

Dual-tunable multiferroic active ring filter for microwave photonic oscillators

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Abstract. A theoretical model of a microwave active ring filter based on a ferrite–ferroelectric layered structure serving as a waveguide for spin-electromagnetic waves is developed. An experimental prototype of the device is fabricated and characterized. The device is implemented as an active-ring resonator with a microwave amplifier and a ferrite-ferroelectric delay line. The resonance properties of this system are studied theoretically and experimentally. The results show dual control of central frequency of the filter with magnetic and electric fields. An effective Q-factor of 50 000 and tuning by 5 MHz with an electric field are achieved at 8 GHz.

Recent years an increased interest for fabrication and investigation of new composite and structured magnetic materials is observed (see e.g. [1]). Spin-electromagnetic waves (SEWs) propagating in artificial multiferroics composed in the form of ferrite and ferroelectric multilayers have a good potential for application in microwave electronics, including filters, phase shifters, etc. [2]. A distinctive feature of SEWs is that their spectrum can be electronically tuned with both electric and magnetic fields. Magnetic tuning is made through variation of the microwave magnetic permeability of the ferrite layer with variation of an external magnetic field. Electrical tuning is accomplished through the variation of the dielectric permittivity of the ferroelectric layer with the application of an electric field.

One of the promising multiferroic devices based on artificial multiferroic structure is an active ring resonator [3]. This device can be used as a *tunable* active ring filter for microwave photonic oscillators. Microwave photonic oscillators typically consist of optical and radiofrequency paths. The radiofrequency path usually contains a frequency selective element (microwave filter) based on a resonator having fixed resonance frequency [4]. In order to obtain frequency tunable microwave photonic oscillator a high-Q tunable microwave filter should be used. An active ring resonator based on ferrite-ferroelectric structure is good candidate as a frequency selective element of such oscillator due to high Q-factor [3, 5]. The most demanding applications are aerospace and avionics industries where the environment is harsh and the compactness, size and power consumption of a component are critical to the system design.

The purpose of this work is theoretical and experimental investigation of active ring filter performance characteristics. The layered structure consisted of yttrium iron garnet (YIG) and barium strontium titanate (BST) was used in the filter as a waveguide for SEWs. Dispersion characteristics of the SEWs are controlled by both bias magnetic and electric fields. Therefore, the central frequency of the filter can be controlled with both electric and magnetic fields.



A schematic view of the investigated filter is shown in Figure 1. The active ring contains a multiferroic delay line described by a complex propagation constant $K=k-i\alpha$ (where k is a wave number and α is a damping constant) and an amplifier characterized with a gain coefficient g_0 . Directional couplers are used for microwave signal input and output. A theoretical model of the active ring filter was developed using the SEW dispersion law [6]. A complex transmission coefficient was derived as a ratio of the input signal amplitude to the output signal amplitude, which was a result of superposition of infinite number of decaying waves circulating in the ring. Thus, formulae for amplitude-frequency characteristic and phase-frequency characteristic were obtained.

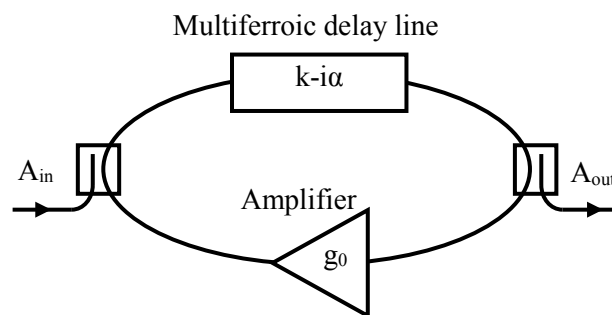


Figure 1. A diagram of the multiferroic active ring filter.

The trial calculations were carried out for a multiferroic bilayer consisting of a 15- μm -thick YIG film and a 500- μm -thick BST slab. A ring length was taken to be equal to a SEW propagation distance of 5 mm. A standard for YIG saturation magnetization $M=1750$ G was used. A BST dielectric permittivity was taken $\epsilon=1500$. A bias magnetic field H was 1500 Oe. Figure 2 shows results of the numerical simulation of the amplitude-frequency characteristic of the filter. Well pronounced peaks correspond to the resonant frequencies of the ring.

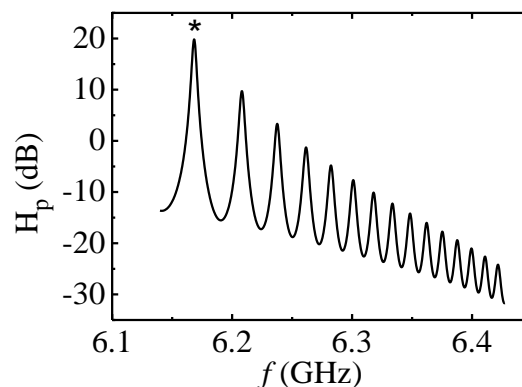


Figure 2. Amplitude-frequency characteristic of the active ring filter.

Let us analyze a pass band of the filter corresponding to the lowest-frequency resonant peak marked by asterisk in Figure 2. Figure 3(a) shows a frequency tuning of the central frequency with the change in ϵ . Note that it is due to SEW spectrum shift shown in Figure 3(b). We also studied magnetic field tuning. Variation of magnetic field from 1500 Oe to 2500 Oe changed the resonant frequency from 6.17 GHz to 9.13 GHz. Therefore, dual tuning of the multiferroic active ring filter was demonstrated.

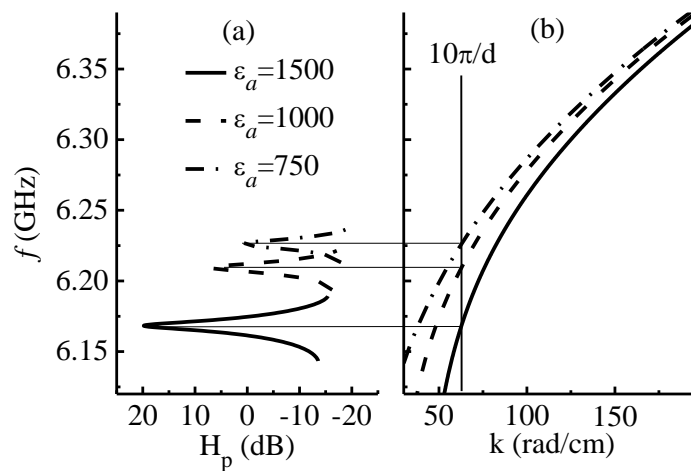


Figure 3. Fragments of theoretically calculated amplitude-frequency characteristics for lowest resonant peak of the active ring filter (a) and SEW dispersion curves (b) for different values of dielectric permittivity.

Experimental measurements were performed for an active ring filter structure similar to that reported in [3]. In consistent with figure 1, the main elements of the filter are a ferrite-ferroelectric delay line, a microwave amplifier, a variable attenuator, and the microwave input and output directional couplers. The ferrite-ferroelectric structure utilized in the delay line was composed of a 5.5 μm thick, 2 mm wide, and 40 mm long single-crystal YIG film and a 500 μm thick, 10 mm wide, and 5 mm long ceramic BST slab. One surface of the slab was covered by 50 nm thick chromium electrode. Such a thickness for the chromium electrode was much smaller than the skin depth for the operating frequencies. A copper electrode with thickness of 5 μm covered the other surface of the BST slab. Two 50 μm wide and 2 mm long short circuited microstrip antennas were used in order to excite and receive waves in the layered structure. The distance between the antennas was taken to be 8 mm. The antennas were fed by the microstrip transmission lines of 50 Ω characteristic impedance. The microstrip parts were fabricated by conventional photolithography on grounded alumina substrates with thickness of 500 μm . The YIG film stripe was positioned over the antennas with the YIG film side in contact with the antennas. The BST slab was pressed from below to the surface of the YIG film so that the chromium covered side was in contact with the film.

In the experiments ϵ was changed through application of electric field to BST. Figure 4 shows comparison of typical experimental and theoretical data for saturation magnetization $M=1815$ G of YIG film and external magnetic field $H=2017$ Oe. In this case centre frequencies were about 7.8 GHz and theoretical data were calculated for parameters used in experiment. The detailed study shows that an effective electric field control of the active ring filter central frequencies of the pass band takes place for relatively thick YIG films.

In agreement with the theory of hybrid spin-electromagnetic waves [6], the shift in central frequencies of the pass band is dependent on the eigenmode number n of the ring. Namely, the shift of central frequencies of the pass band decreased for the modes with higher frequencies, i.e., for higher values of n . The maximum shift of about 5 MHz was obtained for the lowest mode of the ring. At the same time, the maximum Q-factor of about 40 000 for $G=-1.5$ dB is measured. This mode demonstrated a frequency shift of 2.9 MHz. Approaching of G close to zero resulted in an increase in Q-factor up to 50 000. With proper choice for the geometry of the layered structure, in particular, the thicknesses of YIG and BST components, it is possible to increase the electric field tuning bandwidth of the resonator.

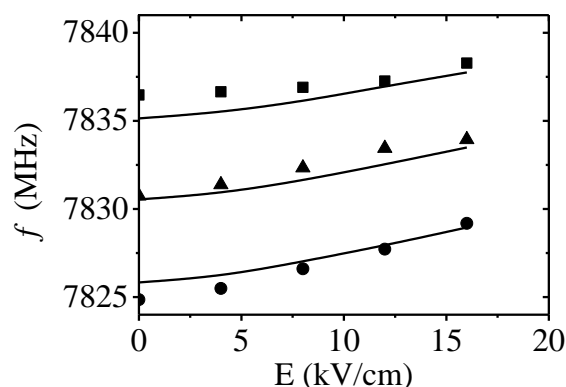


Figure 4. Central frequencies of the pass bands of active ring filter as a function of electric field (signs – experiment, solid lines – theory).

In conclusion, we developed a theoretical model of a microwave active ring filter based on a ferrite–ferroelectric layered structure. The results show a dual control of central frequency of the filter with magnetic and electric fields. An electric field tuning by 5 MHz and Q-factor up to 50 000 were obtained for operating frequencies close to 8 GHz. The investigated tunable active ring filter is very promising for application as a frequency selective element of tunable microwave photonic oscillators.

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