Nonreciprocal Propagation in Ferrite Medium and Their Applications– Microwave Circulator

Ghoutia. Naima. Sabri

Abstract— In the current study, The present work explores the use of microwave ferrites materials in telecommunication domain. Especially examines the role of ferrite in construction and design of passive non reciprocal devices for high frequency applications.

These ferrimagnetic nonconducting oxides are highly resistive, allow total penetration of electromagnetic fields and exhibit a ferromagnetic resonance (FMR) phenomenon in the high frequency. These important properties make them suitable for micro- and mm-wave devices such as circulators. A typical use of the circulator is in communication (radar, mobile phone) equipment where it uses for transmission and reception of the response signal.

Due to the progress of telecommunications, the importance and demand for the variety of microwave ferrite materials is growing. This means that the knowledge and understanding of the correlation between their magnetic properties and their crystal structure and chemical composition are of crucial importance for the development of the materials with desirable properties. This development in materials engineering allows to achieving high levels of performance in circulators and in other microwave ferrite devices.

Keywords—Microwave ferrite, ferromagnetic resonance, circulators, magnetic properties.

I. Introduction

THE ferrites materials are widely used for the construction and the design of devices for high-frequency applications (sometimes called the RF radio frequency) such as telecommunications and radar systems, as microwave technology requires higher frequencies and bandwidths up to 100 GHz and control components below 40 GHz [1].

Ferrites are nonconducting oxides and therefore allow total penetration of electromagnetic fields, in contrast with metals, where the skin effect severely limits the penetration of high-frequency fields [1].

They are highly resistive ferrimagnetic oxides, which exhibit ferromagnetic resonance (FMR) in the micro-and mm-wave region. This makes them suitable for micro- and mm-wave devices and absorbers. Due to the progress of telecommunications the importance and demand for the variety of microwave ferrite materials is growing and they have long challenged the skills of microwave engineers.

Unlike ordinary passive components, microwave ferrites exhibit nonreciprocal behavior under the influence of externally applied magnetostatic bias fields. This behavior makes the microwave ferrites ideal for circulator and isolator applications, but complicates their analysis and design. Analytical solution of this nonreciprocal behavior is impossible in all but the simplest devices.

Microwave ferrites exhibit a variety of magnetic properties depending on their chemical composition, crystal structure and microstructure. The knowledge and understanding of the correlation between those are of crucial importance for the development of the materials with desirable properties.

Until now, electronic design automation (EDA) tools have not been able to predict the performance of microwave ferrite devices with any degree of certainty or accuracy [2].

These devices allow the control of microwave propagation using a static or switchable DC magnetic field and they can be reciprocal or nonreciprocal, linear or nonlinear, and their development requires understanding of magnetic materials, electromagnetic theory, and microwave circuit theory [3].

The nonreciprocal behavior of microwave ferrite materials is a result of the nondiagonal nature of the ferrite's permeability tensor. The permeability tensor is affected by the inhomogeneous and nonlinear properties of the magnetic ferrite material.

In Maxwell's equations a tensor permeability is used to characterise magnetically biased ferrite materials. The entries of this tensor are nonlinear functions of frequency, bias field, material magnetisation and demagnetising effects. The ferrite is characterised by its hysteresis curve [4].

II. The Ferrite Materials for Microwaves

A. Properties of Ferrite Materials

Ferrites are ceramiclike materials with specific resistivities that may be as much as 10^{14} greater than that of metals and with dielectric constants around 10 to 15 or greater [5] .

Ferrites are polycrystalline magnetic oxides made by sintering a mixture of metal oxides and have the general chemical composition MO·Fe2O3, where M is a divalent metal such as Mn, Mg, Fe, Zn, Ni, Cd, etc. In the following text, we expose the important properties of these materials:

- ✓ Since these oxides have a much lower conductivity than metals, we can easily pass microwave signals through them.
- ✓ Relative permeabilities of several thousand are common. The magnetic properties of ferrites arise mainly from the magnetic dipole moment associated with the electron spin.

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✓ The Nonreciprocal electrical property is described by the transmission coefficient through the device which is not the same for different direction of propagation.

✓ The left and right circularly polarized waves have different propagation constant along the direction of external magnetic field B_0 which mean that these waves have an unequal propagation constant in ferrite medium.

✓ As anisotropic magnetic properties, we can explain the permeability of the ferrite which is not a single scalar quantity, but instead is a tensor, which can be represented as a matrix. The most practical materials exhibiting anisotropy are ferromagnetic compounds such as YIG (yttrium iron garnet), as well as the iron oxides.

B. Magnetization Mechanism

If an electron is located in a uniform static magnetic field B_0, a torque[6] is given by

$$\vec{T} = \vec{m} \wedge \vec{B_0} = -\mu_0 \gamma \vec{s} \wedge \vec{H_0} \quad (1)$$

$$\frac{d\vec{s}}{dt} = \frac{-1}{\gamma}\frac{d\vec{m}}{dt} = \vec{T} \quad (2)$$

$$\frac{d\vec{m}}{dt} = -\mu_0 \gamma \vec{m} \wedge \vec{H_0} \quad (3)$$

Where $\omega_0 = eB_0/m_e$is called the Larmor frequency or precession frequency; $\vec{s}$ is spin angular momentum and $\vec{m} = \frac{e\hbar}{2m_e} = -\gamma\vec{s}$ is magnetic dipole moment of an electron due to its spin ($= 9.27\ 10^{-24}$Am^2); where $\hbar$ = Planck's constant/2π and γ is the gyromagnetic ratio(γ $=1.759\ 10^{11}\, coulombs/Kg$).

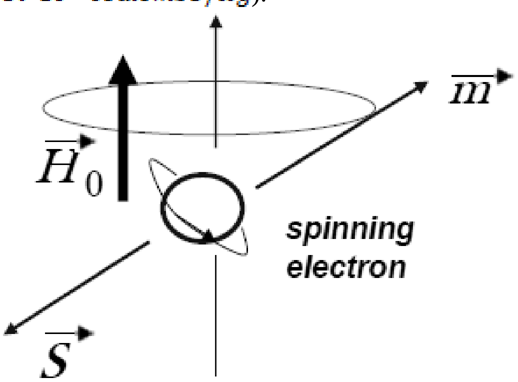

Fig. 1 Orbiting and spinning electron

In the absence of any damping forces, the precession angle will be determined by the initial position of the magnetic dipole, and the dipole will precess about $\vec{H_0}$ at this angle indefinitely (free precession).

In reality, however, the existence of damping forces will cause the magnetic dipole to spiral in from its initial angle until $\vec{m}$ is aligned with $\vec{H_0}$. For N effective electron spinning per unit of volume, the total magnetic dipole moment is :

$$\vec{M} = N\vec{m} \quad (4)$$

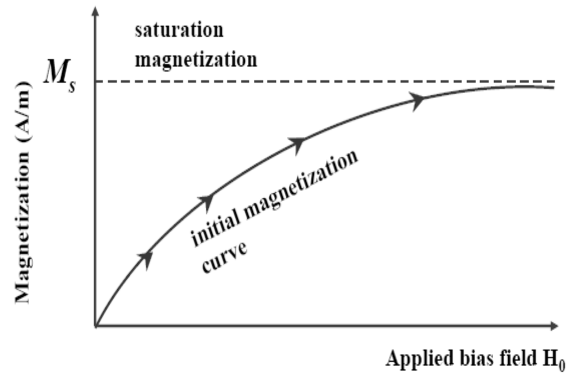

Fig. 2 Magnetization Curve

As is shown on the Fig. 2, if we start with a sample that is initially un-magnetized, with no applied bias field, the initial magnetization is $\vec{M_0}$, As we increase the applied bias field $\vec{H_0}$, the sample becomes increasingly magnetized until it reaches saturation level $\vec{M_s}$, beyond which no further magnetization is possible and in same time more magnetic dipole moments will align with $\vec{H_0}$ until all are aligned, by reaching an upper limit $\vec{M_s}$. (*M*s typically ranges from *M*s=300 to 5000 Gauss). The ferrites are usually operated in the saturated state [5].

Below saturation, ferrite materials can be very lossy at microwave frequencies, and rf interaction is reduced.

The magnetization of the ferrites is due to the spin moments of the magnetic electron. If an electron is placed into a bias magnetic field, its magnetic moment aligns with the field to minimize its potential energy. If an RF (microwave) field is applied perpendicular to the bias field, the magnetization will precess around the equilibrium direction with the frequency of the RF field. In real materials there are damping forces, opposing the precessional motion, and the magnetization relaxes back to the steady-state equilibrium.

C. Curie Temperature

The saturation magnetization of a material is a strong function of temperature, decreasing as temperature increases.

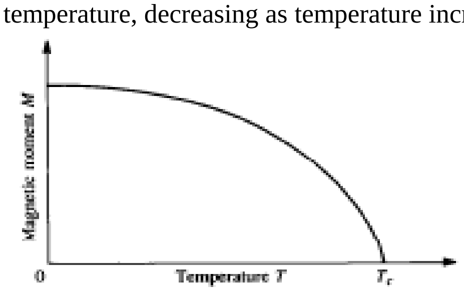

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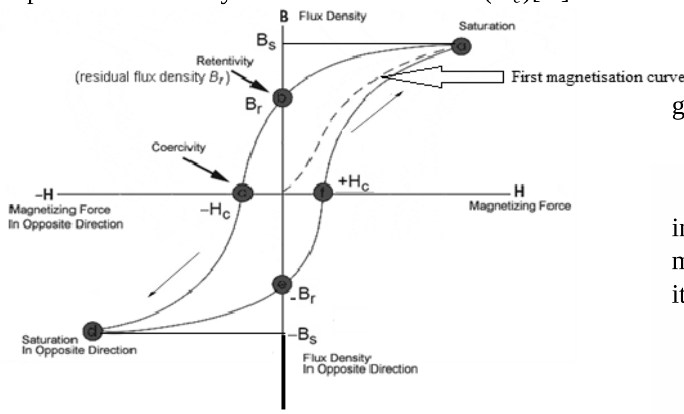
Fig. 3 The magnetization in function of temperature

This effect can be understood by noting that the vibrational energy of an atom increases with temperature, making it more difficult to align all the magnetic dipoles. At a high enough temperature a zero net magnetization results. This temperature is called the Curie temperature, *T*c [7].

D. The hysteresis Loop

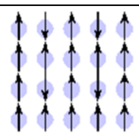
A great deal of information of magnetic material can be learnt by studying its hysteresis loop which shows the relationship between the induced magnetic flux density B and the magnetizing force H. According to the characteristic *B(H)* sketched on the Fig.4, we can define the different magnetic properties of the materials as follow : magnetic permeability (μ), induction of saturation (B_s), induction of remanence (B_r) at the point of retentivity and the coercitif field (H_c)[7].



. Fig. 4 Typical hysteresis loop of magnetic material

The following table summarizes the important ferrimagnetic properties [8].

TABLE I
FERRIMAGNETIC PROPERTIES

Magnetic susceptibility, χ	Atomic / Magnetic Behavior	Temperature dependence	Examples and comments
Positive and large, function of applied field, microstructure dependent, Ba ferrite: ~3		Ferrimagnetic below the Curie temperature and paramagnetic above it.	Atoms have anti-parallel aligned magnetic moments, possesses large magnetization even without external magnetic field, e.g:Fe_2O_3

III. WAVE PROPAGATION IN FERRITE

In applying Maxwell's equations to analyze the propagation of a plane wave in a magnetized ferrite medium, we must first recognize that an RF component of magnetization is induced by the RF magnetic-field component and that the associated RF permeability contains dispersive and dissipative terms. These terms arise from a tensor that results from gyromagnetic effects (ferrimagnetic resonance)[9].

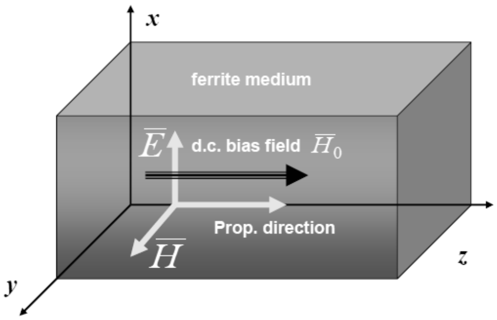


Fig. 5 Wave propagation in ferrite medium

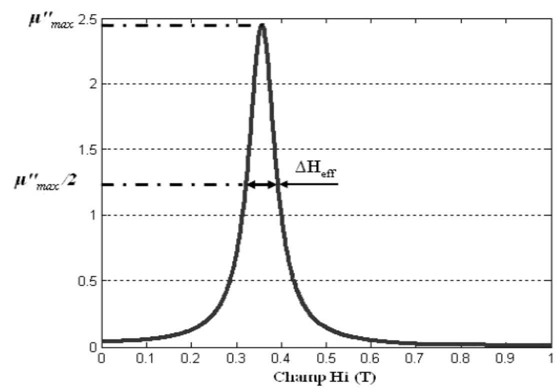
By applying kinetic moment theorem on the electron, we get the following equation of motion of the moment:

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\wedge\vec{H}_i + \frac{\alpha}{M_s}\vec{M}\wedge\frac{d\vec{M}}{dt} \tag{4}$$

γ, H_i and M_S present respectively the gyromagnetic factor, internal magnetic field of material and their saturation magnetization. α is a term of damping in moment motion and it depend on resonance frequency f_r:

$$\alpha = \frac{\gamma\Delta H_{eff}}{2f_r} \tag{5}$$

With ΔH_{eff} is the HWHM resonance width as is shown on the Fig. 6. (Half with at half maximum), [6], [7].



. Fig. 6 Gyromagnetic resonance

By definition the gyromagnetic resonance is related to movement of precession magnetic of electronic spin $\vec{m}$ around the internal field H_i direction. Applying DC magnetic field causes an infinite and free precession characterized by a rotation frequency:

$$\omega_r = \gamma\mu_0 H_i \tag{6}$$

Therefore, microwave propagation in ferrites shows a gyromagnetic resonance with a peak of loss for clockwise polarization of Hi.

IV. APPLICATION OF FERRITE IN MICROWAVE DEVICES

A. Polder Model

Solving the equation of motion of the moment leads to a permeability tensor antisymmetric tensor called Polder [6], for materials saturated with polarization along the z axis (longitudinal direction of propagation k//B_0). This tensor is controlled by the amplitude of applied bias magnetic field and its direction.

$$\bar{\bar{\mu}}_r = \mu_0 \begin{pmatrix} \mu_r & -j\kappa & 0 \\ +j\kappa & \mu_r & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

Where

$$\mu_r = \mu' - j\mu'' = 1 + \frac{(\omega_r + j\alpha\omega)\omega_M}{(\omega_r + j\alpha\omega)^2 - \omega^2} \tag{8}$$

$$\kappa = \kappa' - j\kappa'' = \frac{\omega\omega_M}{(\omega_r + j\alpha\omega)^2 - \omega^2} \tag{9}$$

$$\omega_M = \gamma\mu_0 M_S \tag{10}$$

κ is parameter which depends of ferrite material. The elements of the Polder tensor (real and imaginary parts) are represented in the following figures:

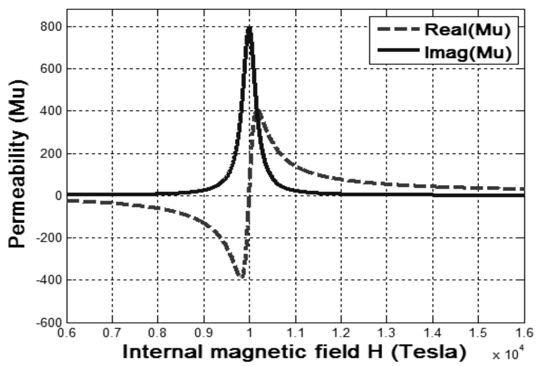


Fig. 7 Real and imaginary part of permeability versus H_i

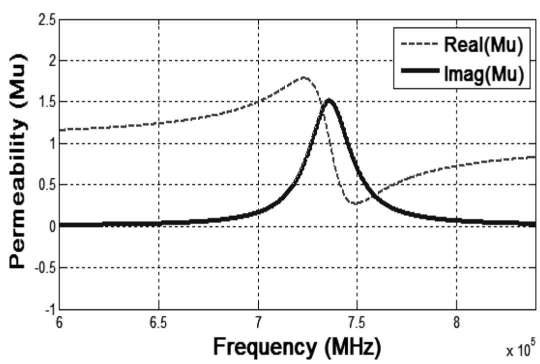


Fig. 8 Real and imaginary part of permeability versus frequency

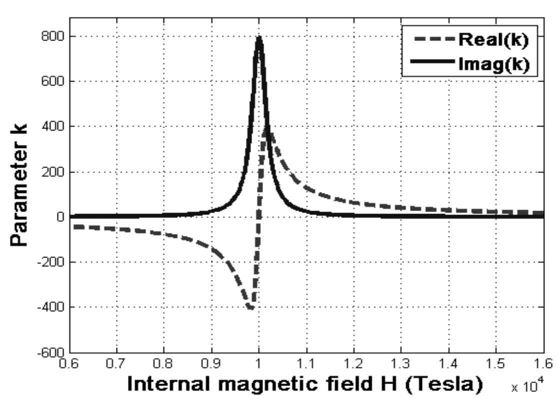


Fig. 9 Real and imaginary part of parameter k versus H_i

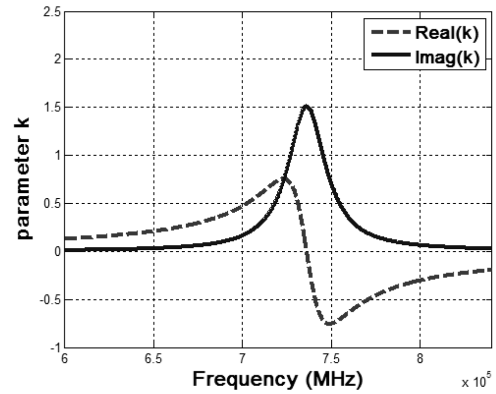


Fig. 10 Real and imaginary part of parameter k versus frequency

If a plane EM wave is propagating through a magnetized, lossless, infinite ferrite medium, characterized by dielectric permittivity ε, magnetic permeability μ and conductivity $\sigma = 0$, then the EM fields in the ferrite are governed by Maxwell's equations. The solution gives two fundamental modes of EM waves propagating in the ferrite with opposite polarization and different propagation constants, determining the effective permeability of the ferrite to the left and right circularly polarized wave:

$$\mu_+ = \mu - \kappa \tag{11}$$

$$\mu_- = \mu + \kappa \tag{12}$$

The ferrimagnetic resonance effect (gyromagnetic resonance) can be visualized if a linearly polarized wave with the RF magnetic-field component normal to the magnetization vector is analyzed in terms of two counterrotating circularly polarized components, one rotating in synchronism with the precession (positive (+)) and the other in opposition to it (negative(–))[10]. The propagation of the two polarizations differs as a function of frequency, with the positive (+) component undergoing the resonance effect [7]. Distinct permeabilities μ_+ and μ_- can then be defined:

$$\mu_+ = \mu'_+ + j\mu''_+ \tag{13}$$

$$\mu_- = \mu'_- + j\mu''_- \tag{14}$$

These four coefficients are presented on the Fig.12.

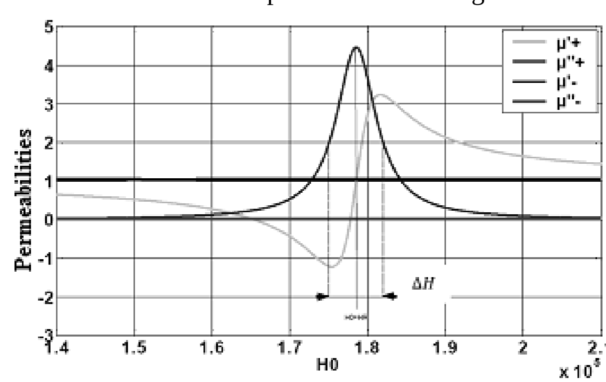


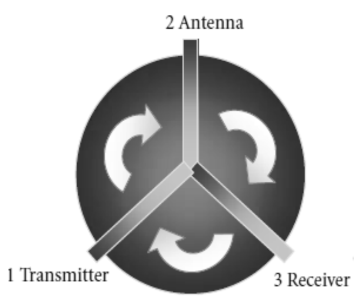
Fig. 12 Variation μ'_+, μ'_-, μ''_+, μ''_- in function of applied magnetic fild H_0 on ferrite

V. Application of Ferrites in Microwave Devices

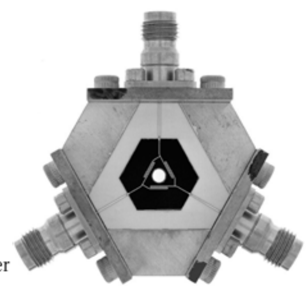
Nowadays, microwave integrated systems include nonreciprocal structures such as circulators, isolators, phase shifters, operating over a broad frequency band. Recently, axially magnetized microstrip or slot ferrite coupled line sections have been developed and employed to realize integrated nonreciprocal devices [11],[12]. The advantage of this class of the devices is a weak magnetic field required for Faraday's effect [6] [13] defining their nonreciprocal operation [14].

A. Nonreciprocal Circulator Device

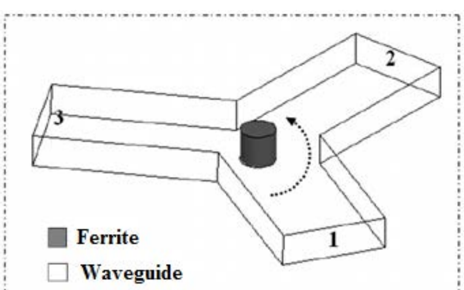
Circulators are important elements in transmit/receive (T/R) modules. The T/R modules allow the transmitter and receiver in a communications or radar system to share the same antenna by isolating the transmitter and receiver from each other, as illustrated in Fig. 11. (a), (b)[2]. This means that they allow the use of the same device for transmission and reception of the response signal. . Integrating the T/R modules with a circulator can result in reduced package size, as well as significant cost savings. Fundamental to these goals is the use of microstrip components. However, the thin geometries found in MMIC devices (monolithic microwave integrated circuits, MMIC) create nonuniform magnetic fields in the ferrite material.



(a) *Circular shaped* [15]



(b) *Triangular shaped [10]*



(c) *Waveguide Y junction circulator[16]*

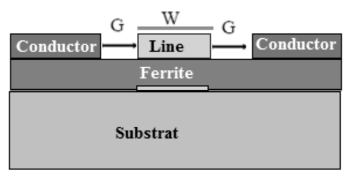
Fig. 11 Schematic representation of circulator for three ports (Y)

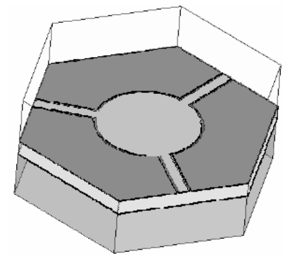
The most common design is a junction circulator, which consists of a circular disk (`puck) of ferrite, with a symmetrical Y-shaped three-port transmission line conductor attached to it in a stripline or microstrip geometry and separated by 120◦.

As shown schematically in Fig.11 (c) [1][10], any signal entering through port 1 exits by port 2, with no connection with port 3. If the generator is connected to port 1 and the antenna to port 2, this is the path of the outgoing signal. The incoming signal enters through port 2 (the antenna) and is directed to port 3, to the receiver. This allows the handling of a strong outgoing signal (ports 1-2) together with a very sensitive detector (ports 2-3), with no risk of damaging the receiver and using the same antenna.

B. Coplanar Structure of Circulator (CPW)

The structure coplanar of circulator is studied in the reference [7],[15] and [16] and is given by the following figure.





(a) Cross section view (b) Top view

Fig. 12 Coplanar structure of circulator

For a three port circulator, the amplitude of the waves entering (a1, a2 and a3) the junction and those of the waves coming out (b1, b2 and b3) are related by the following matrix [6]:

$$[b_i] = (S_{ij})[a_i] \tag{15}$$

To evaluate the performance of the circulator, we calculate the *S*-parameters of the dispersion matrix S:

$$S = (S_{ij}) = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{16}$$

If a device is nonreciprocal such as a circulator, *Sij≠ Sji*, and in our case, the simple expression of the dispersion matrix is:

$$S = \begin{bmatrix} S_{11} & S_{31} & S_{21} \\ S_{21} & S_{11} & S_{31} \\ S_{31} & S_{21} & S_{11} \end{bmatrix} \tag{17}$$

With taking into account that:

$$\begin{cases} S_{11} = S_{22} = S_{33} \\ S_{21} = S_{32} = S_{13} \\ S_{31} = S_{12} = S_{23} \end{cases} \tag{18}$$

The parameters S_{21}, S_{32} and S_{13} are the coefficients of transmission. They give information about the insertion losses and show the best working of device.

The parameters S_{12}, S_{23} and S_{31} are the coefficients of isolation. They take into account the switch defect of power in circulator.

The others parameters S_{11}, S_{22} and S_{33} are the coefficients of reflexion at ports 1, 2 and 3; they allow to evaluate problems of structure desadaptation.

The coefficients of isolation S_{31} (dB), insertion loss S_{21} (dB) and the return loss S_{11} (dB) are presented on Fig.13. in function of frequency.

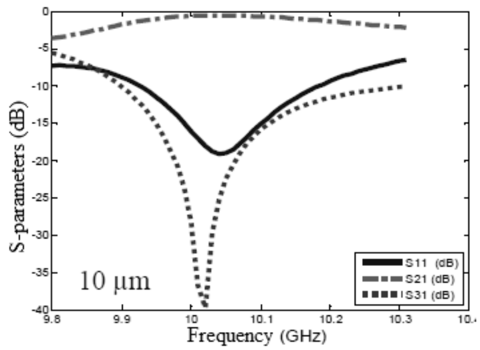


Fig.13 Transmission, isolation, and reflection parameters versus frequency.

The *S*-parameters calculations are based on the analytical model and are plotted for the following data: R (conductor) = 2mm, W = 4008m,G = 1508m, h (YIG) = 20 & 10µm, ΔH = 50Oe, Hi = 0.7T [17] for coplanar structure given by Fig.12.

Modern circulators should be able to work in the 403C to 853C temperature range, in a broad frequency range, with low insertion (reflection) losses from port 2 to 1, high isolation between ports 1 and 3. The linearity should be better than 30 dBc, at a power of several hundred W. Size considerations are important: in the 20GHz range the size of the circulator should be less than 1 cm^2 [1].

VI. Conclusion

In this paper, we presented the fundamentals magnetic properties of ferrite materials. These materials have important properties which make suitable for telecommunication and microwave applications, thank to their high resistivity, low rf losses, non nul naturel magnetization and especially, the ferromagnetic or gyromagnetic resonance which is the origin of nonreciprocal propagation phenomena.

Moreover, the Polder model describes the hyperfrency comportment of these ferrites which are saturated easily, as in the case of YIG which is a soft ferrite. This comportment finds a plethora of applications in passive microwave components such as isolators, circulators, phase shifters, and miniature antennas operating in a wide range of frequencies.

Circulator is a hexapol device which use to transmission and reception of the response signal. The transmit/receive modules allow the transmitter and receiver in a communications or radar system to share the same antenna by isolating the transmitter and receiver from each other. The most common design is a junction circulator with a symmetrical Y-shaped three-port transmission line conductor attached to it in a stripline or microstrip geometry and separated by 120◦, with a circular or triangular disk of ferrite

Modern circulators should be able to work in specific temperature range, in a broad frequency range, with low insertion (reflection) losses from port 2 to 1, high isolation between ports 1 and 3.

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