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V. Malyshev, As. Prof., G. Melkov, Dr.Sci., Prof., O. Prokopenko, Ph.D., Asc. Prof.
Department of Nanophysics and Nanoelectronics, Faculty of Radiophysics,
Taras Shevchenko National University of Kyiv

X-BAND TUNABLE MICROWAVE FILTER BASED ON SURFACE ELECTROMAGNETIC WAVE RESONATOR AND YTTRIUM IRON GARNET FILM

Microwave properties of X-band microwave filter based on the surface electromagnetic wave resonator and yttrium iron garnet (YIG) film are investigated theoretically and experimentally. It is shown that the filter can be easily tuned by an external bias dc magnetic field, and by analyzing the system's behavior in the magnetic field one can determine an effective anisotropy field of the YIG film. Obtained results might be important for the development of magnetically-tuned microwave devices and also for the characterization of magnetic films.

Key words: microwave filter, surface electromagnetic wave resonator, yttrium iron garnet film, magnetic field, coupled oscillations.

Introduction. The surface electromagnetic wave resonator (SEWR) [5–8, 10, 12–16] utilizes the surface electromagnetic waves (SEW), well-known in microwaves, optics and quasi-optics [1, 9]. Microwave properties of bare SEWRs and resonators on different dielectric substrates are studied thoroughly during last 15 years (for instance, see Refs. in [5, 10]). Such interest to the SEWRs is caused by the following important key-features of the resonator [5–8, 10, 12–18]:

(a) It consists of only one conducting (or superconducting) film, instead of microstrip systems, that should have at least two conducting electrodes for proper operation;

(b) In accordance to (a), the fabrication technique of the SEWR is quite easy, at least easier than for microstrip systems;

(c) Fundamental mode of the SEWR can be easily excited by TE_{10} mode of a rectangular waveguide and the efficiency of the resonator can be easily tuned by changing an angle between the SEWR's plane and a wide wall of the waveguide;

(d) Electromagnetic oscillations corresponding to the stationary SEWs are characterized by large amplitude of microwave currents, excited in the conducting film, due to the high concentration of SEWs' electromagnetic field near a surface of the film.

In accordance to (a)–(d) SEWRs could be considered as promising base elements for different waveguide-type microwave devices. It seems that one of the most important applications of the SEWRs is an active microwave device based on nonlinear nano-elements, for instance, Josephson junctions [5, 10, 12–15, 18]. Such systems can be used for the creation of microwave signal sources [5], microwave detectors [5, 10, 12, 15], voltage standards and other metrological applications [5, 18].

However, in typical experimental situation SEWR can not be used for the creation of wide-band microwave devices, because its unloaded Q-factor is quite large (~10^3 for metallic resonators), while the mechanical changing of an angle between the resonator's plane and wide wall of a waveguide is a low-efficient technique that is inconvenient in practical application. In order to realize the non-mechanical tuning of the resonator's frequency, we attach an yttrium iron garnet (YIG) film to the resonator and tune the obtained system by an appropriate change of an applied external dc magnetic field.

In this work we show that the SEWR with attached YIG film operates as a tunable by a dc magnetic field microwave filter. We develop an analytical theory of such filter and compare theoretical results with the data of microwave measurements that allow us to determine an effective anisotropy field of the YIG film. We believe that the obtained results are important for the development of magnetically-tuned waveguide-type microwave devices and also could be used for the characterization of magnetic films.

Experiment. The schematic of used experimental setup is shown in Fig. 1. It consists of a microwave source connected via a microwave transmission line to the standard 3-cm waveguide section 4, where the filter is situated, and the indicator of a scalar network analyzer, which is used to determine the reflection coefficient $|S_{11}|$ of considered filter (see Fig. 1).

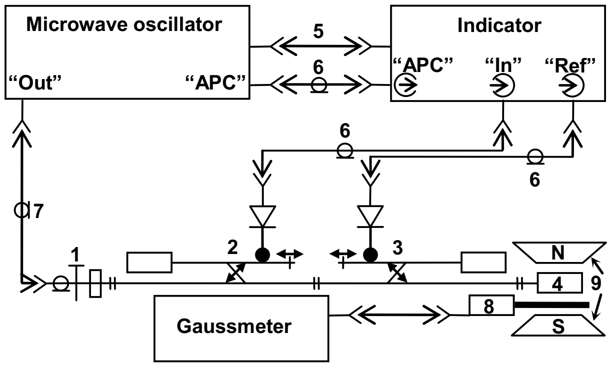

Fig. 1. Schematic of used experimental setup:
1 – waveguide-to-coaxial connector, 2 – directional coupler of the incident wave, 3 – directional coupler of the reflected wave, 4 – the SEWR in the waveguide section, 5 – interconnecting cable, 6 – connecting coaxial cable, 7 – RF connecting cable, 8 – magnetic field sensor based on Hall effect, 9 – electromagnet

To analyze the signals reflected from the resonator we used standard technique based on measurement of the standing wave ratio of the standing wave in the waveguide section 4 using directional couplers 2, 3 (see Fig. 1) [3, 11, 19]. Waveguide section was made from the material that is transparent for an external bias dc magnetic field. The magnetic field was created by a controllable electromagnet 9 and measured by the sensor 8 based on Hall effect (see Fig. 1).

The considered filter consists of the half-wavelength aluminum SEWR (resonator's length is 10.8 mm, its width is 5 mm and its thickness is 15 mkm) on the dielectric substrate (its lateral sizes are the same as for the SEWR and its thicknes is 0.5 mm) and YIG film of lateral sizes of 10.0×5.0 mm^2 and thickness 30 μm on a gallium gadolinium garnet substrate of thickness 0.5 mm. The layout of the filter is shown in Fig. 2. The distance between the aluminum resonator and the YIG film was equal to a sum of the both substrates' thicknesses.

The filter was situated inside the waveguide section as it is shown in Fig. 2. Angle between the resonator's plane and a wide wall of the waveguide, α, was chosen to be approximately 30 degree that corresponds to the optimum excitation conditions of the resonator.

External bias dc magnetic field was in-plane and directed along the length of the resonator; the magnitude of the field was controlled by an electromagnet and measured by a Hall-effect magnetic field sensor. At every value of the applied field we measured the amplitude-frequency curve of the filter in the frequency range 8.15 GHz – 12.05 GHz.

The frequency measurement error was about 50 MHz, while the field measurement error was 10 Oe.

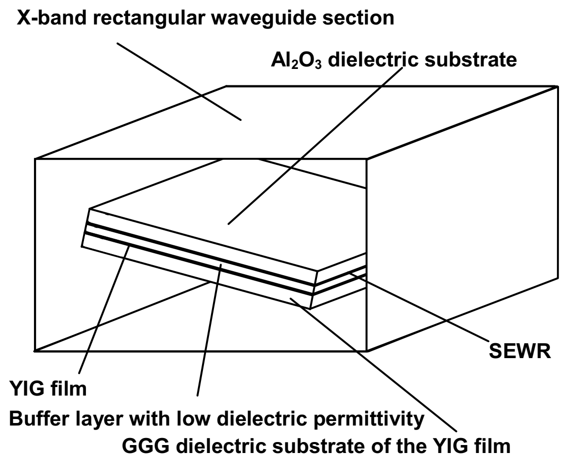

Fig. 2. The layout of the considered filter in the X-band rectangular waveguide section

Theory. Taking into account the complexity of the full electromagnetic problem for considered filter in the waveguide section, we develop an approximate analytic theory based on the method of coupled oscillations [2]. Although this approach is not rigorous, it will give satisfactory results, precise enough to compare results of the theory and the experiment.

Maxwell equations for the SEWR excited by the magnetization $\mathbf{m}$ have the form [2, 4]

$$\operatorname{rot}\mathbf{e} + \mathrm{i}k\mathbf{h} = -\mathrm{i}4\pi k\mathbf{m}, \quad \operatorname{rot}\mathbf{h} - \mathrm{i}k\varepsilon\mathbf{e} = 0, \tag{1}$$

where $\mathrm{i} = \sqrt{-1}$, $\mathbf{e}$ and $\mathbf{h}$ are the complex amplitudes of electromagnetic fields, ε is the dielectric permittivity of the resonator's substrate, $k = \omega / c$, $\omega = 2\pi f$, f is the frequency of the fundamental mode of the SEWR, and c is the speed of light.

From the other hand, magnetization of the YIG film is excited by an electromagnetic field of the SEWR. In that case the linearized equation of motion of magnetization can be written as [4]:

$$\mathrm{i}\omega\mathbf{m} + \omega_H\left[\mathbf{m}\times\mathbf{z}_0\right] = -\gamma M_0\left[\mathbf{z}_0\times\mathbf{h}\right], \tag{2}$$

where $\mathbf{H}_0 = \mathbf{z}_0 H_0$ is the external bias dc magnetic field, $\mathbf{z}_0$ is the unit vector directed along the external field (it is parallel to the surface of the resonator), $\mathbf{M}_0 = \mathbf{z}_0 M_0$, M_0 is the saturation magnetization of YIG film, $\omega_H = \gamma H_0$, $\gamma \approx 2\pi\cdot 28$ GHz/T is the modulus of the gyromagnetic ratio.

We present the microwave magnetic field of the fundamental mode of the resonator as

$$\mathbf{h} = \mathbf{h}_r + \operatorname{grad}\phi, \tag{3}$$

where $\mathbf{h}_r$ satisfies the condition $\operatorname{div}\mathbf{h}_r = 0$ and ϕ is the magnetostatic potential [4].

Eigen fields of the SEWR $\mathbf{e}_\nu$ and $\mathbf{h}_\nu$ can be determined from the equations

$$\operatorname{rot}\mathbf{e}_\nu + \mathrm{i}k_\nu\mathbf{h}_\nu = 0, \quad \operatorname{rot}\mathbf{h}_\nu - \mathrm{i}k_\nu\varepsilon\mathbf{e}_\nu = 0. \tag{4}$$

They also determined by the orthogonality conditions

$$\int_W \mathbf{h}_\nu^*\mathbf{h}_\eta dW = D_\nu\Delta_{\nu,\eta}, \quad \int_W \mathbf{e}_\nu^*\varepsilon \operatorname{grad}\phi dW = 0, \tag{5}$$

where W is the volume, where the fields are not negligible, $\Delta_{\nu,\eta}$ is the Kroneker's symbol.

Eigen functions of the YIG film, $\mathbf{m}_n$ and ϕ_n, must satisfy the equations [4]

$$\mathrm{i}\omega_n\mathbf{m}_n + \omega_H\left[\mathbf{m}_n\times\mathbf{z}_0\right] + \gamma M_0\left[\mathbf{z}_0\times\operatorname{grad}\phi_n\right] = 0 \tag{6}$$

and

$$\int_V \left[\mathbf{m}_n\times\mathbf{m}_l^*\right] dV = \mathrm{i}\mathbf{z}_0 N_n\Delta_{n,l}, \tag{7}$$

where V is the film volume.

Using the equations for eigen functions (4), (6) and taking into account the orthogonality conditions (5), (7), one can obtain from (1), (2), the equations for coupled oscillations:

$$\left(\omega-\omega_\eta\right)a_\eta D_\eta + \omega\sum_n b_n\int_V \mathbf{h}_\eta^*\left(4\pi\mathbf{m}_n + \operatorname{grad}\phi_n\right)dV = 0,$$

$$\left(\omega-\omega_l\right)N_l b_l + \gamma M_0\sum_\nu a_\nu\int_V \mathbf{h}_\nu\mathbf{m}_l^* dV = 0. \tag{8}$$

In the simplest case, when there are only two modes, the one is the fundamental mode of the SEWR (of the frequency ω_r) and other is the fundamental mode of the YIG film (of the frequency ω_f), we can obtain from (8) the characteristic equation

$$\left(\omega-\omega_r\right)\left(\omega-\omega_f\right)D_1N_1 - \omega\gamma M_0 I_1 I_2 = 0. \tag{9}$$

Here $I_1 = \int_V \mathbf{h}_1^*\left(4\pi\mathbf{m}_1 + \operatorname{grad}\phi_1\right)dV$, $I_2 = \int_V \mathbf{h}_1\mathbf{m}_1^* dV$. This means that the frequencies of coupled oscillations $\omega_{1,2}$ are given by the expression:

$$\omega_{1,2} = \frac{\omega_r + \omega_f + K}{2} \pm \frac{1}{2}\sqrt{\left(\omega_r - \omega_f\right)^2 + 2K\left(\omega_r + \omega_f\right) + K^2}, \tag{10}$$

where $K = \dfrac{\gamma M_0 I_1 I_2}{D_1 N_1}$ is the coupling coefficient.

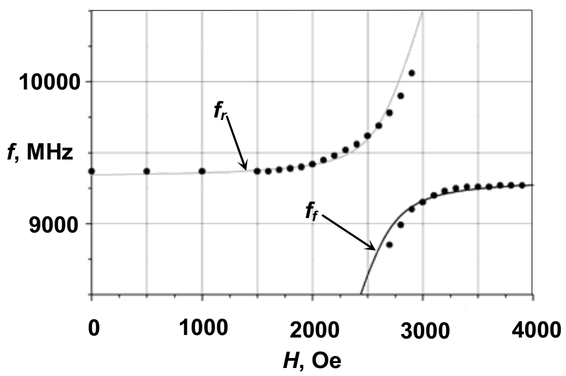

Fig. 3. Dependence of the resonance frequencies of the filter *f* on an external bias dc magnetic field *H*: lines are calculated using Eq. (10), while points are the measurement results

Results and discussion. The dependence of the response frequencies of the filter on a bias dc magnetic field is shown in Fig. 3 (lines are the theory results, while points are measurement's data). As one can see the resonance frequency of the SEWR (curve f_r in Fig. 3) practically does not depend on the magnetic field magnitude, when the field is weak enough. However, this dependence is crucial when the frequencies $f_r = \omega_r / 2\pi$ and $f_f = \omega_f\left(H_0\right) / 2\pi$ are equal and the coupling coefficient K from (10) is maximal. That condition gives a value of the resonance bias dc magnetic field (in our case this field is about 2750 Oe).

Comparing the frequencies calculated using (10) with the measurement points, we found that the optimal fit of the theoretical and experimental results can be obtained when using dc magnetic field $H_0' = H_0 + \Delta H$ in (11). Here H_0 is the real dc magnetic field applied to the YIG film and ΔH

could be the effective anisotropy field of the film. In our case ΔH was small enough, $\Delta H = -67$ Oe. However, we believe that such approach to determine ΔH can be successfully applied for the characterization of magnetic films with high anisotropy fields.

Conclusion. We have demonstrated that the SEWR and attached YIG film operates as a microwave filter, which can be tuned by applying a bias dc magnetic field to the system. Comparing theoretically predicted results and measurements data one can estimate an effective field of the film anisotropy. These results might be important for the development of magnetically-tuned waveguide-type microwave devices.

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В. Малишев, асп., Г. Мелков, д-р фіз.-мат. наук, проф.,
О. Прокопенко, канд. фіз.-мат. наук, доц.
Кафедра нанофізики та наноелектроніки, радіофізичний факультет
Київський національний університет імені Тараса Шевченка

ПЕРЕБУДОВУЄМИЙ НВЧ ФІЛЬТР 3-СМ ДІАПАЗОНА НА ОСНОВІ РЕЗОНАТОРА ПОВЕРХНЕВОЇ ЕЛЕКТРОМАГНІТНОЇ ХВИЛІ ТА ПЛІВКИ ЗАЛІЗО-ІТРІЄВОГО ГРАНАТУ

Теоретично та експериментально досліджено мікрохвильові властивості НВЧ фільтра 3-см діапазону на основі резонатора поверхневої електромагнітної хвилі та плівки залізо-ітрієвого гранату (ЗІГ). Показано, що такий фільтр легко перебудовується по частоті зовнішнім постійним магнітним полем, і досліджуючи поведінку системи в магнітному полі, можна визначити ефективне поле анізотропії плівки ЗІГ. Отримані результати можуть бути корисними при розробці магнітокерованих пристроїв НВЧ та при вивченні властивостей магнітних плівок.

Ключові слова: НВЧ фільтр, резонатор поверхневої електромагнітної хвилі, плівка залізо-ітрієвого гранату, магнітне поле, зв'язані коливання.

В. Малышев, асп., Г. Мелков, д-р физ.-мат. наук, проф., А. Прокопенко, канд. физ.-мат. наук, доц.
Кафедра нанофизики и наноэлектроники, радиофизический факультет
Киевский национальный университет имени Тараса Шевченко

ПЕРЕСТРАИВАЕМЫЙ СВЧ ФИЛЬТР 3-СМ ДИАПАЗОНА НА ОСНОВЕ РЕЗОНАТОРА ПОВЕРХНОСТНОЙ ЭЛЕКТРОМАГНИТНОЙ ВОЛНЫ И ПЛЁНКИ ЖЕЛЕЗО-ИТТРИЕВОГО ГРАНАТА

Теоретически и экспериментально исследованы микроволновые свойства СВЧ фильтра 3-см диапазона на основе резонатора поверхностной электромагнитной волны и пленки железо-иттриевого граната (ЖИГ). Показано, что такой фильтр легко перестраивается по частоте внешним постоянным магнитным полем, и исследуя поведение системы в магнитном поле, можно определить эффективное поле анизотропии пленки ЖИГ. Полученные результаты могут быть полезными при разработке магнитоуправляемых устройств СВЧ и при изучении свойств магнитных пленок.

Ключевые слова: СВЧ фильтр, резонатор поверхностной электромагнитной волны, пленка железо - иттриевого граната, магнитное поле, связанные колебания.

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E. Martysh, D. Sc., Prof.
Taras Shevchenko National University of Kyiv,
V. Yatsenko, D. Sc., Prof.
Space Research Institute of NASU-NSAU

SPACECRAFTS AUTOMATIC DOCKING SYSTEM WITH ACTIVE INFRARED MARKERS

Servicing satellites on-orbit requires ability to rendezvous and dock by an unmanned spacecraft with no or minimum human input. Future space exploration missions will rely upon "smart" autonomous systems that require highly sophisticated vision systems. Emergence of novel computer vision algorithms and active markers will lead to a new generation of rendezvous and docking systems in the near future. Such systems will be capable of autonomously detecting a target satellite at a begining of the last rendezvous phases, estimating its bearing, range and relative orientation under any illumination, and in any satellite pose.

Keywords: satellite rendezvous and docking, marker-based vision, active markers

Introduction. The major space-faring nations are currently developing prospective manned transportation systems of the new generation. They include: advanced manned and cargo transport spacecrafts, inter-orbital transfer facilities, manned missions to the Moon and Mars, Lunar and Martian orbital complexes, landing on the surface of the planets and returning to the Earth. These facilities have diverse operating conditions, tasks specifics and dataware peculiarities at various flight stages. Traffic control and navigation system of the facilities under