Monolithic Paper-Based & Inkjet-Printed Technology for Conformal Stepped-FMCW GPR Applications

First Results

Anya Traille, Antony Coustou, Herve Aubert
CNRS, LAAS
7 Avenue du Colonel Roche
F-31400 Toulouse, France
atraille@laas.fr

Sangkil Kim, Manos M. Tentzeris
Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia, USA
ksangkil3@gatech.edu

***Abstract*—The first design for a monolithic FMCW Ground Penetrating Radar system integrated onto an inkjet-printed patterned flexible substrate is presented. Using advanced materials printing and surface mounting techniques, each signal stage, including the antennas, can be built onto one continuous portable conformal substrate. This would make radar systems easy to roll up to miniaturized highly-portable sizes and volumes, that are really critical especially in "rugged" and hazardous remote environments. This paper addresses several design challenges involved in the development of monolithic paper-based radar systems including unique design, fabrication, and testing procedures that differ from the conventional radar systems. A paper-based mixer circuit is built and the performance is to be compared to that of a state of the art mixer board to verify the advantages of the newly proposed inkjet-printer approach.**

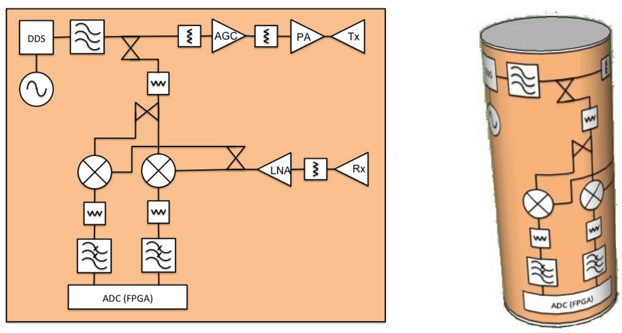
Keywords—Stepped FMCW Radar; ground penetrating radar; inkjet printing; portable radar; monolithic

I. Introduction

Frequency-Modulated Continuous Wave (FMCW) Ground Penetrating Radar has become popular in various applications, many of which are undertaken in the most extreme of environments. These include analyzing active fault zones; studying geomorphology and internal structure of desert dunes; characterizing soil, rock and snow stratigraphy; detecting clay layers; measuring or mapping the spatial variation of soil water content (soil moisture) and porosity, measuring depths to water tables, buried target detection and characterization (forensics, ancient monuments, pipes, landmines); avalanche research; sea-ice thickness measurements in Antarctica and Martian soil subsurface characterization [1, 2, 3].

The use of flexible substrates such as paper, kapton and LCP would make future systems more easily deployable by allowing them to be rolled up, transported and unrolled (or pieced together) quickly and easily for immediate operation (Fig 1) while allowing for lightweight and easy mounting in 'rugged' platforms, such as oil exploration drills. This provides a functional advantage for radars and antennas brought to operate in remote, hazardous and size/volume-sensitive (e.g. Space and flying/diving platforms) environments. Sometimes measurements are performed in places where heavy or bulky cargo is restricted. For many of these locations, extensive climbing or walking is required, and therefore heavy luggage is restricted.

Enhanced portability will also add to the versatility of Ground Penetrating Radars. Selecting the best frequency range and operating point in order to balance the tradeoff between high resolution and large penetration depth is challenging, so often these systems are equipped with several modes of operation. In addition, one type of antenna will not be suitable for all types of targets at it may be necessary to use different antennas for planar versus linear targets. A monolithic design would facilitate the storage and transport of a *multiple* common platform with different functions by allowing lightweight, low profile antennas to be used. In addition to mechanical advantages, this technology will reduce the cost, time and materials needed to manufacture the full system including a variety of easy-to-add-and-subtract antennas.



(a) (b)

Fig. 1. System level *schematic* illustration of portable radar concept

The GPR antenna(s) can be made compact and low profile using inkjet printing technology. Due to the fact that such antennas will still occupy most of the surface in the system, the most size efficient approach would be to place the remaining components within the antenna geometry itself [4].

The paper initially focuses on the mixer, the critical component used in phase detection that can be extended to the stepped FMCW radar to obtain I and Q signal components for accuracy enhanced target detection. Several key challenges are encountered in this design process such as designing a layout that is compatible for inkjet printing process, technology considerations to ensure durability of the completed structure, the development of compact low profile multiboard antennas that can be integrated into the electronics to make a true monolithic radar system. In addition, issues such as noise and Tx/Rx leakage must still be addressed, as these are the most critical complications encountered in the design of high performance FMCW radars in general.

II. Inkjet Printing Technology

The proposed fabrication technique is to inkjet print the feeding and routing circuitry onto paper and to mount the components and ICs using silver epoxy. The antenna itself can be completely printed onto paper and other flexible substrates as it has already been demonstrated in other applications [5]. Paper ($\varepsilon_r = 3\text{-}3.2$, $\tan\delta = 0.02\text{-}0.05$, thickness = 10mil) is chosen because it is the most widely abundant and low cost material known to man. It is inexpensive, lightweight, readily available in reels, conformable, recyclable and can even be made hydrophobic for increased durability. The inkjet printing of the passive circuits and antennas can be performed using a special materials inkjet printer (such as the Dematix). The piezo-controlled jetting nozzle sprays picoliter sized droplets of silver nanoparticle ink onto the paper. Several layers (typically 5-15 layers) of various conductors (e.g. Ag, Cu and Au) as well as dielectrics can printed to guarantee adequate conductivity and the finished printed structure is cured for 1-2 hours in a small industrial oven at 100°C to close the particle gaps and ensure maximum conductivity and metal thickness.

III. Mixer Circuit Design

The LT5560 (Linear Technology) mixer was used in the first design. Preliminary evaluation measurements were performed on the mixer to verify adequate performance for ground penetrating radar applications. The LO signal was mixed with a return signal sent through lossy signal channel to obtain the beat frequency that estimated the cable length.

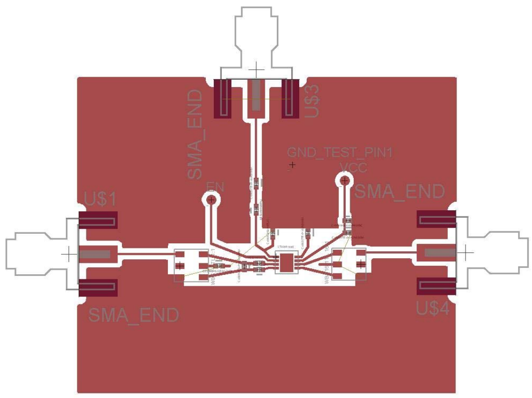


Fig. 2. Mixer Circuit layout in CadSoft Eagle.

For the first design on paper, a very simple lumped element circuit was used to match the LO and RF unbalanced inputs to balanced complex input, and the IF output. The matching circuit was optimized in ADS before selecting components.

IV. Inkjet Printing of Mixer

The components were selected so that their package feature size did not exceed the resolution of the printer. The footprints for each component were carefully constructed in CadSoft Eagle PCB Design Software (Fig 2, Fig 3). The components were placed in a configuration similar to that of PCB however with a few differences in order to cater better to the inkjet printing process. The trace width was designed to compensate for the printers tendency to spread out the transmission line width to be slightly larger than the width indicated in the footprint.

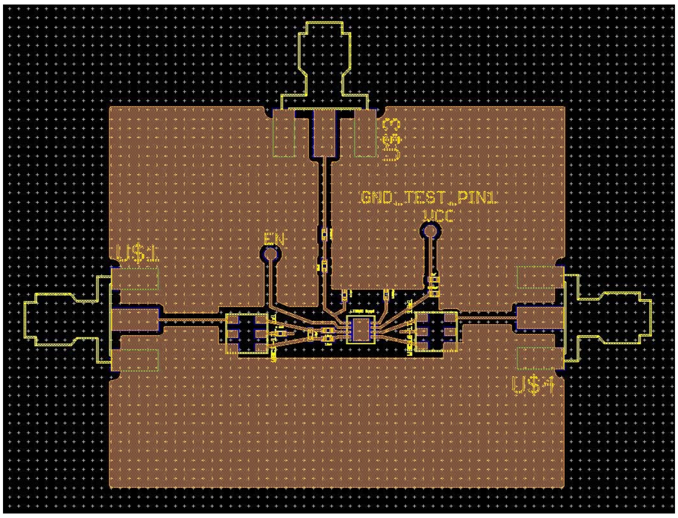


Fig. 3. Inkjet Footprint for Mixer Circuit

The RF, LO and IF ports consist of an end launched SMA connector that is to be custom fitted to the thickness of the paper. The final trace circuitry is shown in Fig 4.

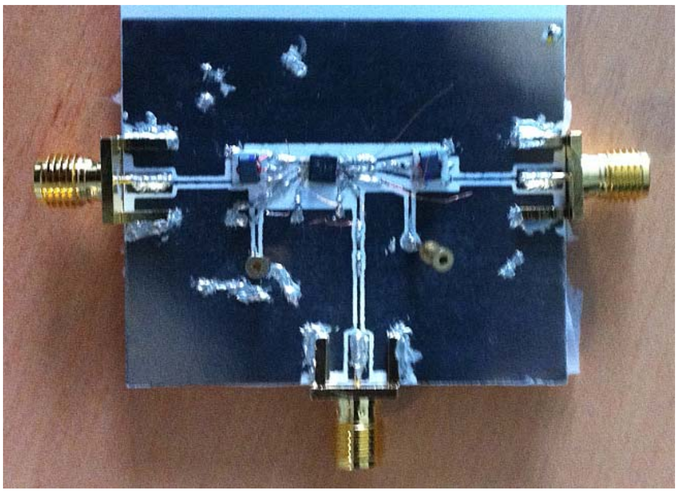


Fig. 4. Paper-based Mixer Circuit

V. MOUNTING COMPONENTS

Surface mounting devices (SMDs) such as inductors or capacitors are mounted and fixed utilizing silver epoxy. It consists of hardener and adhesive, and they should be mixed in certain ratio before applying the epoxy to circuit. The mixing ratio is different from the epoxy's compounds but a one-to-one ratio is commonly used. A curing process is required to make the mixed epoxy conductive. A typical curing setting is 80 ~ 90 ˚C for 20 minutes. The epoxy's silver concentration after curing is usually larger than 75% which results in resistance of 0.01 mΩ·m. Fig 5 shows step-by-step mounting process of SMD on inkjet-printed circuits.

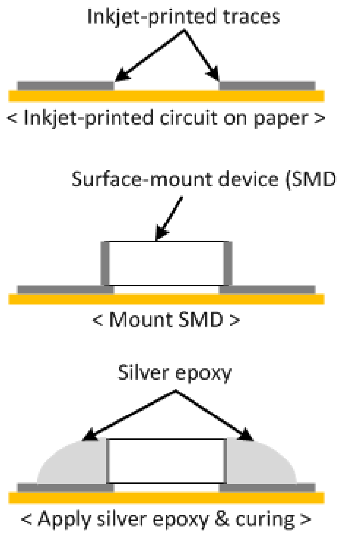
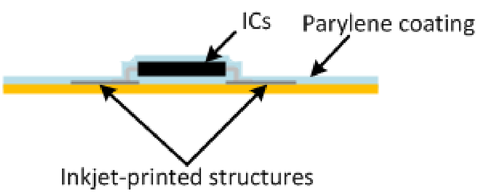


Fig. 5. Mounting process of SMD components

For ruggedness enhancement and to prevent cracking of traces or detachment of ICs and componets when bending the device, parylene is be used. Parylene (-C and -N type) is a very stable chemical and popular material for circuit protection.



(a)

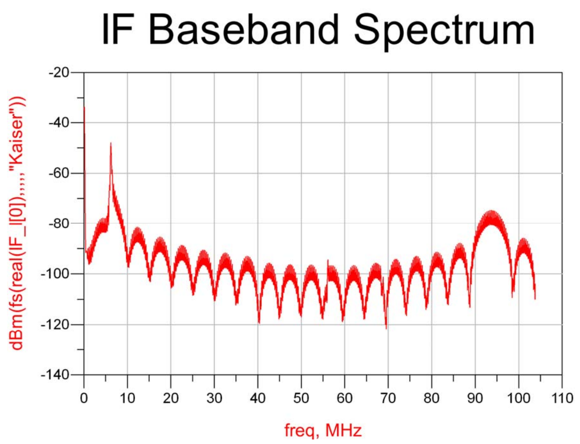
(b)

Fig. 6. Parylene coated circuit (a) before bending (b) after bending.

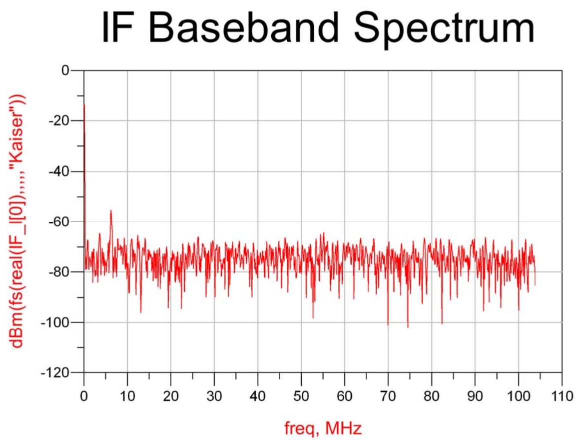
This material is biocompatible, waterproof and has very good electrical properties (ε_r = 2.4~2.95, tan δ = 6×10^{-4} ~2×10^{-3}) [6], making it ideal for the environmental protection and sealing of flexible RF circuits [7, 8]. The coating technique can be applied to inkjet-printed circuits for circuit protection. The thickness of the Parylene is usually 1 ~ 10 µm and it is controllable. The Parylene layer holds the printed structures, substrate and electronic components (such as ICs and SMDs) tightly which results in a more flexible inkjet-printed circuit as shown in Fig 6.

VI. SYSTEM LEVEL SIMULATIONS

Additional challenges in the radar design including noise and Tx/Rx coupling are being addressed through Advanced Design System simulations. Fig 7a shows the simulated beat frequency spectrum for a target 20 meters deep in ε_r = 2.25 soil and Fig 7b shows the effect of both noise and coupling.



(a)



(b)

Fig. 7. ADS beat frequency spectrum (a) ideal (b) with noise and coupling.

The simulation contained a full system level model of a Stepped FMCW Radar using the envelope simulator. New results have been obtained with an even more detailed representation of the noise and coupling effects (including the ADC) using the transient simulation and these results will be presented.

VII. ANTENNA

Several antenna designs are being investigated for the monolithic radar system. The bowtie array is a good candidate for detecting large planar targets in a limited frequency band and can be inkjet printed onto paper without difficulty. The equiangular spiral is another antenna with good performance over a large frequency range. Another potential design for a different mode of operation is a dual rhombic loop with a cross dipole in Fig. 8 [9]. It is circularly polarized making it ideal for smaller shallow more complex targets such as pipes that have depolarizing effects.

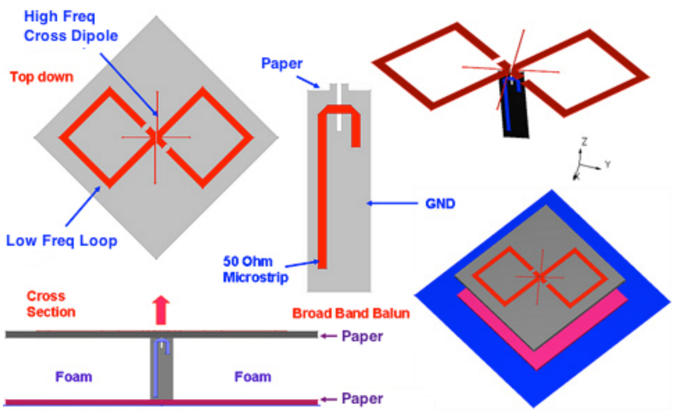


Fig. 8. Dual frequency CP rhombic Loop with crossed dipole.

As stated previously, the antenna structure will occupy most of the space of the system. If the antenna size exceeds the printer area then different parts of the antenna can be printed on different sheets and later assembled together. The final antenna structure can still be low profile and simply folded and unfolded into position for use.

VIII. CONCLUSION AND FUTURE STEPS

Delay cable test will be performed on the paper-based prototype to verify adequate performance for ground penetrating applications. This is to be conducted once the final components and testing pins have been secured onto the device. In terms of power handling capability, there are thermal solutions such as using microfluidic channel structures that can be attached to the system.

Several challenges have been presented in the design, optimization, fabrication, system integration and system reliability of the monolithic paper based inkjet-printed radar system. Other performance aspects will also need to be addressed. For example, in terms of power handling capability, there are thermal solutions available such as using microfluidic channel structures that can be attached to the system.

ACKNOWLEDGMENT

It is wished to acknowledge the "Institut de Recherche pour le Développement" in France and the US National Science Foundation (NSF) for supporting the research and development of a new FMCW radar.

REFERENCES

[1] V. Ciarletti, C. Corbel, D. Plettemeier, P. Ca"\is, S. M. Clifford, and S. E. Hamran, “WISDOM GPR Designed for Shallow and High-Resolution Sounding of the Martian Subsurface,” *Proceedings of the IEEE*, vol. 99, no. 99, pp. 1–13, 2011.

[2] H. Marshall and G. Koh, “FMCW radars for snow research,” *Cold Regions Science and Technology*, vol. 52, no. 2, pp. 118–131, Apr. 2008.

[3] B. Holt, P. Kanagaratnam, S. Gogineni, V. Ramasami, A. Mahoney, and V. Lytle, “Sea ice thickness measurements by ultrawideband penetrating radar: First results,” *Cold Regions Science and Technology*, vol. 55, no. 1, pp. 33–46, Jan. 2008.

[4] A. TAKACS, T. IDDA, H.AUBERT, H.DIEZ , “Miniaturization Technique for Quadrifilar Helix Antenna," *European Microwave Conference*, Amsterdam, NETHERLANDS, 28 October - 02 November 2012.]

[5] R. Vyas et al., “Paper-based RFID-enabled wireless platforms for sensing applications,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 5, pp. 1370–1382, 2009.

[6] H. Sharifi, R.R. Lahiji, L. Han-Chung, P.D. Ye, L.P.B. Katehi, and S. Mohammadi, "Characterization of Parylene-N as Flexible Substrate and Passivation Layer for Microwave and Millimeter-Wave Integrated Circuits," *IEEE Transactions on Advanced Packaging,* vol.32, no.1, pp.84-92, Feb. 2009.

[7] H. Lo, Y-C Tai, "Characterization of Parylene as a Water Barrier via Buried-in Pentacene Moisture Sensors for Soaking Tests," *2nd IEEE International Conference on Nano/Micro Engineered and Molecular Systems, 2007 (NEMS '07)*, pp.872-875, 16-19 Jan. 2007

[8] J. Maeng, K. Byungguk, D. Ha, and W.J. Chappell, "Parylene Interposer as Thin Flexible 3-D Packaging Enabler for Wireless Applications," *IEEE Trans. Micro. Theo. Tech.*, vol.59, no.12, Dec, 2011

[9] A.Traille and M.M.Tentzeris, “Novel Dual-Band Circular-Polarization Antennas for Universal RFID Readers and Cognitive Radio Applications”, *Procs. of the 2008 URSI Meeting*, Boulder, CO, January 2008.