Isolator Concept based on Ferromagnetic Nanowired Substrates

J. Spiegel *, J. de la Torre #, L. Piraux #, and I. Huynen *

*Université Catholique de Louvain, Microwave Laboratory (EMIC), B-1348 Louvain-la-Neuve, Belgium
Phone: +32-10-47-2310, E-mail: judith.spiegel@uclouvain.be
#Université Catholique de Louvain, PCPM Laboratory, B-1348 Louvain-la-Neuve, Belgium

***Abstract*— Microwave devices demand nowadays small sizes and broad bandwidth. Ferromagnetic nanowired membranes are ideal candidates for this purpose. Planar, tunable and nonreciprocal devices can be designed with them. Therefore we propose an isolator concept based on such a material. Its principle is based on a nonreciprocal microstrip line.**

***Index Terms*— Isolators, ferromagnetic materials, nanotechnology, nonreciprocal wave propagation.**

I. Introduction

Ferromagnetic nanowired substrates (Fig. 1) offer, due to their excellent material properties, the ability to build tunable planar devices for very high frequencies, as nowadays requested for wireless communication and automotive systems. The advantages of such materials compared to classical ferrites are a higher operation frequency, a higher saturation magnetization and a higher resonant frequency. They are tunable in frequency by applying an external magnetic field [1]. The nanowires as ferromagnetic inclusions influence the permittivity and permeability of the composite substrate.
The focus of this paper lies on the feasibility of isolators based on such a nanowired substrate. First of all, we explain briefly the topology and the functional principle by showing the importance of the substrate parameters, effective permittivity and tensor permeability. Simulation and measurement results of the prototype will then be shown and discussed.

II. Topology of Ferromagnetic Nanowired Isolator

The basis material of our isolator is formed by a porous insulating polycarbonate membrane filled with ferromagnetic nanowires as shown in Fig. 1. They were formed by electrodeposition. The cylindrical pores of diameter D are randomely distributed and electromagnetic waves can propagate for a nanowire diameter smaller than skindepth [2]. The isolator

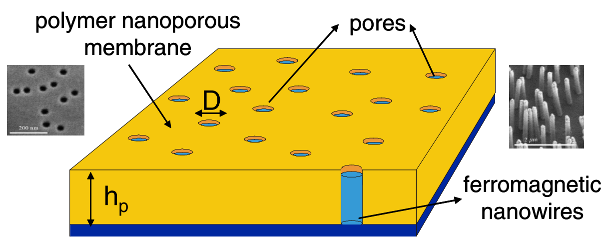

Fig. 1. Ferromagnetic nanowired substrate.

is based on a microstrip topology lying on three different zones of the substrate. The first zone contains no ferromagnetic nanowires, the second zone contains ferromagnetic nanowires of a certain height and the third zone contains in our case also ferromagnetic nanowires which are higher than in zone two. A 2D-model of this topology is shown in Fig. 2. As will be explained in section III, the different filling heights will influence the permittivities in the three zones.

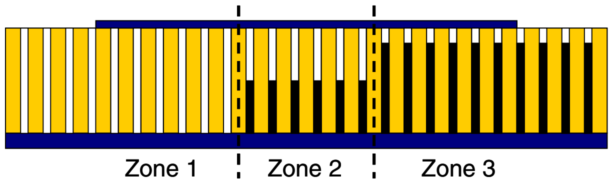

Fig. 2. 2D-model of ferromagnetic nanowired isolator.

III. Functional Principle

The functional principle of the isolator on ferromagnetic nanowired substrate is based on the asymmetrical loading of a microstrip transmission line, containing low and high dielectric material slabs, depending on the nanowire height. In Fig. 2 zone one has a low permittivity, zone two a higher permittivity as zone one, and zone three has the highest permittivity. This asymmetrical edge loading, i.e. the material in zone one is not the same as in zone three, is responsible for the nonreciprocal behavior of the so-called edge-guided mode isolator. For this application, the width of the microstrip line has to be large compared to the substrate thickness with the aim to store the most of the wave energy under the microstrip. The propagation mode is similar to the TEM mode, but it has a strong transverse electric field displacement [3]. This implies the concentration of the wave energy at one border, e.g. between zone two and three of the different material zones under the microstrip line. By changing the input port, the concentration of the wave energy will move to the other border of the material zones, e.g. zone one and two, where losses and permittivity are lower, so that propagation characteristics are modified. Briefly, the propagation constants and the field configurations are different in the two propagation directions, meaning that a nonreciprocal operation is feasible. For the design of an isolator based on ferromagnetic nanowired substrate, it is important to know the dielectric and magnetic properties of the material. Therefore our models for the scalar effective permittivity and tensor permeability will be briefly explained [2], [4].

A. Permittivity

The permittivity model takes geometrical parameters of the substrate such as the porosity of the membrane and the height of the nanowires into account. It is based on a microstrip line approach. The model calculates the total capacitance per unit length of a microstrip line on a ferromagnetic nanowired substrate. The overall permittivity can be calculated from this total capacitance C_{tot} by:

$$\varepsilon_{eff} = \frac{C_{tot} h_p}{\varepsilon_0 W_s} = \frac{h_p}{\frac{h_w}{\varepsilon_w} + \frac{h_a}{\varepsilon_p}}, \quad (1)$$

where W_s is the width of the microstrip, h_p the polymer membrane height, h_a the height between the top of the nanowires and the bottom side of the microstrip line, h_w the height of the nanowires, ε_p the permittivity between the top of the nanowires and the bottom side of the microstrip line and ε_w the permittivity of the layer containing the nanowires. The expressions of the partial permittivities include the porosity of the membrane, the conductivity of the wires and the dielectric loss tangent factor of the polymer. Further details as well as sketches can be found in [2].

Fig. 3 shows the calculation of the effective permittivity depending on the height of the nanowires done with (1). The chosen template material is a polycarbonate membrane with a porosity of 10% as will be used later in the experimental part.

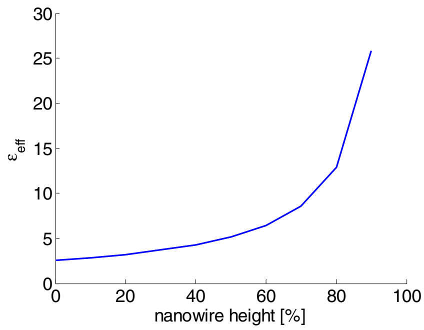

Fig. 3. Effective permittivity of a polycarbonate membrane (porosity$= 10\%$) with nanowires, depending on the filling height.

B. Permeability

The permeability of the ferromagnetic material is based on a tensor formalism [5]:

$$\overline{\overline{\mu}} = \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \quad (2)$$

The elements μ, κ and μ_z of the tensor can be calculated by:

$$\mu = 1 + \frac{h_r p \omega_m (\omega_e + j\omega\tilde{\alpha})}{(\omega_e + j\omega\tilde{\alpha})^2 - \omega^2} \cdot \frac{1+\alpha^2}{2}, \quad (3)$$

$$\kappa = \frac{h_r p \omega_m \omega}{(\omega_e + j\omega\tilde{\alpha})^2 - \omega^2} \cdot \alpha, \quad (4)$$

$$\mu_z = 1 + \frac{h_r p \omega_m (\omega_e + j\omega\tilde{\alpha})}{(\omega_e + j\omega\tilde{\alpha})^2 - \omega^2} \cdot (1 - \alpha^2) \quad (5)$$

according to [6] where p is the porosity of the membrane, $\tilde{\alpha}$ is the damping factor and $\alpha = \frac{M_r}{M_s}$ the magnetization state of the substrate, with M_r the remanent and M_s the saturation magnetization, respectively, while $\omega_e = \omega_m + \tilde{\gamma} H_{DC}$ with $\omega_m = \tilde{\gamma} 2\pi M_s$ and $\tilde{\gamma}$ the gyromagnetic factor. The ratio $h_r = \frac{h_w}{h_p}$ has been added to take the height of the nanowires into account.

IV. Results

For the design of an isolator, these proposed models for the permittivity and permeability are included in a Finite-Element Method (FEM) simulator. The chosen material is a polycarbonate membrane of 21 μm. Its porosity is 10%. This high porosity is needed to have enough ferromagnetic material to obtain a nonreciprocal effect. Since we were looking for an application above 20 GHz, the membrane is filled with Cobalt nanowires having a diameter of 70 nm. These wires are electrodeposited into the pores from an acidic solution with a $pH = 2$. This pH-value leads to the fact that the nanowires have no magnetocrystalline anisotropy and the zero field resonance frequency is close to 25 GHz [7]. The width of the microstrip line is $W_s = 500$ μm, which is large compared to the substrate height. Its length is $l = 2.3$ cm. The parameters for the three different material zones located under the microstrip line are given in Table I. The effective permittivities are obtained from Fig. 3 for the three filling factors corresponding to the three fabricated zones. As shown in section III-A, the higher the nanowires, the higher the permittivity. Fig. 4 shows an image of the home-made isolator.

TABLE I
Effective Permittivities

	zone 1	zone 2	zone 3
h_r	0.0	0.5	0.8
ε_{eff}	2.6	5.2	12.9

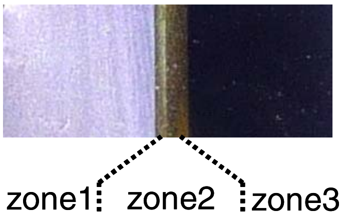

Fig. 4. Picture of the fabricated isolator.

Since the material is ferromagnetic, the device is tunable in frequency by applying an external magnetic DC field. Therefore two cases will be analyzed, the first with no applied external magnetic field, $H_{DC} = 0$ kOe and the second with an applied external magnetic field, $H_{DC} = 9$ kOe. The applied field is parallel to the nanowires.

Fig. 5 shows the comparison of the simulated and measured S-parameters, when no external magnetic field is applied. Both results, simulation and measurement, show the ferromagnetic resonance frequency at 23 GHz. The isolation between S_{12} and S_{21} is relatively low, around 1 dB. The observed low nonreciprocity at remanence can be ascribed to the large diameter of the wires. Indeed, for large diameter of Cobalt wires, the magnetization at remanence tends to zero, which is mainly due to the presence of magnetic domains [8]. This can be directly observed from (2), where the off-diagonal element κ in the permeability tensor tends to zero [6]. Fig. 6 shows

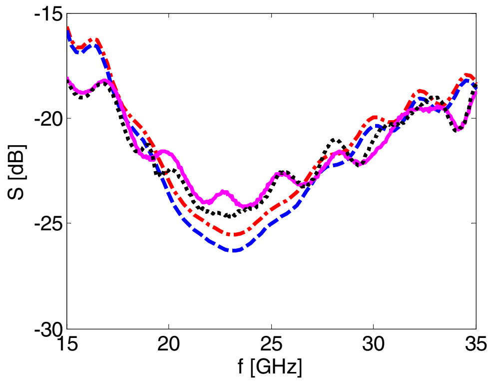

Fig. 5. Simulated, S_{12} (dashdotted) and S_{21} (dashed), and measured, S_{12} (solid) and S_{21} (dotted), S-Parameters of the isolator with no applied external magnetic field.

the comparison of the simulated and measured S-parameters, when an external magnetic field of 9 kOe is applied to the device. Due to the applied field, the ferromagnetic resonance frequeny is shifted to 42 GHz. The isolation between S_{12} and S_{21} is about 6 dB. The applied field rises the magnetization state of the ferromagnetic nanowires nearly to saturation. The displacement of the energy under the microstrip line is now higher than without an applied external magnetic field, so that the device becomes nonreciprocal around the ferromagnetic resonance frequency.

The agreement between the simulation and measurement

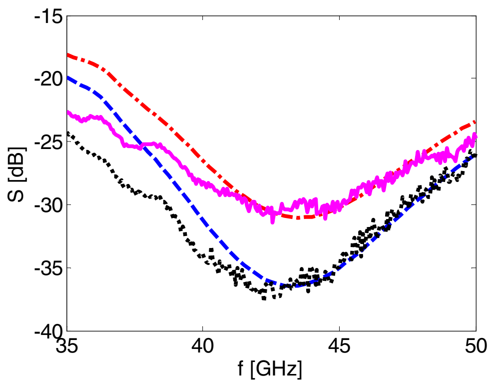

Fig. 6. Simulated, S_{12} (dashdotted) and S_{21} (dashed), and measured, S_{12} (solid) and S_{21} (dotted), S-Parameters of the isolator with an applied external magnetic field of 9 kOe.

results is very good. The difference observed below the resonance frequency occurs due to the fact that the thickness of the metallic microstrip line is very low (< 1 μm) and could therefore not be taken properly into account in the FEM solver. Fig. 7 shows the measurement result of a microstrip line having the same width and length as the isolator on the same polycarbonate membrane with no nanowires inside ($W_s = 500$ μm, $l = 2.3$ cm). For comparison, the measurements of the isolator of Fig. 6 are also reported. As can be seen, the insertion losses in the lower frequency range are similar. The ripple on the S-parameters and the high insertion losses below 30 GHz occur due to the mismatch of the microstrip line with respect to the 50 Ω reference impedance of the measuring setup. Since the ratio $W_s/h_p > 20$ is very high, the impedance of the line is only 8 Ω. If zone one and zone three are filled

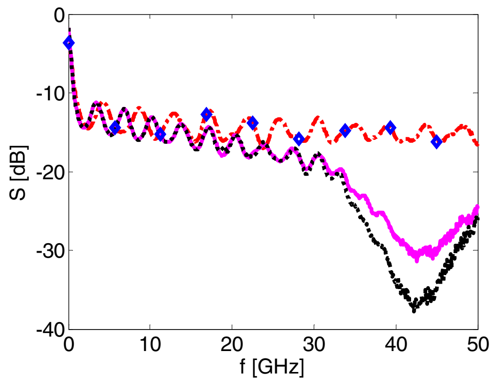

Fig. 7. Measured transmission parameters S_{12} and S_{21} (dashdotted and symbol) of microstrip line of width 500 μm on polycarbonate membrane compared to measured isolator with applied field of 9 kOe.

with nanowires of the same height, e.g. $\varepsilon_{eff} = 8.7$, the isolator will act as a reciprocal microstrip line. This result is shown in Fig. 8. So for the design of an isolator it is necessary to load the two edge zones with materials having different constitutive parameters.

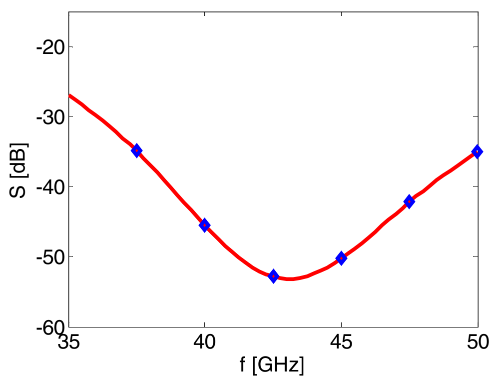

Fig. 8. Simulated transmission parameters S_{12} (solid) and S_{21} (symbol) of microstrip line symmetrically loaded under the edges with $\varepsilon_{eff} = 8.7$ and in the middle $\varepsilon_{eff} = 3.7$.

V. Further improvements

To improve the performance of the isolator, various technological changes are proposed. Another membrane material could be used to avoid the high dielectric losses of the polycarbonate membrane. Furthermore the size of the nanowire diameter should be decreased when using Cobalt nanowires in order to obtain single domain nanowires which have a higher remanent magnetization. To avoid the high absorption around the ferromagnetic resonance frequency observed with Cobalt, another nanowired material could be used, resulting also in a lower operating frequency (10 GHz for Nickel). Finally the geometry should be optimized in order to reduce the mismatch. One solution could be the increase of the membrane thickness h_p or the reduction of the strip width W_s. The improvement obtained when reducing the dielectric losses and mismatch can be easily predicted by normalizing the measured forward and reverse transmission coefficients to the measured transmission coefficients of the microstrip without nanowires represented in Fig. 7. The result is shown in Fig. 9. The isolation of 6 dB is confirmed at 40 GHz with e.g. forward insertion losses lower than 10 dB, meaning a 28 dB improvement. Work is in progress to further reduce the forward insertion losses at the operating frequency.

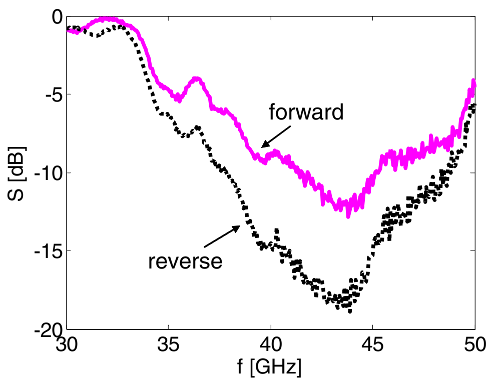

Fig. 9. Transmission S-Parameters of isolator normalized to transmission coefficient of microstrip line without nanowires.

VI. Conclusion

The concept of an isolator on ferromagnetic nanowired substrate has been proposed in this paper. It is based on the asymmetrical loading of a microstrip line. The nonreciprocity occurs due to the transverse electric field displacement. The measurements show a good agreement with the ferromagnetic models introduced into a FEM simulator. This isolator solution is planar and tunable in frequency.

Acknowledgement

The authors wish to thank Professor Spartak Gevorgyan from Chalmers University, Sweden, for fruitful discussion and Etienne Ferain from *it4ip* s.a., Belgium, for providing the polycarbonate membranes. Acknowledgements are also due to the Research Science Foundation (FRS-FNRS, Belgium).

References

[1] I. Huynen, G. Goglio, D. Vanhoenacker, and A. V. Vorst, “A novel nanostructured microstrip device for tunable stopband filtering applications at microwaves,” *IEEE Microwave and Guided Wave Letters*, vol. 9, pp. 401–403, 1999.

[2] J. Spiegel, J. de la Torre, M. Darques, L. Piraux, and I. Huynen, “Permittivity model for ferromagnetic nanowired substrates,” *IEEE Microwave and Wireless Component Letters*, vol. 7, pp. 492–494, 2007.

[3] M. Hines, “Reciprocal and nonreciprocal modes of propagation in ferrite stripline and microstrip devices” *IEEE Transactions on Microwave Theory and Techniques*, vol. 19, no. 5, pp. 442–451, May 1971.

[4] J. Spiegel, L. Piraux, and I. Huynen, “Ferromagnetic material with negative permeability for tunable left-handed devices,” in *Proc. 37th European Microwave Conference, Munich,*, October 2007, pp. 1–4.

[5] J. Helszajn, *Principle of Microwave Ferrite Engineering*. John Wiley and Sons Ltd., 1969.

[6] A. Saib, M. Darques, L. Piraux, D. Vanhoenacker, and I. Huynen, “Unbiased microwave circulator based on ferromagnetic nanowires arrays of tunable magnetization state,” *Journal of Physics D: Applied Physics*, vol. 38, pp. 2759–2763, 2005.

[7] M. Darques, A. Encinas, L. Vila, and L. Piraux, “Controlled changes in the microstructure and magnetic anisotropy in arrays of electrodeposited co nanowires induced by the solution pH,” *Journal of Physics D: Applied Physics*, vol. 37, p. 16, 2004.

[8] R. Ferre, K. Ounadjela, U. Ebels, L. Piraux, and S. Dubois, “Magnetization processes in nickel and cobalt electrodeposited nanowires,” *PhysRev B*, vol. 56, pp. 14 066–14 076, 1997.