25-27] as well as spin-wave solitons [28-33], fractals [34], and chaos [35-40].

In the present work, we have studied experimentally the bistability phenomenon for the surface spin waves (SSWs) which manifests itself due to a negative nonlinear frequency shift. We have investigated an opportunity for broadening the bistable hysteresis loop due to an increase in the loop gain coefficient as well as the bias magnetic field.

2. Experiment
For the experimental investigation, we used an active feedback ring that consisted of the spin-wave delay line, two directional couplers, the microwave amplifier and the variable attenuator (see Fig. 1).
The spin-wave delay line was fabricated with an epitaxial yttrium iron garnet (YIG) film of 5.54-µm-thick grown on a 500-µm-thick gadolinium gallium garnet substrate. The YIG film waveguide had a length of 20 mm and a width of 1.6 mm. The film had a saturation magnetization of $M_s = 1750$ G at room temperature and a ferromagnetic linewidth of 0.5 Oe at 5 GHz. Two 50-µm-wide and 2-mm-long microstrip transducers were placed over the YIG film at the distance of $d = 3.5$ mm from each other. Mutual orientation of the microstrip transducers and external magnetic field was chosen to satisfy the condition for the SSWs excitation in the YIG film. In order to achieve this, the film was magnetized to the saturation by uniform in-plane magnetic field directed in a parallel to the transducers. In the experimental setup water-cooled electromagnet was used for the variation of the bias magnetic field from $H = 1000$ Oe to $H = 3500$ Oe.

The initial test measurements demonstrated that all elements of the ARR, except the spin-wave delay line, operate in a linear regime in frequency range of 1–12 GHz. The microwave amplifier together with the variable attenuator were used to control the loop gain coefficient $G$. The response of the ring was measured through two 10-dB directional couplers using a vector network analyzer R&S ZVA 40. During the measurements the frequency of the microwave signal were swept in both directions upward and downward to observe the bistable behavior of the transmission characteristics. All measurements were performed for the power of $P_{in} = −20$ dBm applied to the ring input to ensure the linear operating mode at low gain values.

3. Results and discussion

Typical transmission characteristic of the ARR measured for the magnetic field of $H = 1150$ Oe is shown in Fig. 2 (a). Let us briefly explain the physics underlying the formation of the observed characteristic. The microwave signal comes in the ring through the input directional coupler and is applied to the input transducer, where it excites the SSW. During the propagation in the YIG film the wave accumulates a phase shift and attenuates. The microwave signal after the output transducer is applied into the microwave amplifier cascaded with the variable attenuator. This cascade is used for the compensation of the losses accumulated by the signal during the propagation in the ring elements (see Fig. 1). Finally, the part of the circulating signal is taken out of the ring by the output directional coupler and applied to the vector network analyzer. The other part of the signal continues its propagation in the ring. As a result, the ring becomes closed. The constructive interference of the circulating signals in the ring produces the periodic sequence of the resonant modes. The first resonant mode is observed at frequency of 5.04 GHz. The frequency range between two neighboring modes changes from 7.9 MHz to 5 MHz with the frequency increasing in accordance with the dispersion of the SSW in the YIG film. It corresponds to variation of the delay time in the YIG film from 126 ns to 200 ns. As soon as the spin-wave delay time exceeds significantly the delay in the other ring elements, the wavenumbers of the resonant modes are determined by $\beta_m = 2\pi m / d$  where $m$ is a number of the resonance. An increase in the loop gain leads to an increase in the transmission peaks amplitudes. Such a ring behavior is limited from above by a transition of the ring into a nonlinear regime and then into a self-oscillating regime.

Initially we investigate the influence of the gain coefficient on the transmission characteristic of the ARR. In the experiment a variation of the gain from -3 dB to -1 dB provides an increase in the Q-factor of the ARR from 4000 up to 25000 at the frequency of 5.078 GHz. This is the fascinating feature of the
ARR, which allows one to adjust the losses as well as the $Q$-factor by the change in the loop gain coefficient $G$. The resonant frequency demonstrating the lowest losses is shown by asterisk in Fig. 2(a). Further increase in the gain leads to the foldover effect of the resonant peak and an appearance of a bistable hysteresis loop. The threshold value of the bistability is observed to be 0.4-dB-below the self-oscillation. Fig. 2(b) shows the nonlinear transmission characteristic measured for the magnetic field of 1150 Oe at 0.01-dB-below the self-oscillation regime. The arrows show the direction of the frequency sweep during the measurement. The bistability hysteresis width is measured as frequency range where two stable states of the transmission characteristic coexist. The hysteresis width shown in Fig. 2 (b) is 77 kHz.

Let us clarify the physics of wave process in the nonlinear regime preceding the self-oscillation. At some certain value of the gain $G$ the circulating wave amplitude exceeds the nonlinear phenomena threshold. As the result the nonlinear phase shift $\varphi_{nl}$ of the SSW propagating in the stable nonlinear regime is accumulated in the YIG film. This phenomenon could be treated as a process of scattering of the initial wave on the waves with closely spaced wave vectors and could be qualitatively explained as follows. The magnetization precession is described by the Landau–Lifshitz equation. The total magnetization vector $\mathbf{M}$ is a sum of the static magnetization component $\mathbf{M}_0$ and the small-signal dynamic magnetization component $\mathbf{m}$, which determines the spin wave amplitude. As follows from the Landau–Lifshitz equation, the length of the vector $\mathbf{M}$ is conserved. Therefore, an increase in the amplitude leads to a decrease in the static magnetization $\mathbf{M}_0$ [41]. This is the cause of the downshift of the SSW dispersion and the appearance of the positive nonlinear phase shift $\varphi_{nl}$. The nonlinear phase shift provides the change in the resonance condition determined by $\beta_m d + \varphi_{nl} = 2\pi m$, which requires a frequency downshift of the resonant modes, where amplitude exceeds the threshold value. The bistability phenomenon occurs when the frequency shift exceeds more than half of the resonance linewidth. The increase in the amplitude leads to the broadening of the hysteresis loop.

In the second part of the work we investigate an opportunity for broadening the bistable hysteresis loop due to an increase in the bias magnetic field. The idea behind this research can be explained as follows. The nonlinear frequency shift is described by $\Delta \omega \equiv N|\mathbf{u}|^2$ where $N = \partial \omega(k,|\mathbf{u}|)/\partial |\mathbf{u}|^2 \bigg|_{k=0} \approx (\omega_m + \omega_a / 2) \omega_m / \omega - \omega$ is the cubic nonlinear self-interaction coefficient.

Figure 2. Transmission characteristic of the ARR on SSW for the magnetic field of 1150 Oe (a) and bistable behavior of the single resonant mode for the magnetic field of 1150 Oe (b), 2750 Oe (c), and 3150 Oe (d).
for the SSW, \( \omega(k, |u|^2) \) is the nonlinear dispersion relation for SSW, \( |u|^2 = |m|^2/(2M_o) \) is the dimensionless amplitude of the spin waves, \( \omega_H = \gamma \mu_0 H \), \( \omega_m = \gamma \mu_0 M \). \( \mu_0 = 4\pi \times 10^{-7} \) H·m\(^{-1}\) is the vacuum permeability, \( \gamma = 2.8 \times 10^{10} \) s\(^{-1}\)·T\(^{-1}\) is the gyromagnetic ratio of electron. As is seen from the expression describing the nonlinear coefficient, \( N \) grows with an increase in the bias magnetic field. This leads to an increase in the nonlinear frequency shift and expansion of the bistable hysteresis.

Nonlinear transmission characteristics of the single resonant mode measured for the bias magnetic field of \( H = 2750 \) Oe and \( H = 3150 \) Oe are shown in Fig. 2(c) and Fig. 2(d), respectively. One can see that an increase in the magnetic field broadens the bistable hysteresis. The hysteresis width achieves the value of 112 kHz for \( H = 2750 \) Oe and 1533 kHz for \( H = 3150 \) Oe. This behaviour has a good agreement with the theoretical description given above.

4. Conclusion
The bistability phenomenon in the ARR based on the SSW delay line has been experimentally investigated. Initially transmission characteristics of the ARR have been measured in order to investigate the influence of the gain coefficient. The variation of the gain from 3-dB-below to 1-dB-below the self-oscillation regime provides the increase in the Q-factor from 4000 to 25000. Further increase in the gain coefficient up to the certain threshold value leads to the foldover effect. The bistable hysteresis loop manifests itself at the resonator transmission characteristic for the gain coefficient above the threshold. The hysteresis width broadens with the increase of the gain coefficient. The value of the gain is limited by the self-oscillation regime. The maximum hysteresis width of 77 kHz has been measured for 1150 Oe at the gain of 0.01-dB-below the self-oscillation regime. In the second part of the work the investigation of the influence of the external magnetic field has been carried out. It is shown that the bistable hysteresis loop demonstrates additional broadening from 77 kHz to 153 kHz due to an increase in the external magnetic field from 1150 Oe up to 3150 Oe.

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