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MODELING OF MAGNETOELECTRIC MICROWAVE DEVICES

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Abstract. *The possibility of computer modeling implementation of electrically controlled magnetoelectric (ME) microwave devices is considered. The computer modeling results of different structures of ME microwave devices based on layered ferrite-piezoelectric structure formed on the slot line, microstrip line and coplanar waveguide are offered. Results are reported as frequency dependencies of insertion losses of ME devices.*

Key words: *magnetoelectric microwave devices, ferrite-piezoelectric resonator, dual magnetic and electrical control*

1. INTRODUCTION

With the increasing significance of the microwave communication systems, radar and navigation in modern society are enhanced requirements for their reliability, mobility, power consumption. Telecommunication and mobile satellite radiotelephone systems, mobile navigation and radar stations, global and local computer networks are need of an electrically controllable and inexpensive devices. This requirement can be achieved by replacing complex circuits with active components to tunable microwave devices based on thin film materials with nonlinear physical properties such as ferroelectric and ferrites.

One way to control the parameters of electronic components is based on the change in the dielectric constant of components under the influence of an external electric field. "Electric" method of control is characterized by high speed and low energy consumption, since the restructuring carried out without leakage currents through the control circuit. Control property under the influence of the electric field is maintained in some ferroelectrics in a wide frequency range - from the lowest to the highest frequencies. This feature is widely used in microwave devices for rapid regulation of the amplitude-frequency and phase-frequency characteristics.

The disadvantages of ferroelectric control structures is a relatively narrow range of operating frequency regulation and a high level of voltage applied to the electrodes. These drawbacks can be overcome by design of new modifications of the transmission lines, as well as the use of layered structures containing not only the ferroelectric, but and ferromagnetic

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films. Using of ferrite-ferroelectric layered structures can manage the performance by electric and magnetic field at the same time. In such devices, you can combine the advantages of an "electric" and "magnetic" management methods, i.e. the high speed and a wide range of operating frequency with the microwave device parameters.

Analysis of the current state in the field of microwave devices controlled by electric and magnetic fields, indicates the existence of scientific and technical issues, including radio physical and physical-technological aspects. This issue determines the number of academic assignments, such as theoretical studies of electrodynamics characteristics and improving the design of microwave transmission lines, experimental investigations of wave processes, design and development of the controlled devices.

Magnetoelectric (ME) materials [1-6], which simultaneously exhibit ferroelectricity and ferromagnetism, have recently stimulated a sharply increasing number of research activities for their scientific interest and significant technological promise in the novel multifunctional devices. The ME effect [7-9] in composite materials is known as a product tensor property, which results from the cross interaction between different orderings of the two phases in the composite. Neither the piezoelectric nor magnetic phase has the ME effect, but composites of these two phases have remarkable ME effect. Thus the ME effect is a result of the product of the magnetostrictive effect (magnetic/mechanical effect) in the magnetic phase and the piezoelectric effect (mechanical/electrical effect) in the piezoelectric.

One of the promising directions of development of microwave technology currently is the development of ME microwave devices. Application of ME non-reciprocal devices eliminates the above drawbacks of ferrite devices. Electric field control allows to implement such devices integrally, i.e. reduces the cost of the devices; improves performance; reduces power consumption in the control circuit; eliminating the interference arising from the magnetic field control [10-11].

2. MODELING OF ME MICROWAVE DEVICES

Magnetoelectric interactions in ferrite-ferroelectric composites have facilitated a new class of microwave signal processing devices. Such devices are based on either hybrid spin electromagnetic waves or mechanical force mediated magnetoelectric interactions. When a ferrite-piezoelectric bilayer is driven to ferromagnetic resonance (FMR) and an electric field $\boldsymbol{E}$ is applied across piezoelectric (ferroelectric), the ME effect results in a frequency or field shift of FMR. Thus devices based on FMR can be tuned with both electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{H}$. Several dual tunable ME devices, including resonators, filters, attenuators, circulators, isolators and phase shifters have been demonstrated so far.

Simulation of ME microwave devices by the modern computer program which calculate multimode S-parameters and the electromagnetic field in the three-dimensional passive structures greatly simplifies the selection of optimal parameters of such devices: the parameters of the transmission line (dimensions and relative substrate permittivity, the size of the conductors) and the resonator parameters (size, shape, material).

As the industry turns to monolithic integrated/hybrid nonreciprocal microwave devices, planar geometries have to be used. This requires the development of planar elements, compatible with strip line and microstrip systems. As high-frequency systems are manufactured using Monolithic Microwave Integrated Circuit (MMIC) designs, the size of the ME resonator must be compatible with the MMIC chip technology.

The difference between the proposed ME non-reciprocal devices and ferrite devices is to replace the ferrite magnetic resonator and magnetic control systems to ferrite-piezoelectric resonator and a system of electrodes connected to the source of the control voltage. ME resonator (Fig. 1) is a layered composite in the form of a disk or plate. As a ferrite phase can be different type of spinels ($NiFe_2O_4$, $CoFe_2O_4$, $Ni_{0.8}Zn_{0.2}Fe_2O_4$, $Co_{0.6}Zn_{0.4}Mn_2O_4$ and other), yttrium iron garnet (YIG thick film or monocrystal); as piezoelectric phase we can use polycrystalline material lead zirconate titanate (PZT), or single-crystal materials as Lead Magnesium Niobate-Lead Titanate (PMN-PT), lead zinc niobate-lead titanate PZN-PT.

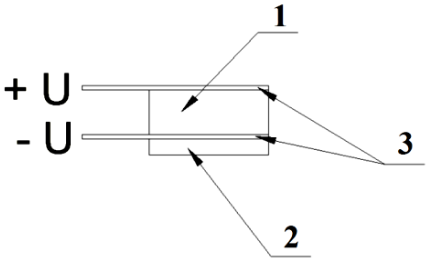

Fig. 1 ME resonator: 1 is piezoelectric component, 2 is ferrite component, 3 is metal electrodes

The basis for the design of ME microwave devices is a microwave transmission line on a dielectric substrate with a ME resonator placed in the transmission line. The operating principle of the ME non-reciprocal microwave devices is based on the ME microwave effect. The point of this effect is to shift the FMR line under the influence of an electric field. ME layered composite operate as a resonator in this case. Electric field control allows carrying out the tuning of the device characteristics in the frequency range. This is also the ability to control the FMR line using a magnetic field. Dual tunability of the devices control parameters open up new possibilities for the design of such devices.

FMR is a powerful tool for studies of microwave ME interaction in ferrite-piezoelectric structures. An efficiency of the magnetoelectric interaction in the ferrite-piezoelectric bilayers is characterized by coefficient of magnetoelectric interaction $A=\delta H/\delta E$, where δH is variation of the internal magnetic field in the ferrite and δE is variation of the electric field applied to the piezoelectric. Magnitude of A depends mainly on magnetostriction constant of the ferrite and piezoelectric coefficient of the piezoelectric. An electric field $\boldsymbol{E}$ applied to the composite produces a mechanical deformation in piezoelectric that in turn is coupled to the ferrite and results in the shift δf in the resonance field. Information on the nature of high frequency ME coupling was therefore obtained from data on shift δf vs $\boldsymbol{E}$. The shift is proportional to linear ME coupling coefficient.

The design of ME microwave device assumes the presence of ME resonator, which is placed on the microstrip line or circuit-resonator, slot line or into waveguide using the circular polarization area of microwave field. The circular polarization of microwave field allows more effectively to use of composite component and allow increase the magnetic susceptibility. The working point is selected depending on the purpose of the device. For example, in case of attenuator or isolator the device is tuned in the resonance absorption. For the phase shifter selects the area near a resonance with the lowest absorption, but maximal depth control.

Computation, design and manufacturing technology of nonreciprocal microwave devices intended for application in receiving-transmitting modules of antenna array have a great interest in current time. Currently, a large development has program High Frequency System Simulator (HFSS) of company AnSoft, which is intended for the analysis of three-dimensional microwave structures, including antennas and non-reciprocal devices containing ferrites and ferroelectrics. Electromagnetic simulation in HFSS is based on the use of the finite element method (Finite Element Method, FEM).

Microstrip line [12], coplanar line and slot line are used in the microwave range. The microstrip lines are used most widely [13-14]. However, at designing the non-reciprocal devices using ferrites it requires the microwave field of circular polarization. In microstrip line this region is absent and the additional elements are needed, for example in the form of stubs to create an area of circular polarization. From this point of view, the slot and coplanar line are of interest. The structure of the microwave field in the slot line and coplanar waveguide is significantly different from the structure of the wave field in microstrip line. Coplanar waveguide (CPW) is a transmission line which consists of a center strip, two slots and a semi-infinite ground plane on either side of it [15]. This type of waveguide offers several advantages over conventional microstrip line, namely, it facilitates easy shunt as well as series mounting of active and passive devices; it eliminates the need for wraparound and the holes, and it has a low radiation loss. Another important advantage of CPW which has recently emerged is that CPW circuits render themselves to fast and inexpensive on-wafer characterization at frequencies as high as 50 GHz. Lastly, since the microwave magnetic fields in the CPW are elliptically polarized, nonreciprocal components such as ferrite circulators and isolators can be efficiently integrated with the feed network.

Fig. 2 (a, b, c) shows the computer model of ME devices on a different type of transmission line.

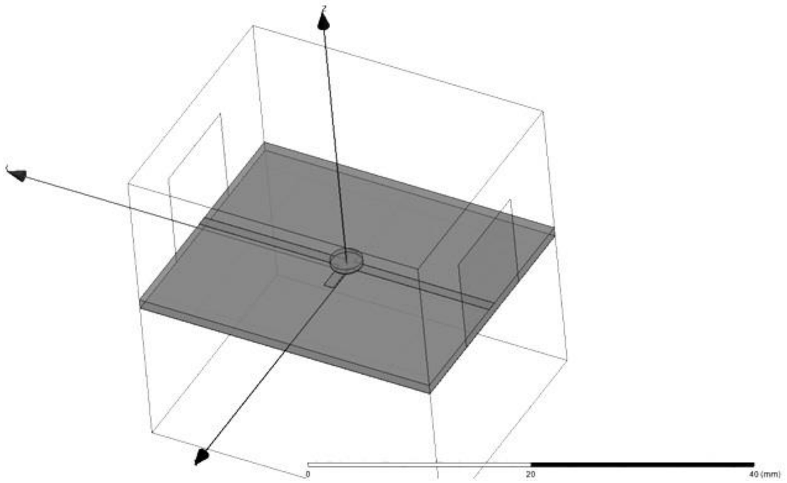

Fig. 2 a) Microstrip line

The transmission line structure in Fig.2a) consisted of microstrip lines of nonresonant lengths with two stubs of lengths 1/8 and 3/8 wavelengths on a dielectric substrate with ground plane on bottom side. the stubs is required for creating of elliptically polarized microwave magnetic field.

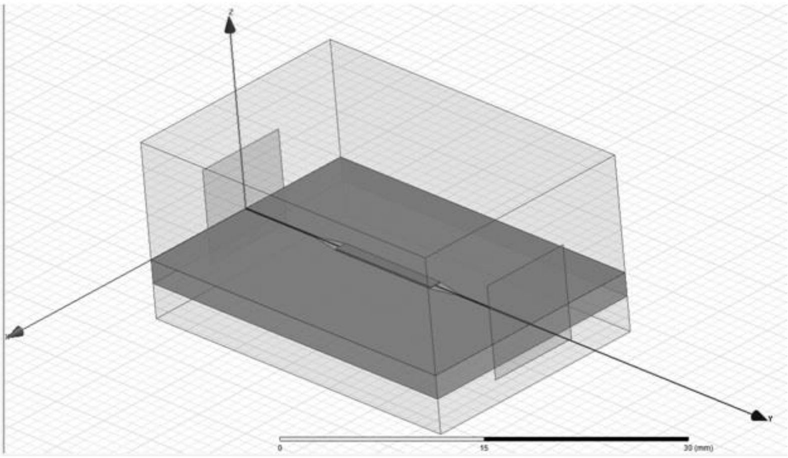

Fig. 2 b) Slot Line

The slot line transmission systems [16-17] has been shown to contain elliptically polarized ***H*** field regions which are required for producing nonreciprocal microwave devices. The development of such a device was dependent on being able to determine a ME composite - slot line configuration that would yield good interaction between the ME resonator and the propagating mode of the slot line with a minimum of concurrent insertion loss. The microstrip to slot line transition is used to convert input microwave signals from a TEM mode to the required slot line mode. The slot width on the transition is designed so as to match into the slot line etched on one of the ME resonator inserts in the slot of the device. The pertinent characteristics of this type of transmission system such as field configurations, propagation constants, and impedance as functions of dielectric material characteristics, dielectric thickness, and slot width were derived. The slot line contained an microwave magnetic field configuration which was suitable for generating nonreciprocal ME devices. There existed regions within the slot line that contained circularly or elliptically polarized microwave magnetic field.

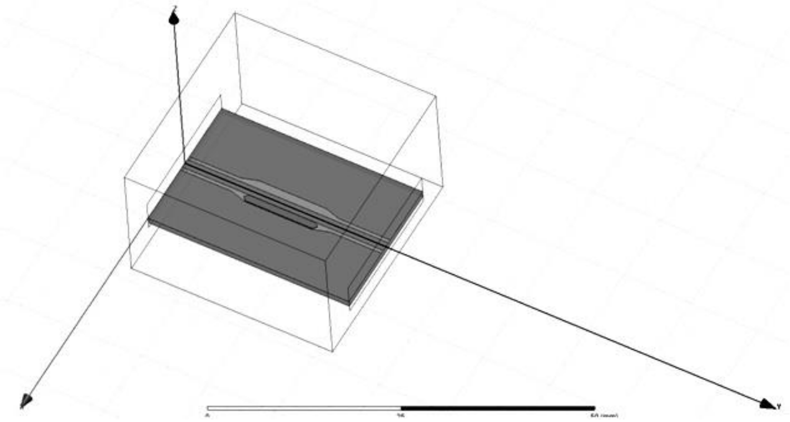

Fig. 2 c) Coplanar waveguide

The use of modern simulation software allows the fast design of various types of non-reciprocal microwave devices. We conducted a simulation of various types of non-reciprocal magnetoelectric devices based on slot and coplanar lines by using the HFSS. A comparison with similar devices based on the microstrip line was made.

3. RESULTS AND DISCUSSION

Simulation of the devices is made in the software environment of the HFSS program. S-parameters in the frequency range are optimized for investigated device. The amplitude characteristics were investigated. Computer simulation results for different designs of ME microwave devices realized on the strip transmission lines are shown in the figures.

Figure 3 shows the frequency dependence of the microstrip line attenuation in the forward and reverse directions.

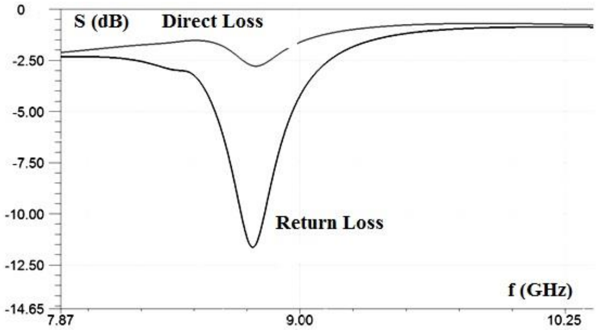

Fig. 3 The microstrip transmission line. Dependence of attenuation vs. frequency. The resonators parameters is YIG disk: thickness is 0.1 mm on GGG substrate with thickness 0.44 mm and diameter of 3 mm; magnetizing field is 2700 Oe.

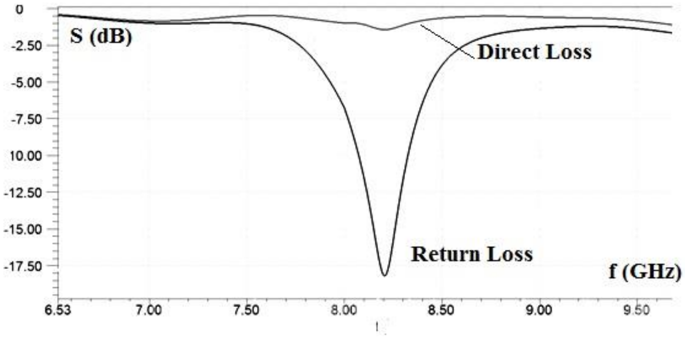

Fig. 4 Slot transmission line. The dependence of the attenuation vs. frequency. resonator dimensions is 10 mm×1 mm×0.2 mm; slot line width is 0.62 mm, widening the gap to 1.2 mm; the relative permittivity of the substrate is 30, the substrate thickness is 2 mm; magnetizing field is 2514 Oe.

Figure 4 shows the frequency dependence of the slot transmission line attenuation in the forward and reverse directions.

Figure 5 shows the frequency dependence of the coplanar transmission line attenuation in the forward and reverse directions.

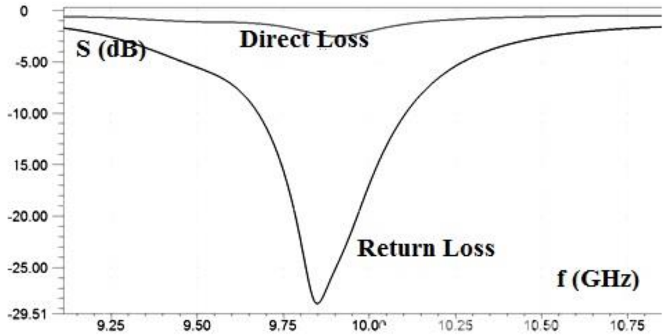

Fig. 5 The coplanar transmission line. Dependence of attenuation vs. frequency. Resonator dimensions is 0.6×4×0.1 mm^3; slot width is 0.4 mm; The center conductor width is 0.6 mm; ε of substrate is 40; substrate thickness is 1 mm; magnetizing field is 3125 Oe.

Figure 6 shows the experimental frequency dependence of the coplanar transmission line attenuation in the forward and reverse directions. The experimental investigation of the ME microwave properties of the bilayer structures were based on the measurements of the resonators frequency responses for different values of external *dc* voltage and bias magnetic fields. Namely, reflection spectra $S_{11}(f) = 10\,log|P_{ref}(f)\,/\,P_{in}(f)|$, where $P_{in}(f)$ is an incident power, $P_{ref}(f)$ is a reflected power, and f is the excitation frequency, were measured. The frequency responses were carried out with Agilent Network Analyzer.

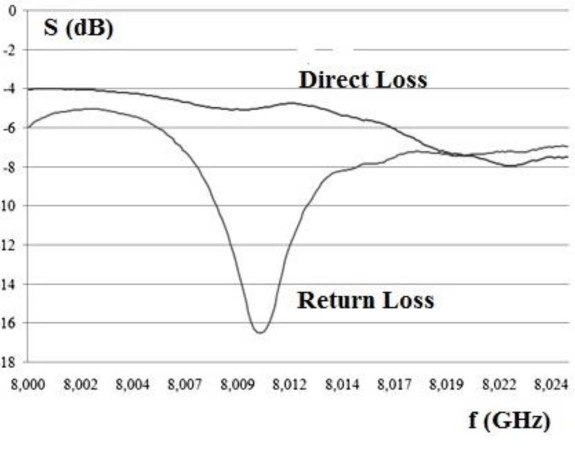

Fig. 6 For comparison. Coplanar waveguide, the experimental frequency dependence of attenuation. magnetizing field is 2780 Oe.

Computation, design and manufacturing technology of nonreciprocal microwave devices have a great interest in current time. The main directions for further research based on the use of modern computer design programs. The use of modern simulation software allows the fast design of various types of non-reciprocal microwave devices.

That simulation allows to get the selection of substrate parameters and the shape of ME resonator. The ME resonator based on layered structure of YIG and PZT was used. To decrease the control voltage and the increase the valve ratio it is necessary to reduce the thickness of the piezoelectric, and hence the thickness of the ferrite. The use of computer simulation for ME structures in the non-reciprocal microwave devices opens promising opportunities for the creation of the new devices.

3. CONCLUSION

Magnetoelectric layered structures are ideal for studies on wideband magnetoelectric interactions between the magnetic and electric subsystems that are mediated by mechanical forces. Such structures show a variety of magnetoelectric phenomena including microwave ME effects. The phenomenon can be used for creating electrical tuning the microwave ME resonators and devices on their basis.

The possibility of ME microwave devices realization on the strip transmission lines controlled by both electric and magnetic fields are shown. The results of computer simulation of various ME microwave devices designs with resonators based on ME layered structures placed into the transmission line are given. The simulated results are compared with the experimental results.

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