Advanced Additive Manufacturing of 3D RF/Microwave Electronics Based on Novel Electromagnetic Nanocomposite Materials

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***Abstract*— This report summarized the main outcomes of the research project awarded by the 2016 MTT-S Graduate Fellowship under the General Category. The research objective is to develop functional electromagnetic (EM) composite materials for 3D-printed microwave components. A cyclo olefin polymer (COP) thermoplastic matrix reinforced by sintered $MgCaTiO_2$, $Ba_{0.55}Sr_{0.45}TiO_3$, and TiO_2 micro-fillers has been prepared and characterized up to 17 GHz or 69 GHz by using cavity resonator based fixtures. Pure COP exhibits a relative permittivity of 2.1 and a loss tangent below 0.0011 up to 69 GHz. Moreover, 30 vol. % COP-$MgCaTiO_2$ composites show a relative permittivity of 4.88 and a loss tangent below 0.007 up to 66 GHz. 17 GHz microstrip patch antennas have been fabricated by a direct digital manufacturing (DDM) approach that combines fused deposition modeling (FDM) of 25 vol. % COP-$MgCaTiO_2$ composites and micro-dispensing of conductive silver paste to form antenna traces, which is compared with reference design implemented using commercial microwave laminates in terms of antenna size and performance.**

***Index Terms* — Additive manufacturing, antennas, composite materials, dielectric losses, permittivity, 3D printing.**

I. Introduction

ADDITIVE MANUFACTURING (AM) market is anticipated to be over $8 billion in the following years while experiencing rapid growth. Nevertheless, the reported progress in AM-compatible functional EM composite materials characterized at *Ku*-band and mm-wave frequencies, specifically those compatible with fused deposition modeling (FDM) has been lacking. So far, most of the prior works are limited to the usage of the standard thermoplastics such as acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), and polyetherimide (PEI) also known as ULTEM™ resin, and so on [1]. Despite some excellent success reported in FDM compatible EM materials by Isakov *et al.* in [2] and Castles *et al.* in [3], some of these materials exhibit high dielectric losses at microwave frequencies while the others are based on a low glass-transition temperature (T_g) ABS matrix, hence limiting their applications to low performance or low power microwave devices, respectively, as shown in TABLE I. In this work, we present a generic methodology to develop FDM-compatible high-permittivity (high-k) and low-loss ceramic-thermoplastic composites, based on cyclo-olefin polymer (COP) loaded with a selected volume fraction of sintered high-k ceramic micro-fillers, for 3D printing of high-performance microwave devices. The effective dielectric and loss properties of the newly developed composites were evaluated up to the *Ku*-band through cavity resonator measurements and up to mm-wave frequencies by using a model 200 circular cavity from Damaskos Inc. As compared to ABS, polylactic acid (PLA), polypropylene (PP), PC, and previously reported works, COP based composites offer higher *Tg*, along with superior and well tailored EM properties as summarized in TABLE I.

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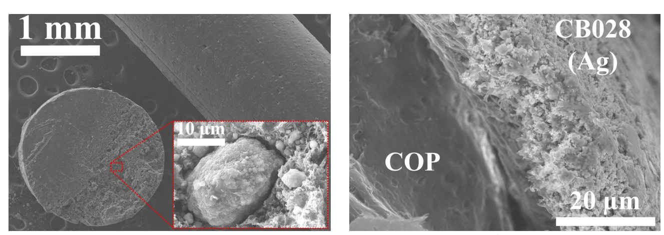
II. Description of the Project

The high-k ceramic fillers were sintered at temperatures up to 1340°C to further enhance their dielectric and loss properties, followed by the re-pulverization of sintered particles by using a high-energy ball milling tool. Thereafter, the COP or ABS thermoplastic matrixes and sintered ceramic particles are then uniformly mixed along with a hyperdispersant using a planetary centrifugal mixer, followed by a hot extrusion compounding process at 260ºC or 190ºC, respectively, to produce EM FDM feedstock filaments with a diameter of about 2.0 mm. The complete material preparation, modeling and device implementation were reported in [4],[5]. Fig. 1(a) depicts the COP-based composites embedded with densified $MgCaTiO_2$ particles, while Fig. 1(b) illustrates the cross-sectional SEM photo showing the actual interface between FDM-produced COP thin sheet and the micro-dispensed silver paste (CB028) as the conductive trace on top of the FDM printed substrate.



(a) (b)

Fig. 1. SEM photos of (a) a 30 vol. % COP-$MgCaTiO_2$ feedstock filament; and (b) a cross-sectional SEM photo showing the actual interface between the FDM printed COP substrate and micro-dispensed silver paste layer [5].

Fig. 2(a) shows some of the 3D-printed thin-sheet and cylindrical ring specimens for dielectric characterization based on COP. Fig. 2(b) shows 17 GHz rectangular edge-fed antennas were manufactured using a 2-step DDM process [1], including the FDM printing of a 25 vol. % COP-$MgCaTiO_2$ composite substrate, followed by a micro-dispending of the silver paste to

TABLE I. MEASURED DIELECTRIC PROPERTIES OF FDM-READY MICROWAVE MATERIALS VS PREVIOUS WORKS

Material/Composite	Year	Technology	Filler	Freq. (GHz)	ε_r	tan δ	Ref.
ABS+$BaTiO_3$	2015	FDM	27 vol.%	15	7.00	0.0342	[2]
$BaTiO_3$/ABS	2016	FDM	29 vol.%	14.13	8.72	0.0273	[3]
ABS+$Ba_{0.55}Sr_{0.45}TiO_3$ (Fired 1340°C)			6 vol.%		3.98	0.0086	
COP+TiO_2 (Fired 1100°C)			30 vol.%		4.57	0.0014	
COP+TiO_2 (Fired 1200°C)			30 vol.%	17	4.78	0.0012	
COP+$MgCaTiO_2$ (Fired 1100°C)	2017	FDM	25 vol.%		4.74	0.0018	This Work
COP+$MgCaTiO_2$ (Fired 1200°C)			30 vol.%		4.82	0.0018	
COP+$Ba_{0.55}Sr_{0.45}TiO_3$ (Fired 1340°C)			25 vol.%		4.92	0.0114	
Pure COP			N/A	69	2.10	0.0011	
COP+$MgCaTiO_2$ (Fired 1200°C)			30 vol.%	66	4.88	0.0070	

form the antenna patch and ground. A similar micro-dispensing process was performed over a Rogers RT/duroid® 5870 dielectric core with the purpose of comparing the microwave material performance. Both printing steps were done in a continuous manner using a tabletop 3Dn nScrypt printer.

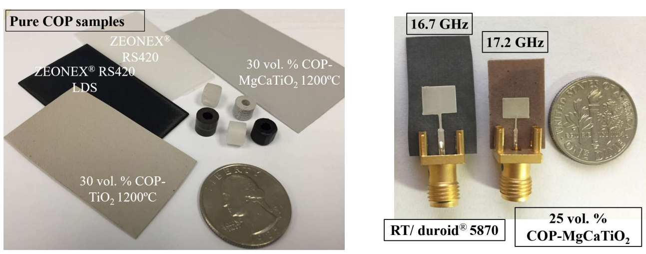


Fig. 2. (a) Loaded and unloaded FDM-printed samples based on sintered TiO_2 (brown) and $MgCaTiO_2$ (gray) fillers along with other FDM printed specimens; (b) DDM printed ~17 GHz antennas based on 25 vol.% COP-$MgCaTiO_2$ composites and a Rogers RT/duroid® 5870 laminate, which shows a 50% antenna patch size miniaturization [5].

Fig. 3(a) presents measured versus EM-simulated (ANSYS HFSS 2017) antenna return loss, revealing an excellent agreement between the simulated and measured responses, Fig. 3(b) depicts the comparison of (normalized) H-plane radiation patterns.

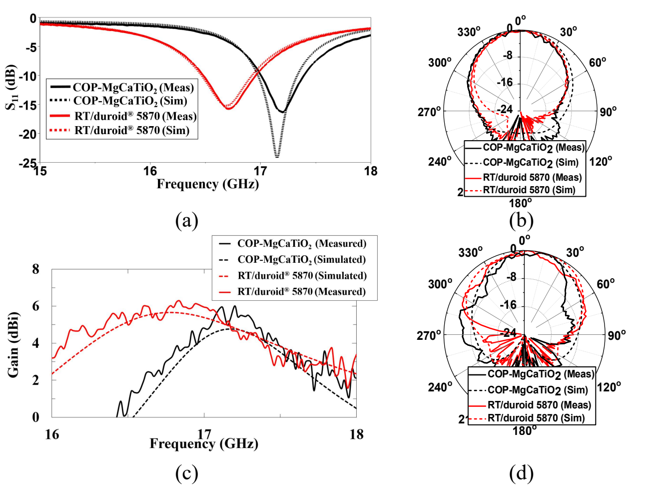


Fig. 3. (a) Comparison of the measured and simulated return loss; (b) normalized H-plane radiation patterns; (c) Measured peak gain vs. frequency; and (d) normalized E-plane radiation patterns, for the 17.2 GHz and 16.7 GHz antennas DDM-printed based on 25 vol. % $MgCaTiO_2$ and a Rogers RT/duroid® 5870 laminate, respectively [5].

Fig. 3(c) depicts the comparison of the measured versus EM simulated (HFSS 2017) antenna peak gain vs. frequency characteristics of the two types of printed antennas, Fig. 3(d) depicts the comparison of (normalized) E-plane radiation patterns. As a key figure of merit, the low dielectric loss of the 25 vol. % COP-$MgCaTiO_2$ composite material has been leveraged to achieve a peak realized a gain of 6 dBi.

III. CAREER PLANS, PUBLICATIONS, FELLOWSHIP IMPACT AND IMS IMPRESSIONS

My career plan is to first gain more practical experience in the RF/MW field by joining industry. But my long-term goal is to seek a teaching and research position in academia. Two peer-reviewed papers have been published in our society during the award period, including a conference proceeding (IEEE MTT-S IMS 2016) [4] and a journal paper published in February 2017 in the IEEE Transactions on Microwave Theory and Techniques [5]. Also, three more peer-reviewed conference proceedings using the EM FDM-ready composites developed by this project has been accepted for publication in peer-reviewed conference proceedings (one in IEEE MTT-S WAMICON 2017 and two in IEEE APSURSI 2017). I would like to express my gratitude to the IEEE MTT-S for awarding this graduate fellowship research proposal and sponsoring my attendance to the IMS 2016 in San Francisco, CA. I had the opportunity to present a paper [4] while attending other technical presentations and conference activities and networking with other colleagues.

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