Journal of Engineering and Development, Vol. 10, No.1, March (2006) ISSN 1813-7822

Effects of the Loss Tangent, Dielectric Substrate Permittivity and Thickness on the Performance of Circular Microstrip Antennas

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Abstract

The effects of loss tangent, dielectric substrate permittivity and thickness on the electrical properties of circular microstrip antenna (CMSA) excited by a coaxial-feed have been investigated using cavity model.

Accuracy of the present results of resonance frequency, input resistance, bandwidth, efficiency, gain, and directivity are compared with previous work which has been done theoretically and experimentally.

الخـلاصـــة

تم في هذا البحث دراسة تأثير الفقدان المماسي والسماحية الكهربائية والسمك للمادة العازلة في الهوائيات الشريطية الدقيقة الدائرية والمهيجة بالتغذية بالأسلاك المحورية حيث تم بناء وتطوير برنامج لهذه الحسابات بالإضافة إلى حساب التردد الرنيني وعرض الحزمة والكفاءة والربحية والاتجاهية.

حيث قورنت النتائج مع النتائج التجريبية والحسابات النظرية لعدد من الباحثين وبينت نتائج حسابات البرنامج الحالي دقة جيدة جدا.

1. Introduction

A conventional microstrip antenna (MSA) is usually comprised of a metallic patch deposited on one side of the substrate and a ground plane on the other side. In recent years, microstrip antennas have a roused great interest in both theoretical research and engineering applications due to their low profile, light weight, conformal structure, and ease of fabrication and integration with solid state device [1]. However, two principal disadvantages of MSA are narrow bandwidth and low gain .In the past decade, extensive research has been devoted to the bandwidth problem, and considerable progress has been made [1,2]. The problem of increasing the gain of MSA elements has received some attention of workers [1-3].

The designer of MSA is often faced with the question of what the best substrate thickness is and what dielectric constant should be used, since low loss is desirable [4]. The losses divided into ohmic, dielectric and radiation losses. Several methods [5-11] are available to calculate the MSA parameters .These methods have different levels of complexity, require vastly different computational efforts, and can generally be divided into two groups: Simple analytical method and rigorous numerical methods. Simple analytical methods can give a good intuitive explanation of antenna radiation properties. Exact mathematical formulations in rigorous methods involve extensive numerical procedures, resulting in round-off errors, and may also need final experimental adjustments to the theoretical results [1]. They are also time consuming and not easily included in a computer-aided design (CAD) package.

In this work, the circular microstrip antenna is modeled as a cavity with magnetic walls along the circumference and electrical walls on the top and bottom of the patch. For this purpose, a computer program written in Fortran-77 language, based on this model is presented and developed. This program has been modified to calculate the effects of loss tangent (tan δ) and dielectric substrate permittivity (ε_r) and thickness on the performance of CMSA excited by a coaxial-fed.

2. Theory

2-1 Resonance Frequency

The resonance frequencies of the TM_{nm}-modes in the circular disk are given as [12,13]:

$$f_{nm} = \frac{\alpha_{nm}.c}{2.\pi.a_e\sqrt{\varepsilon_e}} \quad \text{.......... (1)}$$

where: α_{nm} ,is the mth-root of the derivative of the Bessel-function of order n [14]. For the fundamental TM_{11}-mode the value of α_{11}=1.84118. The (a_e) and (ε_e) are the effective radius and the effective dielectric constant of the CMSA, respectively. The fringing fields along the periphery of CMSA are taken into account by replacing the patch radius (a) by the effective radius (a_e) as given by [13,15].

$$a_e = a.\sqrt{1 + \frac{2.h}{\pi.a.\varepsilon_r}.[\ln\frac{a}{2.h} + 1.41.\varepsilon_r + 1.77 + \frac{h}{a}.(0.268.\varepsilon_r + 1.65)]} \quad \text{............... (2)}$$

The value of ε_e is obtained using:

$$\varepsilon_e = \frac{C(a,h,\varepsilon_0.\varepsilon_r)}{C(a,h,\varepsilon_0)} \quad \text{... (3)}$$

where: $C(a,h,\varepsilon_0, \varepsilon_r)$ and $C(a,h, \varepsilon_0)$ are the total capacitances of dominant TM_{11}-mode of CMSA with and without a dielectric substrate, respectively. These can be calculated as [15]:

$$c(a,h,\varepsilon_0\varepsilon_r) = \frac{0.8525 .\varepsilon_0\varepsilon_r.\pi.a^2}{h} + 0.5.C_f \quad \text{..................................... (4)}$$

In Eq.(4) the first term is the main capacitance of the disk and the second term is the fringing capacitance C_f, which is given by [15]:

$$C_f = 2.a.\varepsilon_0.[\ln(\frac{a}{2.h}) + 1.41.\varepsilon_r + 1.77 + \frac{h}{a}(0.268.\varepsilon_r + 1.68)] \quad \text{................. (5)}$$

2-2 Radiation Pattern

The microstrip element consists of a radiating structure spaced a small fraction of wavelength above a ground plane, allowing radiation to propagate only into the upper half space [16]. Circular element supported by a dielectric sheet is shown in **Fig.(1)**. The far-fields in standard spherical coordinates may be found from a potential function or from the dual solutions of circular loop antennas, which for dominant TM_{11}-mode can be written as follows [16]:

$$\left.\begin{aligned} E_r &= 0 \\ E_\theta &= -j.\frac{k_o.a_e.V_o}{2.r}.e^{-j.k_o.r}.[\cos\phi.J02'] \\ E_\phi &= j.\frac{k_o.a_e.V_o}{2.r}.e^{-j.k_o.r}.[\cos\vartheta.\sin\phi.J02] \end{aligned}\right\} \quad \text{.. (6)}$$

where:

$$\left.\begin{aligned} J02' &= J_o(k_o.a_e.\sin\theta) - J_2(k_o.a_e.\sin\theta) \\ J02 &= J_o(k_o.a_e.\sin\theta) + J_2(k_o.a_e.\sin\theta) \end{aligned}\right\} \quad \text{... (7)}$$

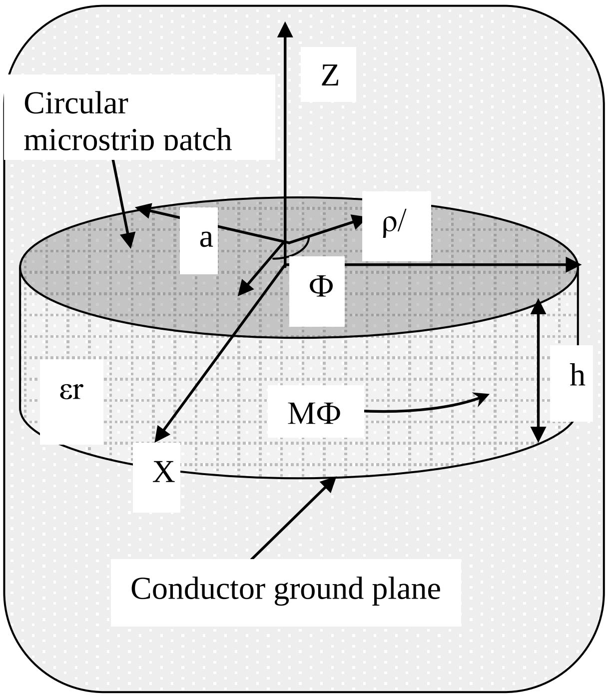

Figure (1) Cavity Model and Equivalent Magnetic Current Density for Circular Microstrip Patch Antenna

The field in the principal planes reduces to:

E-plane: (Φ=0,180 $0 \le \theta \le 90$):

$$\left.\begin{aligned} E_\phi &= 0 \\ E_\theta &= j.\frac{k_o.a_e.V_o}{2.r}.e^{-j.k_o.r}.[J02'] \end{aligned}\right\} \quad \textbf{(8)}$$

H-plane: (Φ=90,270, $0 \le \theta \le 90$):

$$\left.\begin{aligned} E_\theta &= 0 \\ E_\phi &= j.\frac{k_o.a_e.V_o}{2.r}.e^{-j.k_o.r}.[Cos\theta.J02] \end{aligned}\right\} \quad \textbf{(9)}$$

2-3 Conductance and Directivity

The conductance due to the radiated power and directivity of the CMSA can be computed using their respective definitions as follows:

$$P_{rad} = \frac{1}{2.\eta_\circ}.\iint (|E_\theta|^2 + |E_\phi|^2.r^2.Sin\theta.d\theta.d\phi \quad \textbf{(10)}$$

where: η_0 is the characteristic impedance of free space and is equal to (120 π) Ω. Using eqs.(8) and (9) we get:

$$P_{rad} = |V_0|^2 . \frac{(k_0.a_e)^2}{480} . \int [(J02^{/})^2 + \mathrm{Cos}\theta^2 .(J02)^2]\mathrm{Sin}\,\theta.d\theta \quad \textbf{......................... (11)}$$

Therefore the radiation conductance is given by :

$$G_{rad} = \frac{(k_0.a_e)^2}{480} . \int [(J02^{/})^2 + \mathrm{Cos}\theta^2 .(J02)^2]\mathrm{Sin}\,\theta.d\theta \quad \textbf{.......................... (12)}$$

While, the conductance of Eq.(12) accounts for the losses due to radiation, it does not take into account losses due to conduction (ohmic) and dielectric losses, whereas each can be expressed as **[17]**:

$$G_c = \varepsilon_{m0} . \frac{[(k.a_e)^2 - m^2]}{4.h^2.f_r.\mu_0.\sqrt{\sigma.\mu_0.f_r.\pi}} \quad \textbf{.. (13)}$$

$$G_d = \varepsilon_{m0} \frac{\tan\delta.[(k.a_e)^2 - m^2]}{4.h.f_r} \quad \textbf{.. (14)}$$

where: ε_{m0}=1 for m=0 and ε_{m0}=2 for m=0.and μ_0: is permeability= $4\pi*10^{-9}$ H/cm, σ is the cupper conductivity= $5.7*10^5$ S/cm, h is the height of the substrate in (cm) and f_r is the resonance frequency of the TM_{11}-mode in (Hz).

Thus, the total conductance can be written as **[16]**:

$$G_t = G_{rad} + G_c + G_d \quad \textbf{.. (15)}$$

The directivity of an antenna is defined as the ratio of the maximum power density to the average radiated power density. From the previously calculated far-field radiation and the total radiated power, the directivity of the CMSA excited in the TM_{11}-modes can be expressed as:

$$Dr = \frac{(k_0.a_e)^2}{120.G_{rad}} \quad \textbf{.. (16)}$$

2-4 Input Impedance

The input impedance of the MSA at resonance is real, and the input power is independent of the feed-point position along the circumference [16-17]. Taken the reference of the feed at Φ=0, the input resistance at any radial distance $\rho^{`} = \rho_0$ from the center of the patch can be written as [17]:

$$Rin(\rho^{/} = \rho_0) = Rin(\rho^{/} = a_e).\frac{J_m^2(k.\rho_0)}{J_m^2(k.a_e)} \quad \text{.......... (17)}$$

where:

$$Rin\,(\rho^{/} = a_e) = \frac{1}{G_t} \quad \text{.......... (18)}$$

2-5 Quality Factor, Bandwidth, Gain and Efficiency

The quality factor, bandwidth, gain, and efficiency are antenna figures-of merit, which are interrelated, and there is no complete freedom to independently optimize each of them. Therefore, there is always a trade-off between them in arriving at an optimum antenna performance. Often however, there is a desire to work optimize one of them, while reducing the performance of the other [16].The quality factor is represents the antenna losses. The total quality factors Q_t is influenced by all losses namely radiation, ohmic, dielectric and surface wave losses, and in general, can be expressed as [16]:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \quad \text{.......... (19)}$$

For very thin substrates (Q_{sw}) is very small and can be neglected [8,17].While the other type of the quality factors for CMSA are given as follows [4]:

$$\left.\begin{aligned} Q_d &= \frac{1}{\tan\delta} \\ Q_c &= h.\sqrt{\pi.\mu_0.f_r.\sigma} \\ Q_{rad} &= \frac{[(k.a_e)^2 - 1]}{4.h.f_r.G_{rad}} \end{aligned}\right\} \quad \text{.......... (20)}$$

The radiation efficiency of an antenna is defined as the power radiated over the input power. It can also be expressed in terms of the quality factors, for which a microstrip antenna can be written as:

$$\eta = \frac{Q_t}{Q_{rad}} \quad \text{.......... (21)}$$

The bandwidth of the antenna is defined as an inversely proportion to the total quality factor Q_t of the antenna which is given by [13,17]:

$$BW = \frac{s-1}{Q_t.\sqrt{s}} \quad \text{.......... (22)}$$

The gain is a measure of an antennas ability to concentrate the power accepted at its input terminal and mathematically can be expressed as [17]:

$$Gain = \eta.Dr \quad \text{.......... (22)}$$

All the above parameters have been formulated in an additional subroutine namely (circular-parameters)-subroutine which added to the main program which are obtained from ref.[16]. Moreover, the program has been modified by author calculate the effects of loss tangent and dielectric substrate permittivity and thickness on performance of the electrical properties of CMSA exited by a coaxial-feed.

3. Results and Discussion

3-1 Effect of Loss Tangent (tanδ)

The effect of loss tangent (tanδ) on the input resonance resistance with (a=3 cm, ε_r=2.33 and h=0.159 cm) is shown in **Fig.(2)**. This figure shows the calculated and measured variations of the input resistance versus of feed-position for different values of loss tangent. It is obviously seen that, there is a good agreement between measured and calculated value with present work, especially for high losses. In addition, as tanδ increases from (0.0001 to 0.05) the input resistance at the periphery decreases. Hence, to match with (50) Ω, the feed point must be moved away from the center in order to use substrate with large losses.

The effect of the loss tangent at f_r=1.8635 GHz on the other electrical parameters of CMSA is shown in **Fig.(3)** and **Fig (4)**. One sees that, as tanδ increases from (0.0001 to 0.05) the efficiency and gain decreases from (92.7 to 22.12%) and from (7.02 to 0.599dB), respectively. While, the bandwidth increases from (1.04%) at 19.39 MHz to (4.56%) at 85.14 MHz. These behaviors are in good agreement with measured values as given by [13]. So, the MSA on a lossy substrate gives a wider bandwidth with reduced efficiency and hence lower gain.

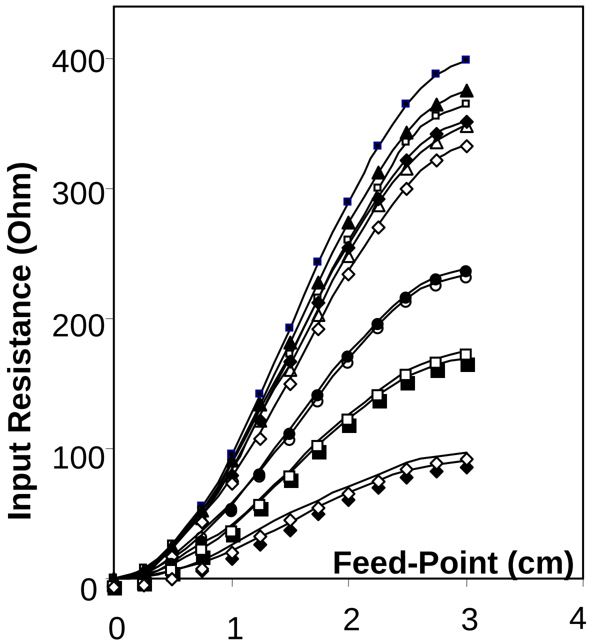

Figure (2) Variation of CMSA-Input Impedance versus Feed-Position and for Different Value of Loss Tangent

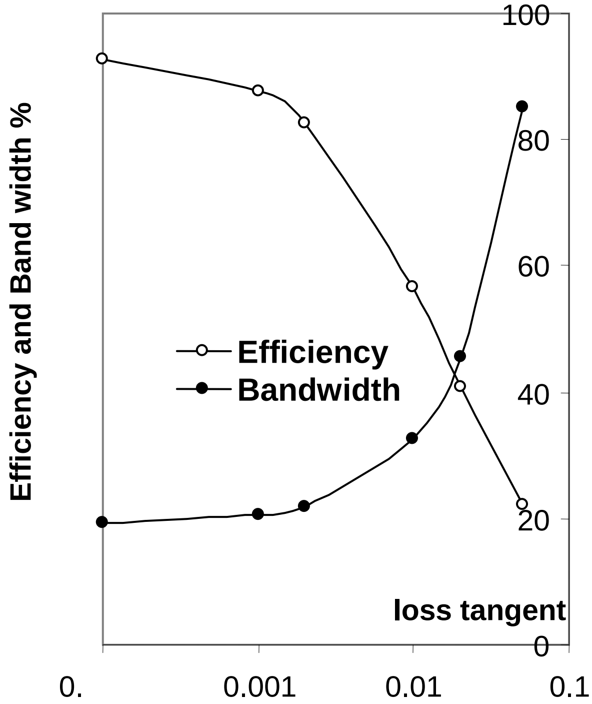

Figure (3) Variation of Efficiency and Band versus Loss Tangent for Circular Microstrip Antennas

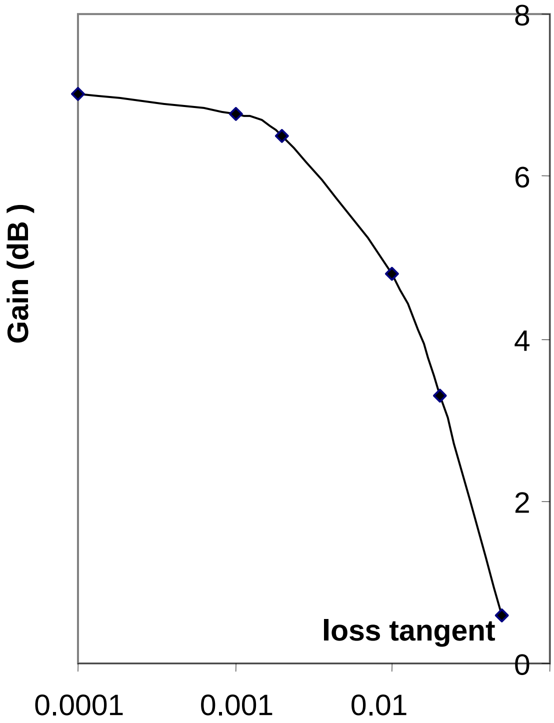

Figure (4) Variation of Circular Microstrip Antenna Gain versus Loss Tangent

3-2 Effects of Dielectric Substrate Thickness and Permittivity (εr)

The theoretical resonance frequencies which have been obtained using Eq.(1) for different εr, a, and h, are represented in **Table (1)**. The compression of the resonant frequencies among previous calculated results [7, 9, 11, 12] and the measured data [8, 15], are also shown. The resonant frequencies calculated by the present method are in good agreement with the measured data .the advantages of this method are their simplicity and accuracy.

The effect of dielectric substrate permittivity on the electrical properties of CMSA with (a=3 cm, h=0.159 cm, and tanδ=0.001) is represented in **Table (2)**. This table indicated that, the resonance frequency, bandwidth, efficiency, gain and directivity of the CMSA decrease with increasing dielectric substrate permittivity. This variation is mainly due to decreasing of the fringing fields and decreasing of the patch area. Thus, the lower dielectric substrate permittivity gives higher value of electrical parameters of MSA.

Table (1) Compression of Calculated and Experimental Measurement of Resonance Frequencies for Circular Microstrip Antennas of Different ε_r, a , and h of the Substrate

ε_r	h (cm)	a (cm)	Resonance Frequency (GHz)			
			Measured [8,15]	Theoretical Calculation[7,11]	Theoretical Calculation[9,12]	Present Work
2.2	0.079	0.7502	7.38	7.73	7.76	7.440
2.2	0.1575	0.6868	7.75	8.23	7.9	7.660
2.32	0.08	6.8	0.835	0.822	0.836	0.842
2.33	0.159	3.0	1.867	1.877		1.863
2.49	0.1524	3.8	1.443	1.43	1.44	1.436
2.5	0.1588	3.493	1.57	1.561	1.567	1.555
2.59	0.0794	1.27	4.07	4.144	4.203	4.175
2.65	0.15875	1.15	4.425	4.428		4.414
2.7	1.27	13.894	0.378		0.372	0.369
4.55	0.235	4.95	0.825	0.882	0.827	0.826
10.2	0.127	0.5308	4.6	5.08	5.08	5.049
10.2	0.254	0.992	2.71	2.68	2.68	2.692

Table (2) Variation of Circular Microstrip Antenna Parameters Via Dielectric Substrate and with (a=3.0 cm, tanδ=0.001, h=0.159 cm)

ε_r	Feed Position	Rin (Ω)	Bandwidth (MHZ)	Efficiency %	Gain (dB)	Directivity (dB)	Frequency (GHZ)
1.0	0.9	57.16	53.25	93.54	9.57	9.86	2.690
2.33	0.75	52.70	20.58	87.7	6.76	7.351	1.863
4.3	0.65	51.51	9.14	77.7	5.05	6.188	1.394
9.8	0.6	56.81	3.26	52.79	2.53	5.389	0.939

Table (3) shows the variation of electrical properties of CMSA as a function of substrate thicknesses with (a=3 cm, ε_r=2.33, and tanδ=0.001). It is seen that all parameters values increase with increasing the substrate thicknesses, except the value of resonance frequency which is decreased. The increased of the bandwidth, directivity, gain and efficiency, are belong to the increasing in the aperture area and size of the patch, while decreasing the resonance frequency is due to the increased effective patch radius.

Table (3) Calculations of Electrical Properties of CMSA for Various Height of Dielectric Substrate with (a=3 cm, ε_r=2.33, and tanδ=0.001)

h (cm)	Feed Position	Directivity (dB)	Gain (dB)	Bandwidth (MHz)	Efficiency %	Frequency (GHz)	Rin (Ω)
0.10	0.85	7.32	6.21	15.06	77.87	1.883	60.7
0.15	0.80	7.34	6.71	19.72	86.75	1.866	59.1
0.20	0.75	7.37	6.93	24.47	90.84	1.850	60.7
0.25	0.75	7.39	7.06	29.11	93.09	1.834	54.0
0.30	0.75	7.41	7.14	33.61	94.50	1.819	53.8
0.35	0.75	7.42	7.21	37.94	95.43	1.805	53.5
0.40	0.75	7.44	7.25	42.11	96.11	1.791	52.9
0.45	0.75	7.45	7.29	46.13	96.61	1.777	52.3
0.50	0.75	7.47	7.32	49.99	97.00	1.763	51.6

Therefore, to increase the bandwidth and other electrical parameters of the CMSA, the substrate permittivity must be lowered and thicknesses enhanced .The effects of increasing the substrate thicknesses and reducing its permittivity with (a=3cm and tanδ=0.001) on the performance of CMSA are presented on **Table (4)**. It is clearly seen that, as ε_r decreased from (2.33 to 1) and h from (0.159 to 0.5), resonance frequency increases from (1.863 to 2.402 GHz), the bandwidth increases from (1.04 to 5.28 %), and gain increases from (6.76 to 9.79 dB) at corresponding center frequency.

Table (4) Calculations of Electrical Properties of CMSA for Various ε_r and Height with (a=3 cm and tanδ=0.001)

ε_r	h (cm)	Feed Position	Directivity (dB)	Gain (dB)	BW (MHz)	Efficiency %	Frequency (GHz)	Rin (Ω)
2.33	0.159	0.75	7.35	6.76	20.58	87.7	1.863	52.4
2.1	0.22	0.75	7.63	7.29	29.99	92.58	1.931	51.6
1.9	0.28	0.8	7.93	7.69	40.92	94.9	1.993	55.8
1.7	0.34	0.8	8.26	8.09	54.21	96.32	2.061	52.6
1.5	0.4	0.85	8.65	8.52	70.54	97.21	2.138	55.0
1.3	0.45	0.85	9.09	8.99	89.64	97.76	2.228	50.7
1.1	0.5	0.9	9.86	9.79	127.0	98.29	2.402	53.7

4. Conclusion

This research demonstrates that, increasing the loss tangent and dielectric substrate permittivity and thicknesses have the following performances on the electrical properties of the CMSA elements:

1. The efficiency and gain of MSA decrease with increasing the value of tanδ, whereas bandwidth increases due to an increase in the dielectric losses in the substrate.
2. The input resonance resistance decrease with increasing the value of tanδ, so to match with (50)Ω, the feed-position must be moved away from the center of the CMSA, in order to use substrate with large losses.
3. Decreased of the resonance frequencies with increasing (ε_r) and (h), associated with the increasing effective patch radius.
4. Decreasing of bandwidth with increasing dielectric permittivity (ε_r) and decreasing substrate thicknesses (h), associated with the increased total quality factor and decreasing in the fringing fields.
5. The increasing of efficiency, gain and directivity, as the substrate thickness increases are due to the increasing of the aperture area and size of the patch.

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