PATCH ANTENNAS ON COMPOSITE PRINTED CIRCUIT BOARDS FOR SPACE APPLICATIONS

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ABSTRACT

This work investigates microstrip patch antennas on composite printed circuit boards in terms of their radiating performance, manufacturing techniques and tolerances, structural and thermal properties. The objective is to validate that the designs are capable of offering stable performance, whilst providing high structural strength with low mass. The results are compared with the ones on conventional builds, and have demonstrated attractive features that are rather suitable for applications in space.

1 INTRODUCTION

Microstrip patch antennas are commonly used in space applications. They are typically fabricated on fibre-glass reinforced resin (FR) or polytetrafluoroethylene (PTFE) -based laminates using standard printed circuit board (PCB) process. Reinforcements with higher relative permittivity (ε_r) are usually needed to offer adequate mechanical strength as rigid laminates. This degrades radiation efficiency of patch antennas due to the fact that less fringing fields can be coupled to free space. The use of low-ε_r materials may be unavoidable for applications, especially when antenna designs with either high gain or broadband are required. Nevertheless, low-ε_r materials are, in many cases, soft and structurally weak, and may deform when bonded into PCBs, resulting in lower tolerance and higher risk of failure. The composite PCB is therefore introduced to address the trade-offs to ensure an efficient design with high structural strength.

One reliable configuration is the integration of *Nomex* honeycomb and PCBs. The *Nomex* honeycomb is made of resin-infused fibre papers, and formed into honeycomb structures. Given the mechanical requirements, cavities of the structure can be either filled with resin, or left as hollow with air when bonded with other reinforcements. Patterns can be deposited on standard PCBs for planar designs, or flexible ones for conformal structures. Antenna design requirements, such as miniaturisation, bandwidth enhancement, gain improvement, polarisation control, multi-band techniques, mutual coupling reduction, can be achieved and implemented using the proposed configuration. The antenna can be readily integrated with 3D conformal structures, such as radomes, polarisers and high-impedance surfaces into a single module for various requirements and applications.

In this work, a series of microstrip patch antennas for small satellite platforms are fabricated on both PTFE laminates and the proposed composite configuration using air-filled honeycomb and flexible PCBs to investigate their properties. Analysis and designs of patch antennas on composite PCBs are given, followed by their applications of miniaturisation techniques. The proposed designs are considerably lightweight, yet providing rigidity and good thermal stability. The measured results of both builds are compared, and improvements noted have shown that the proposed configuration is found to be rather suitable for the application.

2 PATCH ANTENNAS ON COMPOSITE PCBS

Planar antennas are widely used in high-performance aircraft, missile, spacecraft and satellite systems, where size, weight, cost, performance, ease of installation and aerodynamic profile are constraints. Antennas of this type are low profile, being conformable to planar and non-planar surfaces, simple and cost-effective to manufacture using standard PCB technology. With suitable selection of dielectric materials and configurations, they are mechanically rigid when mounted on the surfaces of structures, whilst offering capabilities of incorporating various techniques to achieve system requirements. These antennas are conventionally fabricated on homogeneous dielectric materials, such as fibre-glass reinforced (FR) or polytetrafluoroethylene (PTFE) with different types of reinforcements for various design constraints and operating environments. FR-based materials typically have a relative permittivity (ε_r) of 4.0-4.8, which is relatively high for antenna applications. Despite some techniques can be utilised to minimise its effect to the performance of the antenna, high dielectric loss tangent (tanδ), typically ranged at 0.01-0.03 at 1MHz, degrades the efficiency, and limits its use at lower microwave frequencies up to about 3GHz, especially on cost-driven products. On the other hand, PTFE-based materials have a lower ε_r of 2.1-2.5 with low tanδ of 0.0009-0.0011 at 10GHz, which lends themselves suitable for performance-oriented systems, particularly at mm-wave frequencies. In avionic integrations and assemblies, a common issue found on both material families is their mass, which may become a problem on large and highly integrated platforms. Such constraint has encouraged research and development of advanced composite hybrids that shall be lightweight, being suitable for conformal antenna designs whilst providing design flexibilities and integration capabilities.

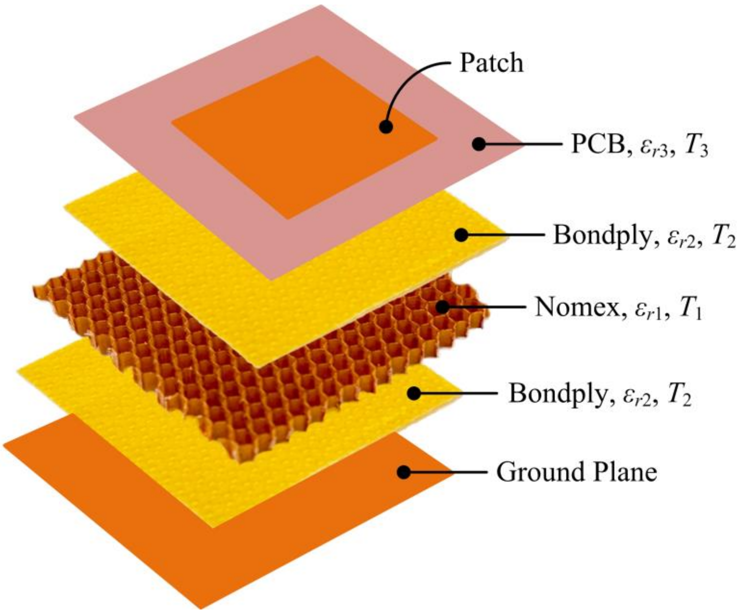

Figure 1. Configuration of Composite PCBs

The configuration of the proposed composite PCB is shown in Figure 1, which consists of multilayer dielectric materials forming an inhomogeneous medium for the antenna. Conductive patterns of designs are fabricated on either flexible or rigid copper-deposited PCBs that are bonded on to low-ε_r materials, such as *Nomex* honeycombs or foams, to generate more radiating fields from the edges of the patch for higher gain and better efficiency. Properties and types of bonding adhesives, such as thickness, electrical and thermal properties, shall be optimally selected to fulfill different requirements. Typically, thermoplastic bond plies have lower ε_r, ranged at 2.5-3.0, which are used for antenna applications to match that of PCB underneath the patch in low-power systems with low heat dissipation. On the other hand, thermosetting pre-impregnated (prepreg) materials have a higher ε_r, typically ranged at 3.8-4.2, which is a kind of composite material synthesised by resin compounds and reinforcements to generate better mechanical rigidity and thermal stability. In this work, *Nomex* is selected to ensure mechanical rigidity and minimum radio frequency (RF) losses. It is bonded by thermosetting prepreg layers of a suitable thickness to generate adequate bond with negligible effects to the performance of the antenna at its operating frequencies.

Design equations for microstrip patch antennas on single-layer homogeneous dielectric can be found in [1], which are considered to be applicable for the patch on inhomogeneous dielectric medium, given that its effective dielectric constant (ε_{eff}) is known. The Lichtenecker's logarithmic mixture law [2] is reviewed and modified for this application to calculate the ε_{eff} of multilayer inhomogeneous dielectric mediums with different electrical properties, given the thickness of each layer with infinite extent. The equation is expressed as

$$\varepsilon_{eff} = \sum_{n=1}^{N} \varepsilon_{r,n} \alpha_n \tag{1}$$

and

$$\alpha_n = \frac{T_n}{\sum_{m=1}^{N} T_m} \tag{2}$$

where $\varepsilon_{r,n}$ is the relative permittivity given by the material suppliers, T_n is the thickness, and the factor α_n is defined as the volume fraction, of the *n*-th layer. Eq. (1)-(2) are used in conjunction with the design equations of the patch to obtain its initial dimensions for full-wave analysis and optimisations. The calculated resonance of the patch using this design procedure is found to have a tolerance within ±0.4% in compared with measurements.

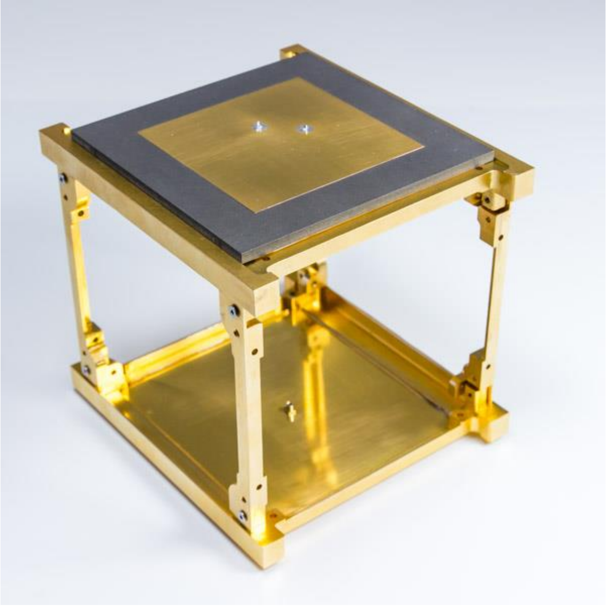

Figure 2. Patch antenna of PTFE build

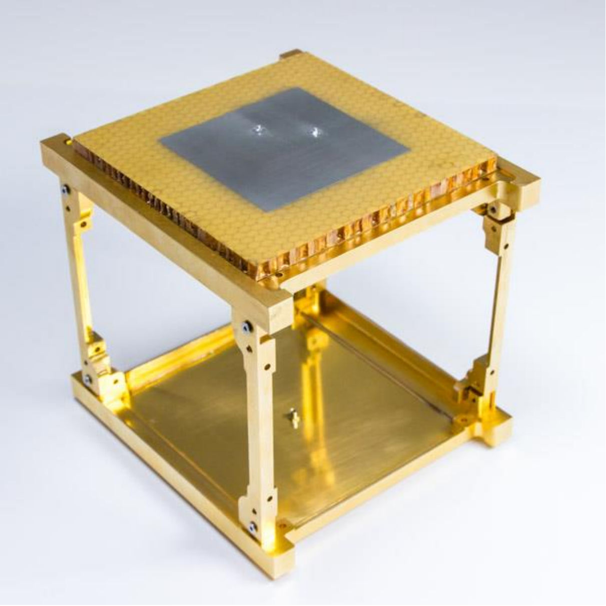

Figure 3. Patch antenna of *Nomex* build

Two microstrip patches operating at *S*-band are fabricated and tested, and their results are compared. One patch is fabricated on double-sided *Rogers RT/Duroid 5880* with ε_r = 2.2, tanδ = 0.0009 at 10GHz, and thickness of 3.175mm with 1/2oz copper cladding and through-hole plated for the connections of pins and connectors. The other patch is fabricated on the proposed composite PCB. The patch and ground plane are fabricated on two double-sided rigid *Arlon 85N* with ε_r = 4.0, tanδ = 0.01 at 1GHz, and thickness of 0.127mm with 1/2oz copper cladding. The fabricated PCBs are bonded on to 5mm *Nomex* honeycomb with ε_r = 1.021, tanδ = 0.0004 at 1GHz, using two 0.06mm prepreg sheets of *Arlon 84N* with ε_r = 4.0, tanδ = 0.01 at 1GHz. The calculated ε_{eff} of the proposed configuration using Eq. (1)-(2) is 1.12. It should be noted that there are two orthogonal ports connected to the patch to measure the coupling in between, which allows investigations on mutual interference when used for dual polarisation, and axial ratio level when operating in the mode of circular polarisation (CP).

Table 1 summarises measured parameters of the two patch antennas at 2200MHz. It is found that the *Nomex* build provides wider usable bandwidth than the PTFE build, thanks to a low-ε_r medium underneath the patch, which also contributes to the increase of boresight gain and a narrower beamwidth as shown in Figure 4. Measured front-to-back ratio (FBR) of both builds are 30dB, which is achieved by slots loaded on the ground plane underneath the patch to effectively neutralise the reactance of the induced current along the edges, generating zero-phase condition, and therefore minimising fields scattered to free space. The most attractive feature of the proposed build is a significant reduction on its mass, which is only 20% of the mass of the PTFE build, and indicates a saving of about five times on launching costs, especially when used in large array systems.

Table 1. Comparison of patch antenna on different builds

Build	Frequency [MHz]	BW [MHz]	Gain [dBi]	Size [mm]	Mass [g]
NOMEX	2200	70 (SWR<1.5)	8	90 x 90 x 4.5	15
PTFE	2200	35 (SWR<1.5)	7	90 x 90 x 3.2	70

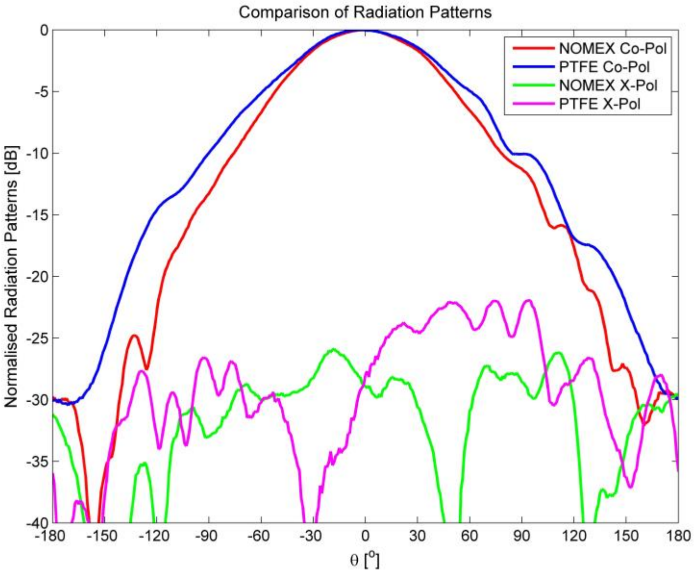

Figure 4. Far-field radiation patterns at 2200MHz of patch antennas on different builds

3 MINIATURISED DUAL-CP PATCH ANTENNA IN SPACE

Grown interests are well noticed on development of advanced antenna technologies for nanosatellite systems. A number of enquiries have been received for non-deployable antenna solutions for missions at *L*-band. Typical requirements are compactness with an antenna size of up to 100mm x 100mm x 6mm, single/multi-/broadband designs depending on missions and fields of applications, circular polarisation, broad beamwidths with intermediate peak gain, simplicity with ease of integration with other electronics, cost-effectiveness and low mass. Conventional PCB laminates, such as FR-4 and PTFE, are normally considered to implement RF specifications whilst being adequately compact to fit in to the given volume. For single-layer patch antenna designs, use of materials with higher ε_r effectively reduces the dimensions of the antenna with trade-offs against radiation efficiency and operable bandwidth. Research activities at *PCL* have been devoted to address such tradeoffs to develop highly efficient designs, yet being compact, lightweight and costcompetitive. One of the solutions is the design of a miniaturised patch antenna on composite PCBs with dual-CP operation at *L*-band. The configuration of a miniaturised design is shown in Figure 5. It is designed and aimed to work at 1264MHz with a 4MHz bandwidth minimum, as well as being able to fit on to a 90mm x 90mm area. The patch and its CP feed are fabricated on two 0.1mm *Pyralux AP* flexible laminates with ε_r = 3.4, tanδ = 0.003 at 1MHz, and bonded with a 4.8mm *Nomex* sheet using two 0.06mm *Isola 370HR* prepregs with ε_r = 4.17, tanδ = 0.0161 at 1GHz. The calculated ε_{eff} is 1.102 using Eq. (1)-(2). The materials are selected so as to ensure a reliable bond, as well as offering a low ε_{eff} medium for the patch to radiate efficiently. An array of holes are punched on the surface of the patch to survive over a considerable temperature and pressure changes through launching and operate successfully in space.

A patch antenna on a 5.1-mm homogeneous dielectric medium of ε_r = 1.102 at 1264MHz needs a resonant length of about 110mm, being too large to fit in for nanosatellite platforms. Therefore, suitable miniaturisation techniques, reviewed in [3], are needed to reduce the size of the patch. Among those available techniques for patch antennas in conjunction with considerations of design constraints whilst achieving the required RF performance, a slot-loaded ground plane is adopted. Slots cut on the ground plane introduce a loading effect that not only provides flexibility to precisely control the mutual resonance with the radiating patch of a fixed dimension to operate at the required frequency, but also neutralises the reactance due to the open effect from surface waves to minimise backward radiation.

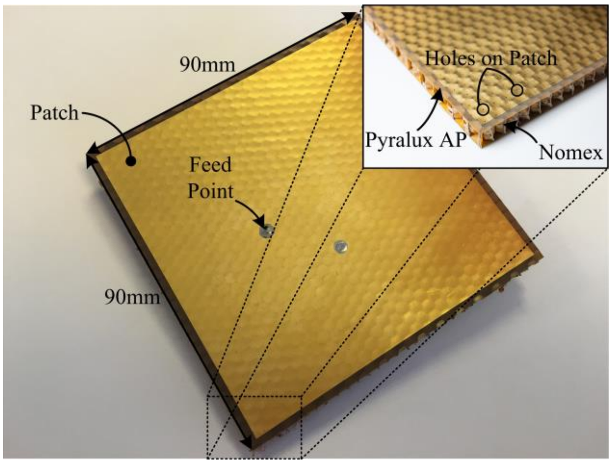

Figure 5. Top view of the antenna

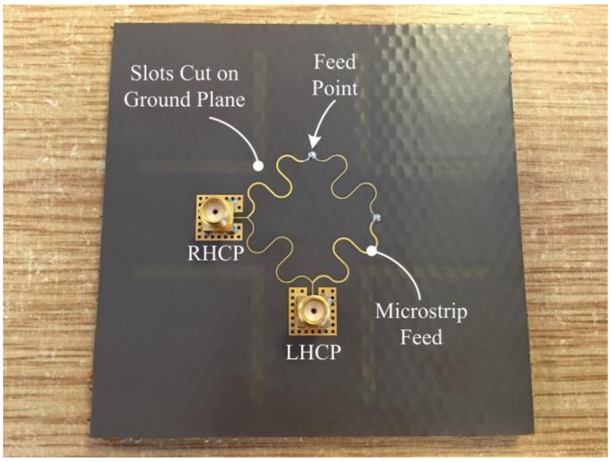

Figure 6. Bottom view of the antenna

Table 2. Measured parameters of the proposed antenna

Frequency [MHz]	BW [MHz]	Peak Gain [dBic]	HPBW [deg.]	ARBW [deg.]	FBR [dB]	Size [mm]	Mass [g]
1264	20 (SWR<1.5)	3.8	90	100-150	13	90 x 90 x 5.1	10

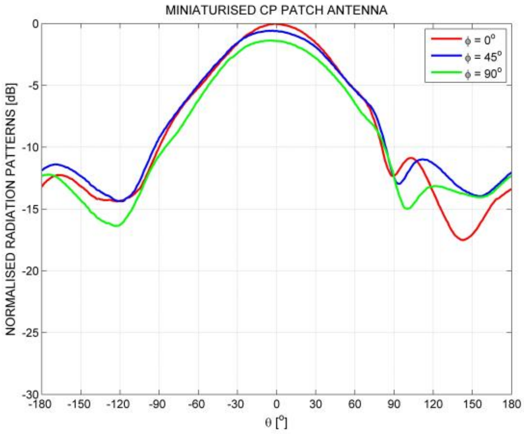

Figure 7. Radiation patterns of the antenna

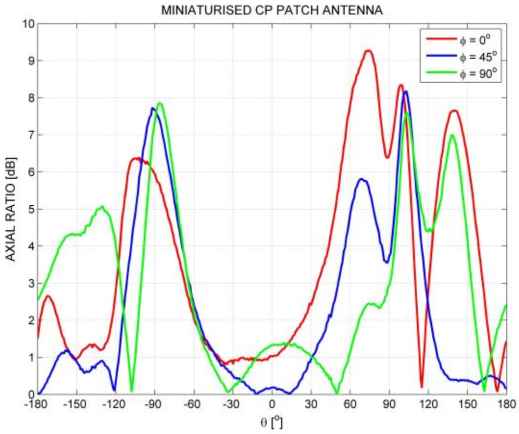

Figure 8. Axial ratio patterns of the antenna

The proposed design are characterised and tested, and key results are summarised in Table 2. The patch is fed by two pins located orthogonally with an optimized distance from its centre so that minimum VSWR is obtained at 1264MHz with an usable bandwidth (VSWR < 1.5:1) of 20MHz. As shown in Figure 6, the pins are soldered on to a feeding network fabricated at the bottom side of the antenna. The incoming signal is loaded and split on to the two branches with a phase shift of 90 degrees to each other to the patch on top, implementing the sequential rotation technique [4-6] to generate circularly polarised waves in either left-handed (LHCP) or right-handed (RHCP) manner. The measured half-power beamwidth (HPBW) is 90 degrees with FBR of less than 13dB, as shown in Figure 7. The measured axial ratio beamwidth (ARBW), as results shown in Figure 8, is more than 100 degrees. In conjunction with a low boresight axial ratio (< 1.5dB) over the operable bandwidth, the antenna is able to generate high-quality CP that lends itself rather suitable for the said application.

4 CONCLUSION

Designs and analysis of patch antennas on composite PCBs are proved to be doable to deliver outstanding RF performance over conventional builds. They can be fabricated on flat panels, as well as being able to be formed into shapes onto non-planar structures. They are thermally stable and structurally strong, yet extremely lightweight. They can be manufactured using standard PCB processes, therefore being rather cost-effective, and allow flexible selection on different categories of laminates and associated plies. Flexible materials can be used for conformal designs, as well as a solution to deployable antenna arrays. The proposed configuration has effectively established an alternative route for antenna engineering. Research work will be carried on, and focusing on advancement of such technology toward high-performance antenna designs.

5 ACKNOWLEDGEMENT

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