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## Bandwidth enhancement in disordered metamaterial absorbers

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In this letter, we show numerically and experimentally that a positional disorder of a collection of absorbing electromagnetic wave resonators operating in the long wavelength regime dramatically enhances the absorption bandwidth. The demonstration is performed by using single-size ring-shaped thin metal pieces periodically or randomly positioned onto a back-grounded dielectric layer. For periodic array, an optimum in the periodicity is pointed out with a narrow bandwidth, while the increasing influence of coupling effects for resonators in close vicinity explains a three-fold bandwidth enhancement in the case of positional disorder. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4894181>]

Absorbing an electromagnetic wave by artificial metamaterial structures has been the subject of extensive interest over the past few years. This success can be explained by two factors. The first one is related to the fact that absorption principles are governed by geometrical considerations and not primarily by the constitutive materials as it is the case for technologies based on non-textured materials, for instance, ferrites at microwaves. Therefore, the metamaterial approach, based on the use of metal-dielectric structures operating in the long wavelength regime, can potentially find application from microwave to optics by a proper scaling. The second favorable factor concerns their sub-wavelength dimensions offering new degrees of freedom for the design of ultra-low profile absorbers with a thickness much shorter than the wavelength. Such a property is especially welcome at microwaves where the thickness and weight of commercial absorbing materials can be unacceptable for many application domains like, for instance, aeronautics. Following this idea, a former study has been published back in 2008 by Landy and coworkers<sup>1</sup> introducing the acronym of PMA standing for Perfect Metamaterial Absorber. The basic principle of PMA is to combine the electrical and magnetic responses of metal patterns arrayed onto a metalized dielectric substrate. Indeed, by exciting antiparallel conduction currents between metallic pattern and ground-plane tightly coupled through displacement currents, one can synthesize a current loop giving rise to a magnetic resonance. The demonstration of absorbance close to unity by Landy *et al.* was performed by using electrical resonator and strip arrays. Since then, numerous articles related to PMA have been published.<sup>2–10</sup> A detailed review of this research field is notably reported in Ref. 11. Most of them are based on a single metallic pattern array in close vicinity of a ground plane. This kind of design, easier to handle both conceptually and experimentally, is able to fully cancel the transmission of an electromagnetic wave. It also induces the aforementioned magnetic resonance for an anti-parallel configuration of the conduction currents in the patterned and ground plane regions. To be quite general, it can be noticed that a magnetic dipole can also be induced by means of high- $k$  dielectric Mie-type resonators so that total absorption is achieved

when such dielectric resonators are associated with a ground plane.<sup>12,13</sup> The main drawback of PMA lies in the fact that they are based on resonance effects, which means that their response is inherently limited to a narrow frequency band. In order to overcome this limitation, the most common idea is the design of multi-scale patterns experimented at centimeter,<sup>14</sup> millimeter,<sup>15</sup> and optical wavelengths.<sup>16</sup> As demonstrated by He and coworkers, pyramidal-shaped metal/dielectric multilayered arrays<sup>17</sup> seem to be the most promising solution when compared to planar multi-size resonator coplanar arrays. However, such multi-layer designs, which can be related to structured HyperBolic Metamaterials (HMMs), are not easy to fabricate, especially when targeting infrared and visible wavelengths. On the other hand, since the emergence of the metamaterial research field, the disorder within artificially structured materials has been a subject of extensive discussions.<sup>18–23</sup> For photonic crystals, some disorder can dramatically degrade the reflection and transmission properties, which are based on constructive interferences. In contrast, metamaterial media, by taking benefit of strong localization effects is, in theory, not affected by a positional disorder as long as the coupling between these resonators can be avoided.

In the present work, special attention will be paid to the absorption properties of an artificial medium made of thin ring-shaped metal pieces deposited onto a back-grounded dielectric substrate operating at microwave frequencies. Absorption by a random arrangement of plasmonic resonators has already been reported in optics with emphasis on the fabrication issues which are very critical at this wavelengths range.<sup>23</sup> Here, we show that random distributions can be used as an efficient way for improving metamaterial absorbance performances in terms of absorption level and relative bandwidth through the disorder and filling factor. Basically, the main originality of the present work stems from a progressive introduction of a position disorder in electromagnetic resonator arrays without intentionally introducing dispersion in the size, geometry (via aspect ratio notably), or material parameter in contrast to the results reported in the literature. It is shown that the sole variation of the resonator inter-distance in a super-cell results in a wide broadening of

the absorption windows due to sub-cell coupling. To this aim, an optimal period for periodic and hence position ordered arrays was pointed out owing to the existence of a critical trapping of the impinging wave. On this basis, a three-fold broadening of the absorption window by preserving a quasi-unit absorbance was evidenced for highly disordered media.

This broadening effect is illustrated in Fig. 1. The resonators are steel rings with the following dimensions: inner diameter 3 mm, outer diameter 9 mm, and thickness 0.83 mm. It should be noted that these rings have been fabricated through an industrial process. Therefore, their size dispersion can be neglected. The rings are positioned onto a back-grounded epoxy substrate with the following parameters: thickness 0.85 mm and relative permittivity  $\epsilon_r = 3.6$  ( $1-j0.02$ ). In the first stage, numerical simulations were performed, by using commercial finite element software, in order to determine the optimal periodicity leading to a maximal absorbance level. The spectrum, obtained for a periodicity  $P_x = P_y = 24$  mm, which was found as an optimum, is plotted in Fig. 1(a) (solid black line). For comparison, we plotted the results obtained for various semi-disordered arrays based on random positioning of a finite number of rings (20 or 30) within an  $80 \times 80$  mm<sup>2</sup> super-cell. Perfect electric and magnetic conductors are used for boundary conditions, insuring mirror-like symmetries along the directions of the electric and magnetic fields, respectively. The broadening effect is clearly evidenced for both 20 and 30 rings distributions within the super-cell. When compared to the periodic case, the Full Width at Half Maximum (FWHM) is about two and three times larger for 20 and 30 rings super-cells, respectively. This FWHM enhancement can be related

to the filling factor. This property will be confirmed by experiments. Nevertheless, this filling factor dependency does not apply in case of periodic arrays, while the optimal period can be understood as an impedance matching condition necessary to cancel the imaginary part of the impedance of the structure and to get a real part close to  $377 \Omega$ , corresponding to the wave impedance in air.<sup>24,25</sup> For a deeper understanding in case of random distributions, we also plotted the magnitude electric field maps in the mid plane of the dielectric for the 30-rings super-cell referenced as “random 3”. First, it can be noted that the absorption mechanism is governed by a resonance phenomenon inducing a magnetic dipole between the rings and the ground-plane. This interpretation is supported by the electric field mode pattern which concentrations along the edges of the ring correspond to resonating displacement currents within the dielectric. With respect to the recent analysis reported in the literature<sup>26</sup> by discussing the scaling rules for absorption and scattering, it is worth to mention that the underlying physics of the present work is somewhat different. As aforementioned, the absorption mechanism is mainly governed by a current loop induced by conduction current in the ground plane and metal patterns and displacement current in the dielectric layer which determines the resonant magnetic frequency.<sup>27</sup> By a proper variation either of the pattern size and/or of the dielectric thickness, it is possible to tune the frequency where absorption is maximum. It is important to note that this absorption mechanism occurs on a very small thickness. As a matter of fact, considering 9 GHz as a central frequency and a dielectric thickness of 0.85 mm, the absorbing thickness is close to  $\lambda_0/40$ , where  $\lambda_0$  is the free space wavelength. Second, instead of being regularly aligned following the

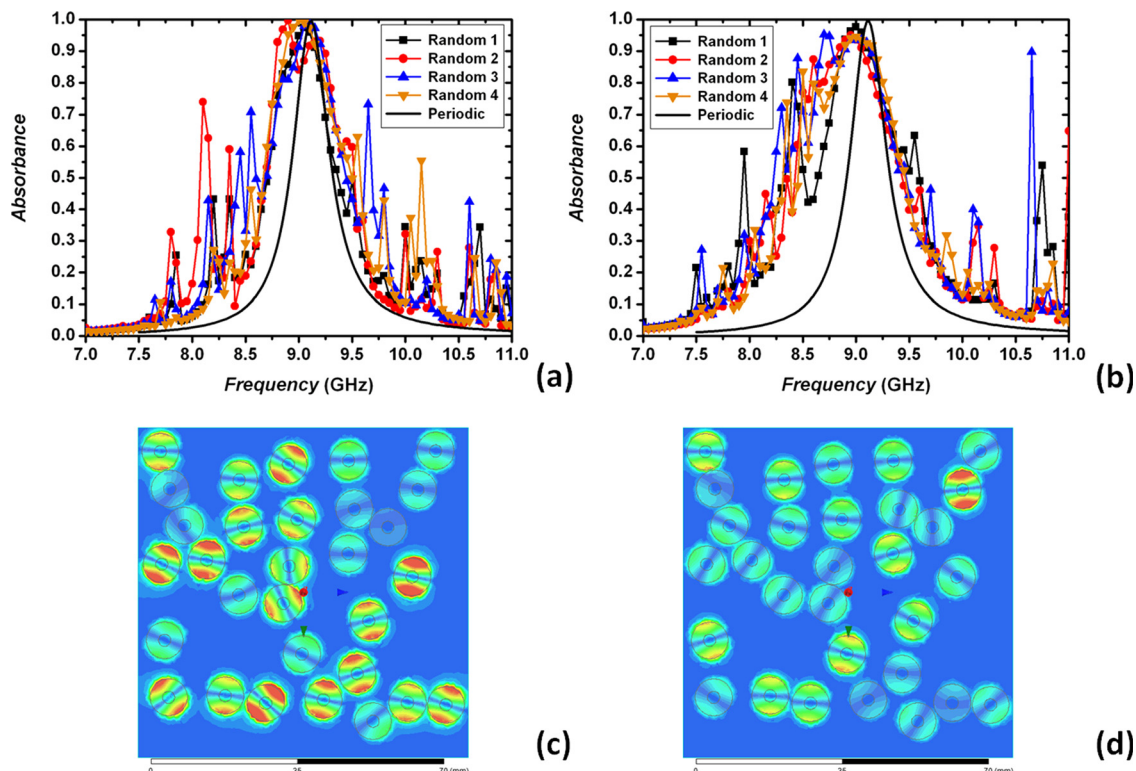


FIG. 1. (a) Periodic (period: 24 mm) versus random arrays absorption spectra for 20 rings (a) and 30 rings (b) within a  $80 \times 80$  mm<sup>2</sup> super-cell. Electric field map in the dielectric mid-plane for the “random 3,” 30 rings array at 8.7 GHz (c) and 9 GHz (d).

polarization direction of the impinging magnetic field (horizontally oriented here) as it would be the case for periodic arrays, the magnetic dipole orientations are distributed as a function of the coupling between adjacent rings. This coupling is revealed by field evanescence with a halo-type pattern including several rings. Finally, this coupling also leads to a spatial distribution of the resonance area as a function of frequency (here observed at 8.7 and 9 GHz), which explains the broadening effect observed in Figs. 1(a) and 1(b).

The measurements have been carried out by means of free space Vector Network Analyzing (VNA). The analyzer is connected to rectangular horn antennas through coaxial cables and coaxial-to-rectangular waveguide transitions. This setup has been calibrated using the TRL (Through-Reflected-Line) method in the output plane of the waveguide transitions. Only the reflection coefficient under normal incidence has been measured here. Therefore, only one horn has been used to launch and measure the parameters of the incident and reflected waves, respectively. The distance between the horn aperture and the under test sample was set to 16 cm as a trade-off between the dimensions of the metamaterial substrate and the horn radiation pattern. This structure, spatially limited to the surface of the grounded epoxy substrate ( $21 \times 29.7 \text{ cm}^2$ ), was surrounded with commercial absorbing foam (*Ecosorb AN 77*) in order to alleviate the influence of parasitic reflections. A normalization process has been performed by taken into account the reflected signal measured from a bare back-grounded substrate. From the reflection measurements, the absorbed power  $A$  can easily be deduced by applying the following equation:

$$A = 1 - S_{11}^2,$$

where  $S_{11}$  is the magnitude of the reflection coefficient for an impinging electric field polarization along the small side of the horn antenna. In this definition, by considering a quasi-plane wave illumination under normal incidence, the multi-angle back-scattering contribution is neglected.

Our first target was to determine experimentally what we termed as the optimal period, that is to say, the period leading to a maximal absorbance value. To this aim, metallic

rings have been aligned along grids whose period varies from 16 to 72 mm. A comparison between simulated and experimental peak absorbance is shown in Fig. 2(a). From the numerical side, for period larger than 35 mm, the simulations show a multimode pattern leading to a multi-peak response, explaining why the numerical data were only plotted around the optimal period. From the experimental side, the points measured for larger periods are not able to describe the response of a periodic array. This can be explained by the limitations due to the finite size of the sample. For a period of 70 mm, for instance, only three meshes can be included along the width of substrate. Nevertheless, the existence of an optimal period around 24 mm, which remains small with respect to the sample transverse dimensions, is numerically and experimentally pointed out. For the results reported in Fig. 2(b), we started from this optimal period and we introduced some disorder by moving rings from their initial positions. For “random 1,” “random 2,” and “random 3,” only 1, 2, and 3 rings, respectively, over a total number of 96 have been moved from their initial sites. A strong influence of this disorder can be pointed out with a progressive FWHM enhancement from 14% to 70%. When this delocalization process is randomly extended to the whole substrate area, this broadening effect becomes more and more significant. For instance, the “random 4” distribution gives an enhancement factor of about 180%, which means that the resulting FWHM is almost three times higher than the one measured from the 24 mm periodic array. For each curve depicted in Fig. 2(b), the total number of rings has been kept constant (96 rings). For some random distributions, the maximum absorbance is sometimes lowered due to a lower local concentration of rings within the illuminating area. As a consequence, for the following (see Fig. 3), the total number of rings has been increased from 51 up to 311. The photograph of the 371-rings distribution is given in Fig. 3(b). It was decided to extend the TRL calibration process down to 7 GHz in order to record the whole absorption spectra of highly disordered structures (see Fig. 3(a)). In this manner, the low frequency attenuation in the short coaxial-waveguide component related to the waveguide cut-off was taken into account by calibration.

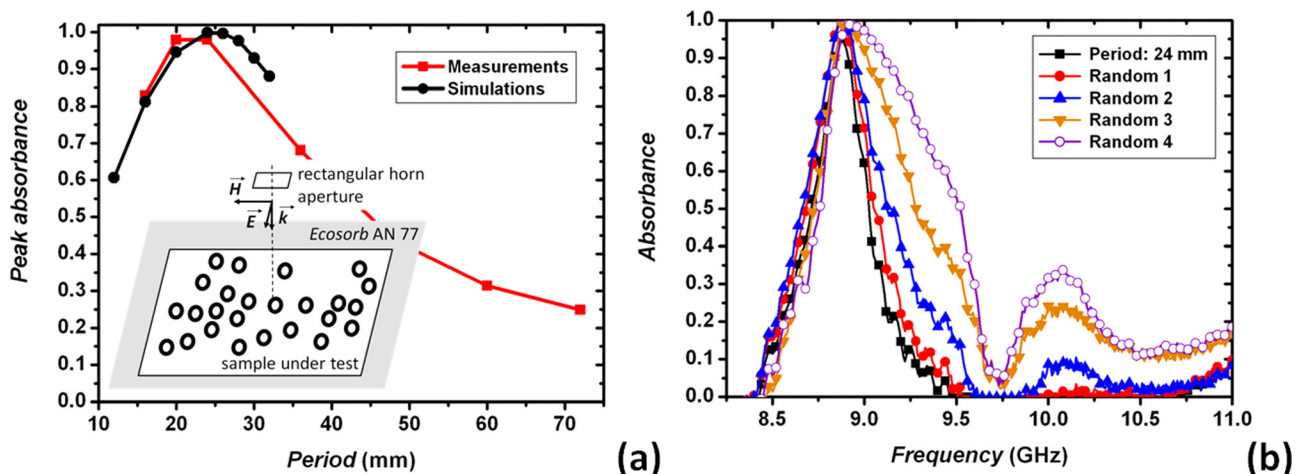


FIG. 2. (a) Peak absorbance as a function of the period of the array, a schematic of the experimental setup is given in the inset. (b) Comparison between the optimal periodic case (24 mm) and various random structures by keeping the number of rings (96) constant.

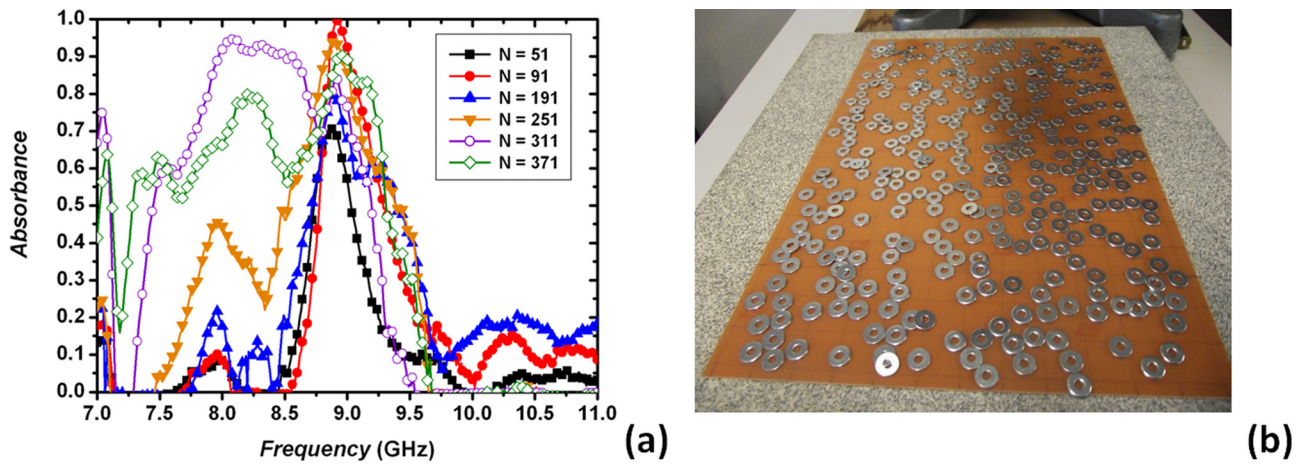


FIG. 3. (a) Absorbance versus frequency measured for randomly distributed metamaterials with number of rings ranging from 51 to 371. Photograph of the measured metamaterial structure including 371 rings (b).

It is worth mentioning that the conditions for the introduction of a positional disorder are not strictly comparable in simulation and in experiment. For the former, the simulation of random media is very time and memory consuming so that the disorder is only introduced in a super-cell which contains a limited number of rings and replicated through periodic boundary conditions. By this means, coupling effect can be simulated within the super-cell and between adjacent super-cells by mirror effect. In contrast for the measurements, the rings have been randomly distributed all over the substrate surface. Despite this difference, it can be shown that the experimental results confirm the broadening of the absorbance window at increasing number of rings.

To sum up, a positional disorder strongly contributes to the absorbance band broadening as evidenced in Figs. 2 and 3. This broadening effect increases with the average filling factor of resonating particles. This rule differs from the optimal period property of periodic array, that is, lost for random media. At last, whatever the random distribution considered, it appears that the broadening effect starts from the absorbance peak of a single isolated particle by assuming a negligible dispersion of the ring diameter. Let us remind that this ground resonance corresponds to the first mode of the magnetic dipole involving the conductive currents on the metal parts and displacement currents within the dielectric interlayer. However, from the observation of the characteristics in Fig. 3(a), especially the  $N = 311$  and  $371$  cases, one can note that the absorption spectra are mainly distributed over the main resonance peak located at 9 GHz and over a

frequency domain centered around 8.25 GHz. This is presumably interpreted as the contributions of electrically interconnected rings due to their overlap. Actually, clusters of electrically contacted resonators are clearly visible on the photo displayed in Fig. 3(b). Such contact situations have intentionally been avoided for the simulations reported in Fig. 1.

This assumption is confirmed by the field maps reported in Fig. 4. In this situation, we considered a super-cell including 10 rings. Among them, 3 rings are interconnected, thus forming a continuous metallic chain. The other rings are electrically isolated from their neighbors. Around the central frequency of 9 GHz (see Fig. 4(c)), the absorption is governed by the resonance of isolated rings. When this operating frequency is shifted down to 7.85 GHz, the role of the 3-ring cluster is clearly illustrated by means of an increase of the mid-dielectric electric field magnitude.

In conclusion, we have shown that the positional disorder of plasmonic resonators can be used as a way for broadening the operating spectrum of metamaterial absorbers. In each case, an absorbing peak close to unity has been obtained for a very low thickness, typically equivalent to  $\lambda_0/40$  at the central operating frequency. Enhancement factors of the FWHM close to three by means of positional disorder have been demonstrated both numerically and experimentally. The relation between this enhancement and the surface concentration of resonating particles has been pointed out. This work opens new design possibilities from microwave to optics where the achievement of sub-wavelength periodic multi-scale arrays remains a challenge.

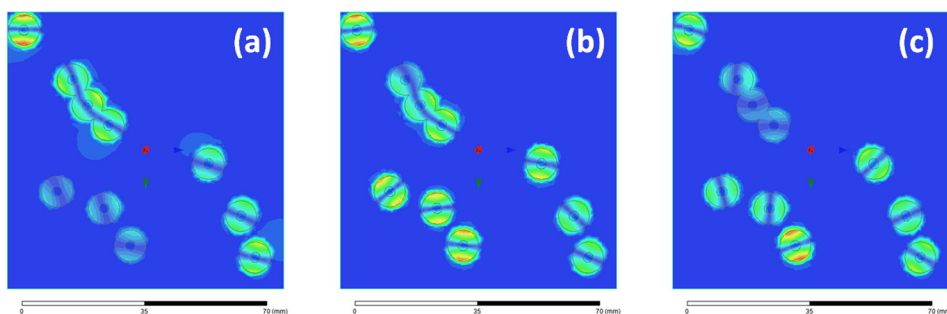


FIG. 4. Electric field map in the dielectric mid-plane for a random 10 rings super-cell at 7.85 GHz (a), 8.40 GHz (b), and 8.95 GHz (c).

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