"Magnetic photonic band-gap material at microwave frequencies based on ferromagnetic nanowires"

Saib, Aimad ; Legras, Roger ; Vanhoenacker-Janvier, Danielle ; Huynen, Isabelle ; Encinas, Armando ; Piraux, Luc ; Ferain, Etienne

ABSTRACT

We present an experimental investigation of a class of microwave photonic band-gap (PBG) materials, in which the magnetic permeability \( \mu \) varies periodically within the material. This material is fabricated using a periodic arrangement of arrays of magnetic nanowires. As for dielectric or metallic PBG, the band-gap behavior varies with the geometrical parameters fixing the spatial periodicity of the magnetic structure. The magnetic photonic band gap is induced by the presence of a ferromagnetic resonance effect in the vicinity of the band gap. (C) 2003 American Institute of Physics.

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Citation: Appl. Phys. Lett. 83, 2378 (2003); doi: 10.1063/1.1610798
View online: http://dx.doi.org/10.1063/1.1610798
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Magnetic photonic band-gap material at microwave frequencies based on ferromagnetic nanowires

A. Saib, a) D. Vanhoenacker-Janvier, and I. Huynen
Laboratoire d’Hyperfréquences, Université Catholique de Louvain, 3 Place du Levant, B-1348 Louvain-la-Neuve, Belgium

A. Encinas and L. Piraux
Unité de Physico-Chimie et Physique des Matériaux, Université Catholique de Louvain, 1 Place Croix du Sud, B-1348 Louvain-la-Neuve, Belgium

E. Ferain and R. Legras
Laboratoire des Hauts Polymères, Université Catholique de Louvain, 1 Place Croix du Sud, B-1348 Louvain-la-Neuve, Belgium

(Received 4 April 2003; accepted 21 July 2003)

We present an experimental investigation of a class of microwave photonic band-gap (PBG) materials, in which the magnetic permeability $\mu$ varies periodically within the material. This material is fabricated using a periodic arrangement of arrays of magnetic nanowires. Indeed, the transmission of a range of frequencies is prohibited in such structures. Although the original research on PBG structures was done for the optical range, there has been an increasing interest in scaling their properties to the microwave frequencies. Up to now, magnetic materials have not attracted much attention for PBG materials, since the relative permeability of magnetic materials $\mu_r$ is equal to unity in the optical range. However, for most ferrites, $\mu_r$ is different from unity in the microwave range and this can be exploited for microwave PBGs. The effect of the magnetic permeability on PBG materials has been studied theoretically by Sigalas et al. They found that the PBG effect can be obtained in periodic materials in which both the dielectric permittivity $\varepsilon$ and magnetic permeability $\mu$ vary within the material. In addition, they show that in the case where $\varepsilon$ and $\mu$ have their maximal values in the same material, the band gaps tend to disappear. In more recent works, the role of a periodic variation of wave impedance $\sqrt{\mu/\varepsilon}$ in the formation of band gaps in PBG materials with magnetic and dielectric properties has been demonstrated. The essential parameter responsible for band gaps is the wave impedance, the refractive index fixing only the central frequency.

In this letter, we present an experimental investigation of a magnetic photonic band-gap (MPBG) material. It consists of a microstrip transmission line on a periodic magnetic substrate fabricated using arrays of ferromagnetic nanowires. Classical ferrites are not suitable for magnetic PBGs at several gigahertz due to their low resonance frequencies and the technological limits related to their integration with other dielectrics. Ferromagnetic materials have higher resonance frequencies than most ferrites. Unfortunately, their high conductivity does not allow electromagnetic wave propagation in bulk material at microwave frequencies. Magnetic nanowires, which consist of an array of parallel ferromagnetic nanowires electrodeposited into a porous polycarbonate membrane, offer a good alternative to overcome this problem. The small wire diameter, compared to the skin depth, as well as the insulating nature of the polycarbonate membrane, guarantee the full penetration of electromagnetic fields inside the nanowires.

The MPBGS investigated here are fabricated as reported in Refs. 8 and 9 for the synthesis of magnetic nanowires into the pores of track-etched membranes. In this work, patterned membranes with pores created in designated areas only are used; they are produced according to a patented process based on a combination of global track-fading and selective track-sensitization steps applied to an energetic heavy ion irradiated polycarbonate film. The selective track sensitization is performed using a UV source illuminating through a UV mask and only these sensitized tracks are converted to pores during the etching. Therefore, the area where the nanowires are electrodeposited into the pores is defined by the used UV mask. By this way, we obtain a periodic structure alternately composed of polycarbonate with and without nanowires. The resulting composite structure is used as a substrate in a microstrip configuration. Figure 1(a) gives a three-dimensional (3D) schematic view of the MPBG topology and Fig. 1(b) shows a top-view picture of the fabricated structure.

We use a simple analytical model, developed in Ref. 1 for microstrip metallic PBGs, for the design of our magnetic PBG structure. This model is based on the similarity between the frequency response of a fiber Bragg grating and a one-dimensional (1D) PBG structure, around their corresponding
central frequencies. The central frequency of our MPBG structure [Fig. 1(b)] is given by Eq. (1) already used by Laso et al. to estimate the central frequency of a metallic PBG structure:

\[
f_c = \frac{c}{\lambda_c}, \quad \lambda_c \approx 2[n_p(a-d) + n_f d],
\]

where \(c\) is the speed of light in the vacuum, \(n_p = \sqrt{\varepsilon_r}\) is the refractive index of the polycarbonate membrane with \(\varepsilon_r = 2.89\) the corresponding relative dielectric constant, and \(n_f = \sqrt{\varepsilon_r / \mu_r}\) is the refractive index of the polycarbonate membrane with nanowires where \(\mu_r\) is the relative magnetic permeability and \(\varepsilon_r\) the relative permittivity of the composite polymer+nanowires. The porosity parameters \(a\) and \(d\) are defined in Fig. 1(a). The relative magnetic permeability is evaluated using the following formulas:

\[
\mu_r = \frac{\mu^2 - k^2}{\mu}, \quad \mu = 1 + (1 - p) \mu_{wire}, \quad k = pk_{wire}.
\]

The parameter \(p\) is defined as \(p = \rho \pi D^2/4\). It corresponds to the porosity of the membrane with \(\rho\) the number of pores per square meter and \(D\) the pore diameter. Parameters \(\mu_{wire}\) and \(k_{wire}\) are, respectively, the diagonal and off-diagonal components of the magnetic permeability tensor of one nanowire given by the classical ferromagnetic resonance (FMR) theory:\(^{12,13}\)

\[
\mu_{wire} = 1 + \frac{\omega_m}{(\omega + j \omega_0)^2 - \omega^2}, \quad k_{wire} = \frac{\omega_m \omega}{(\omega + j \omega_0)^2 - \omega^2},
\]

where \(\omega_m = \gamma M_s / \mu_0\) with \(\gamma\) the gyromagnetic ratio, \(M_s\) the saturation magnetization, \(\mu_0\) is the magnetic permeability in vacuum, \(\alpha\) is the damping factor, \(\omega\) is the angular frequency, and \(\omega_0\) is the FMR angular frequency given by:\(^{14,15}\)

\[
\omega_0 = \omega_m + \frac{1}{2} \omega_m (1 - 3p), \quad (5)
\]

where \(\omega_m = \gamma H_{dc}\) with \(H_{dc}\) the applied static magnetic field.

Various samples with different periodic parameters \((a, d)\) have been fabricated using Permalloy nanowires (Py=Ni_{80}Fe_{20}). Figure 2 shows the measured transmission and reflection of two MPBGs without applied static magnetic field: MPBG 1 (solid line) with \(a = 3.636\) mm, \(d = 1.818\) mm, and MPBG 2 (dashed line) with \(a = 3.078\) mm, \(d = 1.538\) mm. The total length of the MPBG structures is 2 cm. In the transmission curves we see two peaks. The first one, at 16 GHz, corresponds to the FMR frequency of Py nanowires at the remanent state. The second one is due to the PBG effect at 21 GHz for MPBG 1 and 26 GHz for MPBG 2. These last two frequencies are in good agreement with those predicted by the design formula (1). In all samples considered in this work we take \(a = 2d\) in order to simplify this first design. For a given \(\mu_r\), formula (1) relates the central frequency of the band gap and the porosity parameter \(a\).

The FMR peak is located at the same position for both MPBG 1 and MPBG 2 because it depends only on the ferromagnetic material filling the pores.\(^16\) The measured reflections give more details about the origin of each peak. The FMR origin of the first peak is confirmed by \(-6\) to \(-10\) dB reflection around the FMR frequency: the electromagnetic power is absorbed by the magnetic materials. The strong reflection around the second peak (-2.5 dB) proves its PBG origin: the electromagnetic power is not absorbed, it is reflected. Figure 3 shows the effect of a static magnetic field, applied parallel to the nanowires, on a MPBG where \(a = 2.666\) mm and \(d = 1.333\) mm, which gives a band gap at 28 GHz far enough from the FMR frequency. Therefore, we can see the influence of the external magnetic field on the MPBG peak and the FMR peak separately. The position of the FMR absorption varies linearly with the static magnetic field as predicted by Eq. (5). On the other hand, the MPBG peak remains almost at the same frequency. This behavior can be explained by the small variation at 28 GHz of the magnetic permeability \(\mu_r\) within the dc magnetic field range considered in Fig. 3. Equation (2) gives a variation between 0.6 and 0.7 for the real part of \(\mu_r\), which is too small to affect the position of the band gap.
to have a PBG effect with a relative magnetic permeability $\mu_r < 1$. However, the role of wave impedance in the creation of PBGs with dielectric and/or magnetic properties could give a satisfactory explanation. Let us make a comparison between the wave impedance $\sqrt{\mu_r / \varepsilon_r}$ of a classical dielectric PBG and the magnetic PBG investigated here. In general, for dielectric PBGs we have a ratio of dielectric permittivities $\varepsilon_{r1}/\varepsilon_{r2} \approx 1$, which gives necessarily $\sqrt{\mu_{r1}/\varepsilon_{r1}} / \sqrt{\mu_{r2}/\varepsilon_{r2}}$, since $\mu_{r1} = \mu_{r2} = 1$ for dielectric materials. For our MPBG the ratio $\mu_{r1}/\mu_{r2} < 1$ gives $\sqrt{\mu_{r1}/\varepsilon_{r1}} < \sqrt{\mu_{r2}/\varepsilon_{r2}}$ because $\varepsilon_{r1} \approx \varepsilon_{r2} = 2.89$. Therefore, we can say that a magnetic PBG corresponds to the dual of a dielectric PBG. In both Figs. 2 and 3, the spurious losses on the transmission factors outside the FMR and MPBG frequencies are mainly due to the high dielectric losses of the polycarbonate membrane, which increase with frequency.

It should be noted that the MPBG effect obtained here is related to the existence of ferromagnetic resonance in the vicinity of the band-gap frequency. The relative magnetic permeability of the ferromagnetic nanowires $\mu_r$ differs from 1 in the angular frequency band $\omega_0 \pm \Delta \omega$ where $\Delta \omega$ is known as the linewidth of the magnetic material. This frequency band is quite wide (6–7 GHz) for the magnetic material used here, which can be attributed to the random distribution of the nanowires inside the polycarbonate membrane. It is thus possible to have band gaps induced by $\mu_r \neq 1$ in a wide band around the FMR resonance frequency.

In conclusion, magnetic PBG materials have been fabricated using periodically arranged arrays of magnetic nanowires. The band gap is mainly created by a periodic change of the magnetic permeability from $\mu_r = 1$ (polycarbonate membrane) to $\mu_r \neq 1$ (membrane with nanowires). The influence of the geometrical parameters $a$ and $d$ defining the periodicity and of the applied static magnetic field on the MPBG have been studied. Results are in good agreement with the design formulas used for classical dielectric or metallic PBGs. The operation of our MPBG is in agreement with the recent view that wave impedance is an essential parameter in the formation of photonic band gaps. The FMR phenomenon, present naturally in magnetic materials and strongly dependent on the applied static magnetic field, could give additional tuning features to classical PBGs obtained with dielectric or metallic materials.

This work is partly funded by “Region Wallonne,” by Growth Program No. GR5D-1999-0135, the Belgian Inter-university Attraction Pole program PAI (5/1/1), and by the National Fund for Scientific Research (FNRS), Belgium.

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