Magnetic Field Controlled Microwave Hybrid Oscillations in Composite Resonator Dielectric-weak Ferromagnet

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Abstract— The high-frequency properties of a composite resonator comprised of a microwave dielectric and a weak ferromagnet were investigated in the X-band. It was shown that inclusion of the weak ferromagnetic phase leads to possibility of magnetic field control over the resonator frequency, Q-factor and transmission characteristics that are in qualitative accordance with the predictions of perturbation theory. Magnetic field tunable change in insertion losses up to 16 dB and resonance frequency tuning up to 85 MHz have been observed. Such resonators are of interest for application in frequency agile devices with electronically tunable electrodynamic characteristics for the mm and sub-mm wave bands.

1. INTRODUCTION

Current trends in mobile communications, wireless technologies and radiolocation require improvement of the existing UHF components. Stripline and dielectric resonator based UHF filters, which are the key elements of the modern transceiver equipment [1–3] lack the possibility of dynamical tuning of their characteristics. Since utilization of electronically tunable components can greatly increase the functionality of microwave devices (resonators with controlled electrodynamic characteristics can find application in reconfigurable matched filters [4], that dynamically adjust their properties in accordance to the spectrum of an incoming signal), development of frequency agile devices on the basis of high-Q dielectric resonators (DR) is an important and urgent task.

It is known, that electronically reconfigurable devices could be realized by inclusion of ferroelectric [5], semiconductor [6] or ferrite [7] constituent with tunable dielectric constant, capacitance, or magnetic permeability. Other tuning techniques, with the assistance of electromechanical actuators or MEMS [6, 8] also had been demonstrated.

In this report, we present a concept for magnetic field tunable devices based on electrodynamically coupled bulk dielectric resonator and a weak ferromagnet. In such structures unperturbed resonance frequency of bulk DR determines the operating frequency of device, whereas weak ferromagnet component facilitates required electronic tunabilty. Weak ferromagnets are of special interest for applications, due to the strong effect of relativistic Dzyaloshinsky-Moriya field [9] on the frequencies of their magnetic eigen-excitations. Thus, composite resonator, containing weak ferromagnet component, is potentially suitable for reconfigurable microwave devices, operating at frequencies of few tens gigahertz (if quasi-FMR mode is utilized) or even at few hundreds of gigahertz (where quasi-AFMR mode comes into play) with very moderate and easily attainable external bias field [10].

2. EXPERIMENTAL RESULTS

We investigated composite resonator, which consisted from two components: 1) disk-shaped dielectric resonator from commercial grade microwave ceramics and 2) thin platelet of single-crystal iron borate ($FeBO_3$) with lateral dimensions $2.1 \times 2.3\,\text{mm}^2$ and 100 µm thickness. Iron borate is a well-known two-sublattice weak ferromagnet [10, 11], with a spontaneous moment $4\pi M = 115$–120 G at room temperature (Neel temperature is equal to 348 K) and and is transparent in the visible region of the EM spectrum. The material demonstrates an uniaxial magnetocrystalline "easy plane" type anisotropy ("easy plane" is orthogonal to the rhombohedral (111) direction) with negligible in-plane hexagonal anisotropy. For this work, high-quality single-crystal $FeBO_3$ platelets were grown by us from solution in melt [12]. They have had a hexagonal shape with trigonal crystallographic axis C_3 pointed perpendicularly to the developed faces.

2.1. Weak Ferromagnet Characterization

As a first step, a frequency vs. field dependence for $FeBO_3$ was measured, in order to extract crucial magnetic parameters of the material. For the measurements a custom made 50 Ohm coplanar transmission line was manufactured on 0.04 inch thick RT Duroid 5880 substrate. Then the specimen was placed atop of coplanar transmission line and put inside the solenoid coil, which could produce longitudinal magnetic field up to 450 Oe. A set of transmission characteristics of experimental measuring cell for in-plane bias magnetic field in the range from 10 to 415 Oe were recorded using Agilent N5230 vector network analyzer. Quasi-FMR frequency vs. field dependence for investigated sample, extracted from network analyzer data, is presented in Fig. 1 with squared dots According to the results of [10], frequency of the uniform quasi-FMR mode in weak ferromagnet, for the case when an external magnetic field is in basal plane, is given by the following expression:

$$\omega_F^2 = \gamma^2 \left(\left(H_0 + 4\pi M(N_x - N_z) \right) \left(H_0 + 4\pi M(N_y - N_z) + H_{DM} \right) + H_\Delta^2 \right) \tag{1}$$

where H_0 — bias fields, H_{DM} — Dzyaloshinsky-Moriya effective field term, γ is the gyromagnetic ratio, N_i — are the demagnetizing factors, H_Δ^2 is an energy gap due to the magnetoelastic interaction [11]. Since H_{DM} is always large compared to the magnetization, and for a given thin-plate geometry N_x, $N_z \approx 0$, Equation (1) can be simplified to

$$\omega_F^2 = \gamma^2 \left(H_0 \left(H_0 + H_{DM} \right) + H_\Delta^2 \right) \tag{2}$$

Solid line on Fig. 1 is a theoretical curve, drawn using model Equation (2). From the best fit between theory and experiment a magnetic parameters of $FeBO_3$ were determined to be $H_{DM} = 49.9\,\text{kOe}$, $H_\Delta = 2.1\,\text{kOe}$, which are close to previously published values [10, 11].

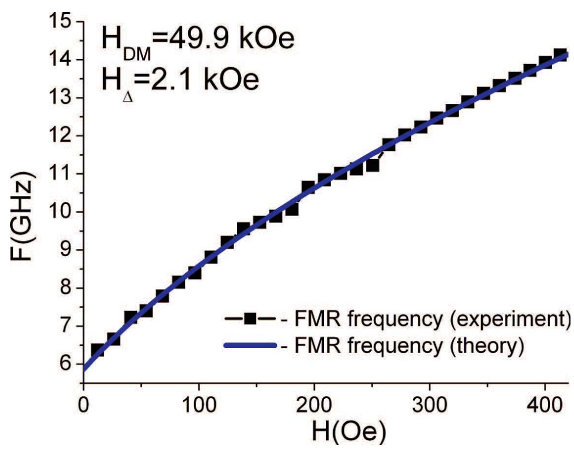

Figure 1: Frequency vs. field dependence for quasi-FMR mode in $FeBO_3$ sample. Dots — experiment, solid line — theoretical calculations using Eq. (2).

2.2. Investigations of Hybrid Oscillations in Composite Resonator Dielectric-weak Ferromagnet

Next, this $FeBO_3$ sample was epoxy bonded to the cylinder-shape dielectric resonator (diameter $D = 5.1\,\text{mm}$ and thickness $S = 3.1\,\text{mm}$), and put inside the rectangular metallic X-band waveguide with $23 \times 10\,\text{mm}^2$ cross-section. Composite resonator was positioned on the waveguide wide wall, with $FeBO_3$ in direct contact with metal and secured in place using slab of foam. External bias magnetic field from solenoid coil was applied in sample's plane, and directed along the waveguide axis. Microwave measurements in transmission mode were done using X-band scalar network analyzer. During the experiment, dielectric resonator was excited on two lower-order $HE_{\pm 11\delta}$ modes. These modes are circularly polarized and have opposite senses of rotation of their rf electric and magnetic field vectors (clockwise and counterclockwise). Due to the lack of cylindrical symmetry of waveguide section metal walls, the frequency degeneracy is removed and modes are well separated. Also, it is worth to note, that actual frequency splitting between modes under consideration would depend on the symmetry of the metal surrounding, i.e., position of resonator inside the waveguide. As follows from the above discussion, our composite resonator consists of two parts, each of which is a microwave resonator of their own. Dielectric resonator is characterized by a discrete set of eigenmodes, with their resonant frequencies and Q-factors depend on dielectric constant, resonator dimensions and position, but do not depend on the external magnetic field. On the contrary, weak ferromagnet constituent has a single resonant frequency, which is nearly independent of sample dimension, but strongly depends on magnetic bias (see Fig. 1). When combined together, large area of contact between ferrite and dielectric in such heterostructure favors substantial penetration of DR high-frequency electromagnetic field into ferrite platelet, resulting in strong interaction and hybridization between both oscillations even for marginal relative volume V_f of the ferrite component. We would treat dielectric resonator modes as the dominant ones, whereas FMR oscillation in iron borate will be considered as a perturbation. Hereafter we assumed that permeability tensor for quasi-FMR mode is the same that for uniformly magnetized ferrimagnet with proper magnitude of saturation magnetization. Then, if the perturbation object is located in a region where the microwave magnetic field is circularly polarized, according to the general perturbation theory, one can expect both resonance frequency shift and quality factor deterioration [13, 14]:

$$\left(\frac{\Delta f_r}{f_r}\right)_{\pm} \propto \frac{\mu' \pm \mu'_a - 1}{2}\frac{V_F}{V_{DR}}, \quad \Delta\left(\frac{1}{2Q}\right)_{\pm} \propto \frac{\mu'' \pm \mu''_a}{2}\frac{V_F}{V_{DR}} \tag{3}$$

where μ and μ_a are the diagonal and off-diagonal elements of the ferrite rf permeability tensor [13, 15] and the $\pm$ sign refers to rf fields sense of rotation (right-hand and left-hand, correspondently). The coefficient of proportionality is related to the DR microwave magnetic field configuration.

Next, since at the given frequency real and imaginary parts of high-frequency right hand scalar magnetic permeability $(\mu + \mu_a)$ reach their maximum values at, correspondently, magnetic field near to and equal to FMR field [15], we can expect the largest impact of ferrite constituent on the hybrid oscillations, when external bias magnetic field is close to the value H_{res}, for which FMR frequency would coincide with the dielectric mode unperturbed frequency: $\omega_F(H_{res}) = \omega_{HE_{\pm 11\delta}}$. Experimental results on the transmission characteristics modification with external in-plane bias magnetic field for composite resonator was positioned at the middle of the wide wall are shown in

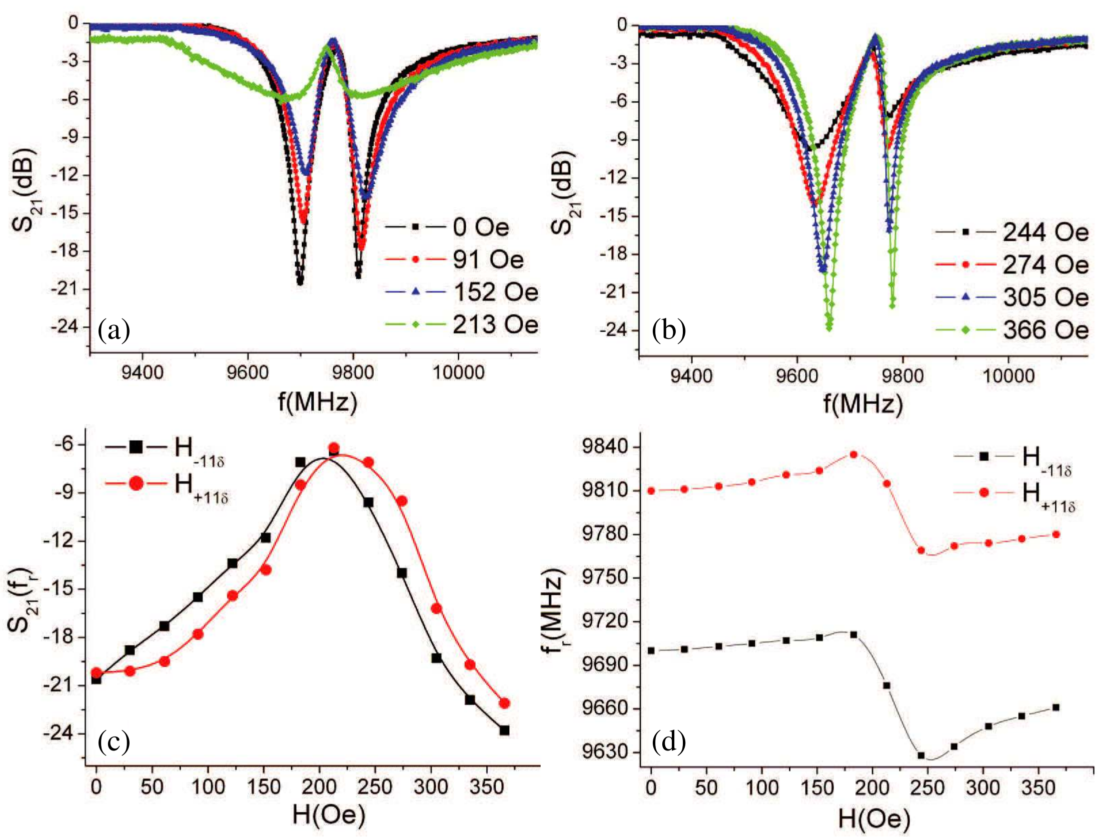

Figure 2: Transmission characteristics of composite resonator at different bias fields.

Fig. 2. Frames a) and b) show evolution of transmission characteristics with increasing bias, frame c) shows dependence of transmission at resonance $S_{21}(f_r)$ vs. magnetic field, and on d) resonance frequency f_r vs. magnetic field is depicted. Solid lines on frames c) and d) are drawn by the eye.

3. DISCUSSION

Figure 2 demonstrates the impact of FMR in weak ferromagnet on the properties of hybrid oscillations. In full accordance with perturbation theory, we observe changes in both eigenfrequency and Q-factor. The latter one is visible not only in the increasing of the resonance curve width, but also in the of transmission losses decreasing. Indeed, transmission coefficient at resonance frequency is inversely proportional to the coupling coefficient K, which, in turn, is directly proportional to the resonator unloaded Q-factor. Therefore, decreasing of Q lead to increasing of $S_{21}(f_r)$. Hence, we can draw conclusions on Q-factor changes directly from the frame c). Also, from the above figures one can observe, that the H-field dependence on frames c) and d) have the rather specific shape, very akin to the shape of, correspondently, $(\mu'' + \mu''_a)$ and $(\mu' + \mu'_a)$ vs. H_0 profiles [13, 15]. Thus, these results agree qualitatively with perturbation theory. Numerical characteristics of coupling strength between quasi-ferromagnetic and dielectric modes are the following: maximum change in transmission coefficient at resonance frequency amounted to 16 and 15 dB respectively (here and below first number corresponds to $HE_{-11\delta}$ mode and the second one — to $HE_{+11\delta}$), whereas the frequency jump in the vicinity of $H_0 = H_0^{\text{FMR}}$ was found to be 85 and 70 MHz. These results allowed as to conclude that in given position an almost equal coupling to both DR modes is provided.

4. CONCLUSION

In this paper, we have investigated the high-frequency properties of composite resonator dielectric-weak ferromagnet in the X-band. Transmission characteristics for different bias magnetic field in range from 10 to 370 Oe were recorder and analyzed. It was demonstrated that inclusion of weak ferromagnet constituent leads to possibility of electronic control over a composite resonator frequency and Q-factor. As far as we used the scalar network analyzer, only magnitude of transmission characteristic was investigated. However, it is known that phase transmission characteristics of any resonator strongly depend on its f_r and Q-factor, one can expect a profound impact of bias field on the phase properties of such composite resonator. It was shown, that profiles of f_r vs. H_0 and $1/Q$ vs. H_0 curves are in qualitative accordance with the predictions of perturbation theory, with maximum impact observed when magnetic field related FMR frequency coincided with unperturbed frequency of corresponding DR mode. Magnetic field tunable change in insertion losses up to 16 dB and DR resonance frequency tuning up to 85 MHz ($\approx 1\%$ of central frequency) have been observed. The magnetic field required for demonstrated here tunability does not exceed 400 Oe and can be conventionally obtained using relatively small and light-weight electromagnets. Therefore we can conclude, that such composite resonators, comprised from high-quality dielectric resonator and H-field tunable weak ferromagnetic constituents, provide a flexible tool for use in agile microwave devices with controlled electrodynamic characteristics and have a potential for both K-band and (in perspective) sub-mm wave applications.

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