Mathematical Model for Calibration of Potential Detection of Nonlinear Responses in Biological Media Exposed to RF Energy

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Abstract **─** An efficient way to test for potential unsymmetrical nonlinear responses in biological tissue samples exposed to a microwave signal is to observe the second harmonic in a cavity resonant at the two frequencies, with collocated antinodes. Such a response would be of interest as being a mechanism that could enable demodulation of information-carrying waveforms. In this work, an electric circuit model is proposed to facilitate calibration of any putative nonlinear RF energy conversion inside a high quality-factor resonant cavity with a known nonlinear loading device. The first and second harmonic responses of the cavity due to loading with the nonlinear and lossy material are also demonstrated. The results from the proposed mathematical model give a good indication of the input power required to detect any very weak second harmonic signal in relation to the sensitivity of the measurement equipment. Hence, this proposed mathematical model will assist in determining the level of the second harmonic signal in the detector as a function of the specific input power applied.

Index Terms **─** Biological responses, nonlinearity, quality factor, resonant cavity, second harmonic.

I. INTRODUCTION

With the explosive growth of mobile communications, large numbers of researchers around the world have studied the interaction mechanisms between electromagnetic fields and biological tissues. The result has been the development of research streams in different aspects of bioelectromagnetic problems at various levels of definition such as tissue level, cell level and ionic level, with intensive effort worldwide [1-17].

However, most of the previous analyses have been performed treating bulk tissue effects as a linear problem. Recently, the tendency of research in this area has moved towards seeking evidence for the existence of nonlinear tissue responses, involving microscopic studies of cellular and molecular processes. Many experiments have been proposed in order to clarify the various nonlinearity hypotheses for biological tissue. Balzano [4-8] has suggested that the detection of the presence of nonlinear interactions can be investigated by exposing living cells to low-amplitude unmodulated RF carriers and observing the possible generation of second harmonics. Such harmonics would be inherent in any unsymmetrically-nonlinear medium; a property essential for demodulation of modulated waveforms. Demodulation has been postulated as a plausible mode for putative non-thermal effects of RF radiation on living organisms.

By implementing a doubly harmonic resonant cavity model, as proposed in [4-8], this paper presents an electric circuit model to verify second harmonic generation from a known nonlinear device and suggests the required level of input power needed to excite the

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bio-preparation in order to maximize the chance of detection of a possible second harmonic signal.

II. METHODOLOGY

The proposed mathematical model is an extension of some earlier work [18]. It consists of two parts: cavity model design and electric circuit model. The cavity model will be first described and S-parameters of the model will be extracted by using CST Microwave Studio software [19]. Once these data are obtained, they will be adopted into the derived equations from the proposed circuit model to calculate the second harmonic power with known input power.

A. Cavity model design

The previously-reported practical work was undertaken with a carrier frequency in the 880-890 MHz band. To investigate whether biological cells exhibit unsymmetrical nonlinearity when exposed to such RF energy, a high quality-factor resonant cylindrical cavity was created, having diameter and height of 248 mm and 272 mm respectively. The cavity was built with two rectangular loop coupling antennas and a support structure for biopreparations, i.e., a butterfly-shaped Lexan lamina and Petri dish, as shown in Fig. 1. As can be seen, the antenna with size 14x105 mm^2 at the bottom of the cavity acts as a transmitter to excite the TE_{111} cavity mode in the 880-890 MHz band; whereas the antenna with size 12.5 x 56.5 mm^2 on the side wall of the cavity was used to detect the energy of the TE_{113} cavity mode in the range 1760-1790 MHz. It should be noted that the lengths of the transmit and receive antennas were fine tuned in order to achieve the TE_{113} mode resonant at exactly double the frequency of the TE_{111} mode.

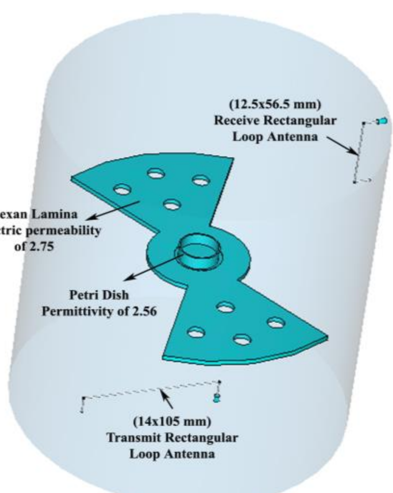

Fig. 1. The dimensions of the cavity modeled, with its Lexan sample support structure and two rectangular loop antennas.

B. Electric circuit model for calibrations

In order to more precisely quantify the amount of input power required in the excitation port to generate a detectable second harmonic signal, a mathematical technique is proposed here to calculate the second harmonic level with known input power.

The procedure of the proposed mathematical model will be demonstrated in the following context. Firstly, the same cavity model used in previous analyses will be implemented. A discrete floating port with metal leads of 1 mm length, resembling a dipole antenna, is placed inside the Petri dish in the cavity and oriented parallel to the transmit antenna, as depicted in Figs. 2 and 3. Then, two simulations will be performed separately at the resonant frequencies of the TE_{111} and TE_{113} modes, in order to extract the 3×3 Z-parameters at both frequencies. This is equivalent to the 3-port network as depicted in Fig. 4. Once the 3×3 Z-parameters are obtained at both frequencies, they will be employed in the proposed mathematical model as depicted in Fig. 5. According to Fig. 5, the input and output ports can be represented as transmit and receive antennas respectively in the cavity, while the nonlinear element is represented as the diode inside the cavity. The equivalent electric circuit of the diode model is illustrated in Fig. 6.

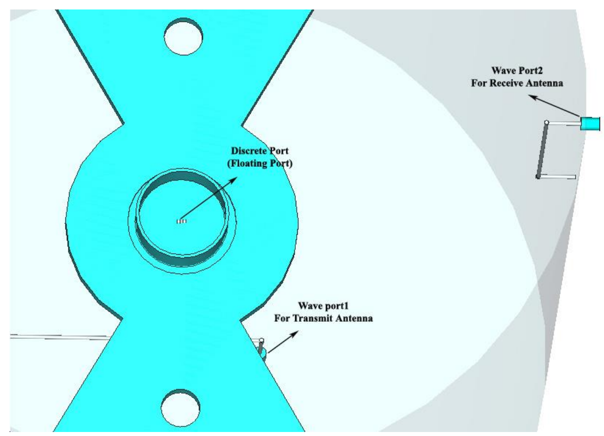

Fig. 2. Proposed cavity model for mathematical analysis.

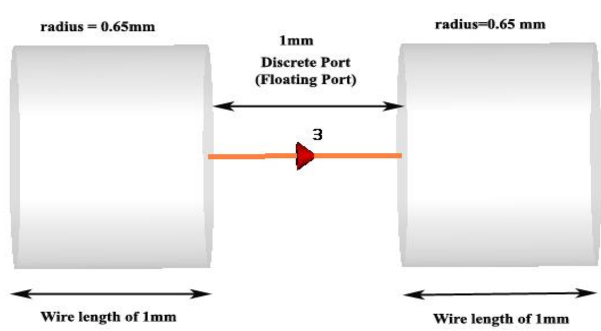

Fig. 3. Discrete port model in the Petri dish of the cavity (enlargement).

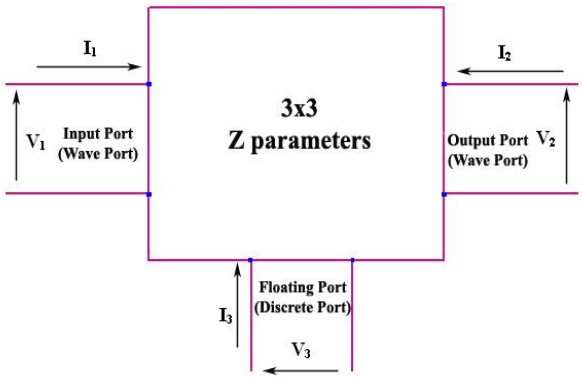

Fig. 4. Simulated model in Microwave Studio [19].

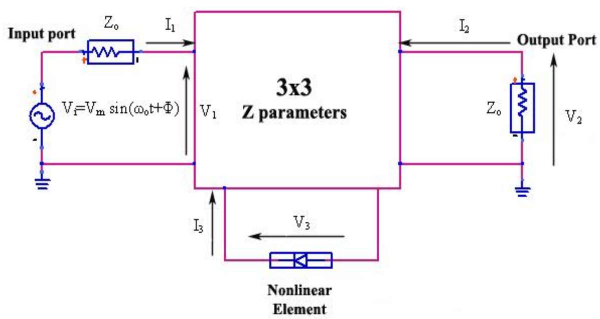

Fig. 5. Proposed mathematical model for TE_{111} mode.

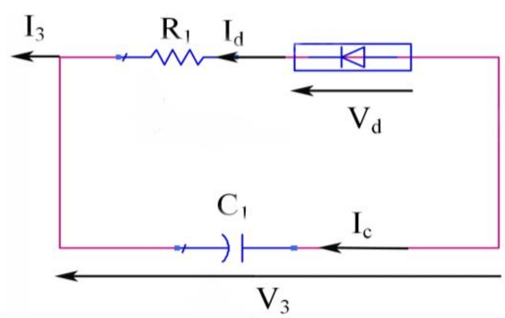

Fig. 6. Electric circuit model of the nonlinear element in Fig. 5.

From Figs. 5 and 6, and by applying Ohm's law, the following equation can be derived:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}_f \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}. \quad (1)$$

From the input port in Fig. 5:

$$I_1 = \frac{V_i - V_1}{Z_o}, \quad (2)$$

where V_i is the input voltage to port 1 and Z_o is the characteristic impedance of 50 Ω. From the output port in Fig. 5, I_2 is given by:

$$I_2 = -\frac{V_2}{Z_0}. \quad (3)$$

From the diode model in Figs. 5 and 6:

$$I_3 = I_c + I_d, \quad (4)$$

where I_d is the current across the diode and I_c is the current across the capacitor in the diode model, as seen in Fig. 6.

From Equation (4), I_3 can be further extended to following equation:

$$I_3 = \frac{V_3}{jX_{C1}} + I_d, \quad (5)$$

where:

$$I_d = I_o\left(e^{\frac{e}{KT}(V_d)} - 1\right), \quad (6)$$

where e is the electron charge (e=1.60217x10^{-19} coulombs):
T is the temperature in Kelvin (T=300 K),
I_o is the reverse current (I_o=1.0x10^{-14} A),
k is the Boltzmann Constant (k=1.38065x10^{-23} JK^{-1}),

$$V_3 = V_d + I_d R_1. \quad (7)$$

Substituting the Equations (2 to 7) into (1), the following expression can be obtained:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_d + I_d R_1 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}_{TE\ 111} \begin{bmatrix} \dfrac{V_i - V_1}{Z_o} \\ -\dfrac{V_2}{Z_o} \\ \dfrac{V_d + I_d R_1}{jX_{c1}} + I_d \end{bmatrix}, \quad (8)$$

where R_1=106.5 *Ω* and C_1=1.5 fF, obtained from reference [20]. V_i is the input voltage to port 1.

Since e, K, T and I_o are known parameters, Equation (6) can be simplified as follows:

$$I_d = I_o\left(e^{\frac{e}{KT}(V_d)} - 1\right) = 1.0x10^{-14}\left(e^{38.6815(V_d)} - 1\right). \quad (9)$$

By assuming the input voltage and substituting the Z-parameters of TE_{111} into Equation (8), the parameters V_1, V_2 and V_d can be found. Then, the input power of the mathematical model can be computed by $P_{in} = 0.5\,\mathrm{Re}\left(V_1 \times I_1^*\right)$.

Once V_d is obtained, it can be used as the excitation source to the previous input and output port, hence the electric circuit can be modified as shown in Fig. 7. From this figure, the following set of equations can be established:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}_{TE_{113}} \begin{bmatrix} \frac{-V_1}{Z_o} \\ -\frac{V_2}{Z_o} \\ \frac{V_3 - V_d}{Z_o} \end{bmatrix}. \quad (10)$$

By substituting V_d from the solution of Equation (8) into Equation (10), V_1, V_2 and V_3 can be computed. Hence, the output power on port 2 can be calculated by $P_{out} = 0.5\mathrm{Re}\,(V_2 \times I_2^*)$.

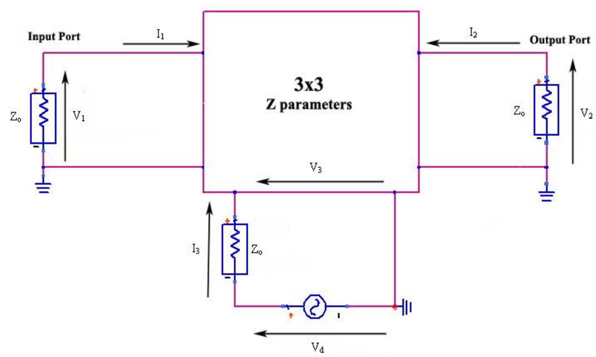

Fig. 7. Proposed mathematical model for TE_{113} mode.

III. SIMULATION AND RESULTS

The bands of operation of the two antennas are shown in Fig. 8. Here the dashed line represents the return loss of the bottom (excitation) antenna at its frequency of operation with an empty 3 cm Petri dish. The frequency has been multiplied by a factor of two to display the second harmonic performance in the same band as the high frequency antenna (receive antenna). The solid line in Fig. 8 illustrates the shift of operating frequency band when a 15µm lamina of lossy water is added to the Petri dish in the cavity, having properties $\varepsilon_r = 78.24$, $\sigma = 0.173$ S/m [2, 13].

Table 1 shows the results obtained from the proposed mathematical model. In order to cross-validate the result, ANSYS HFSS software was adopted for comparison [21]. Figure 9 illustrates the second harmonic power as a function of the input power as the input voltage was increased. As can be clearly seen, both simulation results were in good agreement. Further, it is observed that the relationship between input power and second harmonic output power, applying the Silicon diode model adopted here, is slightly nonlinear. Moreover, the presented results have also compared with the measured results achieved by [8] and it was found that both are agreed well in terms of the level of the second harmonic.

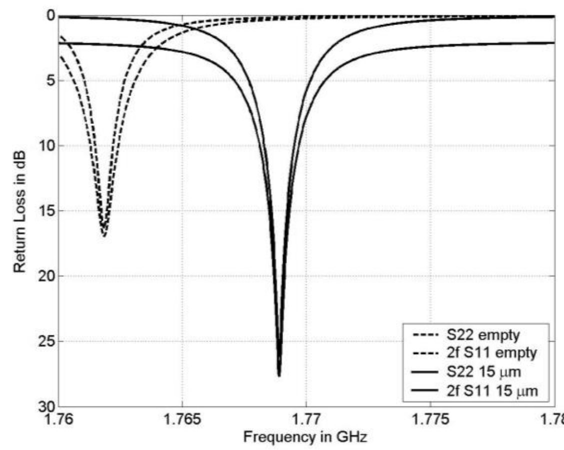

Fig. 8. The fundamental and second harmonic responses of the cavity (fundamental frequency doubled for convenience of display purposes).

Table 1: Input power versus second harmonic power

Input Voltage (Volts)	Input Power (Watts)	Second Harmonic Power (Watts)
1	0.0025	1.1924e-008
2.5	0.0156	7.4573e-008
5	0.0625	2.9818e-007
7.5	0.1405	6.7098e-007
10	0.2499	1.1942e-006
12.5	0.3904	1.8929e-006
15	0.5622	2.5478e-006
17.5	0.7652	3.2223e-006
20	0.9994	3.9630e-006
22.5	1.2649	4.7811e-006
25	1.5616	5.6810e-006
27.5	1.8895	6.6632e-006
30	2.2487	7.7299e-006

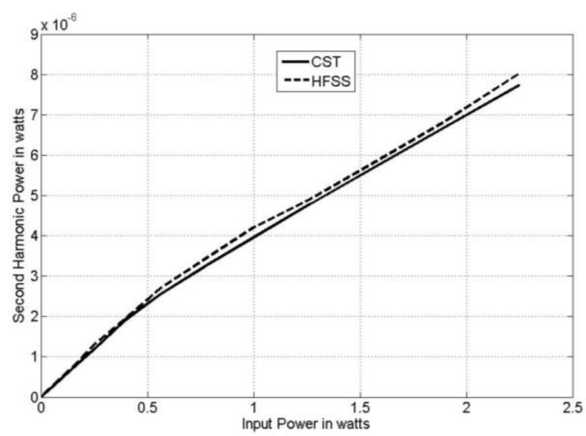

Fig. 9. Input power at Port 1 versus second harmonic power at Port 2.

IV. CONCLUSION

A simulated cylindrical cavity model has been presented, using two rectangular loop antennas for coupling and loaded with a support structure for testing of nonlinear materials. The simulated results show that the tuned TE_{113} mode has double the resonant frequency of the TE_{111} mode. A simple electric circuit model was proposed to calibrate and check the required sensitivity of the detection of the generated second harmonic signal. The nonlinear response of the experiment was tested using a simulated chip diode connected to very short dipole arms. For the diode modelled, a nonlinear relationship was demonstrated between fundamental input power and second harmonic output power. The methodology presented can thus be used to predict such relationships for other nonlinear devices and frequencies applied to the Balzano cavity method or, with some modification, to deduce properties of unknown materials from measured results.

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