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Tunable spin-wave delay line based on ferrite and vanadium dioxide

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Abstract. One of the key elements for modern microwave circuits is a delay line, which is widely utilized for the signal generation as well as processing. Spin-wave delay lines based on ferrite films provide a high delay time and small dimensions. Typically, the performance characteristics of such lines are tuned by the variation of an externally applied magnetic field characterized by some drawbacks. The phenomenon of a metal–insulator transition (MIT) in the phase change materials permits to improve the performance characteristics of the spin-wave delay lines. In particular, this concept allows to reduce the power consumption and improve the control speed of a delay time. *Aim.* Development of a tunable spin-wave delay line based on ferrite and vanadium dioxide films, as well as the study of its performance characteristics. *Methods.* Experimental investigations were carried out for the delay line composed of the yttrium iron garnet (YIG) and vanadium dioxide (VO_2) films. The ferrite waveguide was fabricated from a single-crystal YIG film grown on a gallium gadolinium garnet substrate. A vanadium dioxide film was formed on a silicon dioxide substrate by DC reactive magnetron sputtering. The microwave measurements were carried out using the vector network analyzer R&S®ZVA40. *Results.* It was shown that heating of the VO_2 film induces a sufficient drop of its resistance that causes the transformation of the spin-wave dispersion characteristic. This leads to the decrease in the group velocity of the propagating waves providing a growth of a delay time. Namely, experimental structure of 5-mm length offers a tunable time delay range from 130 up to 150 ns at the operating frequency of 4.33 GHz. *Conclusion.* A proof-of-principle for the MIT control of the delay time composed on the YIG-VO_2 structure has been presented. It was shown that a switch of VO_2 film from the isolating into conducting state produces a 15% change in the delay time. The considered microwave delay lines look favorable for applications as a complimentary part to the traditional approach for general computing and microwave signal processing.

Keywords: spin waves, ferrites, metal–insulator transition, vanadium dioxide, microwave devices.

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Introduction

One of the key elements of modern microwave electronics are delay lines, used to generate and process microwave signals. A feature of analog delay lines is a smooth change in the delay time of signals whose amplitude continuously changes. As a result of the active development of technology, analog delay lines have been developed using waves of various nature, among which optical, magnetostrictive and surface acoustic wave devices have become the most widespread [1]. Among various counterparts, optical delay lines demonstrate a significantly wider operating bandwidth and higher performance. This is an important parameter for ultra-wideband systems.The main disadvantage that limits applications of such devices are the large size. In comparison with listed above devices, spin-wave (SW) delay lines based on epitaxial ferrite films provide a significantly longer delay time and smaller dimensions [2]. The group velocity of SW is less than the speed of light by 4-7 orders of magnitude, depending on the thickness of the ferrite film and its magnetic properties. For example, to travel a distance of 1 mm in a film of yttrium-iron- garnet (YIG) with a thickness of 4 microns, a spin wave takes the same time as light to travel a distance of 100 m in an optical fiber. Due to the emergence of new methods for obtaining YIG films of submicron thickness [3–5], the same delay time can be obtained for micron and submicron propagation distances of spin waves. Thus, YIG films represent very compact SW devices that are fully compatible with the platform of microwave hybrid integral circuits. Another key feature of the propagation of spin waves in epitaxial YIG films is the variety of their dispersion characteristics. This feature allows you to design and create delay lines of various types [2, 6]. Dispersion delay lines with a linear dependence of the delay time on frequency are realized in ferrite films including a metal layer [7, 8]. Nondispersive delay lines consist of ferrite films screened from both sides or by two cascaded delay lines [9, 10]. The general idea of most of the listed works is based on the influence of ideally conducting layers on the propagation of spin waves [11]. An exception is the work [12], in which the effect of finite conductivity on the spectrum of spin waves was investigated. However, electronic control of the delay time in such lines is realized due to the change in the external magnetic field used to magnetize the waveguide structure. This method has disadvantages: such as low speed of operation (on the order of microseconds), significant power consumption, large dimensions.

To overcome these disadvantages, it was proposed to use composite materials with ferroelectric/piezoelectric and ferromagnetic phases separated into different layers, but interacting with each other [13–15]. The high practical significance of such hybrid structures (referred to as artificial multiferroics) is combination the advantages of miniature spin-wave elements with the possibility of dual electronic control of their microwave characteristics. For example, in the work [16],a tunable delay line based on YIG film and magnesium niobate-lead titanate ceramics was developed. The principle of operation of such a device is based on the magnetoelectric interaction in a ferrite-piezoelectric structure, which provides an electrically induced delay of the microwave signal at the operating frequency. The disadvantage of such structures is connected with relatively thick (more than 100 microns) of the piezoelectric layer used for device fabrication. As a result, it is necessary to use a high control voltage (up to 500 V), for effective electric control which limits applications of such delay lines. Thus, an urgent task is to develop alternative ways to control the dynamics of spin waves. One of the possible ways to solve this problem is to use structures consisting of ferrite films and materials with a metal-insulator transition (MIT).

Among the various media exhibiting MIT, vanadium dioxide (VO_2) is one of the most promising materials for practical application [17]. Vanadium dioxide is actively used in field-effect transistors [18], memory and neuromorphic computing devices [19], spintronic systems [20]. Such great scientific interest is due to the unique physical property of VO_2 - a sharp change in its conductivity near the phase transition temperature (about 340 K). Such a transition is characterized by a high switching speed (from picoseconds to nanoseconds) under the influence of various factors: thermal [21], electrical [22], optical [23] or under the effect of external stress [24].

In our theoretical works [25], [26], the effect of the MIT on the spectrum of spin waves in of ferrite/vanadium dioxide layered structures was investigated. Later in the work [27], authors show a proof-of-principle of control the SW dynamics by temperature induced conductivity variation of the vanadium dioxide. In this paper, the MIT effect is used to develop a new type of microwave spin-wave delay line consisting of ferrite and vanadium dioxide films. The study was carried out in three stages. At the first stage, VO_2 and YIG films were prepared, and their physical properties were analyzed. At the second stage, a prototype of the delay line was designed and manufactured. At the final stage, the performance characteristics of the delay line were investigated.

1. Characterisation of VO_2 and YIG films

A film of vanadium dioxide with a thickness of 0.55 microns was deposited on a substrate of silicon dioxide (SiO_2) with a thickness of 500 microns by direct current reactive magnetron sputtering. The sample had dimensions in the plane (4×4) mm^2. To study the electrical properties of the deposited film, the dependences of the VO_2 resistance on temperature were measured. Measurements were carried out in the probe station using a Keithley 2635A measuring source. The experimental results obtained with heating and cooling regimes are shown in Fig. 1 by red triangles and blue squares,respectively.

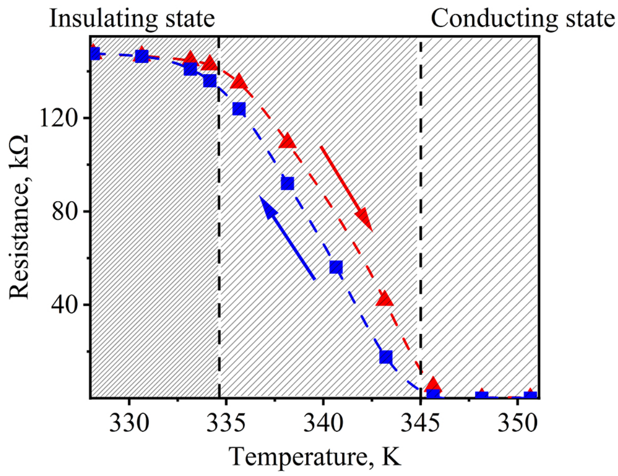

Fig. 1. Temperature dependences of the VO_2 resistance

In Fig. 1 one can see that the VO_2 sample demonstrates a metal-insulator transition at a temperature of $T \sim 340$ K. In this case, the film VO_2 is in the insulating state below 334 K, and in the conducting state above 345 K. Thus, a variation of temperature in a narrow range from 334 to 345 K leads to a sharp drop in resistance from 143 kOhm to 75 ohms. The resistance dependences obtained with the heating and cooling regimes are characterized by a similar behavior, shifted by 3 K. This indicates small stoichiometric deviations in the produced film [28].

At the next stage , a ferrite waveguide was produced. The experiment used an epitaxial YIG film grown on a substrate of gadolinium gallium garnet (GGG) with a thickness of 500 microns. The length, width and thickness of the film were 3 cm, 2 mm and 5.7 microns, respectively. The saturation magnetization was equal to $4\pi M = 1900$ G at room temperature. The half-width of the ferromagnetic resonance curve of the YIG films, measured at a frequency of 5 GHz, was 0.5 Oe.

2. Experimental layout of the delay line based on VO_2 and YIG films

The experimental layout of the delay line is shown in Fig. 2. The delay line consisted of the YIG film on the GGG substrate, a thin layer of VO_2 and microstrip antennas serving for the excitation and detection of SW in GHz frequency range.

A few comments should be made about the design of the delay line. Firstly, the short-circuited microstrip antennas with a length of 2.5 mm and a width of 50 microns were located at

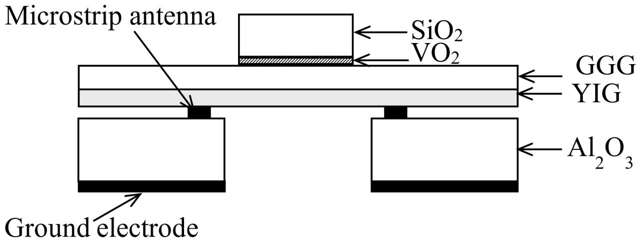

Fig. 2. Sketch of the delay line composed of the YIG film on the gadolinium gallium garnet substrate and the VO_2 film on the SiO_2 substrate

equal distances from both ends of the ferrite film at a distance of 5 mm from each other. The structure under study was placed between the poles of the electromagnet in a uniform constant magnetic field with a strength of 855 E. The field was directed in the plane of the ferrite film parallel to the antennas. This ensured the excitation and propagation of surface spin waves in the structure.

Secondly, the thermal switching of the VO_2 film placed on the top of the YIG film would lead to a significant decrease in the saturation magnetization of ferrite. This causes a frequency shift of the transmission characteristics of the layered structure. To prevent thermal effects, the film VO_2 was located on the opposite side of the GGG substrate. This provided thermal insulation. The thickness of the GGG was chosen to provide the control of the SW dynamics by MIT effect and to minimize the influence of temperature on magnetic properties of the YIG film. To accomplish this, the GGG layer was polished down to a thickness of 100 microns. The YIG film was additionally thermostated at a temperature of 331 K. This ensured the stability of the magnetic properties of the YIG film when the vanadium dioxide film was heated from $T = 331$ K to $T = 346$ K.

Next, let us consider the principle of propagation of surface SW through the studied delay line. Initially, the spin wave is excited by the input microstrip antenna and propagates in the YIG film. At the boundary where the GGG substrate is in contact with the vanadium dioxide film, the dispersion of the surface SW is modified in accordance with the change in resistance VO_2. The wave passes through the layered structure and is received by the output microstrip antenna located on the surface of the YIG film. These antennas were connected to the vector network analyzer R&S®ZVA40 for continuous measurements.

3. Investigation of the transmission characteristics of the delay line based on VO_2 and YIG films

This section presents experimental studies of the delay line containing the films of YIG and VO_2. The group delay time and power transmission coefficient were measured using the vector network analyzer. The results obtained are shown in Fig. 3. To clarify the dynamics of spin waves in the proposed structure, measurements were carried out for the insulating (high-resistance) and conducting (low-resistance) state of VO_2 at temperatures of 331 K and 346 K.

Initially, a spin-wave delay line was investigated at a temperature of 331 K. The results of measurements of transmission characteristics and delay time are shown in Fig. 3, *a*, *c* with black lines. In Fig. 3, *a* one can see that the transmission characteristic of the delay line is described by a smooth increase in insertion losses from 9 to 50 dB in the frequency range from 4.17 to 4.64 GHz. At the same time, the dependence of the delay time on the operating frequency, shown in Fig. 3, *c*, is determined by the spin-wave dispersion and has a nonlinear dependence that can be divided into two regions. In the first region (4.17...4.47 GHz) the delay time increases almost linearly from 100 to 180 ns, providing the group delay $D = d^2\varphi/d\omega^2 = 46\ ns^2/rad$. In the second region (4.47...4.64 GHz) the delay time is characterized by a sharper increase from 180 to 325 ns at $D = 127\ ns^2/rad$. The frequency dependencies shown in Fig. 3, *a*, *c*, are typical for a spin-wave delay line based on the free a ferrite film. This indicates that the vanadium dioxide film in the insulating state has no effect on the propagation of spin waves in the investigated waveguide structure in the experimental frequency range.

Let us discuss transmission characteristics and delay time for the structure with a conducting state of vanadium dioxide at $T = 346$ K. These dependencies are shown in Fig. 3, *b*, *d* by red lines. From the comparison of Fig. 3, *a* and Fig. 3, *b* it can be seen that the MIT in vanadium dioxide has a significant effect on the transmission coefficient of the spin-wave delay line. At the same time, the cutoff frequency of SW $f = 4.17$ GHz does not change. This is due to the design of the delay line. In Fig. 3, *b*, *d* one can see that an increase in the resistance of VO_2 leads to a decrease in the group velocity of spin waves. This causes an increase in delay time and propagation losses and leads to a narrowing of the bandwidth to 310 MHz. This frequency range is due to the presence of an intermediate layer of GGG. As was shown in our previous work [26], an increase in the thickness of the intermediate dielectric layer between the YIG and VO_2 in the conducting state narrows the frequency range where the group of the SW in the layered structure and the free ferrite film differ. The irregularities in Fig. 3, *b*, which is close to the cutoff frequency of surface SW, is explained by the presence of additional sources of losses associated with the mismatch. To reduce the level of insertion losses and to expand the operating frequency range, it is necessary to increase the conductivity of the VO_2 film in the conducting state and increase its thickness [12, 26].

Let us now consider the dependence of the delay time on the frequency, (Fig. 3, *d*). As a result of heating the VO_2 film, the bandwidth of the transmission characteristic narrows. This leads to the formation of an almost linear region, for which the variance of the group delay dispersion is $D = 60$ ns^2/rad. The most remarkable feature of the proposed delay line is an

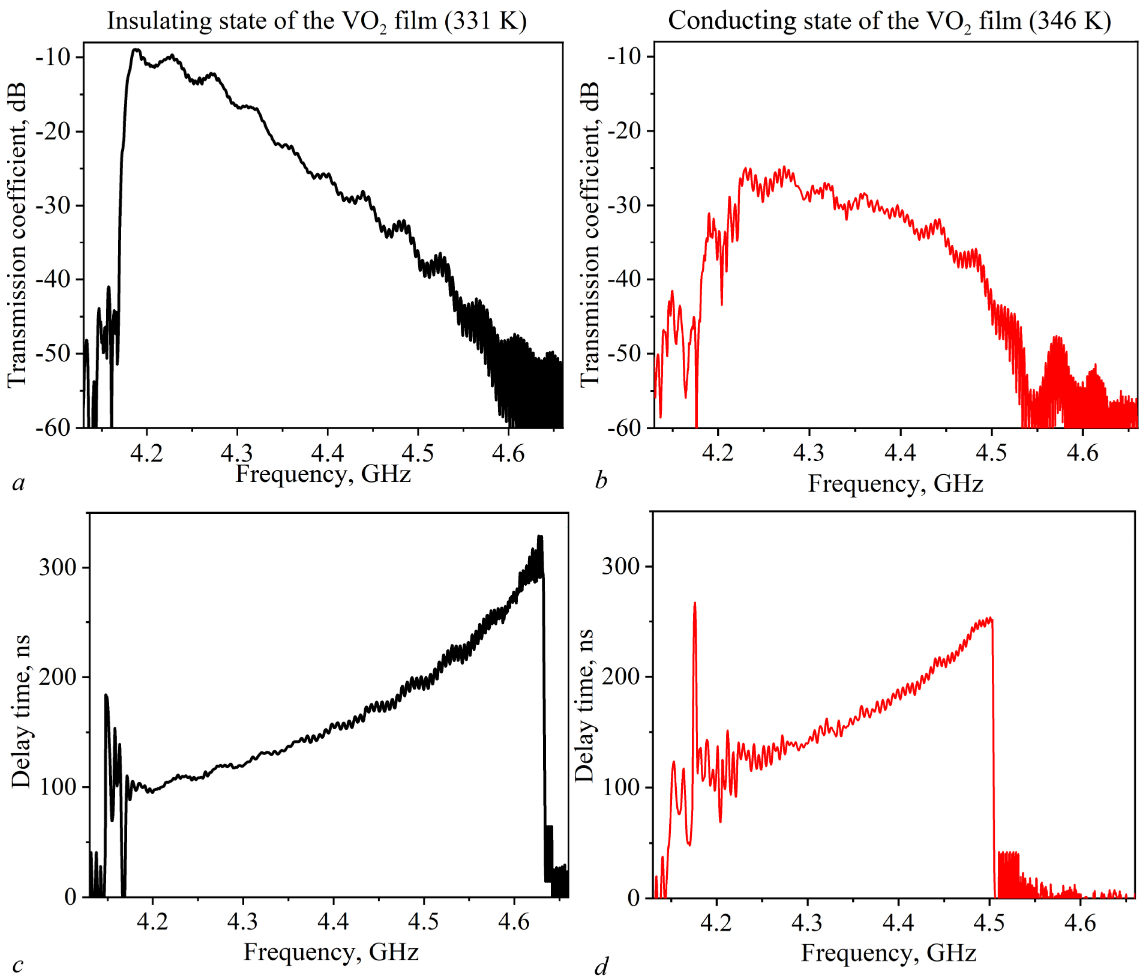

Fig. 3. Frequency dependences of the insertion loss (*a*, *b*) and the delay time (*c*, *d*) accumulated by the spin waves in the designed structure with the VO_2 film exhibiting insulating (*a*, *c*) or conducting (*b*, *d*) state

increase in the delay time by 15% (from 130 to 150 ns at a frequency of 4.33 GHz) in the bandwidth of about 250 MHz. This tuning mechanism is realized due to a controlled change in the resistance VO_2.

Conclusion

This paper presents the results of an experimental study of the microwave properties of a delay line consisting of vanadium dioxide and iron-yttrium garnet films. The principle of delay time control by metal-insulator transition in the film VO_2 is demonstrated. For the structure under study, it was found that the transition of the VO_2 film from an insulating to conducting state leads to a 15% change in the delay time. Investigated structures can be used in various applications in the field of microwave signal processing. Such delay lines can be applied in a new field of neuromorphic computing based on the principles of magnonics [29, 30]. The long delay time and strong nonlinearity possessed by spin waves make it possible to implement an artificial neural network with a nonlinear mapping of data into a space of a larger dimension [31]. This approach makes it possible to implement reservoir computing, which is one of the main methods of information processing in the fields of machine learning and artificial intelligence.

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