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Additive Manufacturing of mm-Wave Multi-Layer Dielectric Rod Waveguides, Dielectric Rod Antennas and Metal Strip-Loaded Dielectric Rod Waveguide Filters

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Low loss wave-guiding structures and high-gain antennas in the millimeter wave and THz regime are necessary for a wide variety of applications such as spectroscopy, imaging and communication systems. Transmission losses in this frequency range mainly originate from: ohmic losses due to metal layers and material absorption inside the dielectrics. A multi-layer dielectric rod waveguide (DRW) design is investigated that can be integrated with mm-wave electronics (tested up to D-band) and 3D printed using direct print additive manufacturing (DPAM) and in-house developed composites. Transitions to rectangular waveguide and planar transmission lines are strategically designed to characterize dielectric rod waveguides. DPAM equipment with multiple nozzles and the availability of different materials such as ceramic, metal, plastic and composite also enable additive manufacturing of multiple layer waveguides. The reduced conductivity of printed silver paste and surface roughness issues make dielectric waveguide or "metal free" waveguides a more attractive design. The multi-layer DRW is comprised of a high permittivity core (ε_r=6-10) encased by a low permittivity cladding (ε_r =1.2-2.0). A mathematical model is proposed and verified to predict the fundamental mode cutoff frequency in terms of core dimensions and core and cladding permittivity. As compared to single layer design, the multilayer waveguides show a 16.7% and 24% bandwidth extension due to lowered 1 dB cutoff frequency. The multi-layer bends also exhibit a significant reduction of the 1 dB low-band cutoff frequency from 20% to 40% when compared to single-layer ones, for the different radius of curvature bends. The associated attenuation and transition loss was extracted by a numerical multiline calibration method. The results indicate a maximum attenuation of ~0.023 dB/mm due to the dielectric losses, an attenuation due to each metal waveguide transition of 0.2-0.55 dB, and an attenuation due to radiation losses of 7×10^{-4} dB/mm.

The effect of a low permittivity cladding used in a multilayer end-fire dielectric rod antenna (DRA) design is studied in terms of return loss, gain, and half-power beam width (HPBW) over mm-wave frequencies. At extended Ku band (10-18 GHz), gain improvement ranging from 4 to 7 dB, when compared to a single-layer design of the same length, is achieved using cladding permittivities between 1.6 and 2.6. For example, a cladding of ε_r = 1.6 leads to a peak gain increment of 4.5 dB at 18 GHz and a 20° HPBW reduction compared to the noncladded rod. It is also demonstrated that this design has the same maximum gain as a noncladded design that is 1.8 times longer. The cladding permittivity in multilayer DRA's can be adjusted in DPAM by modifying the infill ratio of the thermoplastic material to achieve peak performance at different frequencies within the band, while providing gain enhancement in the entire band without reducing the bandwidth. The multilayer DRA also increases the electric field confinement in the core, which translates to a higher potential packing density in an array configuration.

The design and implementation of a metal strip-loaded dielectric rod waveguide band stop filter is demonstrated for operation in the Ku band. A corrugated metal layer was incorporated on top of a high permittivity waveguide core to achieve band stop rejection greater than 20 dB (up to 28 dB) and rejection bandwidths of 10%. The metal strip loading is achieved with patterned copper foils attached to the top and bottom surfaces of the waveguide that can be done by micro-dispending of silver paste. It is experimentally demonstrated that the stop band frequencies can be tuned by adjusting the metal strip periodicity. An equivalent circuit model is proposed to represent the filter characteristics. It is observed that the addition of the conductive corrugated layer does not negatively affect the attenuation in the DRW passband and the DRW's return loss remains below -10 dB. A similar band-rejection configuration has also been demonstrated in both single core and multi-layer dielectric rod antenna designs.

Improved processing methodology of thermoplastic-ceramic composite feedstock filaments has been developed to achieve the highest reported ceramic particle filler volume fraction of 50%. Relative permittivity values up to 12.35 have been achieved for newly developed feedstock filaments for fused deposition modelling (FDM), which exhibited dielectric loss tangent in the range of 0.001-0.007 at frequencies between 4 GHz and 12 GHz. One of the in-house developed FDM-ready feedstock filaments is employed to 3D print a strategically designed 40-mm long dielectric waveguide, which exhibited an insertion loss of 0.48 dB at 25.75 GHz. A reference DRW fabricated using commercially available feedstock filament from Premix Inc. is also designed and characterized that showed a noticeably higher measured minimum insertion loss of 1.55dB over the entire operation frequency range.

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