Ferromagnetic Composite-Based and Magnetically-Tunable Microwave Devices

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Abstract **– This article deals with a new generation of tunable microwave devices using ferromagnetic materials. The sensitivity of the device cut-off frequency to the dc magnetic field was investigated for two filtering resonators (stub resonator and Stepped Impedance Resonator). The stub resonator exhibited a frequency tunability of nearly 40% for a dc magnetic field strength of 250 Oe, whereas the linewidth remained unchanged. A 12.2% tunability of the SIR device was reached under 250 Oe applied.**

I. Introduction

Achievement of tunable microwave devices using frequency agile materials has led to a new generation of components [1],[2]. In this study, microwave properties of ferromagnetic composites are exploited to ensure tunability of filtering functions. In comparison with ferrites, this composite is characterized by a higher saturation magnetization and a better sensitivity to the dc magnetic field. Because of eddy currents in ferromagnetic materials, the ferrocomposites are integrated in microwave devices in a way different from that of ferrites. Correlation between magnetic properties of the composite and tunable microwave devices was first studied [3]. Then, the cross section of a microstrip line in which the material is inserted was optimized in order to have a propagation structure which can be used for tunable devices.

Our investigations were based on this microstrip line and focussed on the use of the gyromagnetic absorption to work out stop-band functions or switches. Unfortunately, the quality factor of the stop-band function is too low to achieve filters. Another way to tune device frequency response is to work on the dc magnetic field dependence of the propagation structure effective-permeability. Exploitation of these properties has led to design tunable phase shifters [4].

Here, this phenomenon is exploited to ensure tunability of filtering devices. The sensitivity of the propagation structures to the external field is reported. It permits to highlight the major interest of ferromagnetic composite application to microwave devices.

II. The Ferrocomposite Test Device

A. The LIFE Composite

Here we used a Laminated Insulator / Ferromagnetic illuminated on the Edge (LIFE) material (Fig.1) [5]. The composite consists in an alternation of ferromagnetic thin films and dielectric layers (thickness of 0.43 and 12.7 µm, respectively). Ferromagnetic layers present an in-plane anisotropy due to the static field generated by the magnetron sputtering. The ferromagnetic layers saturation magnetization ($4\pi M_S$) is about 11.3 kG. The gyromagnetic resonance occurs in the vicinity of 1.8 GHz; the frequency is determined from relation (1):

$$f_r = \gamma.\sqrt{\left(H_0 + H_a + q.\left(N_x - N_z\right)4\pi M_S\right)} .\sqrt{\left(H_0 + H_a + q.\left(N_y - N_z\right)4\pi M_S\right)} \quad (1)$$

where H_0 is the external dc magnetic field applied along Oz axis (easy axis), H_a is the anisotropy field, q is the volumic fraction in ferromagnetic material in the composite and N_x, N_y, N_z are the demagnetizing coefficients of the sample respectively along Ox, Oy, Oz axes. The gyromagnetic frequency is mainly governed by the demagnetizing effects. These fields find their origins in the sample shape and in the rf magnetic flux that passes through the ferromagnetic material.

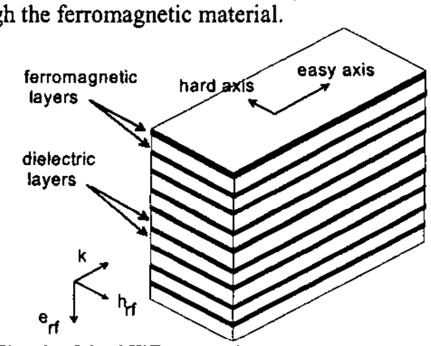

Fig.1. Sketch of the LIFE composite.

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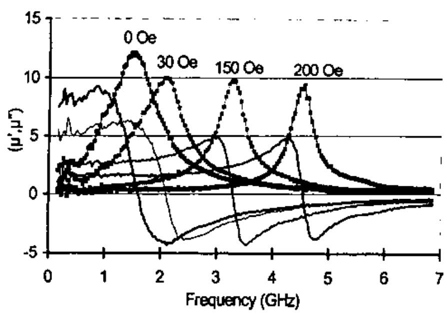

Fig. 2. Real part (μ', plain line) and Imaginary part (μ", dotted line) of permeability under various magnetic dc-field intensities.

Measurements of microwave permeability using an asymmetrical stripline demonstrate that the permeability is clearly affected by the application of a dc magnetic field directed along the easy axis of the composite (Fig. 2), *i.e.* the propagation direction [6]. The LIFE composite is characterized by a high permeability level in the frequency range located beneath the gyromagnetic frequency. The relative real part of the permeability (μ') goes from 9.5 to unity under a 200 Oe dc field, whereas the gyromagnetic frequency shifts from 1.8 GHz to more than 4 GHz. This non-linearity of the permeability under dc field is the basic concept of the change in resonator electrical length. Exploitation of this phenomenon requires the integration of the material in a propagation structure.

B. The LIFE microstrip line

In order to achieve a high tunable microwave permeability level the location of the LIFE material was optimized. Indeed, to be useful at microwave frequencies, the rf electric field must be perpendicular to the ferromagnetic layers when the composite is lighted on the edge. Moreover, the microwave magnetic field has to be parallel to the layers and perpendicular to the easy axis of ferromagnetic layers as shown in figure 1. In the eigenpolarization, the composite behaves as a plain conductor. The electromagnetic quasi-transverse mode of a microstrip line (fundamental mode) makes possible a correct illumination of the composite. The material is inserted in the substrate between the ground plane and the conducting strip to respect the field polarization of the LIFE material (Fig. 3). The sample width must be smaller than the strip one to avoid eddy currents in the ferromagnetic planes. This configuration led us to work out tunable microwave functions based either on the gyromagnetic frequency, or on the in-plane anisotropy, or on the permeability dc-field dependence [3].

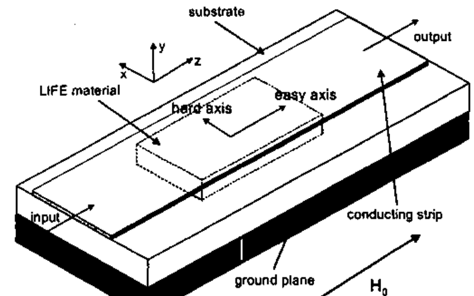

Fig. 3. Sketch of the LIFE composite inserted in a microstrip line.

III. TUNABLE MICROWAVE DEVICES

A. Experimental conditions

The microstrip circuits were measured at room temperature using a HP8720 Network Analyzer. Systematic errors were reduced by performing a conventional Short-Open-Load-Through (SOLT) calibration.

Magnetization of the LIFE composites inserted in propagating structures was performed using a pair of Helmholtz coils. The static magnetic field (H_0) was applied along the easy axis of the LIFE sample in order to obtain a continuous shift of the S-parameters. To get a discrete tunability of the device between the lower and upper frequency responses, $\mu_r' = 9.5$ and $\mu_r' = 1$ respectively, one can apply a dc magnetic field along the hard axis of the LIFE material. In the saturated case, magnetic moments are directed along the hard axis. This configuration led to a permeability level close to unity and no gyromagnetic phenomenon. In this case, the dc field strength must be greater than the sum of anisotropy field (H_a) and demagnetizing fields that depend on the sample shape.

B. Stub resonator

To emphasize the magnetic tunability of microwave devices using LIFE material with low field strength, a band-stop function based on a quarter-wave stub circuit was worked out. The exploited phenomenon is the static field dependence of the ferromagnetic permeability. The microstrip circuit is depicted in Fig. 4. A $25 \times 2 \times 0.635$ mm^3 LIFE sample surrounded with a foam substrate is covered by the center-strip conductor of the quarter-wave line. The stub was designed for a 1.8 GHz cutoff frequency of the circuit; it was smaller than the gyromagnetic resonance frequency of the composite sample to ensure low magnetic losses in the exploited frequency band (0 - 3 GHz). The stub length was calculated with ADS software for a saturated material ($\mu'=1$) is 30 mm.

Application of a variable external dc field in a direction parallel to the quarter-wave line (Fig. 4) modifies the electrical length of the stub, and then the cutoff frequency of the circuit. The magnitude of the transmission coefficient is plotted versus frequency (Fig. 5). It shows that the cutoff frequency shifts from 1.17 GHz at zero field to 1.71 GHz at 250 Oe bias. A tunability of 37% of the stop-band function is obtained. The stop-band depth varies from 15 to 22 dB and the bandwidth slightly depends on the applied magnetic field. The bandwidth is, indeed, within 160 and 190 MHz. The minimum pass-band insertion loss is -1 dB; it is sensitive to the gyromagnetic phenomenon that occurs in the vicinity of 2.8 GHz at zero field.

Fig. 6 depicts the center frequency shift of the stub resonator versus the applied dc magnetic field. The curve slope represents the field sensitivity of the propagation structure. One should note that the major tunability of this microwave device is obtained at low fields. The dc field intensity at which the slope value decreases is close to the field intensity necessary to saturate the LIFE composite.

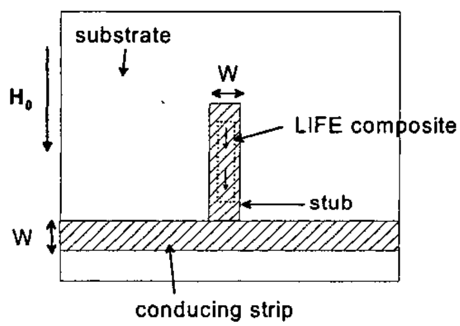

Fig. 4. Top view of a stub resonator made on the LIFE composite.

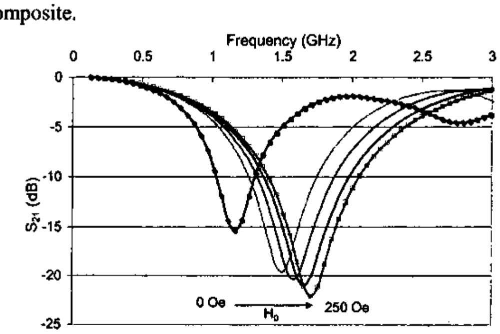

Fig. 5. Measurements of the transmission parameter of the stub resonator under various magnetic dc-field intensities.

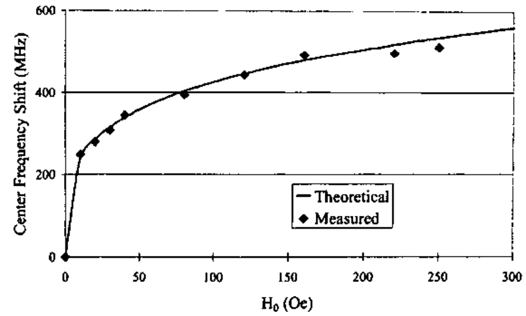

Fig. 6. Cutoff frequency shift versus the dc magnetic field of the stub resonator.

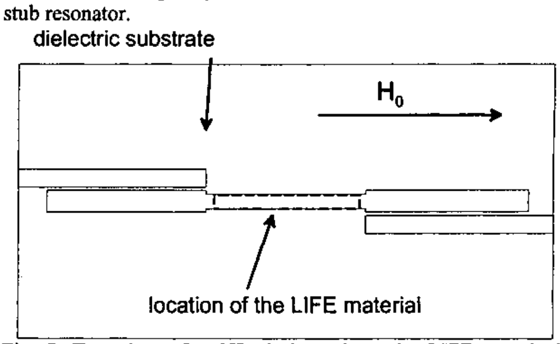

Fig. 7. Top view of a SIR design where the LIFE sample is inserted.

C. Stepped Impedance Resonator

The Stepped Impedance Resonator (SIR) bandpass filters are well known for their numerous advantages [7]. Among them, the control of spurious responses thanks to the resonator characteristic-impedances ratio are of high interest. Indeed, insertion of the LIFE composite in the resonator modifies its characteristic impedance. Moreover, gyromagnetic resonance may affect spurious frequencies, and then results in an attenuation of spurious responses of the device.

A $8 \times 1 \times 0.508$ mm^3 LIFE sample was inserted in the center of a resonator (Fig. 7). Electric components of the microwave mode of coupled lines in the ferromagnetic layers were avoided by inserting the LIFE material out of coupling regions. Access and coupled lines were designed for a 50-Ohm impedance on an Arlon substrate ($\varepsilon_r'=2.2$, $\tan\delta=0.004$). Inner conductor was designed for 60 Ohms. This impedance had been chosen to have the first spurious response in the vicinity of the gyromagnetic resonance frequency. The substrate had been selected for its relative permittivity close to that of the LIFE composite ($\varepsilon_r'=2.25$) to minimize the impedance mismatch at the discontinuities. The dimensions of conducting strips and air gaps were determined for 5% bandwidth at 1.95 GHz on the dielectric substrate without LIFE sample.

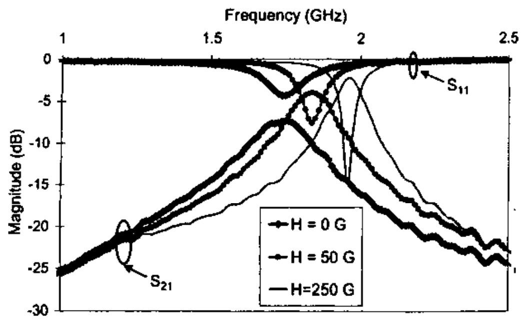

Fig. 8. Measured responses for a SIR filter under various dc magnetic field strengths.

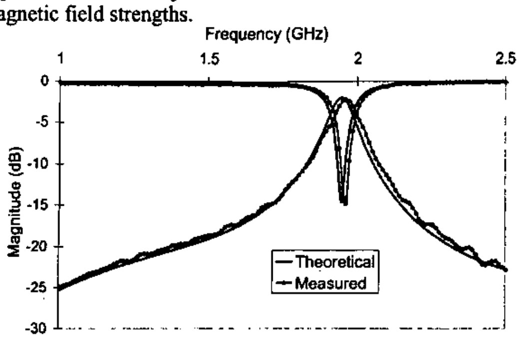

Fig. 9. Magnitudes of the SIR simulated frequency responses and measured one's in the saturate state.

The resonator was biased along the easy axis of the LIFE sample. Fig. 8 shows the frequency response of the SIR under various dc field strengths. The insertion losses of the resonator are -7.42 dB and the relative bandwidth was 13.3 % (Q = 7.5) at zero bias. The insertion losses are improved to -2.23 dB at 250 Oe bias. The center frequency of the SIR shifts from 1.76 GHz at zero bias to 1.97 GHz at 250 Oe bias resulting in a tunability of 12.2%. In the saturate case, the frequency response of the SIR is close to the simulated one (Fig.9). Indeed, a discrepancy of 20 MHz is observed between the two center frequencies. A relative bandwidth of 5.06% (Q = 19.7) is measured in the saturate case, whereas the simulated one is about 5%. The observed insertion losses in the demagnetized state arise from both the impedance mismatch and the high value of the resonance linewidth of the composite (ΔF=0.9 GHz). The former is due to the insertion of the LIFE sample in the propagating structure. The frequency response could be improved by inputting the magnetic losses of dispersion in the permeability model of the simulation software. One should note that the transmission level is lower than –25 dB, that is out of the useful frequency range.

The dc field sensitivity of the SIR function is similar to the stub one's. The major tunability is achieved with low field strength. However, the sensitivity parameter is lower than the stub resonator one's. This is due to static demagnetizing fields which induced a lower internal field.

IV. Conclusion

In summary, LIFE composites have been inserted in the substrate of propagating structures in order to ensure tunable frequency response of devices at microwave frequencies. Two different resonant devices have been reported. Tunabilities of 37 % at 1.71 GHz for a bandstop function and of 12.2 % at 1.76 GHz for the passband function are achieved with low dc field strengths (250 Oe). The major interest of the use of ferromagnetic composite in microwave devices is the high sensitivity of the guided wave structure to low dc magnetic field.

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