American J. of Engineering and Applied Sciences 3 (1): 180-185, 2010
ISSN 1941-7020

Reflectivity of Reflectarrays Based on Dielectric Substrates

[1]M.Y. Ismail, [1]M. Inam and [2]A.M.A Zaidi
[1]Radio Communications and Antenna Design Laboratory,
Department of Communication Engineering, Faculty of Electrical and Electronics Engineering,
[2]Department of Mechanical Engineering, Faculty of Mechanical and Manufacturing Engineering,
University Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia

Abstract: Problem statement: Reflectarrays provide a low cost and low profile solution for antennas required for high gain applications but their use is restricted in some applications due to the narrow bandwidth and high loss performance. These performance limitations can be attributed to different sources of reflectivity of the reflectarrays. This work provides a thorough investigation on the reflectivity performance of reflectarrays designed at 10 GHz using different dielectric substrates. **Approach:** The detailed analytical study of the characteristics and losses of the reflectarrays was presented and a number of dielectric substrates are used to design and analyze the reflectivity of the reflectarrays based on the analytical investigation which is validated by Finite Integral Method (FIM). **Results:** The results showed that the dielectric material with lowest dielectric permittivity and loss tangent values (Teflon) demonstrates an optimum reflectivity performance when employed for the reflectarray design. **Conclusion:** It was concluded from this research that material properties significantly affect the reflectivity of the reflectarrays and hence the bandwidth and loss performance can be pronounced improved by using a low dielectric substrate.

Key words: Reflectivity, reflectarray, reflection loss, bandwidth, phase errors

INTRODUCTION

Reflectarray antenna is a combination of a flat reflector and an array of microstrip patches. It consists of a thin flat reflecting surface and an illuminating feed. The concept of reflectarray was introduced by Berry *et al*. (1963). A new interest in the reflectarray was triggered by the work of Malagasi (1978); Munson (1987) and Huang (1991). Reflectarray antenna has been acknowledged as a potential alternative to the traditionally used high gain antennas such as parabolic reflectors or phased arrays. The need for finding an alternative to the parabolic reflector and phased array antennas is due to some characteristics of these antennas which limit their use in some applications. For example, parabolic reflector is difficult to be manufactured in many cases, in particular at higher microwave frequencies (Huang and Encinar, 2007), due to curvature of its reflector. The shape of the parabolic reflector also causes an increased weight and size of the antenna. Moreover the wide-angle electronic beam scanning is not feasible to be achieved using a parabolic reflector. High gain array antennas which are equipped with controllable phase shifters, allows wide-angle beam scanning to be controlled electronically compared to the parabolic reflector. However in order to avoid the power inefficiency which occurs in the high loss beamformer and phase shifters, the amplifier modules have to be used with the array antennas (Huang and Encinar, 2007). These amplifier modules are usually high cost and make the array antennas a very expensive solution for high gain applications. On the other hand reflectarray is a flat, light weight and a cost effective structure which permits the realization of wide-angle electronic beam scanning. Although the reflectarray has the primary advantages of flat structure and low profile as compared to parabolic reflector, however the bandwidth and the loss performance of reflectarrays are considered as the main performance limitation of the reflectarray antennas. The narrow bandwidth is mainly due to the differential spatial phase delays (Huang, 1995) while the losses occur due to the energy absorption in the conductor and dielectric layer. Spillover and surface wave excitation also contribute to the reduction in loss performance of reflectarrays however, due to the multiple bounces of the wave in the

Corresponding Author: M.Y. Ismail, Radio Communications and Antenna Design Laboratory,
Department of Communication Engineering, Faculty of Electrical and Electronics Engineering,
University Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia Tel: +607-453 8339 Fax: +6074536060

dielectric layer, dielectric and conductor losses are much more significant especially at millimeter wave frequencies (Pozar *et al*., 1997). Many researchers have been working on possible techniques to increase its bandwidth and up to 15% bandwidth has been reported (Encinar *et al*., 2006). This work provides a thorough study on the reflectivity of reflectarrays. The capacitive and resistive effects on the reflectivity performance of reflectarrays and other factors that cause degradation in reflectivity are discussed in details. The loss performance of the reflectarrays is analyzed using numerical equations and different dielectric substrates are used to design reflectarrays at 10 GHz in order to investigate and maximize the reflectivity of reflectarrays.

MATERIALS AND METHODS

Analytical investigation: In the case of an ideal reflectarray antenna design, due to high current density of periodic array of resonant elements, all the incident energy will be reflected back with the normalized reflection coefficient Γ. However, the value of the normalized reflection coefficient Γ is always measured to be less than one because the reflectarray always exhibits some losses and the reflected wave always has a bit lesser energy as compared to the transmitted wave. The reflection coefficient for a reflectarray can be given by the same expression as for the microstrip line i.e.:

$$\Gamma = \frac{Z_c - Z_0}{Z_c + Z_0} \quad (1)$$

Where:
Z_c = The characteristic impedance of the air
Z_0 = The impedance of the reflectarray which is caused by the material used in the reflectarray design

Unlike the conventional microstrip patch antenna, in case of reflectarrays a complete mismatch between the two impedances is required in order to reflect the maximum signal from the reflectarray surface. From Eq. 1 it can also be observed that for complete reflection, the value of impedance of the reflectarray have to be made as close to zero as possible or in ideal case equal to zero. In order to further elaborate the effect of material properties on the reflectivity, the reflectarray can be represented by a parallel plate capacitor having a dielectric substrate between the ground and the conducting patch element. The lumped element model of a capacitor can be represented by a lossless ideal capacitor in series with a resistor. The resistance added in series is termed as the Equivalent Series Resistance (ESR). The ESR represents losses in the capacitor and can be given by:

$$ESR = \frac{\sigma}{\varepsilon' \omega^2 C} \quad (2)$$

Where:
σ = The conductivity of the material
ε' = The real part of the dielectric permittivity of the substrate
C = Represents the ideal or lossless capacitance. In capacitor

Having low-loss, the ESR is very small and in a lossy capacitor the ESR can be large. When representing the electrical circuit parameters as vectors in a complex plane, known as phasors, a capacitor's loss tangent is equal to tangent of the angle between the capacitor's impedance vector and the negative reactive axis, as shown in Fig. 1. The loss tangent can then be given by:

$$\tan\delta = \frac{ESR}{|X_c|} = \omega C.ESR = \frac{\sigma}{\varepsilon'\omega} \quad (3)$$

The loss tangent is also the ratio of the resistive power loss in the ESR to the reactive power oscillating in the capacitor because the same AC current flows through both ESR and X_c. For this reason, a capacitor's loss tangent is also stated as its dissipation factor. From Eq. 2 and 3, it can be observed that the series resistance which represents the losses in a reflectarray is dependent on the dielectric properties of the substrate used for the reflectarray antenna design. Moreover it can also be observed that ESR decreases with the decrease in the loss tangent value of the substrate. Therefore a reflectarray designed with low loss tangent material will have a value of Γ closer to unity and hence exhibits lower reflection loss.

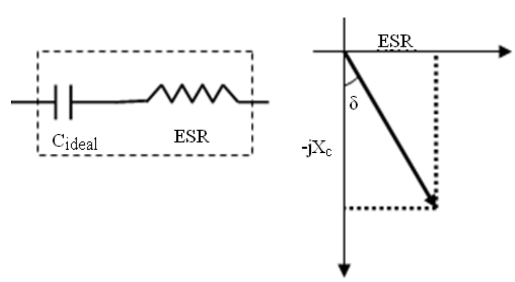

Fig. 1: Real capacitor and the loss tangent shown in impedance plane

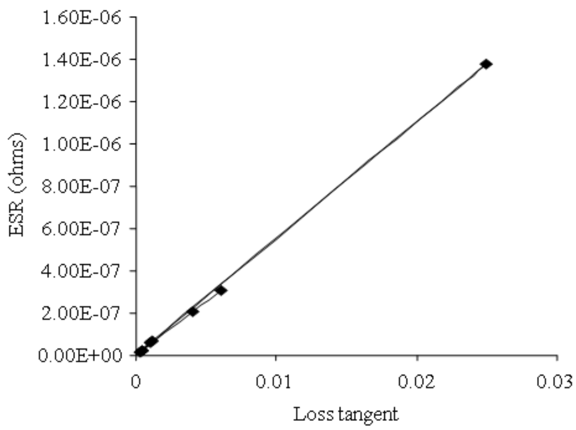

Fig. 2: ESR values for different dielectric substrates

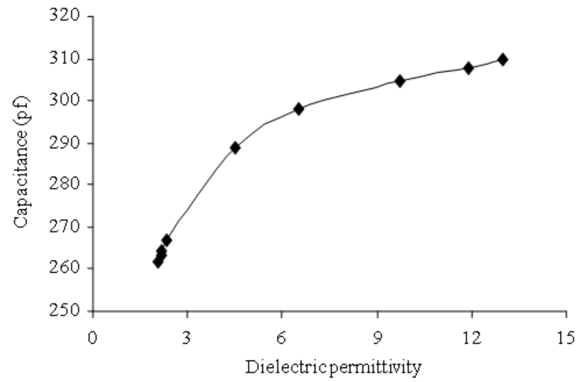

Fig. 3: Dielectric permittivity Vs capacitance of different dielectric substrates

The variation in the ESR with the loss tangent for different dielectric substrates is shown in Fig. 2. It can be observed from Fig. 2 that ESR depends on the loss tangent value and capacitance which is affected by the dielectric permittivity of the substrate. The dependency of reflectivity of the reflectarray on the dielectric permittivity can also be defined by representing the reflectarray with a parallel plate capacitor in which capacitance can be given by:

$$C = \frac{\varepsilon A}{d} \quad (4)$$

Where:
C = The capacitance of a parallel plate capacitor
A = The area of the conducting plates (conductor and ground plane in case of reflectarrays)
d = The separation between the parallel plates (substrate thickness for reflectarrays)

The capacitance is therefore greatest in devices made from materials with a high permittivity and lesser distance between the plates. This higher value of capacitance causes a higher value of Z_0 in equation 1 and hence causes a reduction in the reflection coefficient value. The reduced reflection coefficient value then degrades the reflectivity of the reflectarrays. The capacitive effect of the reflectarray antenna, designed at 10 GHz using different dielectric substrates given in Table 1, is presented in Fig. 3 for a constant conductor separation of 1 mm. As depicted in Eq. 4, it can be observed from Fig. 3 that the capacitance increases as the dielectric permittivity of the substrates used for reflectarray design is increased. This increases the dissipation of energy in the dielectric layer and hence increases the reflection loss of reflectarrays.

Table 1: List of dielectric substrates and their properties

Material	ε_r	Tan δ
Teflon	2.08	0.0004
Vaseline	2.16	0.0010
Roger 5880	2.20	0.0004
Roger 5870	2.33	0.0012
CEM	4.50	0.0250
Beryllia	6.50	0.0004
Alumina 95%	9.75	0.0003
Silicon	11.90	0.0040
Gallium Arsenide	13.00	0.0060

The losses in a reflectarray are mainly caused by the attenuation of microwave energy in the dielectric layer and the conductor (Ismail and Inam, 2010).

Therefore the reflection loss of a reflectarray can be given as:

$$R_l = \alpha_d + \alpha_c \quad (5)$$

where, α_d and α_c are the attenuation factors due to the dielectric and the conductor respectively and can be given by:

$$\alpha_d = \frac{\omega}{2}\sqrt{(\mu_0 \varepsilon_0 \varepsilon_r)}\tan\delta \quad (6)$$

$$\alpha_c = \frac{8.68 R_s}{W Z_m} \quad (7)$$

From Eq. 6 and 7, it can be observed that the dielectric attenuation depends on the dielectric permittivity and the loss tangent value which are discussed above in details. Moreover it can be observed from Eq. 7 that the conductor loss depends on the resistivity of the conducting material used for the patch element design.

Reflectarray design: Table 1 shows a list of dielectric substrates with different dielectric permittivity and loss tangent values. These materials are used to design the reflectarrays using commercially available CST MWS computer model with 1mm substrate thickness. In order to characterize the reflectivity of reflectarray patch elements, the reflection loss and the reflection phase curves were obtained using dielectric substrates having a variety of dielectric constants and loss tangent values ranging from 2.08-13 and 0.0004-0.025 respectively. Moreover the equations given above are analyzed to find out the losses for the reflectarrays using some of the materials form Table 1. The reflection phase curves were obtained using MATLAB $V^{7.5}$ with the help of the predictions presented in (Inam and Ismail, 2009).

RESULTS AND DISCUSSION

Figure 4 shows the reflection loss curves obtained by solving the equations, discussed in the previous section, using MATLAB $V^{7.5}$ while Fig. 5 shows the reflection loss curves obtained by CST MWS Simulations for different materials. It can be observed from Fig. 5 that the trend of the reflection loss is exactly the same as the one obtained by solving the analytical equations. Another important measure that can be used to analyze the reflectivity of the reflectarray is the reflection phase performance. The reflection phases for some materials used to design reflectarrays at 10 GHz with 1mm substrate thickness are shown in Fig. 6.

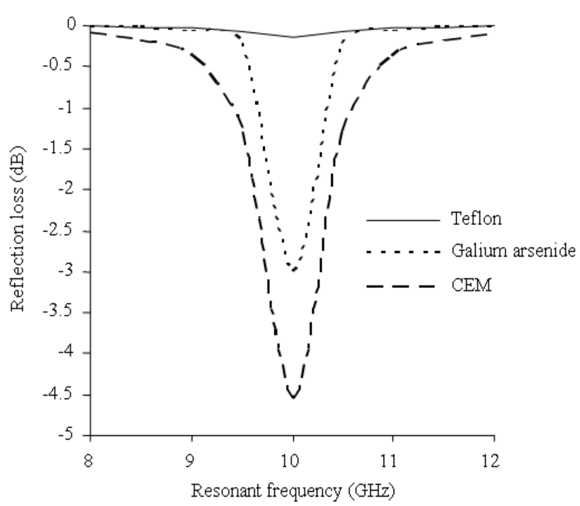

Fig. 4: Reflection loss curves obtained by analytical equations in MATLAB $V^{7.5}$

As depicted in Fig. 4, it can be observed that at resonant frequency of 10 GHz, Teflon shows a very low reflection loss value of 0.135 dB as compared to CEM and Gallium Arsenide which offer the reflection loss of 4.51 and 3 dB respectively. This is because Teflon has very low values of loss tangent and dielectric permittivity as compared to the other two materials as shown in Table 1. It can be observed from Fig. 5 that at 10 GHz Teflon has the minimum reflection loss value of 0.183 dB while Gallium Arsenide and CEM have higher reflection loss values of 4.28 and 6.74 dB respectively. The difference in the reflection loss values for different materials is due to the difference in the reflectivity of reflectarrays as discussed above. The difference in the reflection loss values of both the analysis is due to the fact that in Fig. 4, only the effects of conductor and dielectric loss are considered and the CST MWS simulations (Fig. 5) are carried out taking into account all other factors such as interelement spacing, boundary conditions and port excitation distance. Table 2 shows the reflection loss values of all other materials used for reflectarray simulations in CST MWS. From Table 2, it can be observed that the reflection loss increases as the dielectric permittivity and loss tangent values are increased.

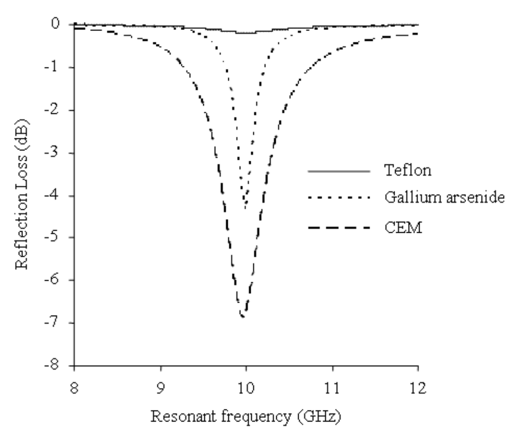

Fig. 5: Reflection loss curves obtained by CST simulations

Table 2: Reflection loss values of different dielectric substrates used for reflect array design

Material	Reflection loss at Fr = 10 GHz (dB)
Teflon	0.179
Vaseline	0.261
Roger 5880	0.180
Roger 5870	0.313
CEM	6.875
Beryllia	0.395
Alumina 95%	0.519
Silicon	2.857
Gallium arsenide	4.326

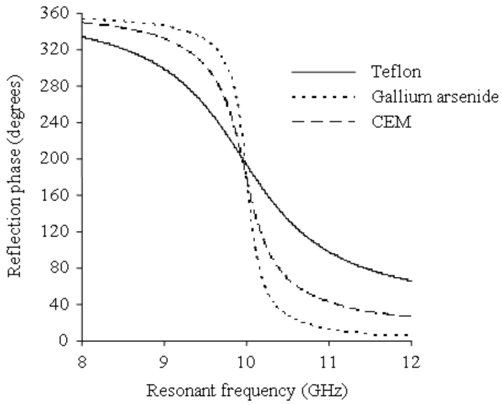

Fig. 6: Reflection phase curves for different dielectric substrates

This is because of the fact that increasing the permittivity and loss tangent cause more multiple bounces of microwave energy and therefore more dissipation in the dielectric layer causes degradation in reflectivity of the reflectarrays. It can be observed from Fig. 6 that unlike the reflection loss of the reflectarrays, the reflection phase curve is affected more by the dielectric permittivity of the material. The slope of the reflection phase versus resonant frequency curve is a measure the bandwidth of the reflectarrays (Pozar *et al*., 1997). The steeper the slope of the reflection phase curve the lesser will be the bandwidth of the reflectarrays. In Fig. 6, it has been demonstrated that Teflon, which has the minimum dielectric permittivity value shows a smoother phase curve as compared to the phase curves of the other two dielectric substrates. But in this case there is a tradeoff between the bandwidth and the occurrence of phase errors. The phase errors will be maximum for the case of Teflon as the reflection phase curve does not cover the whole 360° range of reflection phase on the other hand the phase errors will be least for Gallium Arsenide as it covers a phase range of 355°.

CONCLUSION

The results obtained from the analytical modeling and simulations based on FIM, demonstrate that the capacitive losses in the dielectric layer of the reflectarray can be decreased by the selection of a proper dielectric substrate. Moreover the suitably selected dielectric material decreases the loss performance and consequently improve the bandwidth of the reflectarray antenna which causes an increase in the reflectivity performance of reflectarrays. Furthermore it has also been shown that the material properties can be exploited to reduce the reflection loss and enhance the bandwidth of reflectarrays. However a tradeoff is required to be established in order to figure out the relationship between phase errors and bandwidth performance.

ACKNOWLEDGEMENT

We would like to thank the Ministry of Higher Education Malaysia for providing funds for this research under Fundamental Research Grant Scheme (VOT0558). We would also like to thank the staff of Radio Communications and Antenna Design (RACAD) laboratory of University Tun Hussein Onn Malaysia (UTHM) for the technical support.

REFERENCES

Berry, G.D.G., R.G. Malech and W.A. Kennedy, 1963. The reflect array antenna. IEEE Trans. Antennas Propag., AP-11: pp.645-651. DOI: 10.1109/TAP.1963.1138112

Encinar, J.A., M. Arrebola, M. Dejus and C. Jouve, 2006. Design of a 1-metre reflect array for DBS application with 15% bandwidth. Proceedings of the 1st European Conference on Antennas and Propagation, Nov. 6-10, IEEE Xplore Press, Nice, pp: 1-5. DOI: 10.1109/EUCAP.2006.4584987

Huang, J., 1991. Micro strip reflect array. Proceedings of the IEEE AP-S Symposium Digest, (AP-S'91), IEEE Xplore Press, London, Ontario, Canada, pp: 612-615.

Huang, J., 1995. Analysis of micro strip reflect array antenna for micro spacecraft applications. Spacecraft Telecommunications Equipment Section, TDA Progress Report, pp: 42-120. http://ipnpr.jpl.nasa.gov/progress_report/42-120/120H.pdf

Huang, J. and J. Encinar, 2007. Reflect Array Antennas. Wiley Inter Science, USA., ISBN: 9780470084915, pp: 216.

Inam, M. and M.Y. Ismail, 2009. Numerical analysis and equivalent circuit modeling for loss quantification of reflect arrays using different substrate materials. Proceedings of the IEEE International Conference on Antennas, Propagation and Systems, Dec. 3-5, Johor, Malaysia. http://www.fke.utm.my/INAS09/

Ismail, M.Y. and M. Inam, 2010. Analysis of design optimization of bandwidth and loss performance of reflect array antennas based on material properties. Modern Applied Sci. J. CCSE., 4: 28-35. http://www.ccsenet.org/journal/index.php/mas/article/viewFile/4030/4081

Malagasi, C.S., 1978. Micro strip disc element reflect array. Proceedings of the Electronics and Aerospace System Convention, Sept. 25-27, Institute of Electrical and Electronics Engineers, Inc., Arlington, Va., New York, pp: 186-192. http://adsabs.harvard.edu/abs/1978ieee.conf..186M

Munson, R.E., H.A. Haddad and J. Hanlen, 1987. Micro strip reflect array antenna for satellite communication and radar cross-section enhancement or reduction. US Patent No. 4684952. http://www.freepatentsonline.com/4684952.html

Pozar, D.M., D. Targoski and H.D. Syrigos, 1997. Design of millimeter wave micro strip reflect arrays. IEEE Trans. Antennas Propog., 45: 287-296. DOI: 10.1109/8.560348.