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Research Article

Probing Electric Field in an Enclosed Field Mapper for Characterizing Metamaterials

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Spatially mapping electromagnetic fields in the quasi-two-dimensional field mapper (a parallel plate waveguiding system; Justice et al. (2006)) for characterizing metamaterial devices, especially those integrating the metal boundary, may encounter troubles including electromagnetic leakage caused by the air gap and energy guiding along finitely high metal walls. To eradicate them, a moving contact approach is proposed. The physical air gap between the mobile metal walls and the stationary upper plate of the mapper is closed, while their relative movement is still allowed during the field mapping. We demonstrate the method of closing the gap by mapping the E-field distribution in a rectangular waveguide.

1. Introduction

Over a decade ago, the investigation of metamaterials was initiated by the first realization of negative refraction index in microwave frequencies that emerges from simultaneously negative permeability and permittivity and the concept of perfect lens that utilizes negative refraction to obtain subdiffraction-limit resolution [1–6]. Recently, the introduction of transformation optics [7–9] has intensely boosted the investigation on various complex electromagnetic (EM) materials expanding from negative index metamaterials to zero-index metamaterials [10–12] and to extremely anisotropic metamaterials [13–17], because the full control of whole constitutive tensors of metamaterials will bring about various exotic EM phenomena, including artificial magnetism [18, 19], cloaking [20], and illusion [21–24].

The experimental verifications of these exotic wave phenomena frequently need spatial mapping of EM fields inside metamaterials or functional devices. This task is conveniently done with a quasi-two-dimensional (quasi-2D) field mapper in microwave frequencies which is firstly developed by Justice et al. to characterize negatively refracted fields [25]. Other fascinating wave propagations, such as cloaking [20], perfect imaging [26], and topologically EM state [27], and various transformation devices [28–31] have been visualized sequentially in this setup, and the mapped fields have been seen to agree well with the numerical simulations which are typically the simplified 2D theoretical models reduced from the original three-dimensional problems. The field mapping apparatus consists of a parallel plate waveguiding chamber, where the lower conducting plate (aluminum) rests on the translational stage and carries the metamaterials to move along two orthogonal directions (e.g., the x-y plane) while the upper conducting plate (aluminum) is stationary and has a tiny hole to allow the insertion of the probing antenna and the detection of the electric field (E-field), as schematically drawn in Figure 1(a). However, during the spatial mapping, a ~1 mm gap between the top surface of the metamaterials and the upper plate has to be maintained in order to facilitate the relative movement between them. So, the metamaterial devices as well as the auxiliary boundary materials under test must be finitely high, for example, 10 mm at X-band frequencies (8–12 GHz) [25, 32, 33]. Consequently, the electric wall or perfect electric conductor (PEC) boundary in the 2D simulations cannot be mimicked, in exact sense, by erecting a finitely high metal wall inside the quasi-2D mapper.

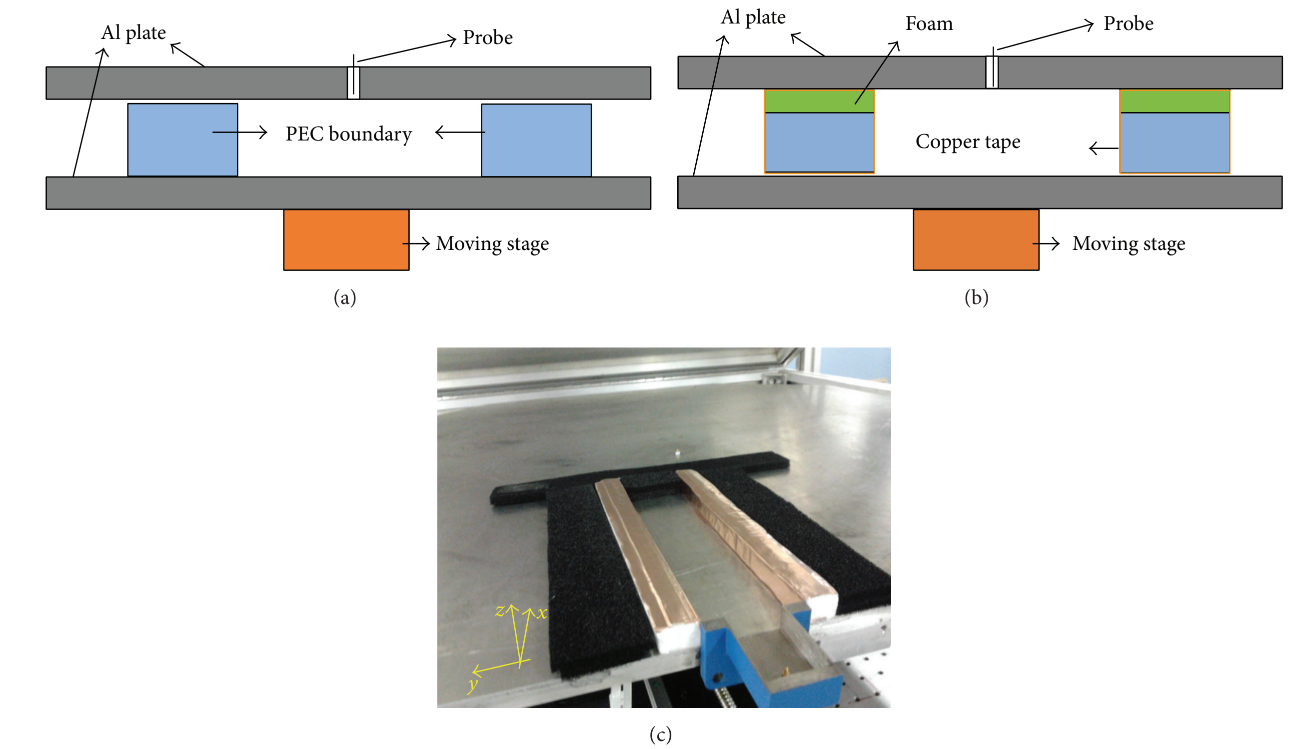

Figure 1: (a) Schematic picture of the quasi-2D electric field mapper with air gap between the metal wall and the upper aluminum plate. (b) Schematic picture of the quasi-2D electric field mapper with the soft contact between the metal wall and the upper aluminum plate. (c) Photo of a section of straight waveguide built with the electrically enclosed metal wall. After the upper plate is in its working position, the waveguide has a rectangular cross section. The lower plate is parallel to the x-y plane.

In this paper, we investigate that the gap can cause inevitable side effects such as EM energy leakage and new energy guiding route along finitely high metal walls, due to which these side effects are undesired for characterizing the metamaterial devices, particularly whose functionality intensely involves or even depends on the metallic boundary. For the first time, we show the spatial mapping of E-fields in an electromagnetically enclosed mapper where the metal wall is contacted physically with the upper plate and at the same time is movable with respect to the upper plate. The moving contact approach has the gap closed and produces the accurate experimental equivalence to the PEC boundary in 2D numerical models.

2. Experimental Procedure

As mentioned above, if the finitely high metal wall acts as the in-plane PEC boundary inside the field mapper, the air gap can cause a leakage of EM energy to unbound exterior regions which are untargeted. Furthermore, it will also make the gap region between the upper plate and the top of metal walls behave as a new waveguiding route, as E-field will be majorly located into the narrow gap, and thus the field characterization of metamaterials under test can be deteriorated. These two problems can be eliminated by closing the gap between the metal wall and the upper plate. In experiments, we cover the top of the metal wall with a soft foam layer and then wrap the foam as well as the metal wall with smooth copper conductive tapes; see Figure 1(b).

Via gently adjusting the height of the lower plate to the position where the metal wall is in physical contact with the upper plate, the air gap is electromagnetically shortened. At the same time, the relative movement between the upper plate and the metal wall is preserved through the foam-capped soft contact between two smooth metallic surfaces (the copper tape and the aluminum plate). A straight waveguide is built in this way, one end excited by a coaxial-to-waveguide adapter that is fixed to the edge of the lower plate and the other end filled in absorbers, shown in Figure 1(c).

3. Results and Discussions

In our experimental configuration, a coaxial is inserted into the hole of the upper plate without the tip extruding into the waveguide cavity, which is important to avoid any scratching on the smooth copper tape, and can sense the E_z component inside the chamber. Both the adapter and the coaxial probe are connected with a microwave network analyzer (Agilent N5230C) to record the S21 parameter including magnitude and phase. We scanned the straight waveguide region including the metal walls at the spatial resolution 2 mm × 1 mm. To make the comparison, we first did the field mapping in the case of air gap and then scanned the same region after we closed the gap and plotted two cases of results in Figure 2.

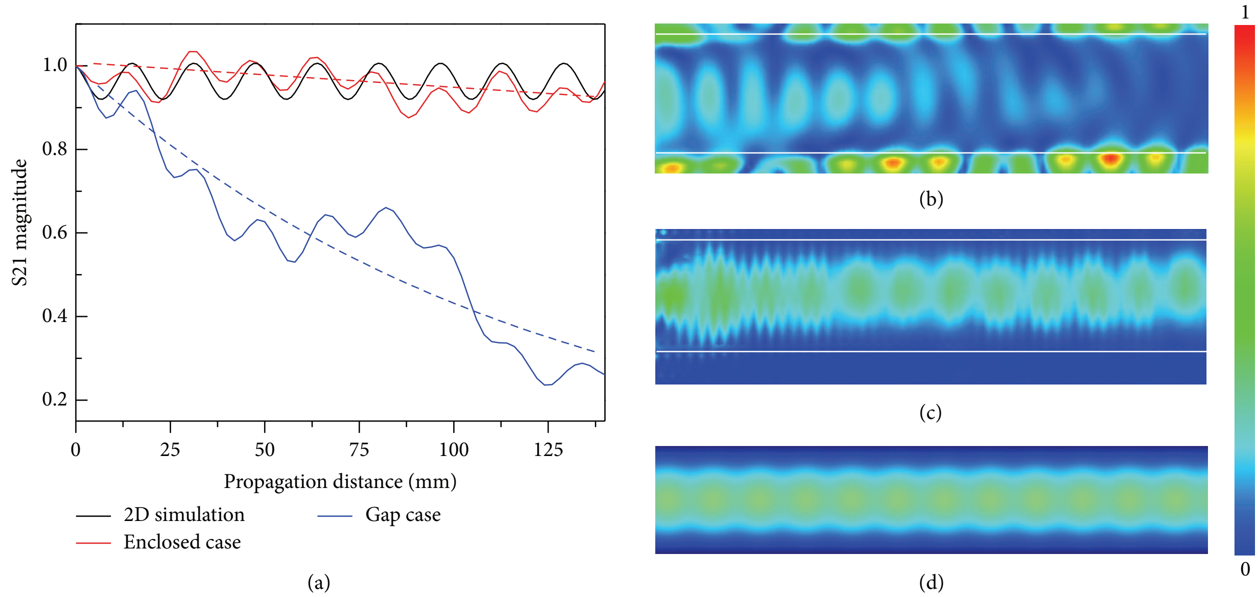

Figure 2: (a) The normalized S21 magnitude along the propagation direction. The solid red and blue lines are the measurement for the enclosed and the gap case, respectively, and the black line denotes the 2D simulation. The dash lines represent the exponential fitting of the magnitude decay with a decay length 1613 mm (red dash line) and 119 mm (blue dash line). (b) and (c) The measured maps of E_z magnitude in the gapped and enclosed case, respectively, where the region sandwiched by the white lines denotes the waveguide cavity. (d) The simulated E_z magnitude map.

Figure 2(a) shows the variation of S21 magnitude at 10 GHz versus the propagation distance where the magnitude has been normalized. It is seen that the severe energy leakage takes place along the propagation direction for the gap case (blue lines) with a decay length 119 mm, and the enclosed case (red lines) has negligible propagation loss with significantly larger decay length 1613 mm. In addition, we performed the 2D numerical simulation (COMSOL Multiphysics) for this waveguiding problem where a pair of PEC boundary defines the waveguide, one end is TE10 excitation, and the other end is the scattering boundary. A good agreement between the enclosed case and the simulation can be seen in Figure 2(a), which indicates the EM leakage problem is corrected by our sealing method. Figures 2(b), 2(c), and 2(d) illustrate the spatial distributions of E_z magnitude at 10 GHz, respectively, for the gap, enclosed, and simulated cases. The region sandwiched by two white lines is the waveguide cavity, and the region outside the lines corresponds to the metal wall. It is seen that the intense E-field is residing over the metal wall in the gap case, Figure 2(b). This is because the electric energy is dominantly stored inside the dimensionally narrower space which has larger effective capacitance, and the wave is guided more efficiently along the metal wall. In contrast, the enclosed case, Figure 2(c), displays a vanishing magnitude of E-field toward the white lines and has no field pattern beyond the white lines, as expected over the PEC boundary in the 2D simulation, Figure 2(d).

By combining the S21 phase, the distribution of the real part of E_z can be found in Figure 3, which reveals the gap-associated problems and shows the good agreement between the enclosed case and the 2D simulation, again. Therefore

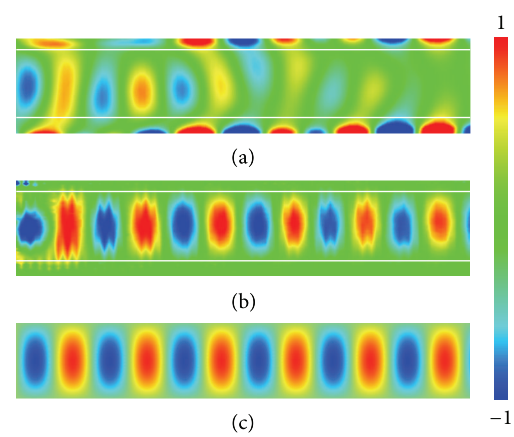

Figure 3: The measured map of E_z real part in (a) the gap, (b) the enclosed, and (c) the simulated case, respectively. The region sandwiched by the white lines denotes the waveguide cavity.

the field mapping in the electromagnetically enclosed surrounding gives rise to the experimental results which can be compared directly with the 2D model simulation.

Although the foam-capped metal wall is gently pressed against the upper plate, the contacting friction due to the relative movement is unavoidable compared to the gapped mapper and thus increases the work loading to the underlying translational motor. The friction might also be responsible for the strip formation in the field map which is noticeable in Figure 2(c). Additionally, as the consequence of the friction, the copper tape needs to be replaced from time to time to maintain the smooth surface. In the future, a soft conducting material with more slippery surface will be beneficial much to this technique. For the only purpose of obtaining the field profiles, the gapped mapper may give rise to the reasonably precise results if the gap is controlled to be as small as possible, because the fringe field around the corner of the tiny gap has the negligible influence on the targeted scanning region. However, for characterizing the energy flow in some metamaterial devices, the gap should be closed.

4. Conclusion

In conclusion, two problems, energy leakage and new guiding path, have been identified in the quasi-2D field mapper for spatially mapping EM fields of some metamaterial devices, especially those integrated with metal boundaries. They are caused by the air gap facilitating the mapping movement and the resultant finitely high metal walls. We have suggested a moving contact technique that closes the gap between the dynamical metal walls and the stationary upper plate of the mapper without impeding their relative movement. The metal walls under soft contacting enable a direct mimic to the PEC boundary in much simplified 2D numerical models. We demonstrate the technique through mapping the E_z field inside a standard waveguide. We believe that our electromagnetically enclosing approach will advance the accurate measurement in characterizing EM fields for metamaterials and transformation media.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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