

Propagation of Electromagnetic Wave in Coaxial Conical Transverse Electromagnetic Wave Cell

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Abstract: In order to solve the problem of broadband field probes calibration with only selected discrete frequencies above 1 GHz, a sweep-frequency calibration technology based on a coaxial conical(co-conical) cell is researched. Existing research is only qualitative because of the complexity of theoretical calculations. For designing a high performance cell, a mathematic model of high-order modes transmission is built according to the geometrical construction of co-conical. The associated Legendre control functions of high-order modes are calculated by using recursion methodology and the numerical calculation roots are presented with different half angles of inner and outer conductor. Relationship between roots and high-order modes transmission is analyzed, when the half angles of inner conductor and outer conductor are $\theta_1=1.5136^\circ$ and $\theta_2=8^\circ$ respectively, the co-conical cell has better performance for fewer transmitting high-order modes. The propagation process of the first three transmitting modes wave is simulated in CST-MWS software from the same structured co-conical. The simulation plots show that transmission of high-order modes appears with electromagnetic wave reflection, then different high-order mode transmission has different cut-off region and each cut-off region is determined by its cut-off wavelength. This paper presents numerical calculation data and theoretical analysis to design key structural parameters for the co-conical transverse electromagnetic wave cell(co-conical TEM cell).

Keywords: coaxial conical TEM cell, high-order mode, cutoff wavelength

1 Introduction

As field probes are being developed in the direction of broadband, the problem of broadband calibration in field probes becomes a serious issue. Currently, calibration of field probes is dependent on building a standard field according to the IEEE standard 1309-2005 “IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz”^[1]. A standard field is respectively established in TEM cell^[2-3] and GTEM cell^[4] with frequency 10 kHz–1 GHz, and in microwave anechoic chamber with frequency 1 GHz–40 GHz. Probes calibration in the microwave anechoic chamber, ten standard gain horn antennas covered together the whole frequency band which is measured for obtaining accurate gain firstly, and then used to produce a standard field. In the process of calibration, the antennas must be replaced one by one because of the narrow frequency band. Because of the cumbersome calibration methods, the period for probes calibration is very long and that only selected discrete frequencies can be operated.

In order to solve the problem above, a co-conical TEM cell of an electromagnetic guiding system for electric signals and power was first developed at NIST(National Institute of Standards and Technology), America in 1999, which was used for RF field standard system^[5-6]. Compared with air-filled rectangular coaxial transmission line structures(TEM cells) or flared TEM(GTEM) cells, the new co-conical line field standard is capable of performing an accurate broadband probe calibration with frequency from 10 MHz to 40 GHz. The co-conical line field standard takes place of these techniques at a considerable savings in capital facilities and realizes sweep frequency calibration. Therefore it has wide range of potential applications in the future.

The structure design of co-conical is the key determining the accuracy of probes calibration, because half angles of internal conductor and external conductor determine the cell's characteristic impedance and the number of transmitting high-order modes. The transmission of high-order modes inside the conical chamber can cause resonance and then a loss of energy, which further will seriously hurt the stability and uniformity of standard field. Hence, research of the relationship between half angles of conductors and propagation of high-order modes in chamber is very significant. Co-conical TEM cell for the

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probes calibration is a relatively new technology in United States, and few numerical data on the cutoff frequency of the present high-order modes is published by WEIL C M, et al^[7], from NIST, America in 2001, however the results are quite limited. For research purpose, some ideas from other conical waveguide equipment^[8-9] and bi-conical antenna^[10-12] design are used for reference. The theoretical foundation for designing waves guided within conical structures is from SCHELKUNOFF S A's theory^[13-15]. Based on the theory, STANIER J, et al^[16], conducted a theoretical analysis on hybrid modes in a dielectric lined conical waveguide. JAMES G L, et al^[17], analyzed the relationship between waveguide discontinuities and transmission of modes. DIRK I L^[18] from Stellenbosch University in South Africa described some theoretical calculation data of cutoff modes about conical transmission line power combiners with half angle of outer conductor being 90° in 2007. In China CUI Furong, et al^[19-21] from South China University of Technology utilized finite difference time domain(FDTD) methodology to analyze the uniformity of field in co-conical TEM cell which was designed with half angles of inner conductor and outer conductor being 15° and 30° respectively, and established its working frequency upper limit being 3 GHz.

Even though some researches have been done on conical structured waveguide equipment by some domestic and international experts, very limited numerical data is provided because of the complicity of the calculations required. In the paper, a thorough theoretical analysis of co-conical geometry is presented for designing high-performance co-conical TEM cell. A complete mathematical description, including Legendre function computation and numerical data, of the cutoff frequency of high-order modes is given. Consequently, a new structure of co-conical transmission lines is designed with better performance and the simulated results about field distributions of the high-order modes are obtained by CST-MWS.

2 Geometrical Construction of Co-conical

The geometrical construction of co-conical transmission line is shown in Fig. 1. It is mainly composed of inner conductor, outer conductor, impedance match, connector, termination and absorber. Generator injects signal into co-conical through connector. There is an electromagnetic field existing between inner conductor and outer conductor. The impedance match section is designed for matching the nominal 50Ω used by the excitation source, coaxial feed cable and connector to the line impedance value. Termination and absorber is used to absorb the traveling electromagnetic wave and then to reduce the wave reflection, which is help to make a homogeneous field at the text volume section for accurate probe calibration. In addition, maintaining the dominant TEM mode structure, reducing losses, and preventing generation of high-order modes is also an important factor for obtaining uniform

field. Therefore, numerical model of high-order mode in the line is presented and the process of propagation is analyzed.

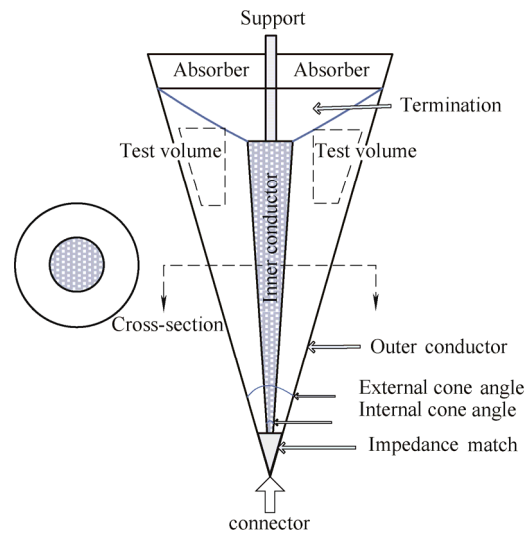


Fig. 1. Geometrical construction of co-conical TEM cell

3 Numerical Model of High-order Modes

The co-conical transmission line is analyzed using the spherical coordinate system. The geometry of a conical transmission line as well as the definition of the spherical coordinate system is shown in Fig. 2. The feed point of the line is set to origin, which is the coincidence peak of the two cones. The half angles of inner conical conductor and outer conical conductor are described by θ_1 and θ_2 respectively. Based on the SCHELKUNOFF's theory^[13-15], the transcendental equations of modal cutoff in co-conical are presented here.

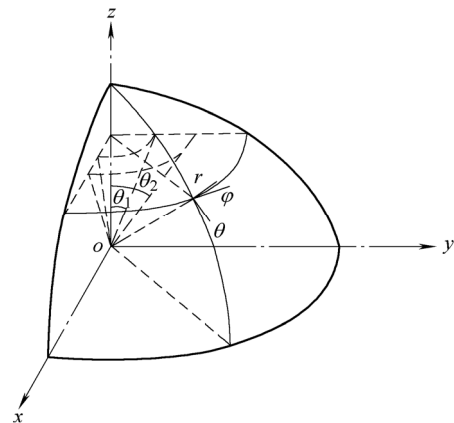


Fig. 2. Geometry of co-conical in spherical coordinate

3.1 Transverse electric(TE) mode

For a TE spherical wave propagating in the region between two coaxial conical conductors, the modal cut-off is defined by the following relationship^[17-18]:

$$\frac{dP_n^m(\cos \theta_1)}{d\theta_1} \cdot \frac{dQ_n^m(\cos \theta_2)}{d\theta_2} = \frac{dP_n^m(\cos \theta_2)}{d\theta_2} \cdot \frac{dQ_n^m(\cos \theta_1)}{d\theta_1}, \quad (1)$$

where m is the number of order, which is an integer($m=0, 1, 2 \dots$); n is the n th eigenfunction root, which is a nonzero integer; θ_1 is the half angle of inner conductor; θ_2 is the half angle of outer conductor; $P_n^m(\cos \theta_1), P_n^m(\cos \theta_2)$ are the first kind associated legendre functions; $Q_n^m(\cos \theta_1), Q_n^m(\cos \theta_2)$ are the second kind associated legendre functions.

3.2 Transverse Magnetic(TM) mode

For a TM spherical wave propagating in the region between two coaxial conical conductors, the modal cut-off is controlled by the following equation^[15, 18]:

$$P_n^m(\cos \theta_1) Q_n^m(\cos \theta_2) = P_n^m(\cos \theta_2) Q_n^m(\cos \theta_1). \quad (2)$$

4 Numerical Evaluation of High-order Mode

4.1 Recursion method

In order to obtain numerical results for the field distributions of the high-order modes in co-conical TEM cell, the transcendental Eqs. (1) and (2) have to be solved for the function root. Because of the much complex analytic expression of Legendre functions, it's hard to obtain the solution directly. There are some recursions used for simplifying the calculation.

The recursions of associated Legendre functions are as follows^[22]:

$$P_n^m(x) = \frac{1}{n-m} [(2n-1)xP_{n-1}^m(x) - (n+m-1)P_{n-2}^m(x)], \quad (3)$$

$$P_n^m(x) = -\frac{2(m-1)}{\sqrt{1-x^2}} xP_{n-1}^{m-1}(x) - (n+m-1)(n-m+2)P_{n-2}^{m-2}(x), \quad (4)$$

$$\frac{d}{dx} P_n^m(x) = \frac{1}{x^2-1} [nxP_n^m(x) - (n+m)P_{n-1}^m(x)]. \quad (5)$$

These recursions are also suitable for the second kind associated Legendre function. The starting values can be calculated from the known polynomials^[22-24] just as follows:

$$\begin{aligned} P_1^0(x) &= x, & P_1^1(x) &= (1-x^2)^{\frac{1}{2}}; \\ P_2^0(x) &= 0, & P_2^1(x) &= \frac{1}{2}(3x^2-1); \\ P_2^1(x) &= 3x(1-x^2)^{\frac{1}{2}}, & P_2^2(x) &= 3(1-x^2)^{\frac{1}{2}}; \\ Q_0^0(x) &= \frac{1}{2} \ln \frac{1+x}{1-x}, & Q_0^1(x) &= (1-x^2)^{-\frac{1}{2}}; \\ Q_1^1(x) &= (1-x^2)^{\frac{1}{2}} \left(\frac{1}{2} \ln \frac{1+x}{1-x} + \frac{x}{1-x^2} \right); \end{aligned}$$

$$\begin{aligned} Q_1^0(x) &= \frac{x}{2} \ln \frac{1+x}{1-x} - 1, & Q_1^2(x) &= \frac{2}{1-x^2}; \\ Q_2^0(x) &= \frac{1}{4}(3x^2-1) \ln \frac{1+x}{1-x} - \frac{3}{2}x. \end{aligned}$$

Therefore the expression of high-order Legendre functions can be deduced.

4.2 Calculation results

In order to obtain a suitable size of calibration space and little high-order modes, a co-conical transmitting line is designed with the half angles being $\theta_1=1.513^\circ, \theta_2=8^\circ$, respectively. A calculation program is made using the numerical software Matlab 6.5 in iteration method. n is the integral with range 0-80, and $m=0, 1, 2$ respectively. The results of the co-conical transmitting line for high-order modes as compared with its values designed by NIST with the half angles being $\theta_1=1.893^\circ, \theta_2=10^\circ$ are as follows.

4.2.1 Results of co-conical with $\theta_1=1.513^\circ, \theta_2=8^\circ$

Result values of Eqs. (1) and (2) are expressed in y . The first three order result curves($m=0, 1, 2$) of transcendental Eqs. (1) and (2) are shown in Fig. 3 and Fig. 4.

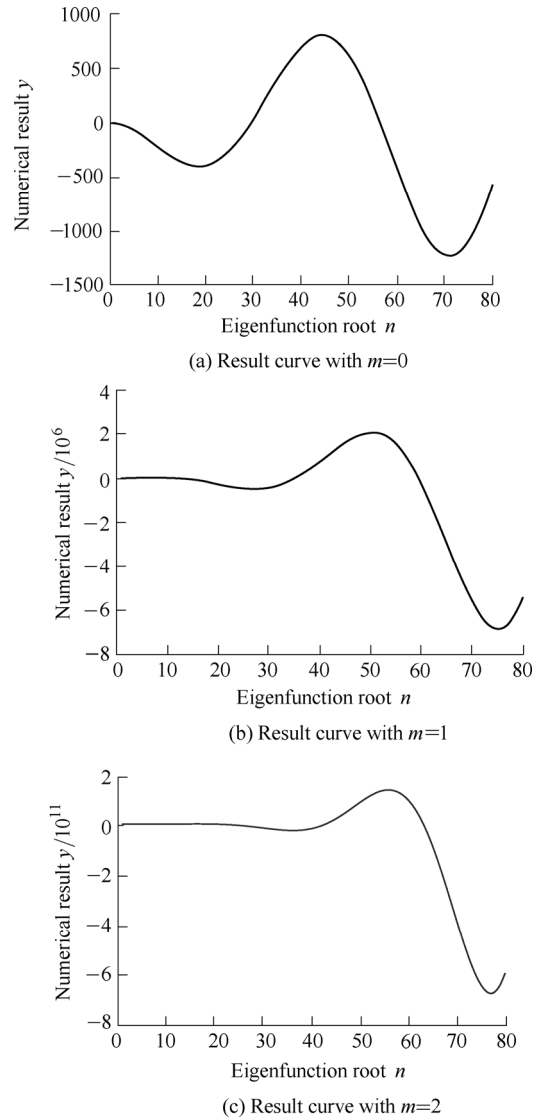


Fig. 3. Result curves of Eq. (1) with $\theta_1=1.513^\circ, \theta_2=8^\circ$

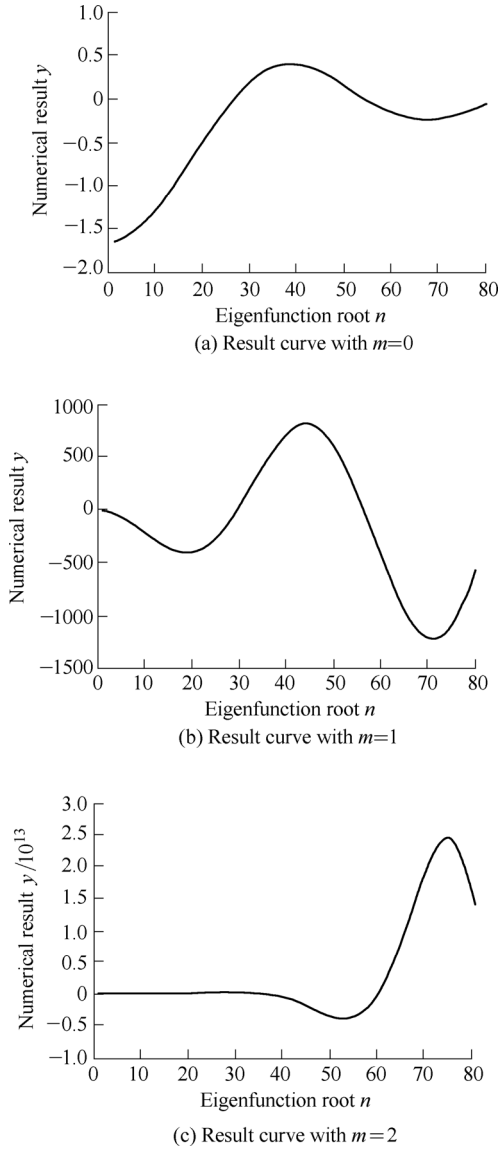


Fig. 4. Result curves of Eq. (2) with $\theta_1=1.513^\circ$, $\theta_2=8^\circ$

The number of cross points that the curve crosses with $y=0$ coordinate axis represent the number of roots of function. For example, in Fig. 3 there have two roots v_{01} and v_{02} with $m=0$, 3 roots v_{11} , v_{12} and v_{13} with $m=1$ and 4 roots v_{21} , v_{22} , v_{23} and v_{24} with $m=2$. Roots of Eqs. (1) and (2) are listed in Tables 1 and 2 separately.

Table 1. Roots of Eq. (1)

Order number <i>m</i>	Root			
	v_{m1}	v_{m2}	v_{m3}	v_{m4}
0	29	57	—	—
1	11.2	35.4	59	—
2	20.3	42.5	51	62

Table 2. Roots of Eq. (2)

Order number <i>m</i>	Root	
	v_{m1}	v_{m2}
0	26.4	54.5
1	29.2	56.4
2	36.1	60.2

4.2.2 Results of co-conical with $\theta_1=1.893^\circ$, $\theta_2=10^\circ$

The first three order result curves ($m=0, 1, 2$) of transcendental Eqs.(1) and (2) are shown in Fig. 5 and Fig. 6.

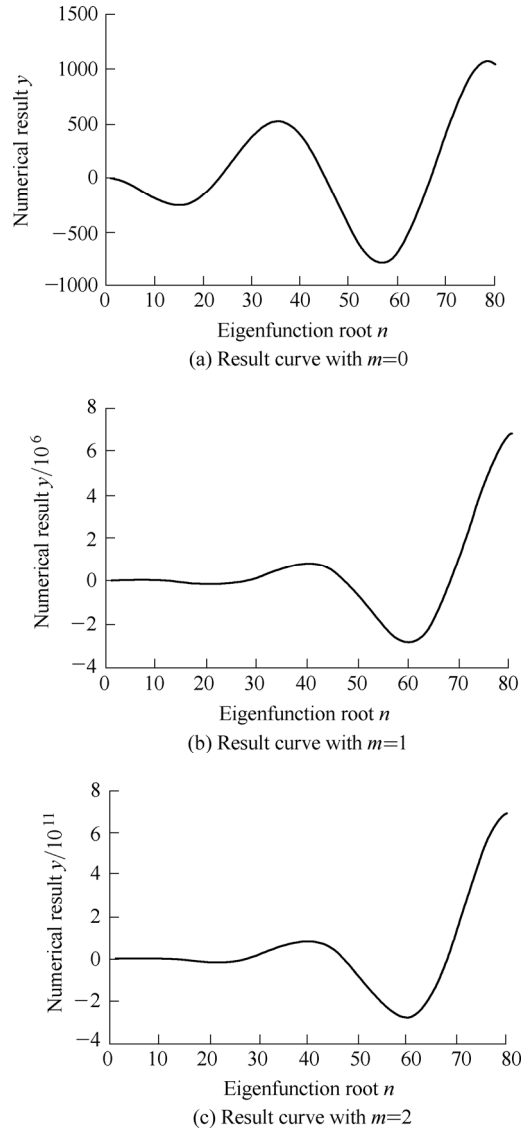


Fig. 5. Result curves of Eq. (1) with $\theta_1=1.893^\circ$, $\theta_2=10^\circ$

The roots of Eqs. (1) and (2) are listed in Tables 3 and 4 separately.

The number of roots represents the number of high-order modes. The more of the roots, the more high-order modes can propagate in the co-conical TEM cell. To improve the quality of standard field in conical chamber, amount of modes must be reduced. From the result above, the characteristic of co-conical TEM cell with $\theta_1=1.513^\circ$, $\theta_2=8^\circ$ is better than that with $\theta_1=1.893^\circ$, $\theta_2=10^\circ$, because of few modes.

4.3 Cutoff frequency of high-order mode

The cutoff frequency for high-order modes in the co-conical line is given by

$$f_c = \frac{c\sqrt{v(v+1)}}{2\pi r}, \tag{6}$$

where f_c —Cutoff frequency of high-order modes,
 r —Distance between cone feed and measure point,
 v —Roots of transcendental Eqs. (1) and (2)
 for the TE and TM mode respectively,
 c —Speed velocity of wave in free space.

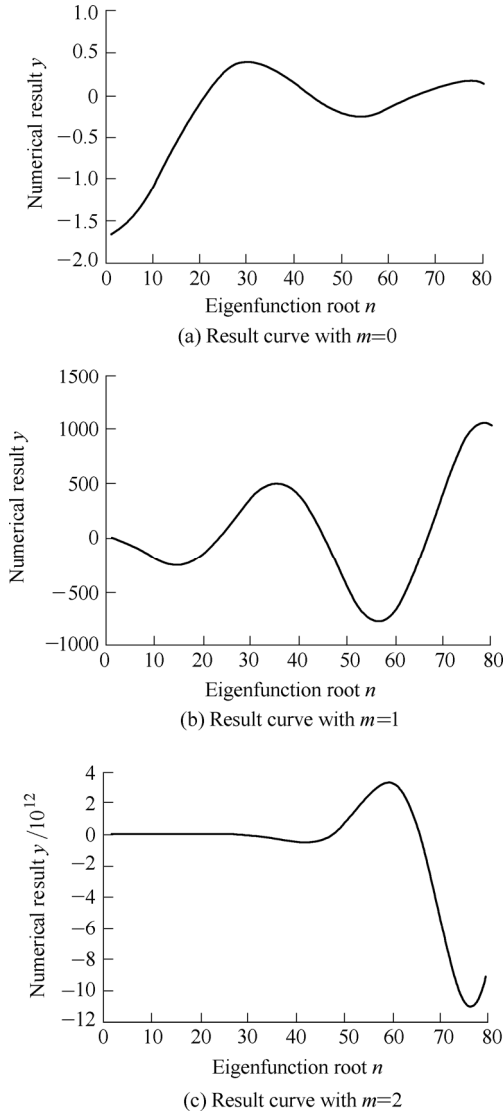


Fig. 6. Result curves of Eq. (2) with $\theta_1=1.893^\circ$, $\theta_2=10^\circ$

Table 3. Roots of Eq. (1)

Order number m	Root			
	v_{m1}	v_{m2}	v_{m3}	v_{m4}
0	23.5	45.2	66.9	—
1	9.2	27.6	47.5	68.3
2	16.6	34.7	50.2	68.4

Table 4. Roots of Eq. (2)

Order number m	Root		
	v_{m1}	v_{m2}	v_{m3}
0	21.5	43.5	65.9
1	23.6	45.3	66.9
2	28.6	47.6	66.4

Depending on the roots and Eq. (6) above, when the half

angles of inner conductor and outer conductor of the co-conical TEM cell are $\theta_1=1.5136^\circ$ and $\theta_2=8^\circ$, the cutoff wave length of the high-order modes is obtained as shown in Fig. 7. The first high-order mode is TE₁₁ with the longest cutoff wavelength $0.53r$. The cutoff zone is the district that wavelength is longer than the cutoff wavelength of TE₁₁. In the region, the high-order modes can be non-propagating and only TEM wave propagating λ_c of the mode is relative to r , therefore there is a gradual transition for mode from the non-propagating to the propagating region. The point of gradual cutoff of a mode is not only dependent on frequency, but also on the spatial coordinates.

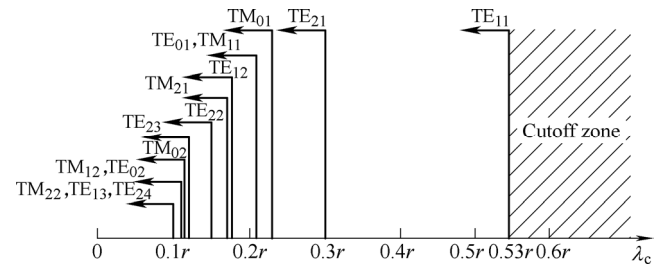


Fig. 7. Cutoff wavelength of high-order modes in co-conical TEM cell

For the co-conical TEM cell with $\theta_1=1.5136^\circ$, $\theta_2=8^\circ$, the position for calibration is decided by space at the place $r=1.8$ m. When $r=1.8$ m the cutoff frequency of several main high-order modes for TE wave and TM wave are shown in Table 5 in order.

Table 5. Cutoff frequency of high-order modes

Mode	Frequency f_c /GHz	Mode	Frequency f_c /GHz	Mode	Frequency f_c /GHz
TE ₁₁	0.32	TE ₁₂	0.94	TE ₀₂	1.54
TE ₂₁	0.57	TM ₂₁	1.00	TM ₁₂	1.54
TM ₀₁	0.74	TE ₂₂	1.13	TE ₂₄	1.70
TE ₀₁	0.81	TE ₂₃	1.39	TM ₂₂	1.70
TM ₁₁	0.81	TM ₀₂	1.49	TE ₁₃	1.70

5 Modal Plots

From Table 6, some high-order modes have lower cutoff frequencies. If the work frequency is from 200 MHz–40 GHz, high-order modes can transmit in the co-conical TEM cell. The transmission characteristics of high-order modes are discussed in the next.

In order to analyze the transmission characteristic, the CST-MWS software is used for simulating the process of electromagnetic wave propagation. Geometry consistent with the proposed co-conical structure will be chosen. The impedance of Z_0 is equal to 75Ω with $\theta_1=1.5136^\circ$, $\theta_2=8^\circ$. The outer radius of the line is chosen as r which is equal to 180 mm. There are two ports which are designed as waveguide. The small one is port 1 from which the signal is injected. The big one is port 2 that is terminated by load.

5.1 Traveling wave

Field plots of the first three modes at frequency 1 GHz

are as follows.

The simulation result plot for TEM wave is presented in Fig. 8. TEM wave can transmit in the co-conical TEM cell without cutoff frequency. When the signal is injected from port 1, TEM wave transmit along with r direction. The wave is reflected at opposition direction from port 2 if there are poor absorbers in port 2. It very clearly illustrates TEM wave can propagate at all region of cavity.

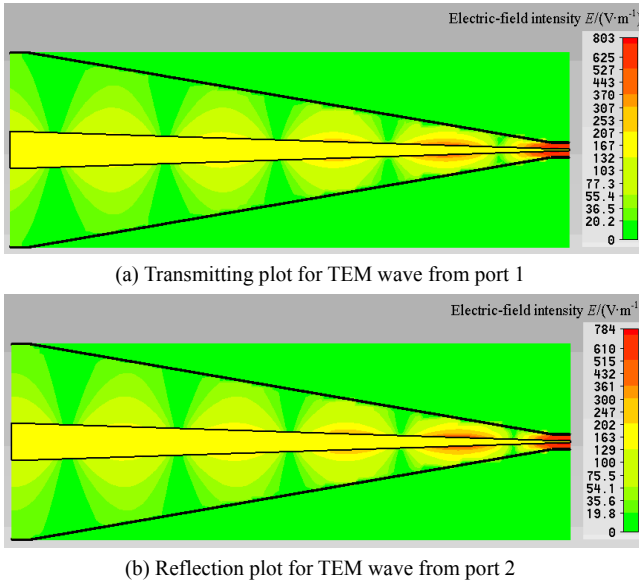


Fig. 8. Simulation result plot for TEM wave transmission

In Figs. 9 and 10 the traveling wave properties of the higher order modes are clearly visible. The modes do not propagate when signal being injected from port 1, they however shall produce a strong field of reflection wave from port 2. Large fields exist in the propagating regions. The point of gradual cutoff of a mode is dependent on frequency and the spatial coordinates. The cutoff radius(a mode is the minimum radius where the mode is propagating at a certain frequency) of TE_{21} is longer than that of TE_{11} , therefore the position of TE_{21} reflection field is closer to port 2 compared with TE_{11} .

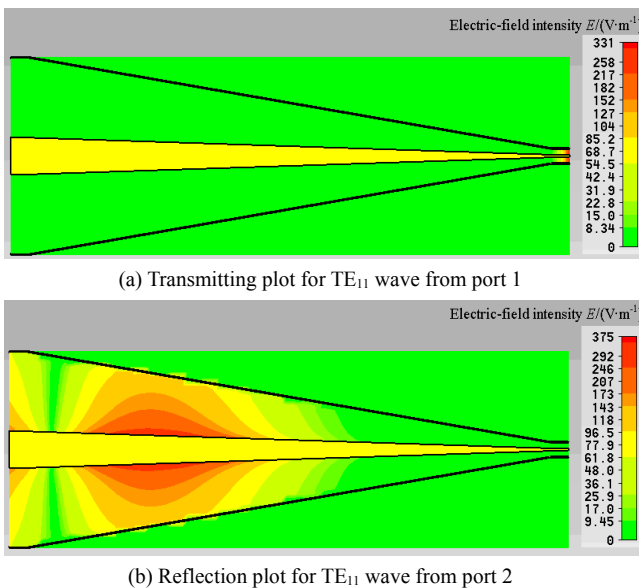


Fig. 9. Simulation result plot for TE_{11} wave transmission

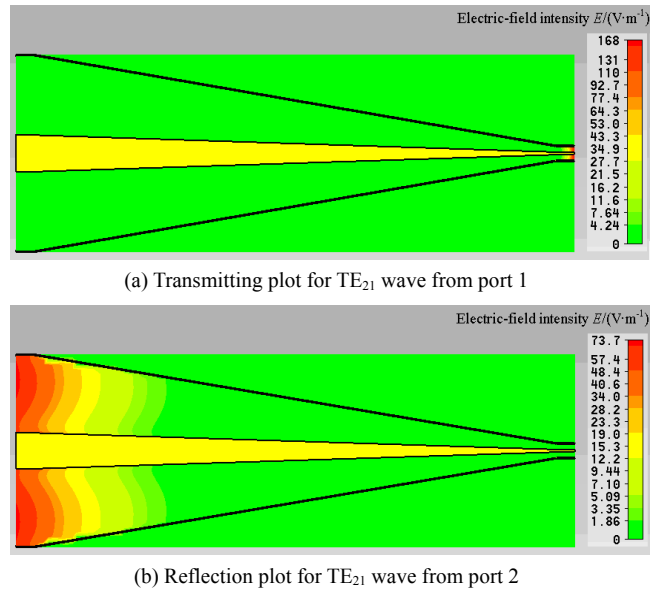


Fig. 10. Simulation result plot for TE_{21} wave transmission

5.2 Standing wave

The field patterns of electromagnetic wave are shown in Figs. 11 to 13. The wave fronts of these modes are visible along the r -axis.

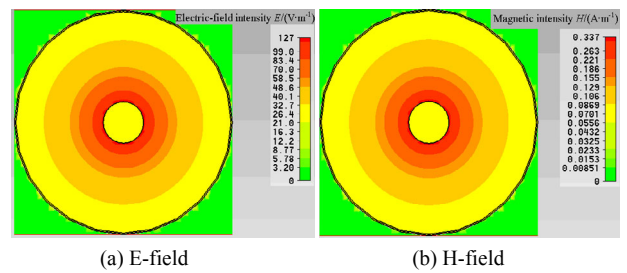


Fig. 11. TEM modal fields at 1GHz

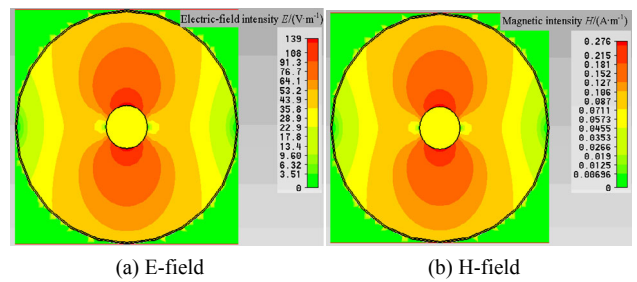


Fig. 12. TE_{11} modal fields at 1GHz

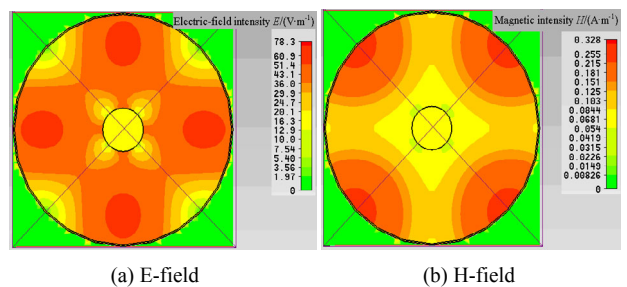


Fig. 13. TE_{21} modal fields at 1GHz

For TEM wave, the amplitude of field is centro-symmetry by inner conductor and decreases gradually from inner to outer. The amplitude of TE_{11} field is axially

symmetry and it is more complex for TE_{21} field. Therefore the standing waves of high-order modes affect the field uniformity of TEM wave. In order to control the transmission of high-order modes, a good match is important for reducing reflection.

6 Conclusions

(1) According to the numerical analysis of high-order mode, the number of high-order modes with $\theta_1=1.5136^\circ$, $\theta_2=8^\circ$ is obviously fewer than that with $\theta_1=1.893^\circ$, $\theta_2=10^\circ$, which means the performance of the standard field produced in the previous structured co-conical TEM cell is better.

(2) From the simulation, when signal is injected in port 1, there is none of high-order modes transmission because of good match and absorbers in port 2. The E-field of TEM is only θ -directed, and the H-field have no component in the θ -direction.

(3) If the reflection wave from port 2 exists, high-order modes propagate at propagating regions that the radius is bigger than the cutoff radius of modes. Strong fields of standing wave are produced.

(4) The higher order of mode, the more complex field of mode is in existence and then uniformity of TEM field may be destroyed. Reflection is one important reason for high-order modes appearance.

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