Invited Paper

Metamaterials design and challenges for THz radiation

Zhaoyun Duan [1*, 2], Su Xu [3], Hongsheng Chen [3], and Min Chen [4]
[1] Institute of High Energy Electronics, School of Physical Electronics, University of Electronic Science and technology of China, Chengdu 610054, China
[2] Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3] The Electromagnetics Academy at Zhejiang University and Department of Information Science & Electronic Engineering, Zhejiang University, Hangzhou 310027, China
[4] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[*1] Email: zhyduan@uestc.edu.cn

(Received May 2, 2013)

Abstract: THz (Terahertz) radiation sources are an important research topic in THz science and technology. Novel THz radiation using double negative metamaterials (DNMs) and electron beam bunches is a promising candidate. In this review paper, we first introduce THz metamaterials, especially DNMs, including the design, fabrication and testing. Then we present our research progress on the enhanced THz radiation based on DNMs using single and multiple charged particles. Finally, we discuss the challenges in metamaterials and associated radiations. The research presented here offers theoretical and experimental foundations for developing new THz radiation sources.

Keywords: Double negative metamaterials, THz metamaterials, THz radiation, THz sources

doi: 10.11906/TST.113-124.2013.06.07

1. Introduction

Currently, Terahertz (THz) science and technology is one of the hottest research fields in both electronics and optics [1]. It can be at least traced back to about 1950s, when the researchers adopted millimeter wave or far infrared ray technical terms. Generally speaking, millimeter wave roughly refers to the frequency range from 30 to 3000 *GHz* and narrowly from 30 to 300 *GHz*. Sometimes, scientists use the sub-millimeter wave to describe the electromagnetic wave in a range from 300 to 3000 *GHz*. From the viewpoint of optics, far infrared ray with a wavelength from about 15 μm to 1 *mm* means its frequency regime from 20 *THz* to 300 *GHz*. Since 1980s, the so called THz electromagnetic spectrum has been revisited. THz radiation is roughly defined as its frequency from 0.1 to 10 *THz* and narrowly from 0.3 to 3 *THz*. Using this definition, THz radiation is located between the short-wavelength edge of microwave band and the long-wavelength edge of far-infrared light. THz band was until recently the last unexploited part of the electromagnetic spectrum. THz science and technology, especially THz sources [2] causes an extensive research boom around the world. This is because THz radiation has some very surprising properties: First, THz radiation is more penetrating than visible light and infrared, and thus can much better penetrate fabrics and plastics; Second, the photon energy of THz radiation is much lower than that of X-rays and thus it is much less damaging to tissues and DNA; Third, its spectroscopy provides rich information about chemical compounds, thus very useful for biochemistry and many other fields. Therefore provided that strong THz radiation sources are available, THz technology could be widely applied to many fields [3] such as medical imaging, chemical and biological sensing, security, scientific research and imaging (for examples, spectroscopy and sub-millimeter astronomy), Communication and radar, and manufacturing.

At the same time, another new research field in the electromagnetics, metamaterial, appeared. According to the current research status, metamaterial can be generally classified as double-negative metamaterials (DNMs), single-negative metamaterials (SNMs), and photonic crystals. Here, DNM is a new kind of artificial electromagnetic material with both effective permittivity and permeability being negative. It would exhibit unique properties such as negative index of refraction, reversed Cherenkov radiation (RCR), and reversed Doppler Effect. Since the first experimental demonstration of negative refraction of left-handed metamaterial was reported in *Science* magazine in 2001 [4], this kind of artificial electromagnetic material has attracted great interests of scientists and engineers all over the world and becomes one of the hot topics in worldwide researching [5]. It has potential applications in sub-wavelength imaging, optical sensing, cloaking, photonic integrated circuits, and solar-cell technology. One new type of electromagnetic radiation using double-negative metamaterial (DNM), the so-called RCR [6], has been studied both theoretically and experimentally [7-20]. It has potential applications such as in the detection of charged particles and in the radiation sources as well as in the characterization of metamaterial macroscopic parameters [13]. Cherenkov radiation based on the photonic crystal has also been investigated [21]. The surface wave (SW) is greatly enhanced using the DNM due to the coupling from the RCR into the SW [19]. In addition, Smith Purcell effect using DNM has received attention in recent years [22, 23]. Hence, these novel electromagnetic radiations using metamaterial have been focused upon in the globe.

In this review paper, we first review the THz metamaterial, including the design, fabrication and testing. Then we move to our recent research progress in the novel electromagnetic radiation, including the RCR and SW. Finally, we discuss the further challenges in the metamaterial and associated novel electromagnetic radiation.

2. THz metamaterial

DNM with different structures instead of SRRs (split ring resonators) can be designed to support the novel phenomenon of RCR. For instance, in our previous research, a type of TM-DNM was experimentally fabricated for Cherenkov radiation detection at 9 *GHz* [12]. The configuration and dimensions of this DNM is given in Figure 1. Two orthogonal copper wires provide negative permittivity in the x-z plane and two L-shaped metallic strips on the top side couple with the other two on the bottom side to form a magnetic resonator, which provides a negative permeability for *y*–polarized magnetic fields. Actually, the negative permittivity is along metallic wires instead of x axis. Thus negative permittivity can be designed to match the direction of radiated electric field for detecting RCR. Besides unit elements mentioned above, S-shaped unit cell can also provide a double-negative index and zero-refractive-index profile in THz range [23-24].

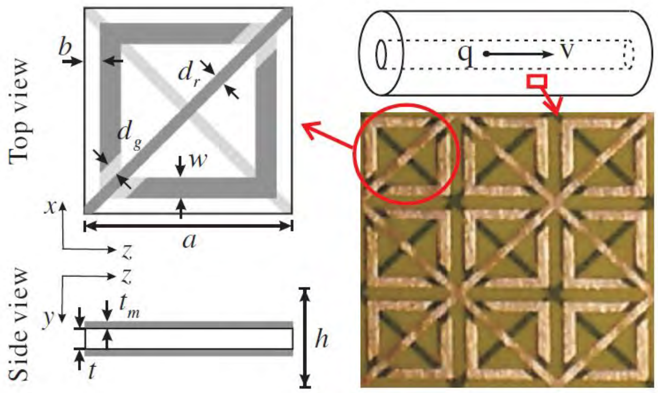

Fig. 1 Configuration of the metamaterial for reversed Cherenkov radiation. Reprinted figure with permission from Ref. [12] by the American Physical Society.

For microwave DNM, metallic patterns in periodic form are usually fabricated by shadow mask/etching techniques on printed circuit board (PCB) [26-29] and for THz DNM, they are fabricated by laser direct writing and lithographic techniques [30-35]. For the realization of THz DNM, dielectric substrates are usually adopted to support the metallic patterns. However recently, an all-metal self-supported DNM realization approach [24, 25] was achieved. This metamaterial is based on the S-shaped resonators with the interconnecting lines which are used to hold S-strings together to create the self-supported mesh, as shown in Figure 2. The interconnecting lines can change the effective capacitances of magnetic resonant loop without destroying the DNM behavior of the meta-foil.

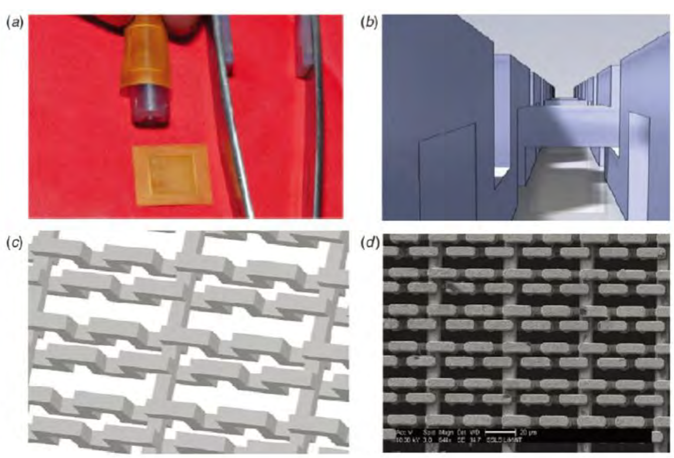

Fig. 2 (a) Photos of flat and bent meta-foils. (b) schematic view of inside of a 2SX meta-foil; (c) schematic view of outside of a 2SP meta-foil; (d) SEM image of the 2SP meta-foil. Scale bar 20 μm. Reprinted figure with permission from Ref. [24] by the Taylor & Francis Group.

To test fabricated THz DNM samples, several terahertz spectroscopic systems are adopted. The first one is the Fourier transform spectroscopy (FTS) [32, 36]. In FTS system, usually the sample is illuminated with a broadband thermal source and the detector is used to detect the interference signal directly. With the Fourier transformation method, the signal can be transformed to the spectral information. However, the spectral resolution from the FTS method is limited. The second one is the narrowband spectroscopy method [37], whose scanning range of source or detector can be tuned to a frequency band of interest. Therefore, it introduces a higher spectral resolution compared to the FTS, while its working bandwidth is much less than that of the FTS. The third one is THz time-domain spectroscopy (THz-TDS) [38-40], which is invented by AT&T Bell Labs and the IBM T. J. Watson Research Center [41, 42]. The transmitted THz electric field can be measured coherently using THz-TDS, which is the most advantageous among the above three methods. A common THz-TDS system can measure the transmitted electric field over a 3 *GHz* bandwidth from 2 to 5 *THz* with relative rapid acquisition time [43]. The fourth one is the optical pump-terahertz probe (OPTP) method [44]. Under various pump power with normal incident, the terahertz signals transmitted through the DNM and reference can be measured respectively in the time domain. Then with fast Fourier transformation method, the transmission amplitude and phase information in the frequency domain can be achieved.

3. THz radiation based on metamaterials

RCR is a novel electromagnetic radiation in the DNM, as stated before. Here, we explained it from the energy flow point of view [16]. Fig. 3(a) illustrates how a fast charged particle generates a forward Cherenkov radiation cone in a conventional material with a positive refractive index of n. We assume the particle travels along the z direction with a speed of $\overline{\upsilon}$. At $t = t_0$, t_1, t_2, and t_3, it moves to position 0, 1, 2, and 3, respectively. At $t = t_0 = 0$, the particle travels at position 0 and drive the medium to radiate a spherical wave spread from position 0. At $t = t_1$, the phase front of the radiated wave represented by the circle travels a distance of ct_1/n (c is the speed of light in vacuum) but the particle has already travels a distance of vt_1 reaching position 1 where another spherical wave start to be radiated. As time passes, the particle travels further, new spherical waves will be radiated out and the former radiated outgoing spherical waves also spread out further from their individual centers. The phase fronts of the spherical waves in phase with one another are marked in the same color as shown in Figure 3(a). It is obvious that the envelope of these spherical waves in the same color forms a conic wave front. If we define θ to be the angle between the direction of motion of the particle and the direction of the radiated shock wave, we find that $\theta = \cos^{-1}[c/(n\upsilon)]$. The direction of the shock wave therefore forms a forward Cherenkov radiation cone with an angle of 2θ.

In a left-handed medium, similar illustration is presented in Figure 3(b). As the particle travels along the z direction, the emitted wave has the energy flowing outward. However, since the refractive index is negative, the phase (represented by the circles) becomes more negative as the waves radiated out further from their individual centers. The phase fronts of the spherical waves therefore do not spread outward from their individual centers, but instead converge towards them as time passed. Different from that in right-handed medium, we see the in-phased circles increase from position 0 to position 3 as the particle travels from position 0 at $t = t_0$ to position 3 at $t = t_3$, yielding a set of planar wavefronts traveling toward the trajectory of the particle. The cone of the energy flow will be directed backward relative to the motion of the particle. The angle of the cone, $\theta = \cos^{-1}[c/(n\upsilon)]$, is hence obtuse for $n < -1$. We note the momentum flows are in the forward direction in both cases.

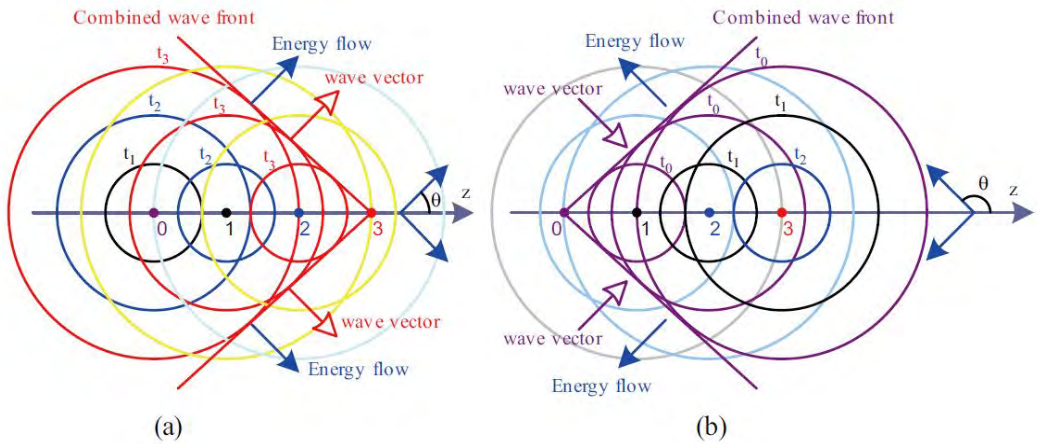

Fig. 3 The geometry of (a) Cherenkov radiation and (b) reversed Cherenkov radiation.

In the following section, we discuss THz radiation using the DNM. Here, we consider the general case of a charged particle traveling above the interface between vacuum and the DNM, as shown in Figure 4. The charge of the particle is denoted by q , the velocity by υ, and the distance from the particle to the boundary is denoted by d. The macroscopic effective material parameters of the DNM, its permittivity and permeability, are characterized by Drude and Lorentz models, respectively. In this case that the Cherenkov radiation condition is satisfied in the DNM, the surface wave (SW) is generated in vacuum and RCR is excited in the DNM. The detailed theoretical analysis is reported in [19]. Through the numerical computations, we find an interesting and important result that the SW is greatly enhanced relative to the normal media case, as shown in Figure [5].We note that the SW is characterized by the time-averaged Poynting vector, $\left|<\bar{S}_{vd}>\right|$ and $\left|<\bar{S}_{vn}>\right|$ denote the amplitudes of the time-averaged Poynting vector at $x = d/2$ in the vacuum half for the present and the normal dielectric material cases, respectively. The physical mechanism for the enhancement is that this DNM can support a double-negative quasi transverse magnetic electromagnetic mode, i.e. RCR, which can resonantly interact with a charged particle. The enhanced RCR interacts with charges at the interface such that the surface wave generated by the charges at the interface is enhanced due to the coupling from RCR into SW.

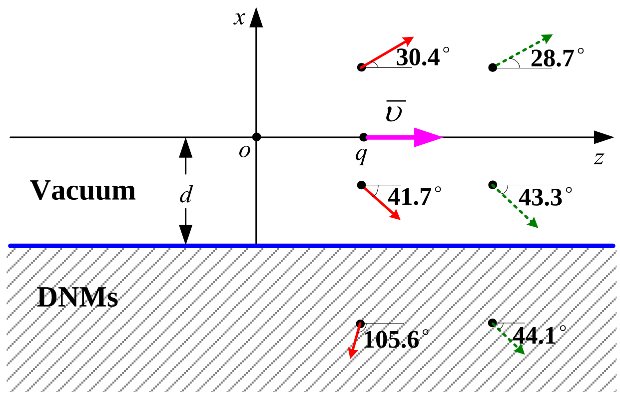

Fig. 4 The directions of the time-averaged Poynting vector in the DNM and vacuum. Reprinted figure with permission from Ref. [19] by the American Institute of Physics.

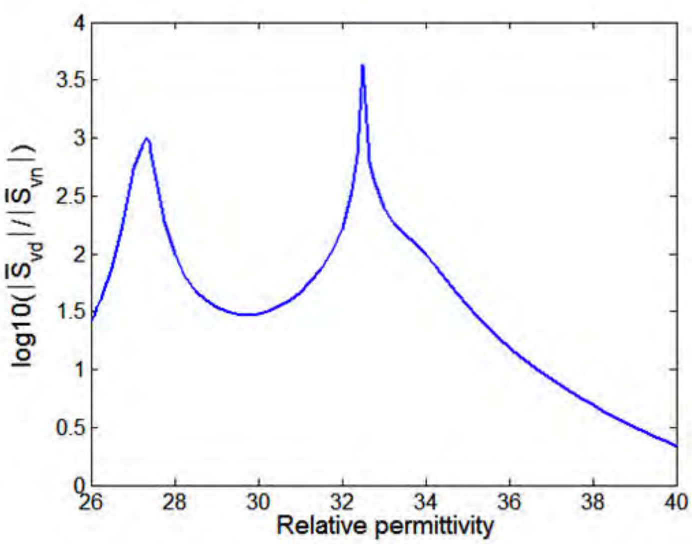

Fig. 5 Comparison of the amplitude of the surface wave between the present and the normal dielectric material cases. Reprinted figure with permission from Ref. [19] by the American Institute of Physics.

Based on the previous work [19], in order to enhance the THz radiation, we employed a sheet beam bunch which passes in close proximity to and over a DNM and can excite THz surface wave (SW) and RCR in the DNM, as shown in Figure 6. Such coherent field addition occurs if the charged particles are compressed into a sheet beam bunch. Its dimensions are characterized by $2x_0 \times 2y_0 \times 2z_0$, and each dimension is less than the wavelength of some desired THz wave. For simplicity, the charged particles are assumed to be uniformly distributed within the sheet beam bunch and move along the z direction with a velocity $\bar{\upsilon}$. When the electron number increases, the amplitude of the SW at $x=-d/2$ and the RCR *quadratically* increases. Due to the limit of the current density, one of the best ways to make the total current bigger is to increase the transverse dimension of a sheet beam, $2y_0$. A paper based on this work was submitted for publication.

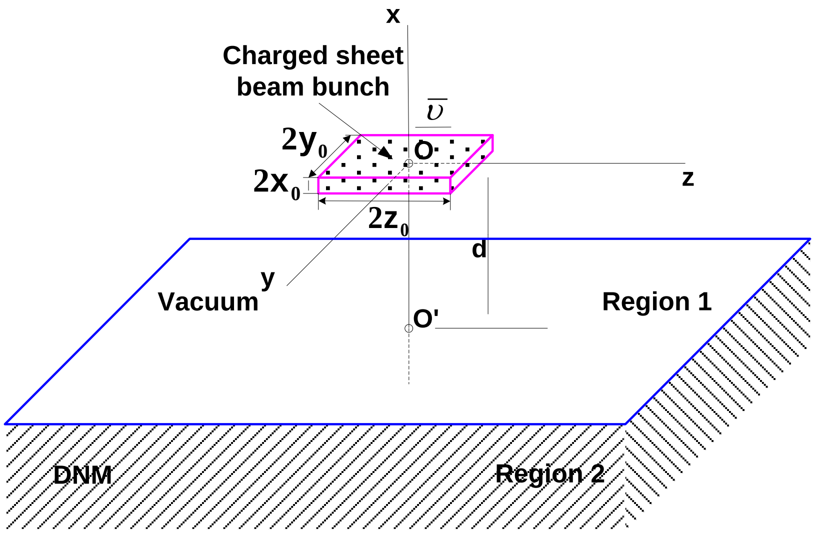

Fig. 6 The schematic of a sheet beam bunch moving with speed $\overline{\upsilon}$ in vacuum parallel to and over a half space filled with DNM.

4. Further challenges

There are several remaining technical problems in the design of practical THz DNM. The challenges in double-negative index bandwidth, periodicity of the unit cell, and material loss make THz DNM difficult to be applied in practice.

The double-negative index bandwidth is mainly restricted by the folded frequency band of negative permittivity and negative permeability. During DNM design procedures, negative permeability plays a more important role than negative permittivity to affect the negative refractive index bandwidth because magnetic response is much more difficult to achieve in THz or higher frequencies compared to electric response. From Pendry *et al.*'s work [45, 46], we have known that the effective permeability is negative within the frequency range $\omega_0^2<\omega^2<\omega_0^2/(1\text{-}F)$ when the loss of metallic wire of SRRs is not considered here. To extend the working bandwidth of a single-band THz DNM, increasing the filling factor F and minimizing the fringe effect [35] may be good choices. It's noticed that the negative refraction index will be shrunk or even disappear if the electric response is destroyed during optimizing the filling factor and fringe effect. Besides the approach above, designing dual-band [47, 48] or multi-band [49-51] THz DNM can also extend the negative refraction index bandwidth.

The periodicity of the unit cell has to be much smaller than the wavelength of interest if we want to describe metamaterials as homogeneous materials. For the THz wave, it's very difficult to design the metallic geometry in a deep subwavelength scale with economic and industrial fabrication method, such as shadow mask/etching techniques method. Increasing the effective capacitance, the effective inductance, and the permittivity in dielectric metamaterials are adopted to overcome the difficulty in the periodicity of the unit cells [52, 53].

Among these aspects, material loss is the most important one. For the dielectric loss caused by substrate, we can choose a kind of low-loss substrate to reduce metamaterial loss. However, in high frequency band, i.e. THz or infrared range, ohmic loss, or metallic dispersion becomes dominant. The natural metallic materials follow the Drude model and are dispersive via frequency. At low frequency or microwave range, metallic material can be considered as a Perfect Electric Conductor (PEC). Therefore the ohmic loss introduced by metal is neglected. However when the frequency is up to Terahertz or infrared range, metals can only be treated as a lossy dielectric media, which will introduce lots of loss in the resonant loops. This will bring the possibility of destroying the double negative band. Figure 7 is an example to show this possibility. A metallic SRR-wire structure is simulated. The material of substrate is Polyimide with refractive index of 1.8. The loss of substrate is not considered here. Gold with the Drude model (the plasma frequency f_p = 2.175e+15 *Hz* and the collision frequency v_c = 6.5e+12 *Hz* [54]) was adopted in the simulation. Three cases of unit cell are designed, whose simulation results are given in Figure 7 for a unit-cell dimension a = 100 μm, 5 μm and 1 μm. Thus each of the dimensions (Table. 1) defining the structure decreases as the unit cell becomes smaller. With frequency increasing, the increasing loss finally destroys the negative refractive index at 40 *THz* even though this DNM shows perfect negative index property at 0.4 *THz*. To overcome this problem, on one hand, materials with larger conductivity can be used. On the other hand, when the frequency increases further (100 *THz* or higher), the skin depth of the metal cannot be neglected. We therefore need to carefully consider the thickness of metallic wires in the metamaterial design and make sure it is larger than the skin depth of the metal.

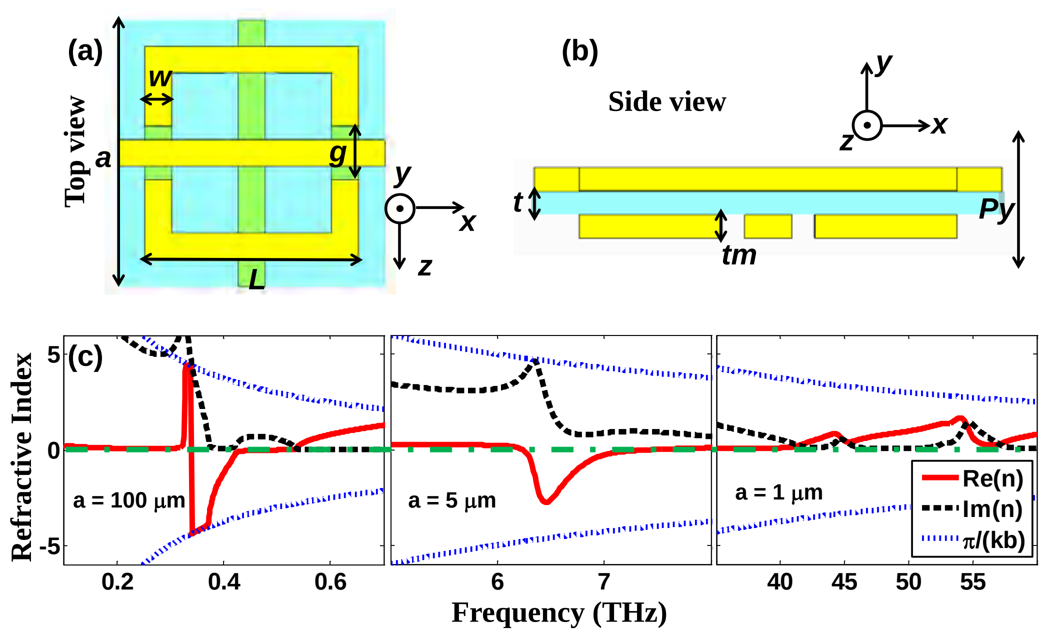

Fig. 7 Top view (a) and side view (b) of the THz DNM unit cell. Dimensional information is enclosed in Table 1. (c) The refractive index for a = 100 μm, 5 μm, and 1 μm.

Tab. 1 Dimensional information of THz DNM unit cell in Fig. 7 (unit: μm).

a	***L***	***w***	***g***	***t***	t_m	P_y
100	80	1	20	5	0.5	26
5	4	0.05	1	0.25	0.025	1.3
1	0.8	0.01	0.2	0.05	0.005	0.26

5. Conclusions

In conclusion, we have summarized the current research status on the metamaterial, including its design, fabrication, and testing. Based on the DNM designed for TM waves, we reported an active DNM driven by charged particles. This DNM can support the enhanced THz radiation. This radiation has a remarkable advantage relative to that using ordinary media: the absolute values of the real part of the effective permittivity and permeability for the DNM can be freely manipulated to be significantly greater than one, resulting in the threshold particle velocity for the RCR generation being much smaller than the light speed in vacuum, thus a lower accelerating voltage can be used to produce intense THz radiation.

Acknowledgements

This work was sponsored by the National Natural Science Foundation of China under Grants No. 61275183, No. 60990320, No. 60990322, No. 60971031, No. 61125103, the Foundation for the Author of National Excellent Doctoral Dissertation of PR China under Grant No. 200950, the Fundamental Research Funds for the Central Universities under Grant No. 2011QNA5020, No. ZYGX2010X010, the Program for New Century Excellent Talents in University under Grant No. NCET-12-0489, and Sichuan Youth Foundation under Grant No. 2010JQ0005. The authors are deeply grateful to PhD student Xianfeng Tang, who helped to collect the related materials and to clear up the references.

References

[1] R. Kleiner. “Filling the Terahertz gap”. *Science*, 318, 1254-1255 (2007).

[2] S. G. Biedron, J. W. Lewellen, S. V. Milton, et. al. “Compact, high-power electron beam based Terahertz sources”. *Proc. of the IEEE*, 95(8), 1666-1678 (2007).

[3] I. Hosako, N. Sekine, M. Patrashin, et. al. “At the dawn of a new era in terahertz technology”. *Proc. of the IEEE*, 95(8), 1611-1623 (2007).

[4] R. A. Shelby, D. R. Smith, and S. Schultz. “Experimental verification of a negative index of refraction”. *Science*, 292, 77-79 (2001).

[5] N. Engheta and R. W. Ziolkowski. “A positive future for double-negative metamaterials”. *IEEE Trans. Microwave Theory Tech.*, 53(4), 1535-1556 (2005).

[6] V. G. Veselago. “The electrodynamics of substances with simultaneously negative values of ε and μ”. *Sov. Phys. Usp.*, 10, 509-514 (1968).

[7] J. Lu, T. Grzegorczyk, Y. Zhang, et. al. “Čerenkov radiation in materials with negative permittivity and permeability”. *Opt. Express*, 11, 723-734 (2003).

[8] Y. P. Bliokh, S. Savel’ev, and F. Nori. “Electron-beam instability in left-handed media”. *Phys. Rev. Lett.*, 100, 244803 (2008).

[9] Z. Y. Duan, B.-I. Wu, J. Lu, et. al. “Reversed Cherenkov radiation in a waveguide filled with anisotropic double-negative metamaterials”. *J. Appl. Phys.*, 104, 063303 (2008).

[10] Z. Y. Duan, B.-I. Wu, J. Lu, et. al. “Cherenkov radiation in anisotropic double-negative metamaterials”. *Opt. Express*, 16, 18479 (2008).

[11] S. Antipov, L. Spentzours, W. Gai, et. al. “Observation of wakefield generation in left-handed band of metamaterial-loaded waveguide”. *J. Appl. Phys.*, 104, 014901(2008).

[12] S. Xi, H. S. Chen, T. Jiang, et. al. “Experimental verification of reversed Cherenkov radiation in left-handed metamaterial”. *Phys. Rev. Lett.*, 103, 194801 (2009).

[13] Z. Y. Duan, B.-I. Wu, S. Xi, et. al. “Research progress in reversed Cherenkov radiation in double-negative metamaterials”. *Prog. Electromagn. Res.*, PIER-90, 75 (2009).

[14] S. N. Galyamin, A. V. Tyukhtin, A. Kanareykin, et. al. “Reversed Cherenkov-transition radiation by a charge crossing a left-handed medium boundary”. *Phys. Rev. Lett.*, 103, 194802 (2009).

[15] Z. Y. Duan, B.-I. Wu, J. Lu, et. al. “Reversed Cherenkov radiation in unbounded anisotropic double-negative metamaterials”. *J. Phys. D: Appl. Phys.*, 42 185102 (2009).

[16] H. S. Chen, and M. Chen. “Flipping photons backward: reversed Cherenkov radiation”. *Mater. Today*, 14(1-2), 34-41 (2011).

[17] Z. Y. Duan, C. Guo, and M. Chen. “Enhanced reversed Cherenkov radiation in a waveguide with double-negative metamaterials”. *Opt. Express*, 19(15), 13825-13830 (2011).

[18] Z. Y. Duan, Y. S. Wang, X. T. Mao, et. al. “Experimental demonstration of double-negative metamaterials partially filled in a circular waveguide”. *Prog. Electromagn. Res.*, 121, 215-224 (2011).

[19] Z. Y. Duan, C. Guo, J. Zhou, et. al. “Novel electromagnetic radiation in a semi-infinite space filled with a double-negative metamaterial”. *Phys. Plasmas*, 19, 013112 (2012).

[20] J. Zhou, Z. Y. Duan, Y. X. Zhang, et. al. “Numerical investigation of Cherenkov radiations emitted by an electron beam bunch in isotropic double-negative metamaterials”. *Nucl. Instrum. Methods Phys. Res. A*, 654, 475-480 (2011).

[21] C. Y. Luo, M. Ibanescu, S. G. Johnson, et. al. “Cerenkov Radiation in Photonic Crystals”. *Science*, 299(5605), 368-371 (2003).

[22] D. Li, M. Hangyo, Z. Yang, et. al. “Smith-Purcell radiation from a grating of negative-index material”. *Nucl.*

Instrum. Methods Phys. Res. A, 637, 135-137 (2011).

[23] A. N. Poddubny, P. A. Belov, and Y. S. Kivshar. “Purcell effect in wire metamaterials”. *Phys. Rev. B*, 87, 035136 (2013).

[24] H. O. Moser, L. K. Jian, H. S. Chen, et. al. “THz meta-foil – a platform for practical applications of metamaterials”. *J. Mod. Opt.*, 57(19), 1936-1943 (2010).

[25] R. Alaee, C. Menzel, A. Banas, et. al. “Propagation of electromagnetic fields in bulk terahertz metamaterials: A combined experimental and theoretical study”. *Phys. Rev. B*, 87(7), 075110 (2013).

[26] L. Ran, J. Huangfu, H. Chen, et. al. “Microwave solid-state left-handed material with a broad bandwidth and an ultralow loss”. *Phys. Rev. B*, 70(7), 073102 (2004).

[27] H. S. Chen, L. X. Ran, J. T. Huangfu, et. al. “Left-handed materials composed of only S-shaped resonators”. *Phys. Rev. E*, 70(5), 057605 (2004).

[28] R. A. Shelby, D. R. Smith, and S. Schultz. “Experimental verification of a negative index of refraction”. *Science*, 292(5514), 77-79 (2001).

[29] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, et. al. “Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial”. *Appl. Phys. Lett.*, 78(4), 489-491 (2001).

[30] S. Zhang, W. Fan, N. C. Panoiu, et. al. “Experimental demonstration of near-infrared negative-index metamaterials”. *Phys. Rev. Lett.*, 95(13), 137404 (2005).

[31] H. O. Moser, B. D. F. Casse, O. Wilhelmi, et. al. “Terahertz response of a microfabricated rod–split-ring-resonator electromagnetic metamaterial”. *Phys. Rev. Lett.*, 94(6), 063901 (2005).

[32] T. J. Yen, W. J. Padilla, N. Fang, et. al. “Terahertz magnetic response from artificial materials”. *Science*, 303(5663), 1494-1496 (2004).

[33] S. Linden, C. Enkrich, M. Wegener, et. al. “Magnetic response of metamaterials at 100 terahertz”. *Science*, 306(5700), 1351-1353 (2004).

[34] D. Lippens. “Metamaterials and infra-red applications”. *C. R. Phys.*, 9(2), 184-196 (2008).

[35] M. Gwinner, E. Koroknay, L. Fu, et. al. “Periodic large-area metallic split-ring resonator metamaterial fabrication based on shadow nanosphere lithography”. *Small*, 5(3), 400-405 (2009).

[36] N. Liu, H. C. Guo, L. W. Fu, et. al. “Three-dimensional photonic metamaterials at optical frequencies”. *Nat. Mater.*, 7(1), 31-37 (2008).

[37] B. Ferguson and X.-C. Zhang. “Materials for terahertz science and technology”. *Nat. Mater.*, 1(1), 26-33 (2002).

[38] H.-T. Chen, W. J. Padilla, J. M. O. Zide, et. al. “Active terahertz metamaterial devices”. *Nature*, 444(7119), 597-600 (2006).

[39] H.-T. Chen, J. F. O'Hara, A. K. Azad, et. al. “Experimental demonstration of frequency-agile terahertz metamaterials”. *Nat. Photonics*, 2(5), 295-298 (2008).

[40] M. Choi, S. H. Lee, Y. Kim, et. al. “A terahertz metamaterial with unnaturally high refractive index”. *Nature*, 470(7334), 369-373 (2011).

[41] D. H. Auston, K. P. Cheung, J. A. Valdmanis, et. al. "Cherenkov radiation from femtosecond optical pulses in electro-optic media". *Phys. Rev. Lett.*, 53(16), 1555-1558 (1984).

[42] C. Fattinger and D. Grischkowsky. "Point source terahertz optics". *Appl. Phys. Lett.*, 53(16), 1480-1482 (1988).

[43] B.Ferguson, and D.Abbott. "De-noising techniques for terahertz responses of biological sample". *Microelectron. J.*, 32, 943-953, 2001.

[44] J. Q. Gu, R. J. Singh, X. J. Liu, et. al. "Active control of electromagnetically induced transparency analogue in terahertz metamaterials". *Nat. Commun.*, 3, 1151 (2012).

[45] J. B. Pendry, A. J. Holden, D. J. Robins, et. al. "Magnetism from conductors and enhanced nonlinear phenomena". *IEEE Trans. Microw. Theory Tech.*, 47(11), 2075-2084, 1999.

[46] S. O'Brien and J. B. Pendry. "Magnetic activity at infrared frequencies in structured metallic photonic crystals". *J. Phys.: Condens. Matter*, 14, 6383-6394 (2002).

[47] S. Hussain, J. M. Woo, and J.-H. Jang. "Dual-band terahertz metamaterials based on nested split ring resonators". *Appl. Phys. Lett.*, 101(9), 091103 (2012).

[48] Y. Yuan, C. Bingham, T. Tyler, et. al. "Dual-band planar electric metamaterial in the terahertz regime". *Opt. Express*, 16(13), 9746-9752 (2008).

[49] E. Ekmekci, K. Topalli, T. Akin, et. al. "A tunable multi-band metamaterial design using micro-split SRR structures". *Opt. Express*, 17(18), 16046-16058 (2009).

[50] B. Q. Liu, X. P. Zhao, W. R. Zhu, et. al. "Multiple pass-band optical left-handed metamaterials based on random dendritic cells". *Adv. Funct. Mater.*, 18(21), 3523-3528 (2008).

[51] K. Song, Q. Fu, and X. Zhao. "U-shaped multi-band negative-index bulk metamaterials with low loss at visible frequencies". *Phys. Scr.*, 84(3), 035402 (2011).

[52] H. S. Chen. "Metamaterials: constitutive parameters, performance, and chemical methods for realization". *J. Mater. Chem.*, 21, 6452- 6463 (2011).

[53] H. S. Chen, L. Ran, B.-I. Wu, et. al. "Crankled S-ring resonator with small electrical size". *Prog. Electromagn. Res.*, 66, 179-190 (2006).

[54] D. Ö. Güney, T. Koschny, M. Kafesaki, et. al. "Connected bulk negative index photonic metamaterials". *Opt. Lett.*, 34(4), 506-508 (2009).