Electrical Tuning of Dispersion Characteristics of Surface Electromagnetic-Spin Waves Propagating in Ferrite–Ferroelectric Layered Structures

Vladislav E. Demidov, Boris A. Kalinikos, Sergey F. Karmanenko, Alexandr A. Semenov, and Peter Edenhofer

***Abstract*—Electrical tuning of dispersion characteristics has been studied experimentally for hybrid surface electromagnetic-spin waves propagating perpendicularly to the direction of the static magnetization in tangentially magnetized layered structures containing ferrite and ferroelectric layers. The tuning is realized through the variation of the dielectric constant of the ferroelectric layer by changing the applied electric field. A comparison between experimentally measured and theoretically calculated dispersion characteristics is presented. It is shown that a good agreement exists between experimental and theoretical results.**

***Index Terms*—Electromagnetic coupling, ferrite films, ferroelectric materials, magnetostatic waves, planar waveguides.**

I. Introduction

RECENT theoretical investigations on hybrid electromagnetic-spin waves (HESWs) propagating in layered waveguide structures containing ferrite and ferroelectric layers have shown that these waves can successfully be used to fabricate electrically tunable microwave phase shifters [1]. The use of these waves for technical applications is based upon coupling effects between spin waves and delayed electromagnetic waves that propagate in ferrite–ferroelectric layered structures. This wave coupling causes a hybridization of dispersion curves corresponding to spin and electromagnetic waves [2]. As a consequence, the dispersion characteristics of spin waves turn out to be dependent on the value of the dielectric constant of the ferroelectric layer. This allows a tuning of the dispersion characteristics of spin waves through the variation of the dielectric constant of the ferroelectric layer. This can be realized by changing an applied electric field.

The advantages of tunable microwave devices based on ferrite–ferroelectric layered structures in comparison with traditional purely ferrite or purely ferroelectric devices are obvious. In contrast to the usual ferrite devices, ferrite–ferroelectric devices do not demand electromagnets in order to tune operating characteristics. Instead of varying the bias magnetic field, the tunability is achieved through varying the constant electric field applied to the ferroelectric layer. The use of this novel tuning mechanism provides increased tuning speed, decreased controlling power, and significant reduction of size in comparison with usual magnetostatic-spin-wave devices. Another important feature of HESWs is the possibility to accumulate a significant phase shift along a relatively short (several millimeters) propagation distance. That is due to very small phase and group velocities of spin waves propagating in ferrite layers [3]. This feature of the HESW makes ferrite–ferroelectric phase shifters much more compact than previously developed phase shifters based on transmission-line sections using a purely ferroelectric substrate [4]–[6]. As shown in [1], a differential phase shift of more than 2π rad can be obtained at a propagation distance as short as 5 mm using ferrite–ferroelectric layered waveguiding structures.

Today, investigations on wave processes in layered ferrite–ferroelectric structures become especially important because of recently reported successful experiments in growing high-quality ferroelectric films on ferrite samples [7], [8].

Despite a large amount of theoretical work aimed at HESWs (see relevant literature in [9]), experimental investigations of HESWs were rare. The papers [10]–[12] report on experimental studies of hybridization effects between magnetostatic spin waves and delayed electromagnetic waves propagating in a layered structure that consists of a ferrite film and a ferroelectric waveguide separated by an air gap. In [10]–[12], wave coupling effects were observed as a narrow notch in the amplitude versus frequency characteristic. It was shown that the frequency associated with this notch corresponds to an intersection point between each of the dispersion characteristics of magnetostatic spin waves and electromagnetic waves of the ferroelectric waveguide modes.

The purpose of this experimental study is to investigate dispersion characteristics of hybrid surface electromagnetic-spin waves propagating in ferrite–ferroelectric layered structures. Moreover, the electrical tunability is investigated when an electric field is applied to the ferroelectric layer. In addition, the obtained experimental results are compared with the predictions of the theory.

Manuscript received December 19, 2002; revised March 12, 2003. This work was supported in part by the International Association INTAS under Grant 99-1812 and by the Deutsche Forschungsgemeinschaft under Grant 436 RUS 113/644/0.

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Digital Object Identifier 10.1109/TMTT.2003.817461

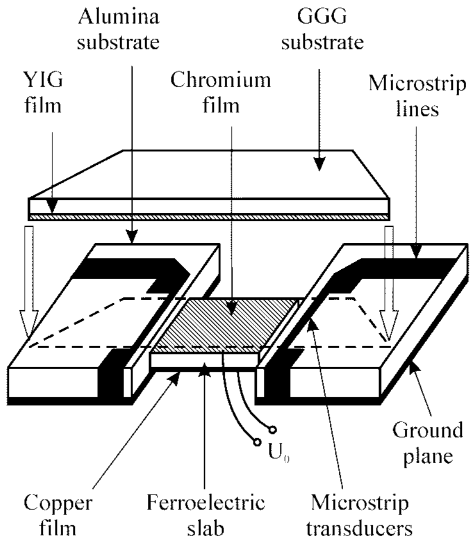

Fig. 1. Schematic of ferrite–ferroelectric layered structure measurement system.

II. Experiment

For our experiments, we used the measurement device shown in Fig. 1. It consisted of standard microstrip transmission lines. Each of these lines had two sections. A standard 50-Ω section and a narrow 50-μm wide and 3-mm-long transducer section. These transducers were short circuited and separated by a distance of 7 mm. The microstrip circuits were manufactured by photolithography on alumina substrates. A spin-wave waveguide of width 2.9 mm, length 20 mm, and thickness 16.5 μm was placed on top of the transducers. The waveguide was manufactured from an yttrium–iron–garnet (YIG) film grown by liquid-phase epitaxy on a gadolinium–gallium–garnet (GGG) substrate with a thickness of 500 μm. A ferroelectric slab of width 3 mm and length 4.5 mm was pressed from below to the surface of the YIG film by means of a special element (not shown in this figure for clarity). This slab was produced from $Ba_{0.6}Sr_{0.4}TiO_3$ ceramics and was covered from the bottom side by a 3-μm-thick copper film. The upper surface of the ferroelectric slab, which was in contact with the ferrite film, was covered by a very thin (100 nm) layer of chromium. The thickness of the chromium layer was chosen to be much smaller than the skin depth in order to allow the penetration of the electromagnetic fields of spin waves into the ferroelectric slab. The experimental investigations show that such a thin layer neither influences the dispersion characteristics, nor increases the propagation losses. A dc voltage in the range of 0–800 V was applied to the system of electrodes, which consisted of the copper and chromium layers, in order to create the controlling electric field inside the ferroelectric layer. The measurement device, as described above, was placed into a constant magnetic bias field of intensity H_0-oriented parallel to the microstrip transducers.

In this measurement setup, the magnetostatic surface spin wave (MSSW) excitations obey the Damon–Eshbach dispersion law near the input transducer [13]. During propagation, these excitations enter the region where the YIG film is in contact with the ferroelectric layer. Here it transforms to a hybrid surface electromagnetic-spin wave, which obeys another dispersion law. In the region near the output transducer, the excitation transforms back to MSSW excitations, which obey the Damon–Eschbach dispersion law.

In order to obtain detailed information about the dispersion characteristics of HESWs propagating in layered ferrite–ferroelectric structures, the measurements were carried out in two stages. In the first stage, phase versus frequency characteristics of MSSWs were measured when the ferroelectric slab was removed. From the slope of these characteristics, the frequency dependence of the group velocity of MSSWs was obtained. Absolute values of wavenumbers were determined assuming the starting frequency of the passband in the amplitude versus frequency characteristics corresponded to zero wavenumber. In addition, the wavenumbers were used as adjustable parameters in fitting the experimentally determined dispersion curve by the Damon–Eshbach dispersion law.

In the second stage, the phase versus frequency characteristics were measured for the ferroelectric slab gradually approaching the surface of the ferrite film toward full contact. During these measurements, the change of the phase characteristics was tracked in order to measure the absolute value of the phase shift caused by the approach of the ferroelecric slab for every frequency point. This allowed us to determine the corresponding shift in the wavenumber caused by the presence of the ferroelectric slab relative to the previously measured dispersion characteristics for pure MSSW excitations. As a result, we obtained two dispersion characteristics. One of them corresponded to pure MSSWs propagating in the ferrite film. The other one was the resulting dispersion characteristic for the waves propagating partially in the ferrite film and partially in the layered ferrite–ferroelectric structure. Finally, using these two experimentally determined dependencies and taking into account the propagation distances in the ferrite film and the layered ferrite–ferroelectric structure, we obtained the dispersion characteristics for HESWs.

Thus, we measured the dispersion characteristics of hybrid waves for intensities of the bias magnetic field in the range of $H_0 = 500 - 1500$ Oe and voltages applied to the ferroelectric layer in the range of $U_0 = 0 - 800$ V.

III. Results and Discussion

Fig. 2(a)–(c) presents the results of measurements performed for a ferroelectric slab with a thickness of 300 μm. The three parts of this figure correspond to an intensity of the bias magnetic field H_0 of 1361, 1047, and 739 Oe, respectively. The solid points show the dispersion characteristics of pure MSSWs measured in the first stage of each experiment. The circles and diamonds show the dispersion characteristics of HESWs obtained at $U_0 = 0$ V and $U_0 = 800$ V, respectively. In addition to the experimental results, Fig. 2(a)–(c) also demonstrates the theoretically calculated dispersion characteristics. The dashed lines show the theoretical dispersion curves for MSSWs calculated by using the Damon–Eshbach dispersion law. The solid lines show the theoretical dispersion curves for HESWs calculated by using the theory developed by Demidov *et al.* [9]. Calculations for hy-

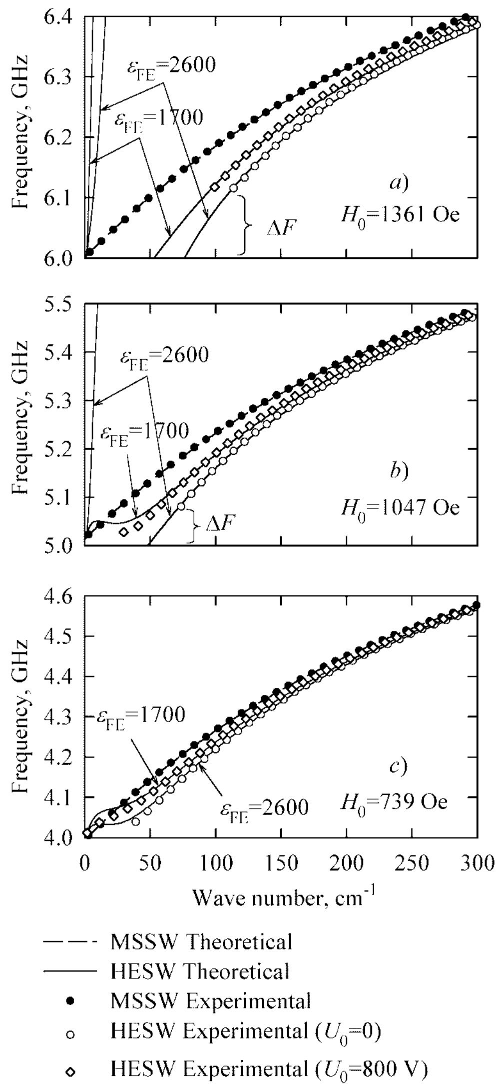

Fig. 2. Experimental and theoretical dispersion characteristics for the ferrite–ferroelectric layered structure containing a 300-μm-thick ferroelectric slab. The frequency interval of spin waves is situated: (a) above, (b) close, and (c) below the cutoff frequency of the electromagnetic mode TE_1. For cases (a) and (b), a parasitic interference appears in the frequency interval ΔF due to a two-mode propagation.

brid waves were performed assuming the initial $(U_0 = 0\ \mathrm{V})$ relative dielectric constant of the ferroelectric slab $\varepsilon_{\mathrm{FE}}$ to be equal to 2600. This value was determined from low-frequency measurements of the capacity of the plane capacitor constituted by the ferroelectric slab and the two metallic electrodes deposited on both surfaces. As far as it was shown in many papers (see, e.g., [14]) that the change in the dielectric constant of the bulk ferroelectric materials does not exceed a few percent in the frequency range of 0–10 GHz, we can use this value for description of our microwave frequency case without any restrictions. The dielectric constant corresponding to the case of $U_0 = 800$ V was determined as a result of fitting the experimental dispersion curve with the theoretical dispersion curve using the dielectric constant as an adjustable parameter. For the case under consideration, this value was found to be equal to 1700. The values of the dielectric constant are indicated in the figure close to the corresponding theoretical dispersion curves.

It is well known from previous investigations (see, e.g., [13], [15], and [16]), that MSSWs exist in a closed frequency interval limited by two frequencies. These frequencies are defined by the value of saturation magnetization of the ferrite film and by the intensity of the bias magnetic field. In the case of no metallic screens, the MSSW dispersion curve starts from zero wavenumber at a frequency corresponding to the lower frequency limit. With an increase of wavenumber, the dispersion curve monotonically approaches the upper frequency limit. With an increase of bias magnetic field, the frequency interval of MSSWs shifts to higher frequencies and becomes narrower. For the YIG film utilized in our experiments, the starting frequency of MSSWs is equal to 4 GHz at $H_0 = 739$ Oe [see Fig. 2(c)]. Under these conditions, the width of the frequency interval of MSSWs reaches approximately 600 MHz when measured in the range of wavenumbers of 0–300 cm^{-1}. With an increase of H_0 up to 1361 Oe [see Fig. 2(a)], the starting frequency shifts to 6 GHz and the frequency interval decreases to 400 MHz. It is evident from experimental dispersion curves for MSSWs shown in Fig. 2(a)–(c) that a nearly perfect fitting can be obtained from the Damon–Eshbach dispersion law.

In case of a ferroelectric slab placed in full contact with the YIG film, waves propagating in such a composite layered structure cannot be described using the magnetostatic approximation where the velocity of electromagnetic waves is taken to be infinite. Due to typically high dielectric constants of ferroelectric materials, electromagnetic waves propagating in layered ferrite–ferroelectric structures turn out to be strongly delayed and, consequently, strongly influence the dispersion characteristics of spin waves. Therefore, it becomes necessary to consider the full spectrum of HESWs constituted by hybridized fast electromagnetic and slow spin waves.

Depending on the relative position between the frequency interval of spin waves and the cutoff frequency of the lowest mode of electromagnetic waves, three typical cases of hybridization between spin and electromagnetic waves can be distinguished. The first corresponds to the situation when the frequency interval of spin waves is situated below the cutoff frequency of electromagnetic waves. The second corresponds to the case when the cutoff frequency is close to this interval. The third corresponds to the case when the frequency interval of spin waves is situated above the cutoff frequency of electromagnetic waves. As shown in [9], surface spin waves can be coupled only with TE electromagnetic waves, thus, the lowest mode of transverse electric electromagnetic waves TE_1 is the most important for our case. Using [9, eq. (3)], we can calculate the cutoff frequency of the TE_1 mode for the case of the layered structure, as described above, containing the 300-μm-thick ferroelectric slab. For the two values of relative dielectric constants 2600 and 1700, the cutoff frequencies turn out to be equal to 4.7 and 5.8 GHz, respectively. This means that the three parts constituting Fig. 2(a)–(c), corresponding to the frequency intervals of spin waves 4.0–4.6 GHz [see Fig. 2(c)], 5.0–5.5 GHz [see Fig. 2(b)], and 6.0–6.4 GHz [see Fig. 2(a)] demonstrate the three above-mentioned typical cases of hybridization.

First consider the dispersion characteristics shown in Fig. 2(c) for $H_0 = 739$ Oe. In this case, the influence of the ferroelectric slab on the dispersion characteristics of spin waves is rather weak because the cutoff frequency of the TE_1 electromagnetic mode is larger than the frequencies of spin waves. As a result, the dispersion curve of hybrid waves (circles) is slightly shifted from the dispersion curve of magnetostatic spin waves measured for the case when the ferroelectric slab is removed (solid points). The strongest shift is observed in a region corresponding to small wavenumbers. With an increase of wavenumber, the difference between the dispersion characteristics of magnetostatic and hybrid waves steadily decreases. Such a behavior is explained by a decreasing penetration of the electromagnetic fields of spin waves into the ferroelectric layer as associated with a decrease of their wavelength. As seen from the figure, the application of an electric field to the ferroelectric slab causes the dispersion curve of hybrid waves to shift to the dispersion curve of purely magnetostatic spin waves. This is due to a further weakening of hybridization between spin and electromagnetic waves owing to a displacement of the cutoff frequency of the TE_1 electromagnetic mode to larger frequencies.

A comparison of the measured and calculated dispersion characteristics of hybrid waves shows a fairly good agreement between them. Significant deviations of the theoretical dispersion curves from the experimental curves occur only for small wavenumbers. As can be seen from Fig. 2(c), in this region of small wavenumbers, the dispersion characteristics of hybrid waves exhibit a “plateau,” where the group velocity of spin waves abruptly decreases. The existence of this “plateau” is a result of the influence of the copper film deposited at the bottom surface of the ferroelectric slab. This phenomenon was studied for the case of MSSWs [15], [16]. O’Keeffe and Patterson [16] have shown that the formation of this “plateau” is strongly influenced by the width of the ferrite film. At the same time, our theoretical model assumes that the layered structure is unbounded in the plane. This is one reason why the experimental dispersion characteristics demonstrate smoother changes of the group velocity along the “plateau” region than predicted by our theory.

With an increase in the bias magnetic field to $H_0 = 1047$ Oe, the frequency interval of spin waves shifts to the frequency range of 5.0–5.5 GHz [see Fig. 2(b)]. In this case, the cutoff frequency of the TE_1 mode, corresponding to the initial dielectric constant 2600 of the ferroelectric slab, is situated slightly below the starting frequency of spin waves. In such a case, hybridization between spin and electromagnetic waves leads to an “exchange” of the cutoff frequencies. This means that the dispersion curve of the spin waves starts from the frequency corresponding to the cutoff frequency of the TE_1 electromagnetic mode (≈4.7 GHz) and the dispersion curve of the electromagnetic waves starts from the frequency corresponding to the lower frequency limit of spin waves (≈5 GHz). As a result, the dispersion curves of spin waves and the TE_1 electromagnetic mode coexist inside the whole frequency interval shown in Fig. 2(b). In practice, this leads to a two-mode propagation regime and, as a consequence, to a parasitic interference between both types of waves. However, in the measurement device used in our experiments, the initially existing MSSW coming to the ferrite–ferroelectric layered structure mainly excites the waves corresponding to the dispersion branch of slow spin waves and does not practically excite the fast electromagnetic waves. Significant interference was observed only in the region of small wavenumbers where the dispersion curve of the initial MSSW approaches the dispersion curve of the TE_1 mode. This interference did not allow us to measure the dispersion characteristics of HESWs inside the frequency interval ΔF indicated in Fig. 2.

In the case when the electric field was applied to the ferroelectric slab, the dielectric constant of the ferroelectric layer decreases to 1700 and the cutoff frequency of the TE_1 electromagnetic mode shifts to 5.8 GHz. As a result, the dispersion branch of the TE_1 mode leaves the frequency interval shown in Fig. 2(b) and the dispersion curve of spin waves shifts to the dispersion curve of the MSSW. Comparing Fig. 2(b) and (c), it is clear that, with an increase in the bias magnetic field, the tunability of the dispersion characteristics of spin waves becomes stronger for the given variation in dielectric constant (2600–1700).

Fig. 2(a) demonstrates the third typical case of hybridization between surface spin waves and the TE_1 electromagnetic mode. This corresponds to the situation when the frequency interval of spin waves (6.0–6.4 GHz) is situated above the cutoff frequency of the TE_1 electromagnetic wave, even if an electric field is applied to the ferroelectric slab. As seen from this figure, the two-mode propagation exists in the whole range of variation of the dielectric constant. As a result, the frequency range ΔF, where the parasitic interference does not allow measurements of dispersion characteristics, is rather wide and does not change practically with the application of an electric field.

Summarizing the discussion of results in Fig. 2, it can be concluded that shifting the frequency interval of spin waves to higher frequencies allows for a stronger tunability of the dispersion curves through the variation of the dielectric constant of the ferroelectric layer. At the same time, in the case when the frequencies of spin waves exceed the cutoff frequency of the TE_1 electromagnetic wave, a two-mode propagation arises leading to parasitic interference. This means that the most appropriate configuration of the layered ferrite–ferroelectric structure for technical applications is that which provides the highest cutoff frequency of the TE_1 electromagnetic waves. It is evident that the simplest way to increase this frequency, without degrading the tunability of the dielectric constant, is to decrease the thickness of the ferroelectric layer.

Like Fig. 2, Fig. 3(a)–(c) now shows the experimental and theoretical dispersion characteristics for the ferrite–ferroelectric layered structure containing a 200-μm-thick ferroelectric slab. The three parts of this figure correspond to the intensity of the bias magnetic field equal to 1360 Oe [see Fig. 3(a)], 1045 Oe [see Fig. 3(b)], and 743 Oe [see Fig. 3(c)].

It is clear that, in this layered structure geometry, the same value of the voltage applied to the ferroelectric slab leads to a stronger change in the dielectric constant in comparison with the previously discussed case. As shown in Fig. 3, applying $U_0 = 0 - 800$ V, the dielectric constant of the ferroelectric slab $\varepsilon_{\mathrm{FE}}$ changes in the range of 2600–1300. Under these conditions, the cutoff frequency of the TE_1 electromagnetic mode is equal to 7.3 and 10.2 GHz for the values of voltage equal to 0 and 800 V, respectively. That means that the cutoff frequency

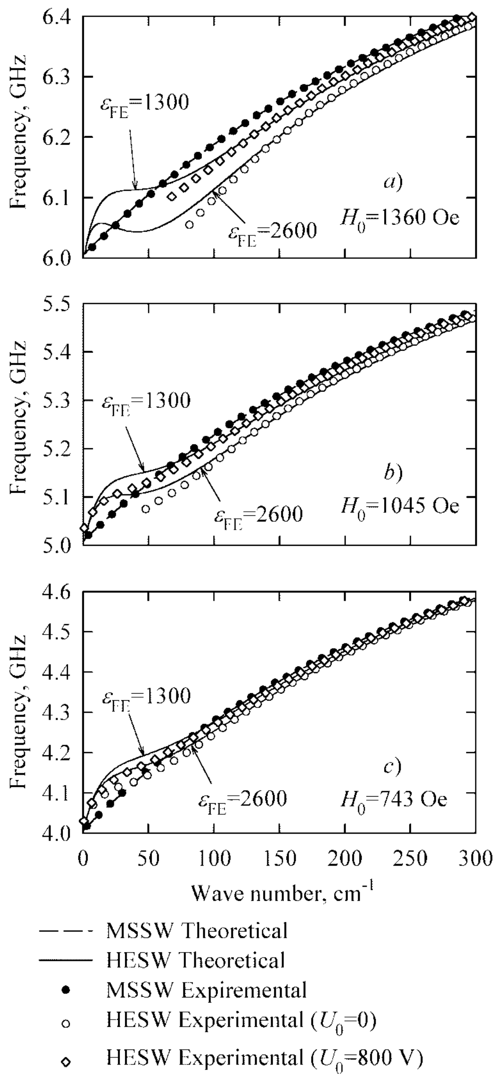

Fig. 3. Experimental and theoretical dispersion characteristics for the ferrite–ferroelectric layered structure containing a 200-μm-thick ferroelectric slab. For all three cases, the cutoff frequency of the electromagnetic mode TE_1 is situated above the frequency interval of spin waves. As a result, there is no parasitic interference.

is situated above the frequencies of spin waves for all three intensities of the bias magnetic field considered. As a result, there is no parasitic interference between waves corresponding to the dispersion branches of spin and electromagnetic waves.

As seen from Fig. 3, in the case of the ferroelectric slab with a thickness of 200 μm, the dispersion characteristics of spin waves experience a very strong influence from the copper film. This results in the "plateau" occupying a significant part of the dispersion curves and, consequently, in strong deviations between experimental and theoretical dispersion curves in the long wavelength region. With an increase in the bias magnetic field, the group velocity of spin waves becomes smaller and even negative in the "plateau" region. This phenomenon introduces difficulties for measurements of dispersion characteristics at small wavenumbers. As a result, the experimental dispersion curves shown in Fig. 3(b) and (c) were measured starting from nonzero wavenumbers.

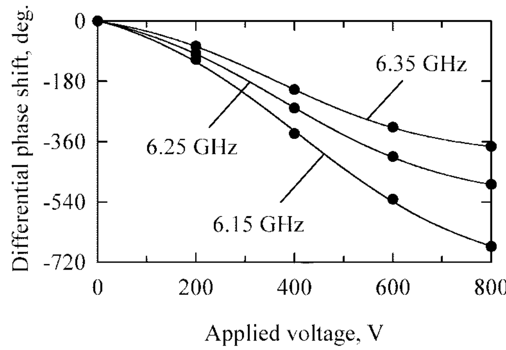

Fig. 4. Experimental dependencies of the differential phase shift of the wave transmitted through the measurement device on the voltage applied to the ferroelectric slab for the case of the thickness of ferroelectric layer equal to 200 μm and intensity of the bias magnetic field equal to 1360 Oe.

Decreasing the thickness of the ferroelectric slab from 300 to 200 μm led to an increase in the voltage tunability of the spin-wave dispersion characteristics. A comparison between Figs. 3 and 2 shows that the same change of the voltage allows for a much stronger variation of dispersion curves for the thickness of the ferroelectric slab equal to 200 μm than for that equal to 300 μm. In addition, the "useful part" of the dispersion characteristics becomes larger due to absence of the parasitic interference between spin and electromagnetic waves. These features of the ferrite–ferroelectric layered structure containing a 200-μm-thick ferroelectric layer are useful for creating electrically tunable microwave phase shifters.

Fig. 4 demonstrates dependencies of the differential phase shift of the wave transmitted through the measurement device on the voltage applied to the ferroelectric slab. Dependencies are presented for the case providing maximum tunability of dispersion characteristics, i.e., for $H_0 = 1360$ Oe [the corresponding dispersion diagram is given by Fig. 3(a)]. The points show the results of measurements of the differential phase shift. The solid lines are sigmoid curves approximating the experimental points. Characteristics are shown for the three values of frequency 6.15, 6.25, and 6.35 GHz.

As seen from the figure, varying the voltage between 0 and 800 V allowed for a differential phase shift of more than 360°, which was observed over a frequency range of more than 200 MHz. The strongest variation of the phase shift corresponds to the frequencies near zero wavenumber. With an increase of frequency, the slope of the dependence of the differential phase shift on the voltage decreases. That is due to a decrease of hybridization between spin and electromagnetic waves with an increase of the wavenumber. All three curves for differential phase shift exhibit saturation at voltages exceeding 600 V. This corresponds to the intensity of the electric field inside the ferroelectric slab equal to 3000 kV/m. This saturation is caused by the saturation of the dependence of the dielectric constant of ferroelectric materials in high electric fields.

As is clear from Fig. 4, the investigated phenomenon could be successfully used for the creation of a novel class of tunable microwave phase shifters that are characterized by a large differential phase shift and small dimensions. At the same time, we have to point out that the results of this study are not enough to evaluate the possible performances of such devices because the measurement device used in our experiments was not optimized from the point-of-view of technical applications. As a result, its insertion losses caused mainly by the microwave circuit mismatch were rather high and reached −20 dB. Absence of matching components allowed us to study the tuning of dispersion characteristics in the large frequency range from 2 to 8 GHz without any changes in the measurement setup. In this connection, it is clear that further investigations are needed in order to achieve commercially competitive performances of ferrite–ferroelectric phase shifters.

IV. Conclusion

Results of this study show that the previously developed theory for HESWs describes their dispersion characteristics with good accuracy. Significant deviations between experimental and theoretical results were observed only in the long-wavelength region where the influence of the copper film situated at the bottom surface of the ferroelectric slab on the dispersion characteristics leads to the appearance of a "plateau." These deviations could be due to the finite width of the ferrite–ferroelectric structure used in experimental investigations. Investigations of the tunability of the dispersion characteristics of hybrid waves through the variation of the applied electric field demonstrate that ferrite–ferroelectric layered structures could be used for the elaboration of microwave tunable phase shifters. It is shown that the most appropriate layered structure geometry for these purposes provides a maximum cutoff frequency of the TE_1 electromagnetic mode. In this study, such conditions were achieved with a layered structure, which consisted of a 16.5-μm-thick ferrite film and 200-μm-thick ferroelectric slab metallized from the bottom. With such a layered structure, differential phase shifts greater than 360° were obtained for a propagation distance of 4.5 mm.

Acknowledgment

The authors gratefully acknowledge Dr. M. M. Scott, Department of Physics, Colorado State University, Fort Collins, for his critical reading of this paper's manuscript.

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Sergey F. Karmanenko, photograph and biography not available at time of publication.

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