Microwave Tunable Devices on the YIG-VO₂ structures

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Abstract. The theory describing a tunability of the spin-wave spectrum for the ferrite/vanadium dioxide layered structures through changing the VO₂ conductivity is suggested. An influence of the various parameters on the spin-wave wavenumber variations and damping decrement is studied. We show that an effective wavenumber variation with minimal losses is achieved by matching the thicknesses of the ferrite and vanadium dioxide films, as well as the value of external magnetic field. We show also that owing to the electrodynamic interaction, a quality of contact between the ferrite and vanadium dioxide layers is not critical.

1. Introduction
For a long time, the microwave devices utilizing excitation and propagation of the spin waves in ferrite films and layered structures attract considerable attention for applications. This attention is determined by the fundamental peculiarities of the spin-wave (SW) dispersion such as tunability, nonreciprocal behavior, and low microwave losses [1]. Without any doubt, investigations of the SW phenomena in composite materials based on the microwave ferrites are perspective for fundamental physics, as well as for technology.

Among topics of general interest in the magnetostatic wave technology, the question of an electrical tunability mechanism for the SW devices is of particular importance. From a historical point of view, the first and widely used tuning mechanism in ferrite media is based on the interaction between the magnetization of the ferrite and the RF magnetic field [2]. Later on, combinations of SW waveguides with ferroelectrics or piezoelectrics were proposed in order to increase tunability efficiency of microwave magnetic devices [3]. Apart from tunable permeability, multiferroic composites and layered structures possess advantages of the electric-field tuning, which utilizes two effects. The first one is a magnetoelectric interaction in piezoelectric and magneto-elastic layers [4]. The second one is an electrodynamic interaction of microwave electromagnetic and spin waves propagating in the layered ferrite-ferroelectric structures [5].

Another tunability mechanism utilizes an influence of perfectly conductive plane on propagation of surface magnetostatic waves. The general idea of this effect is that a SW phase shift in the ferrite film is accumulated due to the change in a distance between the ferrite and conductive planes [6, 7]. However, the key issues inherent to microwave applications of the above-mentioned tuning mechanism are associated with precise control of a conductor position and slow time response.

In order to solve them, investigation of an influence of the conductivity on the microwave properties of the magnetic multilayers is highly relevant [8-11]. Our recent work [12] describes the operational principle of a miniature microwave phase shifter utilizing a metal-insulator transition (MIT). The novel tuning mechanism was achieved owing to the controllable variation of the VO₂ conductivity that had a
pronounced effect on the SW dispersion in the ferrite film. A further progress of the microwave devices based on structures combining the SW and MITs is connected with enhancing the tunability efficiency and decreasing the insertion losses.

2. Theoretical model

Fig. 1 shows schematically a ferrite-dielectric-metal multilayered structure. It consists of an arbitrary number layers stacked along the y-axis. The wave propagates along the x-axis. The structure is magnetized to the saturation by a uniform magnetic field $H_0$ along the z-axis. Ferrite layers have different thicknesses $t_{2i}$, dielectric permittivities $\varepsilon_{2i}$, and saturation magnetizations $M_{2i}$, where $i$ is any integer from 1 to $N$.

The magnetic properties of the ferrite layers are described by magnetic complex permeability tensors $\hat{\mu}_{2i}$ that have the following form

$$\hat{\mu}_{2i} = \begin{pmatrix} \mu_{2i} & j\mu_{2i} & 0 \\ -j\mu_{2i} & \mu_{2i} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where

$$\mu_{2i} = 1 + \frac{(\omega_0 + j\alpha_2(\omega))\omega_{2i}}{(\omega_0 + j\alpha_3(\omega)) - \omega^2}, \quad \alpha_2 = \frac{\gamma H_2}{\omega_0}, \quad \omega_0 = \gamma H_0, \quad \omega_{2i} = \gamma M_{2i}, \quad \mu_{2i} = \frac{\omega_0 \omega_{2i}}{(\omega_0 + j\alpha_3(\omega)) - \omega^2},$$

$\gamma = 2.8$ MHz/Oe is the gyromagnetic ratio of an electron, $\Delta H_{2i}$ is the half width of the ferromagnetic resonance curve, and $\omega$ is an angular frequency. Each ferrite layer is surrounded by the dielectric or metal layers with thicknesses $t_{2i+1}$. Thereby even number $i$ corresponds to a ferrite layer and odd $i$ corresponds to a dielectric layer or metal one. Any odd layer can be a dielectric or conductive by means of complex permittivity

$$\varepsilon_{2i+1} = \varepsilon_{2i+1} = -j\sigma_{2i+1}/\omega,$$

where $\varepsilon_{2i+1}$ and $\sigma_{2i+1}$ are the dielectric permittivity and conductivity of an odd layer, respectively.

The dispersion relation for magnetostatic waves can be found through an analytical solution of the full set of Maxwell’s equations. A derivation using the method of transfer matrix has been described in details in our previous work devoted to the spectrum of the spin-electromagnetic waves in planar multiferroic multilayers composed of an arbitrary sequence of the ferrite and ferroelectric layers [13]. In contrast to the previous work, here the elements of the permeability tensors (1) of even layers and
permittivity’s (2) of odd layers are complex values. As the result, the complex dispersion relation \( \omega(k) \) is obtained, where \( k = k' + jk'' \) is a complex propagation constant, \( k' \) and \( k'' \) are phase and attenuation constants, respectively.

3. Dispersion Characteristics of Spin-Electromagnetic Waves in YIG-VO\(_2\) Multilayers

Let us apply the developed theory for numerical simulations of the dispersion characteristics of magnetostatic SWs propagating in various ferrite-dielectric-metal multilayered structures. Fig. 2 shows the dispersion characteristics calculated for layered structures based on the ferrite film placed in the external magnetic field of \( H_0 = 1500 \) Oe.

![Figure 2. Spin-wave dispersion characteristics for the geometries of D-E (black line and open squares), Seshadri (blue line and circles), and Bongianni (green line and rhombs, red line and triangles)](image)

Here, the solid lines show dispersion characteristics calculated according to the developed theory. The symbols correspond to the results obtained by the Damon-Eshbach (D-E), Seshadri, and Bongianni dispersion relations [14, 6, 7]. The black line and open squares show the dispersion characteristics of the SW in the free ferrite layer (all the layers except the ferrite with the number \( i = 2 \) have zero thicknesses, \( t_2 = 20 \) µm, \( \epsilon_2 = 14 \), and \( M_2 = 1750 \) G). The blue line and open circles correspond to the SWs in the ferrite layer covered by the perfectly conducting plane (\( t_2 = 20 \) µm, \( \epsilon_2 = 14 \), \( \sigma_i \to \infty \), and all the other layers have zero thicknesses). The red line and open triangles as well as the green solid line and open rhombs correspond to the SW in the ferrite-dielectric structure covered by a perfectly conducting metal plane for distance of \( t_3 = 5 \) µm and \( t_3 = 25 \) µm, respectively. Other parameters are \( t_2 = 20 \) µm, \( \epsilon_2 = 14 \), \( \epsilon_3 = 1 \), \( \sigma_i \to \infty \), all the other layers have zero thicknesses. A decrease in distance between the YIG film and perfectly conducting metal plane shifts the SW dispersion closer to the Seshadri dispersion. As is seen, the dispersion characteristics calculated according to the developed theory coincide to a high accuracy with the well-known expressions.

As was shown in our previous work [12], the developed theory can be used for investigation of the SW spectra in ferrite-vanadium dioxide structures. For the calculations, we use typical parameters corresponding to an epitaxial yttrium iron garnet (YIG) film on a gadolinium gallium garnet substrate and a polycrystalline vanadium dioxide film on a sapphire substrate: \( \epsilon_1 = 14 \), \( t_1 = 500 \) µm; \( \epsilon_2 = 14 \), \( M_2 = 1750 \) G, \( t_2 = 15 \) µm; \( t_4 = 0 \); \( t_5 = 0.5 \) µm; \( \epsilon_6 = 10 \), \( t_6 = 500 \) µm. In order to be specific, the problem is considered for the silicon dioxide film with \( \epsilon_3 = 4.6 \) and thickness of \( t_3 = 50 \) µm, which is placed between the ferrite and VO\(_2\) films.

Fig. 3 (a) presents a typical temperature dependence of the VO\(_2\) conductivity \( \sigma_5 \). The circles in Fig. 3 (a) indicate various conductivities for the temperatures across the transition range that are used in the calculations of SW dispersion (see Fig. 3 (b)). The colors of the curves in Figs. 3 (b), (c), and (d) correspond to the colors of the circles shown in Fig. 3 (a). The black dashed line corresponds to the Seshadri dispersion (\( \sigma_5 \to \infty \)), which shows the largest possible influence of the metal layer. An increase in the VO\(_2\) conductivity shifts the dispersion characteristics towards the Seshadri dispersion. Such behavior manifests itself in the same way as changing in a distance for the case of the Bongianni
geometry. Figs. 3 (c) and (d) show the wavenumber variation $\Delta k$ and damping decrement $k''$ calculated for the various VO$_2$ conductivities.

![Figure 3](image)

**Figure 3.** Dependence of VO$_2$ conductivity versus temperature (a); dispersion characteristics calculated for various VO$_2$ conductivities (b); wavenumber variation produced by a change of the VO$_2$ conductivity (c), damping decrement for various VO$_2$ conductivities (d)

The black dashed line in Fig. 3 (c) represents the wavenumber difference between the D-E and Seshadri dispersion relations, which corresponds to the maximum achievable wavenumber variation in the ferrite-metal layered structures $\Delta k_{\text{max}}$. As follows from Fig. 3 (c), an increase in the conductivity broadens the frequency range, where $\Delta k$ achieves the maximum value $\Delta k_{\text{max}}$. The black solid and dashed lines in Fig. 3 (d) show the damping decrements of SWs in the free ferrite ($\sigma_s = 0$, i.e. D-E geometry) and the ferrite covered by the perfectly conductive plane ($\sigma_s = \infty$, i.e. Seshadri geometry). These dependences are inversely related to the SWs group velocity $V_g$ and described by the well-known relation $k'' = 2\pi\gamma H/V_g$.

It is worth mentioning that the group velocity of SWs in the ferrite covered by a perfectly conductive plane is maximal for any wave-number in comparison with any other ferrite-metal structure. Therefore, the damping decrement corresponding to the Seshadri geometry is minimal. As was shown above in the description of Fig. 3 (b), the SW dispersion in the structure based on a ferrite film and a metal with a finite conductivity varies from the Seshadri dispersion to the D-E one. This variation determines the increase in losses with the frequency from the minimum possible value to a local maximum, which is associated with the minimum group velocity. We assume that the operational bandwidth corresponds to the frequency range, where the SW propagation losses in the ferrite-VO$_2$ are less than in the free ferrite film. Fig. 3 (d) shows that the operational bandwidth broadens with the increase in the VO$_2$ conductivity.

An influence of the different parameters of the layered structure on the dispersion behavior of SWs is shown in Figs. 4-6. The characteristics shown by the red solid lines have been discussed in Fig. 3 (c) and (d). These characteristics represent the reference dependences calculated for the high ($\sigma_s = 2500 \, \Omega^{-1}\text{cm}^{-1}$) and low ($\sigma_s = 10 \, \Omega^{-1}\text{cm}^{-1}$) values of the VO$_2$ conductivities. The dashed line in Figs. 4-6 (a) shows the difference of wavenumbers between the D-E and Seshadri dispersion relations $\Delta k_{\text{max}}$. The dash-dotted and dashed lines in Figs 4-6 (b) show the damping decrements of SWs in the free ferrite film and the ferrite film covered by the perfectly conductive plane.
An influence of the vanadium dioxide film thickness $t_5$ is shown in Fig. 4. An increase in $t_5$ broadens the frequency range of the wavenumber variation, where $\Delta k = \Delta k_{\text{max}}$ (Fig. 4 (a)). For instance, $\Delta k$ is equal to 2.8 rad/mm for the frequency $f_0 = 6.23$ GHz and this value remains the same for any value of $t_5$ higher than 200 nm. The damping decrements calculated for the various $t_5$ are shown in Fig. 4 (b). As is seen, $k^*$ defines the operating bandwidth, where the propagation losses are less than in the free ferrite film. The bandwidth is broadened with increasing the vanadium dioxide film thickness. Thus, at the fixed frequency $f_0 = 6.23$ GHz the losses decrease from $k^* = 6$ dB/mm down to $k^* = 1.2$ dB/mm with increasing in the VO$_2$ film thickness from $t_5 = 200$ nm up to $t_5 = 500$ nm. Therefore, the thickness of the VO$_2$ film is more critical for an operating bandwidth rather than for the value of the wavenumber variation.

An influence of the intermediate silicon dioxide layer thickness on the SW wavenumber vibration and damping decrement is shown in Fig. 5. An increase in the thickness $t_3$ narrows the frequency range of the wavenumber variation, where $\Delta k = \Delta k_{\text{max}}$ (see Fig. 5 (a)) and has no effect on the SW dispersion in the frequency range. Similar to influence of VO$_2$ film the increase in the thickness $t_3$ provides a rise of the insertion losses (see Fig. 5 (b)). For instance, an variation in $t_3$ from 50 $\mu$m to 100 $\mu$m at the frequency $f_0 = 6.23$ GHz preserves the wavenumber variation $\Delta k = 2.8$ rad/mm and increases the damping decrement from $k^* = 1.2$ dB/mm up to $k^* = 1.4$ dB/mm. This feature has a considerable practical importance. Firstly, it shows that a quality of the ferrite-to-VO$_2$ contact is not critical. As a result, the structures produced through a mechanical contact of the ferrite and VO$_2$ thin films can be successfully used in practical applications. Secondly, it opens up a possibility for a thermal isolation of the ferrite layer, which is important for realization of the tunability.

Fig. 6 shows dependences of the wavenumber and damping decrement versus frequency for the various thicknesses of the YIG film $t_2$. Due to an inversely dependence of the SW group velocity on ferrite film thickness, an increase in the $t_2$ broadens the frequency range of the wavenumber variation, where $\Delta k = \Delta k_{\text{max}}$ (see Fig. 6 (a)), and reduces in the propagation losses (see Fig. 6 (b)). For example, for $f_0 = 6.23$ GHz an increase in the $t_2$ from 15 $\mu$m up to 20 $\mu$m provides a change in $\Delta k$ from 2.9 rad/mm to 2.2 rad/mm. However, the damping decrement corresponding to this frequency decreases from $k^* = 1.2$ dB/mm down to $k^* = 0.6$ dB/mm.
Figure 6. Influence of YIG film thickness on the SW wavenumber variation (a) and damping decrement (b)

Note that an increase in the magnetic field shifts the SW spectrum towards the higher frequencies that provides an additional enhance of the conductivity influence due to a reduction of the skin depth. It provides an increasing of the wavenumber variation for almost constant damping decrement.

4. Conclusion

In summary, a novel tunability mechanism of the spin-wave spectrum through changing the vanadium dioxide conductivity is studied. In particular, a high tunability efficiency of more than 2.8 rad/mm is achieved in the layered structure composed of the 15-μm thick ferrite film and 500-nm thick vanadium dioxide film. Furthermore, this wavenumber tunability is achieved in the proposed structure with 50-μm thick intermediate dielectric layer. The latter opens up possibilities for the thermal insulation of the ferrite film. In addition, it is shown that the SW propagation losses in the YIG-VO₂ structure are directly related to an operating frequency range. It is found that a comparatively small damping decrement up to 1.2 dB/mm can be obtained at 6.23 GHz. All these features make the proposed structure perspective for the development of novel microwave devices such as phase shifters, resonators, delay lines, and filters.

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