Hybrid electromagnetic resonances coupling in all-dielectric double-negative metamaterials

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Abstract

The sub-wavelength ferroelectric particles, with high permittivity and low loss, have both electric and magnetic resonances at different frequencies. The electromagnetic couplings between two sizes of cubes with different arrangements in the E, H, and k directions are numerically studied by overlapping the magnetic-resonance of the smaller one and the electric-resonance of the bigger one. The results show that the coupling between the electric and magnetic resonances is decided by the direction and spacing of arrangement of these couple resonances. Along the H field, several modes, all of which are nearly "pure" electric or magnetic resonance, are excited. Along the E field, the resonances with large spacing will keep, while the magnetic resonance splits into two modes when one is extremely close to another one. As for wave vector k, two absorption peaks, in which the system has both magnetic and electric resonances regardless of spacing variations, are obviously observed. The results will make contribution to the design of novel isotropic three-dimension double-negative metamaterials.

1. Introduction

The fabrication of isotropic and bulk metamaterials is still a problem, although a lot of works were put on this magic material in the decades [1]. Different from the metal unit metamaterials, the Mie resonance of dielectric particles provides a novel mechanism for the creation of magnetic and electric resonance, and offers a simpler and more versatile route for the production of isotropic metamaterials with higher frequencies. Recently, there are some theoretical works [2-4] have been reported about the achievements of both negative permeability and permittivity using two different sizes of dielectric particles. And few experiments were carried out, such as dielectric rod [5,6], cubes [7,8] etc. However, the double negative isotropic metamaterials are not realized based on the dielectric particles, due to weakness of the second Mie resonance and strong hybrid coupling between the two different resonances. Here, the hybrid couplings between the two different sizes of cubes arranged in three different directions are studied by overlapping the smaller one's magnetic resonance and bigger one's electric resonance. The understanding of the electromagnetic coupling is very important for the realization of double-negative metamaterials.

ISBN 978-952-67611-2-1

2. Simulations and discussions

The S21 parameter calculations show that the two ferroelectric cubes (ε=200+0.2j) with the side length of 1.6mm and 2.2mm have a overlap magnetic and electric resonances at 11.12GHz, which are used in our study with different arrangements. Firstly, we consider the coupling effect along E field. Figure 1 shows that three absorption peaks occur when the distance is 0.1mm due to the strong coupling of two resonances. As the distance decreases to 1.2mm, only one absorption peak can be observed. In order to understand the coupling effect, the magnetic and electric field are calculated at absorption peaks in distances of 0.1mm and 1.2mm (Fig.2). It shows that at the first dip, the smaller cube has obviously magnetic resonance while the bigger cube has really weak electric resonance. At the second dip, the smaller one's magnetic resonance disappears and the bigger one has strong electric resonance. As for the last dip, the field distribution is really like the first case except for the opposite phase. When the distance increases to 1.2mm, these two resonances remain unaffected due to the weakness coupling between them.

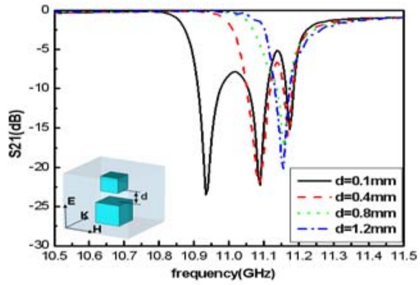

Fig. 1: Simulated S21 parameters of varying spacing of two cubes arranged along the E field.

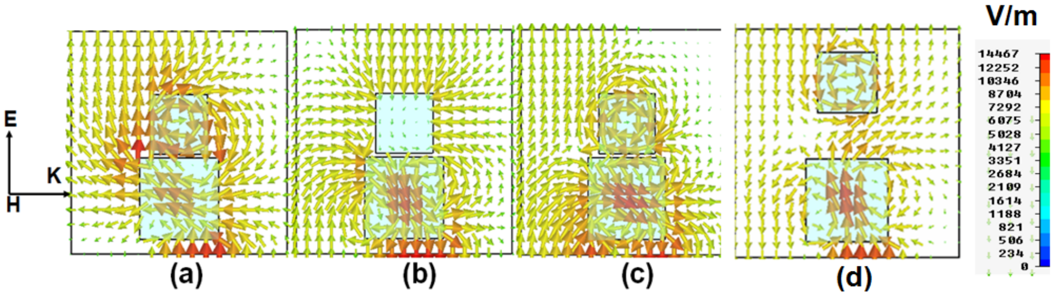

Fig. 2: Simulated E field distribution. (a), (b), (c) are the first, second and third dip for the distance of two cubes of 0.1mm; (d) the dip at 11.12GHz for the distance of two cubes of 1.2mm.

Secondly, the two cubes are arranged along the wave vector k. In this case the propagation direction is the same as the pair axis, so there is a phase difference in the incident wave at the two cubes. It can be seen from Fig. 3 that there are two absorption peaks, of which one shifts intensively to the lower frequency and another one shifts to higher frequency very slowly as the spacing decreases. The electric fields distributions (not shown) show that the system obviously has both magnetic and electric resonances in "low frequency" dips and "high frequency" dips, and what makes difference is that the phases of these couple of resonances have two different cases: consistency and inconsistency.

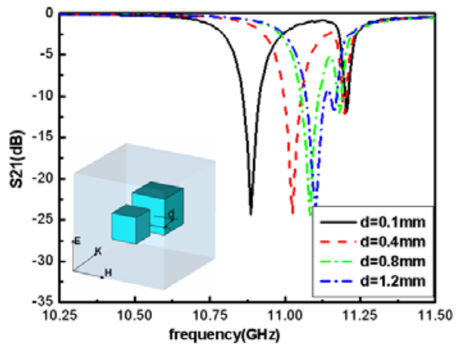

Fig. 3: Simulated S21 parameters of varying spacing of the two cubes arranged along the wave vector.

ISBN 978-952-67611-2-1

Thirdly, the two cubes are arranged along the H field (Fig. 4). In this case, both the magnetic and electric resonances split into two modes excited by indent field. It can be seen from the H field distributions that the two magnetic resonances intensely shift to lower frequency and higher frequency respectively, due to the enhancement of coupling distances; In addition, the two electric resonances also shift to two different frequencies, but vary slowly. Note that the absorption peaks, in contrast to previous cases, are the "pure" resonances.

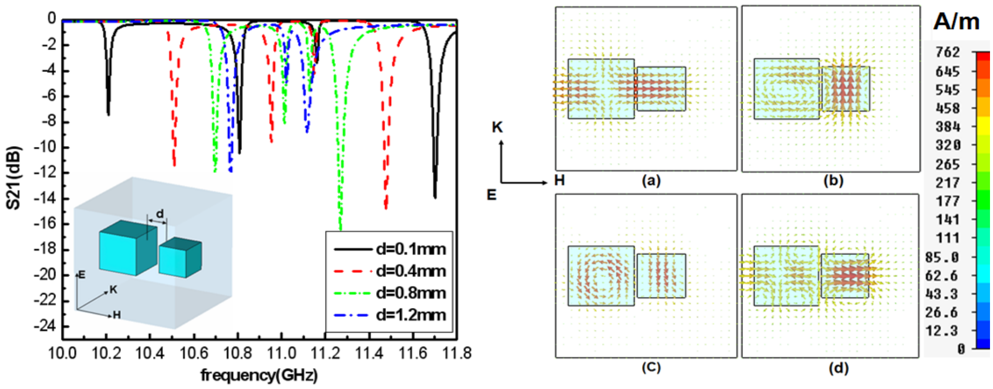

Fig. 4: (left) Simulated S21 parameters for the two cubes arranged along the H field; (right) Simulated H field at different dip frequencies for the spacing of 0.1mm, (a) the first, (b) the second, (c) the third, (d) the last dip.

3. Conclusion

In summary, we have numerically investigated the hybrid coupling of magnetic and electric resonances between two different sizes of cubes arranged in three different directions with various spacings. The analysis of S21 parameters and field distribution at different frequencies are as follows: When the cubes are arranged along the k, the system would have both strong magnetic and electric resonances (magnetic-electric resonances); When the cubes are placed along the E field, magnetic-electric resonances will be created only when the spacing is largeer; But when the cubes are arranged along the H field, in contrast to previous cases, it exhibits pure electric or magnetic resonance in any absorption peaks. The physical mechanism and experimental verification are under studying. The study of coupling effect of hybrid electromagnetic resonances will benefit the design of novel isotropic three-dimensional double negative metamaterials.

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