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Analysis of Design Optimization of Bandwidth and Loss Performance of Reflectarray Antennas Based on Material Properties

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Abstract

An investigation for the enhancement strategy of bandwidth performance and analysis of different types of losses associated with reflectarray antennas is presented in this paper. Studies are carried out using different commercially available dielectric materials with dielectric permittivity (ε_r) values ranging from 2.08 to 13 and loss tangent (tanδ) ranging from 0.0003 to 0.025. The performance of different dielectric materials for the design of infinite reflectarray is analyzed in terms of bandwidth, reflection loss and Figure of Merit (FOM). Bandwidth of patch element unit cell at different levels are observed and it has been shown that 10% bandwidth varies from 84 MHz to 360MHz and 20% bandwidth varies from 126 MHz to 540MHz based on the selection of dielectric substrate for reflectarray antenna design. Moreover it has been demonstrated that the reflection loss of the reflectarray antenna can be factorized into dielectric loss and conductor loss which depends on the material properties employed for the design.

Keywords: Reflectarray, Bandwidth, Dielectric loss, Conductor loss, Figure of merit

1. Introduction

Antennas with high gain performance are the required for some of the applications in communication systems. The conventional high-gain antennas most often used are parabolic reflectors. Although they are efficient radiators, parabolic reflectors are too large and heavy, due to their curved reflecting surfaces. As a result, a planar reflector called a microstrip reflectarray was being proposed as a future candidate high-gain antenna (J.Huang, February 15, 1995). It consists of an array of microstrip patches on the grounded dielectric substrate and is illuminated by a primary feed horn which is placed at a particular distance from the array whose individual elements are designed to scatter the incident field with proper phase distribution required to form a planar phase surface in front of the aperture (David M. Pozar, D. Targoski and H.D. Syrigos, February 1997). The reflectarray antenna can achieve a very high efficiency for a very large aperture and it can also be designed to tilt a large angle (John Huang and Jose Encinar, 2007). Despite of the advantage of the size, cost and easy deployability, the major deficiency of the reflectarray that limits its usage is the low bandwidth performance (M.E.Biallowski and Jose Encinar, 2007). The main factors that limit the bandwidth of reflectarray antenna are the narrow bandwidth of patch elements which is caused by the extended path length between the feed horn and the reflectarray, and the phase errors related to the change in patch size (K.Y.SZE and L. Shafal, *1998*). The feed antenna bandwidth and array element spacing also limits the bandwidth of reflectarrays but these two are not serious concerns if the bandwidth requirement is les than 15% (J.Huang, February 15, 1995). Another important factor, that affects the bandwidth of the reflectarray antenna and has not been discussed in the past thoroughly, is the selection of suitable dielectric material. The effect of properties of dielectric material, used as a substrate for the reflectarray antenna, on the bandwidth and reflection loss performance is discussed in this work.

2. Distinction of different types of losses in reflectarray antennas

Generally the reflection loss of the reflectarray antennas is primarily limited to dielectric absorption in the dielectric layer and conductor loss (M.Y.Ismail and M.Inam, *2009*). The reflection loss of reflectarray antenna depends on the material properties of the dielectric material which includes the substrate thickness, and the conducting material used for the patch element and the ground plane as given in equation (1).

$$R_l = \alpha_d + \alpha_c \quad (1)$$

Where, R_l is the reflection loss and α_d and α_c represent the attenuation factor due to dielectric and conductor loss and can be calculated using equation (2) and equation (3) respectively which are given in the numerical analysis section. The dielectric loss occurs due to the strong electric fields in the substrate region and copper loss occurs due to high current generated on the top surface of the patch element (Harish Rajagopalan and Yahya Rahmat Samii, *April 2008*). The electric field distribution and the surface currents are highest at resonance which is the reason of the highest loss at the resonant frequency. For further investigation of the loss mechanism in a reflectarray antenna, an infinite reflectarray with 0.035mm patch element thickness and 1mm substrate thickness using commercially available CST computer model is designed. Different dielectric materials are used and the dielectric loss is observed by reducing the conductor loss to minimum (or ideally zero by using PEC for patch element and ground plane). Copper with a conductivity of 59.6Ms/m is used for the design of patch element and the ground plane in order to introduce the conductor loss in the reflectarray antenna design. Copper loss or the conductor loss is observed separately by defining the loss tangent values of the dielectric substrate to be zero and hence making the factor due to dielectric loss to be zero. The losses calculated for different dielectric materials are shown in Table 1. It can be observed from the table that the materials with high loss tangent values, such as CEM and Gallium Arsenide have very high reflection loss and the main contributor for this high reflection loss is dielectric loss. This is because these materials exhibit high dielectric absorption in the dielectric layer of the reflectarray antennas. On the other hand materials with low loss tangent values such as Teflon and Alumina have relatively very low reflection loss. This is due to low dielectric loss properties and the dominant loss for this type of reflectarray antenna design is caused by conductor/copper loss. The factorization of the reflection loss for two materials is shown in Figure 1 and Figure 2 for comparison. As shown in Figure 1 and Figure 2, it can be observed that Teflon which has a low loss tangent value (tanδ=0.0004) has very low dielectric loss and Gallium Arsenide which has a high loss tangent value (tanδ=0.006) offers a very high dielectric loss as compared to the copper loss.

3. Bandwidth performance of reflectarrays using different materials

The materials listed in Table 1 are used to design infinite reflectarrays resonating at 10GHz and the 10% and 20% bandwidth is measured by moving 10% and 20% above the reflection loss at 10 GHz. The bandwidth calculated in this work for different materials are presented in Figure 3. As depicted in Figure 3, it can be seen that as the dielectric permittivity of the material used for the reflectarray design is increased, the bandwidth decreases. Gallium Arsenide, which has the highest dielectric permittivity (ε_r=13) has the minimum 10% and 20% bandwidths of 84 MHz and 126 MHz respectively while Teflon which has the lowest dielectric permittivity (ε_r =2.08) has the highest 10% and 20% bandwidths of 360 MHz and 540 MHz respectively. These results can be validated according to equation (4) and can be associated with the material properties of these dielectric materials.

4. Analysis of reflection phases of different materials

The reflection phases of all the designed reflectarrays are also analyzed and it is shown that the materials with low dielectric permittivity, when used for reflectarray antenna design, show gentler slope in reflection phase curve as compared to the high dielectric constant materials. This can also be validated using equation (4), which shows that as the dielectric permittivity of the material is increased, the bandwidth decreases and hence causes a steeper slope in the reflection phase curve. The reflection phase of the patch element unit cell with Teflon and CEM dielectric materials has been observed using different thicknesses of substrate. As shown in Figure 4 and Figure 5, the results demonstrate that a gentler phase curve is generated as the substrate thickness is increased from 1.0mm to 2.0mm. Figure of Merit (FOM) has been defined in order to predict the performance of the linear phase range within a particular frequency range based on reflection phase curves of different materials. The figure of merit (FOM) can be defined as the ratio of the change in reflection phase to the change in the frequency and it can be expressed as by (M.Y.Ismail and M.Inam, *2009*).

$$FOM = \frac{\Delta \phi}{\Delta f} \quad °/\text{ MHz}$$

Where $\Delta\Phi$ is the change in the reflection phase in degrees and Δf is the change in the resonant frequency in MHz of the reflectarray antenna and FOM is calculated here in °/MHz. It has been observed that the FOM increases with the increase in dielectric permittivity. This is because increasing the permittivity causes the reflection phase to get steeper and hence causes $\Delta\Phi$ to increase over the same range of frequencies which increases FOM as shown in Figure 6.

5. Numerical analysis and bandwidth performance

Theoretical equations have been used to perform the numerical analysis of reflectarray and validate the results obtained from CST simulations. This section includes the discussion on the theoretical basis of quantification of different types of losses and provides numerical equations for the prediction of bandwidth performance in the reflectarray. As depicted in equation (1), the total reflection loss of a reflectarray is the sum of dielectric and conductor loss. The attenuation due to dielectric material can be given by the following formula (Balanis. Constantine A. 2005).

$$\alpha_d = \frac{\omega}{2}\sqrt{(\mu_0 \varepsilon_0 \varepsilon_r)}\tan\delta \tag{2}$$

Where

$$\omega = 2\pi f_r$$

$$\tan\delta = \frac{\varepsilon''_r}{\varepsilon'_r}$$

$$\varepsilon_r = \varepsilon'_r - i\varepsilon''_r$$

In order to improve the accuracy of the calculation of attenuation factor due to dielectric, relative permittivity can be used which is given by:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{H}{W}\right]^{-1/2}$$

Also the conductivity of the dielectric material can be defined in terms of tanδ as:

$$\sigma_d = \omega\varepsilon_r \tan\delta$$

So using ε_{reff} and σ_d, the equation for the attenuation constant becomes:

$$\alpha_d = 4.34\frac{1}{\sqrt{\varepsilon_{reff}}}\left(\frac{\varepsilon_{reff} - 1}{\varepsilon_r - 1}\right)\sqrt{\frac{\mu_0}{\varepsilon_0}}\sigma_d \,(dB/cm)$$

The above equation is appropriate for the substrates with higher loss tangent values.

Similarly the attenuation due to the conductor can be simplified as:

$$\alpha_c = \frac{8.68 R_s}{WZ_m}(dB/cm)$$

Where R_s is the surface resistivity and is given by

$$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma_c}}$$

$$\alpha_c = \frac{8.68}{WZ_m}\sqrt{\frac{\omega\mu_0}{2\sigma_c}}(dB/cm) \tag{3}$$

Using α_c and α_d, the reflection loss of reflectarray can be calculated using equation (1) and hence VSWR. The bandwidth of a microstrip antenna or the reflectarray is related to the VSWR and Quality factor by the following relation (Balanis. Constantine A. 2005):

$$\frac{\Delta f}{f_0} = \frac{VSWR - 1}{Q_t\sqrt{VSWR}} \tag{4}$$

Where Δf is the bandwidth of the antenna and f_o is the resonant frequency of design. Q_t, the total quality factor is given by the sum of the quality factor by various losses.

$$\frac{1}{Q_t} = \frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_r} + \frac{1}{Q_{sur}} \tag{5}$$

In equation (5), Q_d, Q_c, Q_r, Q_{sur} are the quality factors for dielectric, copper, radiation and surface loss respectively and Quality factor for each type of loss can be obtained using general relation as:

$$Q = \frac{\omega_r W_t}{P_L}$$

Where P_L is the power loss of different factors and W_t is the energy stored at the resonant which is the same independent of the mechanism of loss and is given by:

$$W_t = \frac{1}{4}\varepsilon_0 \varepsilon_r h L W$$

Q_{sur} can be neglected for thinner substrates and the quality factor for dielectric, conductor and radiation can be calculated by:

$$Q_d = \frac{1}{\tan \delta}$$

$$Q_c = h\sqrt{\pi f_r \mu_0 \sigma_c}$$

$$Q_{rad} = \frac{2\omega\varepsilon_r k}{hG_{t/l}}$$

Where $G_{t/l}$ is the total conductance per unit length and for rectangular aperture:

$$G_{t/l} = \frac{G_{rad}}{W}$$

$$k = \frac{L}{4}$$

G_{rad} (radiation conductance) can be found out by:

$$G_{rad} = \frac{1}{90}\left(\frac{\omega}{\lambda}\right)^2 ; \omega << \lambda$$

$$G_{rad} = \frac{1}{120}\left(\frac{\omega}{\lambda}\right) ; \omega >> \lambda$$

Using the relations for the different quality factors, we can find the total quality factor by equation (5) and hence bandwidth of reflectarray using equation (4).

6. Conclusion

Infinite rectangular microstrip reflectarray antennas with different dielectric materials are analyzed in terms of bandwidth and reflection loss performance and it has been shown that the bandwidth of the reflectarray antenna can be increased by using a suitable dielectric material. It has been shown that Teflon (ε_r=2.08 and tandδ=0.0004) has maximum bandwidth performance compared to Gallium Arsenide (ε_r=2.08 and tandδ=0.0004) which has minimum value of the bandwidth measured at different levels of the reflection loss curve. Different factors of the reflection loss are shown separately which permits the optimization of loss performance of the reflectarrays. Further investigations are required to utilize the material properties in order to enhance the performance of the reflectarray antennas.

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Table 1. Combined, dielectric and conductor loss for different materials

Dielectric Material	Dielectric Constant (ε_r)	Loss tangent (Tanδ)	Conductivity of conductor (Copper) σ (Ms/m)	Combined Loss R_l (dB)	Dielectric Loss α_d (dB)	Conductor Loss α_c (dB)
Alumina (95%)	9.75	0.0003	59.6 Ms/m	0.519 dB	0.148 dB	0.370 dB
Beryllia	6.5	0.0004	59.6 Ms/m	0.395 dB	0.138 dB	0.257 dB
CEM	4.5	0.025	59.6 Ms/m	6.875 dB	6.656 dB	0.187 dB
Gallium Arsenide	13	0.006	59.6 Ms/m	4.326 dB	3.831 dB	0.455 dB
Roger 5870	2.33	0.0012	59.6 Ms/m	0.313 dB	0.189 dB	0.122 dB
Roger 5880	2.2	0.0004	59.6 Ms/m	0.178 dB	0.060 dB	0.118 dB
Silicon	11.9	0.004	59.6 Ms/m	2.857 dB	2.406 dB	0.444 dB
Teflon	2.08	0.0004	59.6 Ms/m	0.183 dB	0.063 dB	0.119 dB
Vaseline	2.16	0.001	59.6 Ms/m	0.261 dB	0.146 dB	0.114 dB

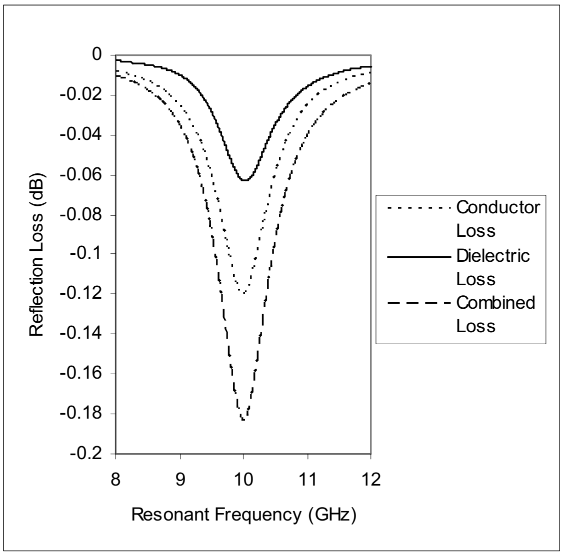

Figure 1. Individual and combined loss for Teflon

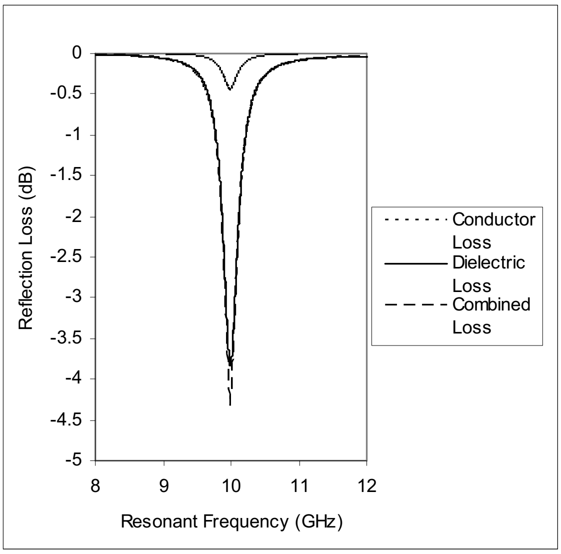

Figure 1. Individual and combined loss for Gallium Arsenide

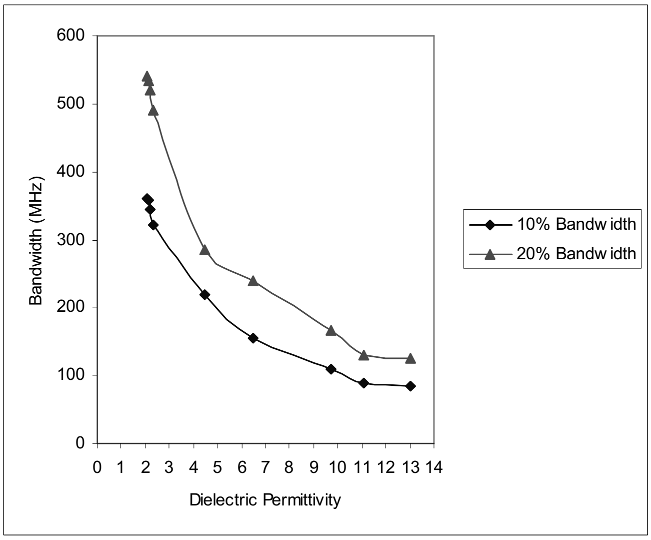

Figure 2. Trend of bandwidth performance

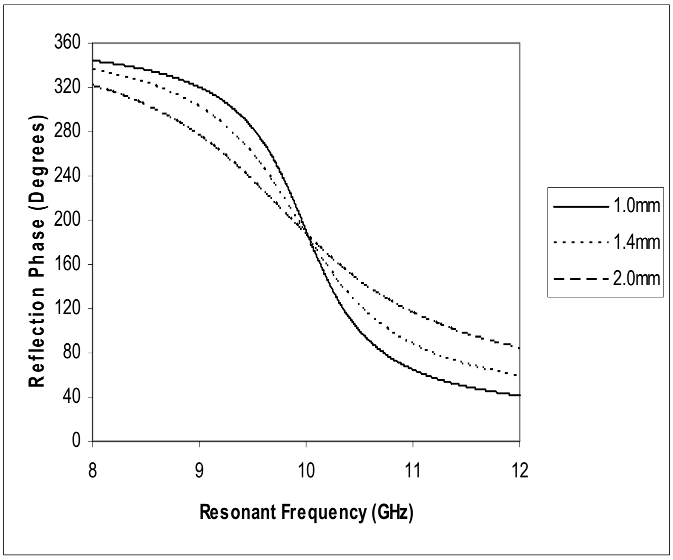

Figure 4. Reflection phase of Teflon with different substrate thicknesses

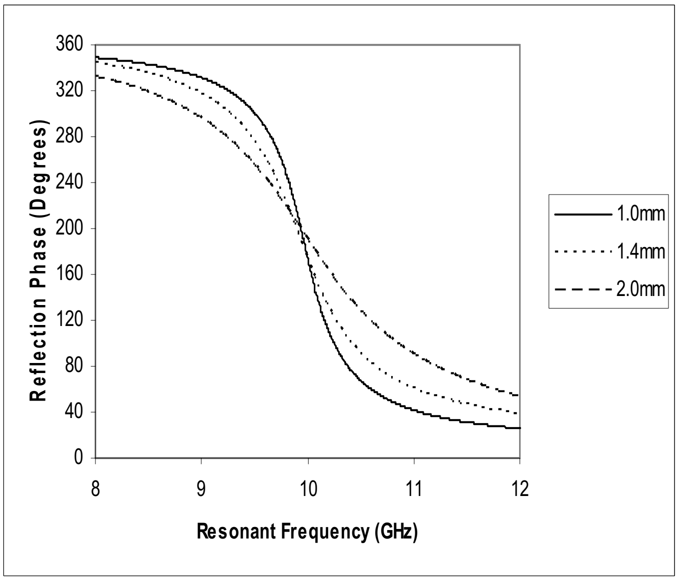

Figure 5. Reflection phase of CEM with different substrate thicknesses

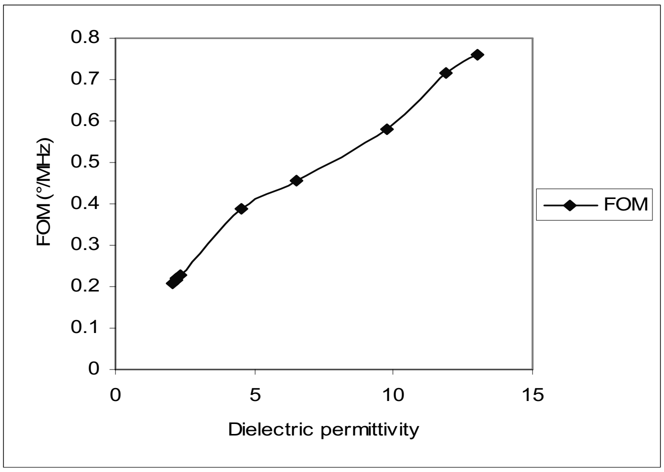

Figure 6. Trend of FOM with increasing Dielectric Permittivity