# 3D-Printed Microstrip Resonators for 4.7T MRI

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**Introduction:** Microstrip transmission line resonators (MTL) are commonly used in high-field transmit/receive arrays because of their efficiency and low coupling between elements[1]. The technology of 3D printing is expanding into the electronics industry replacing traditional fabrication methods and lowering costs. Three-dimensional objects are created by laying down successive layers of polymer material. We demonstrate how MTL resonators for 4.7 T can be 3D-printed with integrated capacitors quickly and efficiently without the use of costly discrete capacitors. Soldering is also eliminated.

**Methods:** In Fig. 1 the ink printing set up is shown including: a desktop 3D printer, dispenser, air-regulator, and syringe. Ink printing is achieved with the syringe using offset correction on the g-code generation software (Slic3r) and calibrated dispenser pressure. A desktop 3D printer (X-series, Machina Corp.) was modified to print conductive silver ink (Ag-610, Conductive Compounds) on substrates previously printed using polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) thermoplastics. Another printer (Objet Eden350V, Stratasys) is used to print UV-curing resin (Objet Verogray RGD850, Stratasys) which provides better mechanical performance than ABS or PLA. The 3D model of the MTL resonator and integrated capacitors is shown in Fig. 2, with tuning capacitors at both ends and a matching capacitor at one end of the transmission line. A traditional resonator of similar dimensions was built for comparison using low-loss Rohacell foam (Evonik Ind.)[2] substrate, copper tape conductors and porcelain capacitors (American Technical Ceramics). Versions of the printed coils were also made using copper tape for comparison. The connections from printed ink to coax are made by soldering its conductors to small pieces of copper tape and attaching them to the resonator with drops of silver ink.

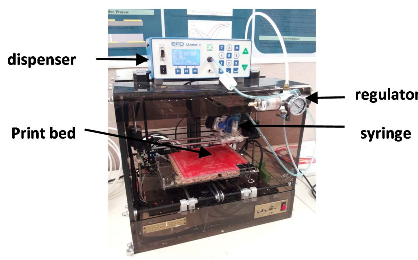


**Fig. 1: 3D printer modified to deposit conductive ink.**

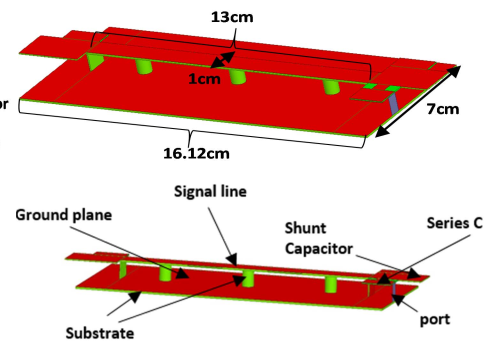


**Fig. 2: CAD drawing of the 3D printed partially air-filled microstrip coil with integrated capacitors.**

The printed resonators are designed and simulated using HFSS (Ansys). Since the permittivity and loss tangent of the substrates can vary due to material inconsistency and air inclusions approximate values were used initially, and then adjusted after the resonator is fabricated to make the resonance frequency and quality ($Q$) factor equal in the simulation and measurement. The complex permittivity for PLA, ABS and UV-resin are estimated from measurements as $1.24(1+i\cdot0.005)$, $1.34(1+i\cdot0.008)$, and $2.0(1+i\cdot0.026)$ respectively. The small permittivity values indicate that volumes are not completely filled with plastic and include air cavities. Measurements are performed on a 36×26×11 $cm^3$ phantom filled with 3.6 g/ℓ NaCl and 1.96 g/ℓ $CuSO_4 \cdot 5H_2O$ to emulate the human body ($\varepsilon_r$=76, $\sigma$=0.8 S/m). Loaded and unloaded $Q$ of each resonator is measured according to [3] using a network analyzer. Gradient-echo imaging ($T_R/T_E$ = 50/5 ms, flip angle = 10°, bandwidth = 391 Hz/pixel, acquisition matrix 256×128, FOV = 30×30 cm, 1 average) is performed on a 4.7 T Varian system to compare signal to noise (SNR) performance.

**Results and Discussion**

Matching, $Q$-factor, efficiency ($\eta = 1-Q_l/Q_u$) [4], and average SNR in three sagittal slices (one central and two offset ±1.5cm; 13×4 $cm^2$ area) of the six resonators are compared in the Table. Resonators made with PLA and ABS show comparable $Q$ and efficiency to those of Rohacell, while the losses in UV-cured resin are much worse. Even though silver ink is more lossy than copper due to its lower conductivity ($2.9\times10^5$ S/m compared to $5.9\times10^7$ S/m), the consequent reduction in image SNR is very limited. An alternative ink with higher conductivity has already been found (PChem, PFI-722 silver nanoparticle ink, $1.9\times10^7$ S/m) that will provide $Q$ performance nearly equal that of copper.

| *RF Coil construction* | *Matching $S_{11}$* | $Q_{unloaded}$ | $Q_{loaded}$ | *Efficiency $\eta$* | *Image SNR* |
|---|---|---|---|---|---|
| *PLA+Cu* | -30dB | 98.9 | 29.8 | 0.69 | 41.5 |
| *ABS+Cu* | -30dB | 79.3 | 33.1 | 0.58 | 59.4 |
| *Resin+Cu* | -15dB | 40.4 | 28.07 | 0.30 | 40.5 |
| *PLA+ink* | -22dB | 29 | 18.2 | 0.37 | 29.4 |
| *ABS+ink* | -22dB | 28.5 | 22.6 | 0.20 | 53.1 |
| *Foam+Cu* | -30dB | 122.8 | 51.4 | 0.58 | 42.4 |

**Conclusion**

This preliminary study shows the great potential of 3D printing technology to fabricate microstrip MR coils in an automated manner directly from 3D geometries used in simulations. Accurate characterization of the complex permittivity of the printed substrates is required. Multiple labor-intensive fabrication steps and the expense of soldering discrete capacitors in traditional construction are thus eliminated. Losses comparable to traditional construction are obtainable using silver nanoparticle ink.

**Acknowledgements:** Funding from the Natural Sciences and Engineering Research Council (Canada), and samples from Evonik. We thank Atefeh Kordzadeh and Peter Seres for assistance with the imaging measurements.

**References:** **1.** G. Adriany, et al. *MRM* 53(2):434-45 **2.** D. O. Brunner et al. Proc. ISMRM. 2007:448 **3.** A. Yahya, et al. *NMR Biomed,* 26(5):533–41 **4.** P. Mansfield, PG. Morris NMR Imaging in Biomedicine, Academic Press, 1982