Development of microstrip ferrite decoupling devices for mm-wave range microwave equipment

A S Semenov1, A G Nalogin2 and A A Alekseev3
1Head of sector, JSC RPC Istok n.a. Shokin, Fryazino, Russia
2Head of research and production complex, JSC RPC Istok n.a. Shokin, Fryazino, Russia
E-mail: alexseyyy91@mail.ru

Abstract. This article considers structural and technological features, which developers encounter during the creation of microstrip ferrite devices for mm-range microwave equipment. The development results of a 8-mm range microstrip ferrite circulator and isolator are presented in the article.

1. Introduction
Currently, mm-wave radio equipment is being actively developed. The equipment is designed for communication systems, navigation of railway transport and aviation, diagnostic imaging of objects in safety control systems, automotive industry, traffic safety systems, etc. Transition to the millimeter range offers the following advantages: it reduces the size of radio equipment, increases the resolution of radio positioning systems, and enables hidden data transmission.

Ferrite decoupling devices play an important role in all radio systems providing the operation of microwave generators on variable loads, stability of amplifier circuits and allow to control radar signals.

In recent years there has been a strong interest in the development of miniature microstrip ferrite decoupling devices (MFDD) operating in the mm-wave range. The development of mm-wave range MFDD is a complex process and developers needs to solve a number of tasks to succeed:
- selection of optimal ferrite material as a substrate;
- precise measurement of ferrite material electromagnetic characteristics;
- structure calculation of ferrite devices;
- process development for ferrite device manufacturing;
- measurement of electrical parameters of ferrite devices, fine tuning of their structure and testing.

These tasks were solved during the development of a microstrip circulator and a Ka-band isolator. Table 1 shows the electrical parameter requirements for the devices.

| Device type          | Operating frequency range Δf (GHz) | VSWR | Insertion loss, α_{ins} (dB) | Isolation α_is (dB) | Continuous input power P_{in} (W) |
|----------------------|-----------------------------------|------|-------------------------------|---------------------|----------------------------------|
| 8-mm range circulator| 36.5–38.5                         | <1.4 | <0.8                          | >20                 | 0.1                              |
| 8-mm range valve     | 33–37                             | <1.4 | <1                            | >20                 | 2                                |

Table 1. Requirements for developed MFDD

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2. Choosing correct substrate material for ferrite device

A key element of any ferrite decoupling device is ferrite material, which enables to achieve device's independent properties in a given frequency range. Existing ferrite materials introduce special features into the development of mm-range ferrite devices, defining maximum parameters and characteristics.

As a rule, ferrite decoupling devices operate either in “subresonance” or in “overresonance” modes nearby the natural ferromagnetic resonance (FMR) of the ferrite material they are made of. The FMR position is determined by the magnetization of ferrite saturation ($4\pi M_s$), internal anisotropy field ($H_A$) (it is insignificant in all ferrites except for the ones with hexagonal structure) and the magnitude of the external magnetic field ($H_o$). Thus, for a thin plate magnetized normally to its plane, the natural frequency of precession is calculated according to the equation [1]:

$$\omega_{pl} = \gamma (H_o + H_A - 4\pi M_s)$$

where $\gamma = 2.8 \frac{\text{MHz}}{\text{Oe}}$ is the gyromagnetic ratio.

From the equation (1) it is clear that if we need to develop a FDD in the upper frequency range relative to the natural FMR material, then it is necessary to either increase the external magnetic field ($H_o$) at the expense of the magnetic system's increased size or reduce the magnetization of ferrite saturation.

However, records show that it is possible to achieve greater broadband in devices by increasing the saturation magnetization ($4\pi M_s$). Ferrogarnets are widely used as substrates for microstrip ferrite devices in the centimeter range, but they are ineffective due to the low value of saturation magnetization. Therefore, in the development of mm-range MFDD it is necessary to choose ferrite materials with a high value of saturation magnetization [2].

Ferrites with a crystalline spinel structure were tested as a substrate material for 8-mm range boards: lithium-zinc spinel (LZ-380) and nickel-zinc spinel (NZV). Table 2 shows electromagnetic parameters of these materials according to specification requirements.

| Name                              | Symbol | Specification value |
|-----------------------------------|--------|---------------------|
| Nickel-zinc spinel (NZV)          |        |                     |
| Dielectric permeability           | $\epsilon$ | 12.3–13.7          |
| Total loss angle tangent          | $tg\delta_\Sigma$ | 1.6×10⁻³        |
| Saturation magnetization (kA/m)   | $4\pi M_s$ | 378±27             |
| Density (g /cm³)                  | $\rho$ | 5.1                 |
| Lithium-zinc spinel (LC-380)      |        |                     |
| Dielectric permeability           | $\epsilon$ | 14.9–15.9          |
| Total loss angle tangent          | $tg\delta_\Sigma$ | 1×10⁻³        |
| Saturation magnetization (kA/m)   | $4\pi M_s$ | 380±27             |
| Density (g /cm³)                  | $\rho$ | 4.73                |

Y-circulator models on LZ-380 and NZV substrates were calculated to determine the most suitable substrate material for the manufacture of Ka-band MFDD. Figures 1 and 2 show the S-parameters of the circulator models calculated with finite element method.
The measurements show that the 8-mm range circulator model made on the NZV board has better characteristics than the model made on the LZ-380 board. In addition, lithium system ferrites are sensitive to techno-chemical processes in the manufacture of microstrip device ferrite boards. Based on the conducted study and considering that the Ni system ferrites surpass the Li system ferrites by the level of threshold properties, it was decided to develop Ka-band MFDD on NZV substrates.

The Ni-Zn spinel has a large value of saturation magnetization ($M_s \approx 380$ kA/m), which will enable a sufficiently large band of operating frequencies for developed ferrite devices. The low tangent of the NZV total loss angle, in turn, will ensure small losses in the forward direction of the microwave signal passing through non-reciprocal devices.

3. **Measurements of ferrite electromagnetic characteristics**

In order to correctly calculate the structure of a ferrite decoupling device, it is necessary to precisely measure electromagnetic parameters of a ferrite material and make its physical model.
The $\varepsilon$ and $\tan\delta\Sigma$ measurements were carried out according to the method based on the frequency dependence of the reflection factor module of the plane electromagnetic wave (TEM-wave) with respect to the plane-parallel layer of the magnetic dielectric [3, 4] at normal incidence. This method is designed to measure the effective dielectric permeability and the total loss angle tangent of plane-parallel workpieces of low-magnetic anisotropic magnetic dielectrics in the 3-mm wave range.

The statistical analysis of electromagnetic parameter spread in two ferrite batches was carried out based on measurements of effective dielectric permeability and the total loss angle tangent of plane-parallel ferrite workpieces.

Samples of ferrite workpieces were rectangular wafers with cross sectional dimensions of $52 \times 32$ mm$^2$ and a thickness of $7.1 \pm 0.02$ mm, $R_a$ – at least 2.5.

| Batch No. | Workpiece No. | Measured dielectric permeability $\varepsilon$ | Measured tangent of total loss angle $\tan\delta\Sigma$ |
|-----------|---------------|---------------------------------|--------------------------------------------------|
| 10        | 1             | 12.6 ± 4 %                      | $1 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$          |
| 10        | 2             | 12.8 ± 4 %                      | $1.2 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 10        | 3             | 13.4 ± 4 %                      | $1.3 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 10        | 4             | 13.1 ± 4 %                      | $1.1 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 11        | 1             | 12.8 ± 4 %                      | $1.2 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 11        | 2             | 13.0 ± 4 %                      | $1.2 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 11        | 3             | 13.1 ± 4 %                      | $1.2 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |
| 11        | 4             | 12.8 ± 4 %                      | $1.2 \cdot 10^{-3} \pm 3.7 \cdot 10^{-4}$        |

Based on the NZV workpiece analysis, the following values were taken for further calculation of the Ka-band MFDD: $\varepsilon = 13$ and $\tan\delta\Sigma = 1.6 \cdot 10^{-3}$.

4. Calculation of circulator and Ka-band isolator construction

It is not enough to produce high-quality ferrite material and accurately measure its parameters. The key stage in the development of any ferrite decoupling device is the calculation of its structure. The more accurate the calculations, the less iterations of model production will be made to get the structure that meets all specification requirements.

In the development of microstrip ferrite decoupling devices it is important to choose a thickness of a ferrite substrate ($h$) for board manufacturing.

On the one hand, reducing the substrate thickness provides:

1) low radiation losses;
2) reduction of potential excitation of surface waves, which is especially relevant for substrates with high dielectric permeability ($\varepsilon > 10$);
3) increase of component density of microstrip devices by narrowing strip conductors.

On the other hand, if the substrate thickness ($h$) is reduced while maintaining constant wave resistance ($Z_0$), it is necessary to reduce the width of strip conductors ($w$), which results in loss increase in conductors, $Q$ factor decrease and, as a consequence, loss increase in decoupling devices [5].

Therefore, when determining the thickness of a ferrite substrate, it is necessary to reach a compromise based on the described factors.

4.1. Calculation of Y-circulator structure

In order to determine the most suitable thickness of the ferrite substrate using the obtained physical model of ferrite material (NZV), calculations of device board layouts were made at 3 different substrate thicknesses and the subsequent simulation was made by the finite element method of ferrite MFDD structures.
The Y-circulator model is a ferrite board with applied layout which has dimensions $5 \times 9.2$ mm. When constructing mathematical models of microstrip ferrite decoupling devices by the finite element method, the following limiting conditions are used:

1) The layout pattern and the back side of the ferrite board are considered to be ideal conductors (except for valve's tantalum load), which excludes free space radiation losses.

2) The external magnetic field is considered to be uniform and applied only to the area under the device circulation disc.

3) According to the model, the devices are excited by concentrated ports with an input resistance of $Z_0 = 50$ Ohms.

![Figure 3. Electrodynamic model of Ka-band Y-circulator](image)

Table 4 shows a comparison of electrical parameters of the 3 different Ka-band Y-circulator models with the electrical parameters specified in the requirement specification.

| Parameter, units | Symbol | Specification parameters | Model parameters on substrate thickness $h = 200$ (μm) | Model parameters on substrate thickness $h = 250$ (μm) | Model parameters on substrate thickness $h = 300$ (μm) |
|------------------|--------|--------------------------|------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Operating frequency range (GHz) | $\Delta f$ | 36.5–38.5 | 36–39 | 36–39 | 36–39 |
| Insertion loss (dB) | $\alpha_{ins}$ | 0.8 max. | 0.55 max. | 0.7 max. | 1.15 max. |
| Decoupling (dB) | $\alpha_{dec}$ | at least 20 | at least 18 | at least 22 | at least 17 |
| VSWR | VSWR | 1.3 max. | 1.22 max. | 1.22 max. | 1.35 max. |

Table 4 shows that only the Y-circulator model on NZV boards with a thickness of $h = 250$ μm meets the requirement specification.

An important criterion in the development of any device is the operation reliability. Ferrite devices on 250 μm boards are rather fragile. That is why underlying substrates made of soft magnetic material (ferrum) are used to improve their strength properties. The Ka-band Y-circulator construction (see Figure 4) was developed based on the results of calculations and simulations.
4.2. Isolator structure calculation

As a rule, developers of microstrip ferrite isolators use a load with a tantalum resist layer, which has such a sheet resistance \( R_s \) that electromagnetic wave, upon getting into the load, completely fades and at the same time, there are no parasitic reflections from the load. On the one hand, the less load resistance, the more smoothly it absorbs microwave energy. But it is necessary to increase the path length of the microwave energy to ensure the required level of isolator reverse losses. The dimension reduction of the isolator planar load can be achieved by increasing the load's resistance. But this leads to an increase in the own VSWR of the load at the cost of an increase in the difference of the input resistance of the supply strips and tantalum load. Therefore, it is necessary to take into account that the bigger the \( R_s \) value, the bigger the mismatch between the load and the isolator circulation disc [5].

Based on the above, we have chosen the configuration of a sector planar load. The load is a sector made of a thin tantalum layer.

Tantalum is used as an absorbent material. To determine the optimal value of sheet resistance \( R_s \) of planar tantalum load, a microstrip isolator was simulated depending on \( R_s \) value (see Figure 5).

\[ \text{Figure 4. 3-D model of Ka-band Y-circulator} \]

\[ \text{Figure 5. Electrodynamic model of Ka-band isolator} \]

| Parameter, units | Symbol | Specification parameters | Isolator model parameters with \( R_s = 45 \) (ohm/sq) | Isolator model parameters with \( R_s = 60 \) (ohm/sq) | Isolator model parameters with \( R_s = 75 \) (ohm/sq) |
|------------------|--------|--------------------------|---------------------------------|---------------------------------|---------------------------------|
| Operating frequency range (GHz) | \( \Delta f \) | 33–37 | 33–37 | 33-37 | 33–37 |
| Insertion loss (dB) | \( \alpha_{ins} \) | 1.0 max. | 0.7 max. | 0.7 max. | 0.7 max. |
| Isolation (dB) | \( \alpha_{is} \) | at least 20 | at least 16 | at least 20 | at least 17 |
| VSWR | VSWR | 1.4 max. | 1.2 max. | 1.25 max. | 1.3 max. |
Table 5 shows that according to the simulation the required level of return losses (isolation) can be achieved if the sheet resistance of the tantalum load is 60 ohm/sq.

Thus, the Ka-band isolator (see Figure 6) was developed as a result of the performed calculations and simulations.

![Figure 6. 3-D model of Ka-band isolator](image)

5. Measurement of electrical parameters of ferrite device and fine tuning of their structure

Measurement of electrical parameters of mm-band microstrip isolators and circulators is carried out on a test bench. Figure 7 shows the schematic diagram of the test bench.

![Figure 7. Structure diagram of test bench for mm-wave range MFDD](image)

Figure 7. Structure diagram of test bench for mm-wave range MFDD: 1 – vector network analyzer, 2 – Anritsu connecting device, 3 – display, 4, 5 – microwave cables, 6 – connecting cable, 7 – test device, 8 – UC-20CE heat and cold chamber

Models of Ka-band Y-circulator and isolator were manufactured based on the proven technology. MFDD ferrite boards are made on substrates using the thin-film group technology: conductive layers on the substrate are applied by thermal sputtering in Cr/Cu vacuum; the resistive layer is applied by Ta magnetron sputtering; the board layout pattern is made by photolithography methods; protective layout coating is made by Au voltaic coating; substrates are divided into boards using diamond disc cutting tools.

Figure 8 shows the model of the 8-mm wave range Y-circulator.
Figure 8. Y-circulator model and ferrum-epoxy load.

The Y-circulator model is a 250 μm ferrite plate soldered on a 300 μm metal base. The ø1.2×3 mm magnet made of KS-25 alloy is glued to the ferrite board on the resonator area. When measuring the Y-circulator with a 2-port circuit analyzer, a match load made of electromagnetic absorbing material is installed on the 3rd circulator arm for matching.

Figure 9 shows electrical characteristics of the Y-circulator model measured with a vector network analyzer.

Figure 9. S-parameters of Ka-band Y-circulator

FDD models made on the basis of calculated data do not always meet specification requirements. In most cases, a developer has to refine their structure in order to improve parameters.

For example, in the case of the Ka-band microstrip isolator, it was found that its isolation did not meet the specification requirements ($\alpha_s\approx 12$ dB) in a given frequency range due to poor alignment of the Y-circulator and planar load on the 3rd circulator arm.

Therefore, to solve this problem, the isolator layout was experimentally adjusted (see Figure 10). It allowed to achieve the required level of isolation ($\alpha_s$ at least 20 dB) in the 33–37 GHz frequency range.
Also, as part of the Ka-band isolator development, the work was carried out to reduce the size of its magnetic system.

The MFDD magnetic system is a cylindrical magnet with a 0.1 mm thick dielectric disc glued to one side. Normally, the magnet diameter is slightly larger than the diameter of the ferrite device circulation area. When assembling the MFDD, the magnetic system is glued to a ferrite board with a down-directed dielectric disc. This results in magnetization of the device circulation area and manifestation of the non-reciprocity properties in the device.

In order to achieve more uniform distribution of the field in the circulation area and improve characteristics of the developed mm-range devices, the underlying substrate made of soft-magnetic material - BT-PN-05 GOST 19904-90 (ferrum) - was added to the device structure. In addition, a dielectric disc was excluded from the structure of the MFDD magnetic system.

The disc exclusion is possible due to the equal diameters of the magnet and the disc of the device's board circulation area. Also for microstrip ferrite devices operating in mm-wave range, the glue dielectric layer between the magnet and the ferrite board essentially plays the role of a miniature dielectric disc, which prevents the distortion of microwave energy distribution in the microstrip ferrite decoupling device resulted from the contact of two conductors.

In order to optimize the device operation, it was also necessary to choose such a magnetic system that would have been as small as possible and at the same time provided the necessary electrical characteristics of the isolator. The dependence of the isolator electrical characteristics versus its magnetic system was studied (see Figures 11 and 12).
The analysis shows that the most optimal magnetic system is a magnetic system consisting of the magnet with a 1.3 mm diameter and a 1.5 mm height. The magnet is glued to the isolator resonator disc. The isolator with this magnetic system has the lowest direct losses and at the same time has the necessary level of return loss (isolation).

The analysis of measurement results (see Figure 12) showed that reduction of direct losses of microstrip ferrite decoupling devices of mm-wave range could be achieved due to the uniformity of internal fields in a ferrite substrate.

The internal field uniformity in the ferrite substrate can be achieved due to the use of an underlying substrate made of soft magnetic material, dielectric disc exclusion from the magnetic system structure, equal diameters of the circulation area of the board layout and the magnet diameter.

6. Conclusion
In the course of the performed works, the Ka-band Y-circulator and isolator were developed and a general approach to the development of microstrip ferrite decoupling devices in the Ka-band was established.

The developed isolators and circulators have successfully passed all tests on the impact of external factors, including the impact of continuous input power.

The developed Ka-band microstrip circulator and isolator have electrical characteristics at the level of existing Russian and foreign analogues. The devices can be effectively used in the development of next generation equipment.

Table 6. Electrical parameters of Ka-band MFDD.

| Parameter, units                      | Symbol  | Y-circulator  | Isolator  |
|--------------------------------------|---------|---------------|-----------|
| Operating frequency range (GHz)      | $\Delta f$ | 36–39         | 33–37     |
| Insertion loss (dB)                  | $\alpha_{\text{ins}}$ | 0.7 max.     | 0.8 max.  |
| Isolation (dB)                       | $\alpha_{\text{Is}}$ | at least 22  | at least 20|
| VSWR in, out                         | VSWR    | 1.3 max.      | 1.4 max.  |
| Continuous input power (W)           | $P_{\text{in,con}}$ | 0.1           | 2         |
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