RESEARCH NOTE

DETERMINATION OF RESONANCE FREQUENCY OF DOMINANT AND HIGHER ORDER MODES IN THIN AND THICK CIRCULAR MICROSTRIP PATCH ANTENNAS WITH SUPERSTRATE BY MWM

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Abstract An accurate model named as the Modified Wolff Model (MWM) is presented as an efficient CAD tool for determination of resonant frequency of the dominant and higher order modes under the multi-layer condition in thin and thick circular microstrip patch antennas. The effects of dielectric cover on the resonant frequency obtained from MWM have been compared against the result of theoretical method of Spectral Domain Analysis (SDA). The accuracy of calculated resonant frequency by the MWM for dominant mode is about 0.5% and the average error for higher order modes is about 0.88%. Sensitiveness of higher order modes and also uncertainty effect on the resonant frequency are calculated by the MWM.

Key Words Modified Wolff Model, MWM, Microstrip Antenna, Microstrip Patch Antenna, Superstrate, Dynamic Dielectric Constant, Transverse Transmission Line, TTL

چکیده تعیین دقیق فرکانس تشدید مدهای غالب و مرتبه بالا و نیز اثرات روکش بر فرکانس تشدید در طراحی آنتنهای ریز نوار بسیار حائز اهمیت است. زیرا آنتنهای ریز نوار از پهنای بسیار باریک برخوردار هستند. برای تعیین فرکانس تشدید مدهای غالب و مرتبه بالا روشهای مختلفی ارائه کرده اند، ولی تا کنون نتایج منسجمی از تعیین فرکانس تشدید مدهای غالب و مرتبه بالا و حساسیت آنها نسبت به پارامترهای دیگر و همچنین تعیین وجود اثرات ناخواسته تأثیرگذار بر فرکانس تشدید در حین تولید در مجلات علمی صورت نپذیرفته است. با توجه به نکات فوق مدل جدید MWM بسیار دقیقی را طرح و برای مطالعه پارامترهای فوق و همچنین اثرات روکش بر روی فرکانس تشدید آنتن های ریز نوار با شکل هندسی مختلفی به کار گرفته و نتایج بدست آمده با آنچه که به طور تجربی در این زمینه در مراجع مختلف جمع آوری و مقایسه شده است و با توجه به دقت بالای نتایج بدست آمده از این روش، آن را برای تعیین فرکانس تشدید مدهای غالب و مرتبه بالا در آنتن های ریز نوار بدون روکش اعمال شده و نتایج حاصله با نتایج عملی بدست آمده از منابع بسیار مختلفی مورد استفاده قرار گرفته است. بعلاوه دقت در تعیین فرکانس تشدید به وسیله MWM برای مد غالب ۰/۵ درصد و به طور متوسط خطا در مدهای بالاتر ۰/۸۸ درصد برآورد شده است.

1. INTRODUCTION

Accurate determination of the resonant frequency is very important for the design of microstrip patch antennas because they have narrow bandwidths and can only operate effectively in the vicinity of the resonant frequency. The circular patch operating at higher order modes has been used as the radiating element with higher gain to control the radiation pattern from broad side radiation to end fire radiation and the conical beam has been obtained with the help of the higher order modes [1-12]. To protect a microstrip antenna from environmental effect, a dielectric cover is usually added at the top of patch [14].

However most of the previous theoretical and

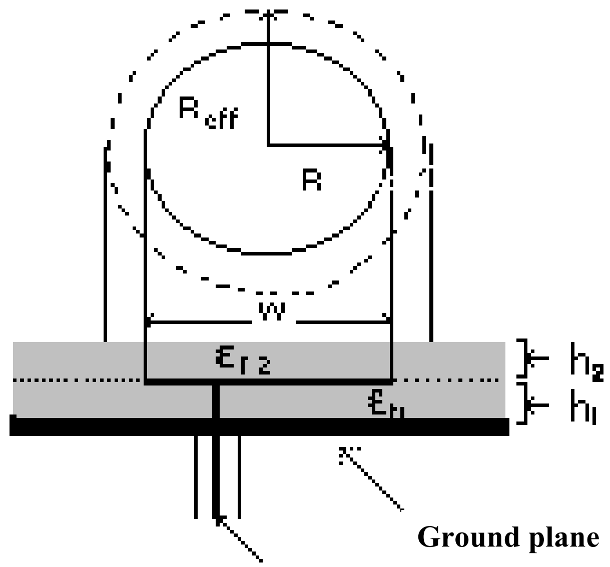

Figure 1. Geometry of circular microstrip patch antenna with cover: a cross-sectional view.

experimental work has been carried out only on electrically thin microstrip patch antennas normally of the order of $0.02 > h1/\lambda g$ where h1 is the thickness of dielectric substrate.

In this paper a unified model MWM is presented to determine the resonant frequency of both thin and thick circular microstrip patch antennas for dominant and higher order modes. In such patches the resonant frequency depends strongly on the effective dynamic dielectric constant and effective radius. Therefore models of Wolff and Knoppick [15] has been modified by using the Transverse Transmission Line (TTL) technique [16] to compute the effective dynamic dielectric constant under multi-layer condition.

The resonant frequency of dominant and higher order modes calculated by the MWM shows good agreement with compare to experimental and available numerical results. The importance of the model is that none of the above-mentioned models is applicable to determine the effect of dielectric cover on the resonant frequency of various patches. Experimentally it is verified that a dielectric cover on a rectangular patch antenna decreases the resonant frequency significantly [16]. Therefore theoretical method for predicting the effect of superstrate on the resonant frequency is of considerable interest. Here we have used MWM to calculate the effect of cover on the resonant frequency and compared the results obtained from SDA [14]. The percentage error calculated by the MWM is 0.88% whereas that of the Antoszieweiz method is 1.3%. The error in the higher order mode in resonating structures may arise due to uncertainty in the fabrication process of microstrip patch resonators and antennas. We have realized that the uncertainty of 1% in increase in radius R of circular patch results into uncertainty 0.9% to 1% in resonant frequency. Likewise 1% uncertainty in ε_r and h1 results into 0.63%. Deviation in resonant frequency of higher order modes is more sensitive to the variation in ε_r. For instance 2% change in εr results in 0.83% change in resonant frequency of the higher order modes.

The resonant frequency of higher order modes in circular microstrip patch has been calculated by J. Q. Howell [17] and the minimum percentage error of resonant frequency is 1.39 % and maximum is 10.6% and the average is 4.87%, whereas the minimum percentage error of resonant frequency for TM_{11} mode obtained by the MWM is zero and for higher order maximum is 9.4%. Meanwhile the resonant frequency of higher order modes calculated by the MWM compared against the results obtained from Antoszkiewiez [6].

2. FORMULATION OF THE MODEL

The MWM is basically a cavity model. The original Wolff Model was developed for a single layer open resonating structure [15]. To generalize the Wolff model to multilayer resonating structure as shown in Figure 1, we have adopted the variational method to calculate dynamic dielectric constant ϵ_{dyn}. Determination of ϵ_{dyn} takes into account the charge distribution along both the longitudinal and transverse directions of the patch. Thus, even though the MWM uses static variational method, it simulates the effect of full wave analysis [8].

For the covered circular patch shown in figure 1, the resonant frequency could be obtained from [9] as:

$$f_{nm} = \frac{X_{nm} V_0}{2\pi R_{eff} \sqrt{\varepsilon_{dyn}}} \quad (1)$$

TABLE 1. Comparison of Measured and Calculated Resonance Frequency of Circular Microstrip Disk Antenna.

R(cm) radius	h_1(cm)	ε_{r1}	h_1/λ_g	F_{mwm} MWM	$F_{1,meas}$ [1-6] MHz	F_1 [13] MHz	F_3 [6] MHz	F_4 [4] MHz	F_5 [7] MHz	F_6 [5] MHz	F_7 [8] MHz	F_8 [9] MHz	F_9 [10] MHz	F_{10} [11] MHz	F_{11} [12] MHz
6.800	0.0800	2.32	0.003392	841	835	840	845	849	840	842	844	838	841	840	842
6.800	0.15900	2.32	0.006692	835	829	831	842	849	833	837	839	831	836	832	837
6.800	0.31800	3.62	0.013159	825	815	815	834	849	821	826	829	819	826	818	826
5.000	0.15900	2.32	0.009106	1131	1128	1123	1141	1154	1127	1133	1136	1124	1132	1125	1133
3.800	0.15240	2.49	0.011567	1434	1443	1432	1445	1466	1427	1436	1439	1423	1435	1423	1436
4.850	0.31800	2.52	0.018493	1104	1099	1100	1115	1142	1098	1105	1109	1095	1105	1091	1105
3.493	0.15880	2.50	0.013140	1553	1570	1550	1565	1580	1545	1555	1559	1541	1559	1539	1555
13.894	1.27000	2.70	0.026000	371	378	371	372	387	367	370	371	366	370	364	370
1.270	0.07940	2.59	0.017336	4171	4070	4168	4203	4290	4145	4175	4187	4134	4173	4120	4175
3.493	0.31750	2.50	0.025268	1523	1510	1510	1539	1580	1513	1522	1529	1509	1523	1498	1522
4.950	0.23500	4.55	0.013785	825	825	823	818	833	818	827	827	816	825	817	827
3.975	0.23500	4.55	0.017210	1025	1030	1022	1014	1037	1016	1027	1027	1013	1026	1013	1027
2.990	0.23500	4.55	0.022724	1358	1360	1352	1339	1379	1344	1356	1360	1340	1359	1336	1358
2.000	0.23500	4.55	0.033468	2013	2003	2002	1972	2061	1990	2009	2012	1984	2012	1966	2009
1.040	0.23500	4.55	0.062659	3755	3750	3750	3627	3963	3749	3744	3737	3739	3752	3634	3744
0.770	0.23500	4.55	0.082626	4945	4945	4945	4722	5353	5001	4938	4922	4987	4943	4817	4938
1.150	0.15875	2.65	0.038118	4424	4425	4413	4461	4695	4401	4413	4437	4388	4422	4328	4413
1.070	0.15875	2.65	0.040684	4735	4723	4722	4776	5046	4714	4723	4749	4699	4731	4630	4720
0.960	0.15875	2.65	0.045006	5242	5224	5224	5289	5625	5226	5226	5257	5209	5237	5121	5226
0.740	0.15875	2.65	0.057146	6634	6634	6636	6733	7297	6682	6644	6648	6661	6658	6499	6644
0.820	0.15875	2.65	0.052300	6068	6074	6043	6125	6585	6066	6047	6084	6046	6061	5920	6047

TABLE 2. Percentage Errors.

	F_{mwm} MWM	F_2 [13]	F_3 [6]	F_4 [4]	F_5 [7]	F_6 [5]	F_7 [8]	F_8 [9]	F_9 [10]	F_{10} [11]	F_{11} [12]
Minimum % Error	0	0	0.13	0.67	0.02	0	0	0.2	0	0.01	0
Maximum % Error	2.4	2.4	4.5	9.9	2.9	2.5	2.8	3.1	2.4	3.7	2.5

Where Xnm is the mth root of derivative of Bessel function of nth order, the value of which for some m's and n's (X_{01} = 3.832, X_{11}= 1.841, X_{21} =3.054, X_{31} = 4.201) andV_0 is the velocity of light in free space. R_{eff} is the effective radius obtained from expression of Chew and Kong [18].

$$R_{eff} = R[1 + 2h_1/R(\varepsilon_{r1}(\ln(R/2h_1) + (1.41(\varepsilon_{r1} + 1.77)) + h_1(0.2668(\varepsilon_{r1} + 1.65))]^{\frac{1}{2}} \quad (2)$$

Where R is the radius of the patch, h_1 is the height of the substrate and ε_{r1} =ε_r is relative dielectric

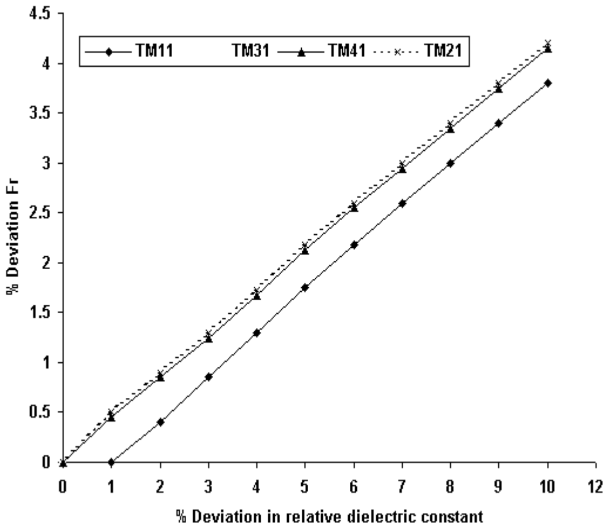

Figure 2. Sensitivity of modes on circular microstrip patch.

constant of substrate. ε_{dyn} is the dynamic dielectric constant which takes into account the fringe field. The dynamic dielectric constant obtained with help of variation method in the Fourier Domain and using the Greens function problem has determined by the TTL method [16].

$$\varepsilon_{dyn} = C_{dyn}(2R, h_1, h_2, \varepsilon_{r1}, \varepsilon_{r2}) / C_{dyn}(2R, h_1, h_2, \varepsilon_{r1} = \varepsilon_{r2} = 1) \quad (3)$$

Where ε_{r1} , ε_{r2} are the relative dielectric constant of substrate and superstrate respectively. C_{dyn} (2R,h1,h2, ε_{r1}, ε_{r2}) and C_{dyn}(2R, h1, h2, $\varepsilon_{r1}=\varepsilon_{r2}=1$) are the total dynamic capacitance of covered and air filled patch respectively. The dynamic capacitance of circular patch, which takes into account the fringe field, and modal variation of the field is obtained [16].

$$\varepsilon_{dyn} = C_{mstatic}(2R, h_1, \varepsilon_{r1}) / C_{fstatic}(2R, h_1, h_2, \varepsilon_{r1}, \varepsilon_{r2}) \quad (4)$$

Where $C_{mstatic}$ (2R,h1,ε_{r1}) is the main static capacitance of the patch and given by:

$$C_{mstatic} = \frac{\varepsilon_0 \varepsilon_{r1} R^2}{\gamma h_1} \left[1 - \frac{J_{n-1}(K_r) J_{n+1}(K_r)}{J_n^2(K_r)} \right]$$

$$\gamma = \begin{cases} 1 & \text{for} \quad n = 0 \\ 2 & \text{for} \quad n \neq 0 \end{cases} \quad (5)$$

K is the wave number. The dielectric cover does not influence the main capacitance of circular disk. For the fundamental TM_{11} mode, static capacitance can be obtained as:

$$C_{mstatic} = 0.3525 \varepsilon_0 \varepsilon_{r1} \pi R^2 / h_1 \quad (6)$$

Where h1 is the substrate thickness of the patch.

To calculate fringe capacitance we have done a structural transformation by replacing W=πR/2 and L=2R which gives very accurate result of resonant frequency. The fringe capacitance can be obtained from the following expression.

$$C_{fstatic} = \frac{1}{2} \left[\frac{Z_0(W, h_1, h_2, \varepsilon_{r1} = \varepsilon_{r2} = 1) L}{V_0 Z^2(w, h_1, h_2, \varepsilon_{r1}, \varepsilon_{r2})} - \frac{\varepsilon_0 \varepsilon_{r1} A}{h_1} \right] \quad (7)$$

Where A is the area of central patch and $Z_0(2R, h_1, h_2, \varepsilon_{r1} = \varepsilon_{r2} = 1)$, $Z(W_1, h_1, h_2, \varepsilon_{r1}, \varepsilon_{r2})$ are the characteristic impedances of the patch of width W=2R on the air substrate and with dielectric respectively. The characteristic impedance can be calculated by using variational method along with TTL technique to obtain the Green's function of the structure[16]. Therefore the capacitance per unit length of the line is obtained from expression [19].

$$\frac{1}{C} = \frac{1}{\pi \varepsilon_0} \int_0^\infty \frac{\left[\frac{f(\beta)}{Q} \right]^2}{\beta} \frac{1}{Y} d\beta \quad (8)$$

Where Q is the total charge on the conducting patch and f(β) is the Fourier transform of the charge distribution function and Y is the admittance function [19].

$$Y = \varepsilon_{r1} \coth(\beta h_1) + \varepsilon_{r2} \left[\frac{\varepsilon_{r2} + \coth(\beta h_2)}{1 + \varepsilon_{r2} \coth(\beta h_2)} \right] \quad (9)$$

TABLE 3. The Effect of Cover on the Resonance Frequency.

R (cm)	ε_{r1}	ε_{r2}	h_1 (cm)	h_2 (cm)	F_{mwm} GHz	SDA [14] GHz
2.5	2.5	2.5	0.1588	0.0635	2.103	2.04
2.5	2.5	1.06	0.1588	0.635	2.151	2.133
2.5	9.8	2.5	0.635	0.254	1.120	1.11

TABLE 4. Resonance Frequency of Higher Order Mode for the Circular Microstrip Disk Antenna. h_1 = 0.318 cm, R = 4.85 cm, ε_{r1} = 2.52.

TM MODE	MEASURED MHz	THEORY [6] MHz I	MWM II MHz	ERROR % I	ERROR % II
01	2241.00	2278.28	2263.30	1.66	0.99
11	1099.00	1094.76	1106.54	0.39	0.68
21	1837.00	1815.99	1845.87	1.14	0.48
31	2540.00	2497.98	2550.88	1.65	0.42
41	3226.03	3161.72	3241.49	1.99	0.48
51	3893.00	3814064	3925.40	2.01	0.83
02	4142.00	4171.39	4145.18	0.71	0.07
12	3120.00	3169.99	3182.48	1.60	2.00
22	3944.00	3987.37	4000.70	1.10	1.43
32	4726.00	4765.74	479500	0.84	1.46
				AV=1.30	AV=0.88

AV= Average

TABLE 5. Resonance Frequency of the Higher Order Mode for Circular Microstrip Patch Antennas. R = 3.4925 cm , ε_{r1} = 2.5, h_1 = 0.3175 cm.

TM Mode	Exper.	Howell [17] I	MWM II	Error % I	Error % II
1,1	**1.52**	**1.59**	**1.52**	**4.6**	**0.0**
2,1	2.53	2.64	2.54	4.3	0.30
3,1	3.58	3.63	3.52	1.39	1.60
4,1 1,2	4.44	4.49 AV=4.55 4.61	4.45 AV=4.46 4.46	2.47	0.40
5,1 2,2	5.74	5.54 AV=5.67 5.80	5.38 AV=5.5 5.62	4.4	1.30
6,1	6.14	6.48	6.23	5.55	1.4
3,2	6.51	6.92	6.75	6.3	3.6
1,3 7,1	7.1	7.38 AV=7.40 7.42	7.16 AV=7.23 7.31	4.22	1.8
8,1	7.54	8.34	8.25	10.6	9.4

3. RESULTS

This paper the MWM is applied to determine the resonant frequency of electrically thin and thick circular microstrip patch antennas and the computed results obtained from the MWM are compared experimentally theoretically verified values which are given in the literature [13] and the total values are listed in Table 1.

The measured values [1-6] and calculated by [1,3,4-12] and the minimum percentage error and the maximum percentage error are listed in Table 2. It can be seen that in Tables 1 and 2 that two models [13] and [10] and our present model MWM have good agreement with experimental results. But the importance of the model MWM is that none of the above mentioned models are applicable to calculate the cover effect on the resonant frequency .The effect of cover on the resonant frequency is calculated by the MWM and compared against the result of SDA and are listed in the Table 3. Our results are in about 1% difference compared to the results from the SDA.

The resonant frequency calculated by the MWM is always higher than that calculated by using SDA. However the resonant frequency calculated by the SDA is between 0.5% and 1% lower than that of measured value for the uncovered patches, this is due to high value of the calculated $\in_{eff}$ using SDA. Thus, the MWM is expected to provide a resonant frequency about 0.5% of the experimental value for covered circular patches. Table 4 shows the accurate determination of resonant frequency of higher order modes as computed by the MWM and compared against experimental and theoretical results of Antoszkiewicz [6]. The average error calculated by the MWM is 0.88% where as, from the Antoszkiewcz method is 1.3%. Table 5 shows the resonant frequency computed by the MWM compared results obtained from Howell [17] and the minimum percentage error of resonant frequency computed by the MWM is zero and maximum is 9.4%, the average error for all modes is 2.2%. Whereas, the minimum percentage error calculated by Howell is 1.39%, the maximum is 10.6% and average is 4.8%. For mode (4,1.1,2), (5,1.2,2) and (1,3.7,1), in Table 5 one resonant was observed during the experiment. Thus, the average resonant frequency of two modes has been taken for error

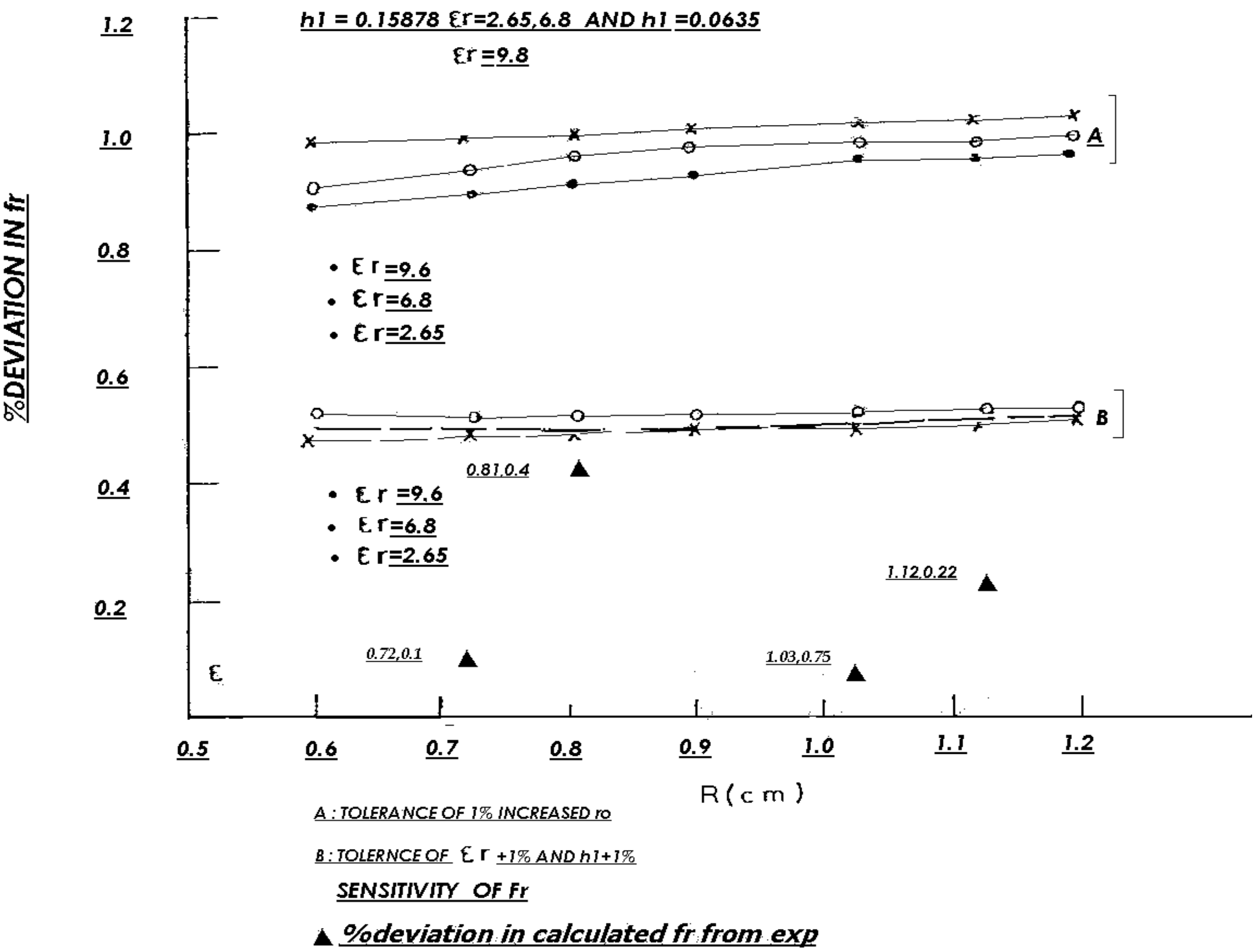

Figure 3. %Deviation in calculated fr from exp.

estimation. Thus, the MWM can be used for the accurate determination of resonant frequency of higher modes of a circular patch. The results of resonant frequency of higher modes of the circular patch from Full Wave Analysis method are not available in the literature.

4. SENSITIVITY OF THE MODES

Figure 2 shows the sensitivity of the resonant frequency of the higher order modes with respect to the variation in ε_r. The resonant frequency of the higher order modes are more sensitive to the variation in ε_r. For instance 2% change in ε_r results into 0.5% change in the resonant frequency of TM_{11} mode whereas, it results into 0.85% change in the resonant frequency of higher modes.

5. UNCERTAINTY EFFECT

Figure 3 gives us the deviation in the calculated resonant frequency by the MWM due to uncertainty in the fabrication process of microstrip patch resonator and antenna. Several resonating circular patches operating in TM_{11} mode have been designed on microstrip thickness h_l= 0.5875 cm dielectric constants

ε_r = 2.65, 6.8 and h_1 = 0.0635 cm, ε_r = 9.6. And also Figure 3 shows that the uncertainty of 1% in radius R of circular patch results into uncertainty of 0.9% to1% in the resonant frequency depending upon the substrate. Likewise, 1% uncertainty in εr and h1 results into 0.63% uncertainty in the resonant frequency of the patch, and also it shows departure of calculated resonant frequency by the MWM against the measured values. It is obvious that the MWM is highly accurate and the deviation in f_r comes within uncertainty in the fabrication process and the data supplied by the manufacturer.

6. CONCLUSION

An accurate unified model, the Modified Wolff Model (MWM), is presented to determine the resonant frequency of dominant and higher order modes under the multi-layer condition in thin and thick circular microstrip patch antennas. The importance of the model is that it is applicable to all kinds of arbitrary geometry of patches. It achieves the accuracy of full wave analysis method without any computational difficulties. Almost in all cases the calculated results of MWM comparing to the results, which obtained from other numerical methods are more closely to the experimental values. The MWM model has also been applied satisfactory for higher order modes and the results compared with the experimental values are more closely than the results obtained from numerical models and also the MWM applied to determine uncertainty effect on resonant frequency and sensitivity of modes to the resonant frequency.

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