MILLIMETRE-WAVE AND TERAHERTZ SYSTEM-ON-SUBSTRATE TECHNOLOGY: PROSPECTS AND CHALLENGES

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The millimetre-wave frequency range has received renewed interest for 5G+ wireless networks, including machine-to-machine (m2m) communications, body area networks and the Internet of Things (IoT). System-in-package (SiP) or system-on-substrate technology is vital for the realisation of miniature millimetre-wave systems, especially some of the very advanced massive MIMO antennas that have been proposed. SoS technology provides a multi-technology platform by which integrated circuits, devices and components from any technology (Si/SiGe, GaAs, GaN, InP, graphene, etc.) can be integrated to form a system alongside high performance passive components. This paper reviews the prospects for system-on-substrate technology and outlines some of the significant challenges that still need to be addressed in order to fully exploit the 100GHz+ part of the radio spectrum.

INTRODUCTION

The progress that silicon technology has made in the last decade is truly remarkable, with f_{max} of >500 GHz achievable with SiGe HBTs and even CMOS giving f_t close to a THz, although the useful maximum frequency of operation for RF circuits is well below that. The International Technology Roadmap for Silicon (ITRS) has been a strategic driving force behind these developments and, amongst its many in-depth reports, the system-in-package White Paper [1] describes a wide range of advanced packaging technologies that could be used to great effect to realise millimetre-wave [2] and even THz transceiver modules.

There is an urgent need to push down the cost of millimetre-wave systems but these still often require quite sophisticated and high performance passive components that cannot be integrated into a tiny package. For example, in future 5G+ communications there are many demands on RF engineers to find low cost ways of realising multi-band and multi-antenna systems as illustrated in Fig. 1. The system-on-substrate or substrate integrated circuit approach pioneered by Wu [3] is an extension of the MCM concept in which an entire substrate becomes the base for systems integration and makes such a large scale integrated antenna/transceiver array feasible. One of the major elements of this concept is the substrate integrated waveguide (SIW) which is a rectangular waveguide embedded into the substrate, normally using rows of via-holes as sidewalls. The important advantage of SIW is that it is significantly lower loss than planar transmission lines (microstrip, CPW, etc) and this makes it feasible to integrate high performance passive components.

However, there is a significant technical challenge to be overcome in order to push the performance envelope so that SoS solutions can be employed for systems beyond 100 GHz, including terahertz systems - as and when the necessary devices become commercially available. System-on-substrate technology will be a key enabler for the explosion in applications of the millimetre-wave bands for applications such as 5G+, IoT, m2m communications, biosensing, imaging, security screening, etc.

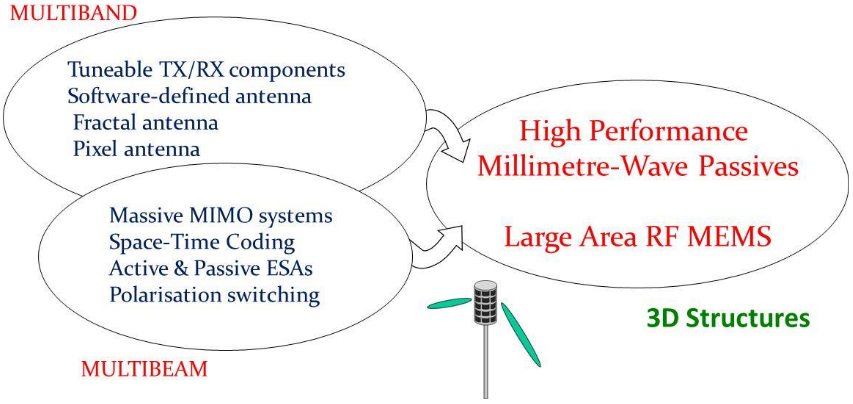

Fig. 1. Systems Requirements in Future Millimetre-Wave Communications: 3D SoS solution

HOLLOW SUBSTRATE INTEGRATED WAVEGUIDES

It is not possible to do justice here to the many papers that have been published on SIW circuits. However, all-too-often papers report the design and performance of filters, couplers, etc., without detailed consideration of whether the performance demonstrated is sufficiently good to meet real systems requirements. For example, if the loss of a SIW power combining network is even a few dB, the impact on power output and efficiency is so great that it has limited practical value. A number of researchers have pursued a different route, for example using micromachining [4] or additive manufacture [5] to realise low loss hollow millimetre-wave / THz waveguides, but this approach is less amenable to the kind of volume manufacture that is envisaged if 5G+, IoT, etc., are to reach their potential and fully exploit the millimetre-wave bands.

Just in the last year, two groups have independently reported hollow (or air-filled) SIWs, using LTCC technology [6] and copper/laminates [7]. In both cases, the reduction in loss is very significant and with further development this approach will be a major contribution to making the system-on-substrate approach the mainstream millimetre-wave technology, just as microstrip was so successful in the 70s-onwards, then being a low-cost replacement for bulky waveguides and coaxial lines. Just as engineers found creative ways of living with microstrip's limitations, so engineers can surely develop advanced system-on-substrate design techniques to deliver amazing new hardware solutions.

Some hollow SIWs (HSIWs) based on standard LTCC technology are illustrated in Fig. 2. This form of HSIW uses standard printed silver paste as the upper and lower broadwalls. It is very challenging to produce samples with the intricate via-fence sidewalls so close to the cavity, but measured results demonstrated that the HSIW was significantly lower loss than a dielectric-filled equivalent. The loss in Ka-band is comparable to a standard waveguide. This is a significant achievement and a number of high-Q passive components, including a waveguide slot antenna array and integrated antenna-filter have been successfully demonstrated [8].

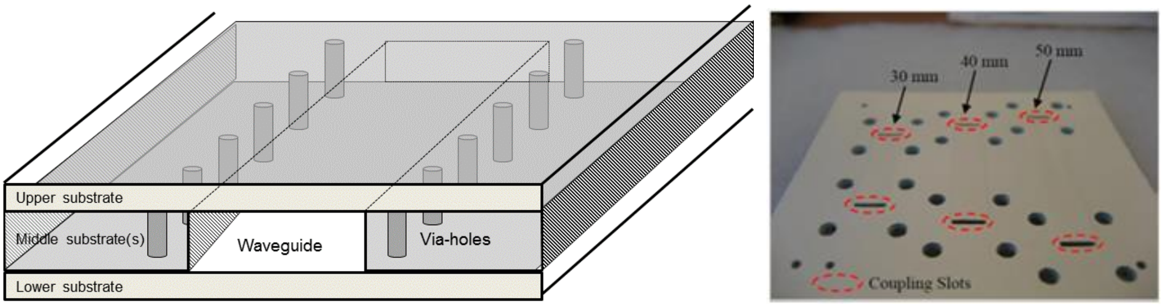

Fig. 2. Hollow SIW in LTCC Technology: Concept and photograph [6]

BEYOND SIW

Whilst the hollow SIW gives a significant reduction in loss, to push significantly beyond 100 GHz requires careful consideration of the importance of surface roughness and metal conductivity [9] and transmission losses will generally increase very rapidly beyond 100 GHz. Indeed, even the precision manufactured WR-1.0 waveguides used with a THz Keysight Technologies PNA-X/VDI system have significant losses at 1 THz. To successfully pursue THz system-on-substrate technology it is surmised that dielectric waveguides need to be re-examined. In an earlier era of millimetre-wave industry-academia excitement, for example, some excellent work on NRD-based transceivers was published [10]. Fig. 3 shows the cross-section of the main candidates for dielectric-based waveguides in MCM technology and Fig. 4 shows early stage work on insular image guides in LTCC technology [11].

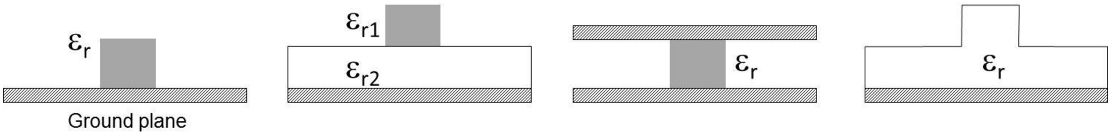

Fig. 3. Well-known dielectric waveguide structures with potential for SoS applications
(Image guide, insular image guide, NRD, rib image guide)

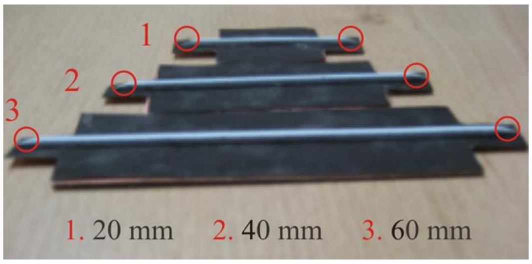

Fig. 4. Insular image guide components in LTCC technology [11]

CHIP INPUT/OUTPUT

The need to shift to dielectric guides highlights another limiting factor in taking current MCM technology to the THz range – the need for a new kind of input/output interface. Supposing bond-wires or tapes can be avoided by using solutions such as flip chip mounting, even then the tiniest bondpads will have significant parasitic capacitance that limits the frequency of operation. It is expected, therefore, that electromagnetic coupling into and out of the chip will be required for true THz applications, using techniques such as on-chip transitions, e.g. as shown in Fig. 5 [12], or antennas - including ones mounted on the back face of a flip-chip device or IC [13].

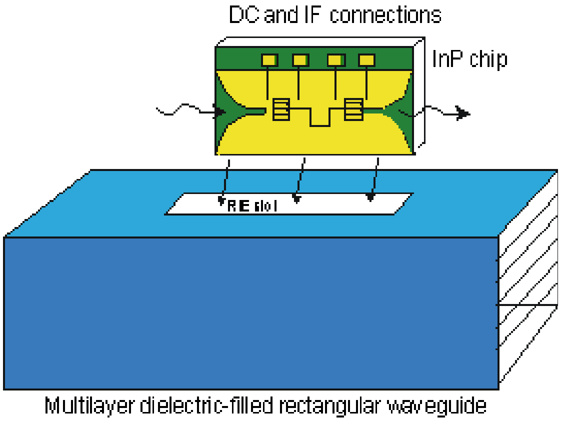

Fig. 5 MMIC coupled into an SIW using on-chip finline transitions [12]

MEMS AND SMART SUBSTRATES

Another important step towards a true system-on-substrate is to meet the systems requirements for reconfigurable hardware that can deliver "all spectrum access" (or close to it). MEMS is widely recognised as an important technology but it is unlikely to be cost effective to procure a large number of individual MEMS devices and integrate them onto a reconfigurable antenna array, for example. A "smart substrate" incorporating large area MEMS could perform many of the switching, beam-steering and frequency-tuning functions that are required in a millimetre-wave system, as illustrated conceptually in Fig. 6. Internationally, a few research teams worldwide have started to study the fabrication of MEMS components in LTCC and laminate technologies. Laminate technologies require low temperature processing, and some excellent work has been reported [14, 15]. Newborn *et al.* [16], have shown that an electrostatically-actuated leaf spring vertical actuator could be realized in LTCC technology by employing sacrificial layers which burn off during firing. Work was reported on attaching foil onto laminate substrates to form a large area frequency-selective surface [17]. This inspired work at Leeds, Imperial College and Loughborough University on RF MEMS in LTCC, previously reported at the ARMMS conference [18], forming part of a project funded by the EPSRC IeMRC [19].

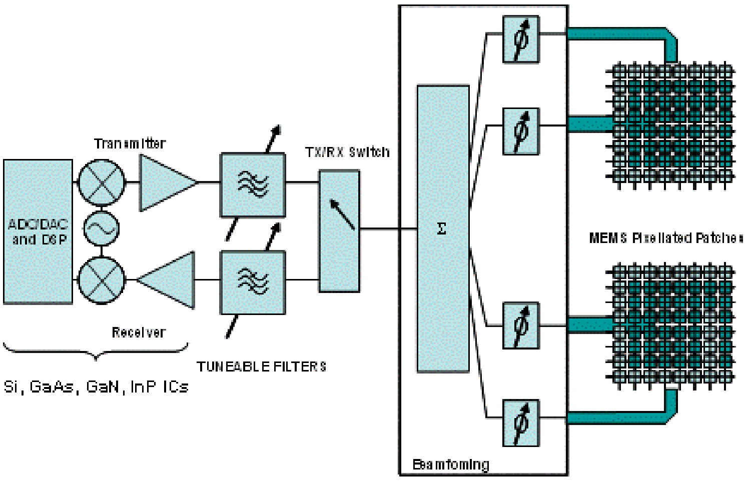

Fig. 6. Smart substrate concept for reconfigurable transceivers [19]

CONCLUSION

System-in-package and system-on-substrate technology provide the key multi-technology platform that brings silicon and III-V technologies together in harmony to realise cost-effective transceiver modules for many applications, such as 5G+ communications, short range radar and sensing systems. With further research into ultra-low loss transmission media and large area MEMS, the capability of this approach can be significantly enhanced and it is likely that some form of this technology will underpin massive MIMO 5G+ systems, which have already been shown in research labs to be capable of Tb/s data rates [20]. A key feature of this approach is that it is agnostic to competing semiconductor technologies and whenever a new device comes along that creates a step-change in capability it can be swiftly integrated into a new design.

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