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Selective-band Metaparticle Based on Bright-bright Mode Coupling for Obscuration Applications

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Abstract—In this paper, we propose a planar metamaterial particle that consists of two bright elements imprinted on a dielectric substrate in the microwave region. The two bright elements are a circular ring resonator (CRR) and an asymmetric single-split rectangular resonator (ASRR). The structure exhibits a narrow transparency band in a wide absorption/reflection band through coupling between the two bright modes. We study the proposed structure through numerical simulation and experiment. We also test different orientations of the structure for possible application as an efficient frequency selective-band obscurant.

1. INTRODUCTION

Wavelength-selective obscuration of electromagnetic radiation by means of small airborne particles is of interest for a variety of military applications. Elementary shapes of particles (i.e., spheres, fibers, discs etc.. . .) have been employed but do not permit complex forms of filtration of transmitted electromagnetic radiation. For the elementary forms, the location and form of the obscured frequency band depend on the size parameter of the particle [1–9]. Some attenuative band shaping can be achieved with, for example, conductive fibrous aerosols; band broadening and proportions of absorption to scattering can be tailored with the degree of translucency (having diameters less than the skin depth of the fiber material) [2, 7].

Attenuation efficiency is usually defined as the extinction cross section (or desired combination of absorption and scattering) normalized to particle volume or mass. An important feature of an airborne particulate obscurant is that the wavelength-selective features are sustained for all or most orientations of the particle with respect to the incoming radiation [3, 5, 6]. For one dimensional particles (fibers) and wavelengths in and beyond the infrared the efficiency is maximum when the fiber is aligned to the incident electric field and zero when the fiber is perpendicular to the field, so the orientation-averaged value is reduced to one third of the maximum value for a resonant fiber [3, 4].

With the option of designing the geometrical forms of not just one but multiple interacting particles, one can obtain complex forms of electromagnetic filtration. A form of filtration that offers a potential advantage would be to block transmission over a wide electromagnetic atmospheric "window" while allowing a narrow transparency band within that window. An additional advantage would be achieved if the wavelength-location of the transparency could be tuned within the "window".

Planar metamaterial structures can produce such filtration through the use of electromagnetically induced transparencies (EIT). EIT phenomena are produced by the coupling of a bright mode that is excited by the incident electromagnetic wave and a dark mode that is excited by the induced magnetic field of the bright element [10–17]. In this phenomenon, an absorption/reflection material is rendered transparent and this is associated with strong dispersion that reduces the group velocity. In order to achieve the phenomena, the symmetry of the structure should be broken. This phenomenon has many

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potential applications in signal processing, optical filtering and sensing technologies [18–21]. In all the previous published structures, a narrow transparency band is induced in a wide absorption/reflection band only for specific orientation of the structure making them inefficient as an orientation-averaged obscurant.

In this article, we propose a metamaterial structure that exhibits a narrow transparency band in the middle of a wide absorption/reflection band through a bright-bright mode coupling instead of a bright-dark mode coupling. Many other designs that employ bright-bright mode coupling have been reported in the literature, see for example [22, 23]. These designs either produce the EIT behavior only for a given orientation, which makes them ineffective as an orientationally-averaged special obscurant or have a wide transmission band compared with the attenuation band. In this article, we propose a planar metamaterial particle that can closely perform the above mentioned features. The structure we propose in this article consists of a circular ring resonator (CRR) and an asymmetric single-split rectangular resonator (ASRR) imprinted on a Rogers 3003 dielectric substrate (dielectric constant $\varepsilon = 3$, loss tangent $= 0.0013$). The resonator material is copper and the dimensions of the resonators where chosen to achieve a narrow transparency band centered at around 5 GHz. The two resonators are both excited by the incident electromagnetic field (i.e., bright elements). The CRR exhibits a wide absorption/reflection band, while the ASRR exhibits a narrow absorption/reflection band through a trapped-current mode resonance or LC resonance depending on the orientation of the electric field with respect to the resonator gap [24, 25]. When the two resonances couple, a narrow transparency band is induced at around 5 GHz in the middle of the CRR wide absorption/reflection band. This structure exhibits the EIT phenomena for a range of orientations which renders it a good candidate for a frequency selective-band obscurant. Also the transparency band is unchanged in frequency with the orientation of the particle. Finally, the location of the transparency-band can be adjusted by changing the size of the resonators.

2. STRUCTURE GEOMETRY AND NUMERICAL SIMULATIONS

Figure 1 shows the geometry of the proposed planar metamaterial structure. The dimensions of the Rogers substrate are ($L = 22$ mm, thickness: $t_r = 0.793$ mm), the dimensions of the CRR are ($R = 8.75$ mm, $w = 0.5$ mm, thickness of the copper clad: $t_c = 0.032$ mm) and the dimensions of the ASRR are ($D = 5.8$ mm, gap width: $g = 0.25$ mm, $t_c = 0.032$ mm). The k-vector of the incident light is normal (incident angle: $\alpha = 0$) to the plane of the structure with the electric field making an angle θ with the gap of the ASRR. The simulations of the transmission spectra were performed using the

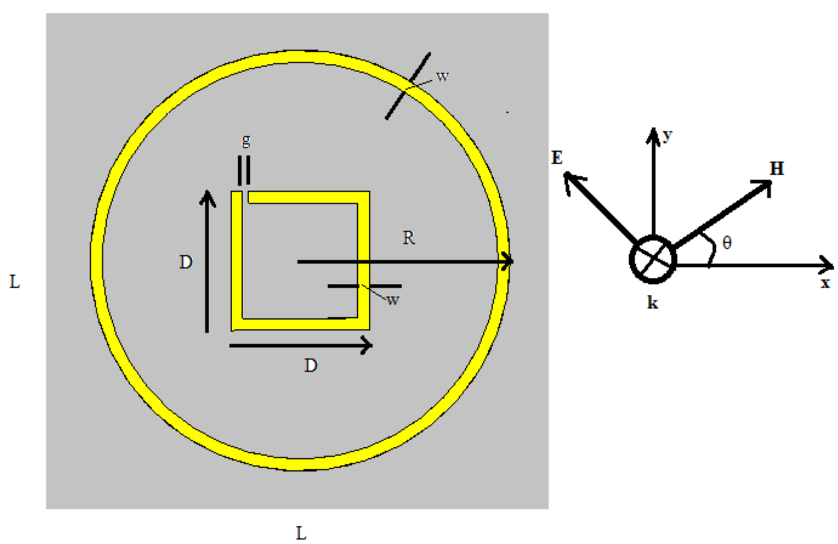


Figure 1. Unit cell, geometry and incident light polarization of the proposed structure.

CST microwave studio suite solver where periodic boundary conditions were applied in the x and y directions [26].

In order to understand the working principle of the structure, we first use the CST software to simulate the transmission spectra for the CRR imprinted alone on the Rogers substrate without the ASRR. Figure 2 shows the transmission spectra (amplitude and phase), the spectra is a wide absorption/reflection window (centered at 5.14 GHz) that is independent of the rotation angle (or

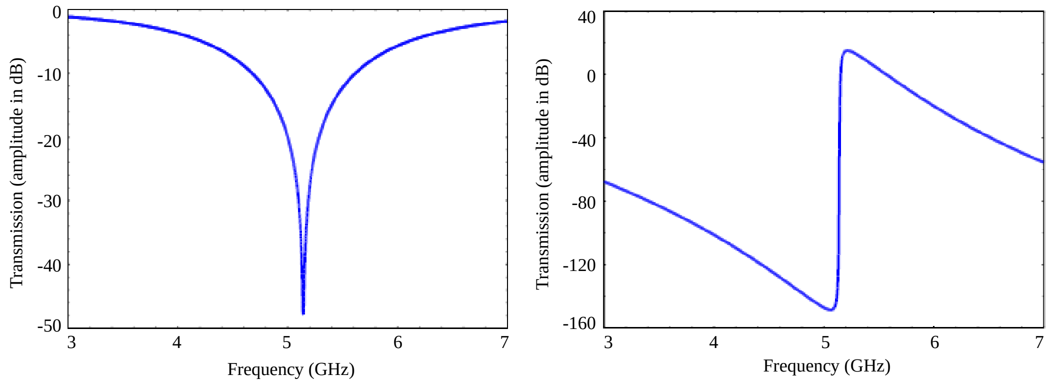


Figure 2. Transmission spectra (amplitude and phase) for the CRR (imprinted alone on the Rogers substrate) when excited normally ($\alpha = 0$ degrees).

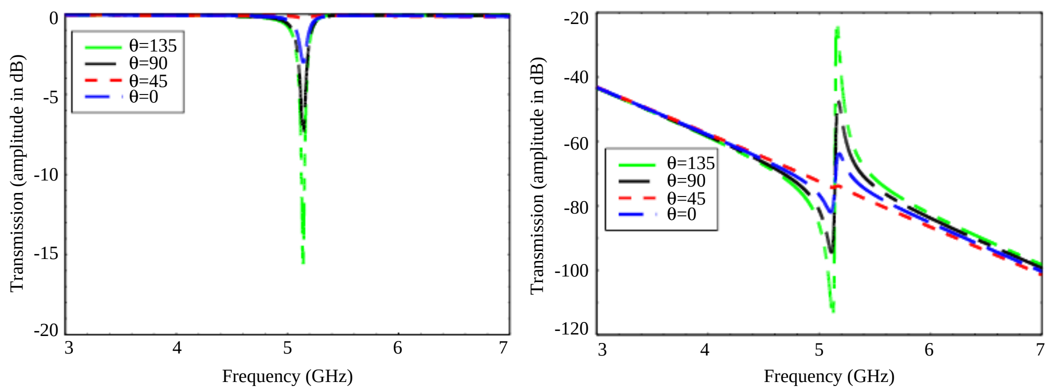


Figure 3. Transmission spectra (amplitude and phase) for the ASRR imprinted alone on the Rogers substrate for different values θ when excited normally ($\alpha = 0$ degrees).

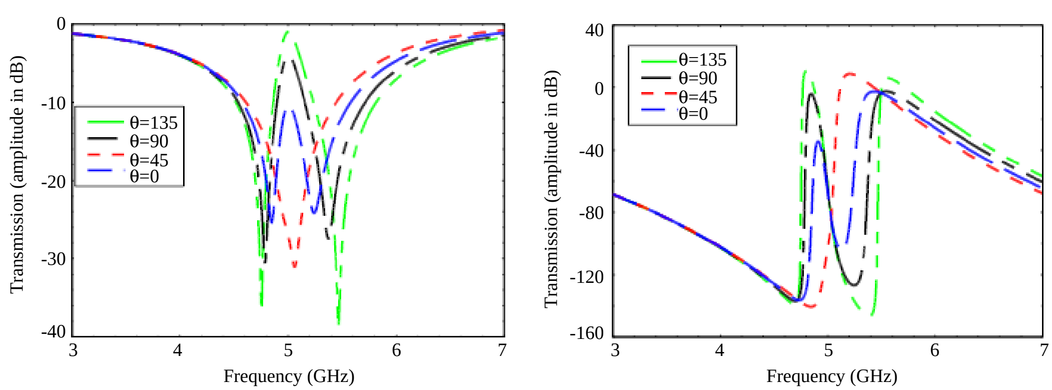


Figure 4. Transmission spectra for the proposed structure of the CRR and ASRR imprinted on the Rogers substrate for different values θ when excited normally ($\alpha = 0$ degrees).

polarization angle of the incident field (θ)) of the particle around the z-axis.

Next, the transmission spectra (amplitude and phase) of the ASRR (imprinted alone on the Rogers substrate without the CRR) for different values of θ is shown in Figure 3. As Figure 3 shows, the strength of the ASRR resonance depends on θ while the corresponding resonance frequency location is fixed and the same as that of the CRR (5.14 GHz). For $\theta = 0$ degrees (i.e., when the electric field is perpendicular to the ASRR gap), the resonance is similar to the trapped-mode current resonance [24]. For $\theta = 90$ degrees (i.e., when the electric field parallel to the ASRR gap), the resonance is an LC resonance [25]. For angles that make the ASRR symmetric or close to symmetric with respect to the E-field, the resonance disappears or becomes weak as is the case for $\theta = 45$ degrees [24].

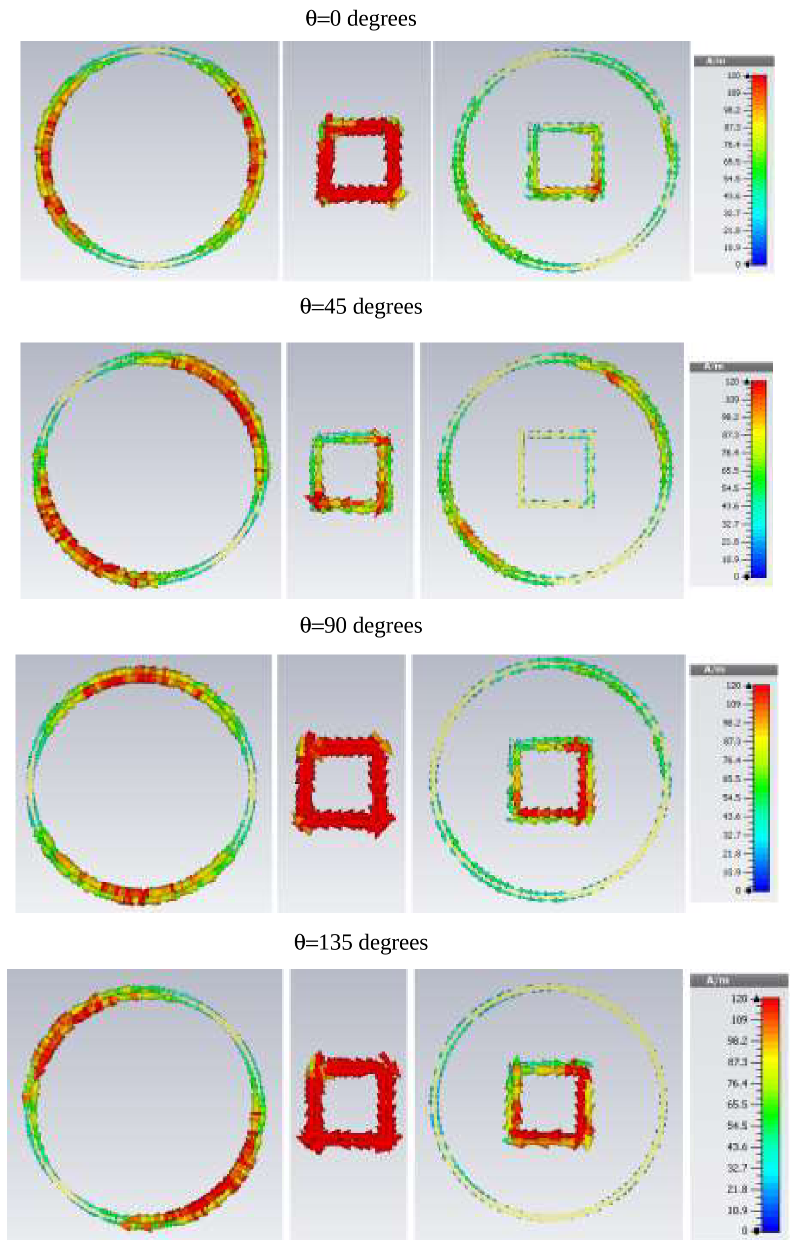


Figure 5. Surface current distributions at the transparency resonance (5.14 GHz) for the CRR alone, ASRR alone and the combined structure at different polarization angles when excited normally ($\alpha = 0$ degrees).

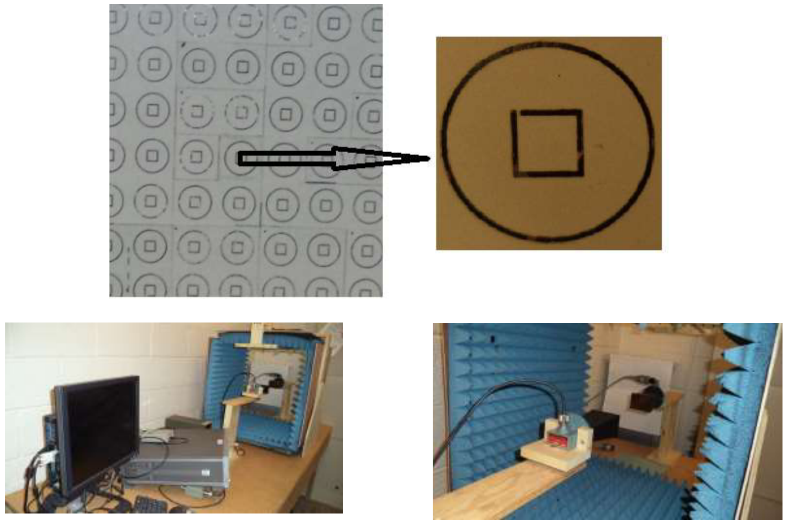
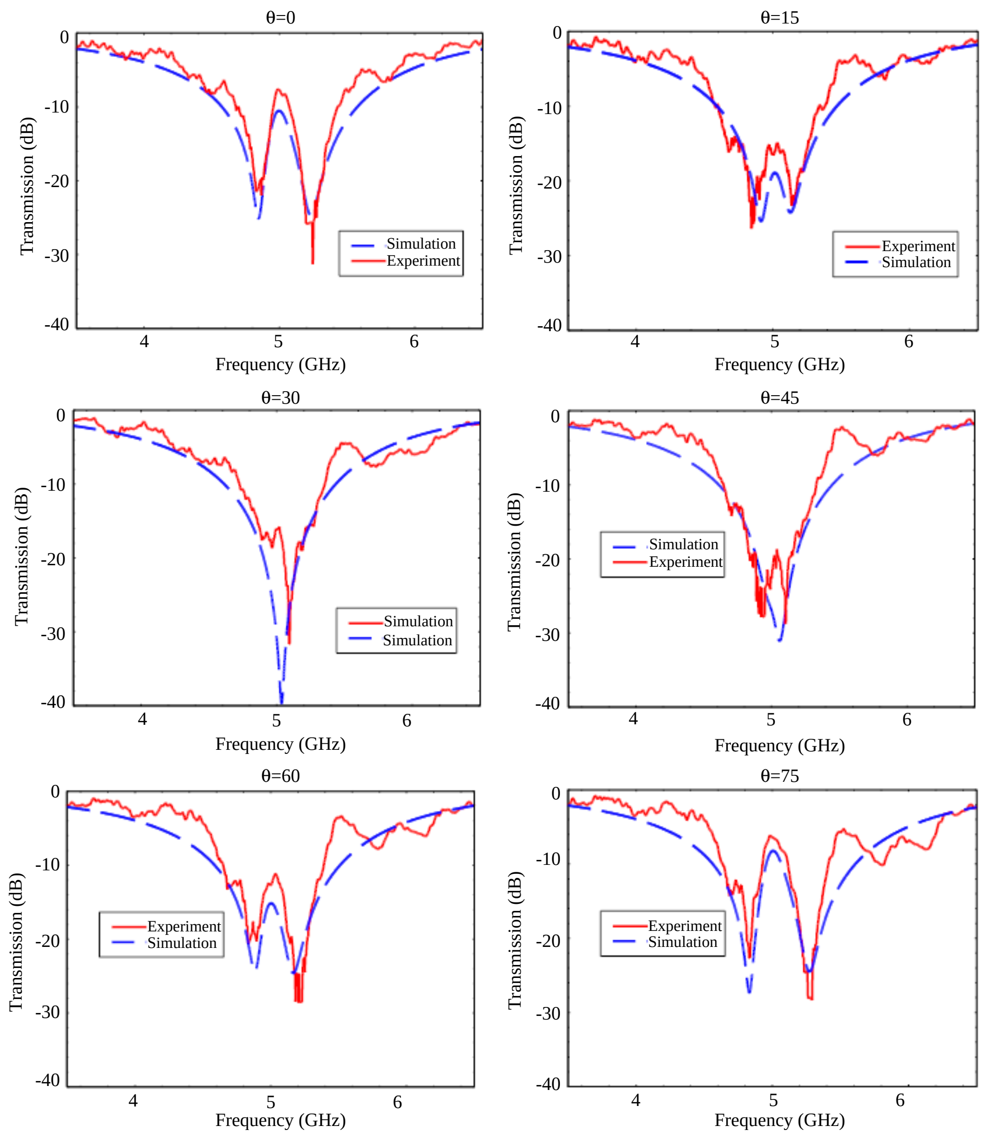


Figure 6. Pictures of the fabricated array sample of the proposed structure and the measurement experimental setup.



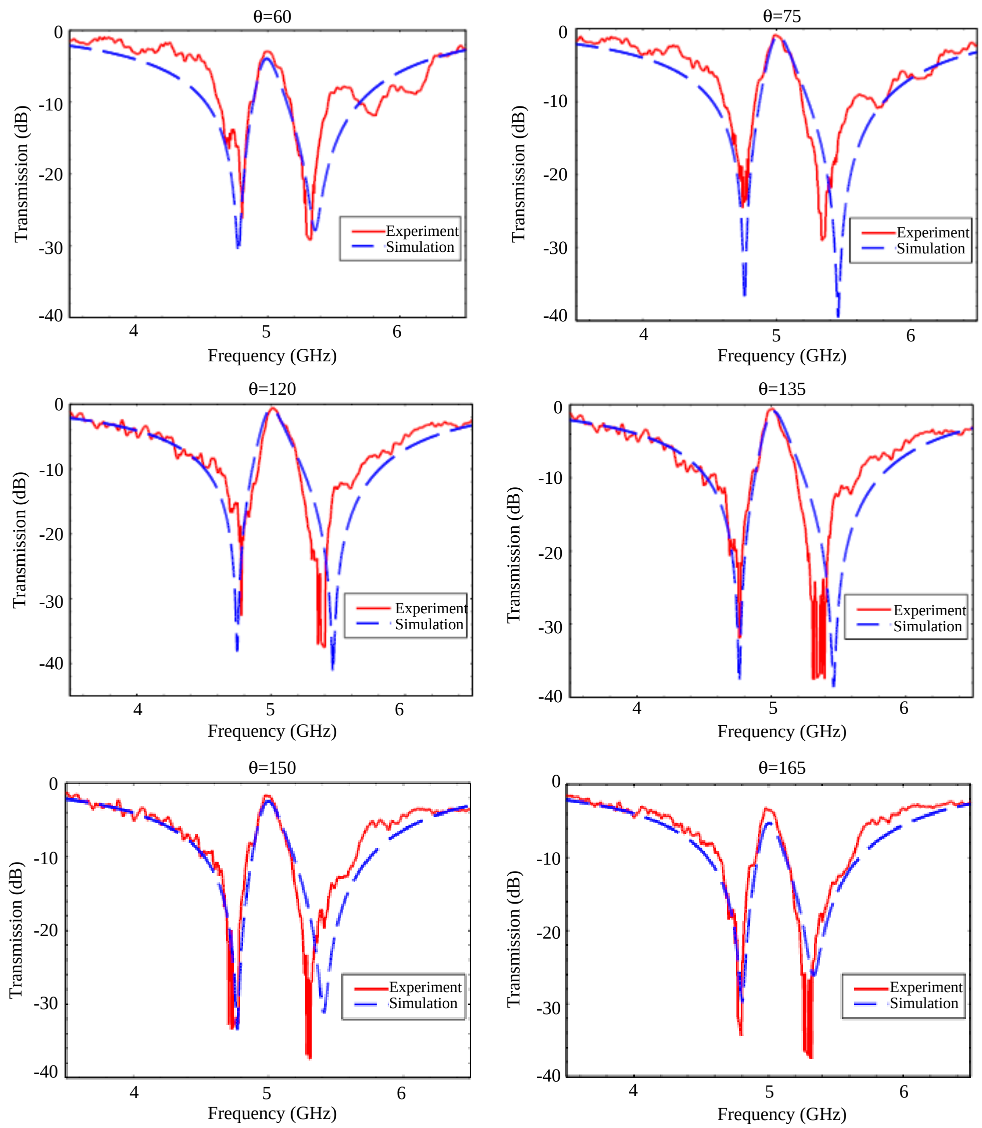


Figure 7. Experimental transmission spectra at normal incidence for the array of the proposed fabricated periodic structure of Figure 6 compared with the corresponding simulation spectra.

For the proposed structure of Figure 1, when the structure is excited normally, the two bright mode resonances of the CRR and ASRR overlap and a narrow transparency band is induced as shown in Figure 4. The strength of this transparency band depends on the bright mode resonance strength of the ASRR (i.e., the orientation of the structure with respect to the incident electric field), which was shown in Figure 3. To get more feeling for this dependence, the surface current distributions at the transparency resonance frequency (5.14 GHz) for the cases $\theta = 0$, 45, 90, 135 degrees are shown in Figure 5. Figure 5 shows the current distribution for the CRR alone, the ASRR alone and the proposed combined structure of Figure 1. As we see in Figure 5, two equal and out of phase (opposite) currents are induced in the CRR when imprinted alone on the substrate and excited normally. The magnitude of the current on the ASRR when exited alone is proportional to its resonance strength. When the ASRR is imprinted inside the CRR and the combined structure is excited normally, a reduction of currents in both resonators occurs. The two out of phase induced currents in the CRR are reduced in magnitude and become unequal which leads to a net resultant current in the CRR. The largest current reduction in the CRR is produced at $\theta = 135$ degrees, which illustrates the most efficient transparency achieved. As expected, for $\theta = 45$ degrees, the two out of phase currents are less reduced through coupling which leads to nearly total loss of transparency as shown in Figure 4.

3. EXPERIMENTAL MEASUREMENTS

The proposed structure was fabricated using the method described in reference [25], and an array was generated for experimental measurements as pictured in Figure 6. The dimensions of the resonators in different unit cells were measured under the microscope and negligible variations were noticed. Subsequent to many single particle measurements made in waveguides/slotted lines [25], an open ended chamber lined with Cuming pyramidal anechoic chamber absorbing pads was constructed with additional absorbing material opposite the receiver. Identical 10-dB gain transmitting and receiving horns were placed on opposite sides of and in the far field of the array. A Wiltron programmable sweep generator and a Hewlett Packard power meter served as source and receiver. The experimental measurements for different values of θ at normal incidence are shown in Figure 7. Transmission measurements were made every 15 degrees to 180 degrees. The results show how the transparency band is affected by changing the orientation of the particle. The transparency band can be seen to occur for a wide range of polarization angles but disappears as the structure comes closer to symmetry with respect to the incident electric field.

4. DISCUSSION

For the research of this paper, a key issue was to design and confirm that the features sought were preserved over a wide range of angles. The features were a narrow transparency band induced in a wide absorption/reflection window using EIT metamaterial. In the proposed structure in this article, the two modes oscillate at the same fixed frequency regardless of the orientation of the particle, though the ASRR resonance strength depends on the orientation to a degree. For example we have shown that it disappears for a narrow range of angles for which the oriented particle appears to be close to symmetric with respect to the incident electric field.

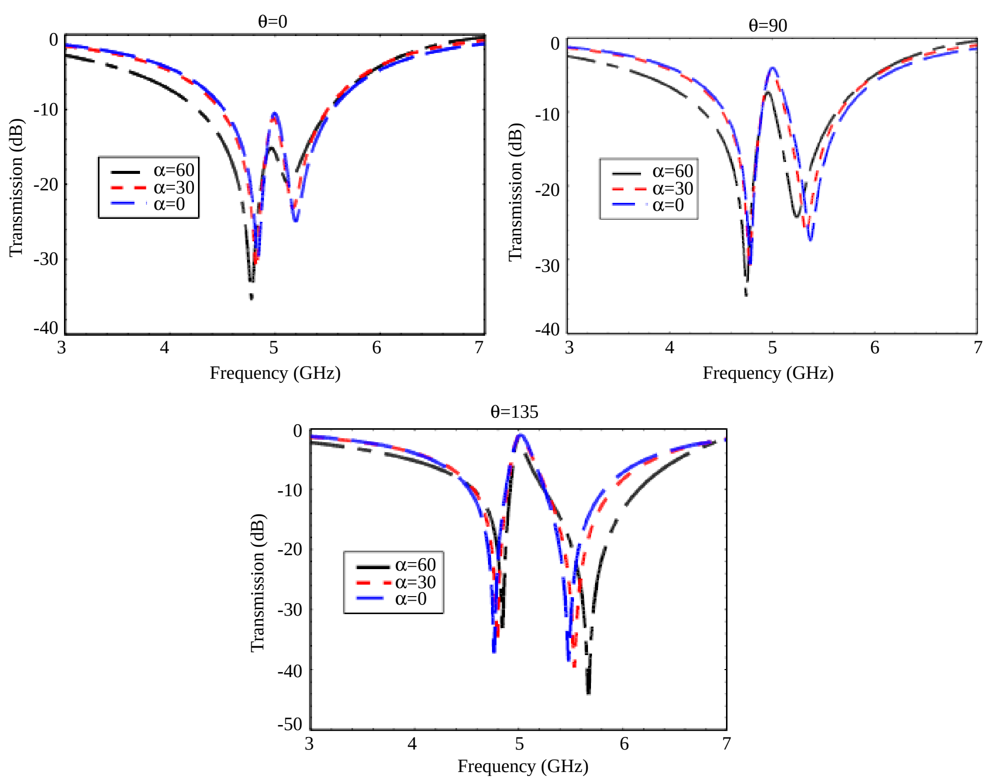


Figure 8. Transmission spectra for the proposed structure for different incident angles (α) and different polarization angles (θ).

Also, orienting the structure in the third dimension is of importance to the efficiency of this structure as a selective-band obscurant particle. To check this point we performed simulation for other incidence angles (α) for the cases $\theta = 0$, 90, 135 degrees. The simulated transmission spectrum is shown in Figure 8. Figure 8 shows that the proposed structure maintains its characteristic as a selective-band obscurant with random orientation in the third dimension. Of course for edge-on incidence (i.e., $\alpha = 90$ degrees), the behavior disappears as the E-field is perpendicular to the plane of the structure and there is no excitation of the two modes. One final point that needs to be addressed here is that the EIT behavior of the periodic structure is an internal characteristic of the individual single unit cell [17]. So an aerosol that consists of the single unit cell particles can serve as a selective-band obscurants for some applications.

5. CONCLUSIONS

A new metamaterial particle is proposed to serve as a selective-band obscurant particle with a narrow transparency band in the middle of a wide absorption/reflection band. The working principle of the structure depends on the electromagnetic coupling between two bright modes and an EIT phenomena is achieved. A novel aspect of this structure is that it maintains its characteristic over a wide range of angles so that a random orientational average maintains, to a large degree, the desired features. To the best of our knowledge, no other reported structure achieves the orientation-averaged characteristic of this structure and at the same time keeps the transparency band as narrow as possible compared with the adjacent attenuation windows. Improvements that enhance the orientation-averaged efficiency and reduce the width of the transparency band would be of great benefit to obscuration applications, especially for the military.

REFERENCES

1. Bohren, C. F. and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley, 1998.
2. Alyones, S., C. W. Bruce, and A. K. Buin, "Numerical methods for solving the problem of electromagnetic scattering by a thin finite conducting wire," *IEEE Trans. Antennas Propag.*, Vol. 55, 1856–1861, 2007.
3. Waterman, P. C., "Scattering, absorption and extinction by thin fibers," *J. opt. Soc. Amer.*, Vol. 22, No. 11, 2430–2441, 2005.
4. Alyones, S. and C. W. Bruce, "Electromagnetic scattering by finite conducting fiber: Limitation of a previous published code," *Journal of Electromagnetic Waves And Applications*, Vol. 25, No. 7, 1021–1030, 2011.
5. Bruce, C. W. and S. Alyones, "Extinction efficiencies for metallic fibers in the infrared," *Applied Optics*, Vol. 48, 5095–5098, 2009.
6. Bruce, C. W. and S. Alyones, "Visible and infrared optical properties of stacked cone graphitic microtubes," *Applied Optics*, Vol. 51, No. 16, 3250, 2012.
7. Bruce, C. W., A. V. Jelinek, S. Wu, S. Alyones, and Q. S. Wang, "Millimeter-wavelength investigation of fibrous aerosol absorption and scattering properties," *Applied Optics*, Vol. 43, 6648–6655, 2004.
8. Willis, T. M. and H. Weil, "Disc scattering and absorption by an improved computational method," *Applied Optics*, Vol. 26, No. 18, 1987.
9. Shepherd, J. W. and A. R. Holt, "The scattering of electromagnetic radiation from finite dielectric circular cylinders," *J. Phys. A*, Vol. 16, 65, 1983.
10. Alyones, S., "Electromagnetically induced absorption in metamaterials in the infrared frequency," *Progress In Electromagnetics Research Letters*, Vol. 47, 19–25, 2014.
11. Liu, N., T. Weiss, M. Mesch, L. Langguth, U. Eigenthaler, M. Hirscher, C. Sönnichsen, and H. Giessen, "Planar metamaterial analogue of electromagnetically induced transparency for plasmonic sensing," *Nano Lett.*, Vol. 10, No. 4, 1103–1107, 2010.

12. Arif, E. Ç., A. Artar, M. Turkmen, A. A. Yanik, and H. Altug, "Plasmon induced transparency in cascaded π-shaped metamaterials," *Optics Express*, Vol. 19, No. 23, 22607–22618, 2011.
13. Li, Z., Y. Ma, R. Huang, R. Singh, J. Gu, Z. Tian, J. Han, and W. Zhang, "Manipulating the plasmon-induced transparency in terahertz metamaterials," *Optics Express*, Vol. 19, No. 9, 8912–8919, 2011.
14. Lu, Y., J. Y. Rhee, W. H. Jang, and Y. P. Lee, "Active manipulation of plasmonic electromagnetically-induced transparency based on magnetic plasmon resonance," *Optics Express*, Vol. 18, No. 20, 20912–20917, 2010.
15. Xu, H., Y. Lu, Y. P. Lee, and B. S. Ham, "Studies of electromagnetically induced transparency in metamaterials," *Optics Express*, Vol. 18, No. 17, 17736–17747, 2010.
16. Dong, Z.-G., H. Liu, M.-X. Xu, T. Li, S.-M. Wang, S.-N. Zhu, and X. Zhang "Plasmonically induced transparent magnetic resonance in a metallic metamaterial composed of asymmetric double bars," *Optics Express*, Vol. 18, No. 17, 18229–18234, 2010.
17. Zhang, J., S. Xiao, C. Jeppesen, A. Kristensen, and N. A. Mortensen, "Electromagnetically induced transparency in metamaterials at near-infrared frequency," *Optics Express* Vol. 18, No. 16, 17187–17192, 2010.
18. Liu, C., Z. Dutton, C. H. Behroozi, and L. V. Hau, "Observation of coherent optical information storage in an atomic medium using halted light pulses," *Nature*, Vol. 409, No. 6819, 490–493, 2001.
19. Phillips, D. F., A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, "Storage of light in atomic vapor," *Phys. Rev. Lett.*, Vol. 86, No. 5, 783–786, 2001.
20. Anker, J. N., W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, and R. P. Van Duyne, "Biosensing with plasmonic nanosensors," *Nat. Mater.*, Vol. 7, No. 6, 442–453, 2008.
21. Liu, N., T. Weiss, M. Mesch, L. Langguth, U. Eigenthaler, M. Hirscher, C. Sönnichsen, and H. Giessen, "Planar metamaterial analogue of electromagnetically induced transparency for plasmonic sensing," *Nano Lett.*, Vol. 10, No. 4, 1103–1107, 2010.
22. Jin, X.-R., J. Park, H. Zheng, S. Lee, Y. Lee, J. Y. Rhee, K. W. Kim, H. S. Cheong, and W. H. Jang, "Highly-dispersive transparency at optical frequencies in planar metamaterials based on two-bright-mode coupling," *Optics Express*, Vol. 19, No. 22, 21652–21657, 2011.
23. Wang, J., B. Yuan, C. Fan, J. He, P. Ding, Q. Xue, and E. Liang, "A novel planar metamaterial design for electromagnetically induced transparency and slow light," *Optics Express*, Vol. 21, No. 21, 25159–25166, 2013.
24. Ibraheem, A. I. A.-N., C. Jansen, and M. Koch, "High Q-factor metasurfaces based on miniaturized asymmetric single split resonators," *Appl. Phys. Lett.*, Vol. 94, 153505, 2009.
25. Alyones, S., A. V. Jelinek, M. Granado, and C. W. Bruce, "Design of metaparticles as sharp frequency-selective obscurant aerosols," *Progress In Electromagnetics Research M*, Vol. 30, 141–152, 2013.
26. CST Microwave Studio, Sonnet Software Inc., http://www.CST.com.