3D Multilayer Integration and Packaging on Organic/Paper Low-cost Substrates for RF and Wireless Applications

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***Abstract*- In this paper, solutions for developing low-cost 3D multilayer integration and packaging on the organic substrate Liquid Crystal Polymer (LCP) and the paper substrate have been presented. The key components in RF wireless applications, namely dual band filters, dual-frequency/dual-polarization microstrip antenna arrays and an RFID tag have been designed and fabricated. Test results of the structures show good agreement between the simulation and measurement over their respective bandwidths, demonstrating stable performance of the organic/paper substrates.**

***Index Terms*—Dual-band antenna, dual-band filter, liquid crystal polymer (LCP), multilayer modules, RF and mm-waves front-end module, system-on-package (SOP), three-dimensional (3D) integration, inkjet-printing, RFID.**

I. INTRODUCTION

The rapid development of wireless communication and sensing applications in the RF/microwave/millimeter (mm) wave regimes require miniaturization, portability, cost, and performance as key driving forces in the RF electronics evolution. In addition, the use of RF in chemical and biomedical sensing and imaging also is promising, which is only expected to crowd the radio spectrum even further in the near future. Current trends have placed an ever-increasing demand on the materials, particularly dielectrics, used in the fabrication of RF devices.

As devices operate over widening bandwidths in the RF range, the substrate used should be able to support the propagation of electromagnetic fields at even higher speeds (low permittivity) without exhibiting significant electric losses (loss tangent). Additionally, substrates should be able to demonstrate these electrical properties over a wide range of frequencies and external conditions such as temperature and pressure. This property becomes particularly useful in the design of broadband applications and in minimizing power leakage into adjacent bands, which is useful especially for communications devices operating in the crowded UWB range. Lastly, substrates used in RF devices should be able to withstand the rigors (e.g. humidity) of its operating environment and of the fabrication processes used in its packaging. This paper will present the designs of various RF passive structures, commonly in use in the wireless communication modules that have been fabricated using the LCP substrate and the paper substrate at the Georgia Electronic Design Center (GEDC).

II. 3D INTEGRATED MODULE ON LCP

Liquid Crystal Polymer (LCP) is a fairly promising thermoplastic organic material [1]. It can be used as a low-cost dielectric material for high-volume large-area processing methods that provide very reliable high-performance circuits at low cost. It has impressive electrical characteristics, which is indirectly related to its low and stable water absorption rate (<0.04%). It has a nearly constant dielectric constant around 3 over the entire RF range up to 110 GHz. In addition, LCP has a very low loss tangent of only 0.002, which increases to only 0.0045 at 110GHz, thereby making LCP very suitable in designing mm-wave applications. Impressively low thermal expansion characteristics of LCP also make it ideal as a high

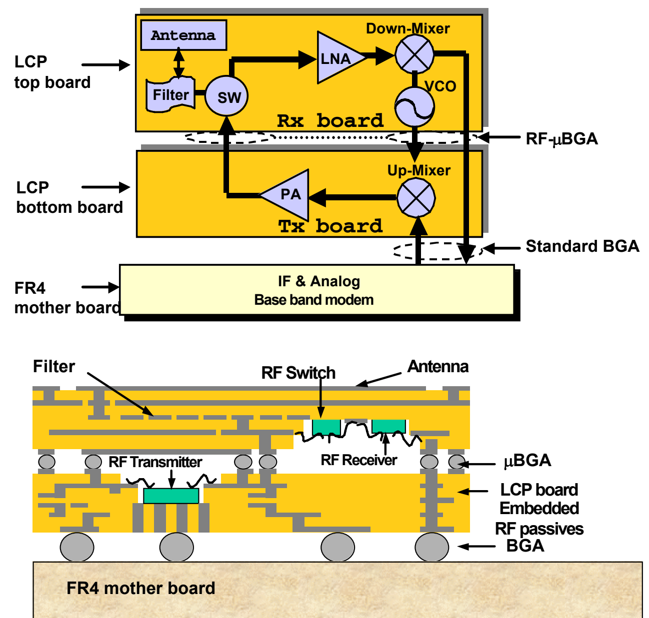


Fig. 1. 3D integrated module concept view.

frequency packaging material. The controllable coefficient of thermal expansion (CTE) of LCP can be engineered to match copper, silicon or GaAs, thereby making metallization on it easier. LCP is flexible, recyclable, impervious to most chemicals, and it is stable up to its high melting temperature making LCP an ideal choice for circuits operating in all kinds of environments. Multilayer circuits in LCP are also possible due to two types of LCP material with different melting temperatures making it ideal for System on Package Designs shown in Fig. 1. High melting temperature LCP (315ºC) can be used as core layers, while low melting temperature LCP (290ºC) is used as a bond ply. An additional benefit in multilayer LCP builds is the functionality provided by the low dielectric constant. This is useful for vertically integrated designs where the antenna is printed on the top layer of an all-LCP module.

A. SISO LCP Dual Band Filter

Passive filters often find use in the front-end modules of wireless transceivers to suppress undesired in-coming or outgoing signals and/or to increase isolation in duplexers. The presented Single-Input Single-Output (SISO) Dual band filter takes advantage of LCP's stable-with-frequency electrical characteristics to operate at two different frequencies with antennas in the UWB band. The SISO dual band filter uses the "dual behavior resonator" technique to operate at the WLAN operating frequency bands, ISM 2.4 GHz and UNII 5 GHz [2]. The dual behavior resonance technique is achieved through the use of two optimized open-ended stub resonators. The prototype dual band filter optimized to get the desired

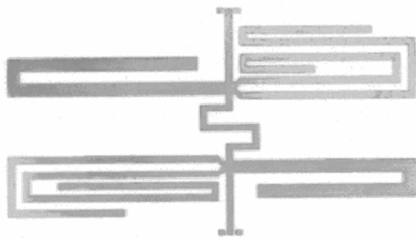


Fig. 2. Photo of fabricated SISO dual band filter on LCP

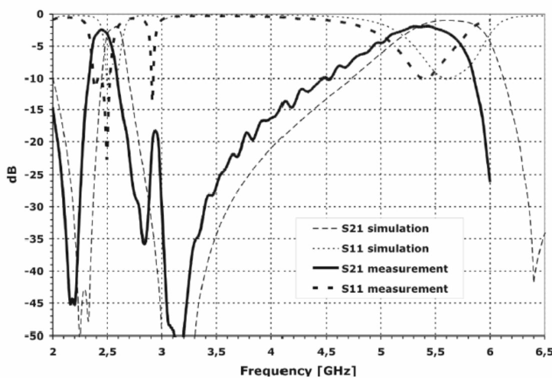
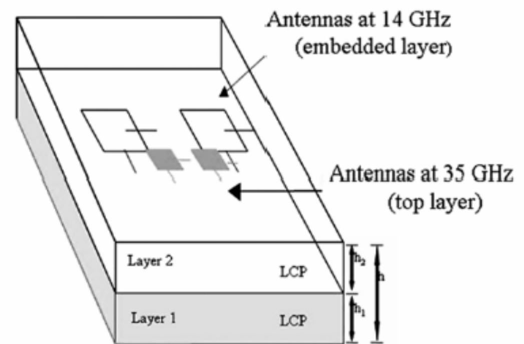


Fig. 3. Performance of the SISO dual band filter on LCP

resonant frequencies was fabricated on a 2 mil thick LCP substrate of copper thickness 9um as shown in Fig. 2. Simulations and measurement show good agreement, as depicted in Fig. 3. The insertion loss and return loss at the central frequency are 2.4dB and 15dB for the 2.4 GHz band, respectively, and 1.8dB and 10dB for the 5 GHz band, respectively. It exhibits also an out-of-band rejection as high as 45 dB between the L and C band.

B. Dual-frequency/dual-polarization Antenna Arrays

Two dual-polarization antenna arrays on LCP multilayer laminated substrates have been designed at operating frequencies of 14 and 35 GHz for precipitation remote sensing applications. The top view of the fabricated antenna arrays is shown in Fig. 4 [3]. The metal was copper (Cu) and had a thickness of 18 m. The total substrate thickness for the design was 425 m, consisting of two LCP layers (each 200 m thick) and a 25 m bonding layer. The substrate thickness was chosen to achieve at least a 1.5% impedance bandwidth at dB, while maintaining a compact structure. The 14-GHz antenna array was placed on the top layer of the LCP substrate, while the 35-GHz antenna array was "sandwiched" between two embedded layers for compactness and crosstalk minimization reasons. The LCP layer under the 35 GHz antenna array had a thickness of 200 m. Both arrays were fed by microstrip lines printed on the same layer as the corresponding array.



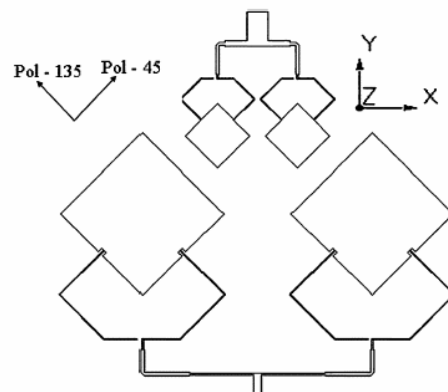
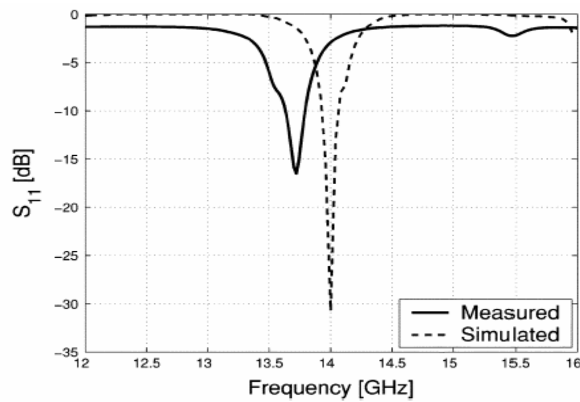
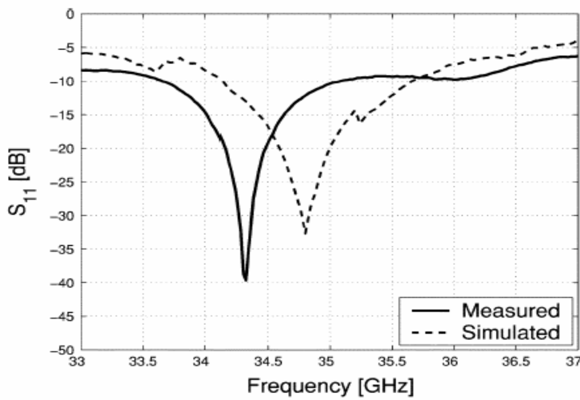


Fig. 4. Multilayer antenna array architecture



(a)



(b)

Fig. 5. Simulated and measured return loss: (a) 14GHz (b) 35GHz

The simulated and measured return loss plots versus frequency are shown in Fig. 5. The dual-frequency array was excited at one frequency, while the other array was treated as a parasitic element. The shift in the resonant frequency can be attributed to fabrication tolerances. The discrepancy in return loss at 14 GHz is due to the extension of the feedline of the embedded (14 GHz) antenna to a point where the top laminated layer of the substrate no longer covers the feedline, thus, modifying its characteristic impedance. The measured impedance bandwidths at both frequencies are in good agreement with those of the simulated designs.

III. 3D INTEGRATED MODULE ON PAPER

Paper has been considered as one of the best organic substrates for low-cost RF/microwave applications, such as Radio Frequency Identification (RFID). First of all, paper is environmentally friendly and can undergo large reel to reel processing. In terms of mass production and increased demand, this makes paper the lowest cost material made. Paper also has low surface profile with appropriate coating. This is very crucial since fast printing processes, such as conductive paste inkjet printing, can be used instead of metal etching techniques, something that will allow for the decrease of the cost down to a few cents for passive tags. In addition, paper is compatible with circuit printing by direct write methodologies. This is one of the biggest advantages of paper since active tags require additional modules like sensors and batteries to be mounted on or embedded in. A fast process like inkjet printing can be used efficiently to print these modules on or in the paper substrate. Paper can also host nanoscale additives, such as fire retardant textiles, and can be hydrophobic. Paper substrate can excellently handle high temperature treatment during the assembly process and the reliability/life time is very high compared to other substrates such as plastic. In addition to this, low thickness can be easily achieved with paper.

Fig. 6 demonstrates the suggested fabrication steps for the development of multilayer 3D coplanar multilayer microwave circuits on paper substrate. Heat-bonding is used to laminate sheets of paper to grow substrate thickness. In experiments, the low melting temperature of the hydrophobic layer covering the paper substrate was found to have a positive effect in ensuring a good adherence. Inkjet-printing is used to realize transmission lines, resistors, capacitors and inductors on the paper surface, following by a curing process. Inkjet-printing is a direct-write technology by which the design pattern is transferred directly to the substrate, and there is not requirement of masks compared with the traditional etching technique which has been widely used in industry. Besides that, unlike etching which is a subtractive method by removing unwanted metal from the substrate surface, inkjet-printing jets the single ink droplet from the nozzle to the desired position, therefore, no waste is created, resulting in an economical fabrication solution. Fig. 7 demonstrates a low-cost paper-based inkjet-printed RFID tag and the simulated/measurement input impedance results. Overall, a very good agreement was observed over the frequency band of interest.

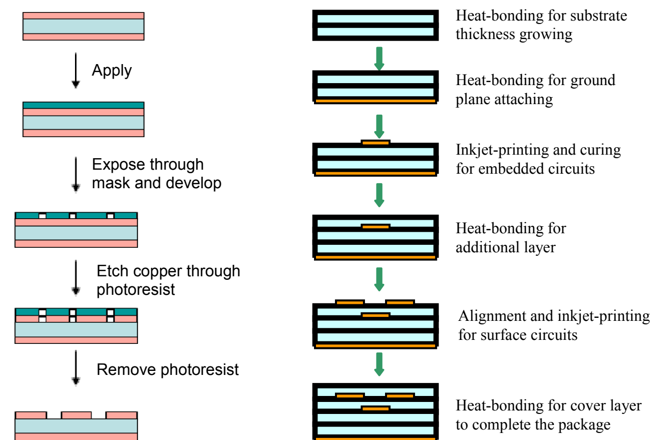
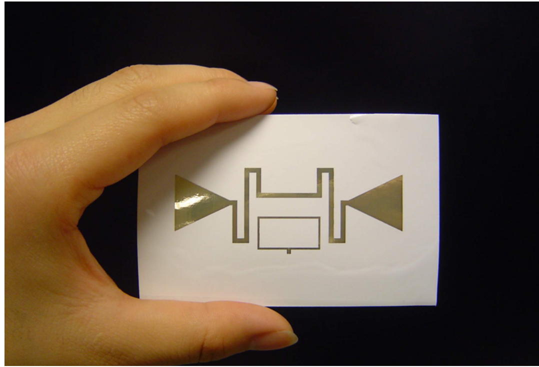
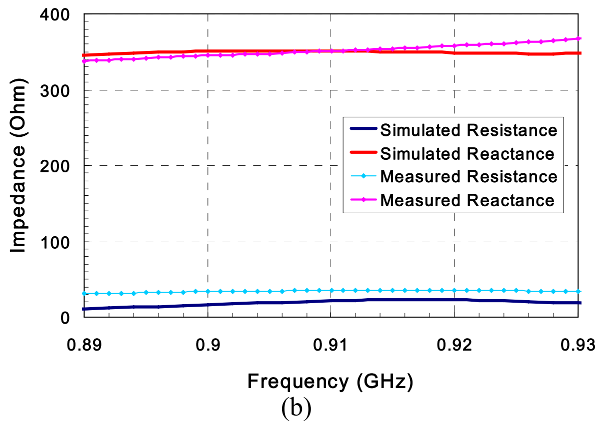


Fig. 6 comparison of the traditional wet-etching technique and the proposed passive microwave circuit embedded process in paper substrate



(a)



(b)

Fig. 7. (a) Photograph of the designed RFID tag with inkjet-printing process (b) Measured and simulated input resistance and reactance of the inkjet-printed RFID tag

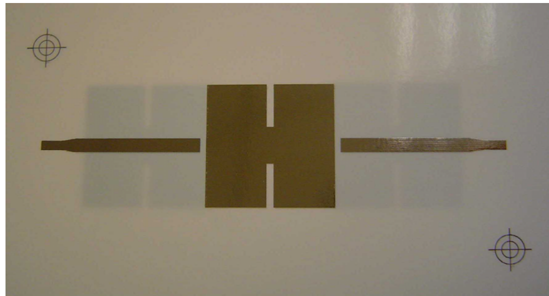


Fig. 8. Photograph of the three-stage inkjet-printed multilayer patch resonator BPF after the laminating process

A three-stage slotted-patch band pass filter for 2.4GHz WLAN application was designed and printed on/in paper substrate to demonstrate the feasibility of this solution. Three laminated paper layers are used. The feeding lines and the middle stage of the filter are realized on the surface layer, while the first and third stages of the filter are embedded in the middle layer. The circuit layout on each layer was inkjet-printed independently at the first step. After alignment, the PHI laminator Q-247C4 was utilized for the bonding process, while 10 tons RAM force was applied under 93 ºC. The fabricated multilayer patch resonator BPF is shown in Fig. 8. It has to be noted that a paper-based multilayer technology would allow for the light-weight miniaturization of "cognitive" sensing devices, through the embedding of IC's, as well as of printed batteries, sensors and power scavenging devices.

IV. Conclusion

In this paper, we present the 3D multilayer integration and packaging technology on organic/paper low-cost substrates. Dual band pass filters, dual-frequency/dual-polarization microstrip antenna arrays and an RFID tag have been realized on LCP and paper substrates, respectively. The RF passive designs show good agreements between simulated and measured results over their respective bandwidths thus showcasing the impressively stable performance of LCP and paper as low-cost substrates for multilayer RF/wireless modules.

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