Theory for ferrite-ferroelectric active ring resonator

A.A. Nikitin, A.B. Ustinov, A.A. Semenov

Department of Physical Electronics and Technology, St. Petersburg Electrotechnical University
5 Professor Popov str., St.Petersburg, 197376, Russia
Fax: +7-812-234-99-83; email: and.a.nikitin@gmail.com

Abstract

A theory is developed for amplitude-frequency and phase-frequency characteristics of "active ring" resonator based on ferrite-ferroelectric layered structure. An active ring resonator (ARR) is a feedback circuit, the main parts of which are a ferrite-ferroelectric waveguiding structure and a microwave amplifier. It is shown that the amplitude-frequency (AFC) and the phase-frequency (PFC) characteristics of the ARR are determined by the dispersion law of the hybrid electromagnetic-spin waves (EMSWs) in ferrite-ferroelectric layered structure. It is demonstrated that the amplitude-frequency and phase-frequency characteristics of the active ring resonator are dual tunable. The dual tunability is achieved through changing the magnetic and/or electric bias fields. The quality factor of the resonance modes is controlled by the amplifier gain coefficient.

1. Introduction

Traditionally, in order to create tunable microwave (reciprocal and non-reciprocal) devices ferrite materials are used. In ferrite devices tunability is realized through the variation of a bias magnetic field. This "magnetic" tuning could be achieved in a very wide frequency range, but is relatively slow and is associated with a comparatively large power consumption. The other materials that can be used for the development of tunable microwave devices are ferroelectrics. In these materials frequency tuning is realized through the variation of the applied electric field that changes the dielectric permeability of the material. This "electric" tuning is possible in a narrow frequency range, but is relatively fast and is not power-consuming. It is clear, that combination of ferrite and ferroelectric materials in a layered structure provides the possibility of simultaneous "magnetic" and "electric" tuning of its microwave properties. In other words, combination of these two materials allows to combine the advantages of both tuning methods. In the recent works [1, 2] it was shown that combination of the ferroelectric and the ferromagnetic materials in the layered structure provides a possibility to create novel devices.

There are two effects in the hybrid ferrite-ferroelectric ("multiferroic") structures that give possibility of the combined electronic tuning. First of them relies on the phenomena of electrostriction and magnetostriction [1]. This effect occurs due to the interaction of the ferrite and ferroelectric crystal lattices. Electric field generates mechanical stress in the ferroelectric layer due to piezoelectric effect. This stress is applied to ferromagnetic layer due to mechanical contact. Magnetization in this layer is changed because of the magnetostriction effect. The operational characteristics of such multiferroic device are tuned by electric field.

Second of them is the effect of electrodynamics. Here, the tuning relies primarily on the hybridization of spin waves in the ferromagnetic layer and electromagnetic waves in the ferroelectric layer. Hybridized EMSWs combine properties of the electromagnetic and spin waves [2]. The second effect provides a strong coupling between ferromagnetic and ferroelectric layers that insures a comparatively big tuning range and small microwave loss, as compared to the first one.

2. Theoretical model

Spectrum of the EMSWs in the ferrite-ferroelectric layered structures was calculated in the work [2]. A typical example of such spectrum is given in Fig. 1a. The conditions for hybridisation between spin waves and electromagnetic waves are similar spatial structures of these waves and equal phase velocities, which correspond to intersection of their dispersion branches (Fig.1b). The dispersion characteristics of the hybrid EMSWs can be tuned by changing ferroelectric layer permittivity (Fig.1c).

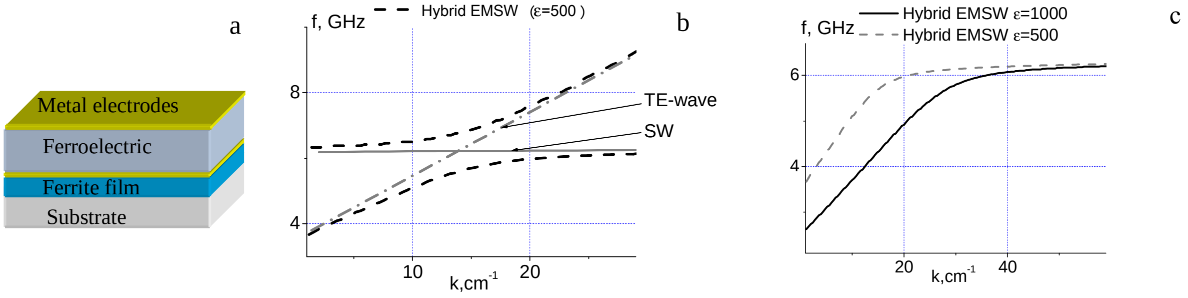

Fig. 1. (a) Ferrite-ferroelectric structure; (b) Hybridisation of electromagnetic (TE) and spin waves; (c) Electric tuning of the hybrid EMSW.

Active ring resonator based on the ferrite-ferroelectric layered structure was experimentally investigated in the work [3]. It was shown that such kind of resonator had very high Q factor. A schematic diagram the active ring resonator is shown in the Fig. 2a. The main elements of the ARR are a delay line based on ferrite-ferroelectric waveguide, a microwave semiconductor amplifier, a variable attenuator, and the microwave input and output directional couplers. All the elements are serially connected to each other. The variable attenuator is used to control the gain value and the amplifier is used to compensate losses in the feedback ring.

The resonance frequencies of such ring are defined by the dispersion law $\omega(k)$ of the hybrid EMSW (Fig. 2b). These conditions hold if the wave number k equals $2\pi n / d$, where n is the number of signal circulations in the ring and d is the ring length. For these discrete k-values it is easy to obtain the resonance frequencies using the dispersion law. In practice the parameter d may be taken as the distance between antennas because the main part of losses in the ring is introduced by the hybrid EMSW as such waves are much slower than electromagnetic waves in the connecting elements. It is clear that the distances between the neighbouring resonance frequencies and their frequency positions are determined by the dispersion law. It means that the AFC and PFC are tunable by the bias electric and magnetic fields.

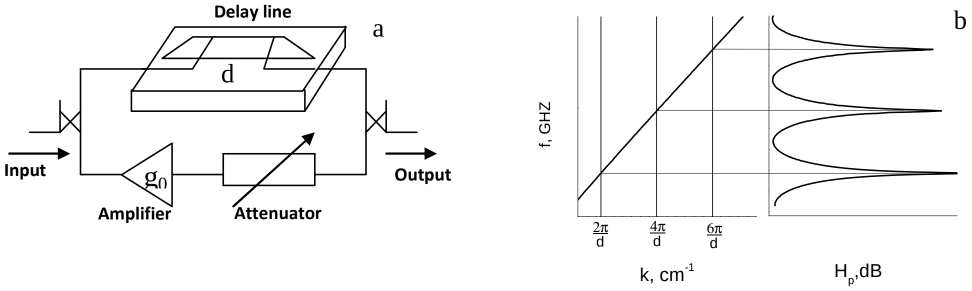

Fig. 2. (a) Block-diagram of an active ring resonator where g_0 is the gain coefficient; (b) Dispersion characteristic of the hybrid EMSW and amplitude-frequency response.

Let us find a complex transmission coefficient as a ration between the complex amplitudes of the output ($A_{out}(\omega)$) and input ($A_{in}(\omega)$) monochromatic signals. After some lengthy algebra we obtain:

$$\mathrm{H}_p = \frac{1}{2} \frac{e^{-\alpha(\omega)dn}}{ch(\alpha(\omega)d) - \cos(k(\omega)d)}, \tag{1}$$

which is the power transmission coefficient, and

$$\phi = arctg \left[\frac{\sum\limits_{n=1} \exp(-\alpha(\omega)dn)\sin(k(\omega)dn)}{\sum\limits_{n=1} \exp(-\alpha(\omega)dn)\cos(k(\omega)dn)} \right] \pm R\pi\,, \tag{2}$$

which is the phase-frequency characteristic of the active ring, where R=0,1,2... and $\alpha(\omega)$ is an effective damping parameter taking into account two competing factors: a spatial relaxation of the carrier wave and its spatial amplification.

3. Modelling results

Some results of the numerical calculations are shown in Fig. 3. AFC of the active ring based on ferrite-ferroelectric layered structure is shown in the Fig. 3a. Tuning value of the one resonance peak (Δf) due to changing ferroelectric permittivity is shown in Fig. 3b. Tuning covers all the frequency distance between two neighbourhood peaks. Tuning of the PFC is presented in Fig. 3c. It is important to note that the quality factor of every resonant peak is controlled by the amplifier gain coefficient and may achieve very big values.

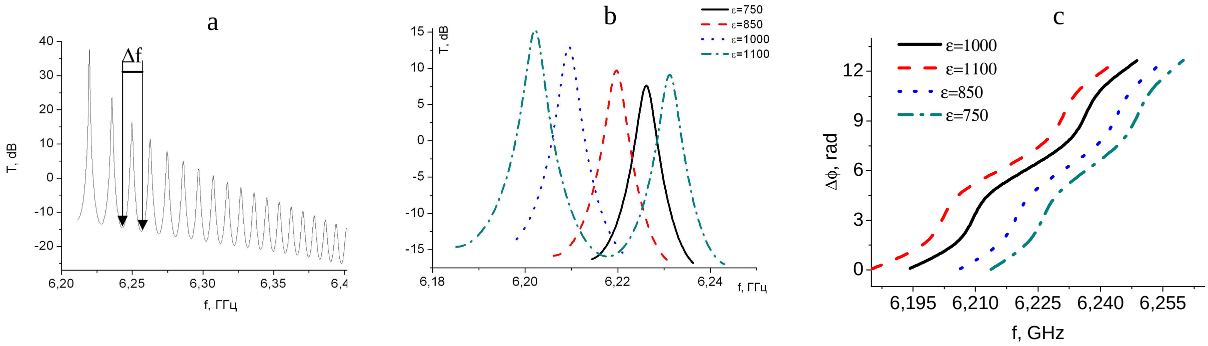

Fig. 3. (a) AFC of the active ring based on ferrite-ferroelectric structure; (b) and (c): AFC and PFC tunable through changing ferroelectric layer permittivity.

4. Conclusion

This work presented the theoretical investigation of active ring resonator based on the ferrite-ferroelectric layered structure. It was shown that the AFC and PFC of such resonator are dual tunable through changing the electric and magnetic bias fields. The Q factor of the resonator is controlled in a wide range by amplifier gain coefficient.

The work was supported in part by the Russian Foundation for Basic Research and the Ministry of Education and Science of the Russian Federation.

References

[1] G. Srinivasan, M. I. Bichurin, D. Viehland, et al., Multiferroic magnetoelectric composites: Historical perspective, status, and future directions, *J. Appl. Phys.*, vol. 103, p. 031101, 2008

[2] A. A. Semenov, S. F. Karmanenko, V. E. Demidov, et al., Ferrite-ferroelectric layered structures for electrically and magnetically tunable microwave resonators, *Appl. Phys. Lett.*, vol. 88, pp. 033503- 033503-3, 2006.

[3] A. B. Ustinov, G. Srinivasan, and B. A. Kalinikos, High-Q active ring microwave resonators based on ferrite-ferroelectric layered structures", *Appl. Phys. Lett.*, vol. 92, p. 193512, 2008.