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Coupling Enhancement of THz Metamaterials Source with Parallel Multiple Beams

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Abstract — In this paper, we propose a terahertz radiation source over the R-band (220–325 GHz) based on metamaterials (MTMs) structure and parallel multiple beams. The effective permittivity and permeability of the slow-wave structure can be obtained through the *S*-parameter retrieval approach, using numerical simulation. Additionally, the electromagnetic properties of the MTMs structure are analyzed, including the dispersion and the coupling impedance. Furthermore, we simulate the beam-wave interaction of the backward oscillator (BWO) with MTMs structure and parallel multiple beams by 3-D particle-in-cell code. It is observed that parallel multiple beams can highly enhance the beam-wave interaction and greatly enlarge the output power. These results indicate that the saturated (peak) output power is approximately 63W with the efficiency of roughly 6% at the operating frequency of 231 GHz, under the beam voltage of 35 kV and total current of 30 mA (6-beam) respectively. Meanwhile, the BWO can generate power of 10–80 W in the tunable frequency of 220–240 GHz.

Key words — Terahertz source, Parallel multiple beams, Beam-wave interaction, Metamaterials.

I. Introduction

Terahertz band commonly refers to the frequency range that lies within 0.1–10 THz. Unlike the neighbouring microwaves and infrared waves, the application of terahertz waves has been insufficient as it is difficult to generate terahertz radiation. Additionally, most natural materials can not exhibit dielectric properties when exposed to incident terahertz radiation [1]. This calls for the demand for metamaterials [2], a kind of novel, artificially designed sub-wavelength structures with unique dielectric properties, such as negative refractive index, reverse Doppler effect and reverse Cerenkov radiation [3]–[8]. The electromagnetic response can be obtained through metamaterials, and a new development direction for terahertz radiation sources besides microwave sources can be expected. In this paper, we propose an efficient THz metamaterials source with parallel multiple beams over R-band, which can be used in various applications [9]–[11], including biomedical imaging, security, wireless communication, and spectrum detection.

II. Electromagnetic Characteristics of Metamaterials

Metamaterials, also known as the left-handed material (LHM), have the properties of negative permeability and permittivity simultaneously. The most popular extraction technique of the doubly negative property is the *S*-parameter retrieval method [12]. We propose a planar geometry metamaterials of the electric-ring resonator (ELC) as the high frequency (HF) circuit of a terahertz source as this structure can be easily fabricated by LIGA technique or other MEMS techniques. The geometry of the resonator unit cell is shown in Fig.1(a) [13]. Let w_1 and c_1 denote the length and width of the copper plate, respectively, t is the thickness of copper. Other parameters are marked in Fig.1(a).

By simulating the *S*-parameter and retrieving the effective permittivity and permeability to optimize metamaterials' structure inserted in a square waveguide with the cross-section dimension of $w_1 \times w_1$, the geometry of square waveguide is shown in Fig.1(b) and the final dimensions of the slow-wave structure (SWS)

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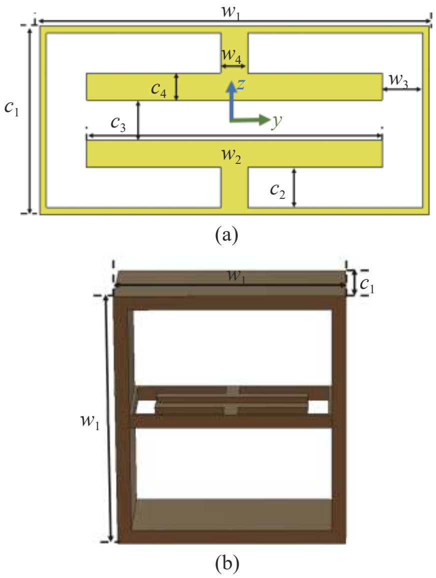

Fig. 1. Schematic diagram of metamaterials and waveguide. (a) Geometry of the metal plate of the metamaterials unit cell; (b) Metamaterials in a square waveguide.

are presented in Table 1. The relative permittivity and permeability versus frequency in the range of 210–320 GHz obey the Drude-Lorentz relationship as shown in Fig.2.

Table 1. Dimensions of the SWS (μm)

c_1	c_2	c_3	w_1	w_2	w_3	w_4	t
140	30	20	290	100	30	20	20

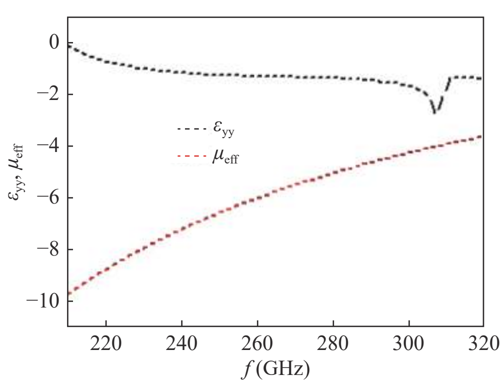

Fig. 2. Relative permittivity (ε_{yy}) and permeability ($\mu_{\rm eff}$) versus frequency.

The dispersion characteristic serves as an essential parameter of the SWS and can describe the relationship between the phase velocity and the frequency. By simulating the unit cell of metamaterials with dimensions in Table 1, we can obtain the dispersion curves of mode1 and mode2 of this structure as shown in Fig.3. We choose the point near the frequency range of 230 GHz as the operating point of the backward oscillator (BWO), whose corresponding voltage is about 35 kV. In the square waveguide with the cross-section dimension of $w_1 \times w_1$, the cut-off frequency of TE_{10} mode is 517 GHz, much higher than that of the fundamental mode in metamaterials in Fig.3.

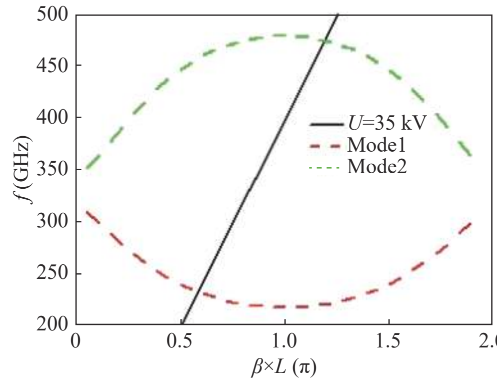

Fig. 3. Dispersion curves of the metamaterials with dimensions in Table 1.

By simulation, the E-field distribution of metamaterials' unit cell is obtained as shown in Fig.4(a), where the E_z-field has symmetry with respect to the metal plate and the beam-wave interaction could therefore be highly enhanced. Based on that, we propose two groups of parallel multi-beams illustrated in Fig.4(b) as the driving source of terahertz to explore and validate the beam-wave interaction. Meanwhile, the height of each beam is kept the same.

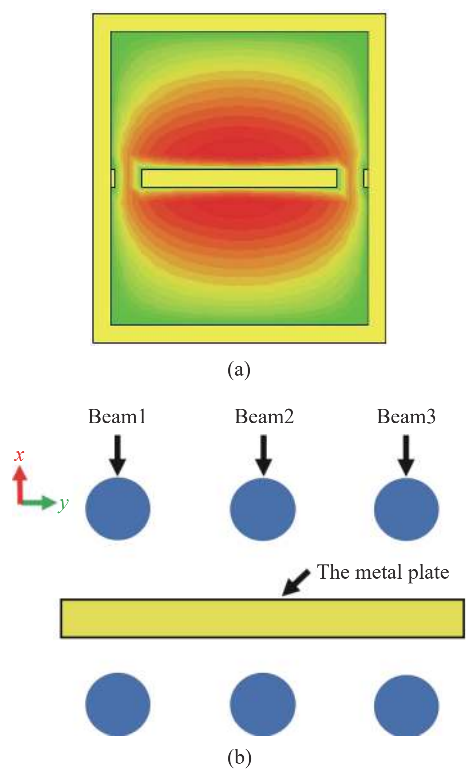

Fig. 4. E_z-field distribution of metamaterial's unit cell and schematic of parallel multi-beams. (a) E_z-field contour in a unit cell; (b) Schematic of multi-beams.

Additionally, the interaction impedance significantly influences the interaction between the electron beam and the high-frequency EM field in the SWS. Notably, Fig.4(b) indicates the impedance of each beam at the center point. When the height h between beam2 and the metal plate surface increases from 0.01 mm to 0.08 mm and the frequency is at 230 GHz, the impedance sharply decreases from 1800 Ω to 80 Ω as shown in Fig.5(a).

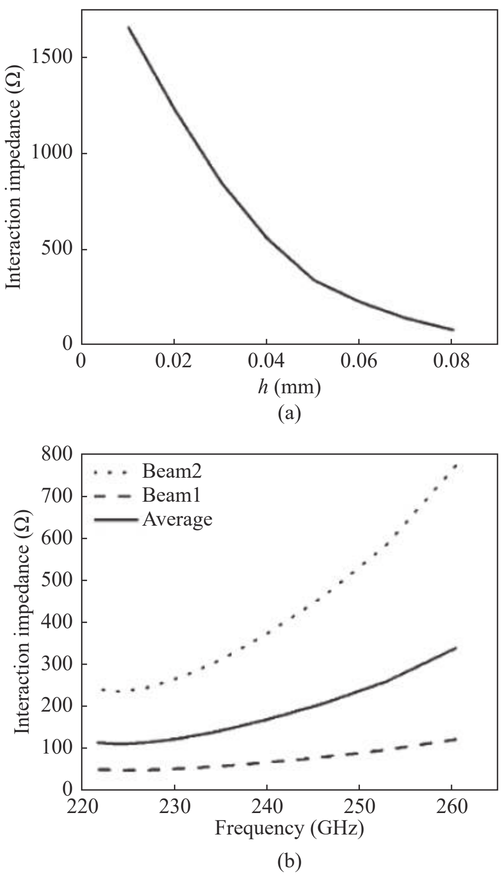

Fig. 5. Impedance with (a) Height and (b) Position and frequency.

The impedance at the center of beam1, beam2 and beam3 remarkably increases within the frequency range of 220–260 GHz in the backward zone when the height h is 0.06 mm, as shown in Fig.5(b). Due to the symmetry of E_z-field, the impedance at the center of beam1 is equal to that of beam3 and this is why we merely take beam1 and beam2 for further comparison. The impedance at the center of beam2 is over 5 times larger than that of beam1. This result implies a stronger beam-wave interaction of the mid-positioned beam than the side one.

III. Beam-Wave Interaction Simulation

According to the dispersion in Fig.3, the electron energy of 35 keV in the metamaterials structure can excite the signal at the frequency of 230 GHz in the backward zone of mode1.

Therefore, a BWO using the metamaterials structure is designed and the beam-wave interaction of the BWO is simulated in CST, including two groups of parallel multi-beam, 45 periodic metamaterials structure, the output structure with a standard WR03 rectangular waveguide, and the matching load to avoid and reduce the reflection. The structure of beam-wave interaction is shown in Fig.6. The height h between the beam center and the metal plate surface is set as 0.06 mm and the beam radius is equal to 0.04 mm.

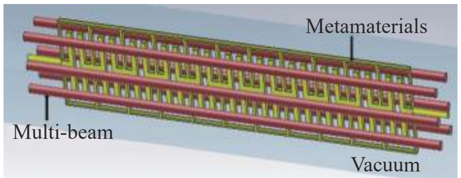

Fig. 6. Schematic diagram of beam-wave interaction.

Firstly, we analyze only one beam involved in the beam-wave interaction, and we explore how the interaction characteristic changes with beam position. If beam2 in Fig.4(b) illustrates the interaction with the wave at the voltage of 35 kV, the beam current of 5 mA and the constant B_z of 0.3 T, the PIC simulation results are shown in Fig.7(a) and (b), corresponding to the E_z-field of mode1. The power is approximately 4.06 W, and the central frequency is about 230 GHz.

If beam1 or beam3 is utilized for the beam-wave interaction with the same above parameters, the simulation results are displayed in Fig.7(c) and (d). The starting time can be extremely long and the main operation frequency is at 450 GHz rather than 230 GHz corresponding to the operation point in the dispersion of mode2 shown in Fig.3, whose E_z-field is shown as the inserted figure in Fig.7(d). By comparison, the beam-wave interaction of a single beam in the middle is much stronger than the side one. Moreover, we can tell from the E_z-field distribution of mode1, mode2 and the PIC simulation results, that one beam in the middle is suitable for interacting with mode1 while the side one applies to mode2.

Then, we analyze the beam-wave interaction with parallel multiple beams. The simulation results are listed in Table 2. For one group of multi-beams composed of 3 beams, with the current 5 mA per beam, the beam-wave interaction performs actively with the output power of 29.65 W, along with the oscillating frequency of 230 GHz. The power is more than 7 times stronger than that of a single beam with 5 mA in the middle, and over 2 times than that with 15 mA in the middle. Meanwhile, when two groups of three beams are symmetrical with the metal plate and a total current of 30 mA is presented, namely 5 mA per beam, the output power of 63.11 W is more than 2 times than that of

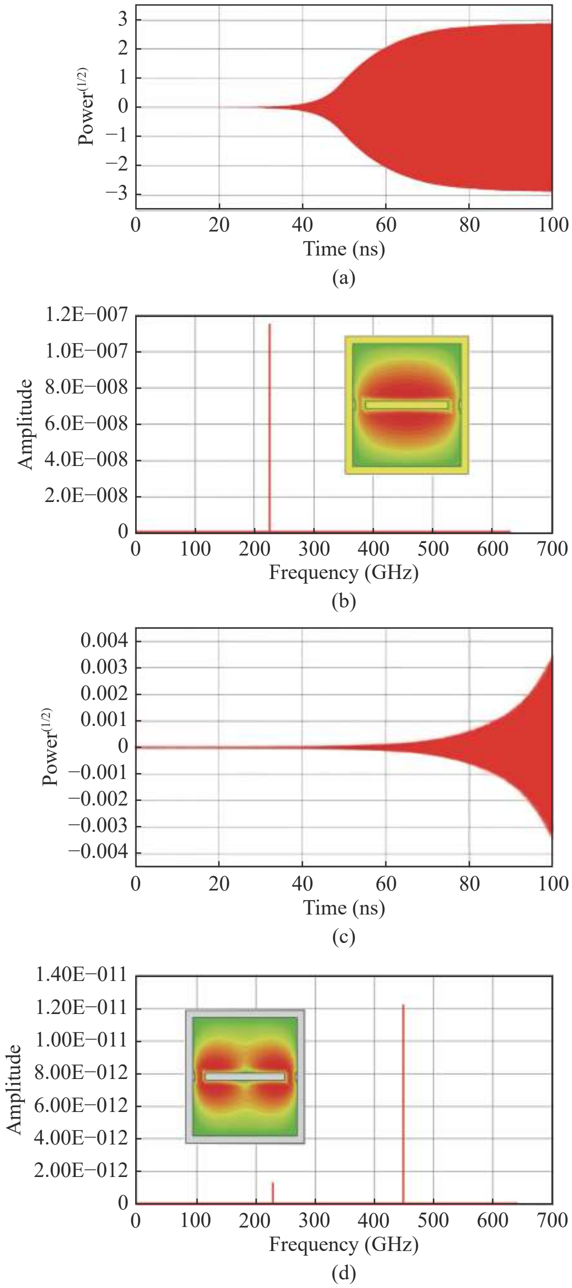

Fig. 7. PIC simulation results by a single beam. (a) Voltage signal by beam2; (b) Spectrum and exciting E-field by beam2 (corresponding to mode1); (c) Voltage signal by beam1; (d) Spectrum and exciting E-field by beam1 (corresponding to mode2).

Table 2. Output power vs. beams

Beam distribution	Current (mA)	Power (W)
Beam2	5	4.06
Beam1	5	–
Beam2	15	12.71
3 beams	15	29.65
6 beams	15	30.89
6 beams	30	63.11

a single group of three beams with 29.65 W. Additionally, given the same total current, the output power of 3 beams is more than that of a single beam and the output power of 6 beams (two groups) is more than that of 3 beams (one group).

Why the multi-beam can greatly enhance the beam-wave interaction? When the electron velocity of the middle beam approximately equals the phase velocity of mode1, the longitudinal electric field component of mode1 bunches the electrons. Simultaneously, the electric field of is gradually excited. Then, the excited electric field can bunch the side beam even if the coupling impedance between the side beam and mode1 is not enough high. Thus, each beam of the multi-beam can highly interact with the electric field of mode1. In this way, the electron beams communicate with each other through a common electromagnetic field, thus providing coupling enhancement between neighboring beams. It is the specific mechanics of coupling enhancement in the parallel multi-beam that multiple beams can greatly improve the beam-wave interaction to increase the output power due to the strong coupling effect among parallel multiple beams.

Furthermore, the beam-wave interaction with 6-beam is discussed in detail as shown in Fig.8. When the total current is in the range of 15–40 mA and other parameters remain the same, the output power approximately linearly increases from 29 W to 78 W in Fig.8(a). When the voltage of beams varies from 15 kV to 80 kV with the total current 15 mA, the output power monotonously increases from 14 W to 78 W, and the frequency increases from 220 GHz to 240 GHz in Fig.8(b). This BWO has a substantially higher output power over the R-band than previous BWOs [14]. The periodic number is 45 in Fig.8(a) and (b). At the same time, the excited power increases in the periodic number range of 36-50 in Fig.8(c) under the condition of 35 kV voltage and 15 mA current. Several merits of BWO with this structure can be expected, such as high power, miniature size and broad tunable wideband, etc.

IV. Conclusions

In this paper, we propose a planar geometry metamaterials of an electric-ring resonator as the HF circuit of a terahertz BWO. The electromagnetic properties of the metamaterial's structure are analyzed in detail, including the dispersion relationship, the E_z-field and the impedance. Meanwhile, we present a schematic with parallel multiple beams to excite backward waves in the structure of the metamaterials to generate terahertz waves based on the E_z-field characteristic. By PIC simulation, the BWO with the electron voltage of 35 kV, the total current of 30 mA of 6-beam and the magnet B_z of 0.3 T can generate terahertz waves with the frequency of 230 GHz and the output power of 63.11 W. We further observe that the BWO with parallel

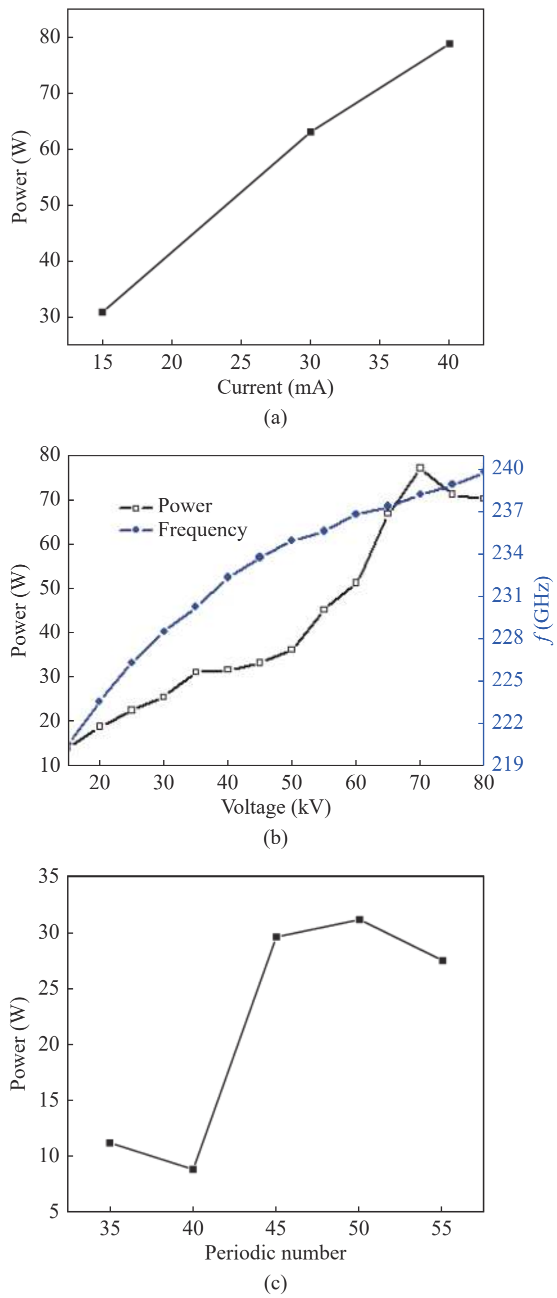

Fig. 8. PIC simulation results for 6 beams with (a) Current; (b) Voltage; and (c) Periodic number.

multiple beams can significantly improve the output power compared with one single beam due to the coupling effect high power terahertz waves for potential THz application in various areas can be expected shortly.

References

[1] B. Ferguson and X. C. Zhang, "Materials for terahertz science and technology," *Physics*, vol.32, no.5, pp.286–293, 2003. (in Chinese)

[2] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and negative refractive index," *Science*, vol.305, no.5685, pp.788–792, 2004.

[3] N. Seddon and T. Bearpark, "Observation of the inverse Doppler effect," *Science*, vol.302, no.5660, pp.1537–1540, 2003.

[4] G. Shvets, "Photonic approach to making a material with a negative index of refraction," *Physical Review B*, vol.67, no.3, article no.035109, 2003.

[5] Z. Y. Duan, B. I. Wu, J. Lu, *et al.*, "Reversed Cherenkov radiation in a waveguide filled with anisotropic double-negative metamaterials," *Journal of Applied Physics*, vol.104, no.6, article no.063303, 2008.

[6] D. Shiffler, J. Luginsland, D. M. French, *et al.*, "A Cerenkov-like maser based on a metamaterial structure," *IEEE Transactions on Plasma Science*, vol.38, no.6, pp.1462–1465, 2010.

[7] Y. S. Tan and R. Seviour, "Wave energy amplification in a metamaterial-based traveling-wave structure," *Europhysics Letters*, vol.87, no.3, article no.34005, 2009.

[8] S. Xi, H. S. Chen, T. Jiang, *et al.*, "Experimental verification of reversed Cherenkov radiation in left-handed metamaterial," *Physical Review Letters*, vol.103, no.19, article no.194801, 2009.

[9] A. J. Fitzgerald, V. P. Wallace, M. Jimenez-Linan, *et al.*, "Terahertz pulsed imaging of human breast tumors," *Radiology*, vol.239, no.2, pp.533–540, 2006.

[10] Y. L. Lim, T. Taimre, K. Bertling, *et al.*, "High-contrast coherent terahertz imaging of porcine tissue via swept-frequency feedback interferometry," *Biomedical Optics Express*, vol.5, no.11, pp.3981–3989, 2014.

[11] G. J. Wilmink, B. D. Rivest, C. C. Roth, *et al.*, "In vitro investigation of the biological effects associated with human dermal fibroblasts exposed to 2.52 THz radiation," *Lasers in Surgery and Medicine*, vol.43, no.2, pp.152–163, 2011.

[12] D. R. Smith, D. C. Vier, T. Koschny, *et al.*, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical Review E*, vol.71, no.3, article no.036617, 2005.

[13] J. Yang, M. J. Yin, H. Y. Gao, *et al.*, "Design and fabrication of reflective phase shifter for two-dimensional terahertz beam-scanning reflectarray," *Chinese Journal of Electronics*, vol.31, no.3, pp.581–588, 2022.

[14] J. C. Cai, L. L. Hu, H. B. Chen, *et al.*, "Study on the increased threshold current in the development of 220-GHz folded waveguide backward-wave oscillator," *IEEE Transactions on Microwave Theory and Techniques*, vol.64, no.11, pp.3678–3685, 2016.

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