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Application of Molded Interconnect Device technology to the realization of a self-biased circulator

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ABSTRACT

This paper describes the first electromagnetic characterization of a self-biased circulator in molded interconnect device (MID) technology. The circulator was designed using a 3D full-wave commercial simulator. It consists of microstrip access lines connected to a Y-junction in Substrate Integrated Waveguide (SIW) technology. Unlike classical technologies, the SIW Y-junction was not fabricated using metallic vias but by a Laser Direct Structuring (LDS) technique. A molded Cyclo-Olefin Polymer (COP) was used as a substrate and 3D metallized. The microwave properties of LDS-compatible COP are not well known so we investigated them through the use of cavity-perturbation and rectangular waveguide characterization methods. The device was then machined to insert a pre-oriented strontium hexaferrite puck doped with cobalt and lanthanum ($Sr_{0,7}La_{0,3}Fe_{11,7}Co_{0,3}O_{19}$). The characteristics of the MID circulator were assessed between 28 and 32 GHz. Without magnets, insertion losses of 3.32 dB were measured at 30.7 GHz. At the same frequency, an isolation level of 13.89 dB and return losses of 19.89 dB were observed. These measurements demonstrate for the first time the high potential of MID technology for the realization of low-cost non-reciprocal devices.

1. Introduction

A Molded Interconnect Device (MID) is generally defined as an injection molded plastic substrate that incorporates a conductive circuit pattern and integrates both mechanical and electrical functions. This technology grew up in the past few years and is now capable of providing components for different markets, such as automotive electronics, telecommunications, computers and medical equipment. Extensive research was conducted on microwave passive components such as antennas in MID technology [1–3], and hundreds of millions of mobile phone antennas are today fabricated using this technology. However, fabricating RF front-ends in MID technology requires going further, so laboratories now focus their attention on the integration of filters [4] and on the improvement of flip chip assembly processes [5,6]. Realizing circulators in MID technology is also a challenge that will be investigated in this paper.

Circulators and isolators are commonly used in modern telecommunications systems. These non-reciprocal devices are used as duplexers to allow the use of a single antenna in full-duplex telecommunications systems or in monostatic radars. When one of the ports is loaded with a power load (isolator mode), these circuits make it possible to protect power amplifiers from radiation or impedance mismatch. In contrast to frequency-selective filters (diplexers), circulators enable transmission/isolation in the same frequency range. However, these devices are mainly fabricated by hybrid technologies (insertion of ferrite pucks in a triplate or microstrip structure) leading to high bulkiness and cost. Furthermore, bulkiness is exacerbated by the need for permanent magnets to polarize the ferrite pucks. Indeed, mass production of low-cost compact circulators remains a hot topic and new ideas and technologies are needed to improve the integration of these devices.

Removing the magnets appears to be a way to decrease circulator size and this solution has attracted the interest of laboratories and industry, leading to intensive studies over the past twenty years. Publications on this topic are mainly focused on the use of pre-oriented polycrystalline hexagonal ferrites [7–12], especially M-type strontium hexaferrites. Several demonstrators were characterized from Ku (10.7–14.5 GHz) to Q band (33–50 GHz) and above. These studies proved that removing magnets by the use of oriented hexaferrites is a viable solution. However, these devices are mainly based on the hybrid integration

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of ferrites into an alumina substrate and are thus not suitable for low-cost mass production. Thus, we propose to investigate the realization of a self-biased circulator in MID technology, which is a technology widely used in the telecommunication industry.

In this paper, the magnetic properties of doped strontium hexaferrites will first be presented. Then, the MID process employed to realize the circulator will be briefly discussed. An investigation of the microwave properties of a Laser Direct Structuring (LDS)-compatible polymer will also be presented at this point. The third part of the paper will focus on the design of the self-biased circulator. We took advantage of the potential for technical innovation offered by MID technology to propose an original topology of a Y-junction circulator in a 3D Substrate Integrated Waveguide (SIW). Performances measured without magnets and as a function of the applied field will be presented and discussed in the final part of the paper.

2. Magnetic properties of doped strontium hexaferrites

Among the available materials that can be used to realize self-biased circulators, M-type strontium hexaferrite (SrM) with magnetoplumbite structure appears to be the most promising candidate because of its high remanent to saturation magnetization ratio and its high coercive field, which make it possible to maintain a stable magnetization state without an externally applied field. SrM generally exhibits a remanent to saturation ratio of about 85%. We previously demonstrated that Lanthanum-Cobalt substitutions make it possible to increase the squareness of the hysteresis loop, and thus, the remanent magnetization level [7].

In this paper, our interest is focused on $Sr_{0,7}La_{0,3}Fe_{11,7}Co_{0,3}O_{19}$ ferrite material, here called $(La,Co)_{0.3}$-SrM. The studied samples of pre-oriented $(La,Co)_{0.3}$-SrM took the form of a flat cylinder (diameter=2.48 mm, length=1.02 mm, length to diameter ratio=0.411). The remanent magnetization was oriented along the *c*-axis, perpendicularly to the plane of the sample (axial axis of the disk). The magnetic hysteresis loops were measured (VSM MicroSense, LotQuantum company, Lowell, Massachssets, USA) over a field range of −22 kOe to 22 kOe at room temperature (290 K). Measurements were performed with the applied field H_{app} directed either along the axial axis or along one of the radial axes (Fig. 1). The measured value of the coercive field along the axial axis and radial axis were $H_C^a=4668$ Oe and $H_C^r=3900$ Oe, respectively. The hysteresis loop of the sample showed a high squareness with a remanent-to-saturation ratio of about 90%. The extrinsic remanent magnetization of the ferrite disk has a value of 304 emu/cm^3 (304 kA/m). As a self-biased operation mode is considered, this value of magnetization will be used for the design of the self-biased circulator. The internal magnetic field $\vec{H}$ was calculated with the relation:

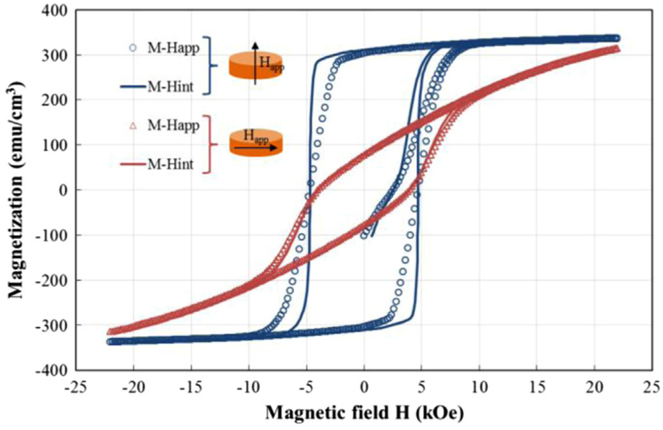

Fig. 1. Dependence of magnetization as a function of magnetic field of the cylindrical sample. Open symbols: H_{app} parallel to the axial axis (circles) and H_{app} perpendicular to the axial axis (triangles). The continuous curves show the dependence of magnetization as a function of the internal magnetic field *H* (blue curve: H parallel to the axial axis; red curve: *H* perpendicular to the axial axis). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\vec{H} = \vec{H}_{app} - \bar{N}.4\pi M \tag{1}$$

where the diagonal demagnetizing tensor $\bar{N}$ is written $\begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix}$, with $N_x+N_y+N_z=1$.

According to Aharoni's formula [13] modified in the case of a cylinder sample by considering a constant surface in the x–y plane compared with a plane-parallel sample, a length to diameter ratio equal to 0.411 leads to $N_z=0.51$, $N_x=N_y=0.245$.

The intrinsic magnetization curves thus obtained are shown in Fig. 1. The high field regions of these loops were fitted using a law of approach to saturation to extract the saturation magnetization. The law of approach to magnetic saturation widely used for the analysis of the magnetization curves of polycrystalline materials is expressed as [14]:

$$M(H) = M_S(1 - a/H - b/H^2) + \chi_{hf} H \tag{2}$$

where M_S is the magnetization at saturation. The term χ_{hf} is the forced magnetization coefficient that describes the linear increase in spontaneous magnetization at high fields. The term a/H is attributed to structural defects and non-magnetic inclusions. It is also well-known that the term b/H^2 is caused by uniform magnetocrystalline anisotropy.

Fig. 2 shows the magnetization, measured along the axial axis, plotted as a function of $1/H^2$. A linear variation between *M* and $1/H^2$ was observed in the field range 14.7–19.8 kOe. According to Eq. (2), the following value was obtained: $M_S=345$ emu/cm^3 (345 kA/m). These results (for the coercive field and saturation magnetization) are consistent with extrapolated values of other experimental data [15].

It has been shown in theory and experiment that investigation of the magnetization curve of a polycrystalline material, through the Singular Point Detection (SPD) method, can lead to the determination of the anisotropy field [16,17]. Actually, according to the SPD approach, the saturation magnetization is obtained at a finite field value, that is the anisotropy field H_k. As a consequence, a cusp in the experimental behavior of the second derivative $\frac{\partial^2 M}{\partial^2 H}$

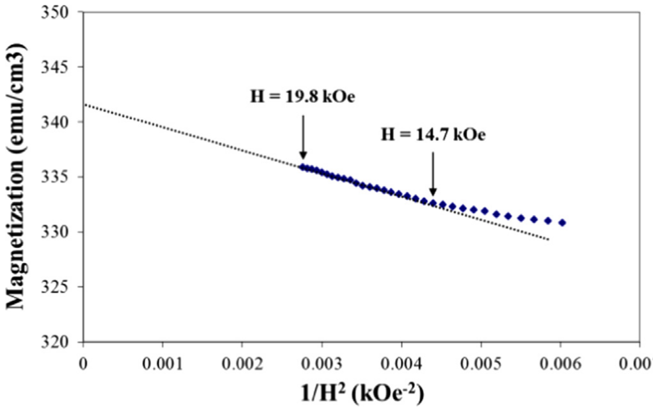

Fig. 2. Magnetization along the axial axis as a function of $1/H^2$. The dashed curve indicates a linear relation between the magnetization and $1/H^2$ in the field range 14.7–19.8 kOe.