Theory, design and characterization of metamaterial absorbers: a formal assessment

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Metamaterial (MTM) absorbers and their design have been of prime interest in view of their capability to absorb electromagnetic waves of high frequencies. Different types of MTM absorbers have been reported in the last two decades. Keeping this in view an attempt was made to review the progress of MTM absorbers in terms of the theory behind them, designing and construction. This paper reviewed the basic theory and design regulations of a perfect MTM absorber at high, narrow and broad band frequencies. Also we reviewed tunable frequency and coherent absorbers. This exercise was done to focus on recent developments in metamaterial absorbers and present the tested results in a more precise way.

(Received November 3, 2022; Accepted March 2, 2023)

Keywords: Metamaterial(MTM) absorbers, Absorption, Tunable absorbers, Coherent absorbers, Narrowband absorbers, Broadband absorbers

1. Introduction

Materials with negative refraction first demonstrated by Veselago in 1968 have brought a big breakthrough in the field of material science[1]. Since then after three decades Pendry developed such material[2].Materials tailored beyond their natural electromagnetic properties called metamaterials (MTM) find extensive applications in antennas, sensors, absorbers etc.[3-6]. In any of these applications a unit cell of metamaterial capable of operating at sub wavelength was designed to have unique electric and or both magnetic responses for an incident em wave [7-9]. This response in a metamaterial results in tailored medium making it highly potential in cloaking devices, sensors, antennas etc.[10-21]. As MTM's suffer with unavoidable loss due to atomic, molecular, chemical or structure realization of low loss devices has been taken up by optimizing the structure [22-24]. At the same time, it is to be noted that applications related to energy harvesting, scattering reduction and thermal sensing require absorption [25-27]. It is reported that tailoring of magnetic and electric resonances lead to usage of above mentioned inherent loss in achieving MTM's of uniform absorption[28-34]. Perfect absorber with metamaterial reported for the first time exhbited narrow bandwidth assigned to resonance condition limiting its usage for practical applications[28]. In order to design MTM based multiband absorbers, unit cells with multiple resonances are designed and combined[35, 36]. Absorption in broadband is obtained for close resonant frequencies[37]. Also MTM absorbers designed with multilayer structures or vertical standing nano-wires [38-41] achieve broadband absorption.

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https://doi.org/10.15251/JOBM.2023.151.31

2. Theory behind MTM absorbers

MTM absorbers mainly function based on Impedance Matching and Interference Theories.

2.1. Impedance matching theory

According to this theory perfect absorption in a metamaterial can be obtained by conspiring its electric, magnetic resonances to alter effective permittivity and permeability values to obtain impedance match with free space [42, 43]. It is also reported that impedance matching in MTM absorber cannot be achieved without concurrent electric and magnetic resonances, thereby indicating no perfect absorber can be possible with MTM of single resonance (electric or magnetic)[44].

2.2. Interference theory

Destructive interference between multiple reflections in a given dielectric substrate forms the basis for interference theory. An MTM absorber was assembled with metallic patterns and high conducting metallic plane on either side of a substrate. The layer of metallic patterns acts as partial reflector and can alter the coefficients of transmission and reflection. The conducting plane acts as perfect reflector producing a delay of 180° phase between incident and reflecting em wave[45,46].This combination leads to absorption based on the individual parameters.

3. Narrowband MTM absorbers

The journey of MTM absorber started in 2006, which proposed an arrangement of split ring resonators (SRR) supported by a resistive sheet [47]. In this design em wave/magnetic field are parallel/perpendicular to SRR plane /SRR array. SRR array is deposited on a resistive sheet for impedance matching with free space. The coefficients of transmission and reflection are found to be less than −20 dB at 2 GHz with perfect absorption. This arrangement is better than a planar structure whose absorption bandwidth is limited.

In continuation a planar MTM absorber with FR-4 substrate sandwiched between electric ring resonators and cut wires was proposed for the first time in 2008[28]. This was the first planar MTM absorber with subwavelength structure whose simulated absorptivity is about 96% at 11.65 GHz and experimental value is 88% at 11.5 GHz. The frequency and strength of absorption depends on the geometry of resonator and substrate thickness. Various MTM absorbers of different spectral range are realized with reference to above design[29-39].

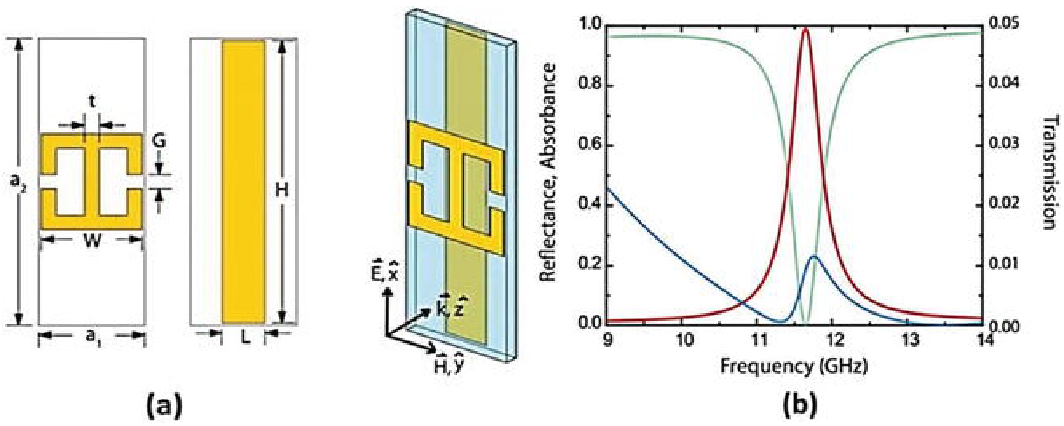

Fig. 1. Image showing planar MTM absorber (a) Unit Cell (b) Plot showing stimulated values of absorbance, reflectance and transmission versus microwave frequency. Courtesy: [44].

In 2009, an MTM absorber with dendritic (branched form) unit cells was reported. Figures 2(a&b)shows a unit dendritic cell along with its absorptivity value of 95% both simulated and experimental at 10.26 GHz. It is also estimated that perfect absorption in optical system can be achieved by reducing the dendritic MTM absorber to nanoscale [46].

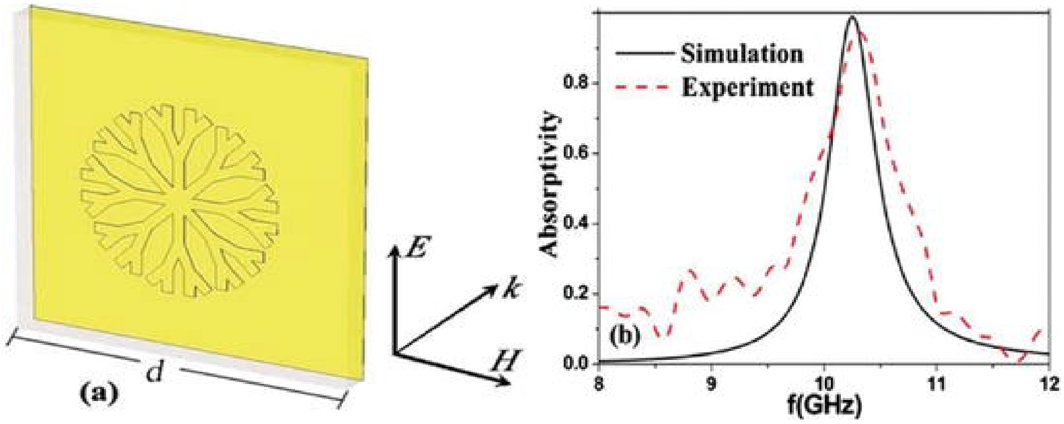

Fig. 2.Image showing Dendritic MTM absorber (a) Unit Cell (b) Plot showing experimental and stimulated values of absorptivity against frequency. Courtesy[44].

In general MTM absorbers has unit cells arranged periodically. It is observed that any disorder in the arrangement leads to decrease in absorptivity and frequency shift (optical regime). Still an MTM absorber can exhibit 95% absorption with random unit cells disordered to certain extent[49].

4. Broadband MTM Absorbers

Expansion of bandwidth in MTM absorbers can be obtained through usage of (a) multilayered structures [38, 39],(b) multiple resonant cells[50,51], (c)lumped elements[52] and (d) high loss dielectrics [53,54].

With reference to (a) a broadband MTM absorber with stacked resonant patches of various different sizes was proposed. As shown in Figure 4. It consists of MTM absorber with twenty one metal patch layers whose net thickness is less than the operating wavelength. It is reported to have full width absorption at half maximum of about 86%. Higher frequency em waves get absorbed at upper patches, while lower frequency em waves are blocked at lower patches[37] realizing ultra-broad bandwidth.

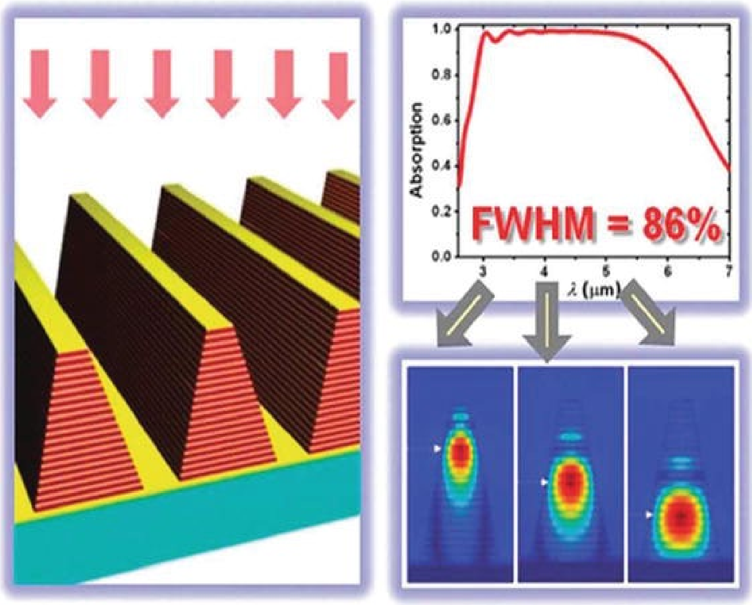

Fig. 3.Image showing Saw-toothed MTMAbsorber along with its absorption spectrum. Courtesy [44].

With reference to (d) high lossy dielectrics exhibit wideband absorption [53, 54].In this context water is one of the best high lossy dielectric in microwave frequency range [55]. MTM absorber designed with water layer in a resin holder with copper plane at bottom was shown(Figure.4). Using this design abosorpitivity greater than 90% between 12GHz-29.6GHz (ultra-broad band) was reported[56]. To check whether this absorption is predominant due to inherent high loss, absorption spectra was compared for full water layer without holes and resin without water. It was observed that absorption of full water layer is about 35%–40%, while it reduced by 20%–40% when emptied [Figure 4(d)]. This confirmed the contribution of absorption (ultra-broadband) to localized resonances in case of water resonator.

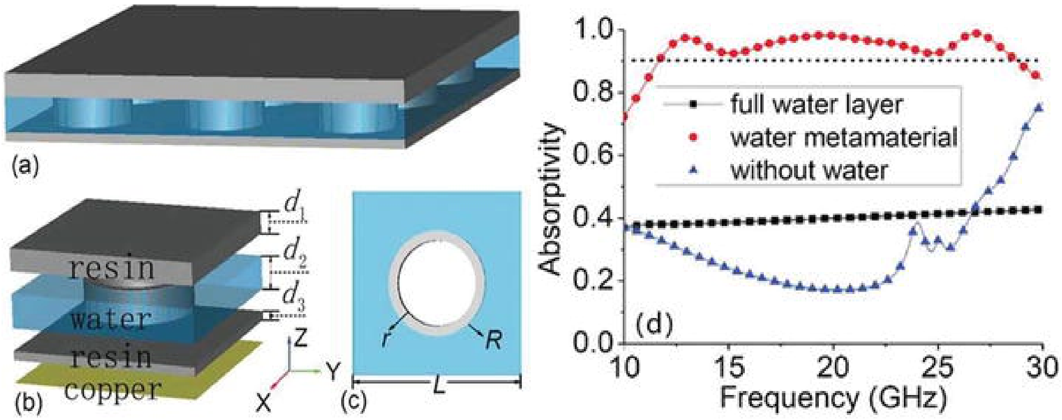

Fig. 4.(a) Water MTM Absorber, (b) Unit Cell (c) Water Layer; (d) Frequency versus Absorptivity Courtesy:[44].

Heavily doped silicon acts as a lossy dielectric at terahertz frequencies and can be used for broadband absorption [53]. A silicon based broadband high absorption MTM absorber was proposed at visible wavelengths[57]. It consists of a sub-wavelength Si layer with holes, SiO2 spacer and a thick gold substrate[Figure.5(a)]. This structure exhibited high absorptivity and large bandwidth [Figure 5(c)]. Similarly another MTM absorber designed with silicon substrate operating between 0.9THz to 2.5 THz was reported[58].

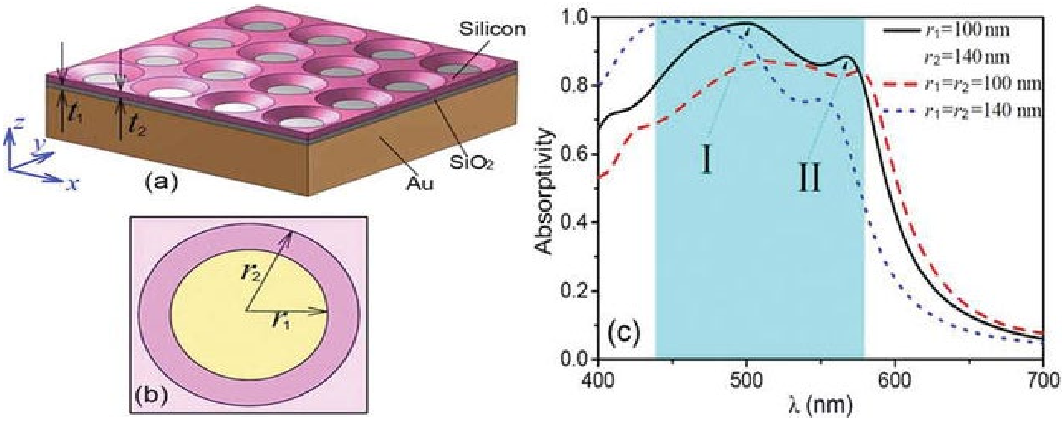

Fig. 5.(a) Si based MTM Absorber (b) Unit Cell. (c) Absorptivity spectra. Courtesy: [44].

5. Frequency tunable MTM absorbers

It is a known that the significance of metamaterials lie in the fact that they can be tailored for arbitrary electromagnetic properties. Once designed, a metamaterial has fixed properties[59-62]. If they are used as absorbers their operating frequency will be fixed limiting their practical applications. In this context MTM absorbers in which frequency can be tuned to desired value is of prime importance. This can be achieved by designing an MTM absorber with a medium having adjustable material properties. Effective methods include elements like varactordiodes, ferroelectrics, ferrites, graphene etc.[63-69].In addition to these methods, mechanical bending was used for a tunable MTM absorber [68-72]. This type of MTM absorber with dielectric resonators on conductive rubber layer with cent % absorption was reported[73]. Figure.6 displays this type of MTM absorber in which stretching of MTM absorber with uni-axial stress increases the distance between dielectric bricks slowly to red-shift the resonance frequency at 410 MHz in X band. Similar type of MTM absorber was demonstrated with multiple absorption bands by varying the shape and size of dielectric slab [74].

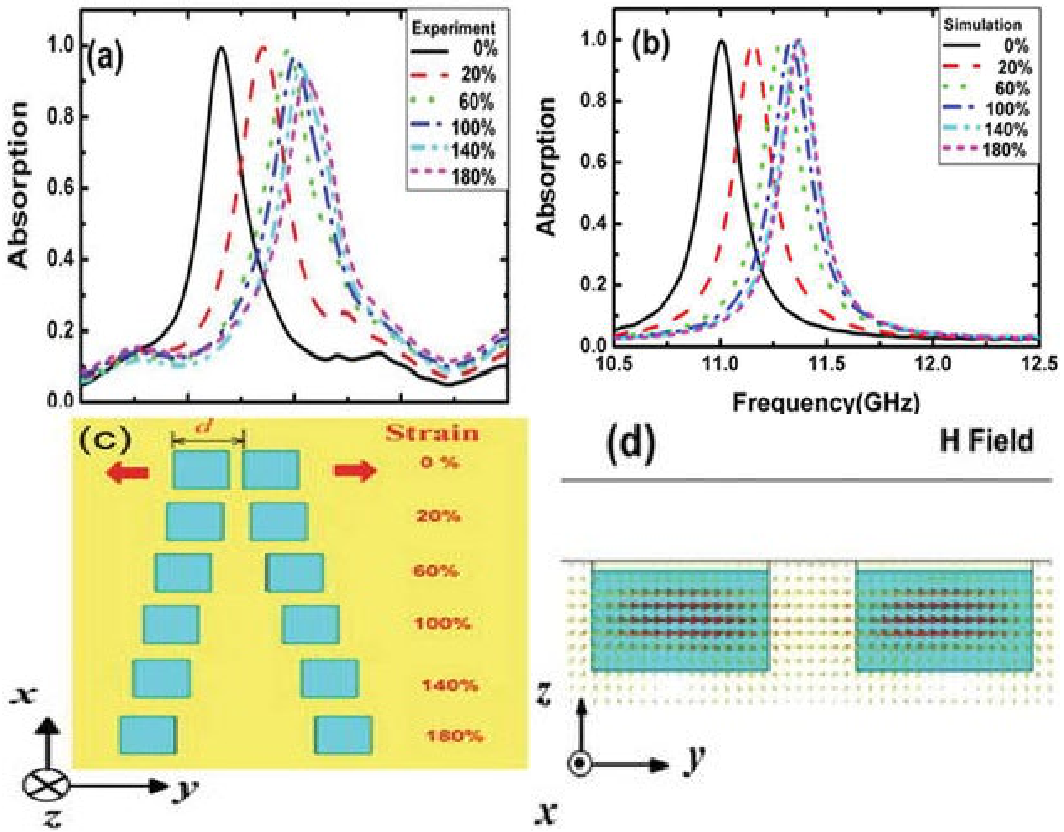

Fig. 6. Plots showing Absorption Spectra of Mechanically Stretchable Dielectric MTM Absorber (a) Experimental (b) Stimulated (c) Image showing stretch in dielectric resonator on a thin conductive rubber layer. (d) Distribution of magnetic field at resonance frequency.
Courtesy: [44]

Graphene can be used to design tunable MTM absorber as the surface conductivity of graphene is tunable. Using graphene wires MTM absorber with cross-shaped metallic unit cells was reported [73-75]. Figure 7(a) show such structure that can be tuned at terahertz frequencies. By adjusting graphene's fermi level (bias voltage and fermi level are proportional) the absorption peak frequency was tuned up to 15% of uniform peak absorption[Figure 7(c)].

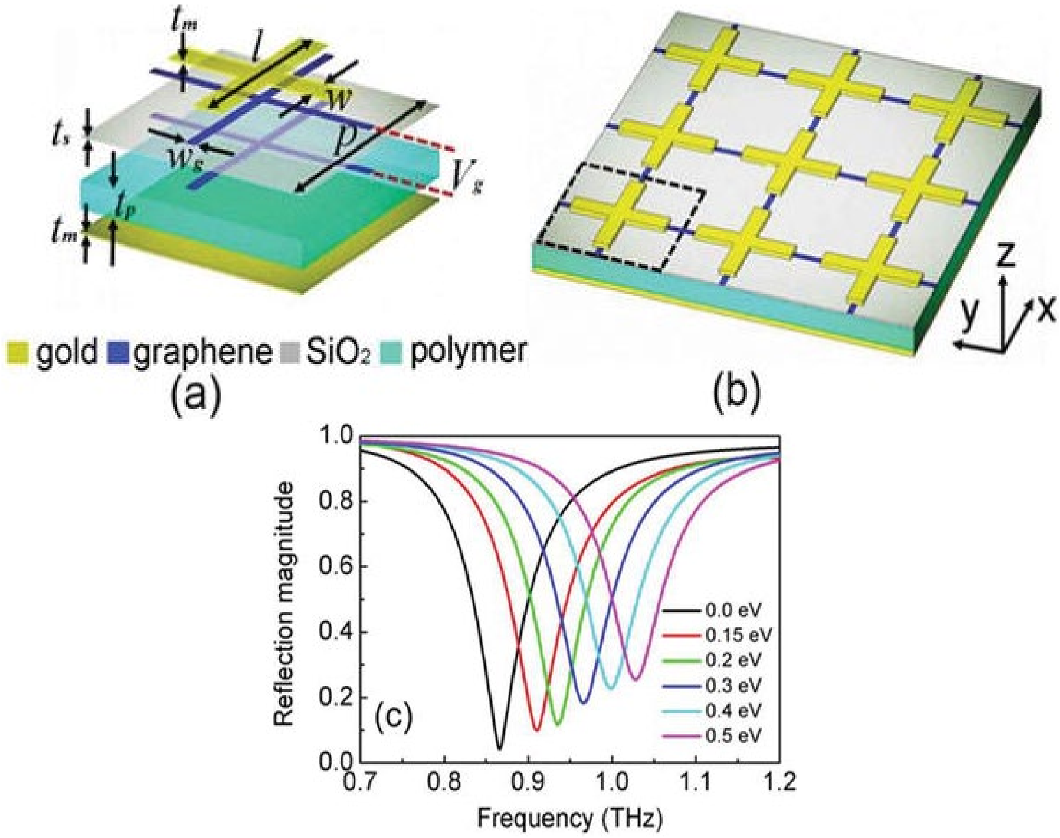

Fig. 7.Tunable MTM absorber with grapheme (a) Unit Cell (b) MTM absorber. (c) Absorptivity vs Frequcny for different bias voltages. Courtesy: [44].

6. Coherent MTM absorbers

As mentioned in the previous section in a given MTM absorber, absorptivity is fixed with design limiting its applications where flexible tunability of absorption is required. This limitation can be addressed through coherent perfect absorption (CPA)[76,77]. The idea behind CPA is to achieve perfect absorption through destructive interference between two propagating waves[78]. Cent percent modulation of absorptivity in this system can be achieved by setting the phase difference between two waves [79]. This dynamic modification of absorptivity make these absorbers significant in various applications. Since the invent of CPA it was observed and reported in various applications[76-82].Majority of coherent MTM absorbers use metallic resonators, while recent reports indicated CPA in metal-free metamaterials. In this context MTM absorber with dielectric ceramic attained tunable absorptivity ranging between 0.38% to 99.85% through phase modulation[83]. A similar structure made of water with high coherent absorption at multiple frequency bands was reported[84]. Apart from perfect MTM absorbers which need powerful magnetic &electric resonances in artificial resonators, CPA can be achieved in natural materials having profound thickness in the order of sub wavelength[83]. Conductivity in thin graphene and MoS_2 layers was found to be tunable making them highly suitable for coherent absorbers[54, 85].

7. Conclusions

This paper mainly reviewed the theory, design and characterization of some of the MTM absorbers reported in the last two decades. MTM absorbers and their operation frequency was discussed. Design of narrowband, broadband, tunable absorbers are reviewed. Mainly perfect MTM absorbers, planar MTM absorbers, coherent MTM absorbers are reviewed. We tried to present a simple review of various MTM absorbers in terms of their design and output absorption. This review helps the enthusiastic researchers to further develop new design and achieve efficient absorption in various frequency ranges.

References

[1] Veselago.V.G,1968. Sov. Phys. Usp., Vol.10(4), Pg.509-514; https://doi.org/10.1070/PU1968v010n04ABEH003699

[2]Shelby.R.A, Smith.D.R, Schultz.S, 2001, Science, Vol. 292(5514),Pg.77-79; https://doi.org/10.1126/science.1058847

[3]Engheta N, Ziolkowski RW. Metamaterials: Physics and Engineering Explorations. New Jersey: John Wiley & Sons; 2006; https://doi.org/10.1002/0471784192

[4]Shelby RA, Smith DR, Schultz S., Science. 2001;292:77-79; https://doi.org/10.1126/science.1058847

[5] Valentine J, Zhang S, Zentgraf T, Ulin-Avila E, Genov DA, Bartal G, Zhang X., Nature. 2008;455:376-379; https://doi.org/10.1038/nature07247

[6]Baimuratov AS, Pereziabova TP, Zhu W, Leonov MY, Baranov AV, Fedorov AV, Rukhlenko ID, Nano Letters. 2017;17:5514-5520; https://doi.org/10.1021/acs.nanolett.7b02203

[7] Zhang X, Liu Z., Nature Materials. 2008;7:435-441; https://doi.org/10.1038/nmat2141

[8] Kang M, Zhu W, Rukhlenko ID., Physical Review A. 2017;96:063823; https://doi.org/10.1103/PhysRevA.96.063823

[9] Zhu W, Rukhlenko ID, Xiao F, Premaratne M., Journal of Applied Physics. 2014;115:143101; https://doi.org/10.1063/1.4870862

[10]Schurig D, Mock JJ, Justice BJ, Cummer SA,Pendry JB, Starr AF, Smith DR., Science. 2006;314:977-980; https://doi.org/10.1126/science.1133628

[11] Zhu W, Shadrivov I, Powell D, Kivshar Y., Optics Express. 2011;19:20827-20832; https://doi.org/10.1364/OE.19.020827

[12] Wang B, Zhou J, Koschny T, Kafesaki M, Soukoulis CM., Journal of Optics A. 2009;11:114003; https://doi.org/10.1088/1464-4258/11/11/114003

[13] Zhu W, Rukhlenko ID, Huang Y, Wen G, Premaratne M., Journal of Optics. 2013;15:125101; https://doi.org/10.1088/2040-8978/15/12/125101

[14] Kang M, Wang HT, Zhu W., Journal of Applied Physics. 2017;122:013105; https://doi.org/10.1063/1.4990996

[15] Cui TJ, Qi MQ, Wan X, Zhao J, Chen Q., Light: Science and Applications. 2014;3:e218; https://doi.org/10.1038/lsa.2014.99

[16] Liu Y,Zentgraf T, Bartal G, Zhang X., Nano Letters. 2010;10:1991-1997; https://doi.org/10.1021/nl1008019

[17] Zhu W, Rukhlenko ID, Premaratne M., Journal of the Optical Society of America B: Optical Physics. 2012;29:2659-2664; https://doi.org/10.1364/JOSAB.29.002659

[18] Zhu W, Rukhlenko ID, Premaratne M., IEEE Photonics Journal. 2012;4:741-748; https://doi.org/10.1109/JPHOT.2012.2196763

[19] Hong W, Jiang ZH, Yu C, Zhou J, Chen P, Yu Z, Zhang H, Yang B, Pang X, Jiang M, Cheng Y, Al-Nuaimi MKT, Zhang Y, Chen J, He S., IEEE Transactions on Antennas and Propagation. 2017;65:6231-6249; https://doi.org/10.1109/TAP.2017.2712819

[20] Si L-M, Zhu W, Sun H-J., IEEE Antennas and Wireless Propagation Letters. 2013;12:305-308; https://doi.org/10.1109/LAWP.2013.2249037

[21] Lin FH, Chen ZN., IEEE Transactions on Antennas and Propagation. 2017;65:1706-1713; https://doi.org/10.1109/TAP.2017.2671036

[22] Cao W, Singh R, Al-Naib IA, He M, Taylor AJ, Zhang W., Optics Letters. 2012;37:3366-3368; https://doi.org/10.1364/OL.37.003366

[23] Zhu W, Zhao X., Chinese Physics Letters. 2009;26:074212; https://doi.org/10.1088/0256-307X/26/7/074212
[24] Zhu W, Zhao X., Journal of Applied Physics. 2009;106:093511; https://doi.org/10.1063/1.3253720
[25] Wang H, Sivan PV, Mitchell A, Rosengarten G, Phelan P, Wang L., Solar Energy Materials & Solar Cells. 2015;137:235-242; https://doi.org/10.1016/j.solmat.2015.02.019
[26]Culhaoglu AE, Osipov AV, Russer P., IEEE Transactions on Antennas and Propagation. 2013;61:462-466; https://doi.org/10.1109/TAP.2012.2220095
[27]Guddala S, Kumar R, Ramakrishna SA., Applied Physics Letters. 2015;106:111901; https://doi.org/10.1063/1.4914451
[28]Landy NI, Sajuyigbe S, Mock JJ, Smith DR, Padilla WJ., Physical Review Letters. 2008;100:207402; https://doi.org/10.1103/PhysRevLett.100.207402
[29] Watts CM, Liu X, Padilla WJ., Advanced Materials. 2012;24:OP98-OP120; https://doi.org/10.1002/adma.201200674
[30] Zhu W, Zhao X, Gong B, Liu L, Su B., Applied Physics A: Materials Science & Processing. 2011;102:147-151; https://doi.org/10.1007/s00339-010-6057-6
[31] Huang Y, Wen G, Li J, Zhong J, Wang P, Sun Y, Gordona O, Zhu W., Chinese Physics B. 2012;21:117801; https://doi.org/10.1088/1674-1056/21/11/117801
[32] Zhu W, Rukhlenko ID, Premaratne M., Applied Physics Letters. 2013;102:241914; https://doi.org/10.1063/1.4812200
[33] Radi Y, Simovski CR, Tretyakov SA., Physical Review Applied. 2015;3:037001; https://doi.org/10.1103/PhysRevApplied.3.037001
[34] Liu X, Starr T, Starr AF, Padilla WJ.,Physical Review Letters. 2014;104:207403; https://doi.org/10.1103/PhysRevLett.104.207403
[35] Park JW, Tuong PV, Rhee JY, Kim KW, Jang WH, Choi EH, Chen LY, Lee YP.,Optics Express. 2014;104:207403; https://doi.org/10.1364/OE.21.009691
[36] Zhou W, Wang P, Wang N, Jiang W, Dong X, Hu S., AIP Advances. 2015;5:117109; https://doi.org/10.1063/1.4935436
[37]Gu S, Su B, Zhao X., Journal of Applied Physics. 2013;104:163702; https://doi.org/10.1063/1.4826911
[38] Cui Y, Fung KH, Xu J, Ma H, Jin Y, He S, Fang NX., Nano Letters. 2012;12:1443-1447; https://doi.org/10.1021/nl204118h
[39] Kim YJ, Yoo YJ, Kim KW, Rhee JY, Kim YH, Lee YP., Optics Express. 2015;23:3861-3868; https://doi.org/10.1364/OE.23.003861
[40] Shen Y, Pang Y, Wang J, Ma H, Pei Z., IEEE Photonics Technology Letters. 2015;27:2284-2287; https://doi.org/10.1109/LPT.2015.2461633
[41] Chen Q, Gu J, Liu P, Xie J, Wang J, Liu Y, Zhu W., Optics and Laser Technology. 2018;105:102-105; https://doi.org/10.1016/j.optlastec.2018.02.049
[42] Tao H, Landy NI, Bingham CM, Zhang X, Averitt RD, Padilla WJ., Optics Express. 2008;(10):7181-7188; https://doi.org/10.1364/OE.16.007181
[43] Li J, Wang F, Wen G, Huang Y, Zhu W., ACES Journal. 2013;28:1236-1243
[44]Weiren Zhu, 2018., Electromagnetic Metamaterial Absorbers: From Narrowband to Broadband http://dx.doi.org/10.5772/intechopen. 78581
[45] Chen H-T.,Optics Express. 2012;20:7165-7172;https://doi.org/10.1364/OE.20.007165
[46]Wanghuang T, Chen W, Huang Y, Wen G., AIP Advances. 2013;3:102118; https://doi.org/10.1063/1.4826522
[47]Bilotti F, Nucci L, Vegni L., Microwave and Optical Technology Letters. 2006;48:2171-2175; https://doi.org/10.1002/mop.21891
[48] Zhu W, Zhao X., Journal of the Optical Society of America B: Optical Physics. 2009;26:2382-2385; https://doi.org/10.1364/JOSAB.26.002382
[49] Zhu W, Zhao X., European Physical Journal Applied Physics. 2010;50:21101;

https://doi.org/10.1051/epjap/2010031
[50]Bouchon P, Koechlin C, Pardo F, Haïdar R, Pelouard J-L., Optics Letters. 2012;37:1038-1040; https://doi.org/10.1364/OL.37.001038
[51] Liu Y, Gu S, Luo C, Zhao X., Applied Physics A: Materials Science & Processing. 2012;108:19-24; https://doi.org/10.1007/s00339-012-6936-0
[52] Cheng YZ, Wang Y, Nie Y, Gong RZ, Xiong X, Wang X., Journal of Applied Physics. 2012;111:044902; https://doi.org/10.1063/1.3684553
[53] Pu M, Wang M, Hu C, Huang C, Zhao Z, Wang Y, Luo X., Optics Express. 2012;20:25513-25519; https://doi.org/10.1364/OE.20.025513
[54] Zhu W, Xiao F, Kang M, Sikdar D, Liang X, Geng J, Premaratne M, Jin R., IEEE Photonics Journal. 2016;8:5502207; https://doi.org/10.1109/JPHOT.2016.2633571
[55]Xie J, Zhu W, Rukhlenko ID, Xiao F, He C, Geng J, Liang X, Jin R, Premaratne M., Optics Express. 2018;26:5052-5059;https://doi.org/10.1364/OE.26.005052
[56] Ellison W., Journal of Physical and Chemical Reference Data. 2007;36:1-18; https://doi.org/10.1063/1.2360986
[57] Zhu W, Xiao F, Rukhlenko ID, Geng J, Liang X, Premaratne M, Jin R., Optics Express. 2017;25:5781-5786; https://doi.org/10.1364/OE.25.005781
[58] Yin S, Zhu J, Xu W, Jiang W, Yuan J, Yin G, Xie L, Ying Y, Ma Y., Applied Physics Letters. 2015;107:073903; https://doi.org/10.1063/1.4929151
[59] Smith DR, Padilla WJ, VierDC, Nemat-Nasser SC, Schultz S., Physical Review Letters. 2000;84:4184-4187; https://doi.org/10.1103/PhysRevLett.84.4184
[60] Plum E, Fedotov VA, Zheludev NI., Applied Physics Letters. 2008;93:191911; https://doi.org/10.1063/1.3021082
[61]Zhong J, Huang Y, Wen G, Sun H, Gordon O, Zhu W., IEEE Antennas and Wireless Propagation Letters. 2012;11:803-806;https://doi.org/10.1109/LAWP.2012.2208172
[62] Fan J, Sun G, Zhu W., Chinese Physics B. 2011;20:114101; https://doi.org/10.1088/1674-1056/20/11/114101
[63] Wen Q-Y, Zhang H-W, Yang Q-H, Chen Z, Long Y, Jing Y-L, Lin Y, Zhang P-X., Journal of Physics D: Applied Physics. 2012;45:235106;https://doi.org/10.1088/0022-3727/45/23/235106
[64] Hand TH, Cummer SA., Journal of Applied Physics. 2008;103:066105; https://doi.org/10.1063/1.2898575
[65] Huang Y, Wen G, Zhu W, Li J, Si L, Optics Express. 2014;22:16408-16417; https://doi.org/10.1364/OE.22.016408
[66] Linder J, Halterman K., Scientific Reports. 2016;6:31225;https://doi.org/10.1038/srep31225
[67] Yao Y, Shankar R, Kats MA, Song Y, Kong J, Loncar M, Capasso F., Nano Letters. 2014;14:6526-6532; https://doi.org/10.1021/nl503104n
[68]Shrekenhamer D, Chen W-C, Padilla WJ., Physical Review Letters. 2013;110:177403; https://doi.org/10.1103/PhysRevLett.110.177403
[69]Mkhitaryan VK, Ghosh DS, Rude M, Canet-Ferrer J, Maniyara RA, Gopalan KK, Pruneri V., Advanced Optical Materials. 2017;5:1600452;https://doi.org/10.1002/adom.201600452
[70] Zhang F, Feng S, Qiu K, Liu Z, Fan Y, Zhang W, Zhao Q, Zhou J., Applied Physics Letters. 2015;106:091907; https://doi.org/10.1063/1.4914502
[71]Pitchappa P, Ho CP, Kropelnicki P, Singh N, Kwong D-L, Lee C., Applied Physics Letters. 2014;104:201114; https://doi.org/10.1063/1.4879284
[72] Zhu W, Huang Y, Rukhlenko ID, Wen G, Premaratne M., Optics Express. 2012;20:6616-6621; https://doi.org/10.1364/OE.20.006616
[73] Zhang Y, Feng Y, Zhu B, Zhao J, Jiang T., Optics Express. 2014;24:22743-22734; https://doi.org/10.1364/OE.22.022743
[74] Zhu W, Xiao F, Kang M, Sikdar D, Premaratne M., Applied Physics Letters. 2014;104:051902; https://doi.org/10.1063/1.4863929
[75] Zhu W, Rukhlenko ID, Si L, Premaratne M., Applied Physics Letters. 2013;102:121911,

https://doi.org/10.1063/1.4799281
[76] Chong YD, Ge L, Cao H, Stone AD., Physical Review Letters. 2010;105:053901; https://doi.org/10.1103/PhysRevLett.105.053901
[77] Wan W, Chong YD, Ge L, Noh H, Stone AD, Cao HScience. 2011;331:889-892; https://doi.org/10.1126/science.1200735
[78] Kang M, Chong YD, Wang H-T, Zhu W, Premaratne M., Applied Physics Letters. 2014;105:131103; https://doi.org/10.1063/1.4896972
[79] Pu M, Feng Q, Wang M, Hu C, Huang C, Ma X, Zhao Z, Wang C, Luo X., Optics Express. 2012;20:2246-2254;https://doi.org/10.1364/OE.20.002246
[80] Feng S, Halterman K., Physical Review B. 2012;86:165103;https://doi.org/10.1103/PhysRevB.86.165103
[81]Gutman N, Sukhorukov AA, Chong YD, de SterkeCM., Optics Letters. 2013;38:4970-4973; https://doi.org/10.1364/OL.38.004970
[82] Kang M, Liu F, Li T-F, Guo Q-H, Li J, Chen J., Optics Letters. 2013;38:3086-3088; https://doi.org/10.1364/OL.38.003086
[83] Zhu W, Xiao F, Kang M, Premaratne M., Applied Physics Letters. 2016;108:121901; https://doi.org/10.1063/1.4944635
[84] Zhu W, Rukhenko ID, Xiao F, He C, Geng J, Liang X, Premaratne M, Jin R., Optics Express. 2017;25:15737-15745;https://doi.org/10.1364/OE.25.015737
[85] Fan Y, Zhang F, Zhao Q, Wei Z, Li H., Optics Letters. 2014;39:6269-6272; https://doi.org/10.1364/OL.39.006269