Characterization of a New, Low Cost Composite Substrate Material

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Abstract — **A new polypropylene and nano-clay powder composite material is investigated for use as an economic planar antenna substrate. Dielectric constant, loss tangent, and thermal properties have been examined. The results show that the dielectric properties are comparable to those of commercial substrate materials.**

I. INTRODUCTION

Patch antennas used in mobile base stations form one of the most expensive system components. Conventional PTFE-glass weave composite used in this application has good performance, but is comparatively expensive. Low cost substrate laminates such as the FR4 glass-epoxy composite are available but are so lossy at RF/microwave frequencies that they cannot be used for this application. For base station efficiency, the dielectric loss must be very low to ensure high radiation efficiency and is a requirement of any new material combined with thermal stability. Good mechanical and processing characteristics are essential for electronic assembly and etching of copper antenna patterns on the new material proposed. The nano-clay addition to the polypropylene facilitates this.

This paper explores a new candidate material for patch antenna applications made from polypropylene filled with a commercially available synthetic nano-clay powder. Polypropylene is a well known thermoplastic semi-crystalline polymer, which has found extensive industrial application. It has a low dielectric constant (ε_r =2.2) and a low loss tangent (0.0003-0.0005 at 1 MHz) and a very high dielectric strength (30-40 kV.mm^{-1}). Its high chemical and water resistance make it suitable for the etching process in circuit fabrication. Its low density is a benefit for reduction of antenna weight. It is much lower in cost compared to PTFE. However, the direct application of polypropylene is limited by its low operating temperature. To overcome this disadvantage, the nano-clay is dispersed into the polypropylene with the overall aim to increase its stiffness, resistance to heat distortion, flammability resistance and to reduce moulding shrinkage. The basic thermal and mechanical properties of the nano-composite are reported elsewhere [1]. In this paper the dielectric characteristics are investigated accurately, using a non-destructive measurement method across the temperature range –50°C to +150°C. The new composite material has been examined both in its solid form and as a laminate combined with pre-treated glass weave. The metallisation of the new laminate has been discussed elsewhere [8,10].

II. EXPERIMENT

A. Material Preparation

A suitable amount of nano-clay powder and polypropylene granules were dry-mixed and melt-compounded using a twin-screw extruder [1]. Once uniformly dispersed but still in molten state, the composite is then hot pressed together with a suitably polymer - coupled glass fibre weave to form a flat rigid substrate. A selection of different weaves have been investigated to find the best option for electrical performance and mechanical stiffness. The proportion of nano-clay used in the mix is important to balance thermal stability of the final modified polymer and the electrical permittivity ε_r and tan δ. The optimum pressing and cooling times have also been optimised from a selection of alternative strategies.

B. Dielectric Characterization

Polypropylene has a low dielectric constant and low loss tangent that demands a highly accurate method for permittivity characterization to achieve acceptable relative errors ($\Delta\varepsilon_r/\varepsilon_r$, $\Delta tan\delta/tan\delta$). Some resonator techniques are not accurate enough, especially for low dielectric constant and low loss materials. Transmission line techniques [2,3,4] are simple methods for broadband characterization. However, the samples have to be exactly machined and the accuracy is less than for resonator methods.

Kent [5] experimentally developed a split resonator method, that is non-destructive with resonator accuracy. It is composed of two cylindrical waveguides with their terminals shorted. The substrate sheet is inserted in the gap between the two cylindrical cavities. The complex permittivity of the substrate is determined from measurement of the resonant frequency and the quality factor of the TE_{011} resonant mode. However, the calculation process for permittivity extraction is complex for this situation because of the open cavity structure.

Kent and Bell [6] proposed an approximate method for calculating the permittivity. Janezic presented a full-wave analysis of the split cylinder resonator [7], including the TE_{011} resonant mode plus evanescent TE_{0n} modes in the cylindrical cavity region. This approach gives a rigorous and well-defined expression for dielectric constant calculation, while including TE_{0n} (n>1) modes causes the permittivity extraction process to be very complicated. Here we use a simplified but accurate calculation equation [8] derived for the TE_{011} mode for extracting relative dielectric constant based on a full wave analysis of the split cylindrical resonator as shown in fig. 1. The machined resonator cavities are shown in fig. 2. Each cavity is excited by a J loop antenna which is then connected to an Agilent 8510B vector network analyser using SMA connectors. A full study of the tolerance issues in this test jig has been reported [10]

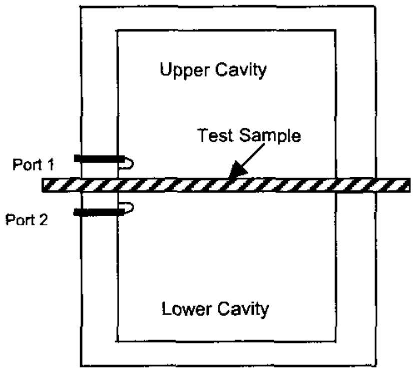

Fig. 1. Split resonator schematic with J loop test ports and nano-clay PP sample between cavities.

Fig. 2. Split resonator cavities illustrating SMA connection to J coupling loop internal

The resonant frequency of the TE_{011} mode and –3 dB bandwidth of the insertion loss can be obtained by measuring the S parameters versus frequency using an Agilent 8510B network analyser. The dielectric constant ε_r can be extracted by considering only the TE_{011} resonant mode from the following equation (1) [8] by a numerical iterative process:

$$\frac{1}{2}\beta_0 \cot \beta_0 L - \left(\frac{\chi_{01}}{a}\right)^2 \int_0^\infty \beta \tan\left(\beta \frac{h}{2}\right) \left[\frac{J_1(\lambda a)}{\lambda^2 - \left(\frac{\chi_{01}}{a}\right)^2}\right]^2 \lambda \, d\lambda = 0 \quad (1)$$

In the above equation:

$$\beta_0^2 = \omega^2 \mu_0 \varepsilon_0 - \left(\frac{\chi_{01}}{a}\right)^2 \quad (2)$$

$$\beta^2 = \omega^2 \mu_0 \varepsilon_0 \varepsilon_r - \lambda^2 \quad (3)$$

In the above equations, J_1 is the first order Bessel function of the first kind, χ_{01} is the first root of $J_1(r) = 0$, which has a value of 3.83171. The λ is the continuous radial eigenvalue. h is the thickness of the sample. The derivation process is omitted because of the limited space [8,10]. The validity of these equations has been demonstrated using the well know closed cavity perturbation method. Ignoring the effects of surface resistance of the cavity and taking account of the effects of coupling loops, loss tangent $\tan\delta$ of the sample can be approximately calculated as follows:

$$\tan \delta = \frac{\Delta f}{f_r}\left(1 + k_1 + k_2\right) \quad (4)$$

Where, k_1 and k_2 are the coupling coefficients of the two coupling loops that can be measured in the experiment [9].

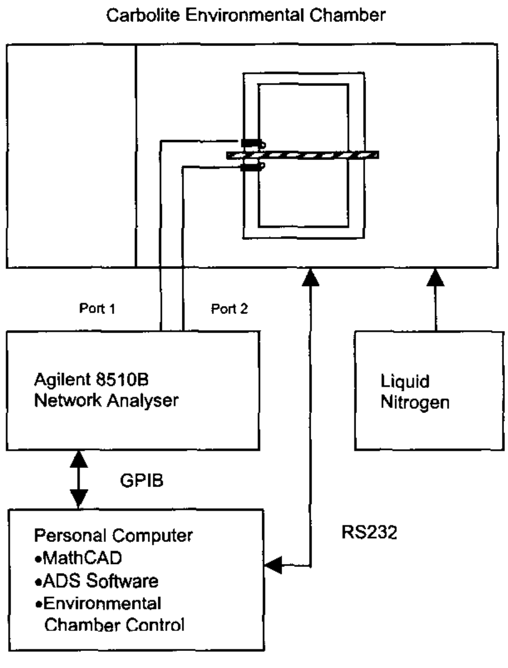

Fig. 3. Schematic for temperature controlled resonant frequency data logging system.

The dielectric properties of the developed composite substrate are measured versus temperature using split cylindrical resonators. The temperature dependence of the dielectric constant and loss tangent are measured by setting the split cylindrical resonator inside a temperature controlled chamber under computer control. This permits a wide range of operation from –50 °C to +200 °C. The automated measurement system is shown in fig. 3. The personal computer simultaneously controls the Agilent 8510B using WinCal™ software and also controls the Carbolite environmental chamber using a proprietary control package through the RS232 port. The resonant frequency of the TE_{011} mode is measured and its associated Q factor extracted. An iterative procedure is then used to compute the permittivity ε_r and tan δ of the substrate material from the measured S parameters of the resonance characteristic. The calibration of the environmental chamber to account for thermal expansion of the test jig was important and provided more accurate

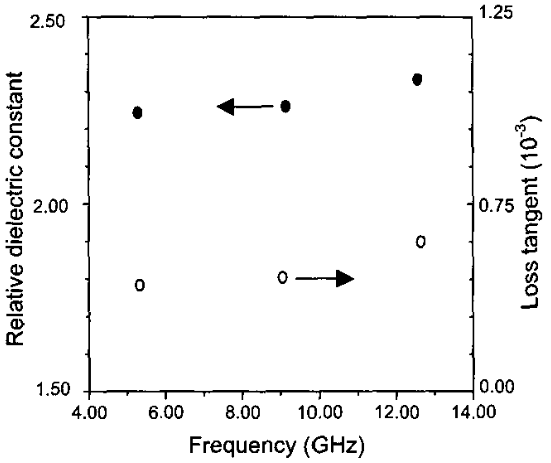

Fig. 4. The measured relative dielectric constant and loss tangent versus frequency using a split cylindrical resonator for the polypropylene nano-composite.

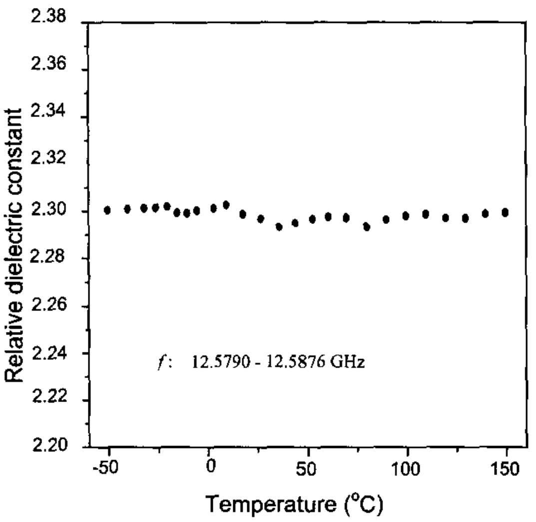

Fig. 5. The dielectric constant versus temperature measured using a split cylindrical resonator for the polypropylene composite.

results across the temperature range under observation.

In all three different cavity sizes were utilised in this work with one cavity being fitted with vernier end plate positioners to enable broadband frequency characteristics to be studied and hence ascertain both permittivity and loss tangent across a frequency range [8].

III. Results and discussion

A Dielectric properties of the substrate

The dielectric constant and loss tangent of the developed material are extracted from equations (1) and (4) when the resonant frequency and −3dB bandwidth of the TE_{011} mode are measured on the curve of S_{21} versus frequency. Fig. 6 shows the relative dielectric constants and loss tangents measured with different sizes of the split cylindrical resonators. It can be seen that the dielectric constant is stable in the frequency range of 5.2–12.6GHz.

Fig. 4 and Fig. 5 show respectively the relative dielectric constant and loss tangent versus temperature. The relative dielectric constant has approximately no change ($\Delta\varepsilon_r < 0.01$) within the temperature range −50 °C to +150 °C. The loss tangent of the substrate does not change significantly versus temperature. This is important for stability of antenna resonance across the working temperature range.

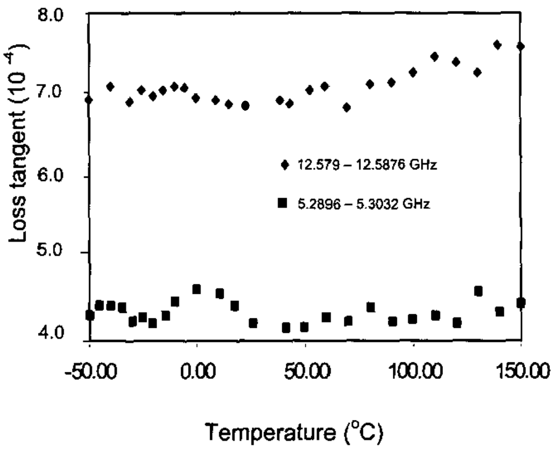

Fig. 6. Loss tangent measured using different sizes of split resonators for the polypropylene nano-composite.

B Operational properties of the substrate

The addition of the nano-clay has stabilised the high temperature properties of the substrate laminate. This has prevented the softening and bowing of polypropylene which occurs above 100 °C. Careful selection of the lamination process has resulted in an antenna substrate of satisfactory planarity for commercial use.

Metallisation of the substrate is still under development. Essentially the pressing and adhesion of copper foil to the nano-clay PP base must be performed quickly using a 'hot-flash' process. This avoids degradation of the base polymer due to long duration exposure to both heat and pressure. An alternative strategy is under consideration using direct write copper.

In this method the antenna pattern is 'printed' onto the substrate using a specially adapted inkjet printer. This has a number of advantages in that (i) there is no subtractive etch pollution problem from waste chemicals, (ii) it is very easy to modify antenna patterns for different applications on a small batch or even single unit basis and (iii) the substrate is not exposed to etching chemicals which is not such a problem for PP as it is very resistant to etching chemistries.

At end of life existing technology will require the destruction and disposal of large areas of PTFE based antennas. Unfortunately PTFE cannot be recycled easily and its destruction requires heating to very high temperatures where it dissociates into very unpleasant chemicals. In contrast the recycling of polypropylene is well known and even with added nano-clay and glass laminate weave this should not present a problem.

Trials have been performed on connecting from feed cables to the nano-clay PP substrate metallisation. This has been tested both with low melting point tin/lead solders and with high melting point tin/silver solders. Due to the new properties of the enhanced PP the maximum solder time for LMP should be restricted to 30 seconds and 20 seconds for HMP. Alternative interconnect strategies using snap connectors are being addressed provided the reliability of the connection can be proven.

IV. Conclusion

A low cost substrate material for patch antenna manufacture is exploited using a nano-clay polypropylene composite. The dielectric characteristics of the new substrate material are determined accurately and non-destructively. The results show that the newly developed substrate has stable dielectric and thermal properties comparable with commercial substrate materials. However, the new substrate material is much cheaper and easier to recycle.

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