Progress In Electromagnetics Research C, Vol. 33, 145–156, 2012

A 2.45 GHz REENTARNT COAXIAL CAVITY FOR LIGUID STERILIZATION BASED ON NON-THERMAL MICROWAVE EFFECT

Y.-L. Zhang, B.-Q. Zeng*, and H. Zhang

National Key Laboratory of Science and Technology on Vacuum Electronics, School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, P. R. China

Abstract—According to the intracellular electromanipulation model, bacteria can be killed at as high as 10^6 V/m electrical fields on microwave band. We designed and constructed a modified microwave coaxial cavity resonator for liquid sterilization. The cavity could concentrate the field on a very small area, and the liquid can pass it in milliseconds. The bacteria can be killed by the very high field, but with a slight temperature increase. The designed resonator is simulated and analyzed by electromagnetic simulation code. The results indicated that when the input power reached 100 W, the electric field on the area of liquid can reach 10^6 V/m. Preliminary experimental results indicated that when the input power was 100 W, the bactericidal rate was $> 90\%$, and the temperature of the liquid only increased 8.6°C.$TM\sum\hat{}$

1. INTRODUCTION

As a developing technique, microwave sterilization has attracted the attention of many researchers due to its cleanness, convenience, and high efficiency [1]. Sterilization is typically based on either a physical or chemical process that destroys or eliminates microorganisms, or both [2–4]. Traditional methods including pasteurization, chemical and radiation sterilization are widely used in food industry. However, these methods are energy intensive, and adversely affect the nutritional quality and flavor of preserved food. Interest in non-thermal sterilization processes has arisen from the need to overcome these disadvantages [5].

Received 17 June 2012, Accepted 24 September 2012, Scheduled 5 October 2012

* Corresponding author: Bao-Qing Zeng (bqzeng@uestc.edu.cn).

The phenomenon of variation caused by interactions between the electromagnetic field and biologic system is called the biological effect of electromagnetic field; it can be classified into thermal reaction and non-thermal reaction. The thermal effect is that after the organism absorbs microwave energy, its temperature rises, which could cause all sorts of biological function changes in the cell internally. The non-thermal effect is that the organism does not have any detectable rise of temperature, but has many changes in the physiology, biochemistry and in its function [6]. The thermal reaction and its mechanism of sterilization using electromagnetic wave have been widely accepted [6–9]. The non-thermal effect has been a research hotspot in recent years [10]. The electric fields of nanosecond duration and above 10 kV/cm amplitude can affect the subcellular structures which can lead to the apoptosis of cells, but do not lead to formation of pores in the outer membrane. This phenomenon is called intracellular electromanipulation effect [11, 12]. So the key issue is how to get the high field strength which can kill the bacteria by non-thermal microwave effect.

In this work, based on the intracellular electromanipulation effect model, a modified microwave coaxial cavity resonator is proposed and designed for liquid sterilization. The coaxial cavity and reentrant cavity can concentrate the field in a small area and enhanced the E-field [13–15]. Its structure is simple. The resonant frequency of the resonator is 2.45 GHz. The results of simulation indicate that when the input power reaches 100W, the area of liquid could get enough E-field strength to realize sterilization. The detailed design and experimental results for the proposed resonator are demonstrated in this paper. The preliminary experimental results proved the simulation and the non-thermal effect of electromagnetic field.

2. RESONATOR DESIGN

The design of resonator is based on capacitive loaded coaxial cavity resonator which consists of a circular waveguide with an inner conductor located along its axis. The electromagnetic field distribution inside the resonator is shown in Figure 1. The direction of electric field is from inner conductor points to the outer conductor. The strongest intensity of E-field is in the area between the inner and outer conductor. However, the direction of magnetic field is purely circumferential, perpendicular to the axis of resonator. The inner conductor is surrounded by the magnetic field, and the largest magnetic field strength is near the short-circuit-side.

TEM mode is the dominant mode of coaxial resonator. In this

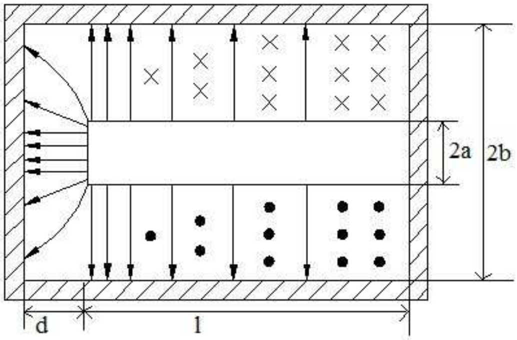


Figure 1. Electromagnetic field distribution of capacitive loaded coaxial cavity.

paper, the resonator that we designed is a single-mode cavity worked on TEM-mode. So we must suppress the generation of higher order modes.

2.1. TM Mode

For TM-mode, $H_z = 0$, $E_z \neq 0$, when $r = a$ and $r = b$, $E_z = 0$, the equation is

$$\begin{cases} B_1 J_m(K_c a) + B_2 N_m(K_c a) = 0 \\ B_1 J_m(K_c b) + B_2 N_m(K_c b) = 0 \end{cases} \tag{1}$$

where B_1 and B_2 are constant. J_m is m order Bessel function, and N_m is Neumann function. Let $p = b/a$, Equation (1) can be expression as

$$J_m(K_c a) N_m(pK_c a) - J_m(pK_c a) N_m(K_c b) = 0 \tag{2}$$

This is a transcendental equation, and there are infinitely many solutions. By using the approximation formula of Bessel function to find an approximation of K, we obtain

$$K_c \approx \frac{n\pi}{b-a} \quad (n = 1, 2, 3 \ldots\ldots) \tag{3}$$

$$\lambda_c = \frac{2\pi}{K_c} \approx \frac{2}{n}(b-a) \quad (n = 1, 2, 3 \ldots\ldots) \tag{4}$$

According to Formula (4), we know that TM_{01}-mode has the longest cutoff wavelength. The wavelength is $2(b-a)$.

2.2. TE Mode

For TE-mode, $Ez = 0$, $Hz \neq 0$, when $r = a$ and $r = b$, $E_\phi = 0$, let $p = b/a$, and the equation is

$$J'_m(K_c a)N'_m(pK_c a) - J'_m(pK_c a)N'_m(K_c b) = 0 \tag{5}$$

When $m \neq 0$, the cutoff wavelength of TE_{m1} is

$$\lambda_c \approx \frac{\pi(a+b)}{m} \quad (m = 1, 2, 3 \ldots\ldots) \tag{6}$$

When $m = 0$, the cutoff wavelength of TE_{0n} is

$$\lambda_c = \frac{2\pi}{K_c} \approx \frac{2}{n}(b-a) \quad (n = 1, 2, 3 \ldots\ldots) \tag{7}$$

The mode which has the largest cutoff wavelength in all higher order modes is TM_{11}-mode ($\lambda_c = \pi(a+b)$), so the single-mode transmission conditions of coaxial resonator is:

$$\lambda > (\lambda_c)_{H11} \approx \pi(a+b) \tag{8}$$

λ is the operating wavelength. On the other hand, attenuation constant of the conductor is

$$\alpha_c = \frac{R}{2}\sqrt{\frac{C}{L}} = \frac{R}{2Z_c} = \frac{\left(\frac{1}{a}+\frac{1}{b}\right)\sqrt{\frac{\pi f \mu}{\sigma}}}{240\pi \ln \frac{b}{a}} \tag{9}$$

The material of the resonator is copper. In order to obtain a minimum of α_c,

$$\frac{d\alpha_c}{d\left(\frac{b}{a}\right)} = 0 \tag{10}$$

We get: $b/a \approx 3.6$.

According to Equations (8) and (10), we know: $a < 8.5\,\mathrm{mm}$, $b < 30.5\,\mathrm{mm}$. So we take $a = 5.0\,\mathrm{mm}$, $b = 20.0\,\mathrm{mm}$. To decrease the action time and increase electric field in liquid, d is taken to be 3 mm. Because of the loading capacitance, the length of inner conductor l should be less than $\lambda/4 = 30.6\,\mathrm{mm}$. Therefore, we take the initial value of l to be 28.0 mm as an adjusting parameter for simulation.

The coaxial cavity structure with high field intensity has been researched [16, 17], but there are few reports about using this structure to sterilize for liquid, because the electric field is too high and because the dielectric constants are much different from air. Here we report a modified microwave coaxial cavity resonator. To increase the E-field strength, the open side of the inner conductor uses cone instead of the planar structure. Because the largest area of E-field is used for sterilization, the magnetic coupling is used here. The resonator is fed by a rectangular feed loop located in the top of resonator. Since the energy is coupled into or out of the cavity through the same coupling mechanism, the resonator is one-port reflection type. Its port impedance is $50\,\Omega$, which facilitates connection with the external circuit [18]. In order to facilitate the flow of liquid, the inner conductor is a tube, and the cone with several holes. The specific structure of the cavity and the design parameters are shown in Figure 2.

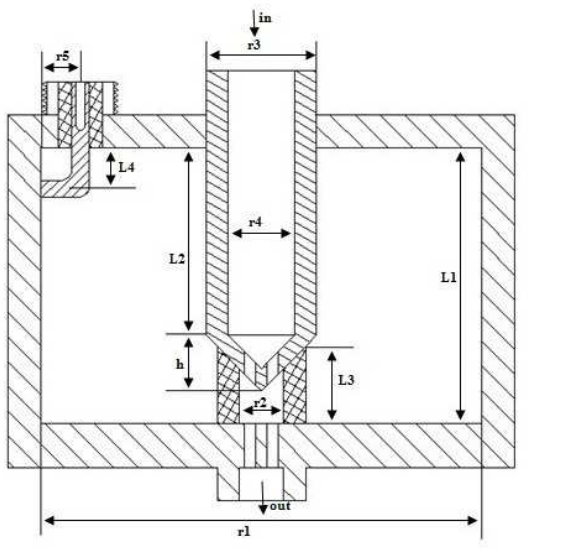
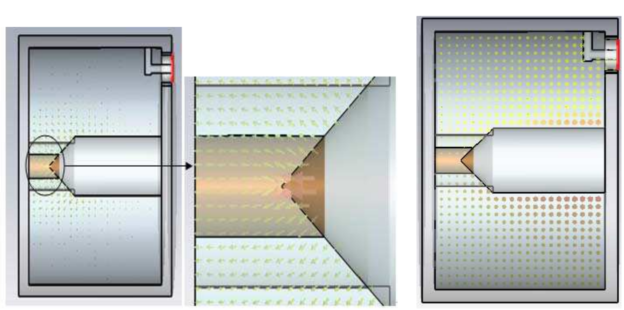


Figure 2. Configuration of the proposed coaxial cavity resonator.



(a) (b)

Figure 3. (a) Electric field distribution and (b) magnetic field distribution of the resonant cavity.

3. RESULTS AND DISCUSSION

We used transient analysis of software CST and the optimized parameters of the coaxial cavity resonator shown in Table 1. Figure 3 is the electromagnetic distribution, which shows the E-field concentrated in the area of liquid. The resonant frequency is 2.45 GHz.

Using the code of CST MICROWAVE STUDIO, we optimized the width r_5 and length L_4 of the coupler to get the lowest S_{11}, as shown in Figure 4. When the $r_5 = 3.8$ mm, $L_4 = 2.7$ mm, the minimal value of S_{11} is below -35 dB. The result indicates that the impedance matching of the resonator is very good at the resonant frequency. The microwave power is almost completely absorbed by the resonator. After optimization, the parameters of the proposed coupling structure and corresponding coaxial cavity resonator are listed in Table 1. The thickness of the Teflon tubing is 2 mm. The resonant

Table 1. The parameter of the coaxial cavity resonator.

Symbol	Property	Dimension (mm)
L_1	The length of the outer conductor	26.4
L_2	The length of the inner conductor	17.4
L_3	The length of the PTFE tube	7.0
r_1	The diameter of the outer conductor	40.0
r_2	The inside diameter of the PTFE tube	4.0
r_3	The outside diameter of the inner conductor	10.0
r_4	The inside diameter of the inner conductor	8.0
h	The height of the cone	5.0

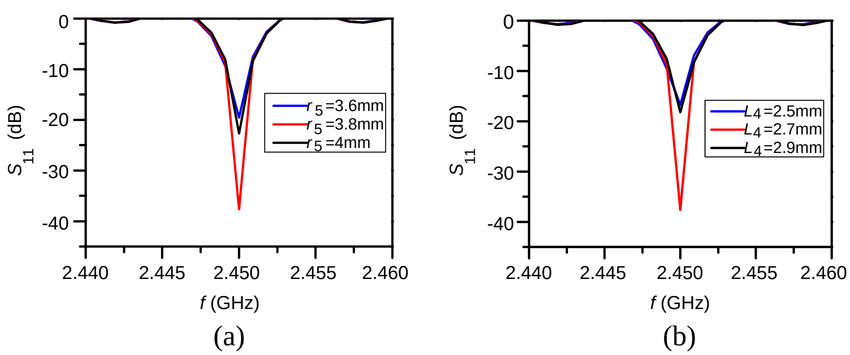


Figure 4. Simulated S_{11} of the proposed resonator (a) as a function of r_5, (b) as a function of L_4.

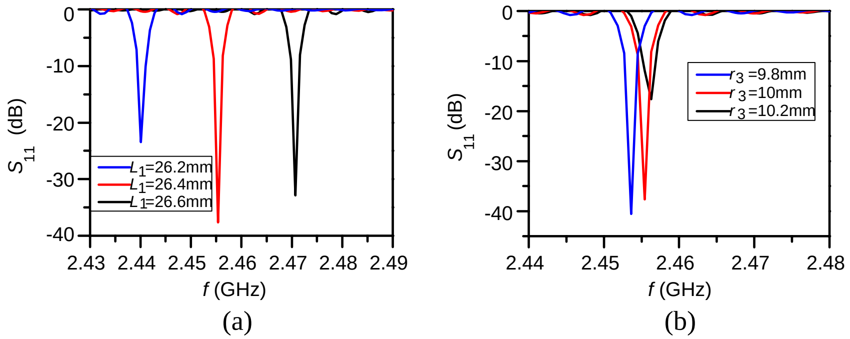


Figure 5. (a) Effects of the length of the outer conductor and (b) the diameter of the inner conductor on the impedance matching of the resonator.

frequency of resonator is 2.45 GHz for employing standard magnetron as the microwave energy source.

The parametric study is important for a new design because it provides some understanding of the resonator characteristics to the designer [19]. Therefore, the effect of the outer conductor's length L_1 on the impedance matching is investigated here, and the return loss for the proposed resonator is shown in Figure 5(a). It is seen that the outer conductor's length has a significant effect on the impedance matching and resonant frequency. The resonant frequency is shifted to lower frequencies with increasing L_1. Figure 5(b) presents the effect of inner conductor's outside diameter on the impedance matching. It is observed that r_3 has a small effect on the resonant frequency, but obvious effect is obtained on the S_{11}. These results indicate that the impedance matching and resonant frequency of the resonator can be effectively tuned by adjusting the length of the outer conductor. Thus, the outer conductor's length should be taken into account in determining the proper parameters for the proposed design to achieve the desired operating frequency.

The input microwave power is 100 W. Figure 6 depicts the electric field distribution on the axis of the resonator in the area of liquid, and Figure 7 depicts the electric field radial distribution in the liquid at the tip of inner conductor. Based on the theory of intracellular electromanipulation, we know that when the input microwave power is 100 W, the electric field in the liquid can reach above 10^6 V/m which would realize sterilization fast. Due to effective shielding of the outer conductor, radiation of the microwave energy is very small, which could avoid the potential harm to the human body. However, it is worth

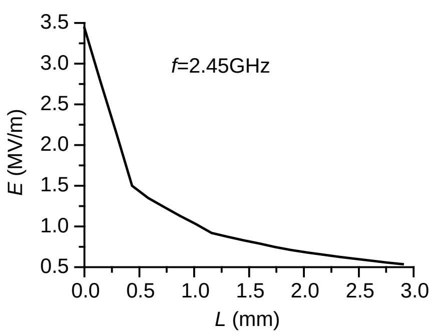


Figure 6. Electric field distribution on the axis of the resonator in the area of liquid.

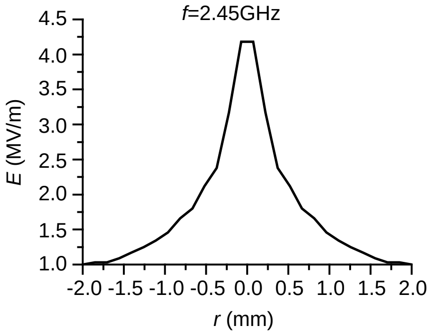


Figure 7. Radial electric field distribution in the liquid near the tip of inner conductor.

(a) (b)

Figure 8. Prototype of the proposed resonator. (a) Top and (b) bottom views of the resonator.

noting that when the electric field reaches 3×10^6 V/m, the air may be breakdown. This breakdown will change the distribution of the electric field within the resonator and may even damage the resonator. To prevent the occurrence of breakdown in air, an effective solution way be filled with dielectric material in the air. The electric field within the dielectric is changed to $E = E_0/\sqrt{\varepsilon_r}$. E_0 is the electric-filed in air and ε_r the relative permittivity of the used dielectric material. In order to not change the distribution of the electromagnetic field, we can use the material with the dielectric constant close to air, but the dielectric strength higher than air.

Both ends of the outer conductor surface where the liquid flows through use metallic mesh structure. Thus, the microwave power can be shielded in the resonator, so it is harmless for human body. Because the microwave has a strong penetrating and short sterilization time, liquid can quickly flow through the sterilizer region to achieve the purpose of sterilization.

Based on the design dimensions given above, the proposed resonator was fabricated and tested. Figure 8 presents photographs of the proposed resonator. The length of the outer conductor L_1 as the tuning parameter is used to adjust the resonant frequency. Finally, when the resonant frequency is 2.45 GHz, the actual value of L_1 is 25.8 mm which is shorter than the simulation length 26.4 mm. The difference is caused by the machining accuracy, material properties, etc. and can be accepted. The s-parameter measurement was carried out with a network analyzer. Figure 9 shows the measured and simulated return losses of the prototype, and there is agreement between the measurement and simulation.

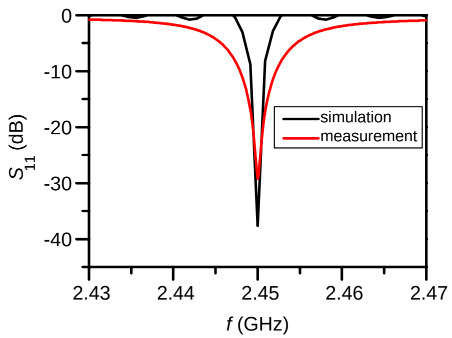


Figure 9. Measured and simulated return loss of the proposed resonator.

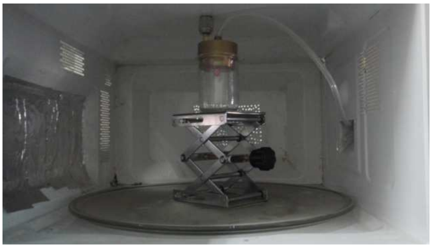


Figure 10. The resonant is put into a modified microwave oven, to prevent the problem of the harm of microwave leak.

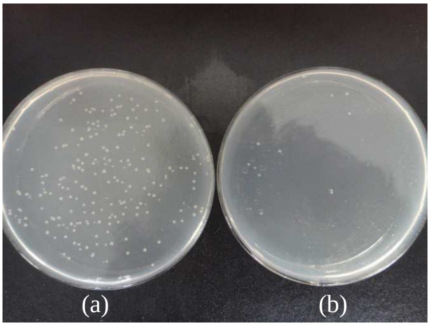


Figure 11. Lethal effect (a) before and (b) after treatment on E. coli.

Based on the above studies, we did the experiment. To prevent the problem of the harm of microwave leak, the reentrant coaxial cavity was put into a modified microwave oven, as shown in Figure 10. Experiment method: E. coli was added to the liquid. We let liquid flow through the resonator at a rate of 10 cm/s. The microwave input power was 100 W. After that put the sample sterilized and the check sample into the agar plates prepared in advance, then the plates were incubated at 37° for 24 h to enumeration. The experimental result shows that the bactericidal effect is very good, as shown in Figure 11. We counted the number of colonies before sterilization is 228, and the number of colonies after sterilization is 17, so the bactericidal rate is 92.5%. The liquid temperature only increased 8.6°. Simulated and experimental results show good agreement, which prove that the design proposal is reasonable and feasible.

4. CONCLUSION

In this paper, a modified microwave coaxial cavity resonator based on the non-thermal effect of microwave sterilization is proposed and designed. Microwave sterilization is direct, efficient and fast because of the strong penetrating effect of the waves. The results of simulation indicate that when the input power reaches a hundred of watts, the area of liquid could get enough E-field to sterilization. Experimental result shows that the bactericidal rate can achieve over 90% and the temperature of liquid only increased 8.6°.

The structure of the coaxial cavity resonator provides a basis for the microwave field distribution of high field strength and energy-flux density in the low-power conditions. In the next work, we will study the relationship between microwave power and bactericidal effect, and observe the ultrastructure of cell by electron microscopy technique.

ACKNOWLEDGMENT

The work is partially supported by UESTC-Media joint laboratory and Postdoctoral granted financial support from China Postdoctoral Science Foundation (20100481377).

REFERENCES

1. Wu, Q., "Effect of high-power microwave on indicator bacteria for sterilization," *IEEE Trans. Biomedical Engineering*, Vol. 43, No. 7, 752–754, 1996.

2. Park, B. J., D. H. Lee, J. C. Park, I. S. Lee, K. Y. Lee, S. O. Hyun, M. S. Chun, and K. H. Chung, "Sterilization using a microwave-induced argon plasma system at atmospheric pressure," *Physics of Plasmas*, Vol. 10, No. 11, 4539–4544, 2003.
3. Chau, T. T., K. C. Kao, G. Blank, and F. Madrid, "Microwave plasmas for low-temperature dry sterilization," *Biomaterials*, Vol. 17, No. 13, 1273–1277, 1996.
4. Moisan, M., J. Barbeau, M.-C. Crevier, J. Pelletier, N. Philip, and B. Saoudi, "Plasma sterilization: Methods and mechanisms," *Pure and Applied Chemistry*, Vol. 74, No. 3, 349–358, 2002.
5. Montie, T. C., K. Kelly-Wintenberg, and J. R. Roth, "An overview of research using the one atmosphere uniform glow discharge plasma for sterilization of surfaces and materials," *IEEE Trans. Plasma Science*, Vol. 28, No. 1, 41–50, 2000.
6. Wu, B. I., F. C. A. I. Cox, and J. A. Kong, "Experimental methodology for non-thermal effects of electromagnetic radiation on biologics," *Journal of Electromagnetic Waves and Applications*, Vol. 21, No. 4, 533–548, 2007.
7. Niu, Z. Q., J. Q. Hou, H. B. Wang, et al., "The window bioeffects of electromagnetic waves," *Chinese Journal of Biomedical Engineering*, Vol. 22, No. 2, 126–132, 2003.
8. Tang, S. J., B. H. Wang, and J. K. Zhong, "Review on the investigation of the mechanism of the biological effects of the electromagnetic radiation," *Foreign Medical Sciences*, Vol. 21, No. 1, 20–23, 1998.
9. Xi, X. L., D. C. Wu, and G. Wang, "Research and development on microwave sterilization," *Journal of Biomedical Engineering*, Vol. 19, No. 2, 334–336, 2002.
10. Angulo. L. D., S. G. Garcia, and M. F. Pantoja, "Improving the SAR distribution in petri-dish cell cultures," *Journal of Electromagnetic Waves and Applications* Vol. 24, Nos. 5–6, 815–826, 2010.
11. Karl, H. S., S. J. Beebe, and E. S. Buescher, "Intracellular effect of ultrashort electrical pulses," *Bioelectromagnetics,* Vol. 22, No. 6, 440–448, 2001.
12. Karl, H. S. and R. P. Joshi, "Ultrashort electrical pulses open a new gateway into biological cells," *Proceedings of the IEEE*, Vol. 29, No. 7, 1122–1137, 2004.
13. Ishihara, Y., Y. Gotanda, N. Wadamori, and J. Matsuda, "Hyperthermia applicator based on a reentrant cavity for localized head and neck tumors," *Rev. Sci. Instrum.*, Vol. 78, 024301, 2007.

14. Barroso, J. J., P. J. Castro, J. P. L. Neto, and O. D. Aguiar, "Analysis and simulation of reentrant cylindrical cavities," *Int. J. Infrared and Millimeter Waves*, Vol. 26, No. 8, 1071–1083, 2005.
15. Carter, R. G., J. J. Feng, and U. Becker, "Calculation of the properties of reentrant cylindrical cavity resonators," *IEEE Trans. Microw. Theory Tech.,* Vol. 55, No. 12, 2531–2537, 2007.
16. Zaginaylov, G. I. and I. V. Mitina, "Electromagnetic analysys of coaxial gyrotron cavity with the inner conductor having corrugations of an arbitrary shape," *Progress In Electromagnetics Research B,* Vol. 31, 339–356, 2011.
17. Li, L. Q., C. H. Liang, and G. Li, "The design technique for coaxial resonator cavity duplexer," *Progress In Electromagnetics Research M*, Vol. 2, 105–114, 2008.
18. Zhang, H., B. Q. Zeng, and Z. H. Yang, "Simulation of the characteristics of electromagnetic field within the coaxial microwave sterilization equipment," *Journal of the University of Electronic Science and Technology of China*, Vol. 36, No. 2, 232–234, 2007.
19. Li, C. M., K. Wang, and C. K. Chen, "Small tri-band monopole antenna for WiMAX/WLAN applications," *Journal of Electromagnetic Waves and Applications*, Vol. 25, Nos. 8–9, 1297–1307, 2011.