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Negative permittivity and left-handed behavior of doped manganites in millimeter waveband

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The "effective plasma frequency" of strontium-doped lanthanum manganite was determined basing on its double negative properties. The zone of high transmission (double negative zone) for spatially partitioned layered manganite specimen, immersed into dielectric matrix, was studied experimentally in millimeter waveband. It turns out that frequency dependence of manganite permittivity is well described by Drude formula, which includes only one parameter—the "effective plasma frequency." Additionally, the negativity of the refraction index has been directly proved in experiments studying electromagnetic waves refraction in manganite prism. © *2010 American Institute of Physics*. [doi:10.1063/1.3491155]

In recent years, the materials with simultaneously negative permittivity and permeability (the so-called left-handed media or LHM), are of special interest.[1,2] A use of these materials experimentally proved[2–4] possibility to create magnetotuneable devices for microwave band. As is known to realize LHM its permittivity and permeability should be negative (double negative medium) and the medium should be dispersive.[1] For this purpose some authors[2] used composite structures consisting of ferrite layers and so-called wire medium (WM). The frequency dependence of the WM permittivity $\varepsilon_{\mathrm{WM}}=\varphi(f)$,[5] is described by known Drude formula for free electron gas,[6] $\varepsilon_{\mathrm{WM}}(f)=\varepsilon_{\mathrm{host}}-f_{\mathrm{pWM}}^2/f^2$, where f is the frequency and $\varepsilon_{\mathrm{host}}$ is the permittivity of the host media (media, where WM is located). But now for WM f_{pWM} is a parameter depending on wires configuration—an "effective plasma frequency." According to Ref. 5 $f_{\mathrm{pWM}}^2=c^2/[a^2\ln(a/r)]$ where a and r are the distance between wires, and their diameters, c is the light velocity. The value of the parameter f_{pWM} makes it possible to narrow down frequency band of LHM existence to millimeter wavelength band.

Recently, features of left-handed behavior in extra high frequency or EHF band have been reported[3,4] for doped manganites (La, A)MnO$_3$ (A=Ca, Sr). The strontium-doped lanthanum manganites $\mathrm{La}_{1-x}\mathrm{Sr}_x\mathrm{MnO}_3$ are ferromagnetic conductors[7,8] with Curie point above the room temperature (for $x\geq 0.17$). The peculiar behavior (the left handed features) of the layered structure with $\mathrm{La}_{1-x}\mathrm{Sr}_x\mathrm{MnO}_3$ ($x=0.225$) manganite as a boundary medium was reported by us earlier.[4] A drastic enhancement of manganite transparency in some frequency band (so-called double negative zone/DNG-zone) resulting from simultaneous negativity of permittivity and permeability is a characteristic feature of transmission spectra for this structure. Thus the doped-manganite-based structures seem to be prospective candidates for the role of LHM in the millimeter waveband,[3,4] especially because their properties can be easily tuned by both external magnetic field and temperature.

The propagation of electromagnetic wave through the structure is determined generally by product of its permittivity and permeability. At the same time knowledge of these parameters separately, their frequency dependence is not only of interest for future applications but can also be indication of physical processes in the system.

In this paper we studied experimentally the $\mathrm{La}_{0.775}\mathrm{Sr}_{0.225}\mathrm{MnO}_3$ manganite in the frequency band 20–40 GHz and determined the frequency dependence of its permittivity. It turned out that the frequency dependence of the permittivity is well described by Drude formula with only one parameter—the "effective plasma frequency." It is noteworthy that the determined value is in compliance with that

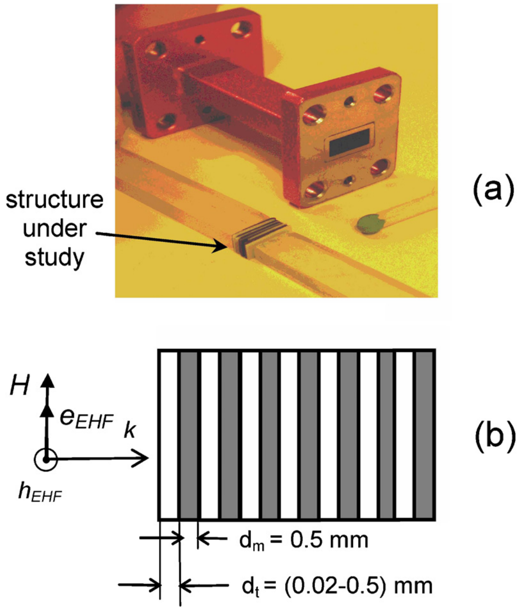

FIG. 1. (Color online) (a) flow chart and (b) configuration of the structure under study.

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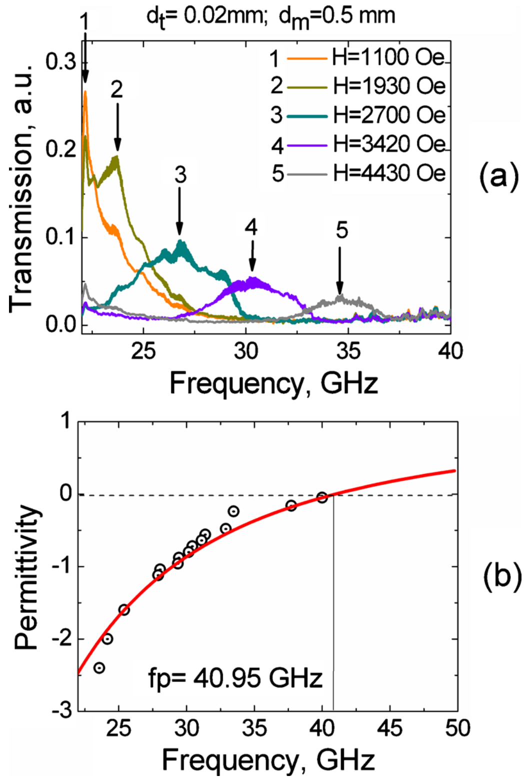

FIG. 2. (Color online) (a) Typical position of the DNG-zone with the magnetic field (H) as a parameter ; (b) the dispersion curve for sintered manganite of lanthanum-strontium $La_{0.775}Sr_{0.225}MnO_3$.

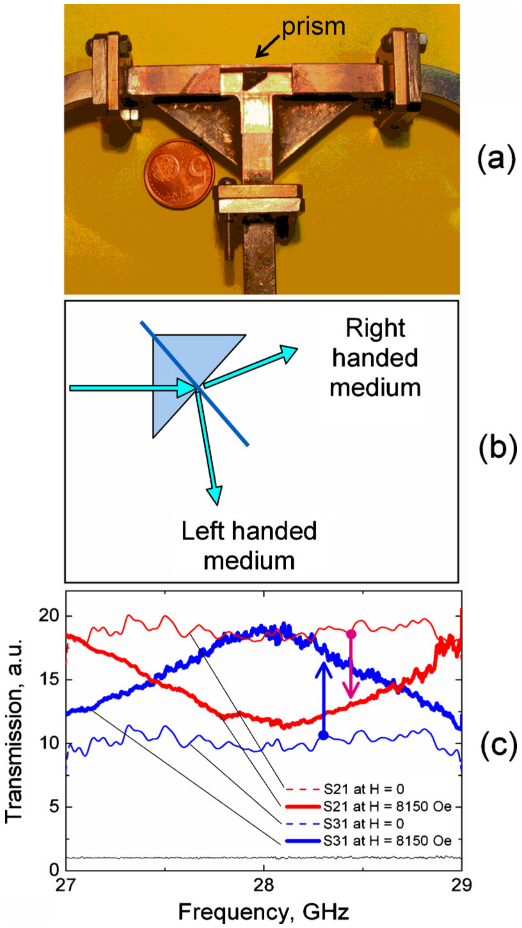

FIG. 3. (Color online) (a) the overview of T-bridge used to demonstrate the negativity of manganite refractive index; (b) the ray tracing in the Left Handed prism (Ref. 9) ; (c) the transmission spectra through the "straight" channel (S21) and "perpendicular" channel (S31) for H=0 and at H=8150 Oe.

obtained in Ref. 3 from measurements in the frequency band of 80–150 GHz.

In order to demonstrate intrinsic features of the LHM refraction, we have carried out the experiment with refraction in the prism made from bulk $La_{0.775}Sr_{0.225}MnO_3$ and placed into T-bridge. The transition of the strontium-doped lanthanum manganite to the LHM state has been accompanied with a sharp ray deflection in T-bridge.

Our researches were performed using Network Analyzer NA5230, which determined the frequency band of experiments being as 20–40 GHz. The specimen represented a one-dimensional finely stratified medium, (Fig. 1) formed by thin ($d_m \ll \lambda$) manganite layers alternating with thin ($d_t \ll \lambda$) teflon layers. The structure was embedded into a single-mode waveguide and the technique of experiment described in Ref. 4 was applied. The effective permittivity of the structure is described by the known formula

$$\varepsilon_{\text{eff}}(f) = \frac{\varepsilon_t d_t + \varepsilon_m(f) d_m}{d_m + d_t}. \tag{1}$$

Where ε_t and ε_m are permittivities of teflon and manganite, correspondingly.

The teflon thickness d_t varies during the experiment, while d_m remains constant. According to Eq. (1) for the given frequency f, the effective permittivity $\varepsilon_{\text{eff}}(f)$ varies with d_t. In the DNG zone we have $\varepsilon_t > 0$ and $\varepsilon_m < 0$. The "plasma frequency" of such finely-stratified medium is the frequency at which $\varepsilon_{\text{eff}}(f_p)=0$. Thus, as it follows from Eq. (1) the permittivity of manganite for this frequency is:

$$\varepsilon_m(f_p) = -\frac{\varepsilon_t d_t}{d_m}. \tag{2}$$

To obtain the negative permeability an external magnetic field is applied to the structure with some definite $d_t^{(i)}$. The appearance of a DNG-zone in the transmission spectrum [Fig. 2(a)] indicates that left-handed features of the medium have appeared. In DNG-zone we have

-the permeability of the structure is negative, $\mu'(f) < 0$: this frequency zone corresponds to the high-frequency wing of the ferromagnetic resonance (FMR) peak,[4] where the real part of permeability $\mu'(f) < 0$;

-the effective permittivity for total structure is negative, $\varepsilon_{\text{eff}}(f) < 0$: this is possible because every manganite element of the structure (Fig. 1) is a conductor.

As the FMR-frequency depends linearly[6] on (H), the DNG-zone shifts toward higher frequencies when magnetic field (H) increases [Fig. 2(a)]. The intensity of DNG-zone falls down and then zone disappears at the "plasma frequency" $f_p^{(i)}(d_t^{(i)})$ for given structure (the finely-stratified medium), when its effective permittivity changes the sign to positive, namely at: $\varepsilon_{\text{eff}}^{(i)}(f)|_{f=f_p^{(i)}}=0$. Now from Eq. (2) we define the magnitude $\varepsilon_m^{(i)}$ of the sintered manganite permittivity at the frequency $f=f_p^{(i)}$.

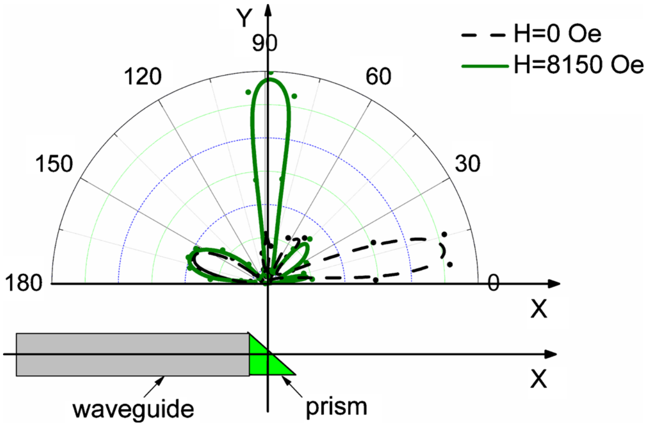

FIG. 4. (Color online) Angular distribution of intensity of electromagnetic field scattered with prism in the presence (solid line) and in the absence (dashed line) of external applied magnetic field (experimental data).

After performing a cycle of measurements with various thickness of teflon layers $d_t^{(i)}=(0.02\div 0.5)$ mm, we restored the dispersion curve $\varepsilon_m(f)=\varphi(f)$ [Fig. 2(b)]. The experimental dependence is well described by the following Drude formula:

$$\varepsilon_{\mathrm{WM}}(f)=\varepsilon_{\mathrm{host}}-\frac{(f_p^m)^2}{f^2}, \tag{3}$$

at $\varepsilon_{\mathrm{host}}=1$.

According to the curve in Fig. 2(b), the "effective plasma frequency" for specimen of sintered lanthanum-strontium manganite $\mathrm{La_{0.775}Sr_{0.225}MnO_3}$, used in our experiment equals $f_p^m=40.95\pm 1.00$ GHz.

To verify the above results, an experiment, which demonstrates negativity of manganite refractive index has been performed. A conceptual design of this experiment is presented in Fig. 3. A prism manufactured from sintered manganite under study is installed into the T-bridge. The external magnetic field (H) applied normally to the trigonal face of the prism.

A sharp change in refraction was observed at transition of the medium into left-handed state (f=28 GHz and magnetic field H=8150 Oe). The "beam" propagating initially in the "straight" channel changed its direction to "perpendicular" channel [see Fig. 3(b)].

As can be seen in Fig. 3(c) at H=8150 Oe the signal in the "straight" channel (S21) drops while in the "perpendicular" channel (S31) it reaches approximately the value of previous signal in the "straight" channel at H=0.

Far-field zone angular distribution of intensity of electromagnetic field scattered with the prism was also studied experimentally in the presence and in the absence of external applied magnetic field. According to Fig. 4 the maximal intensity essentially changes its angular direction after application of external magnetic field. The change in the maximal intensity direction testifies the appearance of left-handed properties of prism material. Note that the presence of side lobes is caused by diffraction effects in the system waveguide-prism.

-the technique for measurement of frequency dependence of metamaterial permittivity in the millimeter waveband is developed;

-the frequency dependence of permittivity for sintered manganite of lanthanum-strontium $\mathrm{La_{0.775}Sr_{0.225}MnO_3}$ is obtained experimentally;

-Drude formula for frequency dependence of manganite permittivity has been established;

-supplementary experiment with T-bridge demonstrates left-handed features of manganite $\mathrm{La_{0.775}Sr_{0.225}MnO_3}$ and transition to left-handed state.

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