### Voltage tunable microwave ferrite resonator

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Abstract — A novel method of implementing a tunable resonator using an applied voltage is presented. Stress is used to tune a microstrip resonator fabricated on a polycrystalline ferrite substrate. The stress was applied either mechanically with screws or electronically using piezoelectric actuators. We have demonstrated tunability of 300 MHz using screws and 50 MHz using a piezoelectric actuator at a center frequency of 2.3 GHz. Explanation of the tuning method is given and means to extend the tuning range is discussed. This method opens the possibility of compact low-power tunable filters with wide tuning range at microwave frequencies.

Index Terms — Tunable filters, Ferrite filters, Microstrip resonators, Microwave filters.

I. INTRODUCTION

There is a need for rapidly tunable resonators and filters with low loss and compact volume operating in the microwave frequency range. We report here on a novel tuning method that uses stress to change the resonant frequency of a stripline resonator fabricated on a suitable polycrystalline ferrite substrate. The stress can be applied with a piezoelectric actuator so that a voltage is used to perform the tuning. This method holds the promise of low power consumption as no holding current is needed to maintain a particular tuning, and small size, barely larger than the microstrip device, as the actuators are very compact. In the following, we show the initial results with both piezoelectric application of stress and mechanical application of stress, with which we were able to show tuning \( \Delta f/f_0 \) of greater than 13% in a microstrip resonator, where \( f_0 \) is the center frequency of the resonator and \( \Delta f \) is the full tuning range, with \( f_0 = 2.3 \) GHz. This method should also be applicable to resonators and filter at X-band and higher frequencies.

II. BACKGROUND

This group has previously demonstrated microstrip filters on ferrite substrates with excellent characteristics [1]. These filters employed a high-temperature-superconductor microstrip at 77 K to achieve extremely low loss. Subsequent work using conventional conductors at room temperature has shown losses of approximately 2 dB [2]. These filters demonstrate that \( \Delta f/f_0 \) of as much as 20% is possible. These previous devices used an externally applied magnetic field, of order one hundred gauss, to change the magnetization of the ferrite and thereby change the effective permeability of the substrate. The tunability is a direct result of changing the permeability. While the low values of magnetic field needed to tune the filters are applied with a rather simple coils, the operation requires current to be applied continuously and thus adds to weight, volume, and power consumption. The added weight and volume compromise the compactness of the microstrip circuit.

Conventional YIG filters [3] operate at the frequency of the ferromagnetic resonance in the material. The tuning results from the change of the resonance frequency. The filter is synthesized from the ferrite material itself and the resonator Q is determined by the ferromagnetic resonance linewidth. In our scheme, the resonator consists of the half-wave microstrip transmission line that operates at a frequency different from that of the ferromagnetic resonance. The tunability results from the change in effective permeability as the magnetization of the substrate changes from perpendicular to the RF magnetic field in the stripline (minimum interaction) to parallel (maximum interaction). In principle, the change in the ferromagnetic resonance frequency is very small and incidental to the change in net magnetization resulting from the application of an external field. This also decouples the resonator Q from the resonance linewidth so that higher Qs can be obtained than would be indicated by the linewidth. However, operating off-resonance in this manner, results in smaller tuning ranges. While YIG filters and resonators can be tuned over more than an octave of frequency, off-resonance tuning is limited to approximately 20% tunability, a number large enough to fulfill the needs of many applications.

III. DEVICE DESCRIPTION

Since the tuning in [1] results from the change in the scalar effective permeability, it is a reciprocal effect and depends on the square of the magnetization. This is the key to understanding the operation of the device described in this report. Because the resonator is a reciprocal device, a net magnetization vector is not required as in the case of a nonreciprocal phase shifter or circulator/isolator. A sufficient condition is the alignment of magnetic domains in 180° patterns. This can be accomplished through magnetoelastic interaction induced by uniaxial stress applied either parallel or perpendicular to the direction of propagation. The 180° rotation of domains by stress is shown schematically in Figure 1. We expect that
compressive stress sufficient to control the orientation of the domain alignment patterns depicted in Figure 1 can be obtained from commercially available piezoelectric transducers. This report demonstrates the use of stress to change the magnetization of the ferrite and produce the tuning of a resonator without the application of a magnetic field. Earlier reports have proposed this idea [4,5]. The stress can be applied with a piezoelectric actuator and thus be induced by a voltage that requires no holding current in the static case. This tuning method can be implemented in a compact volume no greater than the microstrip circuit, requires very low power for the tuning, and should be tunable in times of order $\mu$s.

Figure 1 Schematic diagrams of stripe domain orientations as functions of applied uniaxial stress. 90-Degree closure domains are omitted. This shows the progression of domain orientations as the stress from top to bottom is lowered. The interaction of the domain with the microwave field depends on the direction of magnetization but not the sign.

Ferrites are known to be sensitive to stress [6]. By using a In-substituted YIG, formula $Y_3Fe_{3.7}Al_{0.8}In_{0.5}O_{12}$ [7], the magnetic anisotropy field is designed to be very low, enhancing the stress sensitivity and allowing variation of the magnetization for values of stress producing strain well below the elastic limit. Fig. 2 shows the hysteresis loop for this material. The coercive field is very low. There is a near absence of hysteresis. This indicates that the anisotropy field is low and the magnetoelastic energy density generated by an applied uniaxial stress $\sigma$ along the magnetic field axis must equal or exceed the intrinsic magnetocrystalline anisotropy energy density $K_1$, in order to cancel or reverse the sign of the anisotropy field

$$H_{K,\sigma} = \frac{2K_1}{M} - \frac{3\sigma\lambda}{M}$$

where $\lambda$ is the effective magnetostriction strain constant along the stress axis and $M$ is the magnetization.

Fig. 2 Hysteresis loops for the material used in the experiments. The formula is $Y_3Fe_{3.7}Al_{0.8}In_{0.5}O_{12}$. The inset shows the curves very close to $H = 0$ to demonstrate the very low value of the coercive field.

Fig. 3 Schematic view of ferrite tuning. (a) Tuning by a rotatable magnetic field. The external field magnetizes the substrate with the magnetization of the substrate in the plane. The extremes of tuning are when the magnetization is parallel to the propagation and when it is perpendicular to the propagation. (b) Tuning by rotatable stress. The stress causes the magnetization of the individual domains of the substrate to align perpendicular or parallel to the propagation direction. There is no net magnetization, just the alignment of the domains.

Magnetic-field and stress-tuning methods are compared schematically in Fig. 3. Part (a) of the figure shows the conventional tuning by an external magnetic field. Coils are provided so that the field can be rotated in the plane of the substrate thus producing magnetization in the substrate.
parallel to the externally applied field. When the magnetization vector of the ferrite is parallel to the propagation direction, the interaction between the RF magnetic field of the signal propagating in the microstrip is maximum because the RF magnetic field of the propagating signal is perpendicular to the static field. When the magnetization is perpendicular to the propagation the interaction is minimized. These two orientations thus produce the extremes of tuning of the resonator. The interaction is proportional to the square of the magnetization and so independent of the sign of the magnetization.

Fig. 3(b) shows the application of stress without any external magnetic field. Uniaxial stress can cause the individual magnetic domains of the ferrite to align parallel or perpendicular to the direction of propagation. The domains, however, will tend to be antiparallel to each other, so that the net magnetization remains zero. Since the propagation constant varies with the magnitude not the sign of the magnetization, even without a net magnetization the propagation constant will be affected in the same way as the situation in which a net magnetization exists.

IV. EXPERIMENT

Fig. 4 is a photograph of the test fixture used to demonstrate the stress tuning. A λ/2 microstrip resonator with gold conductor was fabricated on a ferrite substrate 2.5 x 1.3 x 0.05 cm. The resonator is capacitively coupled and designed to be weakly coupled. The package includes screws that can either apply a static stress or preload the resonator so that the piezoelectric actuators can operate under optimum conditions. The resonator is mounted in a rigid stainless steel package. Commercially available actuators are used. In order to produce the estimated strain needed to tune the ferrite, two to three actuators were used. The photograph shows actuators in place to apply stress only in the longitudinal direction. To obtain the maximum tuning stress is also applied in the transverse direction.

Fig. 3 Photograph of the test fixture to demonstrate stress tuning of a ferrite microstrip resonator.

Fig. 4   Photograph of the test fixture to demonstrate stress tuning of a ferrite microstrip resonator.

Fig. 5 Frequency response of the resonator when tuned by stress applied by means of screws located in the test package.

Fig. 5 shows the measured frequency response of the resonator with and without stress applied through the preloading screws. Shown is the relative (uncalibrated) $S_{21}$. The blue curve shows the response without stress, the black curve is measured with stress applied only in the longitudinal direction (parallel to the propagation direction), and the red curve shows the response with stress only in the transverse direction. These curves show the maximum tuning and the tuning is continuous so that any intermediate amount of tuning is also possible. The optically measured displacement in the longitudinal direction for this amount of tuning is $4 \pm 1 \, \mu m$. The strain $\Delta L/L = 2x10^{-4}$ is well below the estimated elastic limit of approximately $10^{-3}$. The full tuning range is 300 MHz, yielding $\Delta f/f_0 = 13\%$.

Fig. 6 Frequency response of the resonator when tuned with two piezoelectric actuators. The voltages used are indicated on the plot. Note that the frequency scale is the same as that in Fig. 5.

Fig. 6 shows the response when tuning the resonator with the piezoelectric actuators applying stress in the longitudinal direction only. The frequency scale is the same as that of Fig. 5. Two actuators in series were employed. As noted the voltage was varied from zero to 160 V. In all cases the static
current is zero. The preloading screws were adjusted to produce the optimum tunability. The tunability with the actuators is 50 MHz. This is smaller than for the case of the screws. A simple model, which uses the Young’s modulus of the ferrite and the force-displacement characteristics of the actuators, predicts a displacement of the ferrite that should produce a tuning range larger by approximately a factor of 5 than that which we measured. We are investigating this discrepancy and further refining the model to obtain agreement with the measurements.

Measurements of the tuning time showed time constants of the order of 1 ms. This time is limited by the capacitance of the actuators and the 50-Ω impedance of the pulse generator available. The off-the-shelf actuators used have a cross section of 1 cm². In a practical circuit the area of the actuator can be made equal to that of the substrate approximately 0.05 cm². This would yield a time constant 20 times smaller and thus faster response. It is expected that the inherent tuning time of the ferrite lies in the μs range.

V. FUTURE WORK

To maximize the tunability, the ferrite is required to have a high \( \lambda/K_1 \) ratio, which can be designed within certain practical limits. Because the garnet family already features low \( K_1 \) values, chemical modifications should be aimed at raising \( \lambda \), which can increase by a factor of ten with only a ten percent concentration of Mn³⁺ ions. A more promising approach lies with the Ni spinel family, in which Co²⁺ ions can not only cancel \( K_1 \) entirely, but will also increase \( \lambda \).

Smaller values of Young’s modulus would lead to larger strain and therefore easier tuning. The garnet ferrites are known to be quite rigid. Other ferrite families hold promise of enhanced operation. For instance (NiAlFe)₃O₄ spinel with a small Co concentration may give the opportunity to raise \( \lambda \) while lowering \( K_1 \).

Other materials and geometries of piezoelectric actuator will be investigated in order for the technology to reach its full potential.

VI. SUMMARY

In summary, we have demonstrated a compact microstrip resonator that can be tuned with an applied voltage, requiring zero holding power and low dynamic power. The tuning speed was measured to be less than 1 ms and with simple design changes we believe that μs tuning is possible. This tuning method should be applicable to multipole filters operating at room temperature with conventional conductors. It is also compatible with high-temperature superconductor circuits operating at 77 K that would allow filters with many poles and narrow bandwidths while preserving very low loss. The demonstrated resonator operated at 2 GHz but we expect that since ferrites operate well at X-band and higher frequencies, a wide frequency range of operation is possible.

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REFERENCES