A review of key development areas in low-cost packaging and integration of future E-band mm-wave transceivers

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***Abstract*— With an ever increasing number of broadband applications in sub-Saharan Africa, mm-wave point-to-point networking has the potential to fill a niche in communications network architectures. Widespread adoption of this technology would benefit from conventional RF soft substrate integration and packaging, as opposed to system-on-chip or thick film processes. A review on the state-of-the-art in E-band soft substrate systems reveals significant reliance on MMICs. We propose that hybrid integration of active devices with off-chip passives, as well as better integration of active components in SIW, will lead to better performing E-band systems in soft substrates. Specific enabling techniques from the microwave domain are identified.**

***Keywords* — electronics packaging; millimeter wave communication; millimeter wave devices; millimeter wave technology; radio transceivers**

I. INTRODUCTION

Limited ICT development in developing countries has been shown to restrict economic growth, with poor access to broadband services cited as a major contributor [1]. A major study into these shortcomings in sub-Saharan Africa's broadband connectivity [2] found that backhaul networks are one of the reasons that broadband is not widely available in the region and remains a niche product, affordable by only a few. For this, and other reasons, the *indigenous* development of future wireless technologies is becoming an important ICT policy point for developing countries [3].

This limitation is relevant even in the developed world, where ever increasing subscriber numbers and limited backhaul connectivity capacity have already impacted on the quality of service offered by mobile networks [4]. Augmentation of backhaul capacity is often hampered by the roll-out cost of DSL or 10 Gbps fiber optic lines, not only not only due to the cost of the fiber itself (up to 10,000 €/km) but also the roadwork and trenching required to install the fiber (up to 300,000 €/km) [5].

Millimetre-wave (30 – 300 GHz) transceivers have received widespread commercial adoption in imaging and automotive RADAR applications due to small size and sharp image resolution over short distances [6]. However, due to the availability of broadcast spectrum above 30 GHz (compared to traditional GSM, LTE and 2.4 GHz ISM bands, Fig. 1) attention is being turned to the underutilised mm-wave spectrum for future wireless communications applications, with mm-wave point-to-point links employed as a solution to last-mile fiber replacement or augmentation [5]. In this role, the E-band spectrum at the 71-76 and 81-86 GHz ITU-regulated bands [7] have received significant interest. The neighboring 92-95 GHz band covers a local minimum in atmospheric attenuation with properties comparable to that of the Ka RADAR band [8] but has received less attention due to far stricter statutory regulations [4].

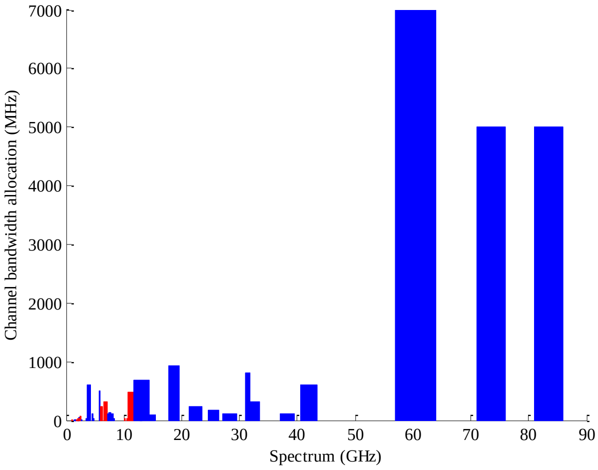

Figure 1: ICASA licensed spectrum and per channel bandwidth allocation [7]. Fully allocated bands are indicated in red.

Although future 5G mobile networks [9] is the prime application example of E-band point-to-point links, a more immediate role may be in smart grid monitoring and control [10][11]. It is envisaged that real time load conditions, insulator degradation, line faults, motion and even widespread video monitoring [12-14] will form part of such a network, as opposed to the traditional telemonitoring and telecontrol of only the high voltage lines. Smart metering *alone* will require more than 100 Mbps transmission per 100,000 customers [15], which is well beyond the capabilities of current VHF and UHF radio links [16], conventional power line communications (2 – 3 Mbps) or other radio standards such as WiMAX (75 Mbps), whilst pushing the capabilities of 100 Mbps broadband power line communications [17] and (expensive to lease) LTE networks [13].

Although there are numerous areas in which further development is needed to make these systems more cost-effective (both to develop and to produce), this paper will focus on system integration. The state-of-the-art in E-band transceiver system integration is reviewed Section II, where two key areas of further system integration development are defined. Hybrid system integration in soft substrates is then discussed in Section III, with Section IV covering integration of active devices in substrate integrated waveguide (SIW) in E-band.

II. A REVIEW OF E-BAND SYSTEM INTEGRATION APPROACHES

The most compact solution to E-band transceivers is to market them as full systems-on-chip (SoC), as has been demonstrated in 100nm GaAs [18-20], 40nm GaN [21][22], 40nm CMOS [23] and 130nm SiGe BiCMOS [24][25] technologies. Though compact and efficient, the non-recurring cost associated with SoC does not make it a feasible option for low volume production or in development environments with limited prototyping resources. Another significant drawback to complete on-chip system integration is the high losses and low self-resonant frequencies of the passive circuitry surrounding the active transistors on the semiconductor die [26] at mm-wave frequencies, an effect exacerbated by nearfield interaction between the on-chip passive and the host substrate after mounting [27]. Typical unloaded quality factors (Q-factors) for on-chip resonators at E-band frequencies have been demonstrated only up to 83 [28] for compound transmission line resonators, 43 for shielded transmission line resonators [29], 25 for single transmission line resonators [30] and below 15 for LC tank resonators [31]. This compares poorly with achievable unloaded Q-factors at mm-wave frequencies of over 200 in SIW [32], over 3,000 for ceramic dielectric resonators [30] and Q-factors in excess of 75,000 for machined waveguide resonators [33].

E-band system integration with off-the-shelf components traditionally makes use of pre-packaged components in WR-12 rectangular waveguide [34][35]. The majority of commercial systems [36][37] and subsystems [38][35][39] are also marketed as WR-12 integrated waveguide assemblies. There are, however, numerous mm-wave transceiver applications where waveguide system integration is not feasible due to size, weight or cost constraints [40] and if mm-wave transceivers are to be rolled out in large quantities, they need to be integrated in a compact fashion and produced at low cost without sacrificing performance [41]. This dominance of waveguide packaging contrasts with microwave systems [42-44] where board level integration is commonplace for a wide variety of systems.

In recognition of a this new need for accessible board level E-band system packaging, more suppliers are moving towards supplying active components (amplifiers, mixers, voltage controlled oscillators (VCOs) and others) as off-the-shelf components ([45-48]) for multi-chip module systems [49]. Since standard QFN-type surface mount technology (SMT) packaging has a feasible upper limit of 45 GHz [50], these off-the-shelf components are usually supplied as bare dies suitable for flip-chip bonding at mm-wave frequencies [51][52]. More experimental packaging technologies such as waveguide apertures, micro-coax and through-wafer vias have also been proposed [50] but not yet commercially adopted. With the availability of commercial RF substrates that perform well at E-band and W-band frequencies [32], it should come as no surprise that board-level E-band transceiver developments are performing amicably [49][41][53][54]. There are, however, still shortcomings in the state-of-the-art, and addressing these shortcomings may lead to improved overall system performances through, amongst others, minimizing interconnect attenuation and reducing the number of on-chip low Q-factor passives.

A. *Hybrid component integration in soft substrates*

Despite the advantage of having access to low loss packaging and integration media for passives layouts, mm-wave multi-chip module development still uses monolithic microwave integrated circuits (MMICs) as components [55] in multi-chip modules (Fig. 2). These devices all rely on extensive transmission line on-chip matching, dividing / combining and other passive networks [56] which may both attenuate significantly (due to the previously noted low Q-factors for passives) and cause unwanted radiation [57]. This loss translates into the degradation of noise figure in E-band low noise amplifiers (LNAs) [58], increase in phase noise of oscillators [59] and reduced efficiency of power amplifiers [31].

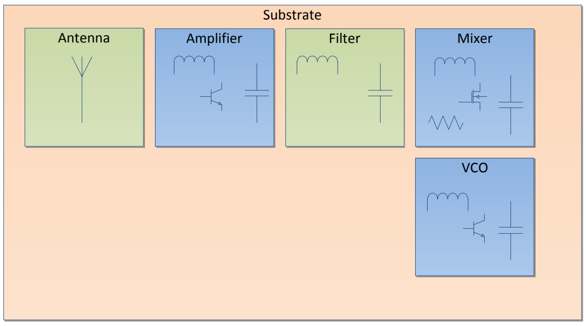

Figure 2: Conventional approach to multi-chip module system integration.

In the microwave domain, discrete transistors (commonly GaAs pHEMTs and GaN HEMTs [60]) are readily available off-the-shelf and are often used for custom circuit designs with off-chip passives. Following the microwave model, an alternative system layout method for future E-band transceivers is hybrid packaging of the system's different circuits (Fig. 3), whereby the system integrates on-chip semiconductor components with off-chip passive components (inductors, capacitors, resonators and other transmission line components [61]) that may even form part of the packaging itself [62]. Even though the principle of full-system distributed packaging has only been demonstrated up to 40 GHz [63], this approach is feasible at much higher frequencies given the availability of the necessary interconnects [52] with below 0.3 dB degradation in performance [56].

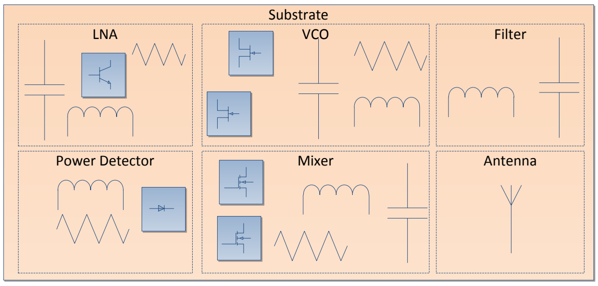

Figure 3: System integration architecture with off-chip passives and several discrete semiconductor device dies.

An extension on the multi-die configuration in Fig. 3 would be to have all the system's active devices *clustered on a single die* (Figs. 4 and 5) with all the system's passive components distributed around that single die. Typical active components could include discrete lumped transistors for LNA / PA design, but also cross-coupled transistor pairs and varactors for VCOs, diodes for power detection, and other common standard components in custom ICs. Although this configuration would prohibit the application of multiple semiconductor technologies (eg. InP for LNAs and GaN for PAs) in the same system, it would allow for more compact system integration, fewer on-chip / off-chip interconnects, and provide a single point of power regulation.

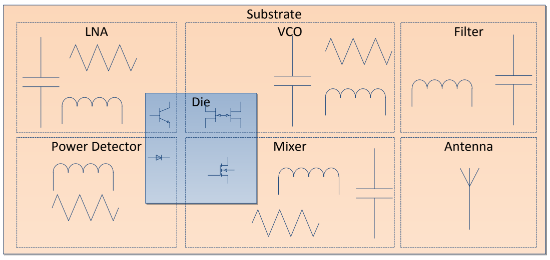

Figure 4: System integration with a single common die and passives distributed around the die

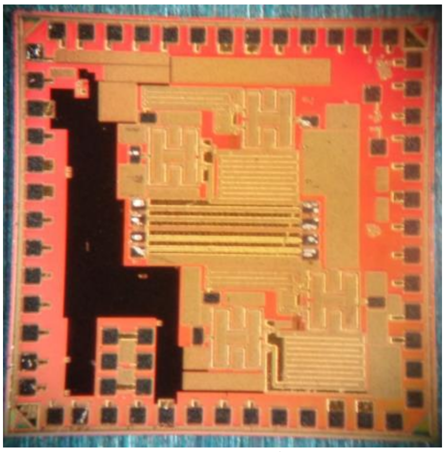

Figure 5: Single die, multi-device chip, manufactured in IBM 8HP 130nm SiGe BiCMOS. Die carries multiple filters, switched delay lines, single transistor for off-chip matched LNA, an oscillator core and a voltage regulator.

III. SOFT SUBSTRATE INTEGRATED WAVEGUIDE SYSTEMS

Substrate integrated waveguide (SIW, Figs. 6 and 7) has been successfully used for integrating E-band passive devices such as antennas and feed networks [64] filters [32] directional couplers [65] and even for partial system integration [41] in conventional RF soft substrates (as well as liquid crystal polymers [66] and low-temperature co-fired ceramics [67], though at higher cost). A significant shortcoming in the state-of-the-art in SIW system integration is connecting active components into the SIW RF path (as is easily done with planar RF transmission media such as coplanar waveguide or microstrip). The conventional approach is to transition from SIW to a planar medium with an exposed signal conductor, such as coplanar waveguide (CPW) [68] and then to integrate the active components in the planar medium. Although a recent paper has shown that this transition is unnecessary and that dies can be wirebonded directly to SIW, even at mm-wave frequencies [69] examples of coherent co-design of complementary active-passive circuits (such as amplifier matching or oscillator tanks) is still absent at E-band.

The president for this integration has, however, already been set for amplifier matching (using SIW discontinuities as matching elements [70]) and VCO design [71] at microwave frequencies, but this interconnected co-design has not yet been applied to other required active system components such as calibration noise sources, mixers, multipliers, switches, and others. Once designs for these devices are published and readily available to design engineers, fully SIW integrated E-band systems may emerge on the market.

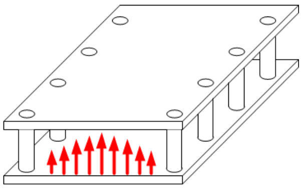

Figure 6: SIW with the dominant TE_{10} E-field distribution indicated

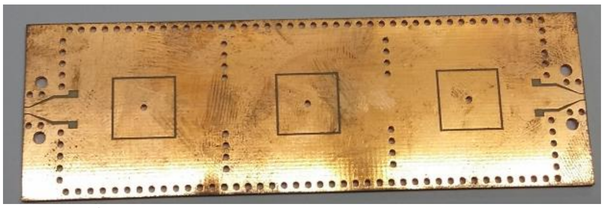

Figure 7: SIW filter with capacitively loaded resonators.

IV. CONCLUSION

The context of wireless system design in developing economies leaves soft substrate system integration the most viable option for E-band development in the near future. Although some strides have been made in this area, this review has shown that the state-of-the-art still relies heavily on a multi-chip module approach using off-the-shelf MMICs. We have presented the benefits of having discrete mm-wave semiconductors available on the market, as well as proposed a new single-chip integration topology for future development. The state-of-the-art in integrating semiconductor devices in SIW at E-band frequencies has been shown to lag behind that in X-band, with the absence of specific circuit developments in SIW still prohibiting true E-band SIW system integration. Addressing these technology gaps will lead to more widespread development of E-band systems in conventional RF substrates and larger scale development in developing economies.

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