Modulation of mm-waves by an Acoustically Controlled Monocrystalline Hexagonal Ferrite Resonator

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Abstract

Modulation of mm waves with RF signals can be accomplished using stable non-linear resonance effects in monocrystalline hexagonal ferrite resonators (HFR), characterized by high crystallographic anisotropy. Acoustic oscillations excited in a piezoelectric slab having a good contact with the HFR can be used to control the HFR ferromagnetic resonance frequency. The design ideas of a modulator based on an HFR-piezoelectric slab structure are considered. Some experimental and calculation results are presented.

Introduction

Stable non-linear resonance effects (SNLRE) at the interaction of microwave and RF signals with a ferrite resonator (FR) can be used for designing microwave modulators. These effects take place in the vicinity of ferromagnetic resonance (FMR) at levels of microwave power smaller than the threshold of spin-wave instability. Due to SNLRE, there are nonlinear relations between transverse and longitudinal components of the FR magnetization vector [1,2].

Monocrystalline iron garnet (YIG or Ca-Bi-V) FR are typically used for different tunable frequency-selective applications at microwave frequencies, but for the mm waveband, the bias magnetic systems needed for garnet FR operation are cumbersome. At the same time, high-Q monocrystalline uniaxial hexagonal ferrites of M-type with fields of crystallographic anisotropy of about 9-20 kOe seem well suited for applications at frequencies of 30-70GHz [1]. However, their resonance line width, presently 20-200MHz, is wider than that of ferrogarnets (units of MHz).

The resonance frequency of an HFR can be varied periodically either using field control, or angular control. At field control, the local RF modulating field is added to the bias field. A spiral microcoil surrounding the FR is typically used for this RF modulation. However, because of the comparatively wide resonance line of an HFR, the field control might be not effective: the required amplitude of the modulation signal might be so big that it would cause the damage of the microcoil. An alternative way is angular control. If it is possible to provide the periodical deviation of the HFR anisotropy \( \vec{H}_A \) axis orientation (or equilibrium magnetic moment \( \vec{M}_0 \)) relative to the bias magnetic field \( \vec{H}_0 \), the resonance frequency of the HFR will be modulated.

A spectrum of the modulation coefficient \( Q(\Omega) \) analyzed using the quasistatic approach [1,3] depends on many factors:

- a signal power \( P(f_0) \); modulation parameters (specifically considering that amplitude and frequency of a modulation signal determine an HFR resonance frequency deviation and speed of its variation);
- the bias magnetic field \( H_0 \) and the detuning of the HFR resonance frequency from the signal carrier res \( | \omega - \omega_{res} | \);
- the transmission line geometry and the position of the HFR in it;
- the geometry of the FR through the form demagnetization factors and the volume \( V_f \) of the FR;
- the FR physical parameters (the saturation magnetization \( M_s \); crystallographic anisotropy constants \( K_{1,2} \), or field \( H_A \); the initial orientation of an easy axis relatively to the bias field \( H_0 \); the width of the HFR resonance line \( \Delta H \)).

As is shown in Fig. 2 of [1], almost 100% modulation depth can be achieved for the optimal angle of orientation (calculated from the static conditions [3]) and optimal parameters of the modulating signal.

Below, it is shown experimentally that an angular acoustic control and the corresponding modulation of mm-wave signals is possible using the HFR-piezoelectric slab (PES) structure.
Experimental Study

Experiments were conducted in the 8-mm waveband using an HFR, placed in a section of a standard metal rectangular waveguide of 7.2×3.4 mm cross-section, with the only main TE_{10} mode propagating (Fig. 1).

The HFR was a spheroid 0.585×0.557 mm, \( H_A = 11.3 \) kOe, and the FMR line width was 31.1 Oe. A rectangular 2-mm thick BaTiO_3 PES with metallization on the two 25 mm^2 surfaces was placed in an aperture in the wide wall of the waveguide. The metallization of the slab closed the aperture in the waveguide. In the metallized surface of the PES looking into the waveguide, there was a small window with a diameter close to that of the HFR. The HFR was glued directly on the piezoceramic or on the mica layer 0.05mm thick. Acoustic resonances for this PES were observed at 0.26 and 1.46MHz, as well as at a number of higher frequencies. However, maximum peak was at 1.46MHz. the corresponding width of the acoustic resonance line was about 80 kHz. The insertion loss in the waveguide with the HFR-PES structure in the 8-mm waveband was less than 1 dB, and the voltage standing-wave ratio was \( K_{SWR} < 1.2 \). The HFR-PES structure absorbed 5dB when tuning in the frequency range 35-41GHz. Experiments have shown the possibility of modulating the mm-waveband signal using HFR and a piezoelectric slab (Fig. 2). The maximum modulation was observed at the steepest slope of the PES acoustic resonance curve. The second harmonic was consistently noticeable with the frequency-selective receiver with 0.3kHz bandwidth and 0.01\( \mu \)V sensitivity.

The modulation is explained by both dilatation and shear modes of the PES affecting the angle of the HFR orientation. At the voltage applied to the metallized surfaces of the PES, the amplitude \( \Delta x \) of mechanical oscillations (due to the dilatation) is proportional to the deviation of the angle of orientation of equilibrium magnetization moment.

The PES made of BaTiO_3 has \( \varepsilon_r = 2000 \) at \( f = 1.5 \) MHz with the piezoelectric coefficient \( d_{33} = 150 \cdot 10^{-12} \) m/V. At the voltage amplitude applied to the crystal \( V = 10 \) V, the amplitude of mechanical oscillations is \( \Delta x = 1.5 \) nm. This is consistent with the deviation of the angle \( \theta_M \) on the order of \( \Delta \theta_M = 10^{-3} \) radians, and variations in the magnetic moment \( 4\pi \Delta M \) are of the order of units of Gauss. To increase \( \Delta \theta_M \) at least 10-30 times, the material with the greater piezoelectric coefficient is needed, e.g., PZT. If possible, higher voltage should be applied to the crystal, and the better acoustic contact should be provided.

The calculated amplitudes of the first and second harmonics are somewhat greater than those obtained in the experiment (Fig. 3 versus Fig. 2). The discrepancy might come from neglecting the effect of the mica layer between the PES and the HFR; overestimating the acoustic contact in the HFR-PES system; neglecting loss in the waveguide; and a lack of accuracy in adjusting the HFR initial angle of orientation. Also, the frequency in experiment was 37.32GHz, while at the computations it was 37.9GHz.

Another structure for modulating mm-wave signals is shown in Fig. 4. A pure quartz glass capsule serving as a conductor of acoustic waves was glued to the PES. The HFR was placed inside the capsule. There were two options. First, the HFR was oriented in the external magnetic field and fixed firmly. And second, the
HFR could freely orient itself inside the capsule. The capsule was placed in the middle of the wide wall of the rectangular waveguide, where the loss was minimum (about 1dB), and $K_{SWR} < 1.2$. The HFR was placed at a point of linear polarization of the magnetic field of the $TE_{10}$ waveguide mode. Measurements were conducted at the frequency of 37.9GHz.

The quartz capsule is a concentrator of electromagnetic energy, and it shifts the electromagnetic field polarization because of its high dielectric constant $\varepsilon_r = 10$. This leads to an increase of the coupling HFR-waveguide, and the absorption at the FMR increases. Non-reciprocal absorption is observed, though the HFR is placed in the center of the wide waveguide wall, where the mm-wave magnetic field is linearly polarized. The free HFR absorbs energy at the FMR more effectively, about 0.5dB greater than the HFR fixed with glue, since presence of glue decreases its Q-factor. The resonance frequency and absorption of the fixed HFR depend on the orientation much greater when the HFR is placed into the capsule.

The calculated optimum angles of the HFR orientation for obtaining the maximum modulation effect are close to $45^0$ (at the corresponding bias field for FMR), as Fig. 5(a) shows, and the experimental value is also close to $45^0$ for the similar HFR. Measurements were conducted using a frequency-selective receiver. The amplitude of the first modulation harmonic versus detuning from the resonance magnetic field at 37.9GHz is shown in Fig. 5(b). The HFR is in contact with the PES either through the quartz capsule, or without. At the HFR $15^0$ angle of orientation, the amplitude of the harmonic is approximately two times smaller than that for $45^0$.

The modulation is more effective when there is a quartz capsule. The coupling of the HFR with the waveguide
is more critical to the small shift of the HFR position caused by the acoustic oscillations, when the capsule is present. Modulation by a free HFR placed into a capsule is not observed, because the acoustic frequency is much smaller than the HFR relaxation frequency. The equilibrium magnetization has enough time to return to the direction along the bias field. Some slight modulation can be observed due to the HFR position shift at the impact of acoustic oscillations. Placing viscous media (petroleum or lube) in the capsule increases the acoustic loss and decreases modulation, and liquids like water or alcohol inside the capsule increase electromagnetic loss.

**Conclusion**

The modulation of the mm waves using an angular acoustic control of the FMR frequency of a hexagonal ferrite resonator is demonstrated experimentally. For the modulator design, optimum coupling between the HFR and PES, as well as between the HFR and the waveguide is needed. This can be achieved by firmly fixing the HFR in a quartz glass capsule without admitting any moisture, liquid, or viscous media inside the capsule. The HFR’s easy crystallographic axis should be oriented at such an angle with respect to the bias field that at the given deviation of the angle, the modulation is the most effective.

**REFERENCES**

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