Additive Magnet Free Circulator for Heterogenous Integration

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Abstract

As RF systems continue to shrink in size and weight, traditional ferrite circulator architectures present an integration challenge due to their reliance on bulky permanent magnets, resulting in components that are heavy and difficult to integrate into compact RF systems. Permanent-magnet-free circulators based on low-loss ferrites, in which magnetic biasing is achieved using externally applied fields, have been proposed in prior work. However, the self-biased puck is traditionally placed in a milled pocket within the substrate or surface mounted. A surface-mounted implementation requires a ramped transition structure to elevate the microstrip from the planar board surface to the top of the puck. Both approaches can be complex and costly using conventional fabrication processes. Additive manufacturing (AM) techniques enable the creation of non-standard three-dimensional geometries that can satisfy the requirements of these ramped transitions while simplifying fabrication. This work presents an additively integrated circulator fabricated using digital light processing (DLP) and aerosol jet printing (AJP). DLP was employed to fabricate the transition structure between the printed wiring board (PWB) test fixture and ferrite puck, while AJP was used to deposit the conductive RF features and dielectric seam structures that enable impedance matched electrical interconnections to the top surface of the ferrite. The ferrite puck is mounted to a ground pad on the PWB using conductive epoxy, and conductive AJP traces are aligned with the fabricated microstrip transmission lines on the test fixture. Measured performance was compared with electromagnetic simulations, demonstrating the feasibility of using additive manufacturing to simplify the fabrication and integration of complex three-dimensional RF structures.

Key words

Additive, Aerosol Jet Printing, Circulator, Interconnects, Printed Electronics, Self-Biased Ferrite.

I. Introduction

There is a persistent demand to reduce the size of RF system components to enable integration into compact or nontraditional form factors. This could require form factors that would be difficult to produce using standard subtractive methods. However, AM techniques can provide 2.5D and 3D solutions that may reduce the size and weight of system components [1].

A standard circulator is a 3-port device comprised of a y-shaped transmission line junction integrated between ferrite pucks and permanent magnets. When the ferrite is subjected to a static magnetic bias from permanent magnets, the ferrite exhibits a direction-dependent permeability, enabling non-reciprocal electromagnetic wave propagation within the transmission line junction. This enables signals to propagate sequentially from one port to the next while suppressing reverse transmission. Circulators allow a single antenna to be used for receiving and transmitting, by separating the functions. Additionally, they are crucial in protecting high-end RF equipment from power that is reflected [2]-[4]. However, permanent magnets are heavy, bulky and the field can interfere with other RF devices when trying to make a circuit more compact. Alternatively, there has been a great amount of work towards fabricating circulators with self-biased hexaferrites (such as barium hexaferrite and strontium hexaferrite), to forgo the permanent magnet entirely. These ferrites contain a high level of crystalline anisotropy and feature a magnetic domain that can be polarized with an external magnetic bias [5]-[6].

Previous studies on self-biased ferrite integration have shown implementations where ferrite pucks are embedded into milled cavities within a substrate. The transmission line junction is then printed atop the ferrite puck and bridged over the substrate-ferrite gap [7]-[8]. However, this approach can be challenging and cost-prohibitive due to the tight manufacturing tolerances and the requirement for a thicker PWB. It would be advantageous to have a solution that is surface mountable much like standard circulators that have magnets. However, this would mean the transmission line would be ramped from the board level to the top of the puck where the junction exists. Utilizing standard subtractive processes, this would cause difficulties and be costly to manufacture [9].

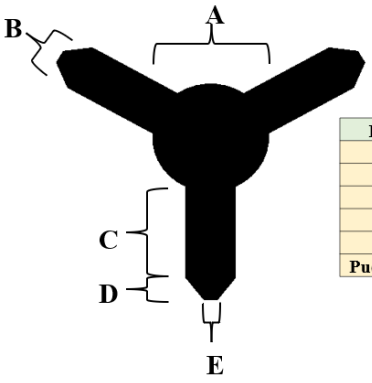
DLP is a 3D printing method that utilizes a high-resolution UV light projection to polymerize voxels in a vat of

photopolymer resin. It can realize sub-millimeter features and complex geometries in 3D space [5].
In this work, an Asiga x27 was utilized. It is an open-source printer that allows a user to use any resin that UV cures at 405 nm.
This work showcases a method of fabricating an additively integrated RF circulator by utilizing a strontium hexaferrite puck that is adhered to a PWB and a DLP printed ramp structure to facilitate the non-planar transition from the board to the top of the puck. The ramping structure was fabricated with Rogers Radix 2.8dk, which is a low loss DLP resin with a dielectric constant of 2.8 and a loss tangent of 0.0043 at 10 GHz [10].

II. Experimental

A. Additive Circulator Design

In this work, the transmission lines and junction were printed directly on top of a self-biased ferrite puck adhered to the ground plane of an RF substrate. The microstrips then transition from the puck to the board level via a printed ramp, where they interface with copper-etched microstrip lines on the PWB. To account for the change in effective dielectric constant and substrate thickness, the microstrip lines are tapered to match the width of the board-level copper traces. Fig 1 presents a top-down 2D view of the circulator geometry and the appropriate dimensions, while Fig 2 shows a cross-sectional view of the structure.



Parameter	Width (mm)
A	3.66
B	1.59
C	3.06
D	0.69
E	0.39
Puck Thickness	3.66

Figure 1: Design and dimensions of the transmission line junction that was used for the additively integrated circulator.

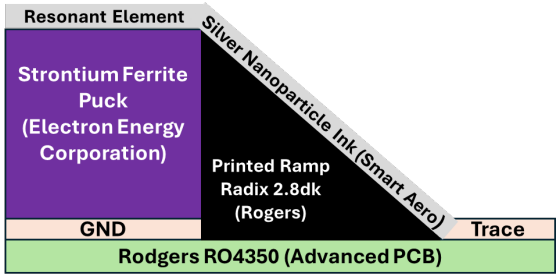
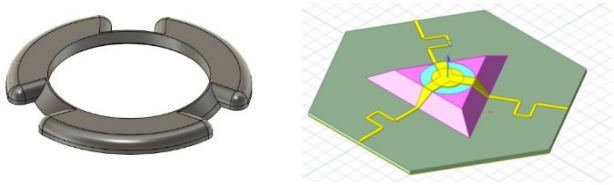


Figure 2: Cross section of the self-biased puck, ramp, and circulator structure, showing the materials used and their corresponding vendors.

The strontium ferrite pucks used in this work were sourced from Electron Energy Corporation. Pucks were mechanically polished using 1200-grit sandpaper to a final thickness of 0.508 mm. The resulting surface roughness on the top face ranged from 0.5 to 1.1 µm. The puck was magnetically polarized with an external magnetic field from an ELMAG20A air gap electromagnet that was powered with 6 kW power supply. The PWBs used in this work were fabricated by Advanced PCB.

The DLP-printed ramp is designed as a ring that can be press-fit around the puck. Three cutouts in the outer wall accommodate 45° ramps for the transmission line. The ring implements a thicker perimeter to improve structural rigidity and to provide increased surface area for adhesive bonding, ensuring the ring remains securely in place.

Electromagnetic simulations were performed using ANSYS® HFSS EM Wave Simulation Software. The ramp geometry and transmission lines were parametrically optimized for operation in the X-band frequency regime. Fig 3 shows an image of the ring and the simulation.



[A] [B]

Figure 3: (a) 3D image of the DLP printed ring ramp structure that was designed in Autodesk Fusion 360. (b) HFSS Simulation of the circulator.

B. Fabrication Process

The fabrication process of the additively integrated circulator was split into 4 steps. First, the puck was mounted onto a ground pad on the PWB. Second, the DLP printed ring was press fit on the puck. Third, a dielectric was printed on the board/ring and ring/puck interfaces to secure the puck. Lastly, the transmission lines were printed on the puck and along the ramps to contact the board-level microstrips. Fig 4 shows a representation of the process flow.

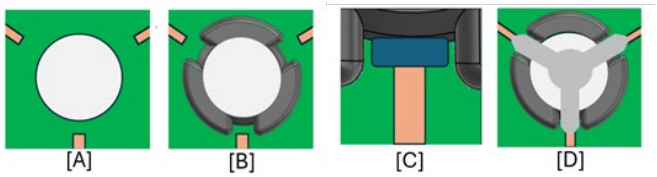


Figure 4: Overview of the fabrication process flow for the additively integrated circulator. (a) puck mounted on the PWB. (b) DLP-printed ring mounted on the puck. (c) dielectric seams printed along the ring edges. (d) transmission lines fabricated using aerosol jet printing.

The first step in the assembly is to secure the ferrite puck to a circular ground plane on the board. This was done by adhering the puck with H20E conductive epoxy. Once placed the samples were cured in a box oven at 150 °C for 15 minutes. A digital microscope was used to visually align the puck during manual placement.

The rings were fabricated using DLP with an Asiga Max X27 UV printer, employing the Radix 2.8dk DLP resin from Rogers. Small DLP-printed parts are prone to warping in the final cure step. To avoid warpage, the rings are left on the build-plate during post-processing. Rings are then ultrasonically cleaned in isopropyl alcohol and subsequently cured in a FormCure UV curing oven at 60 °C for 60 minutes. After curing, the parts were carefully removed from the build- plate using a blade. Fig 5 shows a close up of the rings on the build-plate.



Figure 5: Array of DLP printed ring on the Asiga's build tray.

Under a microscope, the ramps were manually aligned and placed around the mounted puck. A small amount of NEA121, a UV-curable optical adhesive, was applied using a cotton swab beneath the ring to ensure proper adhesion to the PWB. The adhesive was then cured at room temperature for 10 minutes using a FormCure system.

All subsequent layers were fabricated using the Optomec AJ5X aerosol jet printer. Dielectric seams were first printed along the interfaces between the board, ramp, and puck to fill gaps and promote a smooth material transition for the circulator microstrips. NEA121 was also used as the printable dielectric material. To enable printing, the resin was heated to 50 °C to reduce its viscosity. The AJ5X system utilizes integrated 365 nm UV floodlights for in-situ curing during deposition. A 200 µm nozzle and a print speed of 2.5 mm/s were used for dielectric deposition.

Conductive features were then printed using Smart Aero silver nanoparticle ink (Genes Ink). Printing was performed with a 200 µm nozzle, a print speed of 2 mm/s, and a platen temperature of 80 °C. The conductive pattern was divided into three sections: the circular resonator and microstrip on top of the puck, the tapered transition along the ramp, and an additional segment to ensure continuity between the taper and the PWB microstrips. After printing, the samples were cured in an oven at 150 °C for 1 hour.

III. Results and Discussion

A. Results of Printing

The 3D printed ramps were able to provide a smooth transition from board level to the top of the puck. Fig 6 shows a close-up image of the 3D printed ramp.

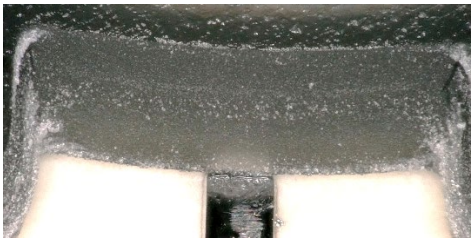


Figure 6: Close up image of the ramp on the 3D printed ring.

Conductive features were successfully printed with AJP and the printed lines exhibited electrical continuity between the three ports. Fig 7 shows an image of the complete circulator and Table 1 shows a comparison of the dimensions of the printed parts to the target values. Dimensions A-D were within 10% of the target specification. Dimension E was larger than specification due to a slight alignment issue when printing the end of the microstrip taper.

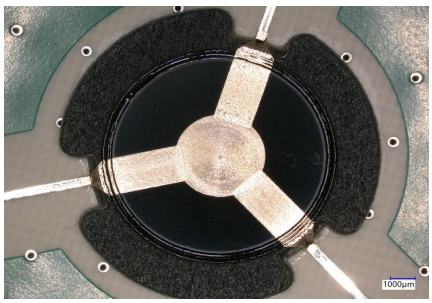


Figure 7: Profilometer scan of the ramp portion of the Ring

Table 1 List of measured geometry of the circulator compared to its designed values

Parameter	Designed (mm)	Measured (mm)	% off from design
A	3.66	3.77	3.01%
B	1.59	1.61	1.26%
C	3.06	3.07	0.33%
D	0.69	0.712	3.19%
E	0.39	0.43	10.26%

B. RF results

To test the RF performance of the device, edge launch connectors were attached to the microstrips. 3 port S-parameters were measured with a Keithly 4200 Parameter Analyzer to find out the device's performance.

The simulated and measured RF results for the fabricated circulator are shown in Fig 8 and Fig 9. Over X-band, the average inertion loss was 1.044, which was 0.61 dB higher than the simualted values. However, past 10 Ghz, performance decreases. This can be attibuted to unideal nature of using silver nanopartilce inks for the transmission lines instead of bulk metal. For X-band, the return loss at each port was below -10 dB, however, the difference in reponse for each port could be attributed to the slight angualr misalignment of the printed tranmission lines. The isolation was below −14 dB for all measured frequiences.

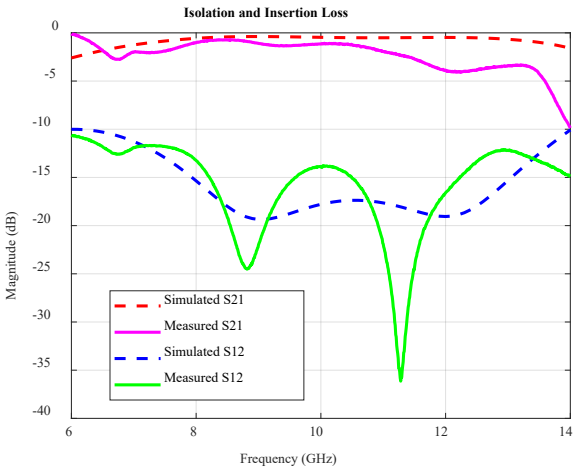


Figure 8: Graph of the isolation and insertion loss of the additive circulator.

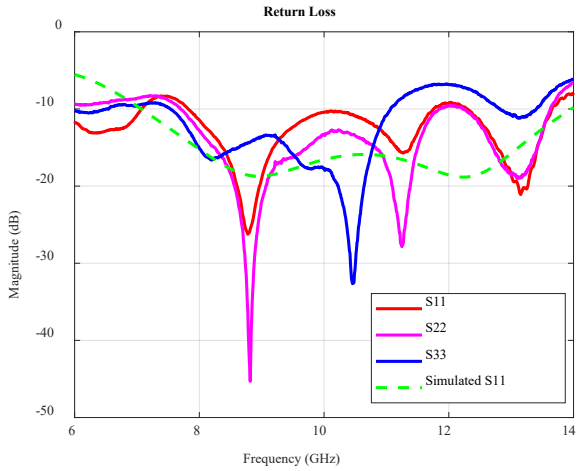


Figure 9: Graph of the return loss for the 3 ports on the additive circulator.

IV. Conclusion

An additively integrated circulator for X Band was successfully fabricated on an RF substrate. A high-resolution DLP-printed ring with an integrated ramp feature was produced and positioned around a strontium ferrite puck adhered to the substrate. The transmission lines were aerosol jet printed onto the puck and ramp. The fabricated dimensions closely matched the design specifications, and RF measurements were successfully obtained. However, further optimization of the fabrication is needed to improve RF performance. Overall, these results indicate that an additively integrated circulator is feasible but requires more work to improve RF performance.

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