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Tunable circularly-polarized turnstile-junction mode converter for high-power microwave applications*

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Frequency tunability has become a subject of concern in the field of high-power microwave (HPM) source research. However, little information about the corresponding mode converter is available. A tunable circularly-polarized turnstile-junction mode converter (TCTMC) for high-power microwave applications is presented in this paper. The input coaxial TEM mode is transformed into TE_{10} mode with different phase delays in four rectangular waveguides and then converted into a circularly-polarized TE_{11} circular waveguide mode. Besides, the rods are added to reduce or even eliminate the reflection. The innovations in this study are as follows. The tunning mechanism is added to the mode converter, which can change the effective length of rectangular waveguide and the distance between the rods installed upstream and the closest edge of the rectangular waveguide, thus improving the conversion efficiency and bandwidth. The conversion efficiency of TCTMC can reach above 98% over the frequency range of 1.42 GHz–2.29 GHz, and the frequency tunning bandwidth is about 47%. Significantly, TCTMC can obtain continuous high conversion efficiency of different frequency points with the change of tuning mechanism.

Keywords: mode converter, high conversion efficiency, frequency tuning performance

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1. Introduction

Many vacuum electronic devices, such as the high-power microwave, millimeter wave, and terahertz wave devices,[1–3] can generate the electromagnetic waves with azimuthally symmetric output modes including circular waveguide mode TM_{01} and coaxial transverse electromagnetic (TEM) mode. These modes will be transformed into a TE_{11} mode in a circular waveguide in order to obtain directed radiation. Coaxial plate-inserted mode converters (CPIMC) and turnstile-junction mode converters (TJMC) have received a great deal of attention because of their particular advantages of high conversion efficiency and easy-to-fabricate. However, these mode converters are only designed for a given frequency,[4,5] whose bandwidth is very narrow. In order to satisfy the need of tunable HPMs, a tunable mode converter should be investigated. In addition, the electromagnetic wave with circular polarization may have a high probability to couple into unknown targets.[6–8] Therefore, a tunable circular-polarized turnstile-junction mode converter (TCTMC) is proposed and investigated in this paper. Compared with TJMC, the TCTMC is designed to realize high conversion efficiency in a broad frequency range.

The rest of this paper is organized as follows. In Section 2, the structure and design approach of TCTMC are described in detail. In Section 3, the analyses and simulations are performed to verify the proposed method. Finally, a brief conclusion is drawn in Section 4.

2. Structure and design

The whole structure of the tunable high-power microwave system is illustrated in Fig. 1. It consists of tunable MILO, TCTMC, and horn antenna. The tunable MILO has been investigated in our previous work.[4,5] Actually, the investigation of TCTMC is to meet the requirements for tunable MILO. TCTMC is also applicable to conventional HPM and other tunable HPM devices.

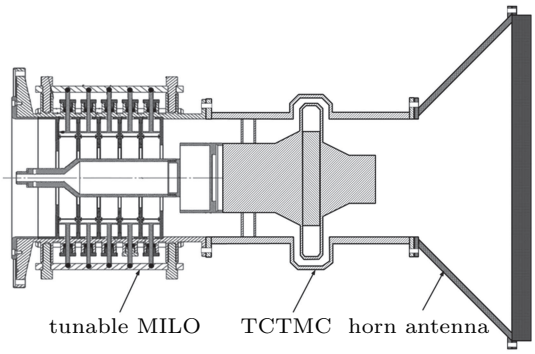


Fig. 1. The structure of the tunable HPM system.

Figure 2 shows the three-dimensional (3D) structure diagram of TCTMC, which can convert a coaxial TEM mode into a circularly-polarized TE_{11} mode. It is composed of a coaxial circular waveguide (CCWG), four rectangular waveguides

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(RWGs), eight metal rods, a transition section, and a circular waveguide (CWG). The four RWGs marked with RWG1, RWG2, RWG3, and RWG4 form an input turnstile junction and an output turnstile junction, respectively. Eight metal rods are distributed equally along the azimuthal direction, of which four metal rods as a whole are named "rod A" (close to RWG) and the others as a whole are called "rod B" (far away from RWG). The transition section includes two cone frustums and two cylinders. Both metal rods and transition section act as the matching sections to reduce or even eliminate the reflections and unwished transmissions caused by the irregular structures in the mode converter.

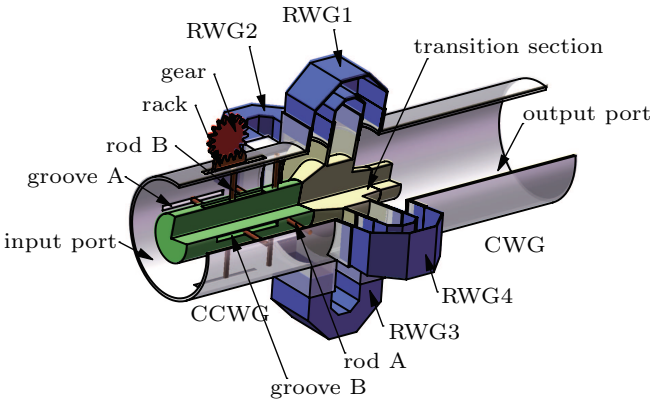


Fig. 2. (color online) 3D structure diagram of the TCTMC.

The operating principle of TCTMC is as follows. A coaxial TEM mode microwave is injected into the CCWG and then further enters into the four RWGs. The microwave transports in the TE_{10} mode in the four RWGs. With different lengths of the four RWGs, the microwave obtains different phases at the output turnstile junction. Consequently, when the four rectangular waveguide mode microwaves with different phases are output from the output turnstile junction, they form a coaxial TE_{11} mode microwave and then enter into a circular TE_{11} mode microwave in CWG.

The mode converter can achieve the output of circular-polarized TE_{11} mode, provided that the phase shift of outputting TE_{10} modes between adjacent RWG is $\pi/2$. The radial lengths of four RWGs are L_1, L_2, L_3, and L_4, respectively, which meet the following equation:[9]

$$\Delta L = L_4 - L_3 = L_3 - L_2 = L_2 - L_1 = \lambda_g/8, \tag{1}$$

where λ_g is the waveguide wavelength in RWG, and ΔL is the difference in length among the RWGs.

Assume that the broad side and narrow side of the rectangular waveguide are a and b, respectively, and the wavelength in free space is λ, then λ_g can be expressed as[10]

$$\lambda_g = \lambda_0/\sqrt{1-(\lambda_0/2a)^2}. \tag{2}$$

In addition, the coaxial TEM mode only stimulates the modes that are even symmetric on the E-plane waveguide in the four RWGs, such as TE_{10} mode and TE_{30} mode. To ensure that RWG transports the TE_{10} mode rather than other unwished high-order modes, the broad side and narrow side of the rectangular port in RWG must meet the following equation:[9,10]

$$\lambda_0/2 < a < 3\lambda_0/2, \quad b < \lambda_0/2. \tag{3}$$

Compared with the conventional TJMC, there are two differences in the TCTMC.

First, the effective lengths of RWGs can be changed continuously in order to meet Eq. (1) in a relatively wide frequency range. Taking RWG1 for example as shown in Fig. 3, the RWG1 is welded with a sleeve, and a screw is inserted in the sleeve. The screw can be rotated and its place is fixed. When the screw is rotated, the sleeve and RWG1 are moved up or down. So the effective lengths of RWGs can be changed. Consequently, the length differences among the four RWGs can be changed to meet Eq. (1).

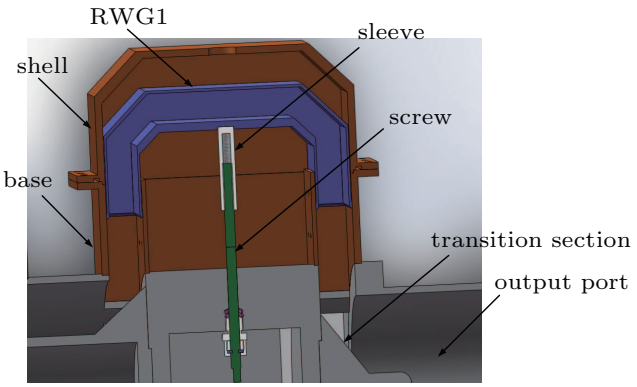


Fig. 3. (color online) Tuning mechanism of RWG1.

Second, grooves A and B consist of four grooves arranged in the outer and inner conductors, respectively, as shown in Fig. 2. Rod B is inserted into grooves A and B. Moreover, rod B can move along the grooves while rod A is fixed. The rack and gear are introduced in order to move rod B. Based on the gear engagement principle, rod B can move along the axial direction via rolling the gear. Thus, the distance between rods A and B can be adjusted appropriately to eliminate the unwished reflections.

It is concluded that the frequency tuning can be achieved, provided that equation (1) is met and the reflection is eliminated effectively. The next part will verify the feasibility of the method.

3. Simulation and analysis

The proposed TCTMC is investigated in a frequency range of 1.35 GHz–2.35 GHz. The optimized dimensions of TCTMC are as follows. The radius of the rod is 2 mm. The lengths of RWGs 1, 2, 3, and 4 are determined according to Eq. (1). The broad side and narrow side of the rectangular port

in each of RWGs are $a = 123$ mm and $b = 26$ mm, respectively. The two radii and the length of the cone frustum in the transition section are 54 and 12, and 55 mm, respectively.

The current model is established successfully and obtains a better result via simulating and optimizing with the CST Studio Suite. The CST software has been widely used in designing the mode converter, which verifies the simulation reliability and the experimental and simulation results are in good agreement with each other.[11–13] The objectives of this work are to improve the conversion efficiency and broaden the bandwidth. To simplify the simulation and analysis, the TCTMC without metal rods is discussed first.

Figure 4 presents the curves of conversion efficiency of TCTMC without metal rods against frequency. It is found that the conversion efficiency is higher than 90% in the whole frequency range of 1.35 GHz–2.35 GHz. Furthermore, it is even above 98% between 1.57 GHz and 2.16 GHz with a corresponding bandwidth of 31.64%. However, from Fig. 5 it can be seen that the reflections of TCTMC at both ends of the spectrum are more than −20 dB, thus lowering the conversion efficiency to some extent.

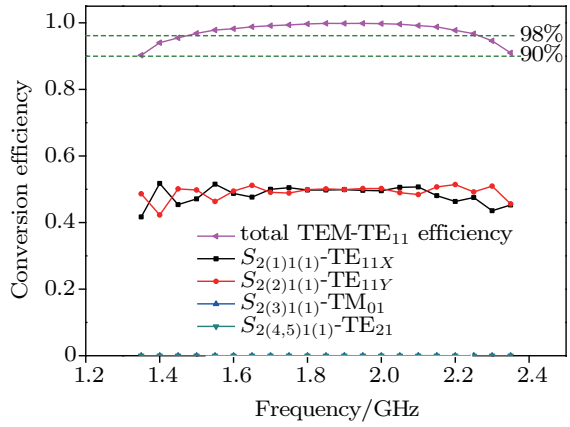


Fig. 4. (color online) Curves of conversion efficiency versus frequency of TCTMC without metal rods.

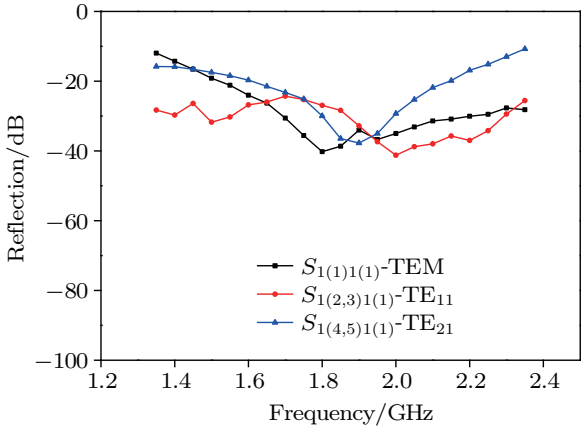


Fig. 5. (color online) Curves of reflection versus frequency of TCTMC without metal rods.

By contrast, the conversion efficiency of conventional TJMC of TEM to TE_{11} is 99% at a center frequency of 1.75 GHz with an axial ratio of 0.03 dB. Over the frequency range of 1.59 GHz–1.90 GHz, the conversion efficiency exceeds 90% and the axial ratio is less than 2.5 dB with a corresponding bandwidth of 18.6%.[9] Obviously, the TCTMC without metal rods obtains a significant improvement in comparison with the conventional TJMC, indicating that the proposed TCTMC is feasible.

For different-frequency microwaves, the reflections of modes and amplitudes are different, which needs matching structures to compensate for the reflections. The common matching structures are stepped or metal rods. However, steps cannot effectively eliminate unsymmetrical modes, such as the TE_{21} mode. Consequently, metal rods are chosen as the matching structures in TCTMC.

When metal rods are added to the TCTMC as described in Section 2, the distance (Z) between rods A and B can be adjusted by moving rod B. Therefore, rod A and rod B play a key role in eliminating the reflections.

Figure 6 describes the plots of the conversion efficiency of the TCTMC with metal rods against frequency. The conversion efficiency exceeds 96% in the whole frequency range of 1.35 GHz–2.35 GHz. Moreover, it can be higher than 98% over the frequency range of 1.42 GHz–2.29 GHz with a bandwidth of 46.90%. It is also found that only the TE_{11} circular waveguide mode is generated in the output of CWG at the frequency in a range of 1.35 GHz–2.35 GHz.

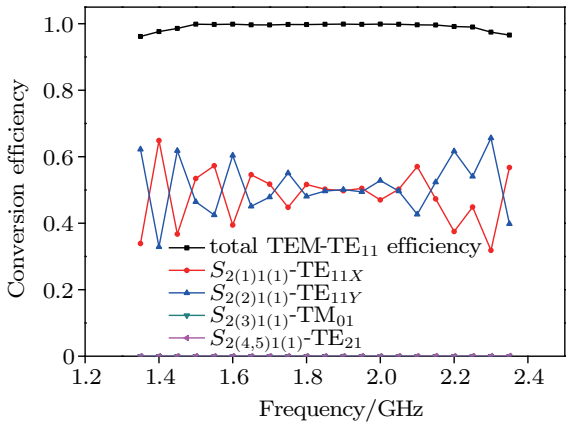


Fig. 6. (color online) Plots of conversion efficiency versus frequency of TCTMC with metal rods.

Comparatively, the earlier mode converters have a great disadvantage. Firstly, structures of most of earlier mode converters were fixed, which can only obtain high conversion efficiency at a certain frequency point. The serpentine mode converter (SMC) by Lawson *et al.* can convert about 99% of the desired incident mode into a desired output mode when the operation frequency is 14.424 GHz.[14] The coaxial waveguide mode converter by Zhang *et al.* can realize dual-band mode conversion but the structure cannot be changed after fabrication.[15] The cross shaped mode converter (CSMC) by Peng *et al.* cannot work well except at 1.75 GHz.[16] Secondly,

for the rest of the earlier mode converters, the structures can be adjusted, like HETMC by Wang *et al.*[17] However, the frequency bandwidth is relatively narrow and the whole length of HETMC is five times the length of the proposed TCTMC.

The moving metal rods can reduce the reflections of TCTMC as shown in Fig. 7. As the frequency ranges from 1.40 GHz to 2.30 GHz, the reflection coefficients of the reflected modes are almost less than −20 dB. However, the magnitude difference between TE_{11X} and TE_{11Y} becomes greater when frequency becomes lower or higher. This suggests that the output is not a standard circularly-polarized wave.

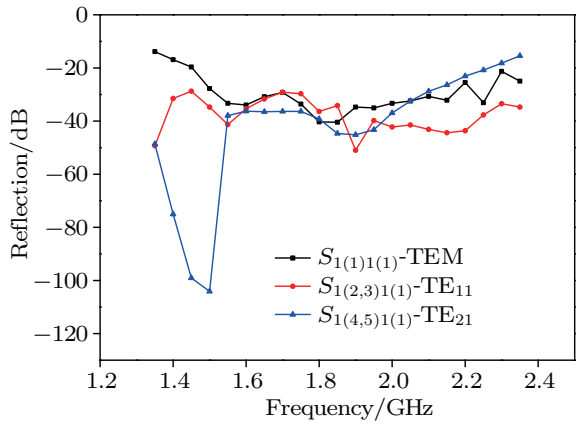


Fig. 7. (color online) Plots of reflection versus frequency of TCTMC with moving rod B.

Note that in our simulations, the distance between rods A and B can be expressed as follows:

$$Z = -1561.39 + 3221.54f - 2596.18f^2 + 930f^3 - 123.51f^4. \quad (4)$$

The distance Z is a sensitive parameter for the TCTMC as shown in Fig. 8. When the frequency of TCTMC is required as a certain point, the values of ΔL and Z can be determined based on Eqs. (1)–(4). For example, when the frequency is 1.50 GHz, the values of ΔL and Z are 42.94 nm and −56.36 mm, respectively. Consequently, both RWG and metal rods move to the corresponding positions through the tunning mechanism. Based on the above theoretical values, the TCTMC of 1.50 GHz is simulated by CST software, and the power conversion efficiency of the TCTMC with metal rods reaches up to 99.86%, whereas that of the TCTMC without metal rods is only 96.84%. Significantly, when the operation frequency of one tunable HPM source changes continuously, the high conversion efficiency of TCTMC can be obtained since the parameters ΔL and Z are variable.

The simulated distributions (by the software CST Studio Suite) of the electric fields at input port, RWG and output port of TCTMC are shown in Figs. 9(a)–9(c), respectively. The injected TEM mode (Fig. 9(a)) in the input port transports into RWG, and is converted into TE_{10} mode (Fig. 9(b)). Figure 9(c) shows the electric field distributions at different times in the output port, indicating that the output mode is the TE_{11} mode. Besides, the direction of polarization changes with increasing time, which means that circularly-polarized output is obtained.

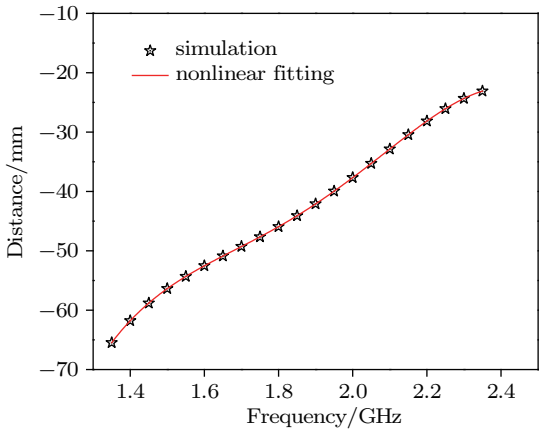


Fig. 8. (color online) Nonlinearly fitted simulated distance (Z) versus frequency.

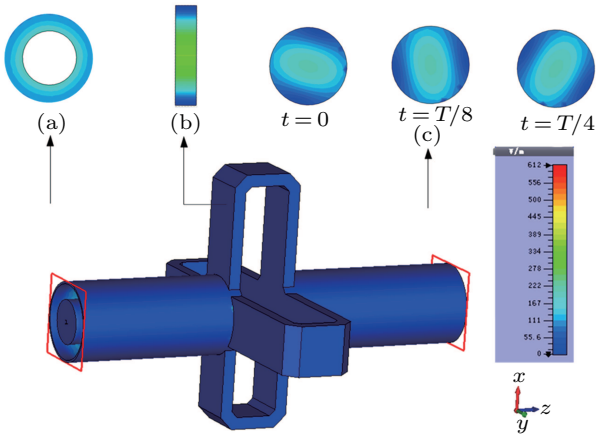


Fig. 9. (color online) Electric field distributions of TCTMC.

The axial ratio (AR) determining the circular polarization, is defined as the ratio of long axis to the short axis of an elliptical polarized wave. In TCTMC, the AR of the output TE_{11} mode can be obtained from[18]

$$AR = \cot\left\{\frac{1}{2}\arcsin\left[-\frac{2S_{21}^{TE11x}S_{21}^{TE11y}}{(S_{21}^{TE11x})^2+(S_{21}^{TE11y})^2} \times \sin(\varphi_x-\varphi_y)\right]\right\}. \quad (5)$$

Figure 10 shows the comparison between ARs of the output TE_{11} mode in TCTMC with and without metal rods. It can be seen that when the corresponding frequency is in the ranges of 1.49 GHz–2.22 GHz and 1.35 GHz–2.35 GHz, respectively, the ARs of the output TE_{11} mode in TCTMC with and without metal rods are both kept under 1.3. These suggest that the output TE_{11} modes in these ranges are almost circularly polarized waves.[19] However, the AR in TCTMC with metal rods is in a range from 1.3 to 1.7 in the other frequency ranges. Although the circular polarization of the TE_{11} mode is not so satisfactory, it is still acceptable.

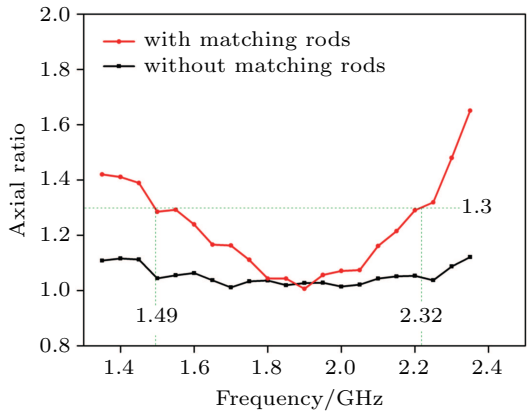


Fig. 10. (color online) Comparison between axial ratios of the output TE_{11} mode with and without matching rods.

Significantly, the AR of the TCTMC is not very good, which needs to be solved in the next investigation on TCTMC.

4. Conclusions

In this research, a tunable circularly-polarized turnstile-junction mode converter (TCTMC) is presented and investigated numerically with the CST Studio Suite. Both the length difference among the RWGs and the distance Z between rods A and B can be adjusted in order to improve the conversion efficiency and broaden the bandwidth. The conversion efficiency of TCTMC can reach above 98% with a bandwidth of 46.90% over the frequency range of 1.42 GHz–2.29 GHz.

References

[1] Wang G Q, Wang J G, Li S, Wang X F, Lu X C and Song Z M 2015 *Acta Phys. Sin.* **64** 050703 (in Chinese)
[2] Li S, Wang J, Tong C, Wang G, Lu X and Wang X 2013 *Acta Phys. Sin.* **62** 120703 (in Chinese)
[3] Li X, Wang J, Xiao R, Wang G, Zhang L, Zhang Y and Ye H 2013 *Phys. Plasmas* **20** 083105
[4] Fan Y W, Wang X Y, Liang H, Zhong H H and Zhang J D 2015 *Chin. Phys. B* **24** 035203
[5] Fan Y W, Wang X Y, Li G L, Yang H W, Zhong H H and Zhang J D 2016 *IEEE Trans. Electron Dev.* **63** 1307
[6] Chen J, Wang J 2007 *IEEE Trans. Electromagnetic Compatibility* **49** 354
[7] Wang J G, Liu G Z, Zhou J S 2003 *High Power Laser and Particle Beams* **15** 1093 (in Chinese)
[8] Jiao C Q and Qi L 2012 *Acta Phys. Sin* **61** 114102 (in Chinese)
[9] Yuan C W 2006 Changsha: National University of Defense Technology
[10] Benford J, Swegle J A and Schamiloglu E 2007 *High Power Microwaves* (New York, Taylor & Francis)
[11] Chittora A, Singh S, Sharma A and Mukherjee J 2015 *IEEE Trans. Microw. Theory Tech.* **25** 633
[12] Liu G, Yan R, Luo Y and Wang S F 2016 *IEEE Trans. Electron Dev.* **63** 486
[13] Peng S R, Yuan C W, Shu T, Zhao X L and Zhang Q 2016 *IEEE Trans. Microw. Theory Tech.* **64** 1163
[14] Lawson W, Arjona M R, Hogan B P and Ives R L 2000 *IEEE Trans. Microw. Theory Tech.* **48** 809
[15] Zhang Q, Yuan C W and Liu L 2011 *Chin. Phys. Lett.* **28** 068401
[16] Peng S R, Yuan C W, Zhong H H and Fan Y W 2013 *Rev. Sci. Instrum.* **84** 245
[17] Wang X Y, Fan Y W, Shu T, Yuan C W and Zhang Q 2017 *AIP Adv.* **7** 035012
[18] Lin C L and Nie Z P 2002 *Antenna Engineering Handbook* (Beijing, Publishing House of Electronics Industry Press)
[19] Zhao X L, Yuan C W, Liu L, Peng S R, Bai Z and Cai D 2016 *IEEE Trans. Plasma Sci.* **44** 1307