Millimeter-wave wireless integrated systems – what to expect for future solutions

Ariana L. C. Serrano[1], Gustavo Marcati[1], Igor Abe[1], Gustavo A. Palomino[1] Gustavo P. Rehder[1]

[1] Department of Electronic Systems, Polytechnique School of the University of São Paulo, São Paulo 05508-010, Brazil, e-mail: aserrano@usp.br

Abstract—**This paper intends to make a brief presentation of in integrated circuits' developments and efforts towards new wireless applications at the millimeter-wave frequencies band. Considering low-cost applications for the consumer market, it is shown that using only one technology is not desirable for cost and size reasons. The 3D integration becomes a necessity for the new applications in such frequencies, pushing forward alternative technologies and new 3D interconnection techniques.**

Index Terms—**Millimeter-wave systems. Millimeter-wave devices. Interposer. 3D interconnection. CMOS technologies .**

I. Introduction

In the millimeter-wave frequency range (from 30 GHz to 300 GHz, referred to "mmW" in this paper) several unlicensed frequency bands are being selected for point-to-point high-bandwidth communication links. These multi-gigabit links are crucial for the infrastructure of the emerging RF, mmW and THz consumer applications serving the markets of high-speed telecommunications systems (next generation of mobile communication, 6G and beyond), 77GHz/120GHz automotive radars, mmW imaging and high sensitivity radar sensors. The telecommunication and radar sensors systems are ubiquitously transforming the fields of transportation (autonomous and connected vehicles), smart mobility, robot's industry for security systems and medical applications, and digital life. For that, one of the key electronic blocks is the phased arrays antennas [1], [2], [3]. In the frequency range of the 5G systems, the whole solution has been addressed and different commercial solutions are available, although in the frequencies above that for future low-cost applications, the challenge remains.

To answer this increasing demand, in the past fifteen years, the CMOS/ BiCMOS technologies have evolved significantly to produce transistors with ft/fmax higher than 300 GHz. These silicon technology capabilities at higher frequency have encouraged many research laboratories and industries to work on the development of low-cost and low-power mmW front-ends for consumer market. Their main focus of development was not only around the unlicensed 60 GHz band [4], but also between 77 GHz [5] and 120 GHz for automotive radars and back-hauling, or even at, 140 GHz and above for mmW imaging, security or medical applications. This makes CMOS a realistic competitor to III-V materials like GaAs pHEMT/mHEMT for some applications, with for example mixers, amplifiers, VCOs and also complete systems, for example a phased array receiver. However, CMOS/ BiCMOS mmW power amplifiers exhibit a poor power-added efficiency (less than 15 %). As the mmW communication required line-of-sight, and the free-space attenuation is high, transmissions are limited to short range of tens of cm if only a single antenna is used. In order to address medium to long communication distances (from one meter up to a km) for back-hauling, antenna arrays with beam-steering capability are needed, since antenna arrays focus the emitted/received signal in the direction of the RX/TX, leading to a longer and more efficient point-to-point communication [6]. Finally, in order to integrate such mmW systems, the overall cost of the system must be significantly reduced [7], [8].

Besides the great improvement of the silicon technology on active components, the development of efficient passive circuits is crucial to improve the performance of mmW circuits and systems. These systems need high-performance baluns, diplexers, filters, matching networks, and distribution networks for antenna arrays. The Back-End-Of-Line (BEOL) of CMOS/BiCMOS technologies is the main limiting factor for the development of high-performance passive circuits. Its thickness is smaller than 10 µm for advanced technologies (40-nm CMOS and below, 130-nm BiCMOS and below), leading to transmission lines with poor quality factor [9].

It seems clear that the critical passive wavelength-based circuits (baluns, diplexers, filters, couplers, antennas) must be realized off-chip for performance and cost reasons. For that, a solution consists on using 3D hybrid integration, either by realizing the passive circuits above IC, or by using an interposer that supports passive circuits, as exemplified in Fig. 1. An interposer is an interlayer placed between different technologies, mostly between the master board (a printed circuit board - PCB) and on-chip circuits (realized in various technologies: Silicon, GaAs, InP, photonics, MEMS etc.) that can interconnect their signals. Circuits can be interconnected in an interposer using transmission lines on its top or bottom surfaces or through the interposer using vias. Several technology suppliers, institutes and academic laboratories have been working on the development of interposers for almost two decades. Today, high-resistivity

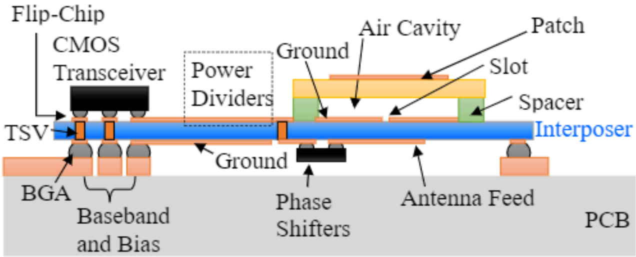

Fig. 1 Example of a mmW wireless system with 3D interconnections to explore the use of the best of each technology aiming a low-cost system for consumer market.

Digital Object Identifier 10.29292/jics.v17i2.627

silicon (HR-Si) is mainly used as mmW interposer [10], [11], [12]. It is reasonably low-cost and it guarantees an expansion coefficient that is compatible with silicon devices (CMOS or BiCMOS). HR-Si interposers can be fabricated using well-established microelectronic processes, derived from CMOS technology. However, they exhibit a major drawback for mmW applications: it is technologically difficult to realize high aspect ratio (defined by the length divided by the diameter) Through-Substrate-Vias (TSV). Further, these vias are frequency-limited due to the intrinsic MOS capacitor of the TSV on HR-Si. Other interposers such as fused silica [13], [14] and liquid crystal polymer (LCP) [15], [16], [17] have also been proposed again with fabrication difficulties and limited performance. In [18], the Metallic-nanowire-Membrane (MnM) interposer is proposed as a new generation of interposer that yields high-performance and miniaturized transmission lines and vias in a simple, low-cost fabrication process, which will be reviewed in this work.

These advances aligned with the 3D interconnections development pave the way for future 3D mmW hybrid circuits and systems.

II. The MnM Interposer

The MnM interposer (Fig. 2), is a 50 µm-thick alumina membrane (Anodic aluminum oxide or AAO) with nanopores that go straight from one surface to the other. Alumina is an excellent dielectric and widely used in the RF industry. The nanopores of the alumina membrane can be easily filled with metal by electrodeposition, forming nanowires, allowing the realization of vias and slow-wave microstrip lines or SIWs. With this configuration, it is possible to design high performance low and high characteristic impedance transmission lines [19] and vias (Fig. 3) reaching 0.09 dB @110 GHz per via transition [20], both with reduced size in a low-cost technology. This technology uses simple fabrication without high temperatures or limited I/O density, proving to be an excellent alternative to the new demands at millimeter-wave.

The accurate modeling of this interposer was described in [21] and several basic circuits in mmW have been demonstrated with good performance. Then, several passive structures used in general microwave systems were developed. Initially, simple structures were demonstrated only for performance purposes without any optimization shown in Fig. 4: baluns [22] with insertion loss better than 1.5 dB @59-69 GHz and return loss better than 10 dB; couplers [23] with power unbalance of less than 0.4 dB and output phase difference of 90° ± 3° @54-67 GHz.

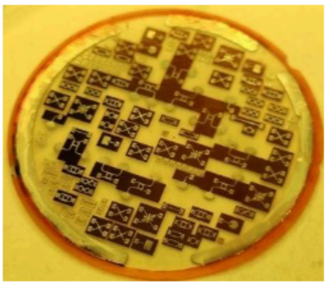

Fig. 2 MnM interposer with different fabricated structures.

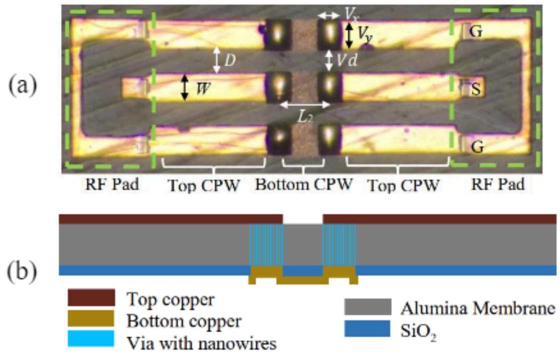

Fig. 3 Nanowire-Vias in the MnM interposer [20]: (a) top view of the fabricated device. (b) side view schematic showing the used layers.

3D structures were further designed due to the availability of high-performance small nanowire-vias in this interposer, such as crossovers up to 110 GHz [24] with maximum insertion loss of 1.5 dB (not de-embedded), imbalance of 0.2 dB, phase imbalance of 3.3°, and isolation of 30 dB (Fig. 4); 3D inductors [25] with SFR of 91 GHz, quality factor of 35 @40 GHz and values up to 17 nH and 3D transformers [26] (Fig. 5) with different impedance ratios and even structures based on substrate integrated waveguide technology which presented state-of-the-art results.

III. Phased array antennas

Nowadays, the key device in a phased array system that still requires a solution is the phase shifter. High-performance phase shifters must be developed, which must offer low consumption in order to address mobile applications and small footprint for cost considerations [27]. Therefore, the digital phase-shifters will not be considered in this review for their high consumption. There are two main families of analog phase shifters - active and passive - presenting trade-offs between power consumption or transmission loss and footprint. The active phase shifters are small, but consume high power [28], [29], [30] leading to complex thermal dissipation mechanisms for systems with large antenna arrays. Several technologies have been used to develop passive phase shifters at mm-waves, including CMOS/BiCMOS, BST, Liquid Crystal, dielectric and MEMS. The passive phase shifters presented in the literature are either small with high losses [31], [32] or large with low losses [33], [34], [35]. Semiconductor-based components (varactor diodes,

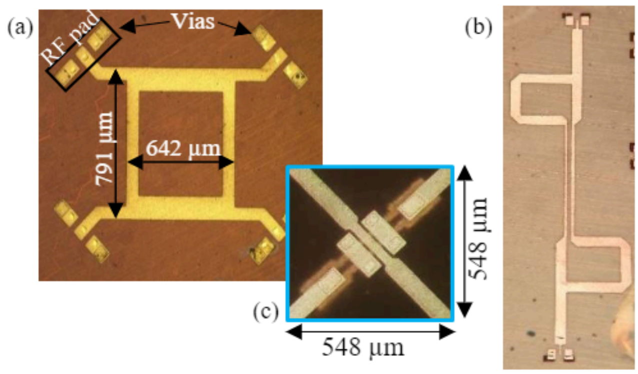

Fig. 4 (a) Hybrid coupler [23] , (b) baluns in a back-to-back configuration [22], and (c) crossover [24] on the MnM substrate

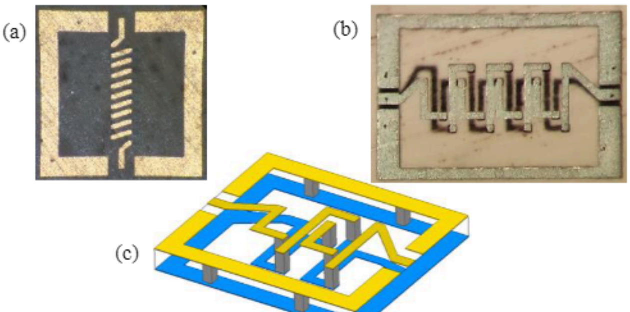

Fig. 5 Fabricated (a) 3D inductor [25] and (b) transformer [26] with its 3D view (c) on the MnM interposer

MOS varactors, FET switches and pin diodes) can be considered as tuning elements, but their quality factor at mmW is still poor. On the other hand, MEMS technology can be a suitable candidate to achieve low-loss circuits [36], [37] especially considering in the mmW front-end path. Some examples of a MEMS phase-shifter [37], [38] are shown in Fig. 6.

Certainly the effort is not restrict to phase-shifters, but is applied to all the devices of a low-cost high performance phased array, high performance crossovers and efficient antenna arrays. The antennas arrays and their feeding network is also to be carefully considered in different substrates to achieve high gains, and therefore better signal range. Electronic high-gain beam steering is necessary to address mobile mmW communication for high-power efficiency and to reduce multipath effects and interference. One solution for low power beam-steering is the use of Butler matrices[39], which direct the beams toward predefined directions [40], shown in Fig. 7. At mmW, the feeding network insertion loss of integrated beam-steering antenna arrays increases dramatically; hence, the antenna should be as close as possible to the RF transceiver front-end [27], or on the interposer, if possible. This explains why several silicon SoC or SiP solutions have been proposed in the literature, especially considering that the size of the antenna arrays (Fig. 8) are far larger than all the rest of the system together.

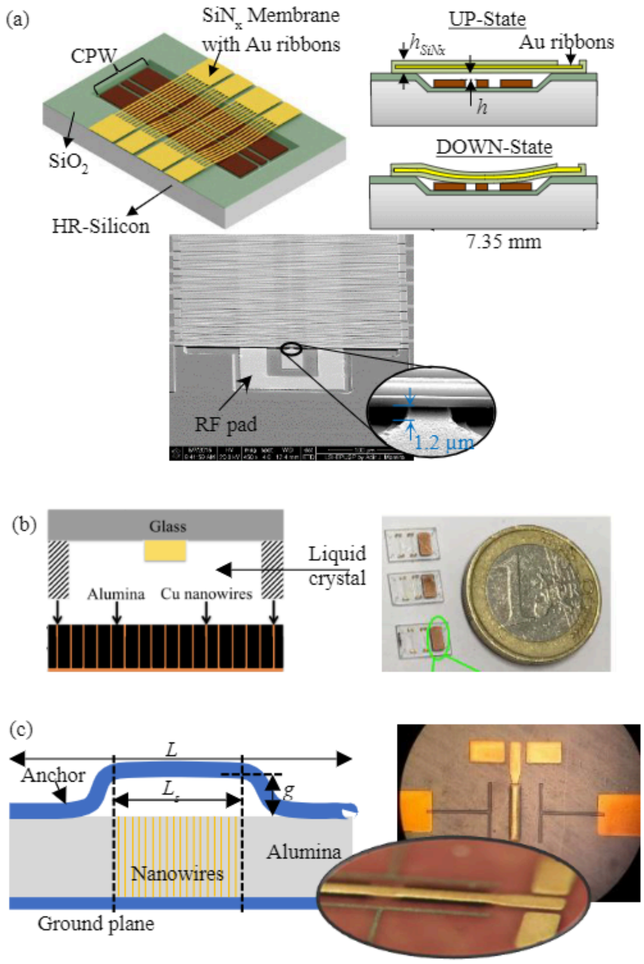

Fig. 6 Examples of MEMS phase-shifters: (a) slow-wave phase shifter fabricated with CEA-Leti MEMS technology; (b) Nanowire-MEMS liquid crystal-based [38] and (c) Nanowire-MEMS air-filled phase shift on the MnM interposer

IV. 3D HYBRID INTEGRATION

The main idea behind 3D hybrid integration is the use of the third dimension - the height, which allows the development of more compact Systems-in-Packages (SiP) by stacking several technologies, leading to a hybrid circuit stack. The use of hybrid circuits using an interposer allows the use of the most appropriate technology in terms of performance and cost for each part of the system. On the other hand, in mmW, the stacking processes, such as flip-chip, wire-bonding, and beam-lead, are themselves a challenge and have to be developed. They work well below 10 GHz, but become more and more challenging at frequencies well above this [41]. The parasitics of such interconnects limits the use of the available bandwidth, while the short wavelength at such frequencies imposes challenging manufacturing and assembly tolerance requirements.

V. MMW CHARACTERIZATION

On-wafer device characterization are required in order to extract the device characteristics from the measured S-parameter. The accurate characterization of devices in mmW

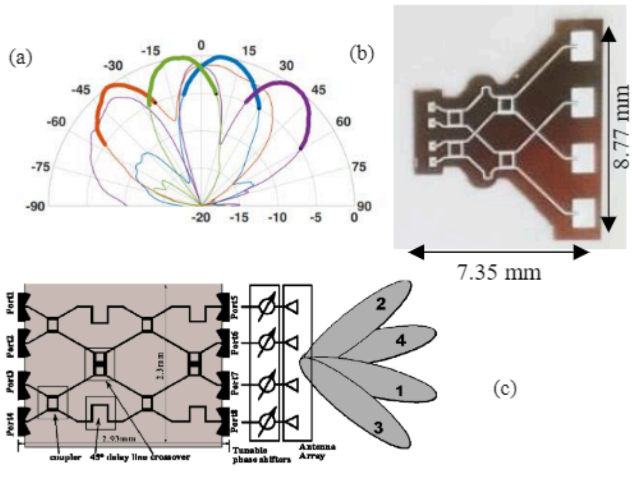

Fig. 7 (a) Measured radiation pattern measured of the (b) 60-GHz Butler Matrix fabricated on the MnM interposer[39].

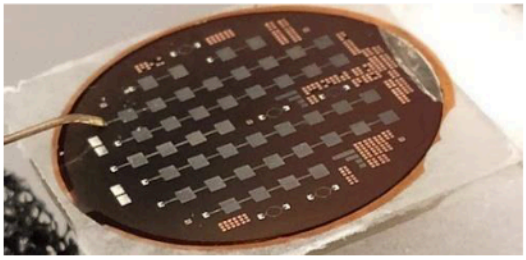

Fig. 8 Antenna arrays in 1 x 8 configuration fabricated on the MnM interposer

is critical and requires efficient measurement and calibration methods, as it is very sensitive to problems of contact, drift, inaccuracies in calibration and the strong effects of parasitic components existing at these frequencies. Therefore, the use of specialized equipment, as well as the correct modeling and interpretation of measurements are of great importance for evaluating the devices and systems performance. The typical measurement setup using a probe station and vector network analyser is shown in Fig. 9, and the specific setup for antennas measurement, in Fig. 10. This setup and techniques at mmW are not trivial, needing an accurate model and methods for: equipment calibration; valid calibration kit; de-embedding method; parameter extraction from measure.

Typically, the device to be characterized is embedded in a setup with essential electrical interface up to the probe tips, which introduce undesirable parasitic effects in the device measurement. These additional parasitics affects the original characteristics of the devices and should be mathematically subtracted from the measurement in order to get the intrinsic characteristics of the device. This subtraction of the unwanted parasitic effects is called "de-embedding"[42]. After the calibration, a de-embedding step should be

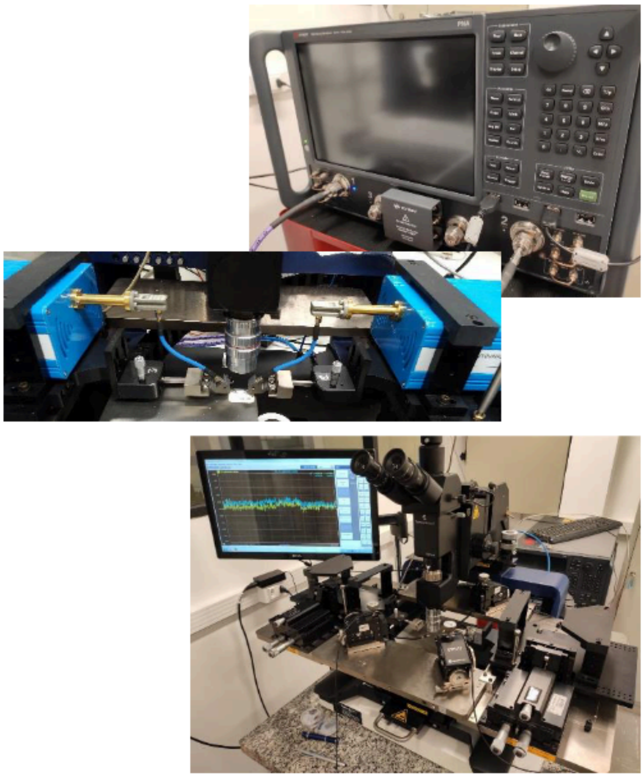

Fig. 9 Typical measurement setup for millimeter-wave devices

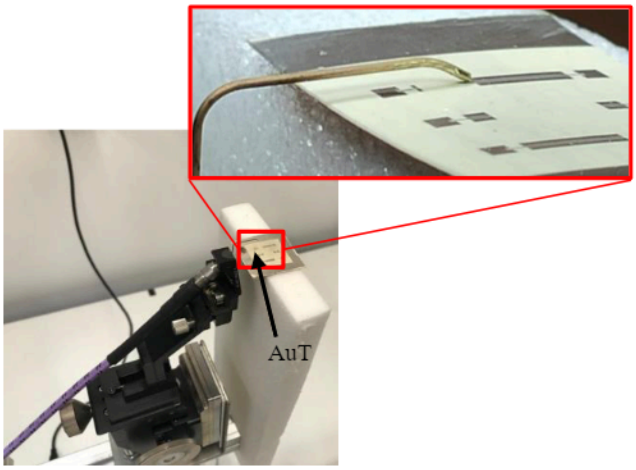

Fig. 10 mmW antenna measurement setup

performed.

De-embedding methods based on lumped circuit models of the test fixture are highly inaccurate for millimeter-wave applications due to the distributed nature of the interconnect parasitic. Additionally, one cannot eliminate the de-embedding error due to the imperfection of the "short-open" standards, commonly used for lower frequencies, in these methods. The standard definitions for calibration methods occupy large silicon area but are needed to achieve a reliable and real measure and for mmW circuits. In mmW, the most advised calibration methods are the TRL (Through-Reflect-Line) [43], although it requires to know the characteristic impedance of the line de-embedding structure to set the reference plane, and can be limited in frequency range; and LRRM (Line-Reflect-Reflect-Match).

VI. Conclusion

3D hybrid integration seems to be the viable alternative for the development of low-cost mmW applications for the future 6G and beyond, in which large phase arrays with beam-steering capabilities will be mandatory. Monolithic integration will lead to prohibitive cost and/or poor performance due to the large size of the antennas and passive circuits. Further, the combination of different technologies at their best will be important to achieve the best performance. Therefore, the development of a mmW interposer to combine these technologies and embed the passive circuits is very important.

Here, several building blocks, such as transmission lines, TSVs, capacitors, inductors, and also circuits, such as crossovers, couplers, baluns, transformers, and antennas operating up to 110 GHz were presented on the MnM interposer, a solution proposed for the low-cost, low-consumption high performance mmW systems.

Acknowledgements

This work was supported in part by FAPESP under Grant 2016/25779-9 and 2018/07467-5, CNPq under Grants 309577/2020-9, 311031/2018-8, and 431200/2018-1.

References

[1] I. F. Akyildiz, A. Kak, and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020, doi: 10.1109/ACCESS.2020.3010896.

[2] T. S. Rappaport *et al.*, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6g and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522.

[3] S. Pellerano *et al.*, "9.7 A Scalable 71-to-76GHz 64-Element Phased-Array Transceiver Module with 2×2 Direct-Conversion IC in 22nm FinFET CMOS Technology," in *2019 IEEE International Solid- State Circuits Conference - (ISSCC)*, 2019, pp. 174–176. doi: 10.1109/ISSCC.2019.8662496.

[4] E. Cohen, M. Ruberto, M. Cohen, O. Degani, S. Ravid, and D. Ritter, "A CMOS Bidirectional 32-Element Phased-Array Transceiver at 60 GHz With LTCC Antenna," *IEEE Trans Microw Theory Tech*, vol. 61, no. 3, pp. 1359–1375, 2013, doi: 10.1109/TMTT.2013.2243749.

[5] K. Doris, A. Filippi, and F. Jansen, "Reframing Fast-Chirp FMCW Transceivers for Future Automotive Radar: The pathway to higher resolution," *IEEE Solid-State Circuits Magazine*, vol. 14, no. 2, pp. 44–55, 2022, doi: 10.1109/MSSC.2022.3167344.

[6] G. Chittimoju and U. D. Yalavarthi, "A Comprehensive Review on Millimeter Waves Applications and Antennas," *J Phys Conf Ser*, vol. 1804, no. 1, p. 12205, Feb. 2021, doi: 10.1088/1742-6596/1804/1/012205.

[7] S. Zihir, O. D. Gurbuz, A. Kar-Roy, S. Raman, and G. M. Rebeiz, "60-GHz 64- and 256-Elements Wafer-Scale Phased-Array Transmitters Using Full-Reticle and Subreticle Stitching Techniques," *IEEE Trans Microw Theory Tech*, vol. 64, no. 12, pp. 4701–4719, 2016, doi: 10.1109/TMTT.2016.2623948.

[8] W. Lee *et al.*, "Fully Integrated 94-GHz Dual-Polarized TX and RX Phased Array Chipset in SiGe BiCMOS Operating up to 105 °C," *IEEE J Solid-State Circuits*, vol. 53, no. 9, pp. 2512–2531, 2018, doi: 10.1109/JSSC.2018.2856254.

[9] A. L. Franc, E. Pistono, D. Gloria, and P. Ferrari, "High-performance shielded coplanar waveguides for the design of CMOS 60-GHz bandpass filters," *IEEE Trans Electron Devices*, vol. 59, no. 5, pp. 1219–1226, 2012, doi: 10.1109/TED.2012.2186301.

[10] S. J. Bleiker *et al.*, "High-Aspect-Ratio Through Silicon Vias for High-Frequency Application Fabricated by Magnetic Assembly of Gold-Coated Nickel Wires," *IEEE Trans Compon Packaging Manuf Technol*, vol. 5, no. 1, pp. 21–27, Jan. 2015, doi: 10.1109/TCPMT.2014.2369236.

[11] Y. Lamy *et al.*, "MmW characterization of wafer level passivation for 3D silicon interposer," *Proceedings - Electronic Components and Technology Conference*, no. 100, pp. 1887–1891, 2013, doi: 10.1109/ECTC.2013.6575835.

[12] A. Margomenos and L. P. B. Katehi, "Fabrication and Accelerated Hermeticity Testing of an On-Wafer Package for RF MEMS," *IEEE Trans Microw Theory Tech*, vol. 52, no. 6, pp. 1626–1636, Jun. 2004, doi: 10.1109/TMTT.2004.828467.

[13] W. T. Khan, J. Tong, S. Sitaraman, V. Sundaram, R. Tummala, and J. Papapolymerou, "Characterization of electrical properties of glass and transmission lines on thin glass up to 50 GHz," in *2015 IEEE 65th Electronic Components and Technology Conference (ECTC)*, May 2015, pp. 2138–2143. doi: 10.1109/ECTC.2015.7159898.

[14] V. Sukumaran *et al.*, "Design, Fabrication, and Characterization of Ultrathin 3-D Glass Interposers With Through-Package-Vias at Same Pitch as TSVs in Silicon," *IEEE Trans Compon Packaging Manuf Technol*, vol. 4, no. 5, pp. 786–795, 2014, doi: 10.1109/TCPMT.2014.2303427.

[15] D. J. Chung, S. K. Bhattacharya, and J. Papapolymerou, "Low loss multilayer transitions using via technology on LCP from DC to 40 GHz," in *2009 59th Electronic Components and Technology Conference*, May 2009, pp. 2025–2029. doi: 10.1109/ECTC.2009.5074300.

[16] D. J. Chung and J. Papapolymerou, "60–110 GHz low loss HDI transitions for LCP-packaged silicon substrate," *Electron Lett*, vol. 46, no. 8, p. 577, 2010, doi: 10.1049/el.2010.0241.

[17] A. Rida, A. Margomenos, J. S. Lee, P. Schmalenberg, S. Nikolaou, and M. M. Tentzeris, "Integrated Wideband 2-D and 3-D Transitions for Millimeter-Wave RF Front-Ends," *IEEE Antennas Wirel Propag Lett*, vol. 9, pp. 1080–1083, 2010.

[18] M. v Pelegrini *et al.*, "Interposer based on metallic-nanowire-membrane (MnM) for mm-wave applications," in *2016 11th European Microwave Integrated Circuits Conference (EuMIC)*, 2016, pp. 532–535. doi: 10.1109/EuMIC.2016.7777609.

[19] A. L. C. Serrano *et al.*, "Slow-wave microstrip line on nanowire-based alumina membrane," in *2014 IEEE MTT-S International Microwave Symposium (IMS2014)*, Jun. 2014, pp. 1–4. doi: 10.1109/MWSYM.2014.6848552.

[20] J. M. Pinheiro *et al.*, "110-GHz Through-Substrate-Via Transition Based on Copper Nanowires in Alumina Membrane," *IEEE Trans Microw Theory Tech*, vol. 66, no. 2, pp. 784–790, 2018, doi: 10.1109/TMTT.2017.2763142.

[21] J. M. Pinheiro, G. P. Rehder, F. Podevin, P. Ferrari, and A. L. C. Serrano, "Slow-Wave Microstrip Line Model for PCB and Metallic-Nanowire-Filled-Membrane Technologies," *IEEE Trans Microw Theory Tech*, vol. 69, no. 2, pp. 1238–1249, 2021, doi: 10.1109/TMTT.2020.3040414.

[22] L. G. Gomes, I. Y. Abe, J. M. Pinheiro, P. Ferrari, G. P. Rehder, and A. L. C. Serrano, "V-Band balun on the Metallic Nanowire Membrane (MnM) Interposer Technology," in *2019 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*, 2019, pp. 1–3. doi: 10.1109/IMOC43827.2019.9317646.

[23] B. M. Verona, G. K. Rocha, A. L. C. Serrano, and G. P. Rehder, "60 GHz low-loss branch-line hybrid coupler on nanoporous alumina interposer," in *2019 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*, 2019, pp. 1–3. doi: 10.1109/IMOC43827.2019.9317661.

[24] D. Wang *et al.*, "Compact DC to 110 GHz Crossover Based on Metallic-Nanowire-Filled Membrane," *IEEE Microwave and Wireless Components Letters*, vol. 32, no. 1, pp. 45–48, 2022, doi: 10.1109/LMWC.2021.3115585.

[25] A. L. C. Serrano *et al.*, "3D inductors with nanowire through substrate vias," 2017. doi: 10.1109/MWSYM.2017.8058952.

[26] T. M. Frutuoso *et al.*, "Nanowire-Based 3-D Transmission-Line Transformer for Millimeter-Wave Applications," *IEEE Microwave and Wireless Components Letters*, pp. 1–4, 2022, doi: 10.1109/LMWC.2022.3159096.

[27] X. Gu, D. Liu, and B. Sadhu, "Packaging and Antenna Integration for Silicon-Based Millimeter-Wave Phased Arrays: 5G and Beyond," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 123–134, 2021, doi: 10.1109/jmw.2020.3032891.

[28] S. Kishimoto, I. Ando, M. Kohtani, N. Hasegawa, T. Arai, and S. Yamaura, "A 79 GHz 13.5 dBm Psat at 150°C transmitter with compact local phase shifter in 40 nm CMOS for automotive radar," *2020 IEEE 20th Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, SiRF 2020*, pp. 66–69, 2020, doi: 10.1109/SIRF46766.2020.9040196.

[29] E. T. Sung and S. Hong, "A Wideband W-band 6-bit Active Phase Shifter in 28-nm RF CMOS," *2019 IEEE International Symposium on Radio-Frequency Integration Technology, RFIT 2019 - Proceedings*, pp. 2019–2021, 2019, doi: 10.1109/RFIT.2019.8929156.

[30] H. Li *et al.*, "W-band Scalable 2×2 Phased-Array Transmitter and Receiver Chipsets in SiGe BiCMOS for High Data-Rate Communication," *IEEE J Solid-State Circuits*, vol. 57, no. 9, pp. 2685–2701, 2022, doi: 10.1109/JSSC.2022.3188917.

[31] F. Meng, K. Ma, K. S. Yeo, S. Xu, C. C. Boon, and W. M. Lim, "Miniaturized 3-bit Phase Shifter for 60 GHz Phased-Array in 65 nm CMOS Technology," *IEEE Microwave and Wireless Components Letters*, vol. 24, no. 1, pp. 50–52, 2014, doi: 10.1109/LMWC.2013.2288266.

[32] B. Biglarbegian, M.-R. Nezhad-Ahmadi, M. Fakharzadeh, and S. Safavi-Naeini, "A Wideband 90° continuous phase shifter for 60GHz phased array transceiver in 90nm CMOS technology," in *2009 European Microwave Integrated Circuits Conference (EuMIC)*, 2009, pp. 479–482.

[33] M. K. Chowdhury, L. Sun, S. Cunningham, and A. P. Malshe, "Mechanically punched micro via fabrication process in LCP substrate for RF-MEMS and related electronic packaging applications," in *Proceedings - 2009 International Symposium on Microelectronics, IMAPS 2009*, 2009, pp. 174–180.

[34] A. Gaebler, F. Goelden, A. Manabe, M. Goebel, S. Mueller, and R. Jakoby, "Investigation of high performance transmission line

phase shifters based on liquid crystal," in *2009 European Microwave Conference (EuMC)*, 2009, pp. 594–597. doi: 10.23919/EUMC.2009.5295928.

[35] N. Ranjkesh, M. Basha, A. Abdellatif, S. Gigoyan, and S. Safavi-Naeini, "Millimeter-Wave Tunable Phase Shifter on Silicon-on-Glass Technology," *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 7, pp. 451–453, 2015, doi: 10.1109/LMWC.2015.2429074.

[36] P. Ferrari, R. Jakoby, O. H. Karabey, G. P. Rehder, and H. Maune, *Reconfigurable Circuits and Technologies for Smart Millimeter-Wave Systems*. Cambridge: Cambridge University Press, 2022. doi: DOI: 10.1017/9781316212479.

[37] G. P. Rehder *et al.*, "MEMS Slow-Wave CPW Phase Shifter for mm-Wave Applications," *J Infrared Millim Terahertz Waves*, vol. 41, no. 10, pp. 1227–1244, 2020, doi: 10.1007/s10762-020-00731-0.

[38] M. Jost *et al.*, "Miniaturized Liquid Crystal Slow Wave Phase Shifter Based on Nanowire Filled Membranes," *IEEE Microwave and Wireless Components Letters*, Aug. 2018, doi: 10.1109/LMWC.2018.2845938.

[39] D. Wang *et al.*, "A Compact Butler Matrix Design Based on Metallic Nanowire Filled Membrane Technology and Tunable Phase Shifter at 160 GHz," *International Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz*, vol. 2019-Septe, pp. 3–4, 2019, doi: 10.1109/IRMMW-THz.2019.8873696.

[40] C. C. Chang, C. C. Lin, and W. K. Cheng, "Fully integrated 60 GHz switched-beam phased antenna array in glass-IPD technology," *Electron Lett*, vol. 51, no. 11, pp. 804–806, May 2015, doi: 10.1049/el.2015.0891.

[41] W. Heinrich *et al.*, "Connecting Chips With More Than 100 GHz Bandwidth," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 364–373, 2021, doi: 10.1109/jmw.2020.3032879.

[42] B. Zhang, Y.-Z. Xiong, L. Wang, S. Hu, and J. L.-W. Li, "On the De-Embedding Issue of Millimeter-Wave and Sub-Millimeter-Wave Measurement and Circuit Design," *IEEE Trans Compon Packaging Manuf Technol*, vol. 2, no. 8, pp. 1361–1369, 2012, doi: 10.1109/TCPMT.2012.2200482.

[43] G. F. Engen and C. A. Hoer, "Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer," *IEEE Trans Microw Theory Tech*, vol. 27, no. 12, pp. 987–993, 1979, doi: 10.1109/TMTT.1979.1129778.