Tuning Electromagnetic Properties of Metamaterials by Mechanical Deformation

Shengqiang Cai, Nicholas X. Fang
Department of Mechanical Engineering, Massachusetts Institute of Technology
Cambridge, MA 02139, United States

Summary This paper studies how to change the electromagnetic properties of metamaterials through mechanical deformation. Some calculation results are presented with qualitative analysis.

INTRODUCTION

Recent advancement of metamaterials provides new opportunities to fold and twist light and acoustic waves. For example, a material of negative index of refraction appears like a folded sheet of paper to the incoming waves in the virtual space. The electromagnetic waves in the folded regions are nearly identical, forming a perfect image of the original object (a superlens). Such an idea has been extended to the field of transformation optics, which has inspired engineers, physicists and mathematicians to discover many intriguing new devices. However, in order to make these metamaterials with desired properties, complex fabrication techniques are usually required, and the properties of a metamaterial are fixed once it is fabricated. Furthermore, for most materials, the influence of deformation on their electromagnetic properties is small and non-controllable. Considering the properties of a metamaterial are very sensitive to its internal structure, this paper studies how to change the electromagnetic properties of a metamaterial through mechanical deformations.

RESULTS AND DISCUSSIONS

Metallic-wire-lattice electromagnetic metamaterials have been studied intensively both in experiments and theories, since they were first proposed to behave like low frequency plasma [1, 2]. However, there is no any study about the influence of the deformation of the metallic wire lattice on its electromagnetic properties. Fig.1 sketches the system we study in this paper. Periodic metallic wires are embedded in a dielectric elastomer (Fig.1a), for example, PDMS. Under uniaxial compression, the metallic wires buckle to a wavy shape with certain wavelength and amplitude (Fig.1b). The wavelength is determined by the bending stiffness of the metallic wire and the modulus of the soft elastomer. Instead of calculating the wavelength by using mechanics models, we arbitrarily select a wavelength to illustrate the main points of this paper. The metallic wire is usually very thin, so it is reasonable to assume the length of the wire is a constant with the deformation. Therefore, the amplitude of the buckling A can be related to the compressive strain γ and the wavelength λ by the simple equation, $\int_0^{\lambda}\sqrt{1+(2\pi A/\lambda)^2\cos^2(2\pi x/\lambda)}dx=\lambda/(1-\gamma)$.

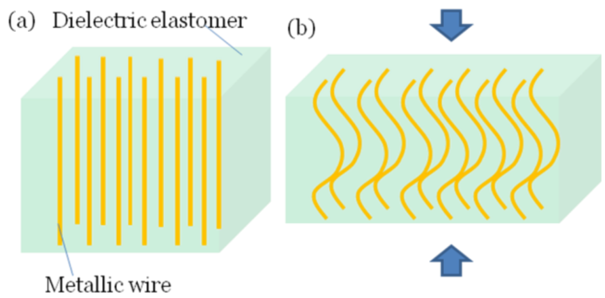

Fig.1. Schematic of a metallic-wire-lattice electromagnetic metamaterials before (a) and after (b) deformation

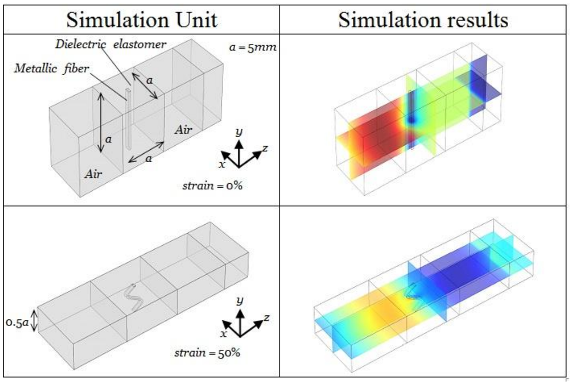

Fig.2 Simulation unit and simulation results for S-parameter calculations

Effective permittivity and permeability are mostly used to characterize the electromagnetic properties of a metamaterial [3, 4]. Different methods have been proposed to retrieve the effective parameters of metamaterials in literatures. We adopt S-parameter method in this paper to obtain the effective permittivity and permeability of the metallic-wire-lattice metamaterial. Considering that structure is periodic, a unit cell is selected for the simulation as illustrated in Fig.2. In the simulation, an incident plane wave is generated with the y-direction polarized electric field and x-direction polarized magnetic field. We prescribe the relative electric permittivity of the dielectric elastomer to be 2.5 and treat metallic wires as perfect conductors. All the simulations are carried out by using the commercial finite element software-COMSOL. Two representative simulation results are plotted in Fig.2. Because the metallic-wire-lattice metamaterial is intrinsically anisotropic, the incident wave described above actually allows us to get the effective permittivity in y direction and effective permeability in x direction.

Combining the numerical simulation results from COMSOL with the methods of retrieving electromagnetic properties described in [3, 4], we plot the effective permittivity and permeability of the metallic-wire-lattice metamaterial as a function of compressive strain at three different frequencies. The results clearly show that both the permittivity and permeability of the metallic-wire-lattice metamaterial can be significantly tuned by the macroscopic deformation. Generally, the deformation can affect the electromagnetic properties of a metamaterial in two ways. A macroscopic deformation can change both the lattice size and the shape of the internal structure of a metamaterial. In order to understand our results better, we scale the frequency by the wave speed and the lattice size and further plot the effective permittivity and permeability of the metallic-wire-lattice metamaterial as a function of compressive strain at a dimensionless frequency, instead of the real frequency, in column 4 of Fig.3. This plot is expected to shows how the shape changes of the internal structure of the metamaterial (buckling of the wires in this case) affect the electromagnetic properties of the metamaterial. For the metallic-wire-lattice metamaterial, the buckling the metallic wires alone can influence the properties of the metamaterial but not very dramatically.

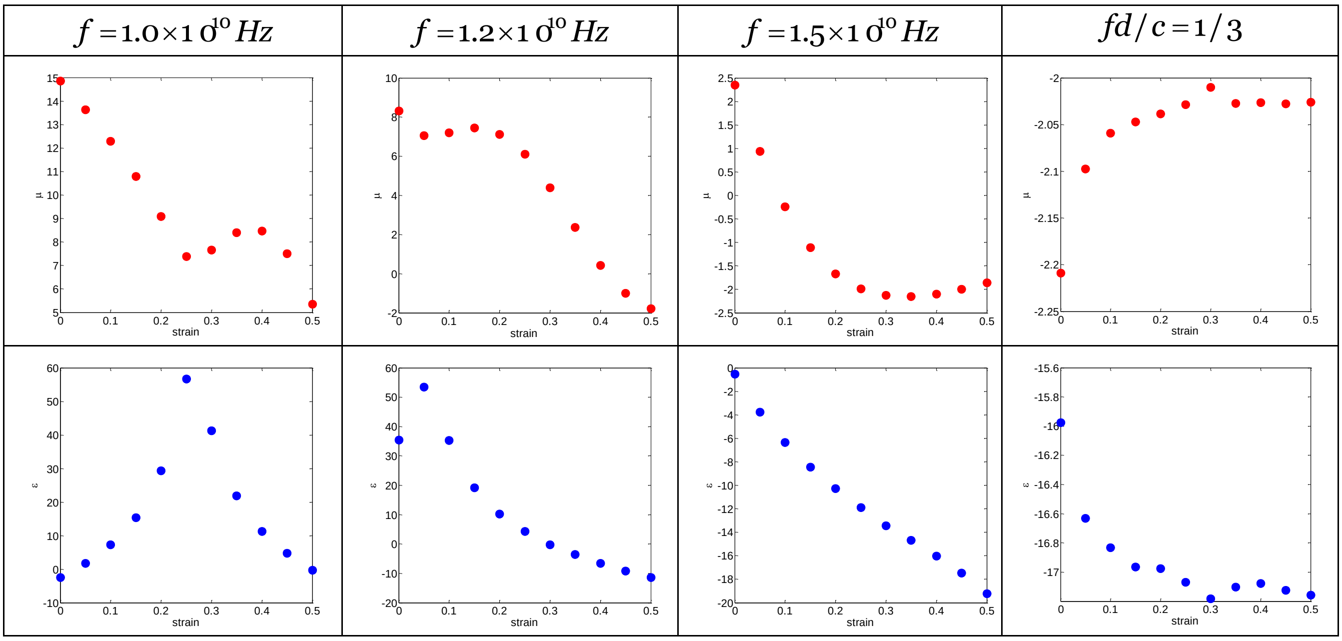

Fig.3 The influence of the deformation on the electromagnetic properties of a metallic-wire-lattice metamaterial at certain frequencies.

CONCLUSIONS

This paper demonstrates that the deformation of a metamaterial can have profound influence on its electromagnetic properties. Both the change of the lattice size and the shape of the internal structure can be used to tune the electromagnetic properties of a metamaterial. With the understanding of the results, we expect to design the internal structures of a metamaterial, whose electromagnetic properties can change with deformation in a more controllable way. It is also hoped that the present work can inspire more studies on this subject.

References

[1] Pendry J.B., Holden A.J., Stewart W.J., Youngs I.: Extremely Low Frequency Plasmons in Metallic Microstructures. *Phys. Rev. Lett.* **76**:4773-4776, 1996.

[2] Elser J., Wangberg R., Podolskiy V.A., Narimanov E.E.: Nanowire Metamaterials with Extreme Optical Anisotropy. *Appl. Phys. Lett.* **89**,261102, 2006

[3] Chen X.D., Grzegorczyk T.M., Wu B.I., Pacheco J., Kong J.A.: Robust Method to Retrieve the Constitutive Effective Parameters of Metamaterials. *Phys. Rev. E.*, **70,** 016608,2004

[4] Chen X.D., Wu B.I., Kong J.A., Grzegorczyk T.M.: Retrieve Effective Constitutive Parameters of Bianisotropic Metamaterials. *Phys. Rev. E.*, **71,** 046610,2005