New circulator-antenna concept based on ferrite material

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***Abstract*—This paper presents the design and implementation of a single-band circulator-antenna using microstrip technology. This term refers to the combination of a circulator and an antenna on a single substrate without using any intermediate matching circuits or a 50-ohm interconnection thereby reducing the device's size and losses. This requires the development of a co-design method for the "circulantenna"(circulator-antenna association) that considers the constraints imposed by both functions integrated on the same composite substrate (ferrite/dielectric). The performances of the developed device are compared to other works reported in the literature, with particular emphasis on the system compactness and efficiency.**

Keywords—circulator, antenna, ferrite, miniaturization, co-design

I. Introduction

Circulators are non-reciprocal passive devices, usually featuring three ports. When paired with an antenna, they play a crucial role in communication systems. Their ability to direct signals in a specific direction — facilitating signal propagation from the source to the antenna for transmission and from the antenna to the receiver for reception — provides an effective solution to avoid interference between transmission and reception, thereby ensuring signal quality.

Given the imperative for compact communication systems, combining the functions of a circulator and an antenna within a single component, termed a "circulantenna," appears pertinent. This co-design approach involves integrating a circulator and an antenna on the same composite substrate (ferrite/dielectric). This strategy, illustrated in Fig. 1, aims to eliminate the 50-ohm interconnection, thereby reducing the device's size and losses.

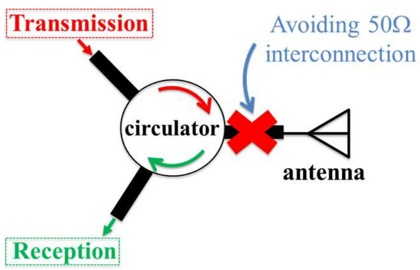

Fig. 1. Diagram of the transmission-reception module

Performance, integration, and compactness are essential criteria in this design approach, prompting the use of microstrip technology to minimize the device's size while facilitating its integration [1] within telecommunication systems. Additionally, this approach reduces the number of required components for the overall system, thus lowering manufacturing costs without compromising system versatility. The proposed device consists of a ferrite disk embedded in a dielectric substrate. A magnet is added to polarize the ferrite, enabling the ferrite to exhibit anisotropic properties. Although circulator design methods have been already reported [2,3], the approach presented in [3] has been adapted to take account of different impedances depending on the port considered. Indeed, the antenna port has a complex impedance that varies with frequency.

While several works connect circulators with other components, few have attempted to integrate a circulator and an antenna into a single unit. Operating at 8.3 GHz, our device offers a bandwidth of 5.7 %, low losses (> -0.2 dB), a radiation efficiency of 97% and a size of $\lambda_0/1.15$. The prototype and measurements will be presented at the conference.

II. Antenna overview

A. Antenna topology selection

A Vivaldi antenna was chosen based on several key criteria. Firstly, the Vivaldi antenna radiates along the axis of the substrate, hence minimizing back radiation which is essential to prevent any disruption to the upstream circulator. Thus, preserving system performance and measurement accuracy. Additionally, this antenna is wideband and exhibits low resonances which simplify achieving and maintaining a stable input impedance across a broad frequency range.

B. Antenna design

The antenna features an alumina substrate with dimensions of 20*31mm and a thickness of 0.6mm, metallized with gold on both sides. On one side, the ground and opening of the Vivaldi are etched, while the microstrip excitation line for the slotline is placed on the other side of the substrate (Fig.2). In a later stage, this microstrip line will join the antenna directly to the circulator without requiring any additional adaptation stubs in between. This design allocates sufficient space to ensure that the circulator can be integrated on this same substrate later on. This approach allows for accurate simulation of the antenna with a larger substrate and ground plane, as both significantly influence the input impedance and radiation pattern of the antenna.

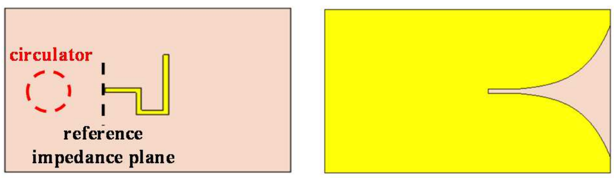

Fig. 2. Front and back views of the Vivaldi antenna

To facilitate impedance matching, it is necessary to achieve a stable and real input impedance. To meet this requirement, the antenna was optimized to operate at a low resonant mode, where the input impedance remains stable across a frequency range and the imaginary component is minimized. This design approach involved a parametric study of the antenna's dimensions in order to achieve the desired input impedance of the antenna. This antenna operates at 8.3 GHz and exhibits an input impedance of 22 Ω (Fig.3).

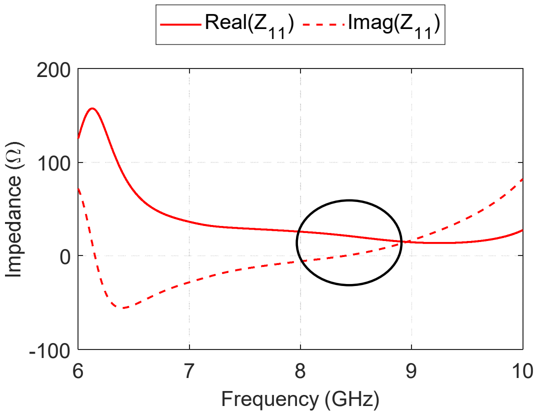

Fig. 3. Real and imaginary part of the antenna's input impedance as a function of frequency

III. Circulator Design

The circulator, designed using microstrip technology, consists of a Y39 ferrite disk embedded in a dielectric alumina substrate. The central conductor is placed on the ferrite disk with a ground plane underneath the structure (Fig.4). This circulator is matched to the input impedance of the previously designed Vivaldi antenna. The antenna is placed at port 2 of the circulator.

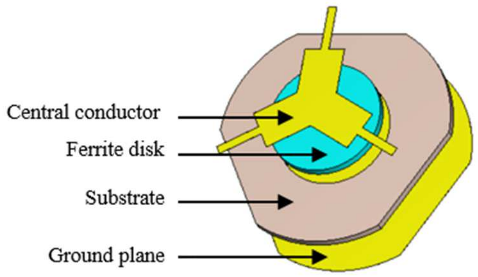

Fig. 4. Structure of a microstrip circulator

A. Ferrite properties

When a ferrite is magnetized to saturation by a static magnetic field, it exhibits non-reciprocal and anisotropic properties. The material behavior can then be described by Polder's permeability tensor (1) [4].

$$\mu = \mu_0 \overline{\overline{\mu_r}} = \mu_0 \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

Where:

$$\mu = 1 + \frac{\omega_m \omega_0}{\omega_0^2 - \omega^2}, \ \kappa = \frac{\omega_m \omega}{\omega_0^2 - \omega^2}, \ \omega_m = 2\pi\gamma \boldsymbol{M_s}$$

With:

$$\omega_0 = 2\pi\gamma \boldsymbol{H_i} + j\omega\alpha, \ \omega = 2\pi \boldsymbol{f}, \ \gamma \approx 2.8\ MHz/Oe$$

The parameters μ and κ depend on the saturation magnetization $\boldsymbol{M_s}$, the static magnetic field inside the ferrite $\boldsymbol{H_i}$ and the frequency $\boldsymbol{f}$. Plotting the real and imaginary of μ highlights the gyromagnetic resonance around which significant losses occur (Fig.5). In this work, the circulator operates in the weak field area as the selected working frequency is 8.3 GHz.

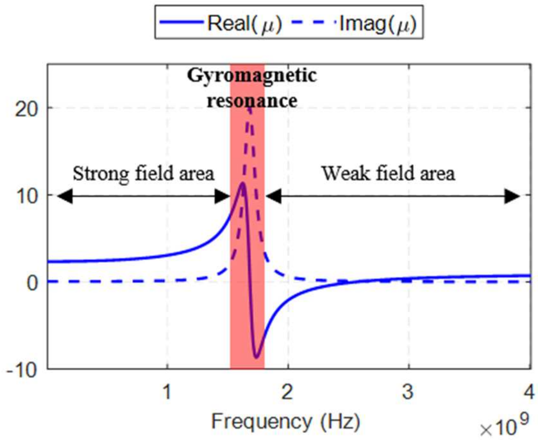

Fig. 5. Frequency dependence of the real and imaginary parts of μ for Y39 ferrite with an internal magnetic field Hi=600 Oe

B. Ferrite resonator sizing

To visualize the ferrite resonator's eigenmodes, the structure is weakly excited in order to uncouple it. This is achieved by disconnecting the microstrip lines opposite the three access points of the central conductor by leaving a 100 µm gap between these lines and the resonator (Fig.6).

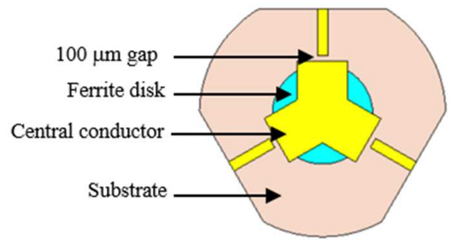

Fig. 6. Microstrip ferrite resonator weakly excited by access lines with a 100 µm gap

The resonator is dimensioned so that the counter-rotating modes HE±1 are centered around the desired operating frequency. This results in a Y-shaped central conductor. The fundamental modes of the uncoupled structure are shown in Fig.7.

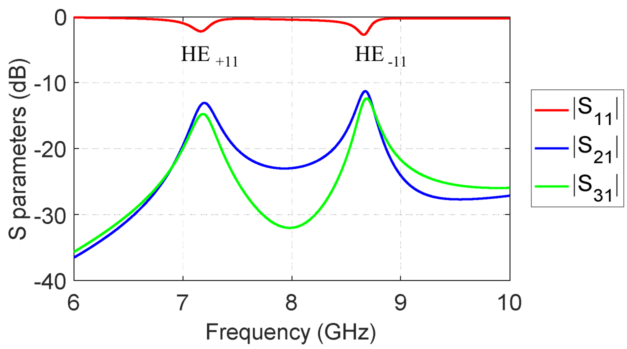

Fig. 7. Simulated S parameters for the structure Fig.6

The properties of the ferrite and the substrate used are given Table.I.

TABLE I. FERRITE AND SUBSTRATE PROPERTIES

Material	Properties	Values
Y39 Ferrite	Permittivity	14.6
	M_s (Gauss)	800
	ΔH_{eff} (Oe)	4
Alumina substrate	Permittivity	9.9

C. Coupling of the resonant modes

The next step in this design process involves coupling the resonant modes in the ferrite cavity in order to obtain a circulation function. This is accomplished by adjusting the dimensions of the resonator.

In this study, an idealized case is considered with a homogeneous internal field within the ferrite. As shown in Fig.8, a circulation phenomenon is observed at 8.3 GHz. This circulator demonstrates good impedance matching and isolation as both are better than 20 dB. Additionally, the circulator also exhibits low losses, less than 0.2 dB.

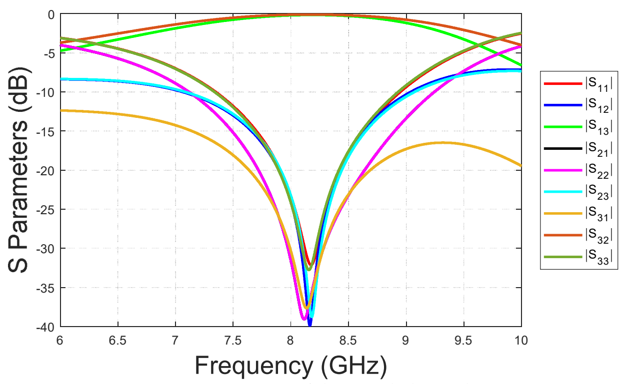

Fig. 8. S parameters of the coupled circulator

IV. CIRCULANTENNA OVERVIEW

A. Electromagnetic study of the "circulantenna"

The circulator and the antenna are integrated on the same substrate. The antenna is connected to port 2 of the circulator (Fig.9).

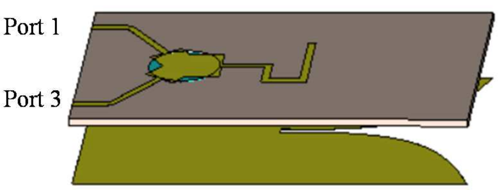

Fig. 9. Structure of the circulator-antenna

The electromagnetic simulation of the system shows a circulation phenomenon at 8.3 GHz (Fig.10). The "circulantenna" achieves satisfactory impedance matching and isolation, better than 20 dB. It also demonstrates minimal losses, less than 0.2dB. Furthermore, it features a 5.7% bandwidth.

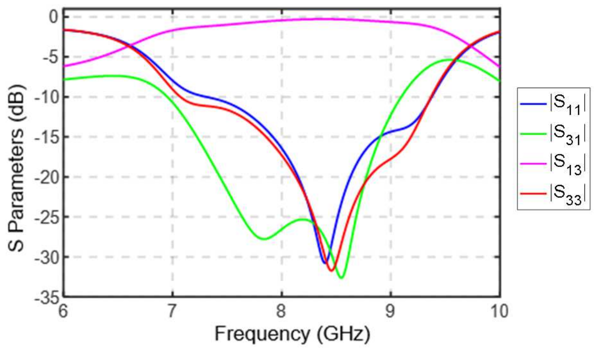

Fig.10. Simulated S parameters of the circulator-antenna Fig.9

B. Comparison with existing devices

The "circulantenna" is compared to others devices found in the literature from Adams [5,6] which integrate a circulator and a Yagi antenna as single integrated systems operating at 15 GHz. These devices require matching circuits between the circulator and the antenna. In contrast, our system, developed through a co-design approach, eliminates the need for any matching circuits. The performances of these devices are summarized in Table.II.

TABLE II. SUM UP OF THE PERFORMANCES OF THE CIRCULANTENNA AND ADAMS' DEVICES

	« Circulantenna »	**Adams' system [5]**	**Adams' system [6]**
Dimensions	$\lambda_0/1.15$* $\lambda_0/1.8$	$\lambda_0/0.38$ * $\lambda_0/0.43$	N/A
Bandwidth ($\|S_{11}\|$ > 20dB)	5.7%	9.7%	2.7%
Impedance matching and isolation	> 20 dB	> 20dB	> 20dB
Insertion losses max	0.2 dB	0.8 dB	2.5 dB
Use of impedance matching circuits	No	Yes	Yes

V. CONCLUSION

This paper introduces the first "circulantenna" which combines the functionality of a circulator and an antenna on a single substrate without requiring matching circuits. The co-design approach employed for this system allows for compactness ($\lambda_0/1.15$ * $\lambda_0/1.8$), low losses and simplified integration. Operating at 8.3 GHz the "circulantenna" provides good impedance matching, isolation and a 5.7% bandwidth. The system demonstrates promising performance, offering a compact solution for future telecommunications applications.

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