Metamaterial Based Compact Patch Antenna Array for Antenna-in-Package Solutions in Frequency Handover Applications

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***Abstract*— A dual band compact antenna array is designed on an ultra-low loss and smooth surface roughness dual-layered fused silica substrate to simultaneously operate in both a 5G new radio (5G-NR) of 28 GHz and an IoT band of 24GHz, for a frequency handover application. The proposed antenna array operates based on coupled resonance theory. The resonant frequencies are the result of resonant coupling between closely located meanderline complementary split ring resonators (CSRRs). A 2 x 2 array is fabricated on a 350µm/180µm double layer fused silica substrate and the measurement results agree well with simulation results.**

Keywords—Antenna in Package (AiP), frequency handover, heterogeneous integration, multiband, 5G, IoT, mmWave, metamaterial, CSRR.

I. Introduction

With the emerging commercial application of the 5G-NR FR2 band in the millimeter wave 28GHz band and IoT applications in the submillimeter 24GHz band, the need for multiband, compact, and low loss passive elements for wireless communication has been raised. Maximizing bandwidth efficiency by using frequency handover techniques [1,2] requires wideband and multiband hardwares with minimum ohmic loss, which in turn increases the demand for heterogeneous integrations and 3D packaging to eliminate or reduce unwanted and intolerable power loss that occurs in conventional two-dimensional transceiver structures and to minimize devices' footprints. Especially in the millimeter region, in which the dimensions of passive elements such as antennas are comparable to those of transceiver chips, efforts have been made to integrate them with the RF front-end MMICs for more than a decade [3]. Although the antenna-on -chip (AoC) solution provides very compact 3D solutions and omits the need for parasitic interconnects, the silicon itself degrades the antenna's performance due to its dielectric loss [4]. Therefore, antenna in package (AiP) solutions were introduced to alleviate the AoC drawbacks. AiP first gained the most interest in 60GHz applications [5-7]. In this configuration, the antenna is designed on a substrate that itself carries the MMIC chips. The MMIC may be bonded to the substrate or attached by embedding solutions. Multiple layers of substrate with different properties are stacked on top of each other to provide a three-dimensional integration of passive and active elements. Organic and ceramic materials are the most widely used materials as substrates. However, each of these materials has some nonnegligible drawbacks concerning path loss, moisture absorption, warpage, scalability, design precision, and cost [3].

More importantly, at mmWave frequencies, the conductor surface roughness plays an important role in total power dissipation [8]. Recently, glass-based substrates have been introduced to AiP solutions. Substrates like fused silica and borosilicate glass exhibit not only a very low dielectric loss, but they also possess a very smooth surface on the order of a few nanometers. This factor is in the order of micrometers in other materials such as polyamides and epoxy molds . Glass also has some other useful properties. The dielectric constant of the glass can be tailored and customized for different applications. Its coefficient of thermal expansion matches that of silicon which is necessary for IC embedding and guarantees secure interconnects in a wider temperature range. It can be used in both large and low-cost panels. And finally, very fine pitches, lines, vias, and spaces can be designed on glass substrates by photolithography methods. Metal widths and spaces as low as 2um are achieved on glass substrates using advanced semi-additive processing methods [9-12].

However, the efficiency of a passive circuit is not only limited to the ohmic loss; it can also be affected by crosstalks and unwanted mutual couplings between different elements of an integrated passive circuit. It could specifically be troublesome in antenna array designs in which the distance between antenna elements plays the main role in minimizing the crosstalks and the resulting power loss. The arrangement of multiple antennas in array configurations is a well-known approach to increase the gain and directivity of the antenna as well as the ability to shape the antenna beam by providing a

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specific phase difference between subarray elements. However, the distance between antennas needs to be carefully selected since the mutual couplings between the antenna elements can degrade the radiation pattern and the total gain. If there is not enough decoupling between the antennas, a portion of the applied power to any antenna element will be absorbed by adjacent antennas instead of radiating. For example, in a two-dimensional patch array, the pitch is selected to be at least $0.5\lambda_0$ to secure a desired mutual decoupling. This restriction makes antenna arrays very large compared to the MMIC circuits. Due to the need to reduce the array size and fit it in small areas, mutual decoupling structures are introduced between antenna elements.

In this paper, the role of metamaterial resonators on frequency response, array size and mutual decoupling is studied with mmWave antenna on fused silica package. In section II, the effect of pitch reduction on the radiation efficiency in a single band 2x2 patch array is investigated. In section III, a dual band array is proposed by introducing the novel complimentary split ring resonator (CSRR) feeding technique which is used to add a second frequency band to the array by leveraging the coupled resonance technique. The fabrication process and results are discussed in section IV, and section V concludes the paper.

II. Radiation Pattern in Compact 2x2 Patch Array

Mostly named as electromagnetic bandgap structures, metamaterial resonators such as split ring resonators (SRRs) and CSRRs are mainly used between antennas to act as a band stop filter in antenna resonant frequencies and block the power transmission between antennas in an array [13-15]. These structures are mostly investigated between two antennas in a 2x1 patch array. Recent studies indicated the effectiveness of such an approach in a 2x2 patch array [16,17]. In these studies, the antenna pitch is reduced dramatically to $0.05\lambda_0$ for a 5GHz symmetric diagonally fed patch array on RF4 substrate. The diagonal feeding is proposed to overcome the impedance variations between the antennas. Impedance variation results in different resonant frequencies for antenna elements necessitating different impedance matching for each antenna. Although these studies mainly focused on reducing the array pitch, the radiation pattern and directivity of the antenna still doesn't show suitable performance.

Fig. 1 illustrates the three-dimensional concept of the proposed compact array working at 28GHz. The design includes two fused silica layers and three metal layers. Patch elements are placed on the top side of a 350μm thick fused silica wafer, while the feedline is placed on the bottom side of a 180μm thick fused silica wafer. The four patch elements are located very close to one another separated by $p = 0.048\lambda_0$ with λ_0 being the free space wavelength. This compactness is only possible by providing decoupling structures. As in [16] diagonal meanderline CSRR resonators are etched on the ground layer to serve such purpose. In this work however, this technique is investigated in the mmWave region and on dual layer fused silica substrates. The novelty of this structure is in the implementation of metamaterials in a fused silica-metal-fused silica stack-up with a eutectic gold bonding method. As a matter of fact, the ground layer containing both apertures and meanderline resonators also acts as the bonding layer attaching the two fused silica wafers together.

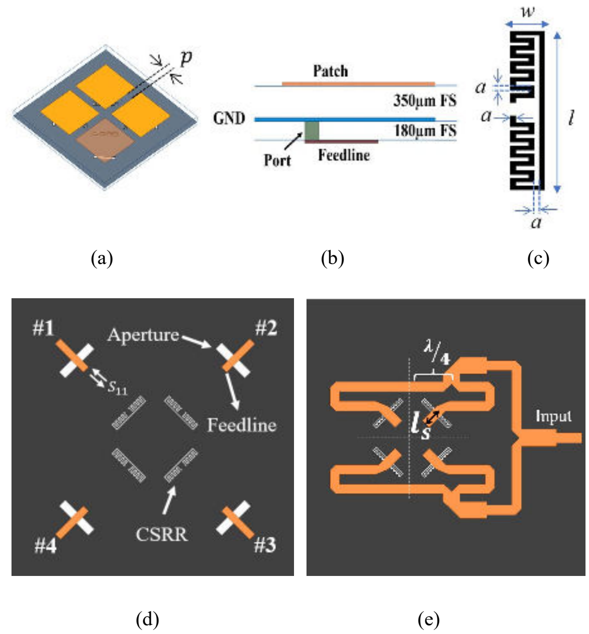


Fig. 1. 2by2 patch array on dual layer Fused-silica substrate a) oblique view b) layer stack up c) Meanderline CSRR structure d) bottom view of the single band aperture fed 2x2 array with ports and meanderlines, e) bottom view of the proposed dual band CSRR fed 2x2 array with the asymmetric power splitter designed for fabrication.

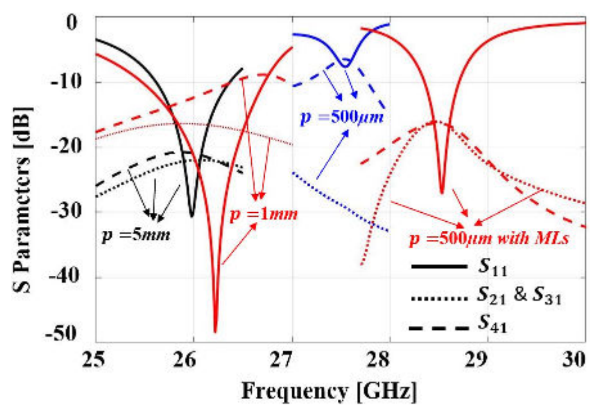


Fig. 2. The effect of array pitch and the existence of meanderlines on the return loss and mutual couplings of the 2x2 patch array.

Unlike ordinary patch arrays, the radiation pattern of a symmetric diagonally fed array is not directive but looks more like a dipole antenna [17]. In fact , a 180^0phase shift is needed to be applied to compensate the geometrical feeding difference caused by the symmetric feeding apertures. Hence, ports 1 and 4 are exited with 180^0phase shifts compared to port 2 and 3.

To investigate the effect of meanderlines on the array properties, full wave simulation by High Frequency Structure Simulator (HFSS) is conducted on a 2x2 patch array with different pitches and a comparison is made in Fig. 2 with and

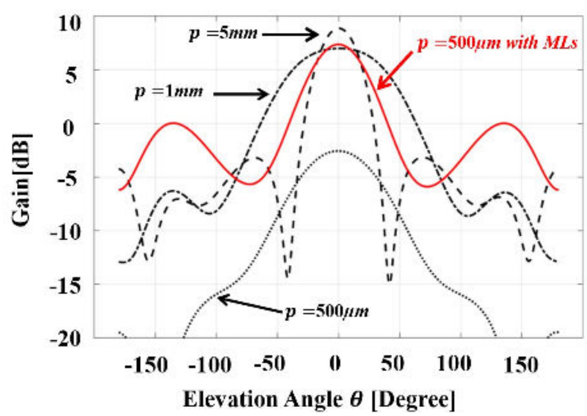


Fig. 3. The effect of array pitch and the existence of meanderlines on the radiation pattern of the 2x2 array.

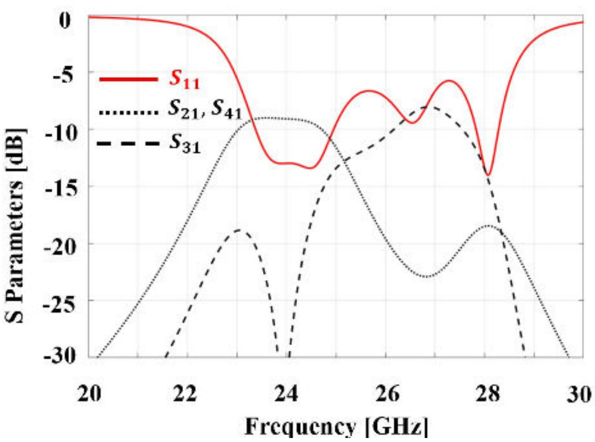


Fig. 4: Reflection coefficient and mutual couplings for a dual band CSRR fed compact 2x2 patch array fed by asymmetric power splitter.

without meanderlines. As expected, reducing the pitch p from 5mm to 0.5mm not only shifts the resonant frequency, but it also increases the mutual couplings and reduces the resonance bandwidth. In this analysis, four lumped ports are assigned to feed the four patch elements in a 2x2 array and scattering parameters for one of the antennas are reported. The HFSS simulation shows that while the coupling between vertical and horizontal elements is below 20 dB for a simple array with p=5mm resonating at 26 GHz, reducing p increases mutual couplings significantly so that the diagonal coupling S_{31} for p=0.5mm is around -5 dB while the 10dB bandwidth is zero.

However, for p = 500 μm, adding meanderlines to the ground layer between the two substrates not only improves return loss BW, but it also decreases mutual decouplings by 10 dB. Since there are four diagonal couplings S_{13}, S_{31}, S_{24}, and S_{42} in each tile, this method will improve the radiation efficiency dramatically especially since the initial coupling was around -5dB meaning at least 25% of the delivered power to each antenna is absorbed by the other antennas and not radiated. Hence, adding the meanderlines increases the radiation efficiency from 10% to 70%.

As mentioned, the asymmetric feeding can provide a directive radiation pattern by improving the gain by more than 10 dB. The effect of mutual couplings on the array gain is also explained in Fig. 3. The simulated elevation radiation pattern shows that for a 2x2 array, the maximum gain decreases by 15 dB if p is decreased from λ_0 to $0.048\lambda_0$. However, adding the meanderlines together with asymmetric feeding network can improve the gain by 10dB. It should be noted that higher gains necessitate a larger p. In other words, a size-gain trade-off needs to be considered in practice.

III. Multiband CSRR-Fed antenna Array

While adding metamaterial resonators to the structure improves the mutual coupling and radiation efficiency, it fails to provide adequate improvement to the frequency bandwidth. As shown in Fig. 2, as p decreases, the BW is also decreased to zero while adding meanderline resonators will increase the BW up to just 2%.

However, despite bandwidth drawbacks, closely located resonators (Antennas and CSRRs) could show some beneficial properties in addition to size reduction. Reducing the distance between two or more identical resonators creates additional resonances called coupled resonance phenomenon. Based on coupled resonance theory, the resonant frequency of a resonator can be affected by adjacent identical resonators if they are coupled together. As in the example of a pair of spring connected pendulum pair, the overall resonance will be a linear combination of two different frequencies. Similarly, the coupling between two or more electromagnetic resonators, either electrically, magnetically, or both, can yield multiple resonant frequencies [18-20].

This phenomenon can be utilized in closely located antenna arrays as all elements are identical single band resonators. The existence of four close meanderlines in this array also adds multiple resonances. Impedance matching for two or more different frequencies, on the other hand, may be difficult and inefficient in aperture-fed or via-fed antennas, necessitating complex matching networks. While apertures are single band and show more mutual coupling at smaller pitches, meanderlines could maintain appropriate decoupling even in very small separation distances which is obvious in reducing the mutual coupling in the compact array. Also, the via position across the antenna area defines the antenna impedance in via-fed antennas, making appropriate impedance matching in multiple frequencies impossible.

In this design, a new method is proposed to couple feedlines to the antenna by replacing the coupling apertures with the CSRR structures which is associated with an asymmetric feedline to realize the required phase shifts between the antennas, as shown in Fig.1(e). Like aperture coupling approach, the feedline is open ended with an optimized stub length l_s to provide impedance match at both resonance frequencies.

Full wave simulation demonstrates that the meander line CSRR is not only as effective as an aperture at exciting the antenna, but it can also couple feedline to the antenna at multiple frequencies. As depicted in Fig. 4, in the special case of diagonal meanderlines, careful optimizations resulted in dual band coupling between the antenna and the feedlines. This

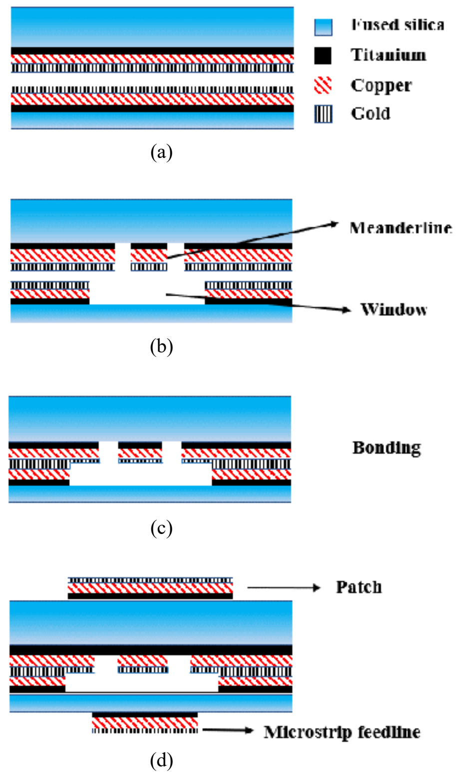


Fig. 5: Bonding procedure, a) Ti-Cu-Au deposition on the bonding side of wafers serving as the ground layer b) etching meanderlines and windows on the ground planes of the top and bottom substrate c) bonded wafers with the meanderlines and corresponding windows on the ground layer d) patch and feedline patterned by photolithography, deposition, and lift-off processes

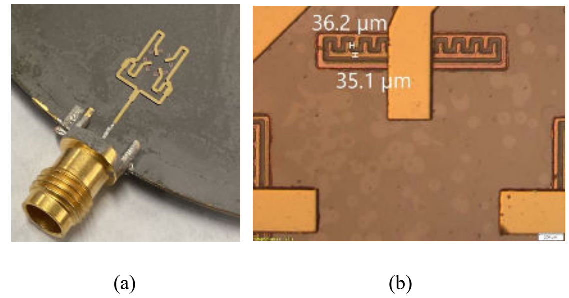


Fig. 6. Fabricated antenna on bonded dual fused silica wafers a) 2x2 array bottom side with microstrip power splitter feedline b) fabricated meanderline dimensions.

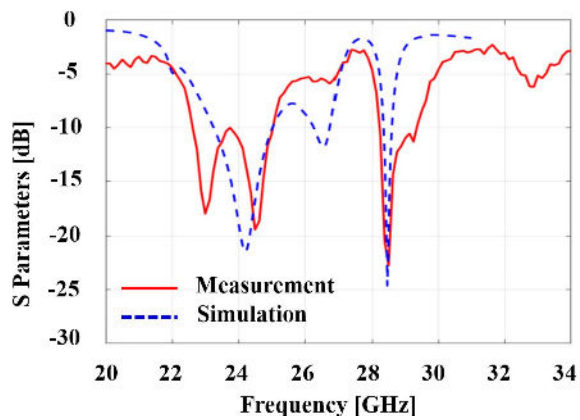


Fig. 7: Measured and simulated reflection coefficient of the compact 2x2 CSRR fed array.

method not only simplifies the 2x2 compact array model by omitting apertures , but it also provides a multi band impedance match for each patch. In this approach, the input feedline can be directly coupled with meanderlines and excite all resonant frequencies and depending on the radiation bandwidths of the patch antennas, some of these frequencies can provide acceptable return loss. As shown in Fig. 4, two standard 1.2cm and LMDS 5G bands can be simultaneously supported with this novel structure. While the mutual couplings stay around -15dB for 28GHz, it will be slightly worse for 24GHz. However, this array also shows a resonance at 27GHz with 9dB return loss which could be improved by further optimization.

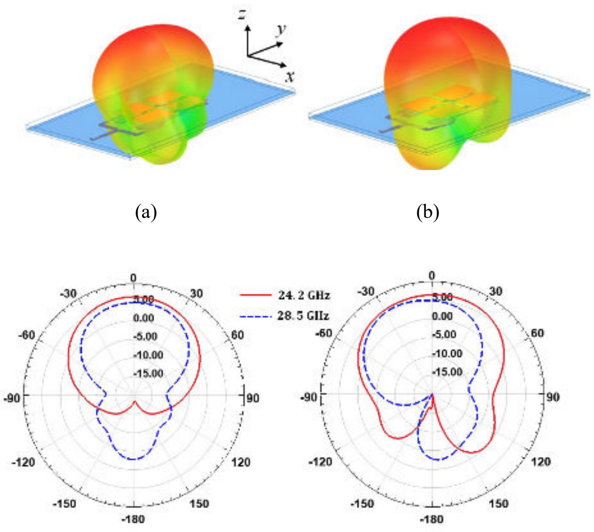
IV. Fabrication Procedure and Results

The proposed antenna array is fabricated on a double layer fused silica substrate. As shown in Fig. 5(a), three metal layers are required for the ground plane in the bonding process. First, a 30nm layer of titanium is sputtered on one side of each wafer to increase the metal-fused silica adhesion properties. This is followed by a layer of 1.5µm thick copper which is then covered by a 50nm layer of gold to prevent Cu oxidization and improve bonding strength.

Before bonding the two wafers together, meanderlines and their associated windows are respectively etched on the top and bottom substrates by photolithographic process. Fused silica wafers are first laminated with 15µm thick Dupont MX5015 dry film negative photoresist and these features are etched away from the metal layer after photolithography process with an exposure dosage of 65 mJ/cm2, under UV light, and developed using a 0.8 wt% potassium carbonate solution. To reduce any misalignment effects on the resonant frequency of apertures and meanderlines, these features are only created on the top substrate while the bottom substrate only contains wider windows etched on its ground layer, as shown in Fig. 6(b). The two wafers are then aligned and inserted into EVG 501 bonder tool under 4500N force for 2:30 hours. This is followed by patterning the antennas and microstrip feedline on the top and bottom surface of the structure, as in Fig. 5(c, d). For antennas and feedlines, photolithography, deposition, and lift off processes are performed respectively.

Fig. 6(a) shows the bottom side of the fabricated compact 2x2 CSRR-fed patch array. An edge mount 1.85mm connector is soldered to measure the reflection coefficient. It should be noted that the dimensions of the fabricated meanderline vary by less than 1 µm. As shown in Fig. 6(b) and based on Fig. 1(c), the width of the etched meanderline is 36.2µm which is slightly larger than the copper width of this resonator with 35.1 µm while the optimized value for a is 36 µm in simulations. Other optimized parameters are w=210 µm, and l=1520 µm in the simulated model.

The input reflection coefficient of the fabricated array is depicted in Fig. 7 and shows a good agreement with simulation



(c) (d)

Fig. 8: Simulated 3D and 2D radiation pattern of the compact 2x2 CSRR-fed patch array a) 3D pattern at 24.2GHz b) 3D pattern at 28.5GHz c) 2D elevation pattern in *xz*-plane d) 2D elevation pattern in *yz*-plane.

at 28.46GHz while a slight shift is observed at the lower band which is measured to be 24.5GHz instead of 24.2GHz.

Fig. 8 shows simulated radiation pattern of the proposed antenna array. The maximum gain for this array is 6.5dB and 5dB with radiation efficiency of 90% and 72% at 24.2GHz and 28.5GHz respectively. As discussed in Section III, the radiation efficiency at 28.5 GHz is directly related to the distance *p* between the antennas. However, increasing *p* will also affect the resonance frequency. As a result, *p* is optimized to 500 µm to yield two commercial bands for NR-5G and submillimeter IoT.

V. CONCLUSION

This work presents a novel compact dual band 2x2 patch antenna array. The proposed array is based on coupled CSRR resonators on the ground plane which also act as bandgap structures to maintain acceptable mutual decoupling among array elements. The fabricated antenna can work both at 24GHz and 28GHz to be utilized in frequency handover applications.

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REFERENCES

[1] Jiao, Long, Pu Wang, Amir Alipour-Fanid, Huacheng Zeng, and Kai Zeng. "Enabling efficient blockage-aware handover in RIS-assisted mmWave cellular networks." *IEEE Transactions on Wireless Communications* 21, no. 4 (2021): 2243-2257.

[2] Mezzavilla, Marco, Sanjay Goyal, Shivendra Panwar, Sundeep Rangan, and Michele Zorzi. "An MDP model for optimal handover decisions in mmWave cellular networks." In *2016 European conference on networks and communications (EuCNC)*, pp. 100-105. IEEE, 2016.

[3] Watanabe, Atom O., et al. "A review of 5G front-end systems package integration." *IEEE Transactions on Components, Packaging and Manufacturing Technology* 11.1 (2020): 118-133.

[4] Karim, Rashid, Adnan Iftikhar, and Rashad Ramzan. "Performance-Issues-Mitigation-Techniques for On-Chip-Antennas–Recent Developments in RF, MM-Wave, and THz Bands with Future Directions." *IEEE Access* 8 (2020): 219577-219610.

[5] Pfeiffer, Ullrich R., Janusz Grzyb, Duixian Liu, Brian Gaucher, Troy Beukema, Brian A. Floyd, and Scott K. Reynolds. "A chip-scale packaging technology for 60-GHz wireless chipsets." *IEEE Transactions on Microwave Theory and Techniques* 54, no. 8 (2006): 3387-3397.

[6] Lee, Jong-Hoon, Gerald DeJean, Saikat Sarkar, Stephane Pinel, Kyutae Lim, John Papapolymerou, Joy Laskar, and Manos M. Tentzeris. "Highly integrated millimeter-wave passive components using 3-D LTCC system-on-package (SOP) technology." *IEEE transactions on microwave theory and techniques* 53, no. 6 (2005): 2220-2229.

[7] Zhang, Yueping, and Junfa Mao. "An overview of the development of antenna-in-package technology for highly integrated wireless devices." Proceedings of the IEEE 107.11 (2019): 2265-2280.

[8] Braunisch, Henning, et al. "Off-chip rough-metal-surface propagation loss modeling and correlation with measurements." *2007 Proceedings 57th Electronic components and technology conference*. IEEE, 2007.

[9] Watanabe, Atom O., Muhammad Ali, Bijan Tehrani, Jimmy Hester, Hiroyuki Matsuura, Tomonori Ogawa, P. Markondeya Raj, Venky Sundaram, Manos M. Tentzeris, and Rao R. Tummala. "First demonstration of 28 GHz and 39 GHz transmission lines and antennas on glass substrates for 5G modules." In *2017 IEEE 67th Electronic Components and Technology Conference (ECTC)*, pp. 236-241. IEEE, 2017.

[10] Watanabe, Atom O., Tong-Hong Lin, Muhammad Ali, Yiteng Wang, Vanessa Smet, Pulugurtha Markondeya Raj, Manos M. Tentzeris, Rao R. Tummala, and Madhavan Swaminathan. "Ultrathin antenna-integrated glass-based millimeter-wave package with through-glass vias." *IEEE Transactions on Microwave Theory and Techniques* 68, no. 12 (2020): 5082-5092.

[11] Bowrothu, Renuka, Haein Kim, Yong Kyu Yoon, and Stephan Schmidt. "3D integrated through fused silica via (TFV) based array antenna for mm wave communications." In *2020 IEEE 70th Electronic Components and Technology Conference (ECTC)*, pp. 95-100. IEEE, 2020.

[12] Lu, Hao, et al. "Design, Modeling, Fabrication and Characterization of 2–5-μm Redistribution Layer Traces by Advanced Semiadditive Processes on Low-Cost Panel-Based Glass Interposers." *IEEE transactions on components, packaging and manufacturing technology* 6.6 (2016): 959-967.

[13] Yang, Fan, and Yahya Rahmat-Samii. "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: A low mutual coupling design for array applications." *IEEE transactions on antennas and propagation* 51, no. 10 (2003): 2936-2946.

[14] Bait-Suwailam, Mohammed M., Omar F. Siddiqui, and Omar M. Ramahi. "Mutual coupling reduction between microstrip patch antennas using slotted-complementary split-ring resonators." *IEEE Antennas and Wireless Propagation Letters* 9 (2010): 876-878.

[15] Hwangbo, Seahee, Hae Yong Yang, and Yong-Kyu Yoon. "Mutual coupling reduction using micromachined complementary meander-line slots for a patch array antenna." *IEEE Antennas and Wireless Propagation Letters* 16 (2017): 1667-1670.

[16] Cho, Hyunho, Woosol Lee, and Yong-Kyu Yoon. "Highly Compact Array MIMO Module for EMI Immune 5G Wireless Communications." *2021 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE, 2021.

[17] Cho, Hyunho, and Yong-Kyu Yoon. "Parallelly and Diagonally Placed Meander-Line Slot Resonators for Mutual Coupling Reduction in a 2x2 Patch Array Antenna." *2021 IEEE 21st Annual Wireless and Microwave Technology Conference (WAMICON)*. IEEE, 2021.

[18] A. P. French, Newtonian Mechanics, The M.I.T. Introductory Physics Series, W. W. Norton & Company, 1971

[19] Seetharaman, S. S., C. G. King, I. R. Hooper, and W. L. Barnes. "Electromagnetic interactions in a pair of coupled split-ring resonators." *Physical Review B* 96, no. 8 (2017): 085426.

[20] Gay-Balmaz, Philippe, and Olivier JF Martin. "Electromagnetic resonances in individual and coupled split-ring resonators." *Journal of applied physics* 92, no. 5 (2002): 2929-2936.