Real-Time Video-Accesses to Internal, External and Surface Microwaves in and around a Two-Dimensional Metamaterial Sample by Live Electrooptic Imaging

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Abstract

We report on a successful demonstration of real-time video-accesses to microwave behaviours in and around a two-dimensional metamaterial sample, which has been performed by the live electrooptic imaging technique having 10,000-parallel measurement channels for high-frequency electric fields. The videos with a definition of sub-unit-cell scale indicate internal backward-travelling plane waves accompanied with some Bloch function features and a symptom of surface wave, which are not achieved in numerical simulations with homogenized material parameters.

1. Introduction

During recent several years, artificial microwave media with negative real parts of the material parameters [1] have been attracting much attention in view of potential applications [2]. It would be considerably attractive if a real-time visual access to propagating microwave in and around a metamaterial sample could be available. Such a tool would enhance intuitive comprehension of unique microwave behaviours in metamaterials and accelerate processes of their analyses and diagnoses. Needless to say, microwaves are inherently invisible and, therefore, numerical simulations and/or scanning electromagnetic probes [2] hitherto have been utilized for the visualization. However, their promptness is not satisfactory enough since both suffer from long period of time needed for appropriate modelling in the former and for mechanical scans in the latter.

In this paper, we report on the first demonstration of real-time video accesses to behaviours of propagating microwaves, i.e. internal, external and surface waves, in and around a two-dimensional (2D) metamaterial sample. This experimental demonstration was based on the live electrooptic imaging (LEI) technique [3], where ultra-parallel (100×100) electrooptic (EO) measurements are provided for amplitudes and phases of distributed high-frequency electric fields. Their propagation behaviours as well as mutual phase relationships have been clearly visualized in a sub-unit-cell scale definition, by which some Bloch function features have been indicated. These video images were compared to those numerically simulated with a homogeneous model, and discrepancies in between were examined.

2. 2D metamaterial sample and experimental configuration for LEI observations

The sample is rather ordinary as shown in Figs. 1a and 1b. It is a right-triangle prism in shape and consists of 2D periodic array of square Cu split ring resonators and Cu wire stripes [2]. The rings and

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wires are on opposite sides of a 0.3-mm-thick printed circuit board material: a polyphenyleneether blend resin system (Megtron6 of Panasonic). The boards are cut and assembled into a 7-layer stack of interlocking lattices. To solidify the assembly, it is covered by acetate tapes at its top and bottom planes and contains Styrofoam square pillars and polypropylene straws as seen in a photo of Fig. 1d.

The experimental configuration is shown in Figs. 1c and 1d. A 25-mm-square EO sensor plate of ZnTe is placed on the top plane of the sample, to which a 780-nm laser beam is incident. The laser light, which is originally modulated at a local oscillator (LO) frequency f_{LO}, is additionally phase-modulated at a microwave frequency f_{RF} by waves' electric fields during its roundtrip in the EO plate. A polarimetric optics causes a spatially coherent frequency mixing and a resultant 2D distribution of intermediate frequency signal is generated within the beam. It is detected in parallel by a fast complementary metal oxide semiconductor (CMOS) image sensor and imaged on a computer display with a visible phase evolution frequency (1 Hz). Detailed descriptions on the optical LO source, optics, CMOS image sensor, and relevant frequency relationships are available in our previous publications [3].

A core of the setup is a tilted horn antenna (Fig. 1c). A small but non-zero tilt angle θ allows visualization of internal waves via the EO interaction at the top plane of the sample. Another point in Fig. 1c is a charge-coupled device (CCD) camera with a 640-nm illumination of a light-emitting-diode (LED), which enables the sample to be monitored optically through dichroic coatings of the EO plate.

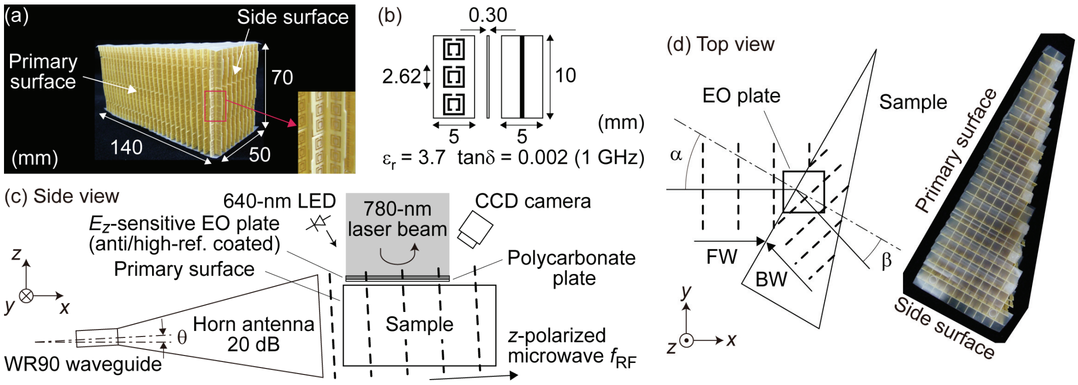

Fig. 1: 2D metamaterial sample and configurations for LEI observation experiments.

3. Visual observation results, material parameter evaluations, and discussions

Fig. 2 shows three sets of observation results for 12.075-GHz microwave; the parameters are the incidence angle α to the primary surface (Fig. 1d) and the EO plate location on the sample. Each set contains a CCD image, a $|E_z|$ image, and a stroboscopic image series for E_z phasor ($|E_z|\cos\varphi$) with a phase interval $\Delta\varphi$ of 0.4π. Each CCD image clearly shows the lattice structure below the acetate tapes within a frame of EO plate holder while their vicinal triangles indicate the surface-nearest boards.

A V-shaped wave front pattern and its upward movement are apparent in the phasor image series of Fig. 2a. These are in good agreement with dashed lines in Fig. 1d, which illustrate wave fronts of external forward (FW) wave and internal backward (BW) wave. The agreement evidences that a BW plane wave does propagate within the sample and it can be visualized by the present LEI configuration. The internal BW wave is visualized also in Fig. 2b, whose wavelength and decay constant were evaluated provided that the sample is homogeneous. The resultant values for refractive index n and dielectric tangent tanδ are −2.08 and −0.15, respectively. Note that some periodicities corresponding to the lattice structure are incorporated in those wave images, which could be an appearance of the Bloch theorem. Their visualization is realized by the image definition of sub-unit-cell scale. In Fig. 2c, both internal and external waves are visualized simultaneously, which travel in two opposite directions. The wave fronts of the former are not parallel to the primary surface, which is probably due to some attractiveness of the sample. As indicated by arrows, there exists a wave localized just outside the side-surface nearest board. Its velocity is extremely low and its wavelength is as short as a unit-cell period.

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Fig. 3 shows wave images generated by a numerical simulator, HFSS of ANSYS, where the lattice and unit-cell structures are ignored and the *n* and tanδ values evaluated in the above are employed together with a negative permeability value of −1.2 in the literature [4]. The V-shaped wave front pattern, its upward movement, and internal BW plane waves are found while neither patterns of the lattice periodicity nor side-surface wave appears. This discrepancy suggests a benefit of the LEI observation scheme. Fig. 3b shows that internal BW plane wave and V-shaped wave front pattern disappear for |tanδ| ~ 0 and |tanδ| > 1.5, which are probably due to strong cavity resonance and high attenuation, respectively. Note that the wave front angle of simulated wave outgoing from the sample's hypotenuse surface is drastically changed at |tanδ| = 0.6. Because of a separate experimental observation result for it, which is not indicated here, the |tanδ| value might be 0.6 or higher and the |tanδ| evaluation result in the above is thus an under-estimated one for some reason. More detailed discussions will be included in future works.

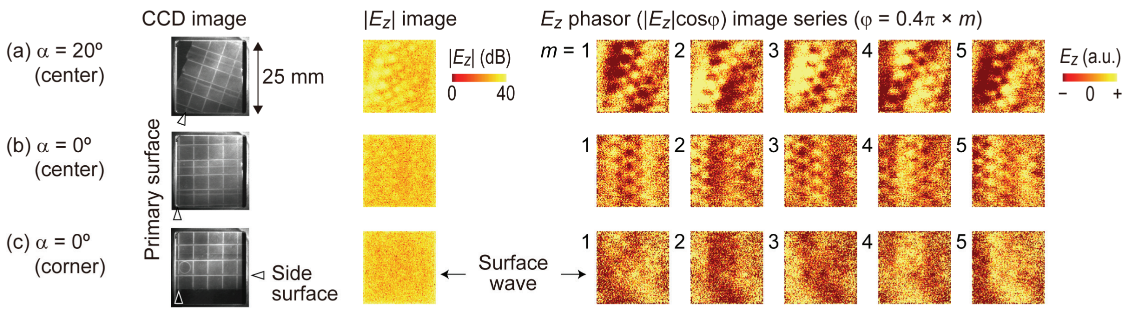

Fig. 2: Experimentally visualized 12.075-GHz microwaves in and around the 2D metamaterial sample.

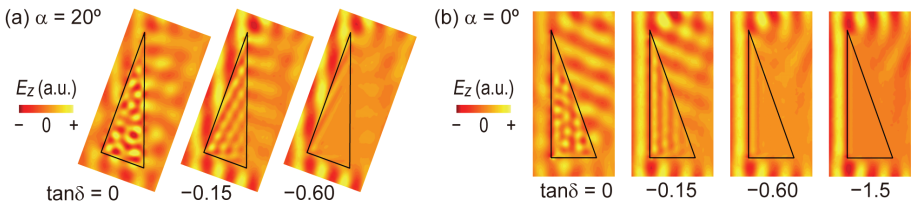

Fig. 3: E_z phasor images generated by a numerical simulator for microwaves in and around a metamaterial prism.

4. Conclusion

It has been demonstrated successfully that characteristic features of microwaves propagating in and around a 2D metamaterial sample can be clarified intuitively by the LEI technique. In addition, it has been shown that quantitative investigations on homogenized material parameters are possible whereas the sub-unit-cell scale definition of wave images can elucidate features of the Bloch function and a symptom of surface wave. The authors thank Dr. Y. Kusama, Prof. T. Morimoto, Prof. M. Honda, and Mr. Y. Kamei for their supports and are grateful to Prof. J. Hamasaki for his encouragement.

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