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Reflection phase analysis of reflectarray antenna based on paper substrate materials

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Article Info	ABSTRACT

This article presents an analysis of reflection loss and reflection phase behavior of a novel microstrip reflectarray antenna, embedded on paper substrate material. Two different paper substrates were first analyzed for dielectric material properties. A detailed analysis of scattering parameters of rectangular patch element with variable substrate heights has been carried out. Rectangular patch elements fabricated using adhesive copper tape over the paper substrate, show that a wide bandwidth is achieved compared to available conventional substrate materials. Fabricated patch elements over paper substrate material show a broadband frequency response of 340 and 290 MHz. It has also been demonstrated that the measured reflection phase ranges for both the substrate cover 310º and 294º at low phase gradients of 0.12 and 0.24 º/MHz respectively.

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1.   INTRODUCTION

High gain reflector antennas are a crucial component of long range communication systems, where performance depends upon the frequency, coverage and operational flexibility. Reflectarray antennas combine the key features of reflectors and array antennas, where an array of printed microstrip patches on a thin dielectric medium is illuminated spatially by a feed horn. The printed elements use a suitable phasing technique in order to focus the incident wave towards the desired direction [1]. However the major consideration of microstrip reflectarray antenna is the intrinsic narrow bandwidth. A microstrip patch antenna backed by a ground plane can achieve bandwidth of 3-5 % only [2]. In order to address the issue of bandwidth, reflectarray antenna with multilayer structures have been proposed for printed elements [3-5]. Multiple layers of printed elements are stacked one above the other and the whole assembly is backed by a ground plane. However multilayer structure was reported to offer various fabrication challenges related to layers alignment and adjustments. Increasing the substrate thickness of printed array does improve the bandwidth but it reduces the reflection phase range. The reflection phase range from every element is desired to achieve 360 deg, in order to avoid phase errors due to fabrication tolerances [6-8].

The slope of the phase curve and the bandwidth are closely related to each other. A gradual slope offers a wider bandwidth response compared to a rapidly rising phase curve. Moreover an inverse relationship exists between the phase range and the bandwidth of reflectarray elements. Increasing the phase range results in bandwidth reduction and vice versa. Addressing the above stated key limitations of reflectarray antennas of low bandwidth and narrow phase range, different single layer elements have also been proposed. Split ring square, concentric ring Malta cross and phoenix element and with improved phase range and improved bandwidth has been proposed [9-11]. Although an appropriate phasing technique has

been proposed that improves the phase range and phase sensitivity, however the bandwidth does not improves considerably. The bandwidth still depends mainly on the substrate height and the dielectric material properties.

This paper presents the phase range and bandwidth analysis of novel combination of cellulose based paper substrate material and reflectarray antenna. Paper substrate materials with controlled material composition have been characterized for dielectric permittivities and dissipation factors. Using a numerical analysis technique based on FIM reflection phase analysis for different substrate heights has been carried out. In the end rectangular patch elements were fabricated over the paper substrates and tested for their scattering parameters.

2.   DIELECTRIC MATERIAL CHARACTERIZATION

The proposed paper substrate materials were first characterized for the dielectric properties. A Speag DAK 3.5 probe was used for this purpose to analyze the material properties at X-band frequency range. In order to obtain reliable characterization results, layers of paper substrate were glued together and passed through drying process to reduce moisture content. Figure 1 shows the complete material characterization setup. Figure 1(a) shows the paper substrate materials with commercially available substrate such as FR-4 and Rogers Duroid 5880. Figure 1 (b) shows the material characterization setup where the probe is attached to a Rodhe and Schwarz 14 GHz vector network analyzer (VNA). The permittivity and dissipation factor data is handled by software platform. Figure 1(c) shows the placing of paper substrate samples under the dielectric probe The VNA is controlled remotely by the software platform installed on the laptop.

The characterization results for both the paper substrate samples (named S1: sample 1 and S2: sample 2) are presented in Figure 2. S1 substrate material shows a dielectric permittivity of 1.68 with a loss tangent of 0.074 while S2 type substrate material shows a dielectric constant of 1.74 at a dissipation factor of 0.082. Figure 2 and Figure 3 shows the permittivity and the loss tangent values of both substrates. Both the plots of loss tangent and the relative permittivity show minor variation of permittivity and loss tangent over the band of internets.

(a)   (b)   (c)
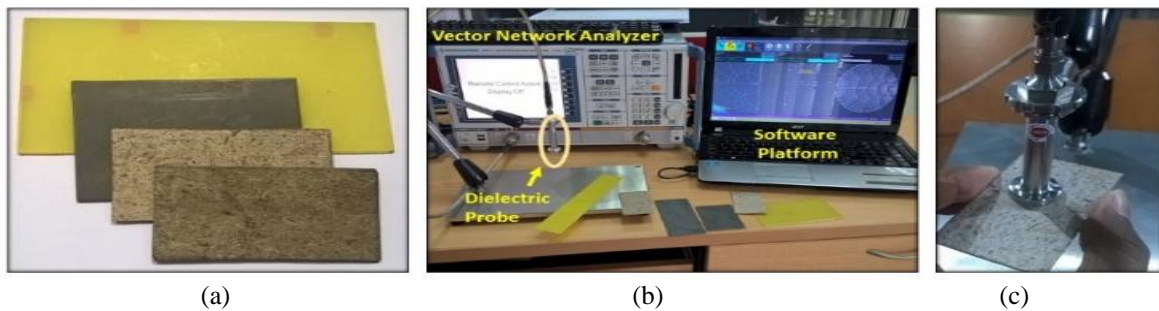
Figure. 1. Material characterization of paper substrate (a) Different types of substrate materials
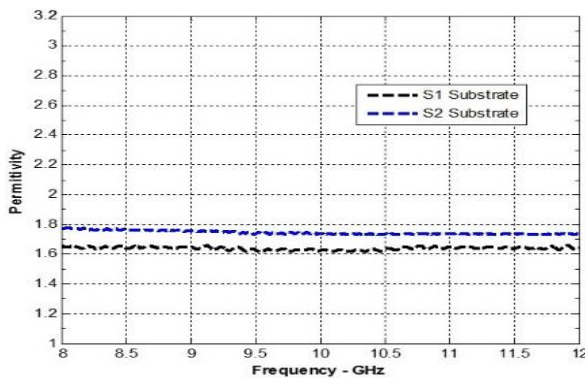(b) Material characterization Setup (c) Paper substrate material under analysis

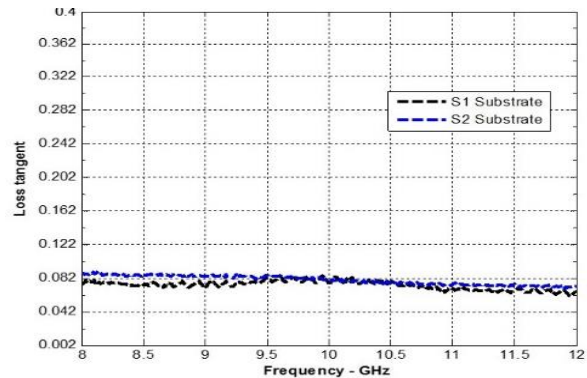Figure 2. Relative permittivity results for material   Figure 3. Loss tangent results for dielectric material
characterization   characterization

Table 1 summarizes the values of material characterization parameters for S1 and S2 substrate materials.The permittivity and the loss tangent values are the mean values over the X-band operation. Both samples were having different substrate heights as mentioned in the Table 1. S1 and S2 substrates were made with the substrate heights of 1.40 and 2.30 mm respectively.

Table 1. Paper Substrate Material Characterization

Material	ε_r	tanδ	Thickness (mm)
S1	1.68	0.074	1.40
S2	1.74	0.082	2.30

3. EFFECT OF SUBSTRATE HEIGHT ON SCATTERING PARAMETERS

Effect of substrate height over the scattering parameters for the proposed reflectarray elements was monitored on proposed paper substrate materials. Single element designs with four different substrate heights were simulated with periodic boundary conditions using CST MWSv15, in order to monitor the reflection loss and the reflection phase range of the elements. Figure 4 shows the simulation results of reflection loss for variable heights of substrate thicknesses. The resonance of the simulated elements were in X-band of operation. With an increase in the substrate height the resonance effect moves towards lower frequencies. For S1 substrate material Figure. 4, as the thickness is increased from 0.8 to 2.30 mm the resonance of the patch element moves from 9.40 to 8.11 GHz. The increase in loss is due to high electric field concentration in the dielectric region between the patch and ground at the resonance [12]. This is also evident from the reflection loss values. The loss decreases from -17 dB to -4.0 dB with substrate increase from 0.8 to 2.30 mm. Similarly for S2 substrate material as rectangular patch element with variable substrate heights were simulated. Figure 5 shows the reflection loss curves of the patch element as the substrate height is increased from 0.8 to 2.30 mm. A frequency drift of 1.34 GHz can be seen as the substrate height is increased from 0.8 to 2.30 mm. Moreover the reflection loss also decreases significantly with from -14.5 to -3.37 dB.
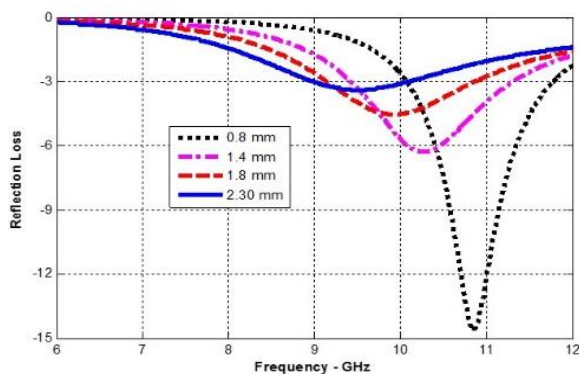

Figure 4. Effect of substrate height over the reflection loss for S1 substrate material
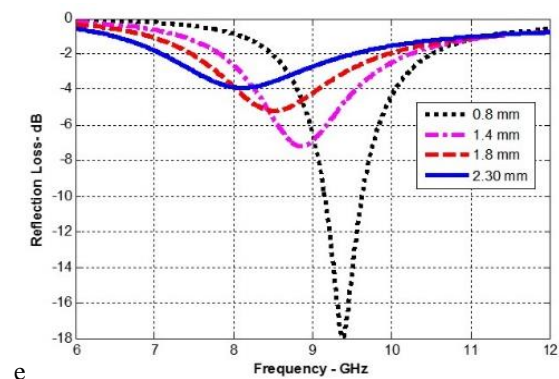
Figure 5. Effect of substrate height over the reflection loss for S2 substrate material

In the design of the reflectarray antennas a wide phase range coverage of 360 degree is desired. A wide phase range coverage is required in order to avoid the phase errors caused due to the fabrication tolerances and etching limitations.

Figure 6 show the reflection phase results of four different substrate heights from 0.8 – 2.30 mm. The reflection phases have been simulated for both types of proposed substrate materials and the analysis has been carried out for X-band operation. Figure 6 shows the reflection phase curves for S1 substrate. The gradient of the reflection phase curves decreases from 0.58 to 0.09 deg/MHz as the substrate height is increased from 0.8 to 2.30 mm. Moreover it can be seen from the range of the phase curves that with the increase in the substrate height the phase range is sacrificed. The phase range reduces from 305 to 125 deg as the substrate thickness is increased from 0.8 to 2.30 mm. Similar trend was noticed in the case of S2 substrate material Figure 7 in which the reflection phase range decreases from 292 to 190 deg when the substrate height is increased from 0.8 to 2.30 mm. Table 2 presents a comparison of important parameters on substrate height analysis.
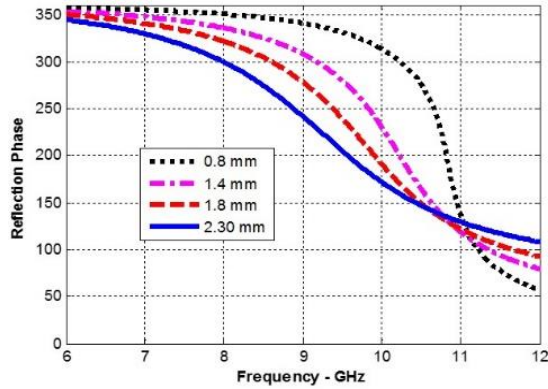
Figure 6. Effect of substrate height on the reflection phase of S1 substrate material
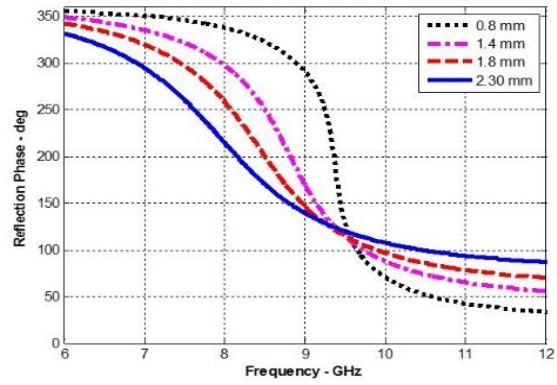
Figure 7. Effect of substrate height variation on the reflection phase of S2 substrate material

Table 2 presents a detailed summary of the effect of substrate height on scattering parameters. It can be seen that the increase in the substrate height increases the bandwidth of the element. The 10% bandwidth is defined by moving 10 % above the maximum reflection loss level. The simulated comparison depicts that bandwidth can be increased from 144 to 790 MHz as the substrate height is increased from 0.8 to 2.30 mm for S1 substrate. Similarly the bandwidth for S2 substrate also increases from 224 to 984 MHz, by the increasing the substrate height from 0.8 to 2.30 mm. This increase in the bandwidth comes at the cost of reflection phase range. So a trade-off is to be made in the design of reflectarray between the phase range and bandwidth to acquire fruitful results.

Table 2. Effect of Substrate Height Over the Scattering Parameters

Substrate S1 (mm)	f_r GHz	RL dB	Δf MHz	ΔΦ Deg	FOM Deg/MHz
0.80	9.40	-17.9	144	305	0.58
1.40	8.86	-7.20	488	241	0.16
1.80	8.52	-5.19	664	141	0.12
2.30	8.11	-3.90	790	125	0.09
Substrate S2	f_r	RL	Δf	ΔΦ	FOM
0.8	10.84	-14.5	224	292	0.34
1.40	10.30	-6.31	609	254	0.13
1.80	9.92	-4.53	815	227	0.09
2.30	9.50	-3.37	982	190	0.07

In order to analyze the reflection phase gradient of phase curves a Figure of Merit (FOM) has been defined for comparison. The FOM is stated as:

$$FOM = \frac{\Delta \varphi}{\Delta f}$$

Where Δφ the static phase is range of the phase curve and Δf is the frequency change during the linear region of static phase. It can be seen that increase in substrate height from 0.8 to 2.30 mm results in decrease of FOM from 0.58 to 0.09 for S1 substrate. A FOM of 0.58 and 0.34 deg/ MHz was achieve for S1 and S2 substrate material respectively at 0.8 mm substrate thickness. This shows that S1 type substrate material will offers an element design more vulnerable to fabrication tolerance and phase errors compared to S2 substrate that offer a lower FOM.

4. FABRICATION AND MEASUREMENTS

In order to validate a paper substrate material reflectarray antennas. Unit cell of rectangular patch elements were fabricated on both S1 and S2 substrate materials. In order to obtain better conductivity performance a 70 μm adhesive thick copper tape was used for the fabrication of patch elements. The copper tape offers the conductivity of bulk copper i.e. 5.8 x107 S/m. The elements were tested for the scattering

parameters using a tapered open ended X-band waveguide. The perfect electric and magnetic boundaries of the waveguide realise the effect of an infinite array of reflectarray elements [13]. Multiple elements were fabricated to ensure repeatability of the results.

Figure 8 shows the fabricated samples and the measurement setup. Figure 8(a) and 8(b) show the fabricated rectangular patch elements on S1 and S2 substrates respectively. Figure 8(c) shows the aperture of the waveguide simulator where the elements are placed for measurements. The typical X-band Agilent adopter attached to the tapered waveguide has been shown in Figure 8(d). The complete measurement setup of the reflectarray has been shown in Figure 8(e) where the waveguide is attached to vector network analyzer and the elements were placed in the waveguide aperture for scattering parameter measurements.
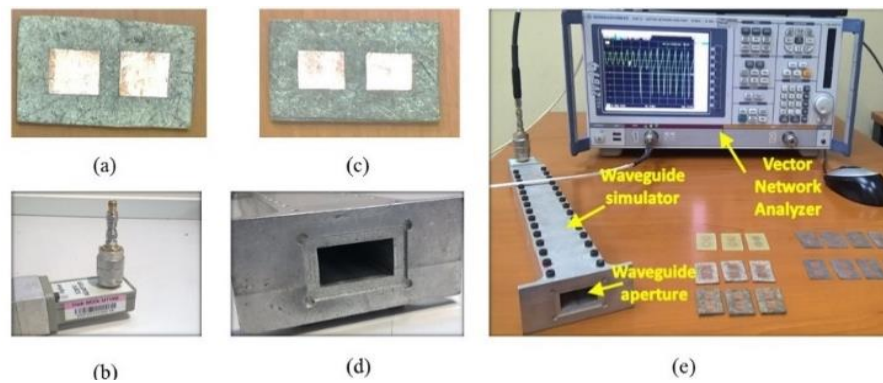

Figure 8. Measurement setup (a) S2 sample (b) S1 sample (c) Aperture of X-band waveguide simulator (d) An X-band adapter for waveguide (e) Complete measurement setup with VNA attached to waveguide simulator

5. RESULTS AND ANALYSIS

A comparison between measured and simulated results has been presented for the validation of proposed paper substrate material. Reflection phase and loss were measured for each of the reflectarray elements. Figure 9 and Figure 10 show the comparison between measured and simulated results. A summary on comparison between measured and simulated results is tabulated in Table 3. As shown in Table 3, substrates S1 and S2 are shown to offer 340 and 290 MHz measured 10% bandwidth respectively. Moreover the measured phase range for both the substrate materials is 310 and 294 deg respectively. The measure phase range is observed to be greater than simulated range due to increase in loss for measured results.
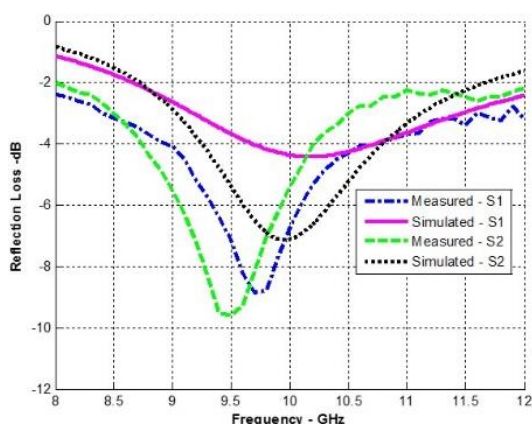

Figure 9. Comparison between measured and simulated reflection loss curves for paper substrates
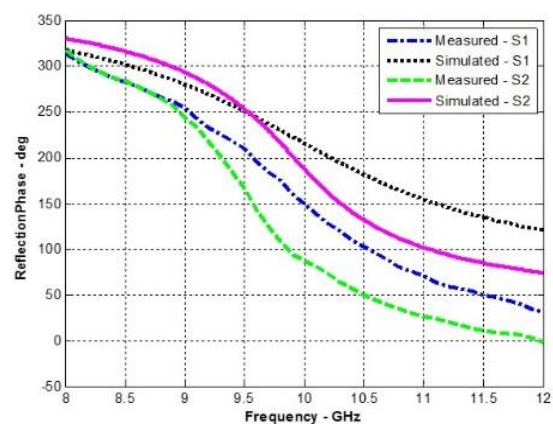
Figure 10. Comparison between measured and simulated results for S1 and S2 substrates

Table 3. Comparison between Measured and Simulated Results

Material	f_r GHz	RL dB	Δf MHz	$\Delta\Phi$ deg	FOM deg/MHz
S1					
Simulated	9.96	-7.17	580	275	0.07
Measured	9.51	-9.60	340	310	0.12
S2					
Simulated	10.18	-4.41	680	220	0.14
Measured	9.68	-8.85	290	294	0.24

The results shown in Table 3 demonstrate a deviation of resonance frequency for both the designs fabricated on S1 and S2 substrates. In the case of both the substrates the deviation is 5% of the simulated resonance. This anomaly might be due to imprecise fabrication process. Moreover the results depicted in Table 3 show that the measured reflection phase shows a good phase range along with an efficient 10% bandwidth. The FOM values calculated for the measured and simulated results show a good agreement. S1 substrate shows an FOM of 0.12 while S2 substrate shows an FOM of 0.24. This shows that the antenna fabricated over S2 substrate material will be twice more vulnerable to phase errors caused by fabrication limitations, as compared to S1 substrate material. The proposed substrate materials present excellent measured bandwidths compared to conventional materials. However in order to allow the long term operation of paper substrate material under harsh environmental conditions, proper laminations and shielding or radomes must be used. Effects of thin transparent lamination on microstrip patch antenna has been analyzed in literature [14]. Thin polythene laminations do not affect the radiation characteristics of microstrip antenna.

6. CONCLUSION

This work presents a novel solution to intrinsic narrow bandwidth problem of microstrip reflectarray antenna. Two differently composed organic substrate material based on recycled materials have been proposed and analyzed for their electric parameters and dissipation factors. The proposed materials show dielectric permittivities of 1.68 and 1.74 with loss tangents of 0.072 and 0.082. Detailed analysis of rectangular microstrip patches on both substrate materials with variable substrate heights has been carried out, monitoring the phase, reflection loss, bandwidth and FOM of the scattering parameters. The simulated results show that the reflection phase range and the defined FOM increases with the decreased in the substrate height. Measured results demonstrate a broadband frequency behavior for both substrate materials. The measured samples show bandwidths of 340 and 290 MHz with low phase gradients of 0.12 and 0.24 deg/MHz. Thus offering excellent bandwidth figures to overcome the narrow bandwidth issue of microstrip patch reflectarray antenna.

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