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Miniaturized and high-performance RF packages with ultra-thin glass substrates

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ABSTRACT

Advanced RF packages are demonstrate with active (low-noise amplifier, RF switch) and passive integration in ultra-thin 3D glass packages with miniaturization and enhanced performance. The novelty of this RF packages is three-fold: 1) Ultra-thin 100 μm glass, 2) Double-side thinfilm RF circuits interconnected with Through-Package Vias (TPVs), and 3) Direct assembly of the glass-core package to the board with Land Grid Array (LGA) connections. An innovative double-via process, starting from prefabricated vias in bare glass, polymer filling and via drilling, is utilized for a robust and high-yield substrate fabrication process. Scalable and low-cost panel laminate processes are utilized to form the RF circuits on the build-up layers. The performance benefits are demonstrated through interconnect loss, impedance match, electrical gain and noise figure measurements. Compared to existing RF substrates, the glass substrates show 2.5X miniaturization in substrate thickness with extensibility to thinner substrates.

1. Introduction

Wireless communications have been a key enabler for the success and prevalence of smartphones, and will play a more prominent role in automotive electronics for functions such as autonomous driving with vehicle-to-vehicle connectivity, in-car smartphone-like infotainment with vehicle-to-network connectivity, privacy and security. These applications have been driving major breakthroughs in packaging innovations for multiband communications (LTE or long term evolution, LoRa or low-power wireless network, WiFi, mmWave) and sensing. In order to connect one device to the other, multiple RF communication standards such as GPS (global positioning system), WLAN (Wireless local area network), GSM (global system for mobile communication) and Bluetooth coexist in a single system [1]. Miniaturized electronic modules with increased functional density, reduced footprints and minimal interference are essential to meet the growing demand for smart mobile systems. Fig. 1 shows a simple block diagram for PAMiD (power amplifier module - integrated duplexer) and FEMid (front end module - integrated duplexer) modules.

Low substrate loss is a key metric for RF applications. RF packaging traditionally evolved with low-temperature co-fired ceramic substrates. The primary reason is the superior properties of LTCC, such as low dielectric loss, low moisture absorption, high reliability based on hermetic nature of ceramics, high thermal stability and ability to form complex 3D multi-layered circuits [2,3].

LTCC technology started to migrate to organic laminate packaging because of its lower cost and higher component density from fine-line multi-layered wiring. Both LTCC and organic laminate substrates coexist in today's smartphones. However, ceramic metallization processes such as screen printing limited the smallest line width that could be achieved with 5% or tighter tolerance demands for RF transmission lines to 100 μm. Additionally, the small panel sizes of 150 and 200 mm increased the packaging cost as module sizes increased with increasing integration levels. Organic substrates that are ∼0.3–0.6 mm thick form the preferred platform for today's modules, with up to two-metal layers on each side of the core. The lines and spaces are approaching 15–20 μm with vias of 100 μm in leading-edge RF substrates [4] although 40–50 μm lines are most commonly used to maintain the required tolerance. In addition, certain inductors are embedded inside the laminate substrate. Although, low-loss organic substrates have gained in popularity for RF applications, their poor dimensional stability and warpage, as well as their moisture uptake pose challenges for miniaturizing RF modules or

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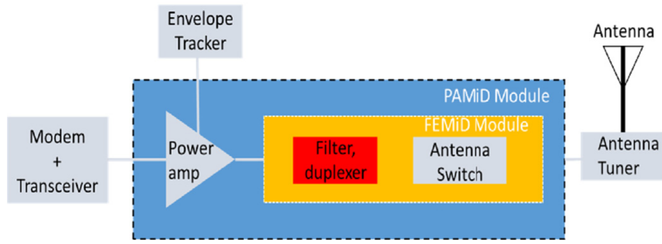
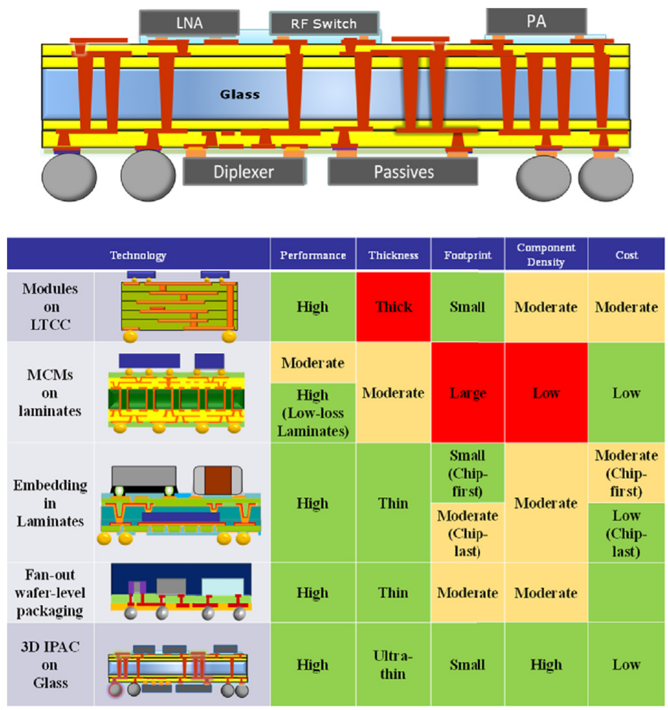


Fig. 1. Block diagrams of PAMiD and FEMiD architectures in a RF Front-end module.



Technology	Performance	Thickness	Footprint	Component Density	Cost
Modules on LTCC	High	Thick	Small	Moderate	Moderate
MCMs on laminates	Moderate High (Low-loss Laminates)	Moderate	Large	Low	Low
Embedding in Laminates	High	Thin	Small (Chip-first) Moderate (Chip-last)	Moderate	Moderate (Chip-first) Low (Chip-last)
Fan-out wafer-level packaging	High	Thin	Moderate	Moderate	
3D IPAC on Glass	High	Ultra-thin	Small	High	Low

Fig. 2. Conceptual cross-section of 3D IPAC RF module in Glass, and its qualitative benchmarking with other approaches.

subsystems. The evolution of fan-out wafer-level packages (FOWLP) further enhanced the performance or RF packages with reduced parasitics and footprint by eliminating the use of wire bonding, thick substrates and solder interconnections. Double-sided multiple redistribution layers are formed to fan-out the transceiver input and output signals and through-mold vias are employed to realize the vertical interconnections. However, the precision RDL can only be achieved by polishing the mold compound surface as well as controlling the warpage of re-constituted wafers, which remains a major concern as module thickness reduces. The RDL yield loss resulting in the loss of known good ICs because of chip-first embedding, and the added process cycle time due to sequential processing of wafers and packages also limit the applicability of wafer-level fanout packages. Panel-based embedding is emerging as another compelling alternative to wafer-level fan-out [4–9].

Glass packaging in 2D and 3D is emerging as an ideal solution for high-performance and ultraminiaturized RF front-end modules with simultaneous reduction in both X-Y and Z directions. Glass combines the benefits of ceramic, organic and silicon. This is because glass provides many advantages such as ultra-thinness, ultra-low electrical loss, silicon-like dimensional stability for precise and fine-pitch circuits, high stiffness, high Tg, high surface smoothness and adjustable coefficient of thermal expansion (CTE). Moreover, it is superior to silicon for RF applications because it enables high-Q RF components due to its high

Table 1
Electrical performance of glass packages compared to silicon and laminate packages.

Structure	Parameter	Silicon	Organic	Glass
Transmission line; 10 mm; 70 Gbps	S21 (4 GHz)	−20 dB	−10 dB	−7 dB
	Eye opening	81	301	314
Through-via	S21	−1.5 dB		−0.2 dB
	Eye opening	352 mV		408 mV

resistivity for ultra-low loss. Compared to organics, glass enables precision circuitry with finer design ground-rules because of its dimensional stability, and ability to process with ultra-thin and low-loss build-up organic or inorganic dielectrics, without process-compatibility issues. Recent advances have demonstrated reliable and fine-pitch through-vias (TPVs) in glass with double-side assembly of active and passive components with ultra-short interconnections [10,11]. In addition to these, glass as a packaging substrate appears to be a perfect solution for its cost effectiveness through panel-scale manufacturability [12,13]. The benefits of glass packaging are illustrated in Fig. 2.

TPVs in thin glass enable double-side integration of active and thin-film passive components on either sides of the glass substrate, thus reducing the X-Y footprint of the modules by about half and reduce the interconnect length between them. Fine-pitch through-via formation using low-cost substrate processing tools and processes such as laser vias and double-side wet metallization techniques, allows interconnecting the components on both sides with standard panel processes at lower cost, leading to a 3D Integrated Passive Active Components (3D IPAC) RF module as illustrated in Fig. 2.

The superiority of glass TPVs is illustrated through the work of Choi et al. [14] and Viswanathan et al. [15]. Cross-talk comparison of signal lines on various substrates clearly illustrates wider eye-opening with glass. The superiority of fine through-vias for seamless transitions is illustrated through a TPV signal-integrity analysis [15]. Fine-vias and low dielectric loss enabled by glass provide unique avenues for seamless

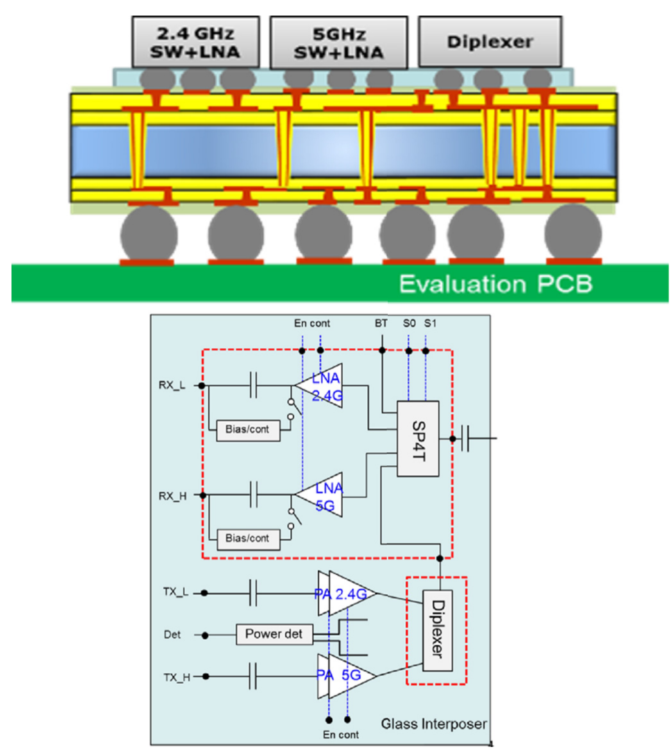


Fig. 3. (a) Schematic ross-section of the Rx part of WLAN Module (b) Block diagram of WLAN Module.

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