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A wideband reflectarray antenna based on organic substrate materials

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Abstract

Significant improvements in terms of bandwidth of reflectarray antennas have been achieved by introduction of innovative paper substrate dielectric materials. Three differently custom composed organic dielectric substrates have been characterized for dielectric properties using a broadband technique based on open ended coax cable method. The substrates show low dielectric permittivities of 1.81, 1.63 and 1.84 along with a loss tangent of 0.053, 0.047 and 0.057. Validation of using the proposed substrates for reflectarray antenna was done by modelling and fabricating reflectarray unit elements on the three substrates. Scattering parameter analysis of unit reflectarray elements show encouraging results with a broadband frequency response of 340 MHz at a phase gradient of 0.14º/MHz. Thus the proposed substrate could serve exceptionally to address the narrow bandwidth problem in reflectarray antennas.

Keywords*: broadband, paper substrate, rectangular patch, reflectarray antenna*

1. Introduction

The modern telecommunication industry requires compact and low profile antennas for versatile applications. Planar reflectarray antennas have presented themselves as a perfect replacement for parabolic dish reflectors due to advantages such as the low profile, ease of fabrication and installation along with a compact structure. They have emerged as a new generation of high gain antennas to merge both the key features of parabolic dish reflectors and phased array antennas along with low costs and simplified feeding systems [1].

Microstrip reflectarray consists of printed layer of radiating elements that are illuminated by a feed source. The reflection phases of the elements are carefully controlled to obtain directive radiation patterns at far field region. Despite the key features of low profile and ease of fabrication microstrip reflectarray antennas suffer from low bandwidth performance due to intrinsic narrow bandwidth of microstrip antennas [2]. In order to address the issue of narrow bandwidth stacked configurations with two or three layers of printed elements have been reported [3–6]. However the introduction of stacked configuration with printed elements poses fabrication challenges and requires accurate alignment of the layers. Narrow bandwidth behavior have also been addressed by the introduction of single layer dual resonance elements such as parallel dipoles, spit rings and combination of different slot configurations [7–12]. However dual resonance elements with resonances in different bands require complex phasing techniques along with dual feeding mechanism that increase the complexity of the array design. Moreover in order to attain a linear phase response with improved bandwidth performance for unit reflectarray elements, air gaps have also been reported to be used between the substrate and the ground layer [13–15]. The introduction of the thicker substrate region does improve the linearity of phase curve but may decrease the efficiency of overall array due to surface wave excitation [14].

The radiation behavior and performance of microstrip antenna is highly dependent upon the material properties of the dielectric substrate. The use of low permittivity materials for microstrip antenna is encouraged, since it will increase the radiation efficiency of the antenna by enhancing the fringing field effect [15]. Among the commercially available substrate materials used for traditional microwave antenna applications, the PTFE Teflon and RT5880 materials shows a minimum permittivity of 2.1 and 2.2 respectively [14]. They offer excellent performance, however the cost of these substrates is usually too high for commercial civilian applications.

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Thus in this work novel paper substrates derived from recycled organic materials have been presented for microstrip reflectarray antenna applications. The proposed substrate materials offer excellent electrical properties with lowest permittivity values compared to commercial substrates. The materials have been thoroughly characterized over a broadband frequency range for electrical properties. In order to validate the material to be used for reflectarray antenna, unit elements have been designed on proposed substrates and the performance have been deeply analyzed. After a brief introduction of proposed paper substrate materials, material characterizations of paper substrate have been presented in section 2. Section 3 discusses the simulated designs of unit reflectarray element based on rectangular patch element. Section 4 presents the fabrication and testing of fabricated elements over the proposed substrates and section 5 and 6 cover the discussion over the results and comparions.

2. Paper Substrate Material

Three different paper substrates with different physical composition have been presented. The proposed paper substrate materials have been derived from recycled materials such as banana fiber, recycled newspaper and recycle carton paper. Controlled composition of the mentioned three materials were processed toghether to produce a custom paper substrate material rather than using commercially available papers since no information about material content is usually known. Table 1 presents the composition of the proposed organic substrates.

Table 1. Physical Composition of Proposed Dielectric Substrate 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 pulp is a constituent of all proposed substrates. The acronyms defined in the Table 1 are based on the quantity of maximum ingredients. The nomenclature is based on the name of ingredient other than banana fiber, since banana fiber is a part of all substrates. The proposed substrate materials are shown in Figure 1. Initial substrate samples were thin sheets, thus in order to achieve structural strength multiple layers were glued together to attain fruitful results. The samples were then passed through heating and drying process multiple times to kill the moisture content that might affect the substrate performance.

Figure 1. Proposed paper substrate materials for microstrip reflectarray antenna

3. Results and Analysis

The first step after preparation of the samples was to determine the electrical parameters of the proposed substrate. The dielectric material characterization was carried out using a broadband characterization technique. Speag Dielectric Assessment Kit (DAK 3.5) was used to determine the dielectric parameters. A 3.5 mm dielectric probe with a broadband analysis range of 0.2–20 GHz was used to assess the material properties. The probe used water as its calibration load due to universal properties of water. Figure 2 shows the dielectric characterization set-up. The dielectric probe is connected to a Rohde & Schwarz 14 GHz vector network analyzer. The probe is controlled remotely by the software platform on the PC. A metallic fixture was used to get an effective contact between the sample and the probe while maintaining the probe position fixed.

Figure 3 shows the close view of the used dielectric probe and its calibration. Figure 3 (a) shows the DAK 3.5 probe. The probe uses air, copper strip and water for open, short and load calibrations respectively. Figure 3 (b) shows the probe dipped into water for calibration. Figure 3 (c) shows the RT5880 substrate material under test above a foam material for support. All three proposed paper substrate materials were characterized using the shown measurement set-up. The results of dielectric material characterization have been presented in Figure 4 and Figure 5.

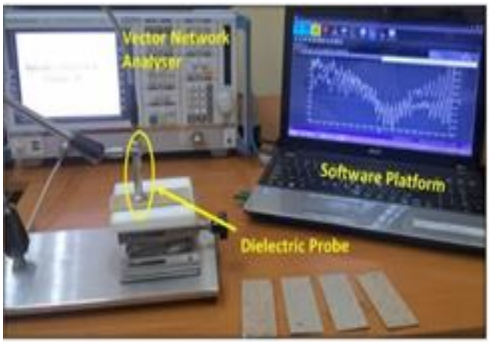


Figure 2. Dielectric material characterization set-up

(a) (b) (c)

Figure 3. Material characterization
(a) Dielectric probe (b) Calibration using water
(c) RT5880 material under test

The dielectric permittivity plots for the proposed substrates have been shown in Figure 4. Figure 5 shows the dielectric loss tangent curves. The results show that the loss tangent for the paper substrates remain in the range of 0.04-0.07 throughout the band of interest. Moreover the loss shows a decrease at higher frequencies. Mean values were calculated from the material characterization results and have been tabulated in Table 2.

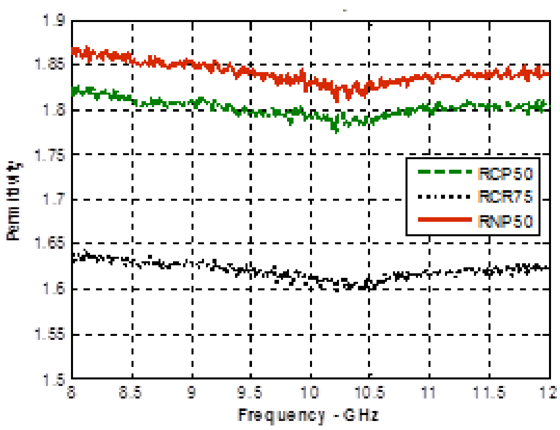


Figure 4. Dielectric permitivity results of proposed materials

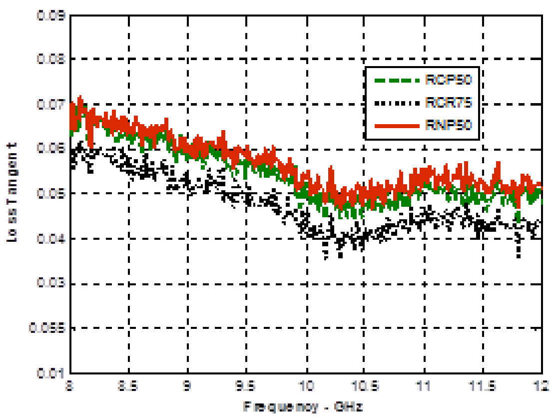


Figure 5. Dielectric loss tangent results for proposed substrate materiasl

Results of dielectric materials characterizaiton tabulated in Table 2 were used in the simulation designs. The results show a close permitivity behavior for both RCP50 and RNP50 substrates. Moreover the substrate heights of the samples are also tabulated in Table 2. RC50, RCR75 and RNP50 samples have 1.45, 1.62 and 1.12 mm substrate thicknesses respectively.

Table 2. Results of Dielectric Material Characterization

Substrate	ε_r	tanδ	Height (mm)
RCP50	1.81	0.053	1.45
RCR75	1.63	0.046	1.62
RNP50	1.84	0.057	1.12

4. Simulation Designs

In order to investigate the feasibility of using proposed dielectric substrate material for reflectarray antenna applications, reflectarray unit element models were designed and simulated in CST MWS. Since the design of a reflectarray antenna is a two-step process. The first step is to design unit reflectarray elements and their assessment on the basis of their scattering parameters. The second step consists of an array construction by arranging the element in a uniform phase dependent pattern where each element get a place depending upon its reflection phase. Many important characteristics of a full scale array are dependent on unit elements such as substrate loss, resonant frequency and reflection phase behavior. This article focuses on the design of first stage for reflectarray antenna based on a novel substrate material to achieve a wideband frequency response.

The simulated model of the proposed rectangular patch element is shown in Figure 6. The model used the dielectric properties found from dielectric material characterization is shown in Table 2. The substrate is backed by a ground patch with a rectangular patch on the other side. In order to realize the effect of an infinite reflectarray, unit element was designed with electric and magnetic boundaries to simulate all the effects that an element faces inside the array such as mutual coupling and related parasitic effects [16]. The excitation E-field of the patch element is shown by the electric vector in Figure 6. The vertical walls are designated as magnetic wall and the horizontal wall were nominated as electric wall. Using the stated boundary conditions the element was tested for its scattering parameter behavior over the X-band of operation.

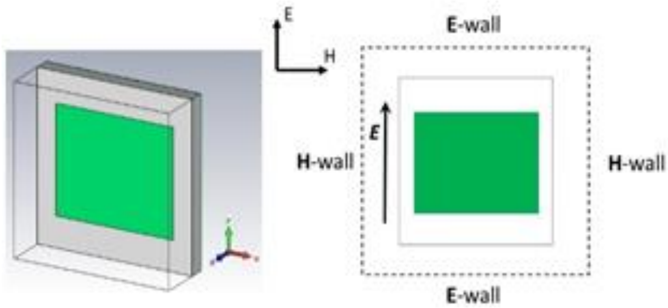
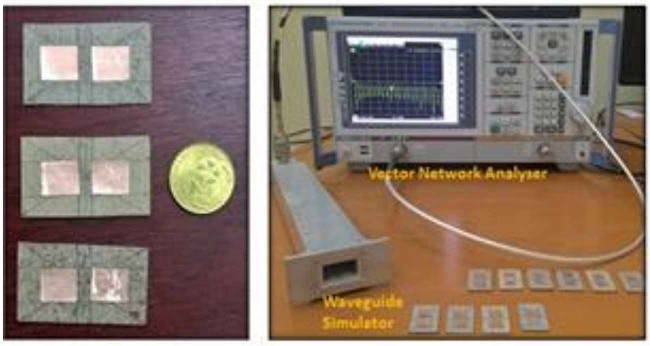


Figure 6. Computer simulated model of unit reflectarray element with electric and magnetic boundaries

5. Fabrication and Measurements

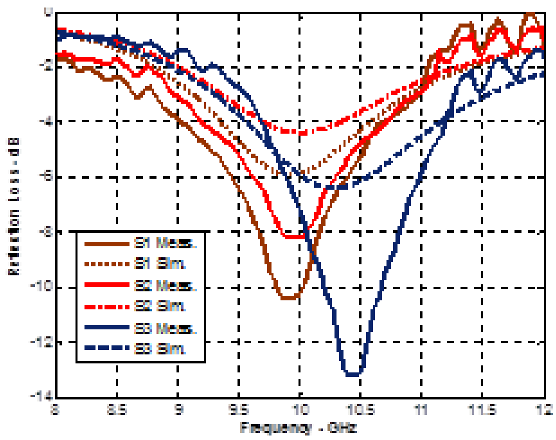
After simulating the reflectarray cell, unit elements were fabricated over the proposed substrates. An adhesive copper tape with 70 µm thickness, was used for the fabrication of antennas. Copper tape was selected instead of conductive inks because of higher conductivity of copper compared to conductive inks. Moreover the paper substrate was not robust enough to withstand the milling or chemical etching process. The element were cut manually to acquire required dimensions. Multiple elements were fabricated and tested to ensure repeatability of the results. Figure 7 shows the fabricated elements along with the complete measurement set-up for scattering parameter measurements. The set-up consists of tapered X-band waveguide attached to a 14 GHz vector network analyzer. The waveguide operates at a fundamental mode TE_{10}. The elements under test is placed inside the aperture of the waveguide to record the scattering parameters of the element under test.



(a) (b)

Figure 7. Fabrication and measurements
(a) fabricated elements (b) scattering paramter measurement set-up

The measured results for all the three rectangular patch reflectarray elements with proposed substrates are presented in Figure 8 and Figure 9. The reflection loss and reflection phase curves show good agreement between the simulated and measured results. The reflection phase curves show ripples in the measured curves. The appearance of ripples may be due to the non-ideal nature of waveguide simulator.



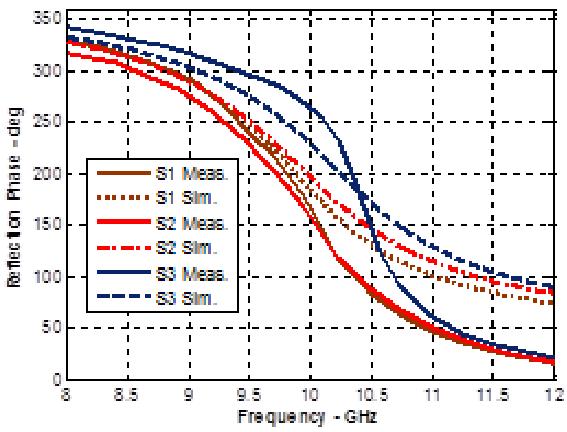


Figure 8. Reflection loss measurements for proposed substrates

Figure 9. Reflection phase measurement results for proposed substrates

In order to thoroughly compare the performance of the proposed three substrates, a comparison has been carried out to investigate the performance of reflection loss, reflection phase range, 10% bandwidth and the gradient of the phase curve. The finding obtained from Figure 8 and Figure 9 have been tabulated in Table 3.

The summary of all the results of scattering parameters is tabulated in Table 3. The results show that the RCP50, RCR75 and RNP50 substrate materials show maximum reflection loss (RL) of -10.36, -8.16 and -13.19 dB respectively. Comparison of reflection loss shows that the RNP50 substrates shows the maximum loss due to higher substrate loss and the least substrate thickness. A 10% bandwidth is also defined to compare the bandwidth of different substrates. The bandwidth is measured by moving 10% above the maximum loss level of the reflection loss curve. The results show that RCR75 substrate material shows a maximum bandwidth of 340 MHz, followed by 312 and 207 MHz for RCP50 and RNP50 respectively.

Table 3. Comparison between Measured and Simulated Scattering Parameter Results

Substrate (height - mm)		f_r (GHz)	RL (dB)	Δf (MHz) 10%	ΔΦ (deg)	FOM (º/MHz)
RCP50	Sim.	9.92	-5.92	465	254	0.13
	Mea.	9.94	-10.36	312	308	0.19
RCR75	Sim.	9.98	-4.38	682	243	0.10
	Mea.	9.95	-8.16	340	301	0.14
RNP50	Sim.	10.46	-6.41	356	275	0.12
	Mea.	10.42	-13.19	207	319	0.28

The reflection phase range of the unit elements is an important parameter since a lower phase range may result in phase errors. Table 3 shows that for all the three substrates the reflection phase curves cover a phase range of greater than 300º. Reflectarray element with RNP50 substrate covers the maximum phase range of 319º while RCP50 and RCR75 cover phase ranges of 308º and 301º respectively. The increase in the phase range for RNP is due to increase in the loss of the substrate material that increases the slope of the resonant phase of element. It can also be seen in Figure 9 and Table 3 that the range of measured reflection phase is greater than the reflection phase simulated, this happens due to increase in the element loss for measured results as the loss increases the slope of the phase curve.

Table 3 also enlists the figure of Merit (FOM) for the measured phase curves. Figure of Merit relates the phase gradient with the fractional bandwidth of patch element. It is defined as the ratio of static linear phase range of phase curve and the frequency range for that linear phase region. FOM calculated for different phase curves show that RNP50 shows the maximum FOM of 0.28º/MHz and RCR75 shows the minimum FOM 0.14º/MHz. The results also show that an increase in FOM results in an increase in phase range while at the same time decrease in the bandwidth of the element. Thus a tradeoff is to be adopted between the phase range and the bandwidth of the patch element.

It can be deduced by the results that the proposed paper substrate antenna offer broadband frequency response that can address the bandwidth problem of reflectarray antennas. The reflectarray antenna based on proposed substrate can use usual polyethylene laminations to avoid contamination from harsh environmental conditions. Since the use of thin lamination does not affect the antenna performance at microwave frequencies [17].

6. Conclusion

A design of reflectarray rectangular patch elements based on innovative organic substrate materials is presented. Three differently composed paper substrate materials derived from recycled materials are proposed. The dielectric material characterization results show low dielectric permittivity behavior for the proposed substrates. Results show low dielectric permittivities of 1.81, 1.623 and 1.84 respectively along with dielectric loss of 0.053, 0.048 and 0.057 respectively. Reflectarray unit elements were fabricated over the proposed substrate materials for performance evaluation. The simulated designs were fabricated using an adhesive copper tape and the elements were designed manually. Scattering parameter measurements of the fabricated samples show broadband frequency response and adequate phase range coverage. A comparison of all three proposed substrate materials shows that maximum bandwidth and minimum loss is presented by the substrate material composed of banana fiber and recycled carton paper. The element shows a promising bandwidth of 340 MHz with a phase range of 301 deg. Thus it can be stated that using the proposed innovative dielectric substrate materials the narrow bandwidth constraint of reflectarray antennas can be addressed.

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