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Design of an Antenna System in Wireless Communication Applications (2.45GHz ISM Band) by Applying FDSC Model

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***Abstract*—The dynamic permittivity of microstrip structure deduced by adopting the Cole-Cole diagram results in a modified smith-chart representation (FDSC) that takes into the account the frequency-dependent influence of the fringing field and lossy characteristics of the line cohesively. This research illustrates microstrip patch antenna system for wireless communications applications that operates on 2.45 MHz ISM band. The impedance matching is a part of the design process to maximize power in the antenna system. This model proposed in this research is compatible with computer aided design system (CAD) and hence, fast and easy for implementation.**

***Index Terms*—Antenna design, computer aided design (CAD), frequency dependent smith chart (FDSC), impedance matching, microstrip.**

I. Introduction

The adoption of frequency-dependent (lossy) Smith-chart representation is proved to be an effective method for rectangular microstrip antenna design [1]. The Industrial, Scientific and Medical (ISM) frequency bands governed by Federal Communications Commission (FCC) Part 15 specifications have seen dramatic growth in recent years, particularly for 2.4000 to 2.4835GHz (ISM-2400) band.

In this paper, the present effort addresses the design of an antenna system for wireless communication applications, which operates in the 2.45GHz (ISM) band. First, the design of the rectangular microstrip patch antenna is demonstrated by using the FDSC model in [2], [3] Then, the impedance matching methods for the antenna are indicated. Finally, the analysis and comparison of the FDSC design and the conventional model [4] are presented.

II. Rectangular Microstrip Patch Antenna Design

For the present design, the rectangular microstrip antenna has a substrate with dielectric constant (ε_r) of 2.5 and the antenna is a direct-feed type. The size of the patch is $4.10\text{cm}(w) \times 4.14\text{cm}(l)$ ($w = 0.335\lambda$; $l = 0.3382\lambda$ at $f = 2.45\text{GHz}$) and a thickness of $h = 0.1524\text{cm}$ ($h = 0.0125\lambda$ at $f = 2.45\text{GHz}$). Fig. 1 shows the input impedances calculated as per the FDSC model [2], [3] and that by the Abboud's model [4] for the patch operating at 2.45GHz. The design of the matching section for the antenna will be the next step and is discussed in the following sections.

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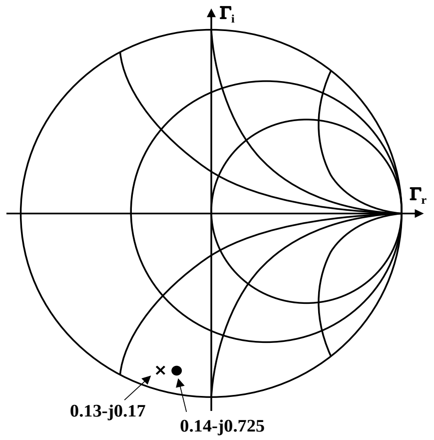

Fig. 1. The input impedance for a patch operating at 2.45GHz •FDSC model × Calculate [4].

III. Narrowband Matching

The impedance matching is a part of the design process for a microwave component or system where maximum power transfer is crucial. Impedance matching is pertinent because:

- Greatest and most efficient level of power is delivered when the load is matched to the line.
- Impedance matching power distribution network particularly in antenna will reduce amplitude and phase errors.

The quarter-wave transformer is a simple structure compatible for matching real load impedance to a transmission line. An additional feature of the quarter-wave transformer is that it can be extended to multi-section designs for broader bandwidths.

As a first step, how the input impedance varies with frequency when a single quarter-wave section is terminated in a pure resistance is considered. A drawback of a single section quarter-wave transformer is that it can only match a real load impedance. Complex load impedance as illustrated in Fig. 1 can be altered to a real part by using an suitable length of transmission line between the load and the transformer as illustrated in Fig. 2. For the example under discussion, the line-length required to transform the complex impedance to the real values are 1.236cm (0.101λ at $f = 2.45\text{GHz}$) and 1.102cm (0.09λ at $f = 2.45\text{GHz}$) for the FDSC model and the Abboud's model, respectively.

The quarter-wave section required for matching should have characteristic impedance R'_0 given by

$$R'_0 = \sqrt{R_R R_0} \tag{1}$$

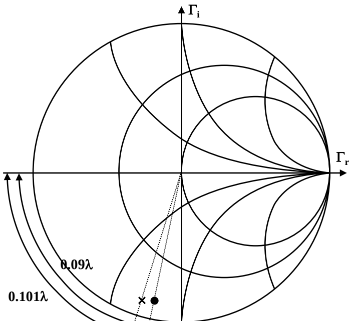

Fig. 2. Moving complex load impedance to a real impedance•FDSC model × Calculate [4]

The input impedance of the matched line, Z_{in} as a function of frequency can be obtained by using a Smith-chart. Normalizing the all quantities with respect to R'_0,

$$r'_r = \frac{R_R}{R'_0} \tag{2a}$$

$$r'_0 = \frac{R_0}{R'_0} \tag{2b}$$

For the design a lossless transformer section is assumed; hence the phase velocity is independent of frequency and $f\lambda = f_0\lambda_0$. Therefore, at any frequency f the transformer length as a fraction of the wavelength is given by

$$\frac{l}{\lambda} = \frac{l}{\lambda_0}\frac{f}{f_0} = 0.25 \tag{3}$$

Eq. (3) is used to compute the electrical length of the transformer in Table I over the range $0.5 \leq f/f_0 \leq 1.5$.

TABLE I: CALCULATION OF Z_{IN} FOR A QUARTER-WAVE TRANSFORMER (ABBOUD'S MODEL)

$f_0 = 2.45$GHz, $r'r = 0.36$, $Z_{in} = 0.36Z'_{in}$

f/f_0	l/λ	Z'_{in}	Z_{in}
1.5	0.375	0.65 – j 0.77	0.23 – j 0.28
1.4	0.350	0.85 – j 0.95	0.31 – j 0.34
1.3	0.325	1.19 – j 1.12	0.43 – j 0.40
1.2	0.300	1.70 – j 1.18	0.61 – j 0.42
1.1	0.275	2.50 – j 0.82	0.90 – j 0.29
1.0	0.250	2.80	1.01
0.9	0.225	2.50 + j 0.82	0.90 + j 0.29
0.8	0.200	1.70 + j 1.18	0.61 + j 0.42
0.7	0.175	1.19 + j 1.12	0.43 + j 0.40
0.6	0.150	0.85 + j 0.95	0.31 + j 0.34
0.5	0.125	0.65 + j 0.77	0.23 + j 0.28

Since R_R is independent of frequency, by using the Smith-chart (Fig. 3) at r'_r, and rotate l/λ on the $S' = r'_r$, circle for each frequency to find the corresponding value of normalized input impedance z'_{in}. A typical rotation is shown in the Fig. 3 for $f/f_0 = 0.5$, $l/\lambda = 0.125$.

The results are tabulated in Table I. By (2b) it may be seen that the match is perfect at f/f_0. The input impedance normalized with respect to R_0 is obtained by,

$$z_{in} = \frac{Z_{in}}{R_0} = \frac{Z_{in}}{R'_0}\frac{R'_0}{R_0} = \frac{R'_0}{R_0} \tag{4}$$

Value of z_{in} are shown in Table I and II for the FDSC model and that of the Abboud's model [4].

From Tables I-II and Fig. 3, Fig. 4, and Fig. 5, it illustrates that the maximum standing wave ratio is stipulated as 2, the allowable bandwidth of the FDSC model shows a greater value than that of the Abboud's model [4], to an extent of about 11.40%. A possible explanation is that $\Delta f/f$ (bandwidth) is directly proportional to the loss of the system [5]. Therefore, when the frequency-dependent characteristic impedance is taken into the calculation, it is reflected in an increase of bandwidth calculated (using FDSC model). The structure and dimension of the designed antenna is obtained in Fig. 6 and Table III.

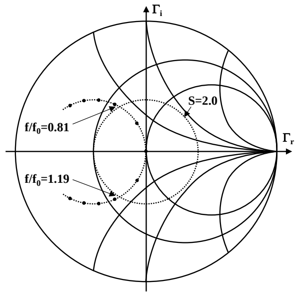

Fig. 3. Frequency response of a quarter-wave transformer for Abboud's model; $\Delta f/f$ (bandwidth) $= 0.38$ or bandwidth ($\Delta f = 0.931$GHz).

TABLE II: CALCULATION OF Z_{IN} FOR A QUARTER-WAVE TRANSFORMER (FDSC MODEL)

$f_0 = 2.45$GHz, $r'r = 0.37$, $Z_{in} = 0.37Z'_{in}$

f/f_0	l/λ	Z'_{in}	Z_{in}	Z_{in} (FDSC model)
1.5	0.375	0.66 – j 0.75	0.24 – j 0.28	0.23 – j 0.24
1.4	0.350	0.87 – j 0.93	0.32 – j 0.34	0.31 – j 0.24
1.3	0.325	1.19 – j 1.08	0.44 – j 0.40	0.43 – j 0.37
1.2	0.300	1.70 – j 1.11	0.63 – j 0.41	0.62 – j 0.38
1.1	0.275	2.35 – j 0.80	0.87 – j 0.30	0.85 – j 0.26
1.0	0.250	2.70	1.00	0.95
0.9	0.225	2.35 + j 0.80	0.87 + j 0.30	0.85 + j 0.26
0.8	0.200	1.70 + j 1.11	0.63 + j 0.41	0.62 + j 0.38
0.7	0.175	1.19 + j 1.08	0.44 + j 0.40	0.43 + j 0.37
0.6	0.150	0.87 + j 0.93	0.32 + j 0.34	0.31 + j 0.31
0.5	0.125	0.66 + j 0.75	0.24 + j 0.28	0.23 + j 0.24

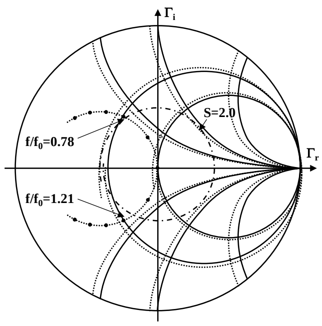

Fig. 4. Frequency response of a quarter-wave transformer for the FDSC model; $\Delta f/f$ (bandwidth) $= 0.43$ or bandwidth ($\Delta f = 1.051$GHz).

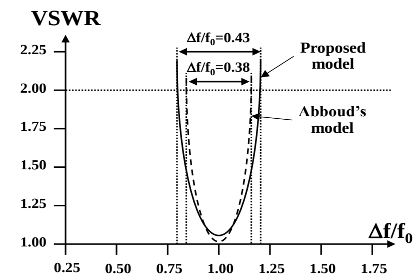

Fig. 5. Comparison bandwidth between Abboud's model and FDSC model with VSWR ≤ 2.0.

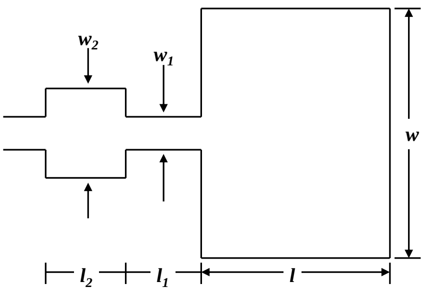

Fig. 6. Antenna structure and double-wave-transformer.

TABLE III: COMPARISON BETWEEN ABBOUD'S MODEL AND FDSC MODEL ($f_0 = 2.45$GHz)

Model	Abboud's model	FDSC model	Δ(%difference)
$w1$	0.435 cm (0.0355λ0)	0.435 cm (0.0355λ0)	0
$w2$	1.650 cm (0.1348λ0)	1.579 cm (0.1290λ0)	4.3
$\imath1$	1.102 cm (0.0900λ0)	1.236 cm (0.1010λ0)	10.84
$\imath2$	3.060 cm (0.2500λ0)	3.060 cm (0.2500λ0)	0
Bandwidth (GHz)	0.931	1.051	11.42

IV. BROADBAND MATCHING

As mentioned earlier, the broadband design can be achieved by using a set of cascaded quarter-wave transformer sections. Assuming that two or more quarter-wave sections are connected in cascade to transform R_R to R_{in}, the problem is then to determine R_0', R_0'', R_0''', namely, the characteristic impedances of these sections. A number of approaches have been identified in the frequency dependent smith chart (FDSC) literature to determine R_0', R_0'', R_0''' .For instance, Slater [6] has suggested the use of common logarithms of the impedance ratios at the junctions in the system with the coefficients of the binomial expansion $(a+b)^n$, as indicated below:

No. of $\lambda/4$ section, n	Logarithm of impedance ratio
2	1 2 1
3	1 3 3 1
4	1 4 6 4 1

For the present application, consider the design of a two-quarter-wave-section system. Reading from left to right-in the inset of Fig. 7, the impedance ratios at the junctions are $R_R/R_0', R_0'/R_0''$, and R_0''/R_0. Since the number of sections, n, is equal to 2,

$$log\left(\frac{R_0'}{R_0''}\right) = 2log\left(\frac{R_0''}{R_0}\right) = 2log\left(\frac{R_R}{R_0}\right) \tag{5}$$

That is, from left to right, the logarithms of the impedance ratios follow the rule 1 2 I in accordance with the above table. Then, taking antilogarithms,

$$\frac{R_0'}{R_0''} = \left(\frac{R_0''}{R_0}\right)^2 = \left(\frac{R_R}{R_0'}\right)^2 \tag{6}$$

Solving for R_0' and R_0'' in terms of R_0 and R_R

$$R_0' = \frac{R_0 R_R}{R_0''} \text{ or } R_0' = \sqrt[4]{R_R^3 R_0} \tag{7}$$

$$R_0'' = \frac{R_0 R_R}{R_0'} \tag{8}$$

The impedance at the junction of the two quarter-wave sections is (Fig. 6)

$$R_0'' = \frac{R_0 R_R}{R_0'} \tag{9}$$

This transformation will now be used to design a double-section system for an over-all transformation ratio of $R_p: R_0$.

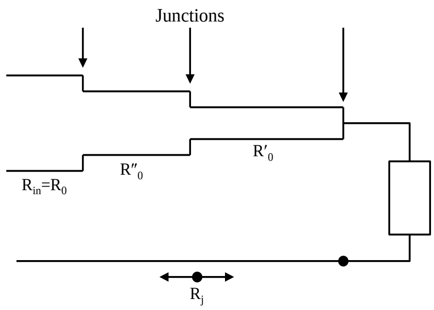

Fig. 7. Two cascaded quarter-wave transformers terminated in a constant resistive load.

As a first step, consider the right-hand section, and normalized R_R with respect to R_o':

$$r_r' = \frac{R_R}{R_0'} \tag{10a}$$

By (9) the normalized input impedance should be

$$r_j' = \frac{R_R}{R_0'} \tag{10b}$$

Following the method of the last section, enter r_r' value on the Smith chart diagram, and rotate on a circle of constant S' the appropriate fraction of a wavelength at each frequency. The values of z_j' are tabulated in Table IV and Table V, and the corresponding locus is shown in the Fig. 8 and Fig. 9.

Now, Z_j is the termination for the left-hand quarter-wave transformer in Fig. 7. To handle this section on the Smith-diagram, all quantities should be normalized with respect to R_0''. The double prime will indicate these quantities; thus,

$$z_j'' = \frac{z_j}{R_0''} = \frac{Z_j}{R_0'}\frac{R_0'}{R_0''} = \frac{R_0'}{R_0''} z_j' \tag{11}$$

Since z_j'' at each frequency and rotating toward the generator on a circle of constant S'' the appropriate distance indicated in the table. Z_{in} is determined by,

$$z_{in} = \frac{Z_{in}}{R_0} = \frac{Z_{in}}{R_0''}\frac{R_0''}{R_0} = \frac{R_0''}{R_0} z_{in}'' \tag{12}$$

The calculated results are shown in Tables IV-VI and Fig. 8, Fig. 9, and Fig. 10. The results indicate that, in the broadband matching, the bandwidth ($\Delta f/f = 0.8$) is greater than that of the narrowband matching ($\Delta f/f = 0.43$) or 46.25% difference as shown in Fig. 5 and Fig. 10. Further, it can be observed that the error between the FDSC model and the Abboud's model is 10% as shown in Table VI. The structure and dimension of the designed antenna is obtained in Fig. 11 and Table VI.

TABLE IV: CALCULATION OF Z_{IN} FOR A QUARTER-WAVE TRANSFORMER (ABBOUD'S MODEL)

$f_0 = 2.45$GHz, $r'r = 0.6, r_j' = 1.67, r_j'' = 0.36r'j, Z_{in} = 0.6Z_{in}''$

f/f_0	L/λ	Z_j'	Z_j''	Z_{in}''	Z_{in}
1.5	0.375	0.89 – j 0.46	0.32 – j 0.17	0.83 – j 1.07	0.49 – j 0.64
1.4	0.350	1.04 – j 0.51	0.37 – j 0.18	1.30 – j 1.15	0.78 – j 0.69
1.3	0.325	1.20 – j 0.50	0.43 – j 0.18	1.85 – j 0.85	1.10 – j 0.51
1.2	0.300	1.41 – j 0.42	0.51 – j 0.15	1.93 – j 0.34	1.16 – j 0.20
1.1	0.275	1.57 – j 0.25	0.57 – j 0.09	1.77 – j 0.04	1.06 – j 0.02
1.0	0.250	1.64	0.59	1.68	1.01
0.9	0.225	1.57 + j 0.25	0.57 + j 0.09	1.77 + j 0.04	1.06 + j 0.02
0.8	0.200	1.41 + j 0.42	0.51 + j 0.15	1.93 + j 0.34	1.16 + j 0.20
0.7	0.175	1.20 + j 0.50	0.43 + j 0.18	1.85 + j 0.85	1.10 + j 0.51
0.6	0.150	1.04 + j 0.51	0.37 + j 0.18	1.30 + j 1.15	0.78 + j 0.69
0.5	0.125	0.89 + j 0.46	0.32 + j 0.17	0.83 + j 1.07	0.49 + j 0.64

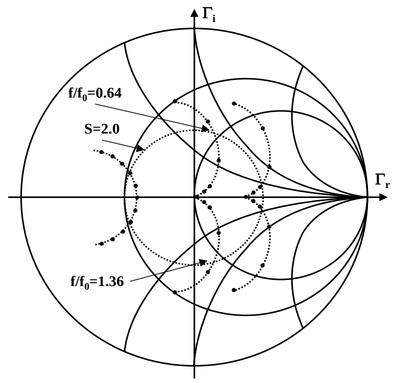

Fig. 8. Frequency response of quarter-wave transformer for Abboud's model; $\Delta f/f$(bandwidth) = 0.72 or bandwidth ($\Delta f = 1.764$GHz).

TABLE V: CALCULATION OF Z_{IN} FOR A QUARTER-WAVE TRANSFORMER (FDSC MODEL)

$f_0 = 2.45$GHz, $r'r = 0.61, r_j' = 1.64, r_j'' = 0.37r_j'$

f/f_0	L/λ	Z_j'	Z_j''	Z_{in}''	Z_{in} (FDSC model)
1.5	0.375	0.88 – j 0.46	0.33 – j 0.17	0.91 – j 1.16	0.54 + j 0.66
1.4	0.350	1.03 – j 0.51	0.38 – j 0.19	1.47 – j 1.15	0.88 + j 0.67
1.3	0.325	1.20 – j 0.51	0.44 – j 0.19	1.94 – j 0.70	1.14 + j 0.39
1.2	0.300	1.42 – j 0.44	0.53 – j 0.16	1.90 – j 0.20	1.12 + j 0.12
1.1	0.275	1.60 – j 0.25	0.59 – j 0.09	1.70 – j 0.02	1.02 + j 0.02
1.0	0.250	1.68	0.62	1.64	0.95
0.9	0.225	1.60 + j 0.25	0.59 + j 0.09	1.70 + j 0.02	1.00 + j 0.01
0.8	0.200	1.42 + j 0.44	0.53 + j 0.16	1.90 + j 0.20	1.10 + j 0.10
0.7	0.175	1.20 + j 0.51	0.44 + j 0.19	1.94 + j 0.70	1.15 + j 0.37
0.6	0.150	1.03 + j 0.51	0.38 + j 0.19	1.47 + j 1.15	0.87 + j 0.66
0.5	0.125	0.88 + j 0.46	0.33 + j 0.17	0.91 + j 1.16	0.54 + j 0.68

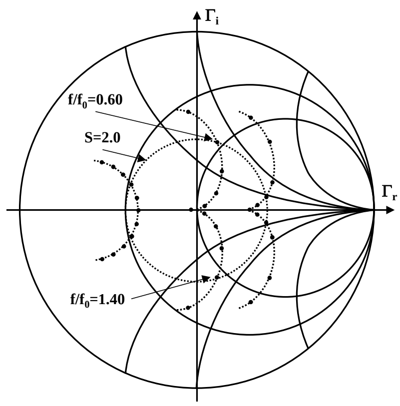

Fig. 9. Frequency response of a quarter-wave transformer for the FDSC model ; $\Delta f/f$(bandwidth) = 0.80 or bandwidth ($\Delta f = 1.96$GHz).

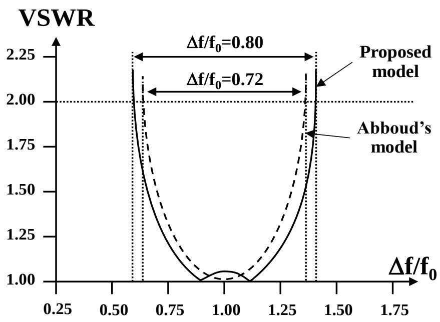

Fig. 10. Comparison bandwidth between Abboud's model and FDSC model with VSWR≤ 2.0.

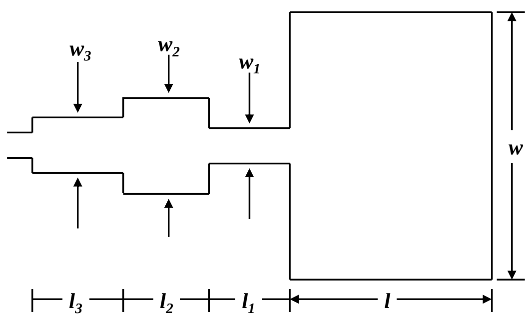

Fig. 11. Antenna structure and double-wave-transformer.

TABLE VI: COMPARISON BETWEEN ABBOUD'S MODEL AND FDSC MODEL ($f_0 = 2.45$GHz)

Model	Abboud's model	FDSC model	Δ(%difference)
$w1$	0.435 cm (0.0355λ0)	0.435 cm (0.0355λ0)	0
$w2$	2.950 cm (0.2410λ0)	2.785 cm (0.2275λ0)	5.59
$w3$	0.880 cm (0.0719λ0)	0.884 cm (0.0722λ0)	0.45
$l1$	1.102 cm (0.0900λ0)	1.236 cm (0.1010λ0)	10.84
$l2$	3.060 cm (0.2500λ0)	3.060 cm (0.2500λ0)	0
$l3$	3.060 cm (0.2500λ0)	3.060 cm (0.2500λ0)	0
Bandwidth (GHz)	1.764	1.960	10.00

V. CONCLUDING REMARKS

The use of modified smith-chart is proved to be an efficient method in representing the frequency characteristics of the microstrip line. This study further demonstrates the feasibility of a cohesive presentation of the dispersion (lossy and lossless) characteristics of a microstrip line via impedance matching. As indicated in this research, impedance matching in design process for the antenna allows efficient and greatest power to be delivered when the load is matched to the line. Further, impedance matching also reduces the amplitude and phase errors. Therefore, in this research it was concluded that in broadband matching, in adopting the FSDC representation in this case, error has been reduced by a significant level increasing the accuracy of the model. As a result, this research illustrates an efficient design of CAD compatible microstrip patch antenna system for wireless communications on 2.45 MHz ISM band.

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