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An X-band Magnetically Tunable Bandpass Filter Based on Novel Waveguide Cavity Resonator

B.A. Belayev [#*1], K.V. Lemberg [○2], A.M. Serzhantov [#○3]
[#] *Electrodynamics laboratory, Kirensky Institute of Physics*
Russia, Krasnoyarsk, Akademgorodok st. 50/38
[*] *Electronics and Telecommunications Department, Reshetnev Siberian State Aerospace University*
Russia, Krasnoyarsk, Krasnoyarskij rabochij st. 31
[○] *Institute of Engineering Physics and Radioelectronics, Siberian Federal University*
Russia, Krasnoyarsk, Svobodny st. 79
[1]belyaev@iph.krasn.ru
[2]jivako@gmail.com
[3]cubicus@mail.ru

***Abstract-* This paper presents a ferrite tunable waveguide filter showing high Q_u and high tunability in *X*-band. A new type of waveguide cavity resonator with an H_{102} operating mode was proposed for the creation of a low-loss, two-pole filter. The filter results in an insertion loss of 3.6–4.1 dB over the tuning range 8.74–9.63 GHz with a relative bandwidth of 0.92–0.79% and biasing magnetic field 0–600 Oe. This design demonstrates an unloaded quality factor of 380–396 over the tunable frequency range.**

I. Introduction

Microwave bandpass filters are essential parts of the radar, navigation and communication systems RF frontends. Tunable bandpass filters used in some radio systems to extend their functionality [1]. One of the main requirements of tunable filters is a high unloaded Q (Q_u) of the filter resonators, which provide low insertion loss of the filter. There are several types of high-Q tunable microwave resonators. The historical first type is a YIG sphere resonator [2]. YIG resonators have high Q_u values (>500) and wide tuning range (up to several octaves), but require high biasing magnetic fields (several kOe) to operate at *X*-band and above. Ferrite loaded waveguide resonators [3] have more than 300 Q_u and a tuning range up to 10% with less magnitude of biasing fields, but they are bulky due to the use of waveguides. Ferrite loaded planar resonators [4, 5] are less bulky, but have low Q_u compared to waveguide resonators. Tunable resonators controlled by the electric field have a considerably smaller size and weight compared to the resonators controlled by the magnetic field due to the absence of the bulky magnetic system. They can be created on the basis of semiconductor varactors [6], ferroelectric varactors [7] or microelectromechanical structures (MEMS) [8, 9]. High losses in semiconductor and ferroelectric varactors lead to the fact that the tunable resonators based on them have a low quality factor (<200). So only the recently appeared MEMS-tunable resonators can be used instead of ferrite resonators to build low-loss tunable filters.

MEMS tunable resonators can be made on the basis of metallic waveguides, substrate integrated waveguides (SIW), or planar transmission lines. They often have Q_u 200–1000. Their tuning range typically does not exceed 10%, but in some cases may reach several tens of percent [10]. The main disadvantage of tunable MEMS filters is the high cost due to the custom design and sophisticated production technology.

Thus, magnetic field controlled resonators based on the ferrites are still the only alternative to create tunable filters with a low loss, wide tuning range and low cost. The purpose of this work is to develop a tunable waveguide filter based on the new type of ferrite-loaded waveguide cavity resonator, having both a wide tuning range (>10%), high Q_u (>300) and low biasing magnetic field magnitude (<600 Oe).

II. Cavity Resonator Design

A new type of ferrite loaded waveguide cavity resonator has been proposed to create the tunable filter. The design of the resonator is shown in Fig. 1. It is a segment of a standard rectangular waveguide bounded by two irises. There are two

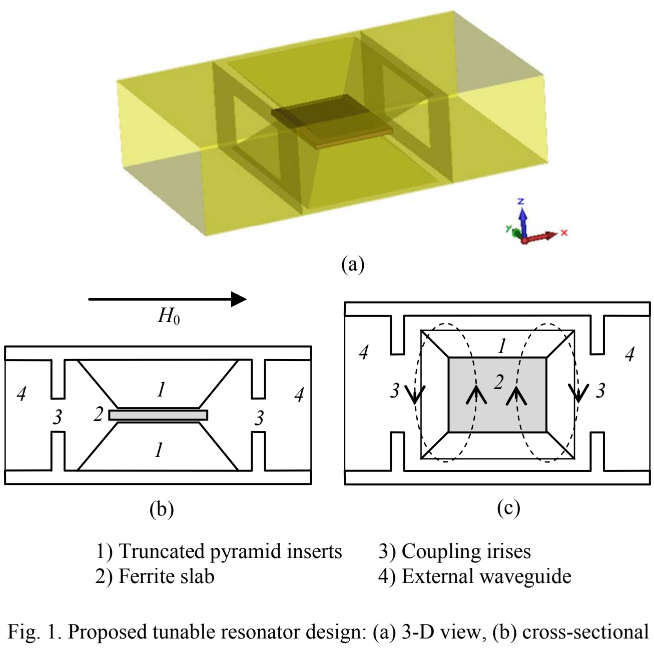

Fig. 1. Proposed tunable resonator design: (a) 3-D view, (b) cross-sectional view in waveguide *E*-plane, (c) cross-sectional view in waveguide *H*-plane

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metal inserts in the form of truncated pyramids in the resonator cavity. A ferrite slab is placed between the tops of the truncated pyramids inserts. The operating mode of the resonator is TE_{102}. The TE_{102} mode magnetic field power lines are shown in Fig. 1(b) by broken lines. The pyramidal inserts distort the field of the operating mode in such a way that the maximum concentration of the high frequency magnetic field is in the area between the pyramids tops where the ferrite slab is placed. Because of this, a wide tuning range of the resonator is achieved even with a small ferrite slab. The biasing magnetic field H_0 is used to tune the resonator frequency. The direction of the H_0 field is shown in Fig. 1(a). The field H_0 and high frequency magnetic field of the operating mode TE_{102} in the ferrite slab are perpendicular to each other. The magnitude of the H_0 field affects the permeability of the ferrite, which leads to a shift in the operating mode frequency. The coupling between the resonator and waveguide transmission line depends on the size of the holes in the irises. Modes TE_{201} and TE_{301}, which have frequencies closely spaced to the operating mode frequency, are not excited, because they have poor coupling with the field in the waveguide. To obtain a filter of the desired order, the corresponding number of the resonators can be coupled in series.

Using simulation in the CST Microwave Studio, we compared the unloaded Q and tuning range of the proposed resonator and conventional rectangular cavity resonator with the TE_{101} operating mode. To be specific, the waveguide cross-section 23x10 mm was chosen, along with the waveguide material – silver with a roughness of 1.5 microns; the size of the ferrite slab – 12x10x0.5 mm; the range of ferrite relative permeability variation – from μ_r=0.7 to μ_r=1; the relative permittivity of the ferrite ε_r=15, and dielectric loss tangent of the ferrite – $tg\delta_\varepsilon=2x10^{-4}$. Magnetic losses in the ferrite are not taken into account. Both the resonators were tuned to the frequency f_0=9 GHz with a relative permeability of the ferrite μ_r=1. In the rectangular cavity resonator, the ferrite slab was placed along one of the narrow walls at the maximum of the high frequency magnetic field at TE_{101} mode.

The calculation results are shown in Table 1. As can be seen, the resonator proposed in this paper provides a significantly higher value of frequency tuning by decreasing unloaded Q. At the same time, its Q_u is still high compared to other tunable resonators based on ferrites and MEMS [1-6, 8-9]. In addition, it has a smaller length as compared with the conventional rectangular cavity resonator.

TABLE I
TUNABLE RESONATORS COMPARISON

Resonator type	Unloaded Q	Length	Tuning range
Rectangular cavity resonator with truncated pyramid inserts	660	20 mm	12.8%
Conventional rectangular cavity resonator	7000	25 mm	0.3%

III. FILTER DESIGN

The two-pole tunable Chebyshev type band-pass filter was designed and manufactured based on the proposed resonator. A filter was developed for X-band with a fixed bandwidth of 80 MHz. The polycrystalline ferrite 10SCH6 slabs with dimensions of 12x10x0.5 mm were used, with a saturation magnetization $4\pi M_s$=1780 G, relative permittivity ε_r=15.1, and dielectric loss tangent $tg\delta_\varepsilon=2x10^{-4}$.

To reduce the magnetic losses in the ferrite slab, it is necessary that the frequency of ferromagnetic resonance (FMR) be far enough from the operating frequency of the filter. For the longitudinally magnetized ferrite slab in the biasing magnetic field with magnitude H_0 FMR frequency can be determined from the Kittel equation [11]

$$f_0 = \frac{\gamma}{2\pi}\sqrt{H_0\left(H_0 + 4\pi M_s\right)}, \quad (1)$$

where $\frac{\gamma}{2\pi} = 2.8\ \frac{MHz}{Oe}$.

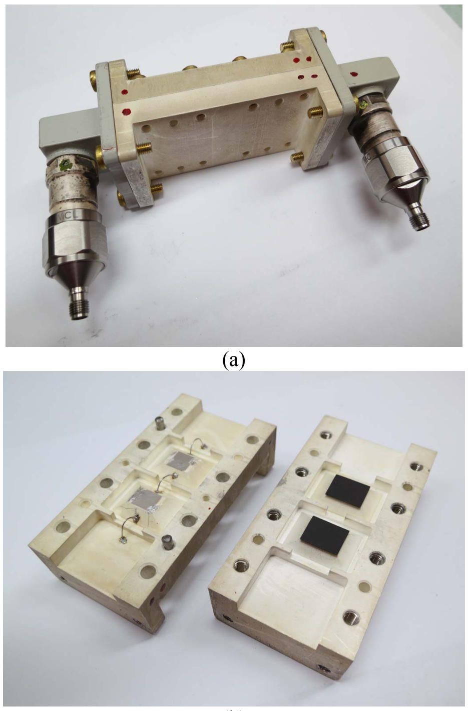
Since the high frequency magnetic field is perpendicular to the ferrite slab magnetization (which coincides with the direction of the biasing field H_0), the relative permeability of the ferrite without losses can be determined by the equation [12]

$$\mu_r = 1 + \frac{f_0 f_m}{f_0^2 - f^2} \quad (2)$$

where f_0 is FMR frequency, determined from (1), $f_m = \frac{\gamma}{2\pi}4\pi M_s$, and f is actual frequency. Using (2) we can calculate that with an increasing magnitude of biasing field H_0 from 0 to 600 Oe, relative permeability of the ferrite μ_r at the X-band frequency 9 GHz will be reduced from 1 to 0.76. FMR frequency f_0, calculated from (1), at such biasing fields, will have a value no higher than 3.4 GHz, which leads to minimum magnetic losses in the ferrite slab at X-band.

A calculated value of the 10SCH6 ferrite relative permeability was used to design the two-pole band-pass filter in the CST Microwave Studio. As a result, the geometric dimensions of the filter were as follows: cross-section of the resonator and the feeding waveguide – 23x10 mm; cavity length – 17.5 mm; the size of the pyramidal inserts bottom – 20.8x15.3 mm; the size of the pyramidal inserts top – 10x7 mm; the gap between the tops of the pyramidal inserts – 0.7 mm; size of the hole in the iris between the resonators – 6x6 mm; size of the holes in the input and output irises – 11.8x6 mm; thickness of irises – 1.5 mm.

A photo of the fabricated filter with the waveguide to coaxial adapters is shown in Fig. 2(a). The filter body was made of two halves that were made from aluminum by milling, and were coated with a silver layer. Fig. 2(b) shows a photo of the filter body halves from the inside. The black slabs of ferrite are seen on the tops of the truncated pyramids on the one of the filter body halves. Pieces of aluminum foil were glued on the other half on the pyramids' tops. Aluminum foil was used to adjust the filter resonators' central frequencies,



(a)

(b)

Fig. 2. Two-pole X-band tunable waveguide filter: (a) filter assembled with waveguide to coaxial adapters, (b) two halves of the filter body.

because the ferrite slabs and thus, resonator frequencies, were not strictly identical. The coupling loops, passing through the irises were used to expand the filter bandwidth when the filter was tuned after manufacturing.

IV. Measurement Results

S-parameters of the filter were measured using the vector network analyzer R&S ZVA20. TRL calibration was performed in the planes of the waveguide to coaxial adapters waveguide flanges before the measurements. Helmholtz coils were used to create a biasing magnetic field H_0. The filter was located in the gap between the coils in the area of the uniform magnetic field. The H_0 field was directed along the filter axis, perpendicular to the high frequency magnetic field in ferrite slabs.

The measured insertion loss and return loss of the filter for different magnetic biasing states are shown in Fig. 3. While the biasing field varies from 0 to 600 Oe, the filter central frequency varies from 8.74 to 9.63 GHz (10.2%), the -3 dB filter bandwidth varies from 80 MHz to 76 MHz (which corresponds to fractional bandwidth 0.92%–0.79%), the minimum insertion loss in the passband varies from 4.1 dB to 3.6 dB, and the return loss does not exceed -10 dB. The filter shows rejection in stop bands of more than 50 dB.

The value of the filter resonators Q_u, extracted from the simulation, was 380-396. As shown by the electrodynamic simulation, the post-fabrication tuning elements (aluminum foil and additional coupling loops) cause the reduced Q factor of the resonators. In the future, we plan to design a filter with the built-in screw-type tuning elements. In this case, the

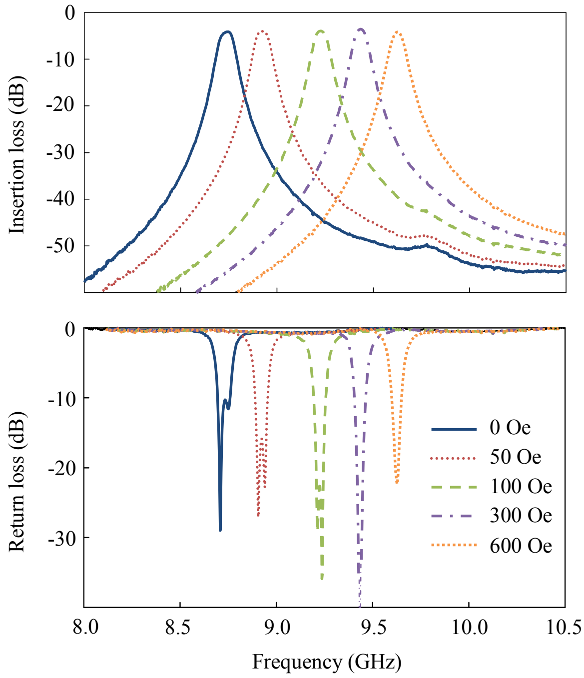


Fig. 3. Insertion loss and return loss of two pole X-band tunable filter for different magnetic bias states.

unloaded Q of the resonators can be increased up to 600, and the insertion loss in the filter passband, reduced to 2 dB.

V. Conclusion

This paper presents a new type of waveguide ferrite loaded resonator, and the results of a two-pole magnetically tunable X-band bandpass filter based on it. The filter shows a high resonators unloaded Q (~390), a wide tuning range (10.2%), and low magnitude of biasing magnetic field (<600 Oe). The proposed design shows promise for the creation of tunable filters with low loss, a wide tuning range and at a low cost.

Acknowledgment

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