Structural tunability in metamaterials

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We propose an efficient approach for tuning the transmission characteristics of metamaterials through a continuous adjustment of the lattice structure and confirm it experimentally in the microwave range. The concept is rather general and applicable to various metamaterials as long as the effective medium description is valid. The demonstrated continuous tuning of a metamaterial response is highly desirable for a number of emerging applications of metamaterials, including sensors, filters, and switches, realizable in a wide frequency range. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3211920]

Metamaterials are prominent for the exceptional opportunities they offer in tailoring macroscopic properties through appropriate choice and arrangement of their structural elements.[1,2] In this way, it is not only possible to design a metamaterial for a required purpose, but also to implement further adjustment capabilities at the level of assembly. This makes metamaterials different from conventional materials and opens exciting opportunities for multifunctionality via tunability.

Tunable metamaterials imply the possibility to continuously change their properties through an external influence or signal with the intrinsic mechanism of tunability. The key means of tuning resonant metamaterials, naturally, lies in affecting the system so as to change the parameters of the resonance. As a consequence, the characteristics of metamaterial can be varied, enabling, for instance, tunable transmission.

The initial approach to realize tunable metamaterials based on nonlinear properties[3] has already been proven experimentally,[4,5] and further methods have been suggested, e.g., based on the reconfigurability of liquid crystals.[6] However, such methods become increasingly difficult to implement at higher frequencies.

In this letter, we put forward an approach that relies on the structural tuning of the entire metamaterial. This concept is independent of the specific realization as well as scalable to any frequency provided that the macroscopic requirements for metamaterials are observed.

The general principle of the proposed tuning method is clear through a simple analogy. Indeed, the properties of crystals are known to be determined by the nature of the atoms as well as by the geometry of the crystal lattice, so in natural materials the collective response of atoms determines the overall response to external fields.[7] In natural materials, however, the possibilities to tune their properties dynamically are limited to naturally available crystals and yield relatively weak effects, such as electro/magnetostriction, photorefraction, etc.

In contrast, metamaterials offer a unique opportunity to design and vary the structure enabling a desired response function and a convenient mechanism for tunability. More importantly, the range of tunability for a given property can be much broader than in natural materials, as the lattice effects can be made much stronger through higher efficiency of collective effects in the lattice, achieved by an appropriate design.

To demonstrate the efficiency of this approach, we consider an anisotropic metamaterial based on resonant elements suitable for providing artificial magnetism, such as split-ring resonators of various kind, as shown in Fig. 1. For sufficiently dense arrays, the interaction between such elements differs considerably from a dipole approximation, and the specific procedure to calculate the effective permeability was developed earlier.[8] The latter converges correctly to a Clausius–Mossotti approximation in the limit of a sparse lattice. Consequently, the effect of mutual coupling is enhanced dramatically as compared to conventional materials, and therefore it is particularly suitable to demonstrate the efficiency of lattice tuning.

Accordingly, if all the characteristic dimensions (lattice constants and element size) are much smaller than the wavelength, we can describe a regular lattice of such elements by the resonant effective permeability,

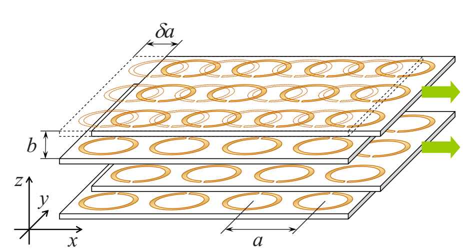

FIG. 1. (Color online) Schematic of the staggered lattice shift with a lateral displacement of every second metamaterial layer.

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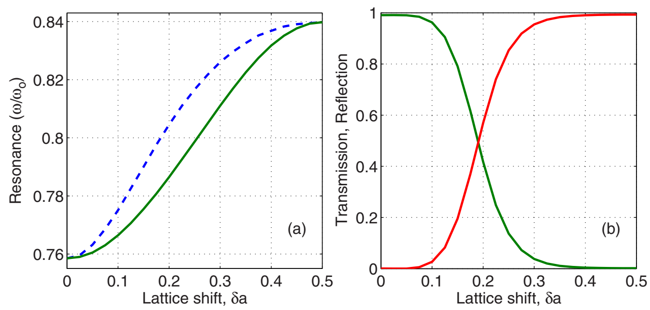

FIG. 2. (Color online) (a) Theoretical shift of the resonance frequency for continuous (dashed) and staggered (solid) lattice shift strategy; (b) Calculated transmission (green) and reflection (red) through a metamaterial slab (one wavelength thick) depending on lattice shift (staggered) at $\omega = 0.96\omega_o$.

$$\mu(\omega) = 1 - \frac{A\omega^2}{\omega^2 - \omega_r^2 + i\Gamma\omega} \tag{1}$$

with the resonant frequency

$$\omega_r = \omega_o\left(\frac{L_\Sigma}{L} + \frac{\mu_o \nu S^2}{3L}\right)^{-1/2} \tag{2}$$

determined by the properties of individual elements, such as the resonance frequency of a single element ω_o, their geometry (which defines self-inductance L and effective cross-section S), concentration ν, as well as their arrangement. The latter effect is determined by mutual interaction between the elements, which in most practically realizable cases is defined by

$$L_\Sigma = L + \mu_o r \Sigma, \tag{3}$$

where the so-called lattice sum Σ can be calculated for a given geometry of elements and their arrangement through mutual inductance

$$\sum_{n' \neq n} L_{nn'}(\omega) = -i\omega\mu_o r \cdot \Sigma, \tag{4}$$

between all the elements in a physically small volume where the average macroscopic field is evaluated.[8]

Note that the collective behavior of a number of elements in the lattice plays a crucial role, so that in anisotropic arrays mutual interactions cannot be reduced to the nearest neighbors approximation as is feasible in isotropic models accounting for spatial dispersion.[9]

The most straightforward lattice tuning approach is to vary the lattice constant b. We have shown[8] that the resonance frequency can be remarkably shifted this way, and confirmed this with microwave experiments.[10] Accordingly, a slab of metamaterial can be tuned between transmission, absorption and reflection back to transmission. A clear disadvantage of this method is that varying b implies a significant change in the corresponding dimension of the metamaterial, which is undesirable for applications.

Here we propose another method of structural tuning, by means of a periodic lateral displacement of layers in the xy plane, so that the resonators become shifted along x (y, or both) by a fraction of the lattice constant δa per each b distance from a reference layer with respect to the original position. This decreases the overall mutual inductance in the system [Eq. (3)] and leads to a gradual increase in resonant frequency, with a maximal effect archived for a displacement of $0.5a$ [see Fig. 2(a)]. Clearly, further shift is equivalent to smaller shift values until the lattice exactly reproduces itself for the shift by a. As a consequence, the resonance of the medium can be "moved" across a signal frequency, leading to a drastic change in transmission characteristics [see Fig. 2(b)]. It is clear that for practical applications it is not even necessary to exploit the whole range of lateral shift—in the above example it is sufficient to operate between $0.1a$ and $0.3a$ where most of the transition occurs.

Within the effective medium paradigm, a continuous shift of each layer with respect to the previous one appears to provide maximal efficiency. For finite samples, however, this poses certain disadvantages. Indeed, for small b/a ratio (which produces a stronger effect) even a small δa shift would imply a remarkable inclination of the sample interface. This would lead to undesirable shape distortion and cause excitation of additional standing waves. Preliminary experiments with this kind of tuning have shown that the system generally features the predicted behavior, however is rather unrepeatable with regards to excitation and measurement methods, so the performance cannot be reliably assessed.

To overcome this difficulty, we consider a staggered lateral shift as shown in Fig. 1, when every second layer is shifted while the rest of the structure remains at the original position. This configuration leads to a slightly different efficiency pattern [compare the two curves in Fig. 2(a)], but is equally useful; obviously, the two tuning strategies converge to the identical result for $0.5a$ shift, as the lattice patterns shifted with either method coincide in this case. For finite samples, the staggered shift is advantageous as it keeps the sample interface straight and parallel to the axis of resonators at all times, while slight regular distortion of the interface shape is not expected to deteriorate the performance, provided that the overall number of elements is sufficiently large so that surface effects are negligible.

For the experimental verification, we opted for a small reconfigurable system, built up of single-split rings (2.25 mm mean radius, 0.5 mm strip width, and 1 mm gap) printed with a period $a = 7$ mm on 1.5 mm thick circuit boards. We have five resonators in the propagation direction x and only one period along y; 30 boards are stacked together in z direction with the minimum possible lattice constant b

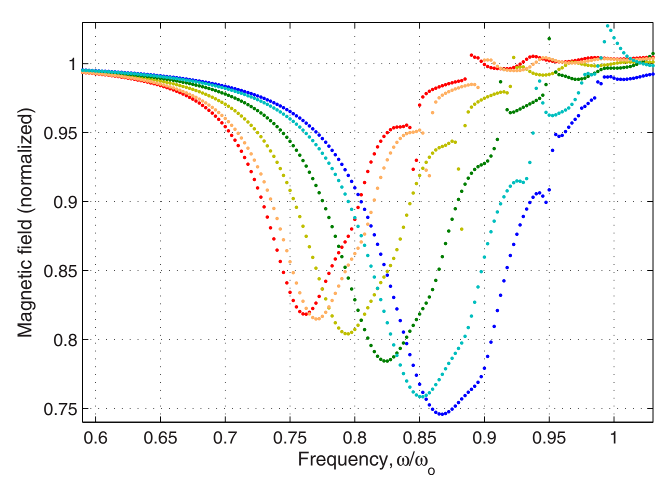

FIG. 3. (Color online) Numerically calculated magnetic field beneath a finite metamaterial slab ($5 \times 1 \times 30$ elements) for a plane-wave incidence. Curves from left to right correspond to increasing lattice shift from 0 to $0.5a$ (with a $0.1a$ increment).

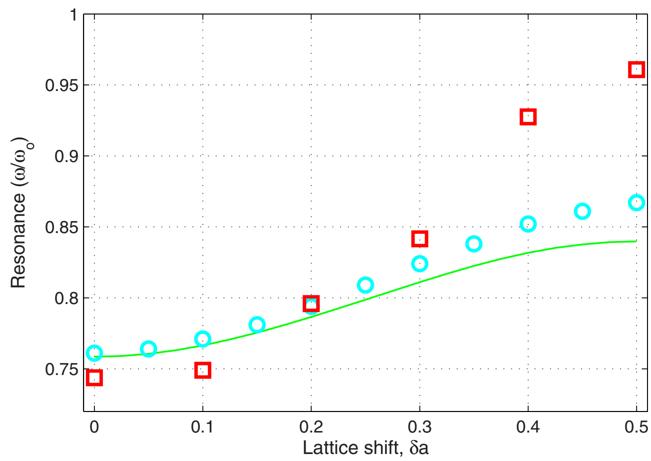

FIG. 4. (Color online) Comparison between theoretical results and experimental data for the resonance frequency shift: Effective medium approach (solid); finite model (circles); experimental results (squares).

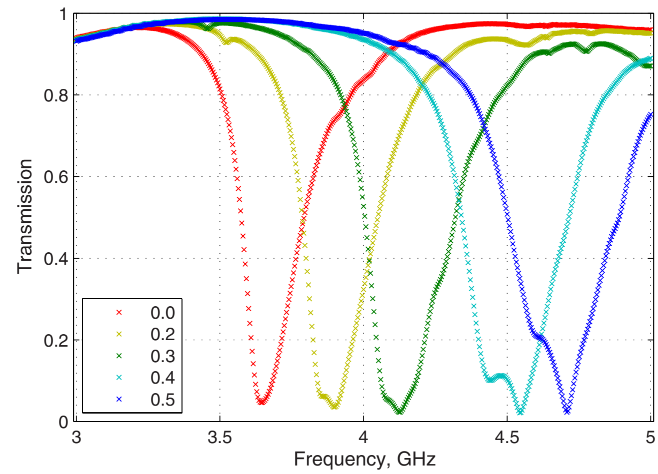

FIG. 5. (Color online) Experimental transmission in a waveguide with metamaterial slab at different shifts. Curves with dips from left to right correspond to increasing lattice shift.

=1.5 mm used for the measurements. The estimated resonance frequency of a single resonator is about 4.9 GHz, however the resonance of the dense metamaterial is significantly shifted to lower frequencies. To minimize the undesirable bianisotropic effects occurring in single-split rings, the boards are assembled so that the gaps are oppositely oriented in adjacent layers (Fig. 1), resembling the design of broadside-coupled split-ring resonators.[11] Transmission measurements (Rohde and Schwarz ZVB network analyzer) were performed for various lattice shifts in WR-229 rectangular waveguide.

Note that the above system of $5\times1\times30$ resonators cannot be described by an effective medium approach, as the number of elements is small. Also, the system is not sufficiently subwavelength for a quasistatic approach to be used and spatial dispersion becomes remarkable.[12,13] For this reason, we also perform semianalytical calculations for the corresponding finite structures, with all the mutual inductances included [Eq. (4)], taking retardation effects into account. Although the particular resonance values obtained this way (Fig. 3), are different from those which would be observed in a medium, the overall effect of lattice tuning was qualitatively the same and predicts excellent performance (Fig. 4).

The experimental transmission spectra are shown in Fig. 5, demonstrating dramatic tuning of the resonance frequency. Furthermore, comparison of the experimental resonance shift with the theoretical predictions shows (Fig. 4) that the experimental system demonstrates even higher efficiency. This effect can be explained by accounting for the mutual capacitance between resonators, neglected in the theoretical calculations. Indeed, for the broadside-like configuration of rings, mutual capacitance between them is distributed along the whole circumference.[11] Clearly, when the resonators are laterally displaced, the mutual capacitance decreases, so that this effect is added up to the increase of resonance frequency imposed by decreased inductive coupling.

The examples analyzed above illustrate the practical feasibility of the proposed tuning concept. Particular details and tuning patterns may differ depending on the specific structural elements used to create metamaterials, however it is clear that a remarkable resonance shift can be realized over a wide range of alternative geometries, including numerous resonator varieties and even fishnet structures which are more popular for higher frequencies. Remarkably, the proposed tuning mechanism is not specific for the microwave range used in the above examples: this can be scaled in size and frequency as long as the metamaterial description in terms of effective medium is applicable. And on the practical side, tremendous efficiency of the structural tuning can be used in a host of applications such as sensors, filters, switches, and all kinds of devices where prompt and sensitive response to changing conditions is required.

In conclusion, we have proposed and confirmed experimentally an efficient concept for tunability of metamaterials through a continuous adjustment of the lattice structure.

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[1]M. Lapine and S. Tretykov, IET Proc. Microwaves, Antennas Propag. **1**, 3 (2007).
[2]A. Sihvola, Metamaterials **1**, 2 (2007).
[3]M. Gorkunov and M. Lapine, Phys. Rev. B **70**, 235109 (2004).
[4]D. A. Powell, I. V. Shadrivov, Yu. S. Kivshar, and M. V. Gorkunov, Appl. Phys. Lett. **91**, 144107 (2007).
[5]I. V. Shadrivov, A. B. Kozyrev, D. W. van der Weide, and Yu. S. Kivshar, Appl. Phys. Lett. **93**, 161903 (2008).
[6]M. V. Gorkunov and M. A. Osipov, J. Appl. Phys. **103**, 036101 (2008).
[7]L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media* (Nauka, Moscow, 1984).
[8]M. Gorkunov, M. Lapine, E. Shamonina, and K. H. Ringhofer, Eur. Phys. J. B **28**, 263 (2002).
[9]J. D. Baena, L. Jelinek, R. Marqués, and M. Silveirinha, Phys. Rev. A **78**, 013842 (2008).
[10]I. V. Shadrivov, D. A. Powell, S. K. Morrison, Yu. S. Kivshar, and G. N. Milford, Appl. Phys. Lett. **90**, 201919 (2007).
[11]R. Marqués, F. Mesa, J. Martel, and F. Medina, IEEE Trans. Antennas Propag. **51**, 2572 (2003).
[12]V. M. Agranovich and Yu. N. Gartstein, Metamaterials **3**, 1 (2009).
[13]C. Simovski, Metamaterials **2**, 169 (2008).