Advanced Polymers for Advanced RF Packaging Applications

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Abstract— **This paper presents advanced polymers for RF packaging applications including filters and antennas. First, micro-scaled LCP technology for front-end modules is presented. Next, nano-scaled ultra-thin RXP technology is introduced with its integration capability and embedded passive performances. Simulated results of bandpass filter, and antennas for 60 GHz are also presented in this paper. RXP technology provides low cost and promising high performance solution for wireless applications operating around microwave and millimeter frequencies. Magneto-dielectric substrates are proposed for effective miniaturization of antennas.**

I. INTRODUCTION

As a rapidly increasing segment of communications industry, wireless communications have been a major aspect of everyday life. From hundreds of MHz to millimeter wave frequency, the evolution of wireless communications includes several indispensible technologies such as cellular communications, wireless local area networks (WLANs), ultra wide band (UWB) and wireless personal area networks (WPANs). The consumer demand for accessing these radio technologies in compact devices has been pushing RF engineers for low-cost, effective integration and miniaturization of RF components. There has been a considerable amount of effort in the past years to find and implement novel packaging technologies to achieve this goal.

Recently, an advanced technology operating around 60GHz (V-band) has been emerging for high-speed short-range wireless communications and WPANs. The high-speed communication and miniaturization factors that can be achieved at 60GHz are especially attractive compared to those that can be achieved at WLAN/WiMAX frequencies (< 10GHz). However, this emerging technology brings new challenges regarding the performance and the maturity of the available integration techniques to support 60GHz wireless communications.

System-on-package (SoP) technology has been proved to provide low-cost highly-integrated modules for the aforementioned wireless applications. SoP architecture is based on integrating high-speed digital, RF and passive components in a compact multilayer substrate. Therefore, in an SoP architecture, the substrate not only provides the mechanical support but also becomes the medium for the electromagnetic wave propagation between the embedded components. This makes the selection of the substrate material critical since the characteristics of wave propagation and capabilities of the technology are determined by the substrate parameters. Hence, advanced packaging technologies require using advanced packaging substrates.

Low temperature co-fired ceramic (LTCC) technology has been a popular solution for applying SoP in both microwave and V bands to integrate RF components and the antenna in a multilayer substrate. Although, high dielectric constant and the low loss tangent of the LTCC substrate have been advantageous for the miniaturization and the integration of RF components, LTCC may not provide a long-term effective packaging solution because of higher processing temperature (> 900°C), larger manufacturing variation, difficulty of embedding actives, bulkier substrate, and higher cost as compared to multilayer organic technologies (MLO) [1].

Liquid crystalline polymer (LCP) has been shown to be a promising organic material with superior electrical properties up to millimeter-wave frequencies [2]. LCP-based MLO substrates have been reported to achieve highly-integrated RF systems [1]. Recently, another organic dielectric material, called RXP, has been proposed to eliminate the limitations of LCP by expanding micro-scale SoP to nano-scale SoP [3].

Another type of novel materials called magneto-dielectrics, materials with $\varepsilon_r > 1$ and $\mu_r > 1$, has been proposed to overcome the limitations of dielectric substrates for effective antenna miniaturization. It has been reported in [4] that magneto-dielectrics can be used to miniaturize the antenna while improving the bandwidth and the radiation properties, which cannot be achieved with high-permittivity dielectrics. In this paper, therefore, these novel packaging materials are presented with their advantages and limitations.

II. LIQUID CRYSTALLINE POLYMER (LCP)

LCP (Ultralam 3850) is a laminate-type organic dielectric material that can be stacked to form multilayer substrates with the use of adhesive bondply layers (Ultralam 3908) in between stacked LCP layers. In addition to being a low-cost dielectric for a large panel area fabrication process, LCP has a combination of good electrical and mechanical properties. LCP has a low dielectric constant of $\varepsilon_r = 2.95$ and a low loss-tangent of 0.002 up to millimeter wave frequencies. LCP also has favorable mechanical properties such as mechanical flexibility, a low coefficient of thermal expansion, and low moisture absorption. Furthermore, LCP has the mechanical strength to be the final printed wiring board (PWB), making it an excellent packaging substrate for SOP applications [2].

As shown in Fig. 1, previous work on RF SoP has shown that high performance front-end modules with significant size reduction can be designed by 3-D integration of RF front-end functional blocks into LCP-based MLO substrates. Full-system integration along with the antenna can be achieved using conformal antenna configuration exploiting the mechanical flexibility of LCP [4]. Applications using multi-layer LCP technology have been commercialized by Jacket Micro Devices, a spin-off company from Georgia Tech [6].

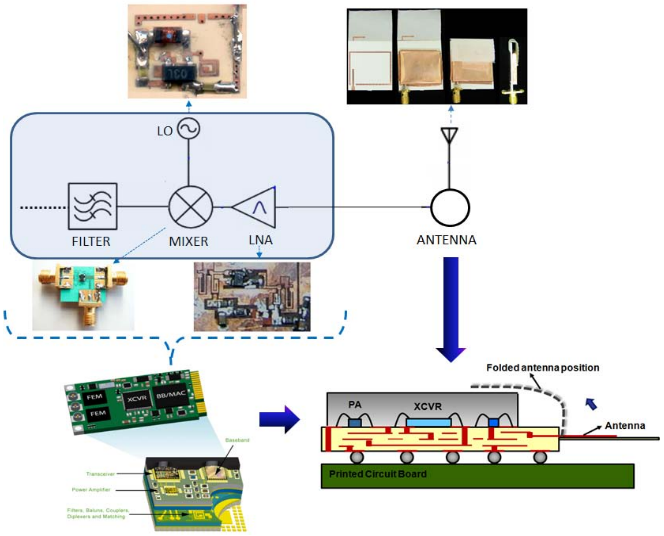


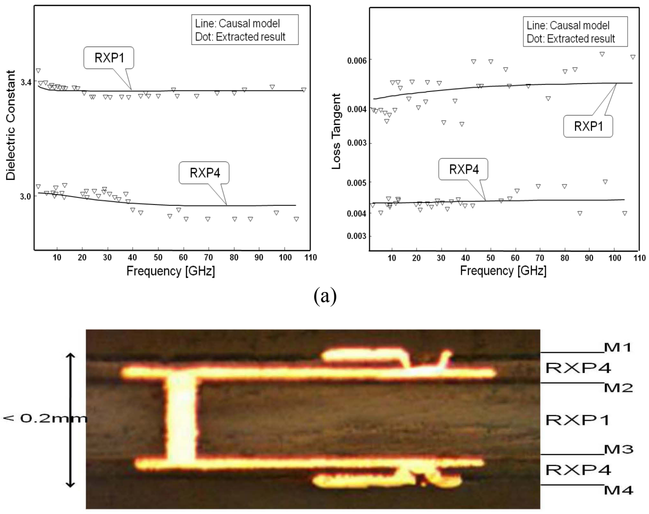
Fig. 1. RF SoP integration based on multilayer LCP-based substrates. The references for the designs shown in the figure can be found in [4].

In spite of the good RF performance and integration capability of LCP, LCP-based MLO technology suffers from a few limitations due to relatively high processing temperature (290^{o}C) compared to FR-4, which is a bottleneck for low cost system integration. Additionally, the need for the bondply material for building stack-ups results in fabrication limitations because of the misalignment of the layers. A new organic material, RXP, can help to overcome these limitations as explained in the following section.

III. RXP

Recently, the micro-scale SoP is being extended to nano-scale SoP based on ultra-thin novel organic dielectric material called RXP. Unlike the bondply layer of LCP, RXP4, one of the RXP variants, can be made ultra-thin (as thin as 20 μm) under a low processing temperature (220^{o}C), which is compatible with standard printed circuit board manufacturing processes.

Similar to LCP, RXP is a low-loss dielectric with a stable frequency response up to 110GHz, being suitable for both microwave and millimeter wave RF applications. The dielectric constant and the loss tangent of the core RXP1 was characterized to be ε_r=3.41±0.06 and tanδ<0.006 up to 110GHz. The dielectric constant and the loss tangent of the build-up RXP4 was characterized to be ε_r=2.98±0.05 and tanδ<0.0053 up to 110GHz as shown Fig. 2a [3].

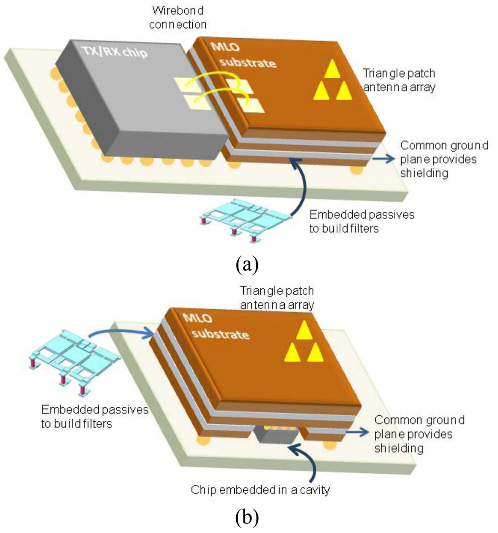


(a)

(b)

Fig. 2. (a) Extracted properties (b) Cross-section of RXP.

Fig. 3 captures the integration techniques targeted using RXP-based MLO substrates. As shown in Fig. 3a, RXP-based MLO substrates can be designed as a separate substrate for the antenna and the passive front-end components. Next, a higher-level integration can be achieved by embedding the chip in a cavity constructed in the MLO substrate as shown in Fig. 3b.



(a)

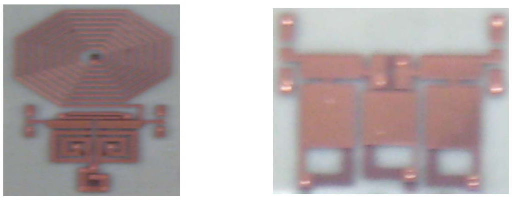
(b)

Fig. 3. Conceptual integration techniques for RXP-based MLO substrates. (a) MLO as a separate substrate housing passive components. (b) Chip embedded in a cavity in the MLO substrate.

Although, exploring the capabilities of RXP-based substrates is on-going, filters and antennas, key passive elements of front-end modules, have been designed and implemented on RXP-based substrates. The filters presented in this paper were designed on a four-metal layer RXP stack-up with a total thickness of 0.191mm. The cross-section of the stack-up is shown in Fig. 2b.

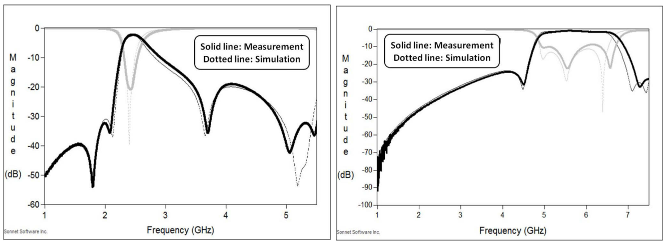
A. Design of WLAN Filters

This section presents two filter prototypes that were designed and measured in RXP substrate targeting the sharpest commercially challenging rejection requirements. Filters fabricated using RXP material have resulted in some of the smallest size filters in the world with excellent performance for WLAN applications [5, 6]. 2.45GHz filter is based on second-order capacitively-coupled resonator with grounding inductor topology, and 5GHz filter is based on third-order unique resonators with feedback capacitor and grounding inductor. The fabrication prototypes are shown in Fig. 4, and measurement with simulation results are shown in Fig. 5.



(a) (b)

Fig. 4. Experimental prototype of (a) 2.45GHz and (b) 5GHz BPFs



(a) (b)

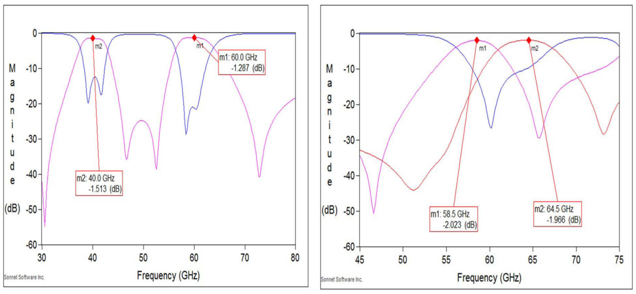
Fig. 5. Measured and simulated (a) 2.45GHz and (b) 5.5GHz BPFs.

Measured responses showed good correlation with simulated responses. For 2.45GHz, measured insertion loss of less than 2.3dB and return loss of less than 20dB at center frequency were achieved. 30 dB rejection at 2.12 GHz and 29 dB rejection at 4.8 GHz were measured. The third-order 5GHz filter exhibited a center frequency of 5.5GHz with 3dB bandwidth of 1.7GHz. The return loss was low 20dB, and the insertion loss was 1.09dB at the center frequency. Furthermore, better than 28dB rejection at 4.4 GHz and 7.2GHz were achieved, which is ideal for rejecting unwanted signals with satisfying commercial challenging rejection specifications.

B. Design of 60 GHz Filter and Duplexer

There are several challenges such as low insertion losses and high rejection requirement for integration of 60GHz filters. In [7], a cavity resonator-based bandpass filter was designed using low-temperature co-fired ceramic (LTCC), which has relatively higher cost than to organic technologies. The insertion loss of 2.4dB for 3.5% 3dB bandwidth was measured. Another work by [8] employed an integrated waveguide-based bandpass filter using LCP. The insertion loss of 1.8dB for 13% 3dB bandwidth at 60GHz was measured.

In this paper, a two-pole dual-band bandpass filter with four transmission zeroes is presented in ultra-thin (<0.2 mm) RXP substrate. The low insertion loss of 1.3dB for 10% 3dB bandwidth at 60GHz and 1.5 dB for 40 GHz were achieved. A duplexer with RX (57-60GHz) and TX (62-66GHz) bands from two bandpass filters and matching networks was also designed with total area of 2.2 mm^2. The simulated filter and duplexer responses are shown in Fig. 6.

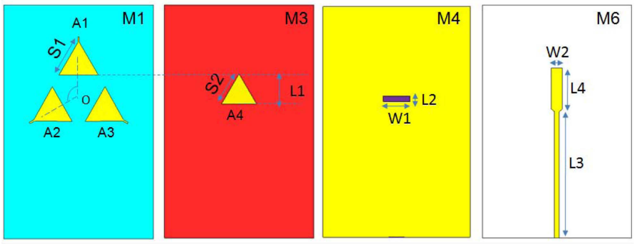


(a) (b)

Fig. 6. Simulated results for 60GHz (a) dual-band filter, (b) duplexer.

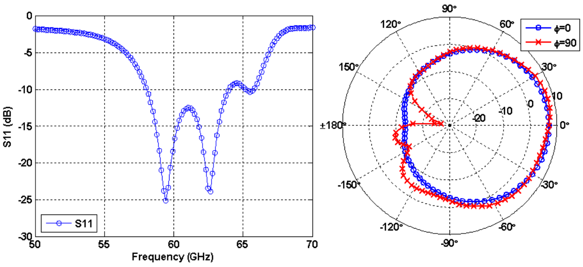
C. Design of Stacked Triangular Patch Antenna

Microstrip patch antennas have numerous attractive features such as low profile, low cost, and easy fabrication. The primary limiting factor in the use of microstrip patch antennas is their inherently narrow bandwidth. Stacked patch antennas implemented on multilayer substrates have been proposed to increase the bandwidth of patch antennas. Recently, a parasitically coupled stacked rectangular patch antenna array on a 1.1mm thick multilayer Teflon substrate was proposed in [11] for the V-band applications.



(a) (b) (c) (d)

Fig. 7. Details of the stacked triangle patch antenna array. (a) Parasitic patches on metal layer M1, (b) Feeding patch on metal layer M3, (c) Ground plane on metal layer M4, (d) Microstrip line on metal layer M6.



(a) (b)

Fig. 8. Simulated (a) S11 (b) far field pattern.

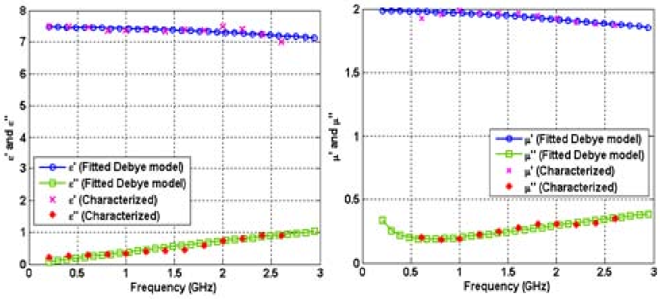
RXP-based multilayer substrates provide a low-profile, low-loss substrate for the stacked patch antenna arrays at 60GHz. A stacked triangle patch antenna array is presented in this paper in a six-metal layer RXP-based substrate with 329μm thickness. The details of the proposed stacked triangle patch antenna array are shown in Fig. 7. Although, the substrate used is composed of six metal layers, only four of them were employed in this design. The array has four triangle patch elements, one of which is excited through aperture coupling of a microstrip line. The other three patches are aligned on the tips of the main antenna and are excited through parasitic coupling.

As seen in the simulated S11 of the antenna array in Fig. 8 (a), 11.67% bandwidth requirement for 60GHz applications was achieved by merging coupled resonances. 8 (b) shows the simulated far field of the optimized design at 60GHz. Simulated peak gain of the antenna was found to be approximately 7 dB along the desired frequency band.

IV. THIN-FILM MAGNETO-DIELECTRIC MATERIALS

Large size of the antenna compared to other RF components is a bottleneck for full-system integration, especially for the microwave frequencies. On the other hand, antenna miniaturization is a difficult problem since the gain and the bandwidth of the antenna are bounded with fundamental limits depending on the size of the antenna. It was shown in [4] that, a novel category of materials called magneto-dielectrics can be used for efficient miniaturization of the antenna. However, the absence of magneto-dielectric materials in nature requires the synthesis of these materials artificially.

Polymer composite thin-films based on insulator-coated nickel (Ni) and cobalt (Co) nanoparticles have been found promising to provide stable and low-loss magneto-dielectric properties. In this synthesis approach, high ε_r and μ_r of the material is sustained with the inclusion of magnetic nanoparticles; whereas, the insulating shell prevents the material loss while improving the stability with frequency [9].



(a) (b)

Fig. 9. Characterized results for sample board (a) ε= ε'- jε" and (b) μ= μ'-j μ".

Several batches have been fabricated and characterized to verify the material synthesis process. The metrology published in [9] was used to characterize the substrates. Fig. 9 shows characterized results from a sample test vehicle. As seen in the figure, $\varepsilon_r \sim 7.5$ and $\mu_r \sim 2$ was characterized and fitted to Debye models up to 3GHz. The substrate was characterized to be a lossy substrate due to oxidation and agglomeration of the nanoparticles. The efforts to decrease the loss of the substrate using alternate routes such as solution reduction methods are on-going.

V. CONCLUSIONS

This paper has presented low-cost packaging solutions using advanced polymers. LCP-based RF front-end functional blocks have been presented in this paper. Moreover, it has been shown that nano-scaled SoP solution based on RXP implementation proposed in this paper leads to size reduction with high integration for filter and antenna design. Finally, thin-film magneto-dielectric substrates based on insulator-coated nano-particles have been discussed for efficient miniaturization of the antenna. Based on work provided here, high-performance advanced polymer with very attractive qualities can provide high-performance packaging solutions for RF applications.

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