A Study on Upper Limit Frequency of Symmetric Extended TEM Cells

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Abstract **─** TEM Cells is a commonly used electromagnetic field test device. The upper limit frequency of the TEM Cells is limited to the first resonant frequency. Through the electromagnetic numerical simulation, this paper analyzes the resonant frequency law of high-order modes and studies the resonant frequency characteristics and the upper limit of the frequency of symmetrically extended TEM Cells. Studies have shown that there is an error in the estimated value of the X_{mn} parameter used in the conventional standard TEM Cells resonant frequency calculation method, which may lead to errors in the order of the resonant modes. Symmetrically extended TEM Cells do not change the original resonant frequency, but because of the coupling modes of even mode and odd mode between two cell units, each of the original resonant frequencies will split two close resonant frequency.

Index Terms **─** Resonant frequency, resonant modes, TEM Cells, upper limit frequency.

I. INTRODUCTION

TEM Cells was originally proposed by Crawford in 1974 [1], which is a transverse electromagnetic (TEM) wave transmission structure like coaxial lines, mainly composed of an intermediate transmission section and a transition section.

The working frequency of the TEM Cells is limited to the first resonant frequency. Above this frequency, electromagnetic waves in the TE mode or TM mode will be generated in the TEM Cells, affecting the distribution of the electromagnetic field in the TEM mode, thereby affecting the test accuracy. Hill pointed out that the TE01 mode is the first higher-order mode to propagate in the intermediate transmission section of TEM Cells, followed by TE10 mode [2]. The calculation method for the cutoff frequency of TE01 mode and TE10 mode respectively proposed by Wilson and Ma [3] and Crawford and Workman [4] were recommended in IEEE STD 1309-2005 [5]. Chen found that Wilson's method leads to erroneous conclusions in the calculation of higher-order modes. Then he gives a computer code to compute higher-order modes and a fitting curve for the first higher-order mode cutoff frequency of 50 Ω TEM Cells [6]. Chen's method was recommended by IEEE STD 1309-2013 [7] to replace the original method. To expand the bandwidth of TEM Cells, Deng et al. proposed some methods, such as slitting the outer wall, placing magnetic rings or ferrite components, and attaching absorbing materials [8,9].

In order to extend the test space, Wilson and Ma proposed asymmetric TEM Cells [3]. Malathi studied the extended characteristic impedance of asymmetric TEM Cells [10]. Virginie proposed a three-dimensional TEM cell [11]. Dai and Song et al. proposed TEM Cells with dual and quadruple symmetric extensions [12,13]. When expanding the space, the higher-order mode cutoff frequencies of TEM Cells are not expected to be reduced. This paper will further study the upper limit of the use frequency of symmetric extended TEM Cells.

II. THE LAW OF HIGH-ORDER MODE RESONANCE FREQUENCY OF TEM CELLS

In Fig. 1, the bottom walls/plates of two identical TEM Cells are bonded together first and removed then. By applying an ideal differential excitation to the input ports, a virtual electric wall can be formed at the overlapping walls. Therefore, it will not change the electromagnetic field distribution when removing the overlapping plates, thereby multiplying the test area.

Hill proposed two models with the same structure but different dimensions [2]. The basic TEM Cells used these two models to analyze the high-order mode resonant frequency. Figure 2 shows the Radial diagram of the TEM Cell model. The size of model I is a=b=3m, g=0.26m, $\boldsymbol{L_c}$ = $\boldsymbol{L_E}$ =3.0m; the size of the model II is a=6.1m, b=7.32m, g=1.02m, $\boldsymbol{L_c}$=6.1m, $\boldsymbol{L_E}$=6.86m. Hill, Wilson, and Chen calculated that the cut-off frequencies and resonant frequencies of the first few higher-order

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modes of the two models are basically the same [2,3,6], as shown in Table 1 and Table 2. Hill gives the relationship between resonant frequency and cut-off frequency [2]:

$$f_{R(mnp)} = \sqrt{f^2{}_{c(mn)} + (\frac{pc}{2L_{mn}})^2}, \quad (1)$$

$$L_{mn} = L_c + X_{mn}L_E. \quad (2)$$

Where

c is the speed of light ($\approx 3 \times 10^8 \mathrm{m/s}$),

m, n, p are mode numbers,

L_{mn} is the equivalent electrical length of the TEM Cells,

L_c is the length of the central section,

L_E is the sum of the lengths of the two tapered sections,

X_{mn} is a mode-depended fraction.

Approximate values of X_{01}= 0.77 and X_{10}= 0.47 can be used [7].

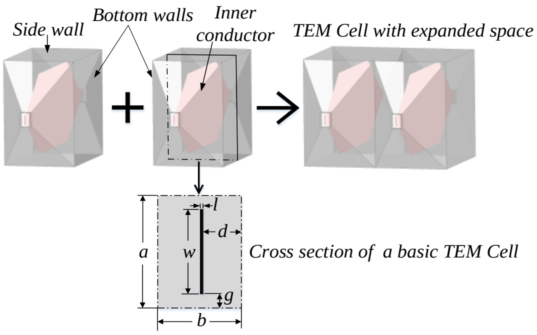


Fig. 1. Symmetrically extended TEM Cells.

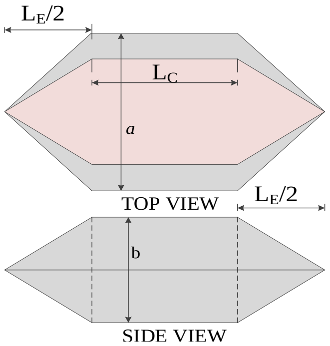


Fig. 2. Radial diagram of a basic TEM Cell.

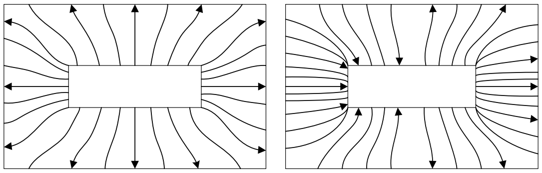
Table 1: Cutoff frequencies and resonant frequencies of Model I (a=b=3m, g=0.26m, L_c=L_E=3.0m)

Mode	$f_{C(m,n)}$ (MHz)	Mode	$f_{R(m,n,p)}$ (MHz)
TE01	29.0	TE011	40
TE10	50	TE101	60
TE01	29.0	TE012	63
TE11	63.5	TE111	73
TE10	50	TE102	84
TE01	29.0	TE013	89

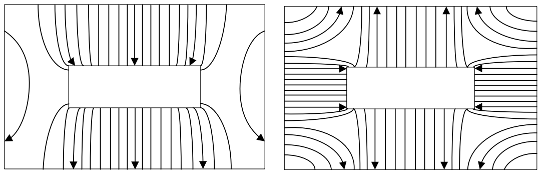
Table 2: Cutoff frequencies and resonant frequencies of Model II (a=6.1m, b=7.32m, g=1.02m, L_c=6.1m, L_E=6.86m)

Mode	$f_{C(m,n)}$ (MHz)	Mode	$f_{R(m,n,p)}$ (MHz)
TE01	15.2	TE011	20.7
TE10	24.6	TE101	30.01
TE01	15.2	TE012	31.51
TE11	31.3	TE111	36.08
TE10	24.6	TE102	40.98
TE01	15.2	TE013	42.06

Hill gives a description of the field distribution of higher-order modes in TEM Cells [2], as shown in Fig. 3.



TEM mode TE01 mode



TE10 mode TE11 mode

Fig. 3. The TEM mode and the first three high-order modes on cross section of a TEM Cell.

The quality factor is a quality indicator that represents the ratio of stored energy to lost energy. When the material is an ideal metal, its loss energy is zero, so the quality factor is infinite. To compare the difference between the real metal boundary and the ideal boundary, the simulations of the two cases were simulated respectively. Model I and Model II were analyzed in the eigenmode of HFSS where simulations were performed for both models. In the first case, walls and septum are set to PEC. In the other case, walls are set to aluminum and septum is set to copper. The simulation results are shown in Table 3.

Table 3 shows that the resonant frequency is not affected by the material, and the quality factor is dependent only on the structural geometry. Comparing Table 1, Table 2, and Table 3, the resonant frequencies in the grey part of Table 3 are the higher-order mode frequencies appearing in Tables 1 and 2. However, Table 3 has more higher-order modes than Tables 1 and 2. They are given in the 1st line, 3rd line, 6th line, and 10th line of Table 3 shown in white background. Figure 4 shows that the distributions of the E-field vectors on these four modes on cross section of Model I conform to the TEM mode shown in Fig. 3.

Table 3: Resonant frequencies and quality factors calculated by HFSS

No.	Model I			Model II			Mode
	PEC	Cu & AL		PEC	Cu & AL		
	f_R (MHz)	f_R (MHz)	Q	f_R (MHz)	f_R (MHz)	Q	
1	24.63	23.15	2253	11.59	11.10	5498	TEM
2	39.21	39.56	14993	20.53	20.71	43591	TE01
3	46.72	44.36	3210	22.06	21.28	7846	TEM
4	58.80	59.10	12285	30.01	30.01	164607	TE01
5	61.58	61.57	108379	30.37	30.68	34829	TE10
6	68.66	66.10	4497	32.58	31.61	10974	TEM
7	73.47	73.91	63825	36.01	36.10	121977	TE11
8	79.61	80.13	13688	40.12	40.48	37769	TE01
9	85.24	85.24	135189	40.86	40.85	205474	TE10
10	92.36	89.43	5506	43.98	42.81	13516	TEM

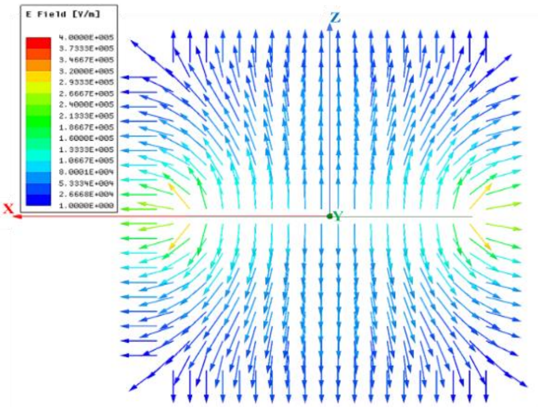
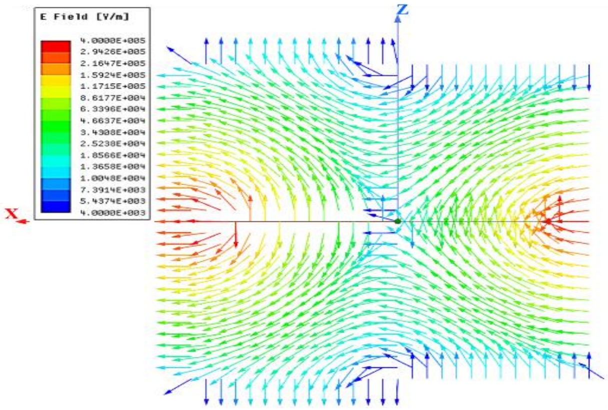
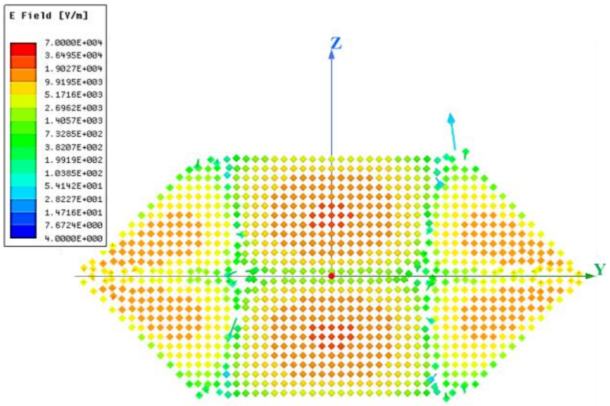


Fig. 4. TEM mode field distribution in Model I.

In the eigenmode of HFSS, to enhance the internal resonance effect of TEM Cells, the input and output ports of the TEM Cells are set as total reflection ports instead of the actual matching impedance. Therefore, the simulation results show that the resonant mode is the TEM mode, like a dedicated coaxial resonant cavity, which will not occur in actual use. The quality factor of this virtual resonant mode is also significantly lower than other real resonant modes. Therefore, these situations are excluded when analyzing high-order modes. The 2nd, 4th, 5th, 7th, 8th, and 9th resonant modes in Table 3 respectively correspond to the TE011, TE012, TE101, TE111, TE013, and TE102 modes. According to the cross section, the m, n of the resonance mode can be known, and the k of the resonance mode can be known from the longitudinal section. For example, Fig. 5 shows the electric field distribution of the 8th mode. It is known by the cross section that it is the TE01 mode. According to the longitudinal section, it has three standing waves, so it is the TE013 mode.



Cross section



Longitudinal section

Fig. 5. The 8th resonant mode field distribution in Model I.

The order of the first six higher-order modes obtained by HFSS simulation are inconsistent with Hill and Chen's calculations. The order given by them is TE011, TE101, TE012, TE111, TE102 and TE013 modes. Possibly, X_{mn} estimated value given in Equation 2 may lead to the problem. Hill believes that the same cutoff mode has the same X_{mn}. However, a more reasonable speculation is that there is an inverse relationship between the wavelength and X_{mn}, and the opening angle of the tapered section is proportional to X_{mn}. Table 4 is the X_{mn} values calculated from the HFSS simulation results.

Table 4: X_{mn} calculated by HFSS

p	Model I		Model II	
	X_{01}	X_{10}	X_{01}	X_{10}
1	0.86	0.39	0.66	0.38
2	0.94	0.45	0.8	0.45
3	1	0.88	0.86	0.63

The estimated value of X_{mn} is calculated by Hill based on the frequency of the first high-order mode, so this error has no effect on the first high-order mode, but only affects the order in which the higher-order modes appear. Because the operating frequency of the TEM Cells is limited to the first resonant frequency, the error caused by it does not affect the upper limit frequency of the TEM Cells.

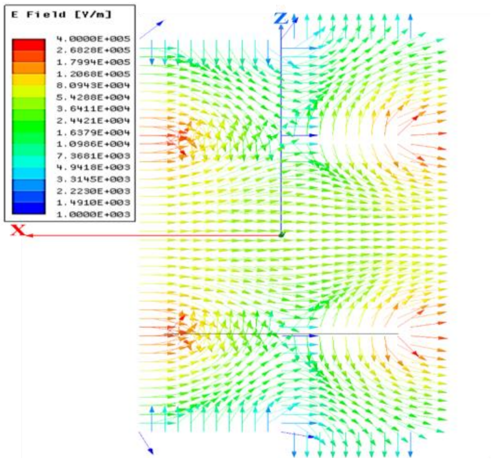
III. UPPER LIMIT FREQUENCY OF THE SYMMETRICALLY EXTENDED TEM CELLS

When the basic TEM Cells are symmetrically expanded into dual cells and quadruple cells, the test space will be multiplied, and the resonant frequency may be reduced. The Model I and Model II were extended to dual TEM Cells in HFSS, and the resonant frequency is shown in Table 5.

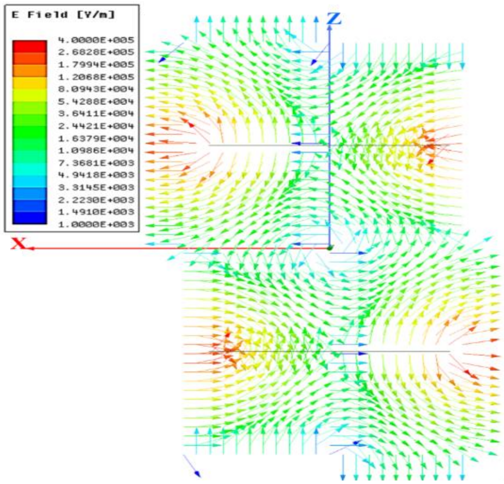
Table 5: Resonant frequencies and quality factors of dual TEM Cells calculated by HFSS

No.	Model I		Model II		Mode
	Cu & AL		Cu & AL		
	f_R (MHz)	Q	f_R (MHz)	Q	
1	23.14	2241.38	11.02	4182.52	TEM/ Even mode
2	23.36	2245.40	11.09	4179.41	TEM/ Odd mode
3	36.10	13948.24	18.72	40885.57	TE01/ Odd mode
4	39.55	15078.79	20.75	43753.47	TE01/ Even mode
5	43.48	3180.38	20.79	5953.72	TEM/ Odd mode
6	44.36	3202.32	21.14	5910.43	TEM/ Even mode
7	58.60	12257.61	30.01	185562.56	TE01/ Odd mode
8	59.10	12265.43	30.48	34103.58	TE01/ Even mode
9	61.57	126363.77	30.49	12448.22	TE10/ Even mode
10	63.37	7052.79	30.73	34104.86	TE10/ Odd mode

Comparing Table 3, Table 5 shows that two resonant frequencies occur near each resonant frequency of the basic TEM Cells. Taking the 3rd and 4th modes of Table 5 as an example, observe the E field vectors on cross section (Fig. 6). The distribution of electric field vectors on cross section of the 3rd mode can be regarded as two TE01 mode fields of the same amplitude and directions, which is equivalent to an even mode (or common mode); The distribution of electric field vectors on cross section of the 4th mode can be regarded as two TE01 mode fields of the same amplitude and opposite directions. The merging of the distribution is equivalent to an odd mode (or differential mode).



The 3rd mode (TE01/Odd mode)



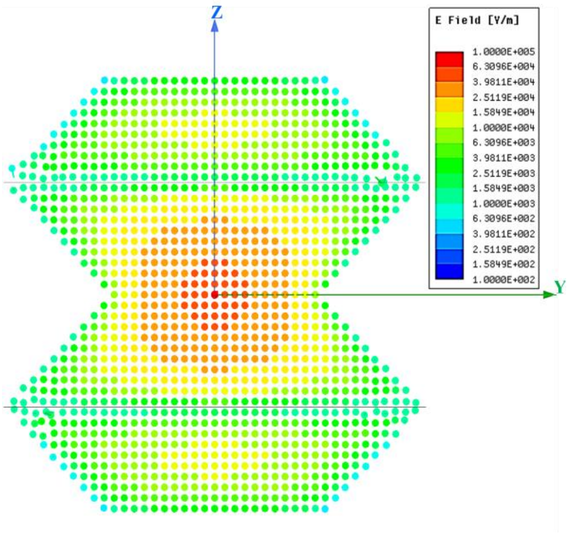
The 4th mode (TE01/Even mode)

Fig. 6. The distributions of E field vectors on cross section.

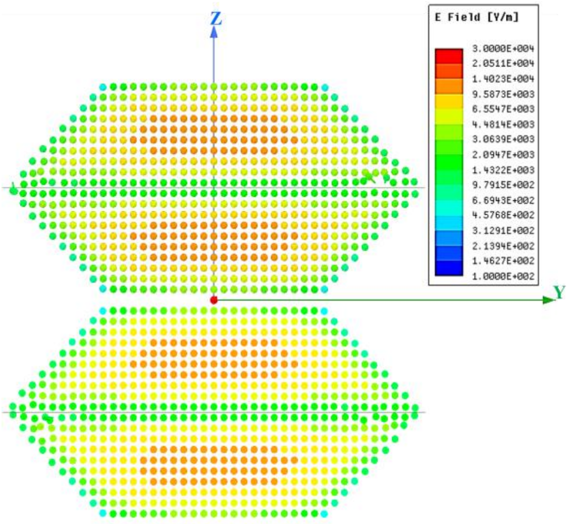
Comparing Fig. 7 and Fig. 5, the distributions of E field vectors on longitudinal section of these two modes shows that there is only one standing wave, indicating that they are both TE011 modes.

Compared with the basic TEM Cells and dual TEM Cells, the boundary conditions of the first higher-order modes do not change, so the resonant frequency do not change too. However, the original resonant mode is split into an even mode (or differential mode) and an odd mode (or common mode).

The cutoff frequency of the first higher-order mode $f_{C(m,n)}$ is determined from the cross section of the TEM ell [7]. The dominant mode for a rectangular TEM cell is either the TE01 mode or the TE10 mode; therefore, the first resonant frequency is either $f_{R(011)}$ or $f_{R(101)}$. In dual TEM Cells, the common mode excitation enhances the E-field of the TE01 mode, and the differential mode excitation enhances the E-field of the TE10 mode. Then the interference of the E-field is increased. To avoid the influence of this interference on the field distribution, the use frequency of dual TEM Cells still should be strictly limited to the resonant frequency of the TE011 or TE101 mode. The calculation method can continue to use the method for the standard TEM Cells high frequency resonant frequency recommended in IEEE STD 1309-2013.



The 3rd mode (TE01/Odd mode)



The 4th mode (TE01/Even mode)

Fig. 7. The distributions of E field vectors on longitudinal section.

IV. CONCLUSION

By comparing and analyzing the resonant frequency data of the high-order mode, it is found that the resonant frequency is not affected by the material, and the quality factor is related to the characteristics of the metal material. However, the order of the resonant modes calculated by TEM Cells will have some errors with the actual results. This paper believes that there is an error in the estimated value of the X_{mn} parameter used in the traditional standard TEM Cells resonant frequency calculation method, which is the cause of this error. The relationship between the X_{mn} parameter and the TEM cell opening angle will be further studied in the future, and the previous estimation value can be replaced with a more accurate X_{mn} parameter, so that the calculation of the resonance frequency will be more accurate.

Based on the high-order mode resonant frequency law of standard TEM Cells, the resonant frequency characteristics and upper frequency limit of symmetric extended TEM Cells are studied. Compared with the basic TEM Cells and dual TEM Cells, the boundary conditions of the first higher order modes do not change, so the resonant frequency remains unchanged. However, due to the two coupling modes of even mode and odd mode between the two cell units, each of the original resonant frequencies will split two close resonant frequencies, which is to further study the two modes of even mode and odd mode. The law of variation of the coupling mode provides the basis.

For symmetrically extended TEM Cells, the two resonant frequencies split by each resonant frequency are very close to each other. Therefore, the frequency of use of dual TEM Cells should be strictly limited to the resonant frequency of the first higher-order mode. The calculation method can continue to adopt the standard TEM Cells high frequency resonant frequency calculation method recommended in IEEE STD 1309-2013.

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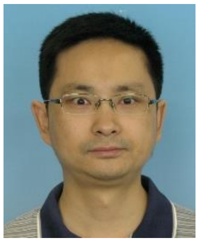

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