RF System Integration and Miniaturization using Advanced Polymers

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ABSTRACT — This paper presents the design of filters and antennas in advanced polymers based on a new material called RXP. Integration capability of the RXP and the performance of WLAN filter design have been verified through the measurement data presented in this paper. Simulated results of 60GHz filters and antennas are also included in this paper. RXP provides low cost and promising high performance advanced polymer solution for wireless applications operating around microwave and millimeter frequencies.

Index Terms — Antenna, bandpass filters, lumped-element, multilayer, RXP, SoP, WLAN, WPAN, 60GHz.

I. INTRODUCTION

Wireless communications have been a major aspect of everyday life, making it a rapidly increasing segment of communications industry. The evolution of wireless communications includes several indispensible technologies such as cellular communications, wireless local area networks (WLANs), and ultra wide band (UWB) technology spanning the frequency range from 800MHz to 10GHz. The consumer demand for accessing these radio technologies from a single handheld device has been pushing RF engineers for 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.

Another technology operating around 60GHz (V-band) has been emerging recently for high-speed short-range wireless communications and wireless personal area networks (WPANs). The miniaturization factors and high-speed communication that can be achieved at 60GHz are especially attractive compared to those that can be achieved at WLAN/WMAX frequencies. However, this emerging technology brings new challenges by widening the frequency range of interest for the mobile wireless industry to include millimetre wave frequencies. Another issue arises regarding the performance and the maturity of the available integration techniques to support 60GHz wireless communications.

Several packaging technologies have been proposed to achieve RF integration for the aforementioned wireless bands. Low temperature co-fired ceramic (LTCC) technology has been a popular solution for both WLAN and V bands, providing a multilayer substrate to integrate RF components and the antenna. High dielectric constant and the low loss tangent of the LTCC substrate have been advantageous for the miniaturization and the integration of RF components. However, LTCC may not provide a cost effective packaging solution due to higher processing temperature (>900°C) and larger manufacturing variation as compared to multilayer organic technologies (MLO) [1]. Therefore, system-on-package (SoP) solution based on liquid crystalline polymer (LCP) has been considered as a promising candidate for RF system integration due to its superior electrical properties up to millimeter-wave frequencies [2]. However, LCP is based on a relatively high processing temperature (290°C) compared to FR-4, which is a bottleneck for low cost system integration.

Recently, the micro-scale SoP is being extended to nano-scale SoP based on ultra-thin organic dielectric material called RXP. Unlike LCP, RXPs variant, can be made ultra-thin (down to 20um) under a low processing temperature (220°C), which is compatible with standard printed circuit board (PCB) manufacturing processes [3]. Fig. 1 captures the integration techniques aimed to be achieved using multilayer RXP-based substrates introduced in this paper.

As a first step of integration, RXP-based MLO substrates can be designed as a separate substrate for the antenna and the passive front-end components, as shown in Fig. 1a. Next, the integration can be further improved by placing the chip in a cavity constructed in the MLO substrate, as shown in Fig. 1b.
This paper is organized as follows. In section II, the material properties of RXP are introduced. Filter designs both for WLAN and V-band applications implemented in RXP-based multilayer substrates are explained in section III. In section IV, circularly polarized antenna designs for V-band applications in the same RXP-based MLO substrates are presented. Finally, the paper is summarized with a conclusion.

II. MATERIAL PROPERTIES OF RXP

Packaging materials with stable dielectric properties at low frequency may have frequency-dependent dielectric properties at RF frequencies. Since mobile applications operate at high frequencies, it is necessary to characterize materials as a function of frequency. Microwave techniques for characterizing materials can be broadly classified into two techniques, namely non-resonant and resonant based methods. Non-resonant based methods use wave propagation on a transmission line to extract dielectric properties over a continuous frequency range of interest [4]; whereas, resonant based methods are used to extract dielectric properties at discrete frequencies corresponding to the resonant frequency of the device. The advantage of the resonator based method is its sensitivity to small changes in low loss dielectric properties [5]. A resonant based method has; therefore, been used in this paper.

In [5], split-cylinder resonator was used to extract material properties. However, asymmetrical movement of the two terminations results in considerable measurement error using this approach, especially at high frequencies. In [2], LCP was characterized using microstrip ring resonators and cavity resonators from 30 to 100GHz. The methods mentioned above are suitable for characterization of relatively thick dielectric materials. However, the methods may be inaccurate for characterizing ultra-thin dielectric materials at millimeter frequencies where conductor surface roughness may be dominant.

To overcome the limitation, the cavity resonator method using corner-to-corner probing was used to characterize organic dielectric material at microwave frequencies. Using the cavity resonator method, the dielectric properties of next generation thin dielectrics, RXP1 and RXP4, were characterized up to 110GHz [3]. For characterization, scattering parameters of the cavity resonator were measured using vector network analyzer. Surface profiler was used for surface roughness, and dielectric thickness was measured using cross-sectioning. Fig. 2 shows the extracted dielectric constant and loss tangent of RXP materials as well as its Debye model that can be directly used in electromagnetic simulators. RXP shows superior dielectric properties for RF applications.

The extracted dielectric constant and loss tangent of core RXP1 was $3.41 \pm 0.06$ and $\tan \delta < 0.006$ up to 110GHz, respectively. The extracted dielectric constant and loss tangent of build up RXP4 was $2.98 \pm 0.05$ and $\tan \delta < 0.0053$ up to 110GHz, respectively.

![Fig. 2. (a) Extracted dielectric constant and (b) loss tangent with Debye model of RXP1 and RXP4.](image)

III. INTEGRATED RXP-BASED PASSIVES

This section presents passive elements of the key RF modules that were implemented in the RXP technology. All of passive components were designed using integrated lumped-element inductors and capacitors and hence, the designs are fully-embedded.

A. Design of WLAN filter

In RF applications, a filter is an essential device for transmitting passband signals and rejecting stopband signals, which requires low insertion loss at passband frequencies and high rejection at stopband frequencies. A major challenge for the filter design is to obtain sharp rejection at the stopband frequencies corresponding to the transmitter and receiver in a wireless module.

This section presents several filter prototypes that were designed in RXP substrate targeting the sharpest rejection requirements. 2.45GHz and 5.5GHz lumped-element bandpass filters were designed and fabricated in RXP substrate [6, 7]. 2.45GHz filter is based on second-order capacitively-coupled resonator with grounding inductor topology and 5.5GHz filter is based on third-order unique resonators with feedback capacitor and grounding inductor. The sizes of designed filters are $2.2 \times 3.0 \times 0.191 \text{ mm}^3$ for 2GHz and $2.6 \times 2.1 \times 0.191 \text{ mm}^3$ for 5GHz as shown in Fig. 3, and measurement with simulation results are shown in Fig. 4.
Fig. 3. Physical layout of (a) 2.45GHz and (b) 5.5GHz BPFs

Fig. 4. Measured and simulated (a) 2.45GHz and (b) 5.5GHz BPFs.

Measured responses show good correlation with simulated responses. For 2.45GHz, measured insertion loss of less than 2.2dB and return loss of greater than 15dB at 2.4GHz were achieved and rejection of greater than 30dB below 2.0GHz and 35dB at 4.7GHz was achieved. The third-order 5GHz filter exhibits a center frequency of 5.5GHz and a 3dB bandwidth of 1.7GHz. The return loss is low 20dB, and the insertion loss is 1.09dB at the center frequency. Furthermore, better than 28dB rejection at 4.4GHz and 7.2GHz are achieved, which is ideal for rejecting unwanted signals with satisfying commercial challenging rejection specifications.

**B. Design of 60GHz Filter and Duplexer**

Multimedia applications such as wireless internet require wireless transmission over short distance. 60GHz V-band is special interest for such wireless communication applications because of its specific rejection characteristic of atmospheric oxygen (10-15dB/Km) [8]. There are several challenges such as low insertion losses and high rejection specifications for integration of 60GHz filters.

In [9], a cavity resonator-based bandpass filter was designed using low-temperature co-fired ceramic (LTCC), which is relatively high cost compared to organic technologies. The low insertion loss of 2.4dB for 3.5% 3dB bandwidth was measured. In [10], an integrated waveguide-based bandpass filter was designed using LCP. The low insertion loss of 1.8dB for 13% 3dB bandwidth at 60GHz was measured.

In this paper, a two-pole coupled bandpass filter with two transmission zeroes is designed on ultra-thin (<0.2 mm) RXP substrate. The low insertion loss of 1.6dB for 10% 3dB bandwidth at 60GHz was achieved. The simulated frequency response of the filter is shown in Fig. 5.

Fig. 5. Simulated response of 60GHz bandpass filter.

A duplexer with RX (57-60GHz) and TX (62-66GHz) bands consisting of two bandpass filters and matching networks was also designed with size of 2.2 mm². The simulated frequency response of the duplexer is shown in Fig. 6.

Fig. 6. Simulated response of duplexer.

**IV. DESIGN OF 60GHz ANTENNA**

In addition to the advantages regarding the size and the throughput of the system, the high carrier frequency around 60GHz bring several challenges, such as increased path-loss and indoor material attenuation, and increased multipath interference due to reflections from small objects. This brings importance on the antenna selection at 60GHz. Preliminary studies on the characterization of the channel at 60GHz show that directional antenna with circular polarization can be used to improve system performance by reducing the multipath contributions [11].

To realize the required antenna design for 60GHz wireless communications, a linearly polarized triangular microstrip patch antenna was designed on a multilayer RXP stack-up using proximity coupled feed. Triangle antenna was chosen since it can provide the same performance in a more compact size compared to rectangular patch antenna. The antenna was then converted to a circularly polarized antenna by using several techniques proposed in the literature [12]. These techniques include adding a stub at the tip of the patch, inserting a slot parallel to the base of the triangular patch, and inserting two perpendicular slots, as shown in Fig. 7 (a), (b) and (d), respectively. The number of the stubs can be
increased for tuning purposes, as shown in Fig. 7 (c). Additionally, an asymmetric feed was used to achieve the desired circular polarization. All of these methods were successfully implemented to split the dominant TM10 mode into two near-degenerate modes, achieving circular polarization.

![Fig. 7. Antenna configurations to achieve circular polarization. (a) A stub at the tip of the antenna, (b) A slot parallel to the base of the triangle, (c) Additional stub, (d) Crossing slots in the center of the triangle.](image)

The variables used for optimizing the antenna performance are the width and the length of the stubs, the width and the length of the slots, the length of the side of the triangular patch, the offset and the position of the feeding line passing under the antenna. Fig. 8 (a) shows the simulated return loss of several designs optimized for 60GHz wireless band. In most cases, two resonances, one due to the stub and the other one due to the patch, were merged to achieve the desired frequency coverage. An example of the simulated far field pattern of the antennas designed on E-plane is shown in Fig. 8 (b). As seen in the figure, good circular polarization performance can be achieved. Far-field pattern in H-plane is similar to the pattern in E-plane since the antenna has a broadband pattern. The axial ratio can be improved by tuning the same variables used to tune the return loss of the antenna.

![Fig. 8. Simulated (a) return loss (b) far field pattern.](image)

V. Conclusion

This paper has presented low cost packaging solutions for integrating WLAN and 60GHz wireless communication applications including the bandpass filter, the duplexer and the antenna. It has been shown that the RXP implementation proposed in this paper leads to size reduction with high integration. RXP is a high-performance ultra thin advanced polymer with very attractive qualities as a packaging material for RF applications.

REFERENCES