Parametric Study of the Rectangular Microstrip Antenna using Cavity Model

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Abstract

A cavity model well suited for computer aided design is presented and developed to study the rectangular microstrip antenna. The patch is described by geometrical and electrical parameters. The resonant frequency, resonant resistance, bandwidth, efficiency and other electrical parameters of RMSA have been presented as a function of varying the patch dimension and substrate parameters. The accuracy and usefulness of the method are investigated through comparison with experimental results as well as other previous theoretical methods.

الخلاصـــــة

تم استخدام إسلوب الفجوة في بناء وتطوير برنامج تصميمي لدراسة الهوائيات الشريطية الدقيقة المستطيلة حيث تم تحديد معلمات وأبعاد المستطيل الفعال (patch) هندسيا وكهربائيا وتم حساب كل من التردد الرنيني والمقاومة الرنينية وعرض الحزمة وكفاءة الهوائي بالإضافة إلى المعلمات الأخرى والتي تم دراستها مع تغيير أبعاد المستطيل الفعال وبينت النتائج الدقة العالية التي يعطيها البرنامج الحالي مقارنة بالنتائج التجريبية والحسابات النظرية لدراسات منشورة.

1. Introduction

Modern communication systems demand low coast and low profile antennas. Microstrip antenna (MSA) is one of the candidate antennas meeting those requirements due to its conformal nature and capability to integrate with the rest of the printed circuitry [1].

The MSA is a resonant structure that consists of a dielectric substrate sandwiched between a metallic conducting patch and a ground plane. The patch is generally made of copper or gold and can take any possible shape [2,3].

During the past decades, microstrip antennas experienced a great gain in popularity and hence become a major research topic in both theoretical and applied electromagnetic. They are well known for their highly desirable physical advantage characteristics [4].However, two principal disadvantages of MSA are narrow bandwidth and low gain. Numerous researches have investigated their basic characteristics and recently extensive efforts have also been devoted to the bandwidth and gain problems and considerable progress have been made [5-10].

There is a number of techniques available for analyzing microstrip patch antennas. The analytical techniques include transmission line model [11-13], and cavity model [14-16]. The most common numerical techniques used are moment method [17] and the finite difference time domain method [18]. The later technique is time consuming while the former method and the analytical techniques have been applied to regular shapes only like, rectangular, circular, and elliptical shapes [11]. However, the analysis of MSA is normally difficult to handle which is primarily due to the existence of a dielectric substrate to support the conductor [19].

The aim of this work is to use the cavity model to study the rectangular microstrip antennas operating in the range of (3GHz) which excited by a coaxial feed. For this purpose a computer program written in Fortran-77 language, which is based on the cavity model is presented and developed for the first time prior to this work. Moreover, this program has been also modified in order to investigate the effect of various parameters on the performance of rectangular microstrip antennas operating in the range of (3GHz).

2. Theory

2-1 Resonance Frequency and RMSA Dimension

The MSA consists a conducting plate separated from a ground plane usually by a thin layer of dielectric. A shape of rectangular microstrip antenna is shown in **Fig.(1)**. A cavity model was used to calculate the resonant frequencies whenever a magnetic wall is introduced at the sides of the patch while the electric wall is introduced at the bottom and top of the patch. By employing this simple model, the dominant TM_{10}-resonant frequency mode of RMSA is given by [14]:

$$f_r = \frac{c}{2.L_{eff}.\sqrt{\varepsilon_{eff}}} \quad \text{.......} \quad (1)$$

where, (c) is the velocity of electromagnetic waves in space, L_{eff} and ε_{eff} are effective length and effective dielectric substrate permittivity respectively. The effective length is given by [20]:

$$L_{eff} = L + \Delta L \quad \text{.......... (2)}$$

Since the length of the patch has been extended by (ΔL) on each side so it can be expressed by [21]:

$$\Delta L = 0.412.h.\frac{(\varepsilon_{eff} + 0.3).(\frac{W}{h} + 0.264)}{(\varepsilon_{eff} - 0.258).(\frac{W}{h} + 0.8)} \quad \text{.......... (3)}$$

where, (h) is the substrate thickness and (W) is the width of the patch which is given by [20]:

$$W = \frac{c}{2.f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad \text{.......... (4)}$$

While the effective dielectric substrate permittivity can be expressed as [22]:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2.\sqrt{1 + \frac{12.h}{W}}} \quad \text{.......... (5)}$$

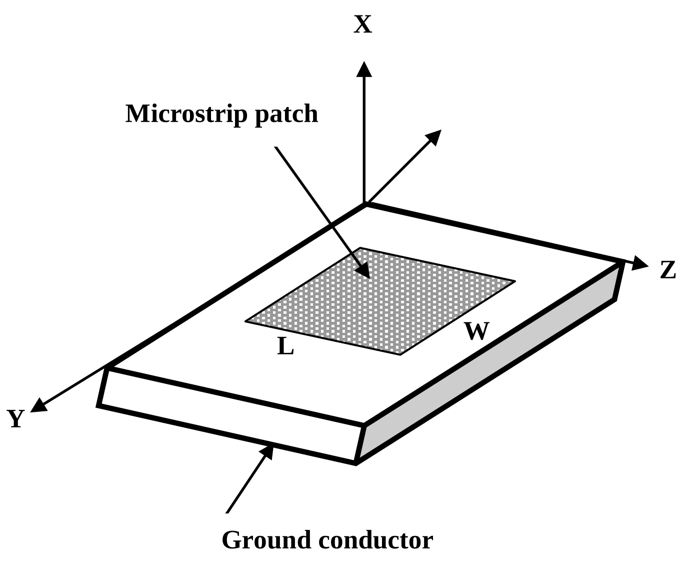

Figure (1) Microstrip antenna element

2-2 Radiation Pattern of Rectangular Patch

The far-field radiation pattern of a rectangular microstrip patch operating in the TM_{10}-mode is broad in the E and H-planes. The pattern of a cavity with two perfectly conducting electric walls (top and bottom), and four perfectly conducting magnetic walls (side walls) are given by [20]:

$$\left.\begin{aligned} E_r &= 0 \\ E_\theta &= 0 \end{aligned}\right\} \quad \text{(6-a)}$$

$$E_\phi = j.\frac{k_o.W.V_o}{\pi.r}.e^{-j.k_o.r}.[\mathrm{Sin}\theta.\frac{\mathrm{Sin}X}{X}.\frac{\mathrm{Sin}Z}{Z}].\mathrm{Cos}(\frac{k_o.L_{eff}}{2}.\sin\theta.\mathrm{Sin}\phi) \quad \text{(6-b)}$$

where,

$$\left.\begin{aligned} X &= \frac{k_o.h}{2}.\mathrm{Sin}\theta.\mathrm{Cos}\,\phi \\ Z &= \frac{k_o.W}{2}.\mathrm{Cos}\,\theta \end{aligned}\right\} \quad \text{(7)}$$

and $V_o=h.E_o$ is the voltage across sides of radiating edge of the patch, then, the principal E and H-planes reduces to:

E-plane (θ=90, 0≤Φ≤ 90, and 270≤Φ≤360):

$$E_\phi = j.\frac{k_o.W.V_o}{\pi.r}.e^{-j.k_o.r}.[\frac{\mathrm{Sin}(\frac{k_o.h}{2}.\mathrm{Cos}\phi)}{\frac{k_o.h}{2}.\mathrm{Cos}\phi}].\mathrm{Cos}\frac{k_o.L_{eff}}{2}.\mathrm{Sin}\phi) \quad \text{(8)}$$

and H-Plane (Φ=0 , 0≤θ≤180):

$$E_\phi = j.\frac{k_o.W.V_o}{\pi.r}.e^{-j.k_o.r}.[\mathrm{Sin}\theta.\frac{\mathrm{Sin}(\frac{k_o.h}{2}.\mathrm{Sin}\theta)}{\frac{k_o.h}{2}.\mathrm{Sin}\theta} * \frac{\mathrm{Sin}(\frac{k_o.W}{2}.\mathrm{Cos}\theta)}{\frac{k_o.W}{2}.\mathrm{Cos}\theta}] \quad \text{(9)}$$

2-3 Input Impedance

The input impedance of a RMSA excited by a coaxial feed can be determined by returning to the cavity model approximation for the fields in the patch. The input impedance is given by Ohms law:

$$Zin = \frac{Vin}{I_o} \quad \text{(10)}$$

With V_{in} is the input voltage at the feed-point and it can be computed as [23]:

$$Vin = -j.w.\mu_0.h.I_o \sum \frac{\psi^2{}_{mn}.(x_f, y_f)}{k^2 - k_{mn}{}^2}.G_{mn} \quad \text{.. (11)}$$

where,

$$\psi_{mn} = \sqrt{\frac{\varepsilon_m.\varepsilon_n}{L.W}}.Cos(\frac{m.\pi.y_f}{L}).Cos(\frac{n.\pi.x_f}{W}) \quad \text{.................................... (12-a)}$$

$$\varepsilon_p = \begin{Bmatrix} 1 for.p \neq 0 \\ 2.for.p = 0 \end{Bmatrix} \quad \text{... (12-b)}$$

$$G_{mn} = \frac{Sin(\frac{m.\pi.d_x}{2.W})}{\frac{m.\pi.d_x}{2.W}} . \frac{Sin(\frac{n.\pi.d_y}{2.L})}{\frac{n.\pi.d_y}{2.L}} \quad \text{.. (13)}$$

and,

$$k^2 = k_o{}^2.\varepsilon_r.(1 - j.\delta_{eff}) \quad \text{.. (14)}$$

Equation (10), can then be evaluated for the dominant TM_{10}-mode at $k^2 = k_{10}{}^2.\varepsilon_r$ which leaves the input resistance as [24]:

$$Rin = \frac{4.\pi.f_r.\mu_o.h}{k^2{}_o.\varepsilon_r.L.W.\delta_{eff}}.Cos^2(\frac{\pi.x_f}{L}) \quad \text{... (15)}$$

where, (x_f) is a distance from the edge of the patch and ($\delta_{eff}=1/Q_t$), where Q_t can be calculated using section 2-5. However, there is another accurate expression for the input resistance of RMSA excited by a coaxial feed given by [25] as:

$$Rin = R_e.Sin^2(\frac{\pi.x_f}{L}) \quad \text{.. (16)}$$

where, (x_f) is a distance from the center of the patch, and

$$R_e = \frac{1}{2.(G_r + G_m)} \quad \text{.. (17)}$$

where, (G_r)is the radiation conductance which is given in section 2-4, and G_m is the mutual conductance and it is expressed as [25]:

$$G_m = G_r . F_g \quad \text{……………………………………………………………….. (18)}$$

$$F_g = J_0(l) + \frac{p^2}{24 - p^2} . J_2(l) \quad \text{…………………………………………………… (19)}$$

where, $l = k(L + \Delta L)$, $p = k\Delta L$, $J_\circ(l)$ and $J_2(l)$ are zero and second order Bessel functions, respectively.

2-4 Power and Directivity

The radiation power (P_{rad}) over a sphere of radius (r) is given by a definition of the Pointing vector as [20]:

$$P_{rad} = \frac{1}{2.\eta_\circ} . \iint (E * H^*) . r^2 . Sin\theta . d\theta . d\phi \quad \text{……………………………………… (20)}$$

where, $\eta_\circ$ is the characteristic impedance of space and equal to (120π)Ω ,Then, for a RMSA operating in the dominant TM_{10}-mode, Eq.(20), becomes:

$$P_{rad} = \frac{V_o^2 . (W.k_o)^2}{240.\pi^3} . \iint [Sin\theta . \frac{SinX}{X} . \frac{SinZ}{Z}]^2 . [Cos(\frac{k_o . L_{eff}}{2} . Sin\theta . Cos\phi)]^2 . Sin\theta . d\theta . d\phi \quad \text{…... (21)}$$

So the radiation conductance (G_r) is given by:

$$G_r = \frac{2.P_{rad}}{|V_0|^2} \quad \text{………………………………………………………………... (22)}$$

The usual HPBW is defined by the angles at which the antenna element power pattern falls 3dB below the main beam peak [26] and the relation of E-and H-plane of HPBW are given by [23]:

$$\theta_E = 2.Sin^{-1} \sqrt{\frac{7.03}{(3.L^2 + h^2).k_o^2}} \quad \text{………………………………………………… (23)}$$

$$\theta_H = 2.Sin^{-1} \sqrt{\frac{1}{2 + k_o . W}} \quad \text{……………………………………………………... (24)}$$

The directivity of an antenna is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions, and mathematically can be expressed as:

$$D_r = \frac{4.\pi.U_{max}}{P_{rad}} \qquad (25)$$

For RMSA-operating at TM_{10}-mode, the directivity is given by:

$$D_r = \frac{(W.K_o)^2}{30.\pi^2.G_{rad}} \qquad (26)$$

2-5 Quality Factors, Bandwidth, Efficiency and Gain

At resonance, the MSA element can be assigned a quality factor, Q_t, to describe its bandwidth. The Q_t factor is the total of all quality factors associated with system losses, which include dissipated losses within the patch due to loss metal conductors and substrates, power loss due to radiation and surface wave propagation on a dielectric coated conductor. For very thin substrate ($h \ll \lambda_o$) of arbitrary shapes (including rectangular and circular) there are approximate formulas to represent the quality factors of various losses [20-21]. These can be expressed as:

$$\left.\begin{aligned} Q_c &= h.\sqrt{\pi.\mu_o.\sigma.f_r} \\ Q_d &= \frac{1}{\tan\delta} \\ Q_{rad} &= \frac{\pi.f_r.\varepsilon_r.W.L}{h.G_{rad}} \end{aligned}\right\} \qquad (27)$$

where, (μ_o is a permeability $=4\pi*10^{-9}$ H/cm, σ is the copper conductivity $=5.7*10^{5}$ S/cm, f_r is the resonance frequency in Hz and $\tan\delta$ is the loss tangent). Therefore, the total quality factor Q_t influenced by all of these losses and is, in general, written as [21]:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} \qquad (28)$$

The fractional bandwidth of MSA elements is usually determined from the total quality factors with (VSWR=2:1) and is given by:

$$BW = \frac{s-1}{Q_t.\sqrt{s}} \qquad (29)$$

The radiation efficiency is defined as the ratio of the power radiated to the power received by the input to the element. It can also be expressed in terms of the quality factors, which for a MSA, can be written as [20]:

$$\eta = \frac{Q_{rad}}{Q_t} \quad \text{.......... (30)}$$

However, the antenna gain is a measure of an antennas ability to concentrate the power accepted at input terminal and mathematically is related to the directivity and efficiency as:

$$\text{Gain} = \eta . D_r \quad \text{.......... (31)}$$

All the above equations have been formulated in the computer program in several subroutines to identify their values with respect to the variation of various parameters of RMSA, excited by a coaxial feed.

3. Results and Discussion

To test the accuracy of the computer program, which is based on the cavity model, the resonance frequency and resonance resistance of TM_{10}-mode have been calculated. **Table (1)**, represents the results obtained in this work and compared with measured values of Ref. [27] and other previous theoretical methods [16,17],for different values of (ε_r, h, w, L, and tanδ). It is obviously seen that the resonant frequencies obtained in this work are in good agreement with measure data compared to the other theoretical methods. However, there are some discrepancies between the measured and calculated resonant resistances. The reasons can be explained these differences are attributed to the surface wave effect which is assumed to be negligible in this work and the fields are assumed to be constant in the direction normal to the substrate planes [27]. Moreover, the computed resonant resistances, by using Eq.(16), are better than those obtained with Eq.(15) in comparison with measured values. After that the effect of varying various parameters of RMSA such as dielectric constant, width, substrate thickness and loss tangent (tanδ) have been carried out using the computer program which is based on the cavity model.

The dimension of the RMSA has been taken as: (W=4 cm, L=3 cm, h=0.159 cm, ε_r=2.55 and tanδ=0.001).

3-1 The Effect of Varying the Dielectric Constant (ε_r)

The effect of varying the dielectric constant (ε_r) from (1 to 2.6) on the electrical properties of RMSA with the feed-point fixed at (0.7 cm) from the center of the patch are shown in **Fig.(2)** for bandwidth and **Fig.(3)** for both directivity and antenna gain. It is clearly seen that, the bandwidth decreases from (187.9 to 60 MHz), the gain decreases from (9.62 to 6.68 dB) and directivity decreases from (9.75 to 6.96 dB). So the dielectric constant of higher value of permittivity gives lower electrical parameters of RMSA. However, when the feed-point location is optimized for each (ε_r) and the dimensions of the RMSA are scaled to operate at around (3 GHz) then a better comparison of the effect of (ε_r) can be obtained. **Table (2)**, represents the computed and measured values of some electrical properties of

RMSA for four different values of (ε_r).One can sees that our calculated results of bandwidth, gain and resonance resistance are very close to their corresponding measured values. In addition, as the (ε_r) increases from (1 to 9.8) the bandwidth decrease from (82.7 to 26.6 MHz) due to a decreases in the fringing fields. Also, the gain decrease from (9.6 to 4.7 dB) due to a decrease in the aperture area.

Table (1) Comparison of calculated and measured values of resonant frequency and resonant resistance of the rectangular patch with different ε_r, tanδ, and substrate thickness

ε_r	h (cm)	X_f (cm)	W (cm)	L (cm)	tanδ	Resonance frequency (GHz)				Resonance resistance (Ω)				
						m.v.	p.w.	[17]	[16]	m.v.	P.W. Eq.16	P.W. Eq.15	[17]	[16]
						fr.	fr.	fr.	fr.	Rin	Rin	Rin	Rin	Rin
2.22	0.079	0.4	4	2.5	0.0009	3.94	3.95	3.89	3.89	89	82.67	102	101	83
2.22	0.079	0.2	2	1.25	0.0009	7.65	7.74	7.61	7.53	99	84.63	110	130	81
2.22	0.15	0.4	4	2.5	0.0009	3.84	3.87	3.81	3.77	87	84.47	110	127	81
2.5	0.1524	2.07	4.14	4.14	0.001	2.23	2.26	2.27	-----	284	259	316	397	------
2.5	0.1524	2.07	6.858	4.14	0.001	2.20	2.24	2.23	-----	108	106.8	135	180	------
2.5	0.1524	2.07	10.8	4.14	0.001	2.18	2.23	2.21	-----	53	54.17	69.7	90	------
10.2	0.127	0.65	3	2	0.0023	2.26	2.32	2.28	2.23	85	90.73	82.3	100	72
10.2	0.127	0.32	15	0.95	0.0023	4.49	4.77	4.58	4.43	53	73.91	81.7	75	56
10.2	0.254	0.65	3	1.9	0.0023	2.24	2.38	2.29	2.21	80	69.61	78.2	75	53

m.v.= measured value
p.w.= present work

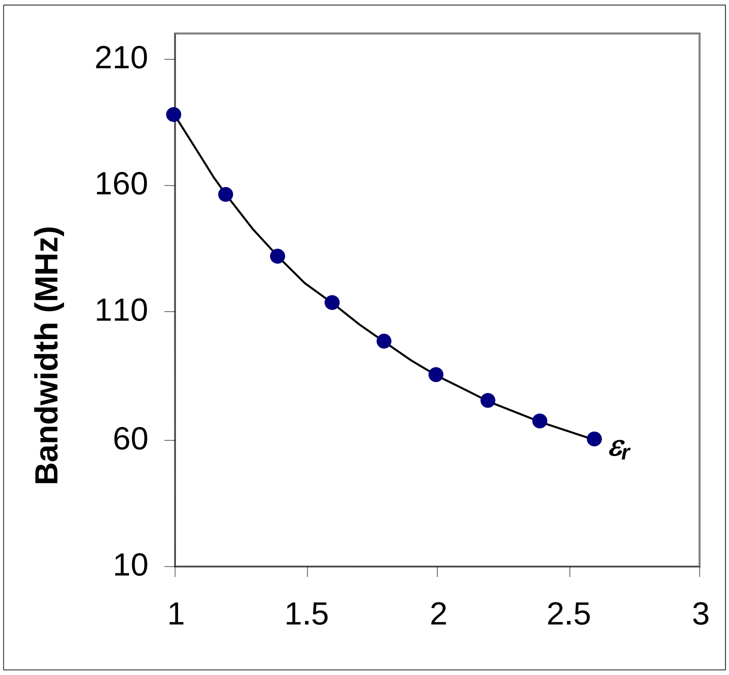

Figure (2) Variations of bandwidth versus the substrate permittivity (εr)

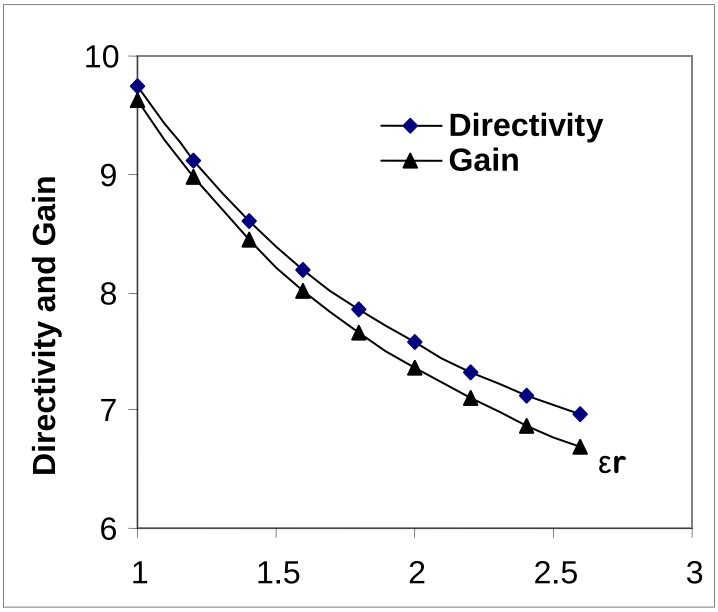

Figure (3) Variations of directivity and gain versus the substrate permittivity (εr)

Table (2) Comparison of calculated and measured values of the effect of the substrate permittivity on the electrical properties of RMSA with (h=0.159 cm and tanδ=0.001)

ε_r	W (cm)	L (cm)	X_f (cm)	Rin (Ω)			Frequency (GHz)		Bandwidth (MHZ)		Gain (dB)	
				m.v.	p.w. Eq.16	p.w. Eq.15	m.v.	p.w.	m.v.	p.w.	m.v.	p.w.
1	6.2	4.65	1	54	48.4	62.7	2.99	3.07	74	82.7	10	9.6
2.55	4.0	3.0	0.65	62	62.4	80.1	2.97	3.05	64	61.7	6.8	6.7
4.3	3.1	2.3	0.4	52	56.63	70.9	2.98	3.08	49	47.2	5.6	5.7
9.8	2.0	1.51	0.2	51	66.7	80.7	3.02	3.12	30	26.6	4.4	4.7

3-2 The Effect of Varying the Value of the Width (W)

The effect of varying the value of the width (W) from (1 to 5 cm) on the electrical properties of RMSA with feeding point located (0.7 cm) from the edge is shown in **Fig.(4)** for bandwidth and efficiency and **Fig.(5)** for H-plane HPBW. It is seen that the bandwidth increases fro (21 to 71 MHz) and efficiency increased from (81.32 to 94.73 %), while the H-plane HPBW decreases from (89 to 70). However, they are not very evident from these plots, because the feed point is not optimum for the different width. Accordingly, a better comparison will be obtained when the feed point is optimized for the individual widths. **Table (3)** represent the measured and calculated resonant frequency, resonant resistance by using Eq.(16), bandwidth, gain and H-plane HPBW with the computed value of directivity and efficiency. This table indicates that computed results of electrical parameters of RMSA are in good agreement with the corresponding measured values. Furthermore, except the value of H-plane HPBW, all the other parameters are increased with increasing the value of the width due to an increase in the aperture area of the patch. While the HPBW in the H-plane decreases, whereas it remains almost the same in the E-plane, because the increase in the width is in the H-plane.

3-3 The Effect of Varying the Substrate Thicknesses (h)

The effect of varying the substrate thicknesses (h) on the bandwidth and efficiency of RMSA with (ε_r=2.55, W=4 cm, L=3 cm, tanδ=0.001 and feed-point x_f=0.7) are shown in **Fig.(6)**. It is observed that the bandwidth increases from (42.32 to 147.26 MHz) and efficiency increased from (88.65 to 98.23 %) due to an increase in the radiation power. This implies that, thicker substrate gives higher values of electrical parameters of RMSA.

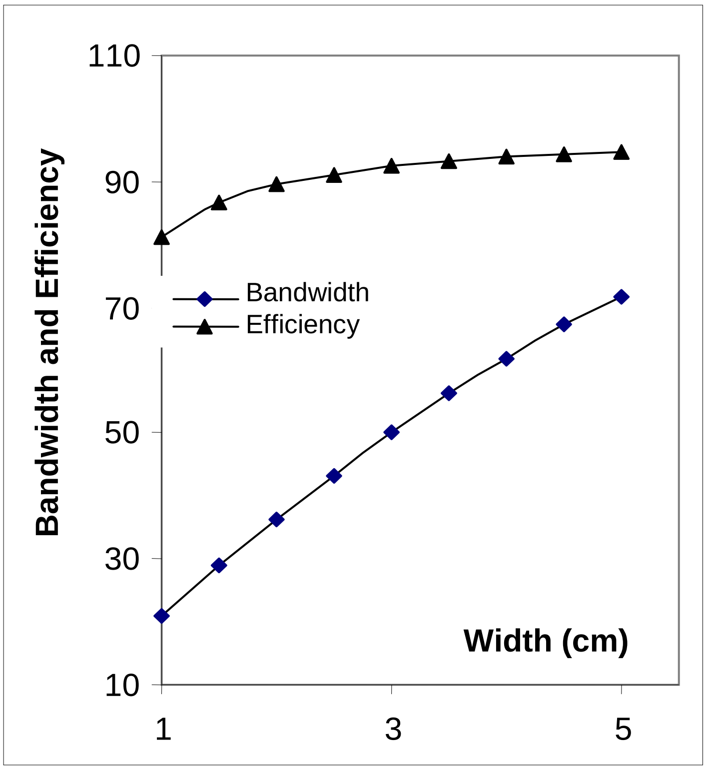

Figure (4) Variations of bandwidth and efficiency versus the patch width

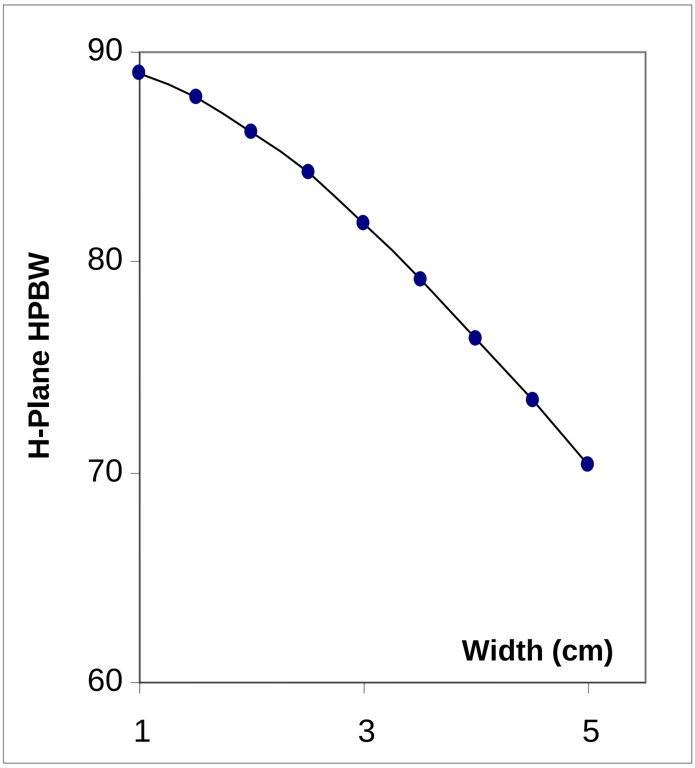

Figure (5) Variation of H-Plane half power beam width versus the patch width

Table (3) Comparison of calculated and measured values of the effect of the width of the patch on the electrical properties of RMSA with (L=3 cm, εr=2.55, h=0.159 cm and tanδ=0.001)

W(cm)	X_f (cm)	Rin (Ω)		Frequency (GHz)		Bandwidth (MHz)		Gain (dB)		H-plane HPBW ^{0}		Directivity (dB)	Efficiency %
		m.v	p.w.	m.v	p.w.	m.v	p.w.	m.v	p.w.	m.v	p.w.		
2	0.35	57	72.7	3.03	3.11	42	36.28	6.2	6.20	86	86.2	6.69	89.38
3	0.5	61	66.17	2.99	3.07	54	50.04	6.5	6.46	81	81.8	6.81	92.36
4	0.65	62	62.47	2.97	3.05	64	61.69	6.8	6.73	76	76.4	7.00	93.87
5	0.75	53	53.92	2.96	3.04	73	71.84	7.0	7.01	70	70.4	7.25	94.73

m.v.= measured value
p.w.= present work

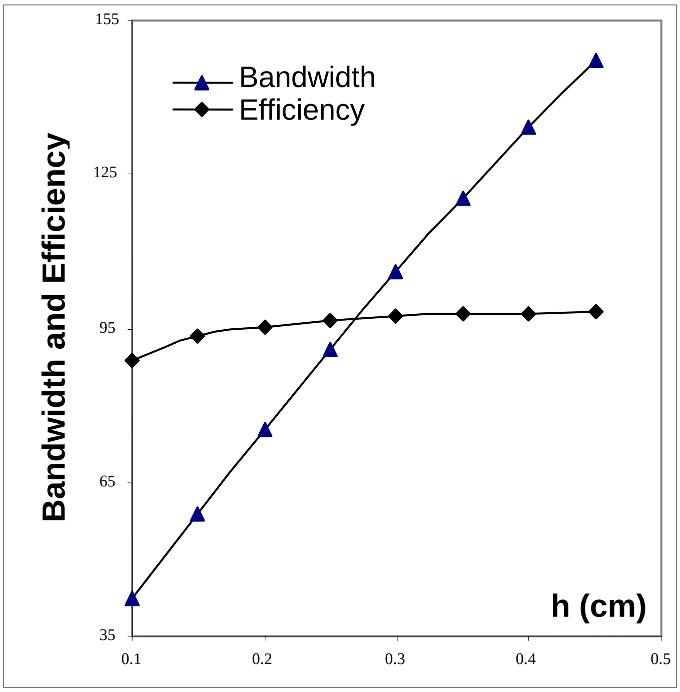

Figure (6) Variations of bandwidth and efficiency versus the substrate thicknesses

3-4 The Effect of Increasing the Value of Loss Tangent (tanδ)

Finally, the effect of increasing the value of loss tangent (tanδ) on the bandwidth and efficiency of RMSA is investigated with (ε_r=2.55, h=0.159, W=4 cm, L=3 cm and feed-point x_f=0.7 cm from the center of the patch) and is shown in **Fig.(7)**. It is seen that, with an increase in the value of (tanδ) the bandwidth increases from (81.4 to 167.78 MHz) and efficiency decreases from (71.45 to 34.66 %). So the use of loss material leads to increase the bandwidth and to reduce the efficiency which gives lower gain.

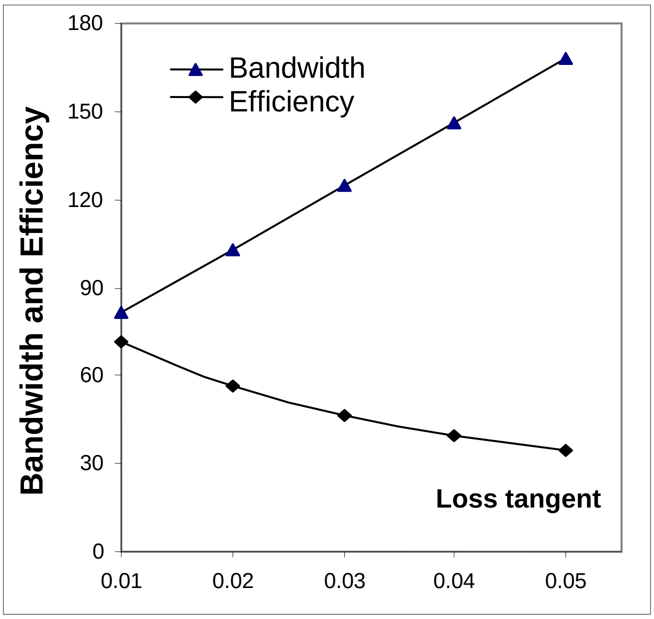

Figure (7) Variations of bandwidth and efficiency of RMSA versus the loss tangent

4. Conclusion

As a result of the effect of varying the patch dimension and substrate properties on the electrical properties of RMSA, we arrived to the following conclusion.

1. The computed results of resonance frequency and resonance resistance values obtained with present method are in good agreement with the reported experimental and theoretical values.
2. The advantage of the cavity model is that has faster speed of computation and reasonably good accuracy. However, the disadvantages are that the antenna should be symmetrical with respect to the feed-axis and the variation along the width should be small.
3. In order to design a RMSA operating at high efficiency with broader bandwidth and higher gain, its desirable to use a material with lower dielectric substrate permittivity, and thicker substrate of higher losses. In addition the width of the patch must be as large as possible for a given frequency to increase its radiation power.

5. References

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