Abstract

Engineered Nanocomposite Materials for Microwave/Millimeter-Wave Applications of Fused Deposition Modeling

It is expected that the additive manufacturing (AM) market worldwide will reach $8 billion by 2023. AM technologies are expected to become a promising enabler for the next generation of wireless/microwave devices in the Internet of Things (IoT) era. However, the reported progress in AM functional electromagnetic (EM) composite materials, particularly to offer more options other than the standard thermoplastics currently being used by the microwave community that are amenable to fused deposition modeling (FDM), has been lacking. In this dissertation, a variety of high-permittivity (high-*k*) and low-loss ceramic-thermoplastic composite materials, based on Cyclo-Olefin Polymer (COP) embedded with sintered ceramic fillers, have been developed and investigated for direct digital manufacturing (DDM) of microwave components. The composites studied in this dissertation leverage a high-temperature co-firing process up to 1500°C to further enhance the dielectric/loss properties of the ceramic fillers. The EM properties of these newly developed FDM-ready composites were characterized up to the Ku-band by the cavity perturbation technique. Several models for prediction of the effective dielectric permittivity of composites based on the filler loading volume fraction have been evaluated, among which Hanai-Bruggeman and Maxwell models have shown the best accuracy with less than 2% and 5% discrepancies, respectively. The 30 vol. % COP-TiO_2 FDM-ready composites with fillers sintered at 1200°C have exhibited a relative permittivity (ε_r) of 4.78 and a dielectric loss tangent (tan δ_d) lower than 0.0012 at 17 GHz. Meanwhile, the 30 vol. % COP-$MgCaTiO_2$ composites with fillers sintered at 1200°C have exhibited an ε_r of 4.82 and a tan δ_d lower than 0.0018. The DDM approach combines FDM of the engineered EM composites and micro-dispensing for deposition of conductive traces to fabricate by 3D-printing of edge-fed patch antennas operating at 17.2 GHz, and 16.5 GHz were demonstrated by employing a 25 vol. % COP-$MgCaTiO_2$ composite FDM filament with the fillers sintered at 1100°C and a pure COP filament. These composites were both prepared and melt extruded following the process described in this dissertation. The low dielectric loss of the 25 vol. % COP-$MgCaTiO_2$ composite material (tan $\delta_d < 0.0018$) has been leveraged to achieve a peak realized gain of 6 dBi. Also, the high-permittivity (ε_r~4.74 which corresponds to an index of refraction of 2.17) results in a patch area miniaturization of 50% when compared with an antenna designed and printed over a state of the art Rogers RT/duroid® 5870 laminate core through micro-dispensing of CB028 silver ink. This reference antenna exhibited a measured peak realized gain of 6.27 dBi. Also, two low-loss FDM composite materials for DDM technologies are presented and characterized at V-band (mm-wave) frequencies. Pure COP thermoplastic exhibits a ε_r of 2.1 and a tan δ_d below 0.0011 at 69 GHz, whereas 30 vol. % COP-$MgCaTiO_2$ with fillers sintered at 1200°C composites exhibit a ε_r of 4.88 and a tan δ_d below 0.0070 at 66 GHz. These EM properties (combination of high-*k* and low loss) are superior to other 3D-printable microwave materials reported by the microwave community and on par with materials developed for high-performance microwave laminates by RF industry. This new class of high-*k*, low-loss EM composite materials have shown some promising attributes for enabling the next generation of high-performance 3D-printed RF and microwave devices and antennas operating at Ku-band and mm-wave frequencies.