Effects of Substrate Permittivity on Planar Inverted-F Antenna Performances

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***Abstract*—This paper quantifies the gain and matching bandwidth variations of a planar inverted-F antenna (PIFA) for several dielectric substrates. The performance of the PIFA is assessed in two configurations. First, the PIFA is studied with different substrates for a radiating patch of fixed dimensions of 4.92 cm x 2.13 cm. The effects of the dielectric constant of the perfect and lossy substrates on the resonant frequency, bandwidth and gain are investigated. A gain drop of 2 dB per decade is observed. In the second evaluation, the physical dimensions of the radiating element of the PIFA are adjusted to achieve resonance at 1.14 GHz. The gain drop reduces to 1.5 dB per decade.**

***Index Terms*—PIFA, gain, substrate materials**

I. INTRODUCTION

The substrate permittivity (ε_r) combined with the thickness h of a microstrip antenna affect the resonant frequency, gain, matching bandwidth and polarization. Microstrip antenna theory [1]-[5] indicates a degradation in performance when ε_r increases. High permittivity substrates reduce antenna size at the cost of the gain and matching bandwidth. This study evaluates these parameters when antenna dimensions and resonant frequency of a rectangular PIFA (Fig. 1) are fixed. The evaluation is performed using the Finite Element Method [6]-[9] from the commercial software Ansoft HFSS v.10 [9]. Air and other dielectric materials provided by HFSS, such as Duroid, FR4_Epoxy, Mica, Silicon-Nitrate, Alumina, Roger3210, Silicon and Gallium Arsenide are used to quantify the performance variations of the PIFA.

Two methodologies are used for the evaluations. First, the physical dimensions of the radiating element of the antenna are fixed. Using different substrate materials [10], the resonant frequency and the corresponding gain are evaluated. In the second configuration, the simulations are repeated for constant PIFA resonant frequency and ratio of the patch lengths. In HFSS some of the materials used are ideal, i.e., the loss tangent δ is zero, while others are lossy ($\delta > 0$). This parameter is accounted for by evaluating the lossy materials with default δ not equal to zero, and as perfect dielectrics, with $\delta = 0$. The effects of δ are also reported.

For both methodologies, the feeding distance (d) in relation to the shorted side of the PIFA is optimized. A conventionally accepted return loss greater or equal to 10 dB is targeted in order to reduce errors related to poor matching.

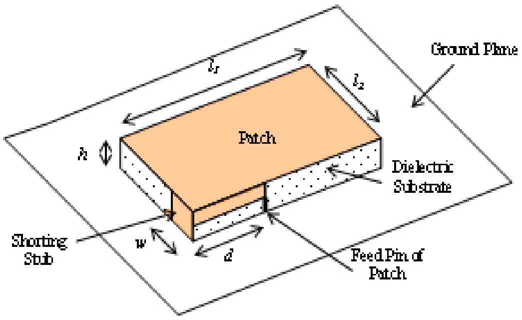

Figure 1. Configuration of a simple PIFA [14]

II. THEORY

PIFAs are compact microstrip antennas with a shorting stub connecting the radiating element to the ground plane [11]-[13]. The short introduces a return path for the facial currents of the antenna and triggers resonance for electrical dimensions smaller than half-a-wavelength (λ/2) as demonstrated in [2], [3], [11]. The resonant frequency of a PIFA is given by [14]:

$$f_r \approx \frac{c}{4\sqrt{\varepsilon_{reff}}\left(l_1 + l_2 - w + h\right)}, \qquad (1)$$

where c is the velocity in free space, l_1 and l_2 are the dimensions of the radiating patch, w is the width of the short, h is the thickness of the substrate and ε_{eff} is the effective permittivity of the substrate material between the radiating patch and the ground plane. The effective permittivity (ε_{eff}) is approximated using (2):

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2}\,. \qquad (2)$$

While the physical parameters of PIFA are directly computed using ε_{eff}, the data will be reported in terms of ε_r.

From (1), it should be observed that the resonant frequency of a PIFA is affected not only by the physical lengths (l_1 and l_2), but also by the width of the short (w) and the thickness (h) of the substrate material. For fixed radiating patch lengths, the resonant frequency increases as w decreases. Optimum performance is achieved when the ratio of l_1 and l_2 is 2 : 1. From 1, this suggests a resonant length of λ/6 can be achieved for a given w and h.

The substrate's electrical properties as well as h affect the performance of a PIFA in terms of gain and bandwidth. Thin substrates of high ε_r lead to poor radiation and narrow bandwidth. Substrates with high loss tangent are very lossy and thus result in low gain. Hence, antennas are often designed with thick substrates with low δ and ε_r [2], [5]. However, h should be limited to avoid surface waves, which will degrade the radiation efficiency [2].

III. SIMULATION SETUP I

Using Ansoft HFSS v.10, the PIFA is evaluated with fixed geometrical dimensions. The radiating lengths l_1 and l_2 are 4.92 cm and 2.13 cm, respectively. The thickness of the substrate and the width of the shorting element are chosen to be 0.44 cm. Hence, (1) can be simplified as

$$f_r \approx \frac{c}{4\sqrt{\varepsilon_{reff}}\,(l_1 + l_2)}\,. \qquad (3)$$

The ground plane is selected to be 14.76 cm x 6.39 cm. The structure is encompassed in a rectangular air box, which is defined as a radiation boundary. The air-box boundary is drawn so that the recommended quarter-wavelength (λ/4) minimum distance from the sides of the radiating structure (including the ground plane) is satisfied [1], [9]. The structure is excited by a lumped port [9], [14] located at the edge of the patch feeding structure. The feeding distance is made variable for matching purposes.

The simulations are performed for different configurations of PIFAs, with air, Duroid, FR4, mica, silicone-nitrate, alumina, Roger 3210, silicon, and gallium arsenide substrates. Table I lists the values of ε_r and δ used in this study. The evaluation is performed at the resonant frequencies occurred per configuration. The feeding distance (d) is adjusted to achieve at least 10 dB return loss (VSWR ≤ 2), to minimize errors associated with poor matching.

Table I shows that the resonant frequency of the structure decreases as ε_r increases. The trend follows a square-root pattern due to the fact that the resonant frequencies are affected by the square-root of ε_{eff}. Also the resonant frequencies obtained from (3) and the simulations are about the same, with a difference less than 5% on an average. The normalized frequency deviation is defined as

$$\frac{\Delta f}{f} = \frac{f_x - f_0}{f_0}\,, \qquad (4)$$

or

$$f_x = f_0\left(1 - \frac{\Delta f}{f}\right), \qquad (5)$$

where f_0 is the resonant frequency for the structure with no substrate and f_x is the resonant frequency generated by the selected ε_r. Fig. 2 depicts the normalized frequency deviation with respect to ε_r.

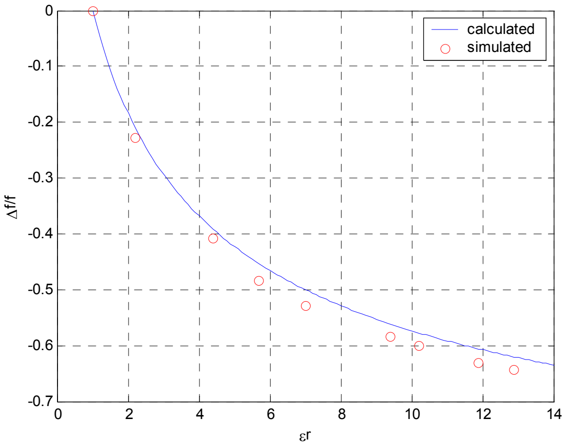

Figure 2. PIFA normalized resonant frequency deviation in relation to the relative substrate permittivity

From Table I, it can be seen that a return loss ≥ 10 dB could not be achieved for the silicon (7.28) and gallium arsenide substrates (2.1) for the given antenna dimensions. The poor return losses suggest that the structure, as is, does not resonate. Altering the width, length or thickness of the PIFA could improve the matching, but this approach is beyond the scope of this study. The gain reported herein is acceptable because it is computed in HFSS from the power at the antenna feed point as oppose to the input power. Consequently, the gains in Table I do not include reflection losses and hence are independent of the matching conditions.

TABLE I.
PIFA Data Table for Fixed Patch Dimensions (l_1=49.2 mm and l_2 =21.3 mm)

Material	ε_r	Loss Tangent δ	Resonance Frequency		Matching Bandwidth (MHz)	Feeding Distance (mm)	Return Loss (dB)	Gain (dBi)
			Calculated (MHz)	Simulated (MHz)				
Air	1	0	1063.83	1140	10	2.94	-25.85	4.6
Duroid	2.2	0	841.03	880.8	6.2	2.86	-32.54	4.6
FR4	4.4	0.02	647.43	675	10	4.84	-33.28	-3.79
Mica	5.7	0	581.23	589	1	1.4	-17.7	2.08
Silicone-Nitrate	7	0	531.91	538	0.55	1.1	-16.93	3.18
Alumina	9.4	0.01	466.52	474.75	2.5	2.86	-17.55	-8.38
Roger 3210	10.2	0.003	449.55	455	0.9	1.76	-24.87	-6.63
Silicon	11.9	0	418.88	419	-	0.79	-7.28	2.28
Gallium Arsenide	12.9	0	403.53	407	-	1.76	-2.1	2.28
Custom1	4.4	0	647.43	661	1.5	2.42	-15.66	3.44
Custom2	9.4	0	466.52	471.2	1	1.32	-11.8	3.05
Custom3	10.2	0	449.55	455	-	1.1	-9.69	2.63

Table I reveals that the 10 dB matching bandwidth of the PIFA decreases as ε_r increases. As the value of the substrate ε_r rises, the antenna gives higher Q. With ε_r = 1, the antenna provides a maximum matching bandwidth of 10 MHz. A maximum gain of 4.6 dBi is achieved when the permittivity of the substrate is minimum (ε_r = 1), as well as when ε_r = 2.2 (Duroid). This is due to the fact that the square root of the effective dielectric constant of Duroid is equal to 1.26, which is very close to 1. However, as ε_r increases, the gain varies unpredictably. Mica and Silicone-Nitrate substrates, with ε_r equal to 5.7 and 7 lead to a gain of 2.08 dBi and 3.18 dBi, respectively. The gain drops significantly for FR4, alumina and Roger 3210, which result in a gain of -3.79 dBi, -8.48 dBi, and -6.63 dBi, respectively. On the other hand, the gain of the antenna enhances with higher ε_r materials. Silicon and gallium arsenide both yield 2.28 dBi. It was determined that the major gain reduction resulted from the inclusion of substrate dielectric loss tangent δ.

To substantiate the findings, δ was set to zero to emulate an ideal dielectric. Hence, alumina, Roger 3210 and FR4, with typical δ, were replaced by ideal materials of similar ε_r defined as Custom1, Custom2 and Custom3, respectively. The simulation results with these materials show a substantial gain improvement of up to 11.5 dB (Fig. 3). A linear relationship among the different materials could be established if the lossy FR4, alumina and Roger 3210 substrates are excluded from the analyses. The gain drop as the dielectric constant of the substrate increases is equivalent to 2 dB per decade.

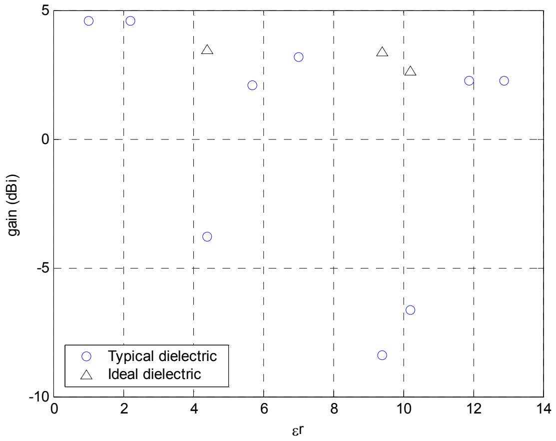

Figure 3. PIFA gain vs. substrate's relative dielectric constant

IV. Simulation Setup II

The second setup consists of evaluating the PIFA at a fixed single resonant frequency. The dimensions l_1 and l_2 of the radiating patch are modified as the substrate's permittivity is varied. However, to limit variables in this study, the ratio between l_1 and l_2 is maintained constant (l_1/l_2 = 2.31). Additionally, w and h are also fixed to 0.44 cm. Similar to Simulation Setup I, d was varied to improve the matching. The PIFA with ε_r = 1 is selected as the reference antenna. The physical parameters l_1 and l_2 are adjusted with respect to ε_r to achieve resonance at 1.14 GHz. An expression to compute the patch length l_2 at the resonant frequency (f_r) can be derived using (3):

$$l_2 = \frac{0.01988}{\sqrt{\varepsilon_{eff}}}. \qquad (6)$$

TABLE II.
PIFA DATA TABLE FOR FIXED l_1/l_2 RATIO AT 1.14 GHZ

Material	ε_r	Loss Tangent δ	Resonant Frequency (GHz)	Patch length l_2		Feeding Distance (mm)	Return Loss (dB)	Gain (dBi)
				Calculated (mm)	Simulated (mm)			
Air	1	0	1.14	19.88	21.3	2.94	-25.85	4.6
Duroid	2.2	0	1.14	15.71	17	3.3	-35.51	4.44
FR4	4.4	0.02	1.14	12.1	13.75	5.28	-13.9	0.29
Mica	5.7	0	1.14	10.86	12.2	1.85	-18.33	3.53
Silicone-Nitrate	7	0	1.14	9.94	11.3	1.54	-20.33	2.98
Alumina	9.4	0.01	1.14	8.72	10.25	1.98	-20.97	-1.05
Roger 3210	10.2	0.003	1.14	8.4	9.95	2.2	-11.67	0.11
Silicon	11.9	0	1.14	7.83	9.35	1.13	-17.35	2.96
Gallium Arsenide	12.9	0	1.14	7.54	9.05	1.1	-22.88	3.16
Custom1	4.4	0	1.14	12.1	13.5	3.3	-13.54	4.05
Custom2	9.4	0	1.14	8.72	10.25	1.98	-8.11	3.3353
Custom3	10.2	0	1.14	8.4	9.85	1.1	-18.32	3.0799

After several iterations, the HFSS model's lengths of l_2 leading to resonance at 1.14 GHz, as well as the computed values of l_2 using (6) are listed in Table II for the different substrates. A normalized expression for the resonance length deviation of the antenna can be defined as

$$\frac{\Delta l}{l} = \frac{l_x - l_0}{l_0}, \qquad (7)$$

where l_0 corresponds to the resonance length of the PIFA with substrate permittivity equal to unity, l_x corresponds to the length l_1 of the PIFA with the ε_r evaluated in this study ($l_x = l_1 = 2.31 * l_2$). Note that the normalized resonant length is not expressed in terms of the wavelength because this parameter is related to the square-root of ε_{eff}.

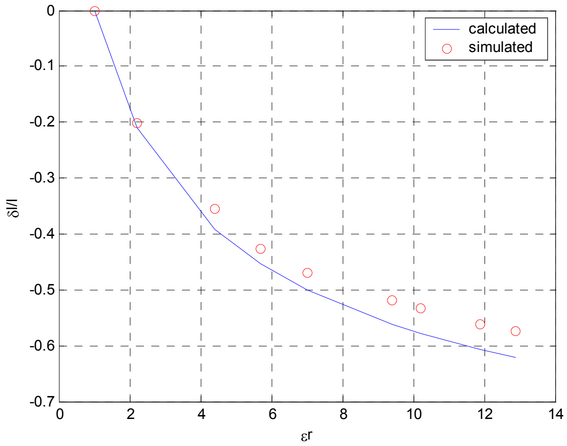

Figure 4. PIFA normalized resonant length (l_2) deviation in relation to the relative substrate permittivity

Fig. 4 plots the normalized calculated and simulated resonant lengths. The curves show a square-root trend, which is also linked to $\sqrt{\varepsilon_{eff}}$. The curves also indicate that the normalized resonant length simulated values deviate from the normalized calculated values as ε_r increases. The disparities for the high value dielectric constants are also due to the estimating accuracy of (2).

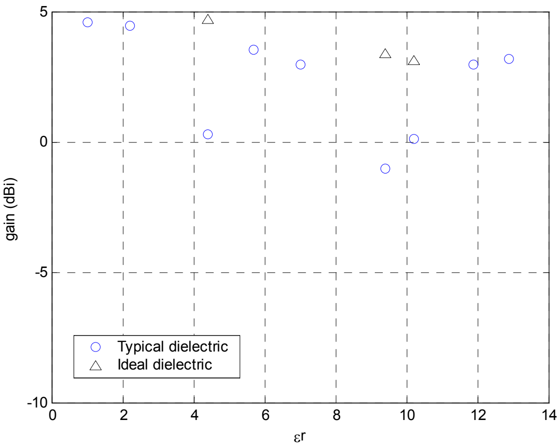

Figure 5. PIFA gain at 1.14 GHz

From Table II, the best performance is achieved with $\varepsilon_r = 1$. The gain of the antenna then decreases as the permittivity increases. Consistent to Simulation Setup I, FR4, alumina and Roger 3210 bring about the worst performance with gains of 0.29 dBi, -1.05 dBi, and 0.11 dBi, respectively. Also, the gain deterioration is due to the non-zero δ. These materials were replaced with the aforementioned equivalent ideal dielectric substrates. The results show a gain improvement of 4 dB on an average, with alumina leading to a maximum gain improvement of 4.39 dB. Fig. 5 reveals a linear gain drop of 1.5 dB per decade when the lossy dielectric materials are excluded.

A constant matching bandwidth of 10 MHz is achieved for the various substrates except for FR4, alumina and Roger 3210, which provided a wider bandwidth of 20 MHz. The wider bandwidth is due to the δ lowering the quality factor of the antenna.

V. Conclusion

The resonant frequency and the gain of a PIFA are simulated with the substrate permittivity varying from 1 to 12.9. When the antenna dimensions are kept constant, the normalized simulated resonant frequencies decrease, following a square root trend, which correlate with calculated resonant frequencies from (3). Both bandwidth and gain decrease as ε_r increases for perfect dielectric. A linear relationship of 2 dB drop per decade is observed between the gains and ideal ε_r evaluated in the range of this study.

The second simulation setup reveals that the normalized simulated resonant lengths, where $l_1 = 2.31 * l_2$, also follows a square-root trend. However, the curve deviates from the normalized theoretical value as ε_r increases. The bandwidth does not vary for lossy substrates. However, the gains drop linearly by 1.5 dB per decade for increasing ε_r.

For both cases, the results portray significant losses in gain when the loss tangent of the material is included in the simulations. The impact of δ is less at 1.14 GHz, for the fix ratio of $l_1/l_2 = 2.31$. A 4 dB gain drop is obtained on an average, as compared to the fixed patch length configuration where a maximum drop of 11.5 dB is yielded.

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