Review Article

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Embedment of Carbon Nanotubes in Carbon Fibre Reinforced Polymer for Carrier Plates in Space Payload

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ABSTRACT

Microwaves for space payload are designed for a wide range of microwave frequencies. They are also capable of withstanding the stringent space and launching environments. They provide electrical interfaces between the components in the spacecraft system, ensuring high reliability. The package consists of a number of carrier plates on which the substrates are attached. A carrier plate is used as a metallic carrier to support the alumina substrate on which the microwave circuit is etched. The indigenous development of CFRP-based carrier plates is a possible replacement for the standard Kovar-based carrier plates, to reduce the mass by six times and make them lighter than the existing topology. However, CFRP is having significantly lower conductivity compared to Kovar material. The lower conductivity directly affects the heat dissipation, electromagnetic shielding, current carrying capability and surface treatment process. To overcome these problems and gain a full advantage, Carbon Nanotubes (CNTs), an advanced nano-filler material, can be added to the polymer. The use of CNT composites will not only reduce the weight but improve thermal and electrical parameters. This paper provides a research overview of the enhancement of thermal and electrical properties of CFRP and helps to design microwave package assembly. The challenge is to identify the suitable fabrication technique, process parameters and characterization of the CNT composite.

Keywords: Carbon Fiber Reinforced Polymers; Carbon Nanotube Composites; Carrier Plates; Microwave Package; Space Payload.

1. INTRODUCTION

A microwave package is designed to operate specifically over microwave frequencies of the order of a few GHz, which requires line-of-sight propagation between satellite and ground hardware. These packages are designed to provide enclosure for integrated microwave circuits (MIC) and printed circuit boards (PCB), as shown in Fig. 1. The package consists of substrate-mounted carrier plates, stepped cover and electronic devices which are mounted on the substrate as well as the tray surface; the purpose is to integrate all the components of a sub-system so as to minimize size, mass, complexity and cost. Compartment height, width and length are based on the size of components and their location, types of R.F. connectors, feed-through, substrates and electronics devices. The number of mounting hardware are determined after finalizing the overall size, weight and load. Moreover, the need for microwave packages to withstand stringent launch and space environments is another factor to be considered while designing. These requirements call for high-density assemblies, miniaturization of components and optimization of thermo-mechanical stresses on components.

The integrated microwave circuits (MIC) are engraved on alumina substrate. In a typical carrier plate assembly, an alumina substrate is bonded to a Kovar plate using a solder preform (Fig. 2). The carrier plates are used in different sizes and shapes and the MIC substrates are properly soldered on them. They are firmly secured with the enclosure on their extension, which is known as mounting lugs. Carrier plates are made of Kovar material with high cobalt and nickel content to have a low coefficient of linear thermal extension. Different sizes and various topologies of carrier plates are used for the microwave package, as shown in Fig. 2. The thickness of this carrier plate is 0.8 mm at the functional area (alumina substrate mounting area) and the mounting lugs have a thickness of 1.5 mm. Kovar material is poor in corrosion resistance and hence they are gold-plated in the range of 4 to 6 microns. Gold provides an excellent corrosion resistance due to being noble in nature, good electrical conductivity and good solderability for attaching gold-plated alumina substrate (Vartak *et al.* 2014).

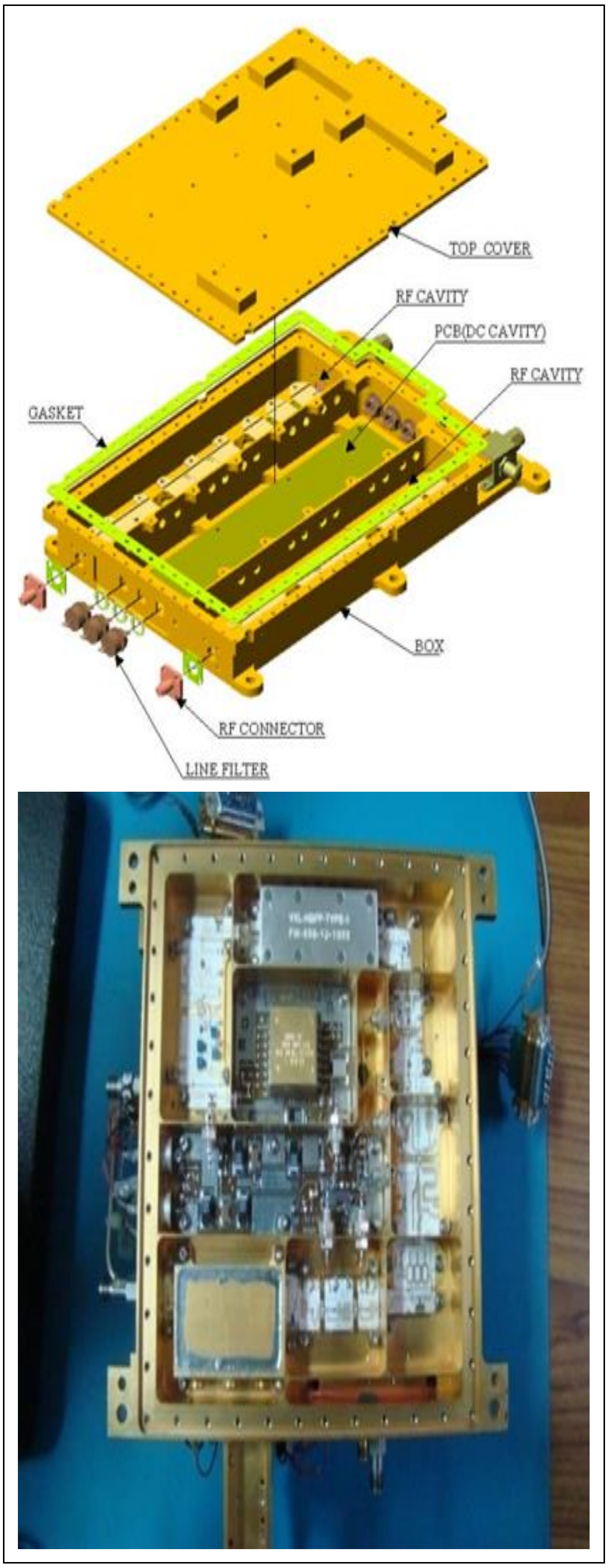

Fig. 1: Microwave electronics package for communication payload

2. CARBON FIBRE REINFORCED POLYMER (CFRP)

Miniaturization and mass reduction are important factors for the space payload systems. For space payload, mass is important since launching a heavier spacecraft is more expensive. The launch cost of the satellite reaches up to Rs. 4000/gram. Even a gram reduction in weight can save thousands of rupees in launching cost; therefore, the use of lightweight materials has always been desirable. Carbon fibres are the strongest fibers, which are used to make composites with plastics, producing Carbon Fiber Reinforced Polymer (CFRP). CFRP has greater prospects and capabilities due to its favorable property of specific stiffness. Therefore, it is proposed as a suitable material for microwave package for space applications.

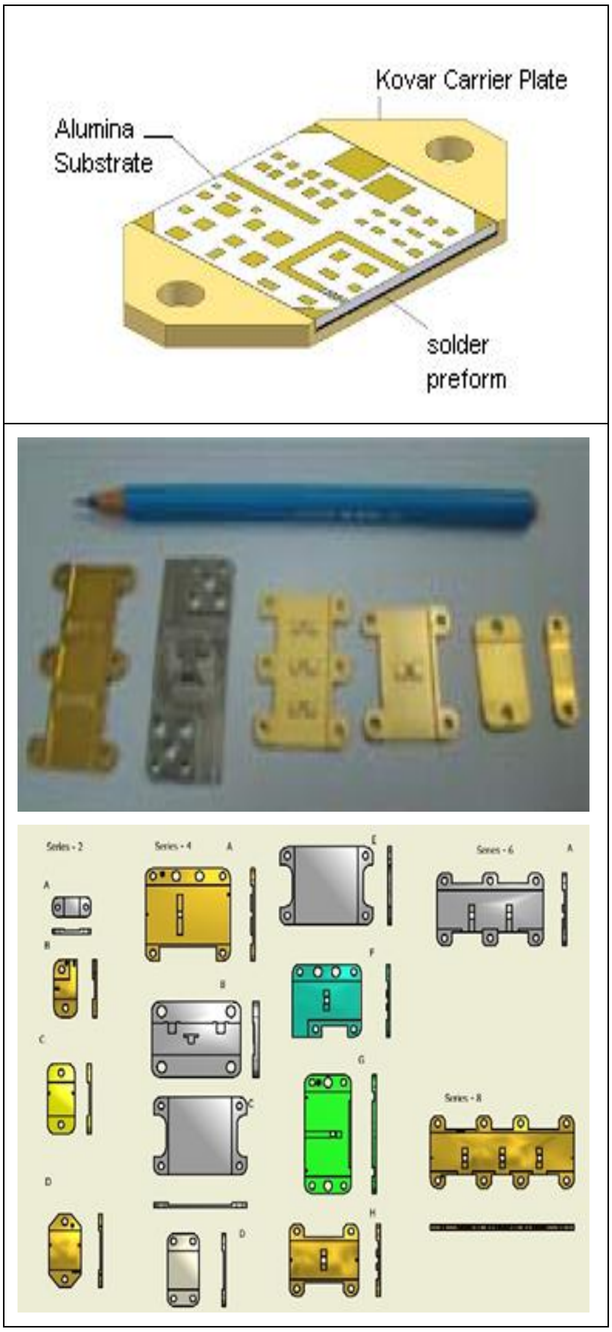

Fig. 2: Different types of carrier plates of microwave electronics package (Vartak *et al.* 2014)

CFRP-based carrier plate is developed for the RF circuits attachment; Gold electroplating (strike) of the carrier plates, Process for substrates attachment, ribbon/wire bond and connector soldering and electrical and environmental tests were already carried out (Singh *et al.* 2018). The development of CFRP carrier plate encompasses all indigenous processes for the same and can be easily reproducible. The added advantage is the faster turnaround time, ease of re-work and enhanced corrosion resistance.

However, one of the disadvantages of CFRP lies in its significantly lower conductivity compared to Kovar. The lower conductivity directly affects the heat transfer, electromagnetic shielding and current-carrying capability and surface treatment process. Moreover transversal (in-depth) conductivity of CFRP is very low because of the laminar epoxy layers. Resin conductivity increases the conductivity of CFRP (Martins *et al.* 2018). A possible solution is to increase the conductivity of the resin by using Carbon Nanotubes (CNTs). CNTs have attractive mechanical, electrical and thermal properties, superior to the 'state-of-art materials' currently being used. In recent years, CNTs are being considered as the most popular filler material for CFRP, owing to its ability in improving electrical conductivity, mechanical and thermal properties of polymer without increasing the weight (Guedes *et al.* 2019; Vartak *et al.* 2020).

3. ENHANCEMENT OF THERMAL AND ELECTRICAL PROPERTIES

Addition of CNT modifies the thermal properties of the polymer matrix favourably; it increases the thermal conductivity, glass transition, melting and thermal decomposition temperatures (Fig. 3). The multi-walled carbon nanotubes (MWCNTs) are found to most significantly improve the thermal conductivity of polymer composites among all CNT types.

Electrical percolation of transitions in the carbon nanotube/epoxy composites occurs at concentrations below 0.1 wt. %, as shown in Fig. 4. There is a decrement in volume and surface resistivity at 0.5 wt. % of CNT (Bal *et al.* 2007). The well-dispersed CNTs can improve electrical conductivity significantly (Zhang *et al.* 2019). Glass transition temperature (T_g) depends on the motion of polymer chains and a free volume in the presence of the CNTs. Addition of CNTs decreases the free volume and hence increases T_g (Table 1).

Table 1. Increase in T_g and reduction the volume resistivity and surface resistance (Roy *et al.* 2018)

Sample	T_g (°C)	Micro hardness (HV)	Volume Resistivity (ohm-cm)	Surface resistance for 1 cm² area (ohm)
Epoxy Pure	77.3	17.2	1.31 x10^{11}	7.1 x 10^{9}
Epoxy-CNT-Raw	95.3	20.8	0.8 x 10^{9}	0.9 x 10^{9}

Moreover, Microwave Packages are made up of Aluminum boxes that can be replaced by pitch-based CFRP-CNT composites. Feasibility studies were carried out to obtain thermally conductive CFRP materials using an out-of-autoclave RTM (Resin transfer moulding) process with demanding characteristics typically obtained in autoclave processes. A mass reduction of 23% may be obtained when compared to an equivalent aluminum housing. MWCNT-CFRP exhibits higher Electro-Magnetic Interference (EMI) Shielding Effectiveness (SE) than AA6061-T6 due to higher absorption and multi-layered structure. EMI SE of -80 dB can be achieved in a wide frequency band with the incorporation of 0.2 wt. % of MWCNTs in CFRP (Tariq *et al.* 2017) (Fig. 5a). EMI shielding is a significantly important property for MIC packages. Electrical conductivity significantly increases with CNT loading as shown in Fig. 5b.

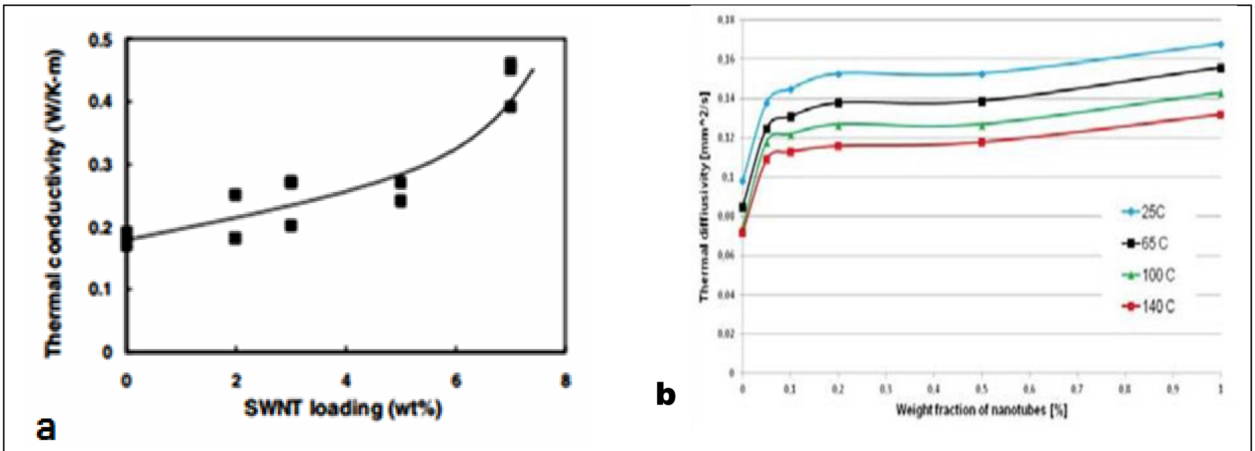

Fig. 3: (a) Thermal conductivity vs. single-walled carbon nanotube loading (Du *et al.* 2006) and (b) thermal diffusivity vs. weight fraction of carbon nanotubes with different temperature (Ciecierska *et al.* 2014)(*Ewelina Ciecierska*)

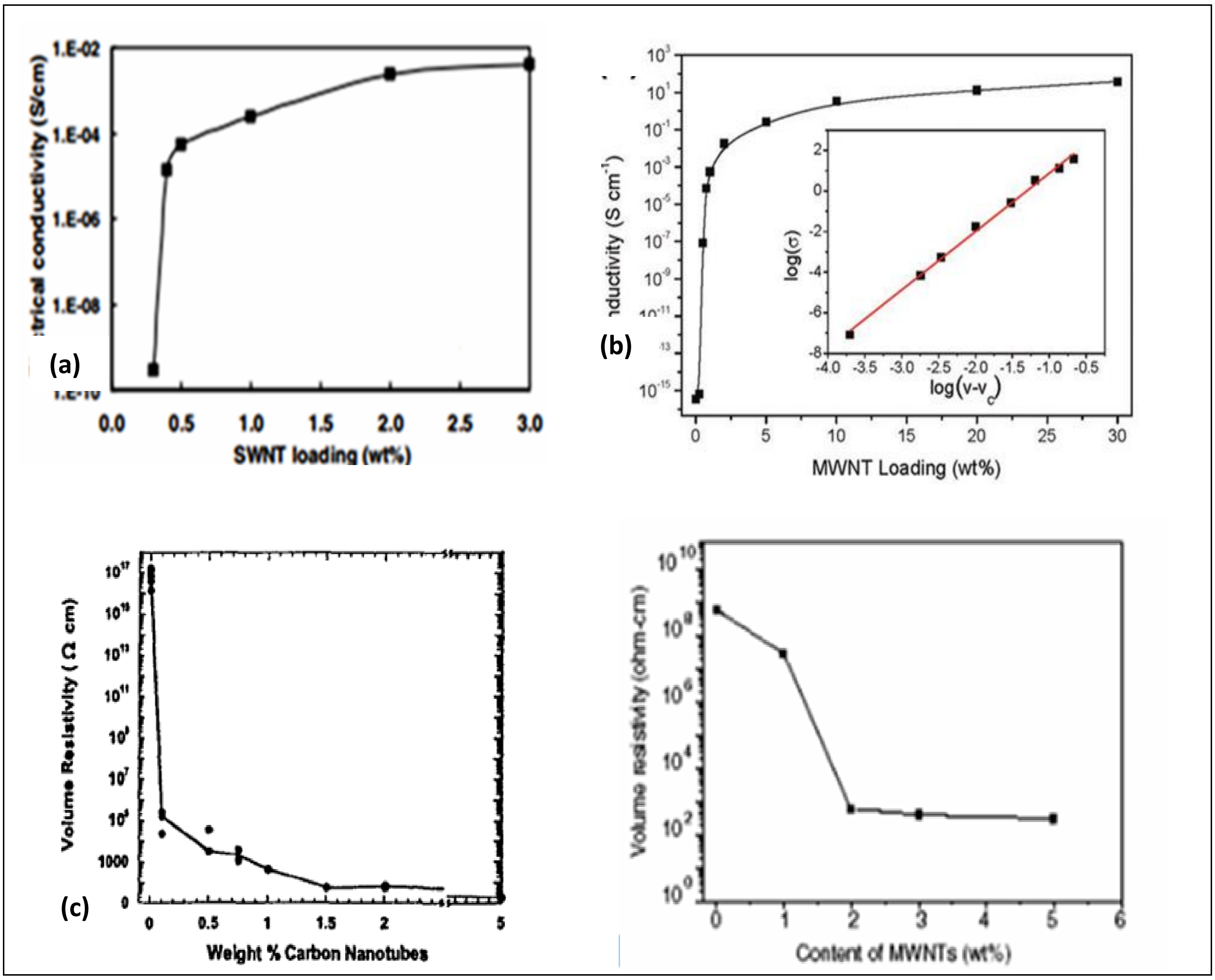

Fig. 4: (a & b) Electrical conductivity vs. SWNT/MWCNT loading (Bellucci *et al.* 2007; Gouzman *et al.* 2019) (c & d) volume resistivity vs. SWNT/MWCNT (Khare *et al.* 2005)

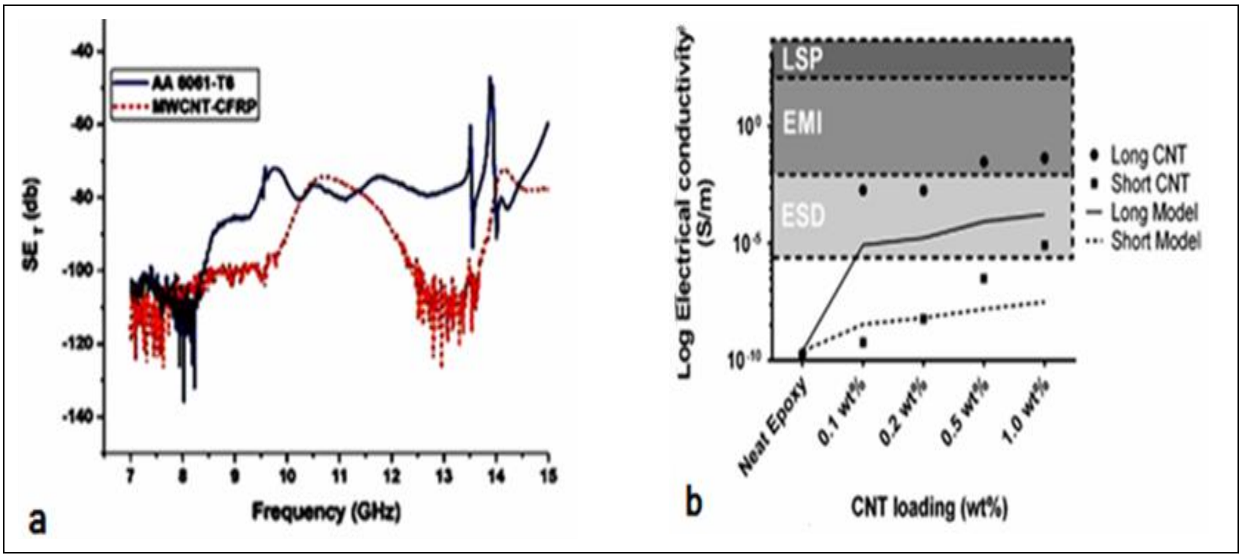

Fig. 5: (a) Comparison of EMI shielding effectiveness of MWCNT-CFRP and AA6061-T6 (Tariq *et al.* 2017) (b) effect of electrical conductivity in EMI, ESD applications vs. % wt. of CNT (Russ *et al.* 2013)

Thermal stresses are induced due to the periodic temperature fluctuations in MIC packages. The large difference in coefficient of thermal expansion (CTE) of fiber and matrix may cause thermal fatigue in neat CFRP package. Thermal experiments demonstrate that the MWCNT-CFRP is thermally stable up to 354 ºC and has considerably lower CTE than AA6061-T6 as shown in Table 3. It is found that MWCNT-CFRP can survive the thermal cycling in a range of -40 ºC to 120 ºC without any detectable cracking and de-lamination.

Table 2. Comparison of Al alloy, CFRP and MWCNT-CFRP (Tariq *et al.* 2015)

Parameters	Al6061-T6	Neat CFRP	MWCNT-CFRP
T_g (°C)	-	125	120
CTE in 35-55 /°C	23.6 x 10^{-6}	-7.55 x 10^{-6}	-3.9 x 10^{-6}
CTE in 55-100 /°C	23.6 x 10^{-6}	3.4 x 10^{-6}	3.1 x 10^{-6}
T_D (°C)	-	356	354

4. CHALLENGES

The addition of CNTs significantly increases the viscosity of the matrix (Song *et al.* 2013). The polymer solution allows dispersing nanotubes relatively easy; but some challenges exist depending on the polymer matrix used, carbon nanotube type and processing conditions. It is identified that there are two major interrelated issues of processing parameters of CNT composites (i) lack of uniform dispersion when mixed with polymer resins and (ii) poor interfacial adhesion between CNTs and various polymers. The uncertainties of these two issues are often problematic at different stages of nanocomposite fabrication. Space qualification is an important process to demonstrate whether CNT composites are capable of sustaining space environment, with the highest reliability. The CNT composites have to undergo various severe environmental tests like Thermal Cycling, Humidity, Thermovac, Radiation Resistance, EMI/EMC and Outgassing Properties (CVCM-TML) and measurements like mechanical strength, electrical and thermal conductivity and CTE. Only qualified materials are to be used for the fabrication of the flight-worthy components for space payload.

The dispersion process with a suitable solvent like Acetone and Propanol can be carried out by mechanical mixing, magnetic stirring or sonication. The solvent can reduce the viscosity and dissolve or evaporate from epoxy at elevated temperatures. Subsequently, the dispersed CNTs Epoxy solution is mixed with a hardener and the nanocomposite is finally obtained by precipitating or casting the mixture.

Table 3. Comparison of kovar material with CFRP and CNT-CFRP (Sayed-Ahmed *et al.* 1998)

Material	Kovar	CFRP	CNT-CFRP
Density g/cc	8.3	1.5-1.7	1-2
Thermal conductivity W/mK	17	In-Plane 1.8 thru thickness 0.609	Increase by 30% in-plane, 10% thru thickness
Electrical Resistivity Ωm	50 x 10^{-8}	Longitudinal 3.4 E^{-5} thru thickness 12.5E^{-5}	Decrease by by 12 times in-plane and 60% in thru thickness
Coefficient of Thermal Expansion/10^{-6} K^{-1} (25-200 ˚C)	5.5	Less than 1	Less than 1

The increase in the electrical conductivity of this polymer material by the addition of CNT is the major advantage of fabricating CNT/polymer nanocomposite. A significant improvement in thermal & electrical conductivity is observed at very low CNT loading for MWCNT (0.5-1% wt.) whereas SWCNT (0.3-0.5 % wt.). CNT composites carrier plates provide very high stiffness, strength, low density, reduced thermal stress, warpage and distortion and achieve tailorable thermal and electrical properties associated with this development. Enhancement of thermal and electrical properties improves thermal dispersion, electromagnetic shielding and current carrying capability and leads to surface plating process, respectively. Table 3 shows the comparison for of Kovar carrier plate with CFRP and CNT-CFRP composites. It is advantageous to fabricate CNT/CFRP composite carrier plates in terms of mass reduction compare to Kovar and enhancement of thermal and electrical conductivity compared to CFRP.

This development has the potential to replace all the Kovar-based carrier plates presently employed in all frequency transponders and payloads applications resulting in considerable weight reduction and improvement of thermal &electrical properties required for functional aspects.

The Space Qualification Process for CNT-CFRP composites and characterisation for mechanical, thermal and electrical properties have to be carried out to determine the required properties of the composites for the carrier plate of the microwave package.

5. CONCLUSION

The developments of CFRP-based carrier plate and MIC packages reduces the mass by more than 60% than traditional space-qualified materials. Solution mixing is the most common and easy method for the fabrication of CNT/polymer nanocomposites. The indigenous development of CNT/CFRP-based carrier plates is a possible replacement for the standard Kovar-based carrier plates, to reduce the mass by six times and make them lighter than the existing topology.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Bal, S. and, Samal, S. S., Carbon nanotube reinforced polymer composites—A state of the art, *Bull. Mater. Sci.*, 30(4), 379–386 (2007). https://dx.doi.org/10.1007/s12034-007-0061-2

Bellucci, S., Balasubramanian, C., Micciulla, F. and Rinaldi, G., CNT composites for aerospace applications, *J. Exp. Nanosci.*, 2(3), 193–206 (2007). https://dx.doi.org/10.1080/17458080701376348

Ciecierska, E., Boczkowska, A., Kubi, M. and Chabera, P., Enhancement of thermal and electrical conductivity of CFRP by application of carbon nanotubes, ECCM16 - *16th European Conference on Composite Materials*, Seville, Spain, 22-26 (2014).

Gouzman, I., Grossman, E., Verker, R., Atar, N., Bolker, A. and Eliaz, N., Advances in polyimide-based materials for space applications, *Adv. Mater.*, 31(18), 1807738 (2019). https://dx.doi.org/10.1002/adma.201807738

Guedes, J. F., Martins, M. S. S., Martins, R. and Rocha, N., Carbon nanotube layer for reduction of fiber print-through in carbon fiber composites, *Adv. Polym. Technol.*, 2019, 01–11 (2019). https://dx.doi.org/10.1155/2019/6520972.

Khare, R. and Bose, S., Carbon Nanotube Based Composites- A Review, *J. Miner. Mater. Charact. Eng.*, 04(01), 31–46 (2005). https://dx.doi.org/10.4236/jmmce.2005.41004

Martins, M., Gomes, R., Pina, L., Pereira, C., Reichmann, O., Teti, D., Correia, N. and Rocha, N., Highly conductive carbon fiber-reinforced polymer composite electronic box: Out-of-Autoclave manufacturing for space applications, *Fibers*, 6(4), 92-100 (2018). https://dx.doi.org/10.3390/fib6040092

Roy, S., Petrova, R. S. and Mitra, S., Effect of carbon nanotube (CNT) functionalization in epoxy-CNT composites, *Nanotechnol. Rev.*, 7(6), 475–485 (2018). https://dx.doi.org/10.1515/ntrev-2018-0068

Russ, M., Rahatekar, S. S., Koziol, K., Farmer, B. and Peng, H.-X., Length-dependent electrical and thermal properties of carbon nanotube-loaded epoxy nanocomposites, *Compos. Sci. Technol.*, 81, 42–47 (2013). https://dx.doi.org/10.4236/jmmce.2005.41004

Sayed-Ahmed, E. Y. and Shrive, N. G., A new steel anchorage system for post-tensioning applications using carbon fibre reinforced plastic tendons, *Can. J. Civ. Eng.*, 25(1), 113–127 (1998). https://dx.doi.org/10.1139/cjce-25-1-113

Singh, K., Kansara, H. R., Venkatesh, V., Nirmal, A. V. and Sharma, S. V, Microwave circuits characterization on carbon fibre (CFRP) based carrier plates, In: 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES). IEEE, 19, 01–04 (2018). https://dx.doi.org/10.1109/ICPEICES.2018.8897446

Song, K., Zhang, Y., Meng, J., Green, E., Tajaddod, N., Li, H. and Minus, M., Structural polymer-based carbon nanotube composite fibers: Understanding the processing – structure – performance relationship, *Mater. (Basel).*, 6(6), 2543–2577 (2013). https://dx.doi.org/10.3390/ma6062543

Tariq, F. and Shifa, M., Multifunctional carbon nanotubes filled carbon fiber composite for satellite structural applications, *68th International Astronautical Congress* (IAC), Adelaide, Australia, (2017).

Tariq, F., Shifa, M., Tariq, M., Kazim Hasan, S., Baloch, R. A., Hybrid Nanocomposite Material for EMI Shielding in Spacecrafts, *Adv. Mater. Res.*, 1101, 46–50 (2015). https://dx.doi.org/10.4028/www.scientific.net/AMR.1101.46

Vartak, D.A., Failure analysis of substrate of carrier plate of electromechanical package for space payloads, 3(3), 1572–1576 (2014).

Vartak, D. A., Satyanarayana, B., Munjal, B. S., Vyas, K. B., Bhatt, P. and Lal, A. K., Potential applications of advanced nano-composite materials for space payload, *Aust. J. Mech. Eng.*, 01–09 (2020). https://dx.doi.org/10.1080/14484846.2020.1733176

Zhang, S., Hao, A., Nguyen, N., Oluwalowo, A., Liu, Z., Dessureault, Y., Park, J. G. and Liang, R., Carbon nanotube/carbon composite fiber with improved strength and electrical conductivity via interface engineering, *Carbon.*, 144, 628–638 (2019). https://dx.doi.org/10.1016/j.carbon.2018.12.091