Left-handed behavior of strontium-doped lanthanum manganite in the millimeter waveband

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Left-handed behavior of strontium-doped lanthanum manganite was revealed in the millimeter waveband. The bulk specimen of $La_{1-x}Sr_xMnO_3$, was used as a boundary medium for one-dimensional photonic crystal. In the absence of magnetic field known Tamm peak appears in the forbidden zone of photonic crystal indicating that manganite is a single negative medium (negative permittivity). In the presence of external magnetic field somewhat above frequency of ferromagnetic resonance the additional (field sensitive) transparency peak appears in photonic crystal forbidden zone, indicating that manganite becomes double negative medium (negative permittivity and permeability). Model theoretical calculations corroborate the experimental findings. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3204004]

The interest in left-handed media (LHM) is in many respects provoked by good prospects of their application in communication and visualization systems of microwave and optical ranges, namely for manufacturing of electronically controllable devices.[1–3] Rather high transparency,[2,4] which demonstrates LHM due to negativity of their effective constitutive parameters, their permittivity, and permeability, is used as a basic idea. The possibility to control both sign and magnitude of these effective constitutive parameters can provide the tunability of transparent frequency band for such structure (see, for example, Refs. 5 and 6). A technological realization of this task meets the problem of manufacturing such LHM for which effective constitutive parameters could be changed simply enough.

To date, there are a few publications showing that such LHM can be realized in microwave band.[5,7,8] So, the effects characteristic for LHM were observed at low temperatures in thin films, based on lanthanum manganite $LaMnO_3$, in which 30 at. % of La were replaced by Ca.[7] The results also suggest the possibility to control the LHM parameters by external magnetic field.

The compounds of the $La_{1-x}M_xMnO_3$ system, where M is a divalent element, are crystallized in perovskite structure.[9,10] Specific feature of such materials is a phase transition from ferromagnetic metallic to paramagnetic dielectric state.[11] The temperature of the phase transition (Curie temperature, T_C) can be changed by changing concentration of doping element.[11] In films studied in Ref. 7, calcium was chosen as a doping element. Note that phase transition temperature (T_C) for whole range of replacements[11] of $La_{1-x}Ca_xMnO_3$ system lies below the room temperature.

On the contrary, in strontium-doped lanthanum manganite $La_{1-x}Sr_xMnO_3$, fabricated by us and employed in this study, T_C is above the room temperature (T_C=350 K) for concentrations within the range $x \approx 0.2-0.5$.[11,12] This fact is evidently of great importance for future potential applications.

This paper gives strong experimental evidence of existence LHM in strontium-doped lanthanum manganite $La_{1-x}Sr_xMnO_3$ (x=0.225) in external applied magnetic field, which control the appearance of left-handed behavior.

Our experimental technique is described in details in Ref. 13. A one-dimensional photonic crystal (1D PC) (Ref. 14) was assembled of six to eight double cells (bilayers). Each cell consisted of Teflon (ε_T=2.06, thickness d_T =1.1 mm) and quartz (ε_Q=4.5, thickness d_Q=1.9 mm) layers (Fig. 1). These PC parameters have been chosen in order to obtain the forbidden zone at 22–40 GHz.[13] It is known[14–16] that if a PC interfaces with a conductor, a Tamm-peak appears in the PC forbidden zone. Tamm-peak width, frequency, and amplitude depend on effective constitutive parameters of the boundary medium. In our experiments the $La_{0.775}Sr_{0.225}MnO_3$ specimen (Fig. 1) was used as a boundary medium. The specimen was synthesized by conventional solid-state technology.[9,11] The system, PC with the medium, was embedded into a waveguide and located between poles of an electromagnet. Electrodynamic spectra were registered with Network Analyzer NA5230 at temperatures (T =290–400 K) and magnetic fields up to 7500 Oe. The vector of a permanent magnetic field is parallel to PC layers and

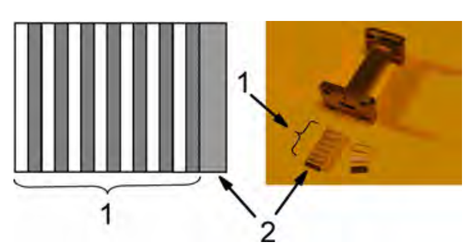

FIG. 1. (Color online) The structure under study: (a)—Scheme; (b)—Overview. 1—PC, 2—$La_{0.775}Sr_{0.225}MnO_3$ specimen.

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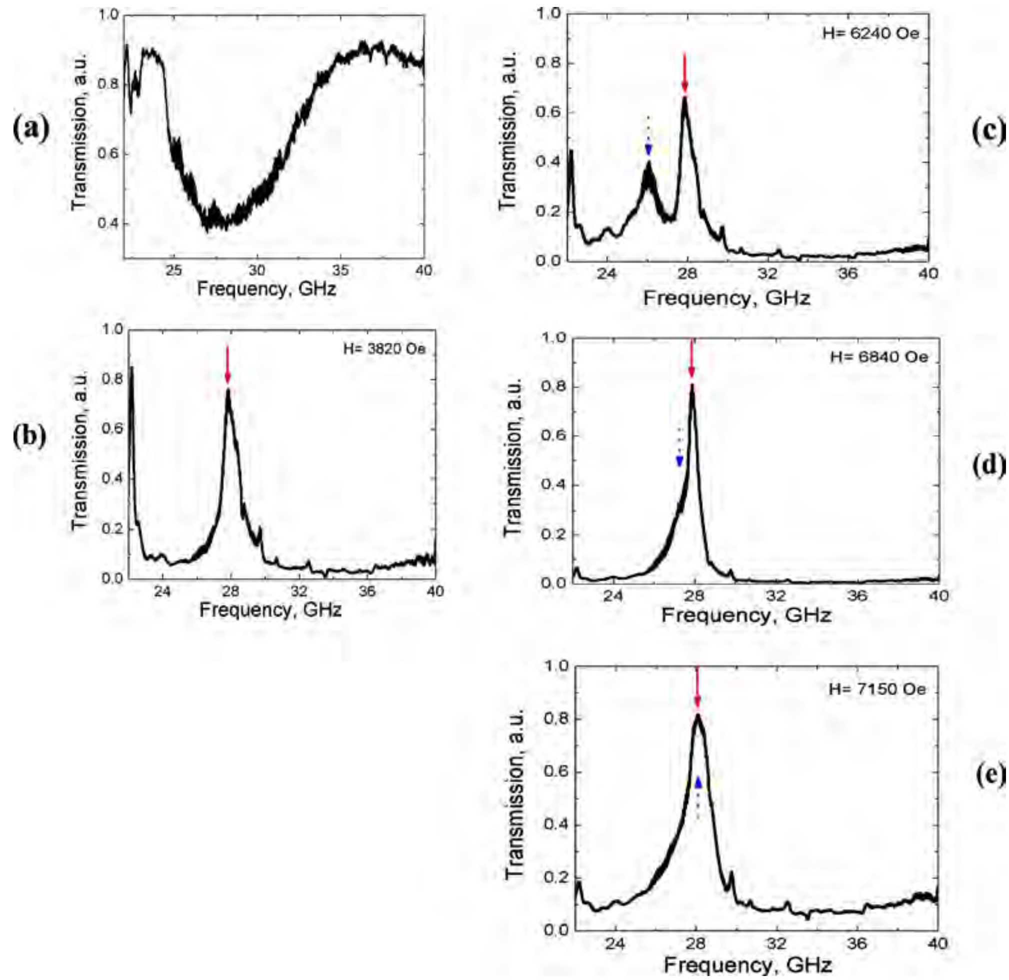

FIG. 2. (Color online) Experimental transmission spectra: (a) Forbidden zone for PC without a boundary medium; (b) Zone spectrum for PC bounded by $La_{0.775}Sr_{0.225}MnO_3$ specimen. $H=0$. Red solid arrow—the Tamm-peak, (peak 1); (c)–(e) Zone spectrum for PC bounded by ferromagnet conductive medium, $H>0$. Blue dashed arrow—peak 2, (DNG-peak).

is directed normally to the magnetic component of alternating field.

A typical forbidden zone detected experimentally in PC transmission spectrum in the absence of the boundary medium is shown in Fig. 2(a). In the presence of manganite-perovskite specimen at the PC boundary, a Tamm peak (peak 1) appeared in the forbidden zone [Fig. 2(b)]. Its quality factor Q depends on the number of PC bilayers: Q is 30 for four layered PC and about 200 for eight layered PC. The peak frequency position depends only on thickness of PC layers but does not depend on the external magnetic field.

When a static magnetic field is applied, a second peak (peak 2) appears in the PC forbidden zone. After appearing in the vicinity of low-frequency edge of the forbidden zone the peak moves toward its high-frequency edge as the magnetic field increases [Figs. 2(c) and 2(d)]. The quality factor of the second peak is lower, as compared with Tamm-peak Q-factor.

The temperature of the system does not affect noticeably the peak 1, at the same time it changes essentially the peak 2. In particular, the intensity of the peak 2 decreases as the temperature increases. The peak 2 disappears completely at temperature $T_C \geq 350$ K.

We elucidate the observed phenomena assuming LHM behavior of the manganite boundary medium. As it was shown,[9,11,17,18] up to $T=350$ K the $La_{0.775}Sr_{0.225}MnO_3$ specimen (further—the specimen) is a metallic ferromagnet. A high-conductive medium at the boundary of 1D PC (Fig. 1), gives rise to surface oscillations of electromagnetic field, known as Tamm-surface state.[14,16] Tamm state manifests itself as a narrow peak (Tamm peak) in forbidden zone. The experimental position of the Tamm peak (peak 1) [Fig. 2(b)] in the PC forbidden zone confirms the metal-type conductivity (negative permittivity) of the manganite specimen in this temperature range.

In external static magnetic field the specimen can be in ferromagnetic resonance (FMR) conditions. As it is known,[7] in high-frequency side of the FMR peak, the real part of the permeability is negative and the imaginary part is rather small [negative permeability zone (NP zone)]. For our specimen with metal conductivity real parts of permittivity and permeability will be negative in NP zone and the specimen will behave as a left-handed medium. As the magnetic field increases the FMR peak and NP zone move toward higher frequencies. When the NP zone reaches the forbidden zone of PC, the region of high transparency known as double negative region[2] (DNG region) appears. In this frequency region a backward wave propagates through the LHM, and consequently the transmission of energy through the whole structure essentially increases. In experiment we see a DNG peak (peak 2) in this frequency region [see Figs. 2(c)–2(e)].

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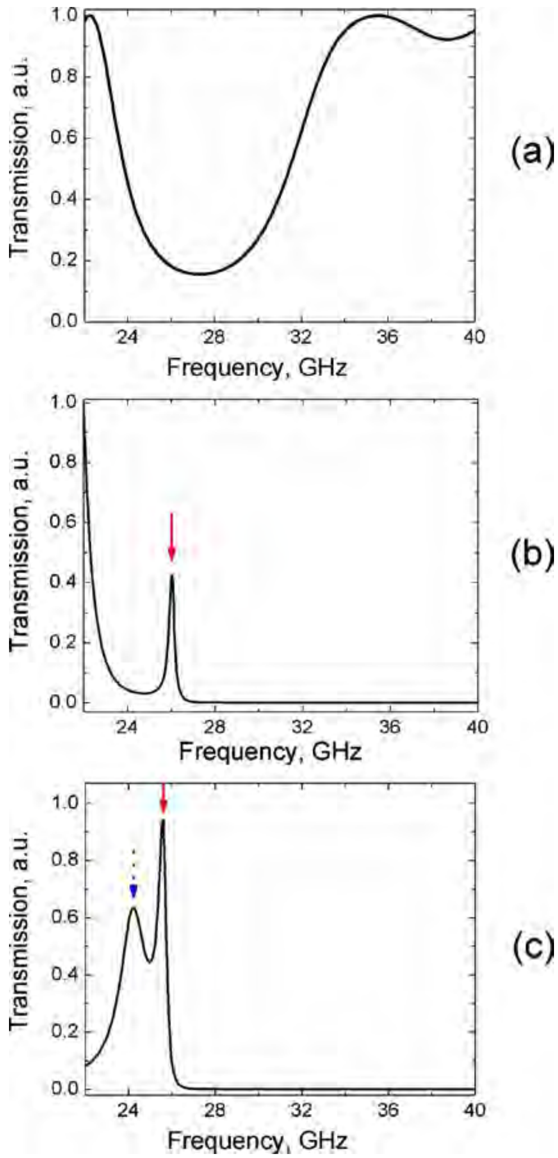

FIG. 3. (Color online) Calculations of experimental findings: (a) Forbidden zone of PC; (b) Zone spectrum for PC bounded by the ferromagnet conductive medium, $H=0$. Red solid arrow—the Tamm-peak; (c) Zone spectrum for PC bounded by ferromagnet conductive medium, $H>0$. Blue dashed arrow—the DNG peak.

The frequency of DNG peak strongly depends on the magnetic field.

To confirm our conclusions based on experimental data, we calculated the transmission spectra for PC, bounded with a model structure with negative permittivity (does not depend on the external magnetic field) and negative permeability (depends on the external magnetic field by known FMR law). For calculations, we used the known transmission matrix method, which is described in detail in the solution of similar problems in Refs. 14 and 16. Parameters of the calculated PC corresponded to experiment. The permeability and the permittivity of the specimen estimated on the base of FMR-experimental data and by the known technique described in Refs. 13 and 16.

According to our calculations, the forbidden zone for the PC in the absence of boundary medium lies in the frequency band 22–40 GHz [Fig. 3(a)]. When the ferromagnetic conductive boundary medium (at $H=0$) is attached to PC, then the Tamm-peak appears [Fig. 3(b)]. Due to the boundary medium influence, PC pass zones become less pronounced as compared with Tamm peak.[14] The DNG peak (depending on magnetic field) arises in the spectrum when $H>0$ and moves toward high-frequency side as the magnetic field increases. When H exceeds 5 kOe the DNG peak enters the PC forbidden zone [Fig. 3(b)]. The calculations describe well the physical processes, observed in our experiments with the specimen $La_{0.775}Sr_{0.225}MnO_3$.

In summary:

- the Tamm peak has been revealed in the forbidden zone of the PC bounded by the perovskite-manganite specimen, which implies the negative permittivity of the specimen;
- for temperatures below the $T_C=350$ K transparency peak (DNG peak), which appears at nonzero external magnetic field and corresponds to negativity of both permittivity and permeability, has been revealed experimentally;
- the phenomena revealed have been analyzed and confirmed theoretically;
- the disappearance of the DNG peak has been detected above Curie temperature ($T_C=350$ K) when metal ferromagnet $La_{0.775}Sr_{0.225}MnO_3$ specimen converts to paramagnetic insulator.

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