Central Power Research Institute

Vol. 19(2)/139-143, December 2023
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v19i2.1141

Power Research

Investigation of Planar Antenna Performances on Commercially Available Dielectric Materials

S. Subin*, Vijay K. Goyal and Vivek Sanadhya

Control Instrumentation Division, Bhabha Atomic Research Centre, Mumbai – 400085, Maharashtra, India; subins@barc.gov.in

Abstract

Planar RF antennas with their conformal geometry, good RF performances and ease of construction find a wide range of applications ranging from mobile phones to RADAR and wearable electronic gadgets to medical implant devices. The selection of a suitable dielectric material is by far the most crucial step in the antenna design process to achieve the desired RF characteristics. The directivity, efficiency and bandwidth of an antenna depend on the substrate dielectric constant, loss tangent and material thickness. This paper investigates the RF performances of two planar antennas designed using two commercially available dielectric materials namely RT Duroid and FR4 with a full wave 3D EM simulation tool. The results show the superior RF characteristics of the antenna designed using RT Duroid over FR4. The antenna designed with RT Duroid substrate is fabricated and the measurement results obtained are found to be in good agreement with the simulation results.

Keywords: Dielectric, FR-4, Loss Tangent, Microstrip, RT Duroid

1. Introduction

With the rapid advancement in the field of wireless communication, the quest for miniaturized antenna development is ever-increasing. The planar microstrip antennas are ideal choices for compact antenna dimensions with acceptable RF performance. Their smaller size, conformal shape, and ease of integration with monolithic microwave circuits make them attractive for cellular phones and aerospace applications. However, microstrip antennas do suffer from performance limitations like low radiation efficiency and narrow bandwidth[1]. Also, the use of microstrip antennas is often limited to low-power applications.

This study on antenna substrate dielectric substrates was carried out as part of the development of a thin, flexible antenna for a low-power, long-range RF beacon locator transmitter. The beacon transmitter requires a directional, conformal antenna with good gain characteristics. A microstrip patch antenna with a thin substrate was found to be ideal for the beacon application owing to its directional radiation characteristics and conformal shape. The microstrip antenna geometry consists of a dielectric material sandwiched between two metal planes. One of the planes serves as a radiating conductor while the other plane acts as ground. The function of the dielectric material is to provide the necessary mechanical support while offering minimum dielectric loss and optimum bandwidth. Various dielectric substrates can be used in the antenna design and their dielectric constants generally fall in the range of 2.2-12[1]. The two most commonly used dielectric materials, RT Duroid and FR4 were selected for the antenna designs. The RT Duroid (PTFE) dielectric has superior electrical properties but is costly to procure while FR4 is cheaper and has adequate properties to achieve optimum antenna RF performances.

The previous reported works on microstrip antenna performance with various dielectric materials were mainly focused on the analysis of antenna performance on thick high permittivity substrates at microwave or millimeter wave frequencies[2-5]. These works lack the information about practicality of substrates for low-cost, large-volume applications.

*Author for correspondence

Hence objective of this paper is to analyze the RF performance of dielectric materials at a sub-GHz ISM frequency by considering parameters like machinability and cost.

2. Dielectric Materials and Electrical Properties

A dielectric is a non-conducting material, which becomes polarized when subjected to an external electric field. In the absence of an external electric field, dipoles are randomly aligned. The application of an external electric field causes the dipoles to align themselves in the direction of the electric field and make the net electric field zero. The dielectric constant (ε_r) and loss tangent (tanδ) are the key parameters to be considered while selecting a suitable substrate material for any RF design. Moreover, thermal expansion coefficient, chemical resistance, and machinability are other parameters that need to be considered for material selection.

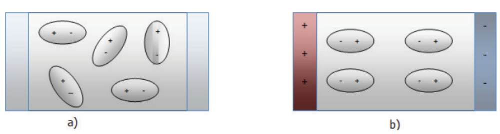


Figure 1. Polarization in a dielectric in the absence **(a)** and presence **(b)** of an electric field.

The dielectric constant ε_r determines the size of the antenna. The higher the dielectric constant smaller the antenna size and vice versa. For a microstrip antenna, the size is proportional to the effective wavelength λ_{eff}. The effective wavelength in turn depends on the material dielectric constant as follows

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\varepsilon_{reff}}} \quad (1)$$

where, ε_{reff} is the effective dielectric constant and is given by Pozar[6]

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \text{ for W/h >1} \quad (2)$$

The dielectric substrate dissipates a fraction of RF energy within the substrate. At higher frequencies, the dielectric losses are significant. The dielectric loss is expressed in terms of dissipation factor or as loss tangent of a dielectric. The expression for dielectric loss obtained from references[7,8] is,

$$\alpha_d = 27.3\frac{\varepsilon_r}{\varepsilon_{reff}}.\frac{\varepsilon_{reff} - 1}{\varepsilon_r - 1}.\frac{\tan\delta}{\lambda_0} \text{ Np/m} \quad (3)$$

where, loss tangent is given by,

$$\tan\delta = \frac{\sigma}{\omega\varepsilon} \quad (4)$$

where, σ is the conductivity of the material, ε is the permittivity and is the operating frequency. In microstrip antenna design, it is desirable to use a high dielectric constant and low-loss tangent dielectric material[9]. Using a low-loss tangent material as an antenna substrate reduces the substrate losses and increases the radiation efficiency. The electrical properties of some of the commonly used substrate materials are given in Table 1.

Table 1. Electrical properties of common dielectric material used in antenna design

Dielectric Material	Dielectric constant (ε_r)	Loss tangent (tan δ)
Air	1	0
RT Duroid 5880	2.2	0.0009
Quartz	3.78	0.0001
FR4 (Epoxy/glass)	4.2-4.4	0.013
Alumina (ceramic)	9	0.0001

Microstrip antennas with air dielectric have high radiation efficiency but the high gain comes at the cost of the largest antenna dimensions for a given frequency. RT Duroid has low dielectric loss, good chemical resistance, stable electrical and good machining properties making it an excellent choice for microwave applications. Quartz's superior electrical properties along with its low thermal expansion coefficient make it an ideal substrate material but the high cost and poor machinability render them unattractive for most commercial applications. FR4 is a low-cost substrate material, which is widely used in commercial applications. FR4 offers good electrical performance up to 1GHz. Alumina, also widely used as ceramic substrate has excellent electrical and mechanical properties but its application is limited to specific areas due to its poor machinability. In recent times, manufacturers have tried to make substrate materials with good electrical and mechanical properties by combining different dielectric materials. As a result, low-loss dielectric materials with reasonable costs are now available in markets.

3. Microstrip Antenna Design

The microstrip antenna structure shown in Figure 2 is designed and simulated with a full wave 3D electromagnetic simulation tool. The antenna dimensions were calculated using numerical expressions given in [1,6].

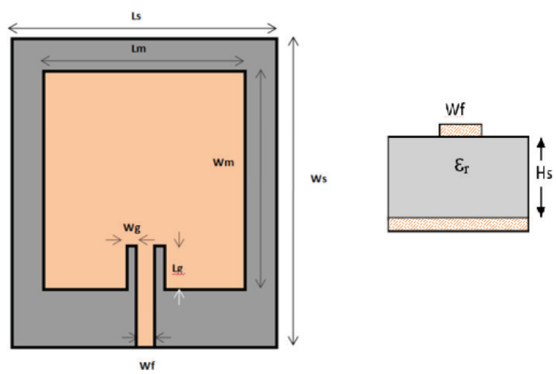


Figure 2. Microstrip antenna structure.

Two antenna models were simulated, one designed with RT Duroid substrate and another with FR4. Both antennas are designed to radiate at 866MHz to meet the ISM band requirements. The selected antenna substrate thickness is 0.625mm. Thinner substrates were chosen to make the antenna flexible. Further, an inset feed was added to the antenna geometry to match the antenna input impedance to a 50ohm excitation port.

Table 2. Microstrip antenna dimensions in millimetres

Parameter	RT Duroid 5880	FR4
Hs	0.625	0.625
Ls	150	150
Ws	150	150
Lm	117	85
Wm	137	107
Lg	20	5
Wg	2	1.5
Wf	2	1.5

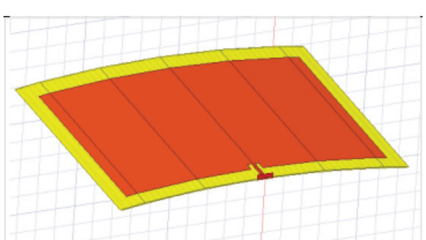


Figure 3. 3D model of conformal microstrip antenna with a thin substrate.

4. Results and Discussion

Both antenna designs are optimized to maximize the return loss while keeping the substrate height the same. The simulation results given in Table 2 suggest that for a given resonance frequency the length of an antenna with FR4 (Lm=85mm) is significantly shorter than the RT Duroid antenna (Lm=117mm). This is due to the higher dielectric constant of FR4 (ε_r=4.4). As per Equation (1), the higher the dielectric constant, the smaller the effective wavelength and hence the smaller the antenna size. The antenna with RT Duroid substrate shows better return loss characteristics than the FR4-antenna. This might be due to the optimized impedance matching of the inset feed on the RT Duroid substrate. Moreover, the antenna with RT Duroid substrate shows a higher peak gain in comparison to the antenna with FR4. This reduction in the gain of FR4-antenna can be attributed to its higher loss tangent. This is by Equation (3), where a high-loss tangent substrate exhibits higher dielectric loss and hence lower radiation efficiency. The peak gain values of both antennas 3.1 dB and 1.16 dB as per Figure 4, were found to be lesser than the microstrip patch antenna gain of 4.1 dB reported in reference[10]. The gain reduction is primarily due to the use of thinner substrate material for the antenna design. Microstrip antennas made up of thin substrates exhibit lower gains due to lower radiation efficiencies[9,10]. The conformal shape of the antenna also degrades antenna directivity and reduces the gain further.

The antenna design with RT Duroid substrate was finally selected for fabrication. RT Duroid antenna's superior gain characteristics over FR4 make it suitable for low-power, long-range beacon applications. Table 2 presents the measurement results of the fabricated. The return loss of the fabricated antenna shows a shift in resonant frequency. This shift in resonance frequency could be because of the inaccuracies in the antenna fabrication process. The return loss of the fabricated antenna appears to be better than the simulated antenna. The reason for this improvement could be a better impedance matching of the feed on the fabricated antenna. The peak gain of the fabricated antenna was estimated to be 1.5 dBd. The antenna gain was estimated with an RSSI measurement in which the received signal strength at the output of the test antenna was compared to the output of a Taoglas dipole antenna[11]. The test was conducted in an open field environment to reduce reflections. The Taoglas antenna straight type has a peak gain of 2.04 dB. The gain of the fabricated antenna, calculated as 3.5 dB, is slightly higher than the simulated value of 2.9 dB. This difference in gain value might be due to non-ideal conditions present in the antenna gain measurement setup.

Table 3. Antenna characteristics of simulated and fabricated antennas

Antenna Substrate	Resonance Frequency	Return Loss	Peak Gain
RT Duroid	866MHz	-16.80dB	2.9 dB
FR4	863MHz	-11.25dB	1.3dB
RT Duroid fabricated	869MHz	-25.32dB	3.5dB

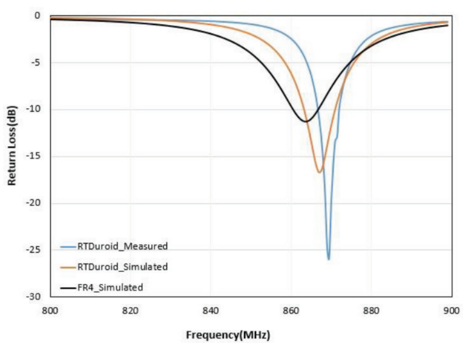
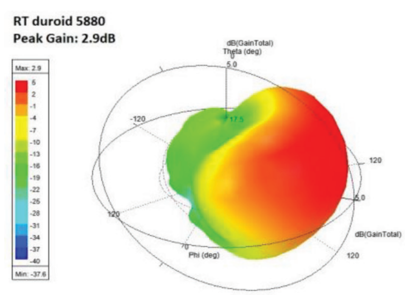
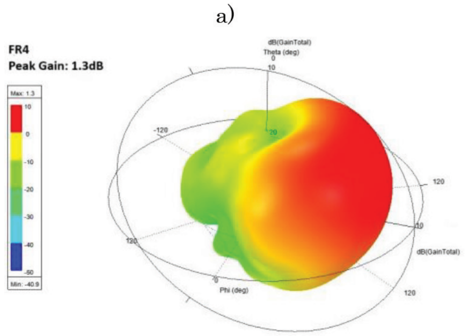


Figure 4. Return loss characteristics of simulated and fabricated antennas.



a)



b)

Figure 5. 3D Gain plots of **(a)** RT Duroid and **(b)** FR4 antennas.

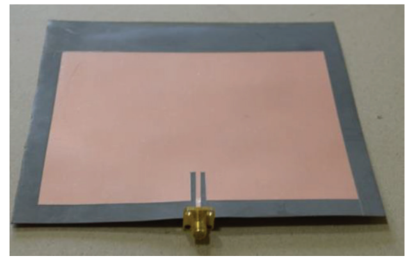


Figure 6. Antenna fabricated on RT Duroid 5880 substrate.

5. Conclusion

In this paper, the effects of dielectric substrate material on the RF performances of antenna have been studied and understood with the help of electromagnetic simulation. RF performances of two antennas, designed with commercially available dielectrics FR4 and RT Duroid, are evaluated. The antenna with RT Duroid shows a superior gain characteristic over FR4 for a given resonant frequency. The low permittivity RT Duroid 5880 substrate is suitable for making antennas for applications where higher antenna efficiency and gain are paramount. The FR4 substrate, on the other hand, is suitable for making miniaturized antennas with acceptable gain characteristics. Moreover, FR4, a cheaper dielectric, allows the designers to integrate planar antennas with RF and digital circuits on the same PCB.

There exists a trade-off between RF performance and miniaturization in microstrip antenna design. A designer has to choose the substrate material judiciously when designing monolithic microwave integrated circuits. A high permittivity, thin substrate material allows for a high level of RF integration with good EMI characteristics. On the other hand, a low dielectric, thick substrate material is suitable for designing an efficient PCB antenna. The results of this investigation can help the designers in selecting suitable antenna substrates for making low power-low range radio devices. Due to time constraints, the current study of antenna dielectrics substrates is limited to FR4 and RT Duroid 5880. Ceramic substrates with their excellent dielectric properties are drawing attention in the field of miniaturized electronic devices like bio-medical implant devices. For this reason, a study on the RF performances of antennas with ceramic substrates at sub-GHz ISM band frequencies is promising.

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