Performance Improvement of Reflectarray Antennas using Organic Substrate Materials

M Y Ismail,* H I Malik and M H Mokhtar

Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja 86400, Batu Pahat, Johor, Malaysia.

*Email: yusofi@uthm.edu.my

Abstract. An innovative approach to address the issue of narrow bandwidth in reflectarray antennas have been demonstrated using organic substrate materials. Three robust paper based substrate materials with controlled material composition have been proposed with efficient dielectric material properties. Material characterization results show low dielectric permittivity results of 1.81, 1.63 and 1.84 along with loss tangents of 0.053, 0.046 and 0.057. Moreover in order to overcome the problem of linear phase range Double C slot element configuration have been implemented on the proposed substrate materials. Scattering parameter measurements of the proposed design show promising bandwidths of 265, 326 and 242 MHz along with a phase ranges of 310°, 297° and 317° respectively.

1. Introduction

Microstrip reflectarray antennas have gained a prestigious positon in for wireless communication systems. Due to their flat profile, ease of fabrication along with low ohmic losses since they do not use any feeding strip lines like phased array antennas. Moreover, due to the planar structure with printed elements reflectarrays present themselves as attractive compared to bulky parabolic dish reflectors. They have proven their efficiency in long range radar and spaceborne applications [1], [2].

Reflectarray antennas have evolved a lot with the advent of printed circuit board technology. On a reflectarray antenna the reflection phase of unit element is controlled in such a way to have a progressive phase distribution. Using this phase distribution of elements the incident beam front is focused in a particular direction and acquiring a planar wavefront at far field region [1]. The reflection phase curves of reflectarray unit element are of key considerations in terms of phase range and the phase gradient. A linear phase curve with a phase range of 360° is desired to avoid phase errors due to fabrication tolerances. Different element configuration has been proposed in the literature with linear and wide phase range coverage, such as square ring, malta cross, circular split rings and delay line coupled cut ring patch element [3]–[6].

In addition to reflection phase consideration in microstrip reflectarray antennas, the performance is highly obstructed by the intrinsic narrow bandwidth behavior. Efforts have been made to broaden the frequency response of microstrip reflectarray by proposing design schemes such as stacked configuration of patches, dual band resonances and by introducing thicker substrate layers [7]–[11].
Moreover, in single layer structures proposed using phoenix elements [10] and stub loaded circular patches [11] an air gap is introduced between the substrate layer and the ground plane. The thicker substrate and stacked layer configurations or with air gap introduced pose fabrication challenges in terms of layer alignment and maintaining uniform structural gaps.

Organic substrate materials have been reported to be used for conventional microstrip antennas. Various types of commercially available paper substrates have been reported with different printed microstrip structures [12]–[14]. However, despite using paper substrate material, the physical composition of organic paper has not been taken into consideration. Moreover, the proposed paper substrates show high electrical parameters such as permittivity and loss tangents. Thus, this work focuses on address two key limitations of microstrip reflectarray antenna technology such as:

1. Narrow bandwidth performance
2. Insufficient phase range behavior

In order to address the above mentioned shortcomings, this work presents a combination of a novel Double C slot element configuration based on a paper substrate material. This work presents three different substrate materials with controlled chemical compositions based on recycled materials. The paper has been divided into various sections. Section I covers the dielectric material characterization of proposed paper substrate material, section 2 describes the proposed Double C slot element configuration. Section 3 contains fabrication discussion over the comparison of measured and simulated results.

2. Dielectric material characterization

Three dielectric materials with different physical composition have been proposed. The paper substrate material has been derived from banana pulp, recycled carton paper, copier paper and newspaper. Controlled compositions of the mentioned constituents have been processed together to manufacture substrates with suitable thickness. The composition of proposed substrate is presented in Table 1, where the names have been assigned according to the composition of the materials.

| Substrate | Banana fiber | Recycled Newspaper | Recycled Carton paper | Recycled Copier paper |
|-----------|--------------|-------------------|----------------------|----------------------|
| RCP50     | 50           | --                | --                   | 50                   |
| RCR75     | 25           | --                | 75                   | --                   |
| RNP50     | 50           | 50                | --                   | --                   |

Table 1 shows that the banana fiber used is the component of every proposed substrate. The compositions were carefully controlled to achieve versatile substrate properties. The initial substrates were having low substrate heights and were merged using glue to achieve suitable substrate heights. The samples were then passed thought several drying stages to kill the moisture content that might affect the substrate properties.

The proposed dielectric materials were first characterized for electrical properties. A broadband material characterization was used to characterize the material for X-band operation. A Speag Dielectric Assessment 2Kit (DAK) was used for this purpose. DAK 3.5 probe was used for the experiment that offers measurement over a frequency range of 0.2 to 20 GHz. The dielectric material characterization setup and the dielectric probe used is shown in Figure 1. The probe is connected to a
vector network analyzer and is controlled remotely by the software platform on the PC. All the three proposed substrates were characterized using the same setup.

| Substrate | $\varepsilon_r$ | tanδ | Height (mm) |
|-----------|----------------|------|-------------|
| RCP50     | 1.81           | 0.053| 1.51        |
| RCR75     | 1.63           | 0.046| 1.62        |

**Figure 1.** Dielectric material characterization (a) dielectric probe (b) material characterization setup.

The dielectric material results are presented in Figure 2 and Figure 3. Dielectric permittivity results for proposed substrates are presented in Figure 2. The results show a stable permittivity behavior for all the substrates over the X-band operation. Loss tangent results are presented in Figure 3. The findings form the Figure 2 and Figure 3 are tabulated in Table 2.

**Table 2.** Dielectric material characterization results.

**Figure 2.** Dielectric permittivity results of proposed substrates.

**Figure 3.** Loss tangent results for proposed paper substrate materials.
The substrate heights used for the dielectric substrate materials used are also listed in Table 2. The results show that RCR75 paper substrate with a composition of 75% recycled carton paper and 25% banana pulp shows the minimum value of permittivity and the loss tangent. While RCP50 and RNP50 substrate that are composed of 50% banana pulp show higher loss and permittivity value. Heights of all the substrates was kept as close as possible to acquire a fair comparison of results.

3. Double C – Slot element configuration

Reflection phase curves provides valuable information about the bandwidth and the phase errors that might affect the radiation efficiency of the array. A linear phase range with gradual phase slope is usually desired to achieve required array efficiency. Thus, this article utilizes a Double C – slot element configuration as proposed for wide phase range coverage [15]. The proposed element was to be integrated with innovative paper substrate materials to acquire a wide band phase range behavior along with a broadband frequency response. The proposed element shape was modelled over the proposed paper substrate materials using a Finite Integral Method (FIM) technique using CST MWSv15. Perfect electric and magnetic boundary conditions were applied to achieve the effect of an infinite reflectarray.

Figure 4 shows the simulated model of Double C – slot element with two C – slots as a mirror image of each other. Figure 4(b) shows the boundary condition applied to realize an infinite array.

![Figure 4](image)

(a) Double C - slot element (a) CST MWS simulated model (b) Boundary conditions for simulated model.

The excitation vector of the incident E-field is indicated by an arrow. The resonant frequency of the element can be changed by altering the width of the C – slots. Figure 5 shows the surface current distribution of the patch element.
The flow of the surface charge carrier on the patch depict the major movement of charges between the lower and upper radiating edges. Moreover, it can also be seen that most of the charge carriers follow the path around the outer edges of the C–slot. That is the reason a higher charge concentration can be seen between the non-radiating edges and the other edges of the C–slot. Simulation results were carried out for all the three paper substrate materials with similar simulation parameters.

4. Fabrication and measurements

The proposed Double C – slot element configuration was fabricated over the three innovative paper substrate materials. The presented paper substrate materials were not suitable for CNC milling or wet etching process for the fabrication of element shapes, so the elemental shapes were cut manually. An adhesive copper tape with a thickness of 70 μm was selected to cut the proposed shapes. Copper tape was selected instead of printable conductive inks since the copper tape offers the conductivity of bulk copper. Moreover, the copper tape is also more resilient, since the printed ink is vulnerable to cracks thus leading to efficiency degradation. Additionally, the commercially available conductive inks results in a rampant increase in the fabrication cost [14].

A translucent paper was used to get the element designed, printed by a laser printer. Then the paper was placed over the copper tape and the slot was cut manually. Multiple elements were fabricated to achieve the desired fabrication quality and also to ensure the repeatability of the results. Moreover, the dimension of the fabricated elements was measured using a digital Vernier caliper and the dimensions were accumulated in the simulation designs. Figure 6(a) shows the fabricated elements of Double C–slot configuration over three proposed paper substrate materials. Two identical elements were fabricated on a single dielectric substrate to get the element dimensions equal to the waveguide aperture. The fabricated elements were having dimensions of \( \lambda_0 \times \lambda_0/2 \) to fit into the waveguide aperture. Figure 6(b) shows the complete measurement setup for the scattering parameters measurement of the fabricated samples. The setup consists of Rodhe & Schwarz 14 GHz network analyzer and an X-band waveguide simulator. The complete setup was thoroughly calibrated to eradicate any measurement errors.
5. Result and comparison

This section presents the results and discussion on scattering parameter measurement of Double C – slot element fabricated over proposed substrate materials. The recorded data from measurement setup was plotted using MATLAB with a comparison between measured and simulated results. Figure 7 (a) and (b) shows the reflection loss and phase curves of Double C – slot element configurations over three different proposed substrates.

Figure 7. Comparison of measured and simulated (a) reflection loss curve (b) reflection phase curve for Double C-slot element with proposed paper substrates.

A comparison of all the three measured reflection loss curves from Figure 7(a) shows that RNP50 and RCP50 substrate materials show maximum reflection loss compared to RCR75 substrate material. The measured reflection loss curves also show slight ripples in the curves when compared to smooth simulated curves. These ripples are due to the non-ideal nature of the waveguide simulator.

Figure 7(b) shows the comparison of measured and simulated reflection phase curves for all the three proposed substrate materials. The reflection phase curves follow a water fall trend for both the measured and simulated curves. The curves show a maximum gradient at the resonance frequency of patch element. The finding from the Figure 7 are tabulated in Table 3.

Table 3. Comparison of scattering parameter results for double C – slot element configuration on proposed paper substrate materials.

| Substrate | $f_r$ (GHz) | RL (dB) | $\Delta f$ (MHz) 10% | $\Delta \Phi$ (deg) | FOM (%/MHz) |
|-----------|-------------|--------|----------------------|-------------------|-------------|
| RCP50     | Simulation  | 10.0   | -7.87                | 430               | 276         | 0.14        |
|           | Measurement | 10.18  | -11.30              | 265               | 310         | 0.18        |
The performance comparison of three substrates with Double C – slot element configuration have been done on the basis of reflection loss, 10% frequency bandwidth, reflection phase range and the phase curve gradient at the resonance point. The results show that the fabricated elements show resonances at 10.18, 9.85 and 9.61 GHz for RCP50, RCR75 and RNP50 substrate samples. The measured reflection phase curves show losses of -11.30, -9.80 and -11.55 for RCP50, RCR75 and RNP50 substrate materials respectively. The proposed 10% bandwidth is calculated by moving 10 percent above the maximum loss level of the reflection loss curve. A comparison of 10% bandwidth shows that RCR75 shows a maximum measured bandwidths of 326 MHz followed by the RCP50 and RNP50 substrates with bandwidths of 265 and 242 MHz respectively. The difference between measured and simulated bandwidths is due to the increased loss in the measured results due to experimental setup.

The reflection phase results are also listed in Table 3. The reflection phase range (ΔΦ) is the maximum phase range for X-band operation between 8 – 12 GHz. The measured reflection phase curves show that the maximum phase range of 317º is shown by RNP50 substrate material and the minimum phase range of 295º is shown by RCR75, while RCP50 shows an intermediate phase range of 310º. The measured reflection phase curves show a broader phase range behavior compared to simulated curves due to increase in the measured loss of the element. The reflection phase range is an important parameter in the design of reflectarray antenna since a wider phase range helps reduce the fabrication tolerances and increases the array efficiency. Table 3 also lists down the reflection phase gradient of the phase curves. The results show that the RCR75 shows the minimum phase gradient of 0.16 º/MHz, followed by 0.18 and 0.19 º/MHz for RCP50 and RNP50 substrates. A lower phase gradient is always desired to avoid phase errors in the array via fabrication tolerances. Since a rapidly changing phase with higher gradient, when affected by dimensional tolerance will result in a greater change in resonant frequency compared to a phase curve with lower gradient.

The comparison of results for all the substrates show adequate bandwidth to address the issue of narrow bandwidth in reflectarray antennas. Moreover it can also be seen that the Double C – slot element configuration over the proposed substrates show good phase ranges of greater than 300 MHz. From the results it can also be deduced that there is a tradeoff between the measured bandwidth and the reflection phase range of the elements. Double C – slot element with RCR75 substrate shows a maximum bandwidth while a minimum phase range and phase gradients. On the other hand the RNP50 substrate element shows the maximum phase range with a minimum bandwidth behavior. Thus, in order to achieve fruitful results for a reflectarray antenna design a tradeoff will be adopted.
The proposed paper substrates will be used for the design of a full scale reflectarray antenna to realize a broadband reflectarray antenna with efficient phase range coverage. It can also be deduced from the composition of the paper substrates that increased amount of banana fiber in the paper results in a higher loss tangent of the material. Thus, further investigation will be done to achieve better and effective implementation of a reflectarray antenna based on paper substrate material.

6. Conclusion

This article presents a novel approach to address the narrow bandwidth and low phase range problem in reflectarray antennas. Novel organic substrates derived from recycled materials such as carton paper, copier paper and banana pulp have been presented for microstrip reflectarray antenna. The materials were extensively characterized for the dielectric material properties. The broadband analysis of proposed substrates offers low dielectric permittivity values of 1.81, 1.63 and 1.84 that suitable for high radiation efficiencies in microstrip reflectarray antennas. In order to achieve a good phase range also a Double C – slot element configuration have been modelled and analyzed using computer simulation models based on CST MWS. The simulated models were then fabricated over the proposed substrates and the dimensional tolerances were precisely incorporated in the simulation designs. Measurement of scattering parameters was done using a waveguide simulator technique. The results depict a broadband behavior for all the three substrate materials with a maximum measured bandwidth of 326MHz for RCR50 substrate material while the maximum phase range of 317º have been reported by RNP50 substrate material. Thus, from the results it can be concluded that the proposed paper substrate materials offer broadband frequency behaviors along with good phase range behaviors to address the challenges of microstrip reflectarray antenna technology.

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