Tuning of photonic bandgaps by a field-induced structural change of fractal metamaterials

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Abstract: Bandgaps of a structure with electrorheological fluids sandwiched between planar metallic fractal electrodes are investigated in the microwave regime. Our results show that bandgaps are tunable as a result of the electrorheological effect induced by the external electric field applied directly to the structure. A finite-difference time-domain simulation reveals that the tunability of bandgaps is not related to the average dielectric constant but is caused by the field-induced structural change in the electrorheological fluids.

OCIS codes: (260.5740) Resonance; (350.4010) Microwaves; (160.4670) Optical materials

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1. Introduction

Photonic bandgap (PBG) materials exhibit the interesting property of excluding the passage of electromagnetic (EM) waves of certain wavelengths while permitting the passage of others, and they have attracted much research attention since the end of the last century [1,2]. In the past decade, great progress has been achieved in this field, especially in the microfabrication of PBG materials operating at optical frequencies [3, 4]. Furthermore, a tunable PBG, which is desirable for many applications, has also been realized in many structures activated by several external parameters, including electric field (E field) [5-7], temperature [8], magnetic field (H field) [9], and strain [10]. The tunability of bandgaps is usually achieved by controlling the electric permittivity or the magnetic permeability of the constituent materials as the Bragg gap positions are governed by the average refractive index of the composite.

It is well known that electrorheological (ER) fluids, also called smart fluids consisting of nanometer- to micrometer-sized dielectric particles suspended in an insulating liquid, can abruptly change from liquid to solid upon the application of an external E field due to structural change when the particles align themselves along the field to form columns [11]. Apart from their controllable rheological property, ER fluids have the characteristic of being anisotropic dielectric, with the dielectric constant increasing along the field direction while decreasing in the transverse direction [12]. This property of ER suspensions may be utilized to design tunable PBG materials by controlling the status of an external E field. In this paper, we report ER-fluid-based tunable bandgaps in the microwave regime. The bandgaps are obtained from a specifically designed PBG structure with ER fluids sandwiched between two fractal-like electrodes. The bandgap of such fractals [13], different from conventional PBG, is based on resonances rather than the Bragg mechanism; hence, our structure is expected to have specific tuning properties compared with typical tunable PBG materials.

2. Measurement and results

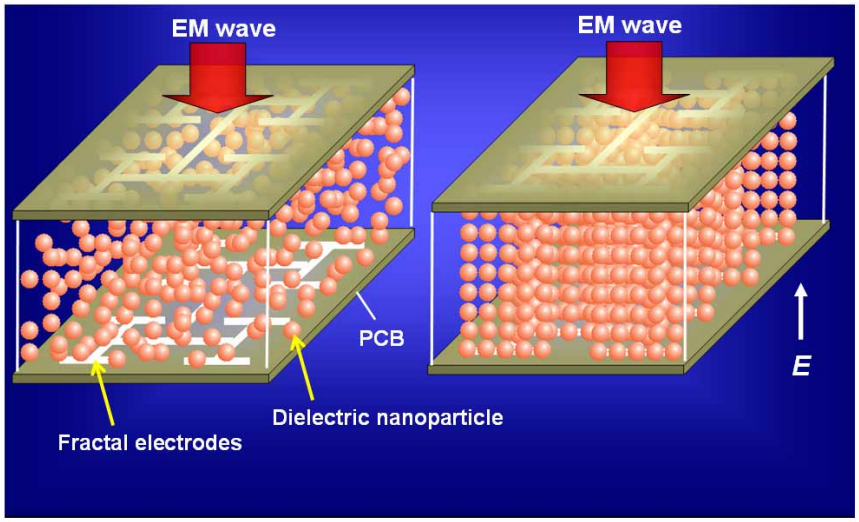

Fig. 1. Schematic illustrations of the ER-fluid-sandwiched structure without the external E field (left) and with it (right), where the gap between two PCB is exaggerated for a better view.

A sketch of our ER-fluid-based PBG is presented in Fig. 1. A pair of printed circuit boards (PCB) with identical metallic fractal patterns was aligned face-to-face to form two electrodes connected to a dc power supply. The etched fractal pattern was an eight-level H-fractal in

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which the first-level line length was 72 mm; the line width, 1 mm; and the thickness, 0.1 mm [13]. The gap between the two electrodes was fixed to be 0.6 mm after solidification of the glue sealing the side walls, and our newly developed giant ER fluid [14] at a dilute concentration of 2.0 (oil/nanoparticle=20 ml/10 g) was then injected into the cell. In the absence of the E field, the particles were randomly suspended in the liquid; they migrated and formed columns between the two fractal electrodes when an external E field was applied. The surrounding area was thus occupied with oil only (see the right of Fig. 1). Two double-ridged waveguide horns were used as the microwave generator and receiver. The PBG sample was placed between the two horns at a distance of 20 cm from the receiver. An S-parameter network analyzer (Agilent 8720ES) was connected to the horns to measure the normal transmission.

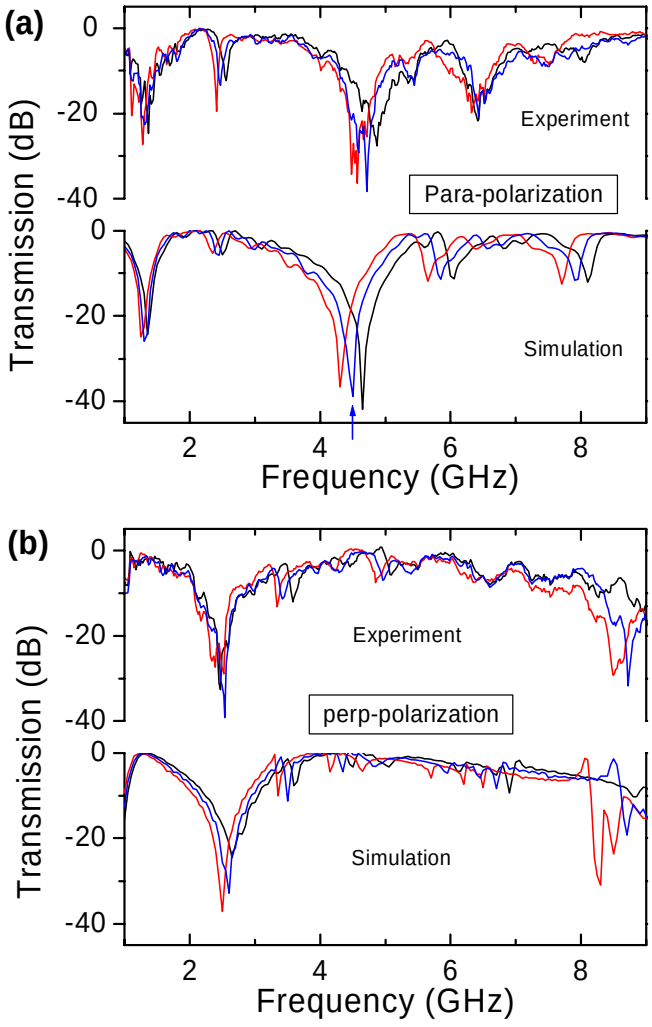

Fig. 2. Measured and calculated normal transmissions of the ER-fluid-sandwiched structure under (a) parallel and (b) perpendicular polarizations for three cases: without the ER fluid (the black curve), with the ER fluid but no voltage supply (the red curve), and with both the ER fluid and the voltage supply (the blue curve). The microwave was incident with its E field parallel and perpendicular to the first-level line of the H-fractal.

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The transmissions at the normal incidence of the microwave, measured for three cases–the PBG structure without the ER fluid, with the ER fluid but no voltage supply–and with both the ER fluid and the voltage supply, are plotted in Fig. 2. Two polarizations were considered in the measurement, the incident E field parallel and perpendicular to the first level line of the H-fractal. It is observed from the experimental curves in Fig. 2 that the stop bands shift toward low frequencies with respect to the original bands (black curve; here, the cell was empty with zero voltage) after infiltration of the ER fluid (red curve). When the sample was loaded with 1.5 kV voltage from the dc power supply, the new bands (blue curve) were found to shift back to higher frequencies. For example, for the band between 4 GHz and 5 GHz in the upper panel of Fig. 2(a), the maximum rejection positions corresponding to the three cases are 4.87, 4.52, and 4.72 GHz, and a tuning, Δf=0.2 GHz, is obtained by the ER-fluid-sandwiched structure. It should be mentioned that the dynamic field (microwave frequency) was far weaker than the static field (dc field between the fractal electrodes) in the experiment and consequently the incident microwave did not interfere with the ER effect.

3. Calculation and analysis

Finite-difference time-domain (FDTD) simulation was utilized to explain the experimental results [15]. In the simulation, we treated the fractal electrodes on the PCB as a perfect conductor and the ER fluid as a homogenous dielectric before undergoing the voltage, due to random distribution of nanoparticles in the oil. We modeled the ER fluid with the voltage supply as the nanoparticle aggregation just below the electrode-plus-silicone oil occupying the rest of the area, taking into account the fluid becoming macroscopically inhomogeneous at the moment. The dielectric constant of the materials involved, necessary to run simulations, was obtainable using the HP85070C dielectric probe kit. The constants were measured to be 4.7 for the PCB substrate, 2.5 for the silicone oil, and 3.9 for the ER fluid. The imaginary parts of their dielectric constants with very small values were ignored. The nanoparticle aggregation had the same geometry as the electrode and was described as a dielectric fractal with a thickness of 0.6 mm and a reasonably estimated permittivity of 4.3 [12]. The previous simulations had pointed out that higher frequency gaps are determined by higher level substructures [16], and thus we focused on the six-level subdomain of the sample and calculated the normal transmission, as shown in Fig. 2, which is in good agreement with the measurements.

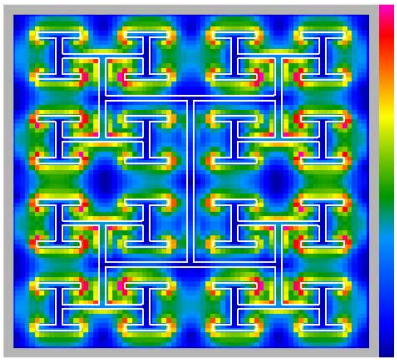

Fig. 3. Intensity distribution of the dynamic E field inside the cell after triggering the ER effect, simulated for the 4.45GHz stop band. The magenta denotes the strongest field and the blue denotes zero. The closed white contour traces out the nanoparticle assembly.

The first shift of the bandgaps towards low frequencies (black and red curves in Fig. 2) originates from the injection of the ER fluid. It has been found that stop bands are caused by resonances intrinsic to the fractal [13, 16] and that the attachment of a dielectric slab would

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lower the resonance frequency due to increasing the capacitance and the inductance in the circuit [17]. Thus, the stop bands shift down after the empty cell is filled with the ER fluid of the dielectric constant larger than one. The resonant EM fields inside the ER fluid subjected to the 1.5 kV voltage can help us to understand the next shift (from the red one to the blue one in Fig. 2). Figure 3 illustrates the dynamic |E| distributions inside the cell after triggering the ER effect, simulated for the 4.45 GHz bandgap [indicated by the arrow in Fig. 2(a)], where the closed white contour traced out the aggregated nanoparticles. The field is significant only in the regions surrounding the white contour; that is to say, the dynamic fields concentrate in the oil rather than in the particles. Actually, the charges and currents induced on two fractal electrodes at the resonance frequency oscillate almost in phase, which leads to the exclusion of the E field from the gap space shadowed by the fractal electrode and the cancellation of the H field there. The resonant EM field in the cell would thus experience the effective reduction of the dielectric constant from the homogeneous ER fluid to the silicone oil after the aggregation of the nanoparticles, and this reduction reasonably results in the back shift of the bands.

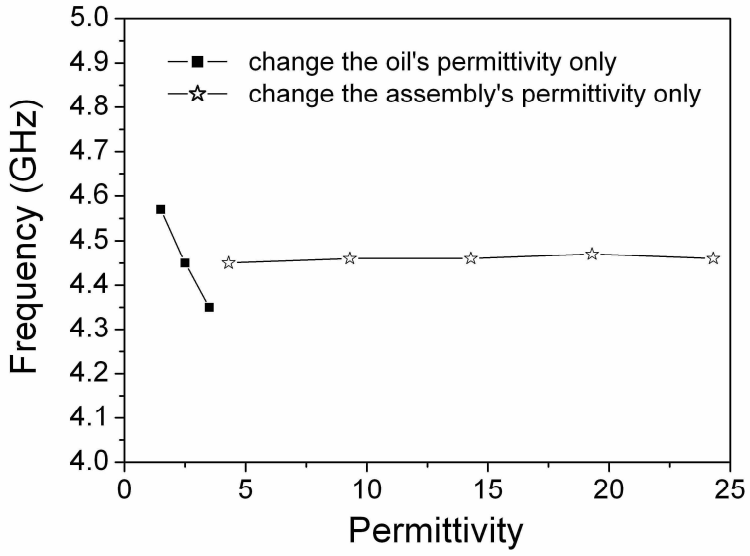

Fig. 4. Maximum rejection positions of the stop band corresponding to the various permittivity values of the oil and the nanoparticle assembly. Squares denote the result of changing the oil's permittivity while keeping the assembly's permittivity at 4.3; stars denote the result of changing the latter while keeping the oil's permittivity at 2.5.

We also altered the permittivity values of both the oil and the dielectric fractal modeling of the nanoparticle assembly in the simulation and calculated the corresponding maximum rejection positions of this stop band under the ER effect (see Fig. 4). We found that the stop band position is independent of the permittivity of the nanoparticle assembly, whereas it is ready to shift once there is a change in the oil's permittivity. This is consistent with our analysis that the EM energy inside the fluid is mainly stored inside the oil surrounding the nanoparticle assembly. Here, we re-emphasize the physical mechanism for tuning the band gaps of our fractal metamaterial. The field distributions in between two electrodes are strongly inhomogeneous at the stop band frequencies, as shown in Fig. 3, even before triggering the ER effect. Switching on the DC voltage forces the ER particles to move into the low-field-intensity regions, which leads consequently to the reduction of the permittivity in the high-field-intensity regions. Thus, the bandgaps get tuned through utilizing ER effects and

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stimulating a structural transition. Most tunings are achieved from the average index change caused by varying the permittivity of a component; however, the tunability here is attributed to the field-induced structural change in ER suspensions, and the ultimate band gap position is related only to the oil's index. A large band gap shift can be brought about if the insulating oil and dielectric particles of ER fluids are properly selected; for example, oils of lower permittivity and particles of larger susceptibility.

One point, which is very important for practical applications, is the tunability response time. Although the response time of ER nanoparticles is measured to be less than 10 ms, the bandgap tunable response time is much slower than that of ER fluid. We determined that at the 1.5 kV dc voltage, the response time for forming stable shifting of the bandgap varied from more than a few minutes to less than half an hour with different sizes of the fractals. However, the time can be shortened through increasing the DC voltage and modifying ER particles. In addition, in the report the tunable fractal metamaterial works on microwave frequencies. We believe it can be scaled down to shorter wavelengths such as infrared, with good design and careful selection of materials, to avoid absorption of ER fluids and to minimize dissipations of metals.

4. Conclusion

We make an experimental and theoretical study on tuning microwave bandgaps of metallic fractal plates by means of applying ER fluids. It is found that after infiltrating ER fluids, bandgaps will red shift due to the increase of the dielectric constant of the sandwiched medium. The gaps can blue shift when a DC voltage is applied to the structure due to aggregation of the ER particles, which is the result of the field-induced structural change in the ER fluids.

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