PCB Design for High Frequency RF Circuits

1st **Rajeshwari**
rajeshwari@acharya.ac.in

2nd **Gagandeep R**
gagandeep.23.beec@acharya.ac.in

3rd **Darshanraj K N**
darshanraj.23.beec@acharya.ac.in

4th **Bhargavi S**
bhargavi.23.beec@acharya.ac.in

Department of Electronics and Communication Engineering
Acharya Institute of Technology
Bengaluru, Karnataka

Abstract— The development of the high-frequency communication systems, e.g., 5G sub-6GHz, IoT networks, radar, and satellite transceivers, has increased the necessity to have an efficient RF front-end module. RF mixers and RF oscillators are required components which facilitate the process of frequency translation and generation of constant signals. This paper focuses on PCB implementation of these two RF circuits at various degrees of completion. RF mixer implementation has been carried out to bare PCB manufacture with the RF oscillator implementation being finished to Gerber file output.

The RF mixer layout was done as a systematic process that involves schematic capture, footprint layout, RF component placement, and impedance-controlled 4-layer FR-4 stack-up multilayer routing. Following successful DRC and DFM check, the design was produced in the form of bare PCB. Conversely, the RF oscillator was created with a 2-layer (top and bottom) stack -up on a Rogers substrate to improve the performance at high frequencies. This oscillator layout focused on controlled impedance, good grounding and minimization of parasitic, and went up to Gerber generation. This paper presents the significance of a PCB layout approach and experience in selecting materials to ensure the reliability of RF circuit performance.

Keywords— *RF System, RF Mixer, RF Oscillator, PCB Design, PCB Stack Up.*

I. INTRODUCTION

The majority of the modern wireless communication systems are based on radio-frequency (RF) circuits, which can be used in the frequency range of 300 GHz to 3 kHz. These circuits are used in radar, satellite, mobile and defense systems to process the high frequency signals. In contrast to low-frequency circuits, RF circuits are much more affected by the parasitic effects, electromagnetic behaviour, and transmission-line effects. Impedance matching, S -parameters, skin effect and dielectric losses also become critical design at higher frequencies.

The RF building blocks such as the amplifiers, oscillators, mixers, filters, and transmission lines are necessitated by the amplification, filtering, and frequency translation of the signals in the RF systems. RF mixers and oscillators became important in the case of up-conversion and down-conversion processes directly influencing linearity of the system, noise and spectral purity.

This paper focuses on PCB design of an RF mixer with the implementation to the bare PCB fabrication and RF oscillator design to the Gerber file stage with the emphasis on the controlled-impedance routing, grounding, and layout considerations of reliable functioning at high frequencies.

II. LITERATURE REVIEW

Kared et al. [1] introduce a SiGe HBT double -balanced down conversion mixer to work at UHF, with a functioning band of 0.5-1.8GHz. The transformer-free architecture that implements two-feedback linearization offers a conversion gain of about 12dB, low noise and high LO/RF/IF isolation. The paper shows that the RF-stage symmetry can be carefully designed to achieve the high the linearity and isolation at the same time.

Yun et al. [2] introduce a 2.4/5 GHz dual-band WiFi-6 receiver based on passive mixers and a new feedforward OPAMP in 22 -nm SOI CMOS. The architecture is low noise, highly linear, and offers excellent EVM as well as low power consumption. The article puts emphasis on RF–baseband co-design to high-performance WLAN receivers.

Han and Kwon [3] present a calibration-free IIP2-quadrature passive mixer of LTE and 5G NR sub-6 GHz systems. Further switching routes allow inherent IM2 cancellation, with 13-16 dB IIP2 improvement. The design shows strong wideband behaviour without the need to do any calibration.

Chrisben Gladson et al. [4] introduce an ultra-low-power single-to-differential RF mixer in the sub-6GHz 5G IoT applications. The mixer can reach high IIP3 with a power consumption of just 223 µW using current bleeding and body-effect linearization. Its design is appropriate in the small, battery-operated wireless equipment.

III. PCB Design of RF Mixer

RF Mixer: RF mixer This is a vital element of an RF system, which performs frequency translation by the nonlinear interaction of an input RF signal and a local oscillator (LO) signal. The mixer allows a down-conversion to lower intermediate frequency of high frequency RF signal (down-conversion) or an up-conversion during transmission. Additional parameters being conversion gain or loss, noise figure, linearity, port isolation and spurious response suppression characterize mixer performance and are highly dependent on circuit design and PCB layout practices.

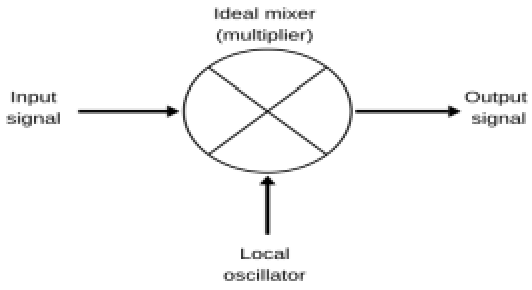


Fig: RF MIXER

Schematic

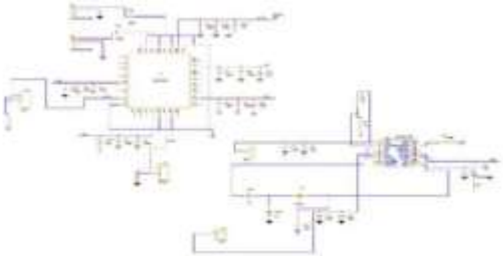
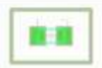
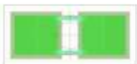
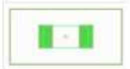
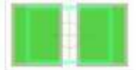


Fig: SCHEMATIC OF RF MIXER

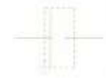
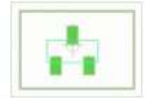
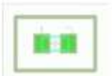
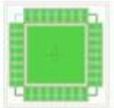
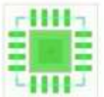
The presented schematic is a complete RF mixer module in microwave. frequency conversion reductions. The HMC6505A passive RF mixer is in the centre of the circuit. IC, that does the frequency translation using a local oscillator (LO) that is applied externally. signal. The LO signal is passed on using an SMA connector and it is channeled to the LO input of the mixer. Trace using controlled-impedance. RF filtering, RF grounding, and RF decoupling are all done properly. fitted round the mixer to maintain its constant operation, excellent isolation, and low noise at high frequencies.

The schematic also contains to ensure a safe and reliable operation of the mixer. HMC981LP3E bias control IC, which produces and sequences and required positive and negative bias voltages. This bias controller will make sure that negative gate bias is in place prior to the positive supply, which prevents damage of the HMC6505A when starting up. Multiple Supply noise is suppressed and protection diodes prevented through the use of decoupling capacitors transients. On the whole, the synchronized work of the HMC6505A mixer and the HMC981LP3E bias controller with the filtering networks around them leads to a stable operation with low noise and a high level of the HMC981LP3E performance RF mixer module

SYMBOLS AND FOOTPRINT

Sl No	Manufacturing Part No	Designator	Description (VALUE)	Symbol	Footprint
1	0402	C1, C3,C5, C7,C9,C24, C25	Ceramic capacitor, 100pf, 5%, 50V		
2	CAPC1608X90	C2,C4,C6,C8,C10	Ceramic capacitor, 1000pf, 10%, 50V		
3	1206	C11,C12,C13,C14,C15	Tantalum capacitor, 2.2uf, 25V,10%		
4	0402	C16	Ceramic capacitor, 1uf, 5%, 25V		
5	1206	C17,C18	Ceramic capacitor, 4.7uf, 5%, 25V		
6	CAPC2012X145N	C19,C20,C23	Ceramic capacitor, 10uf, 5%, 25V		
7	0402	C21	Ceramic capacitor, 100nf, 5%, 25V		

Schematic symbols and PCB footprints have been defined in the RF mixer PCB design with every component being defined by its electrical functionality as well as its actual implementation on the PCB. Circuit connectivity and functional intent is represented by schematic symbols (like C1, C25, R1, R6, R7, R8, D1, D2, J11, J14, U1 and U2) and is represented by the footprint of these symbols to be placed correctly mechanically and to be manufacturable. This symbol-to-footprint mapping is especially essential in RF circuits, where layout-related parasitic may have a severe impact on the system performance and signal quality in general.

8	0402	C22	Ceramic capacitor, 15nf, 5%, 25V		
9	BAT54SLT1	D1,D2	Dual Series Schottky diode		
10	CONSMA002-SMD	J11,J12,J13, J14	RF connector		
11	0402	R1	0.266 ohm Resistor, 0402 pkg		
12	0402	R6,R7	10K ohm Resistor, 0402 pkg		
13	HMC6505A	U1	Device under tes(DUT)		
14	HMC981LP3E	U2	HMC981LP3E Active bias controller		

The design uses capacitors in a variety of ways that are RF coupling, decoupling, bias stabilization, and power-supply filtering. RF coupling and local decoupling are done with high-frequency ceramic capacitors in small 0402 packages whereas larger-value capacitors in 1206 and 2012 footprints are used to do bulk decoupling and improved supply filtration. To reduce high-frequency noise and provide stable biasing smaller size decoupling capacitors are located close to active device supply pins. Current sensing and bias control Resistors in 0402 footprint are used that provide smaller routing and less parasitic impact. Dual series Schottky diodes are used to offer both protection and bias control and the footprints in them are designed to be as small as possible to minimize the parasitic contribution to RF-sensitive paths.

The RF interfaces are the SMA connector symbols which have special SMD footprints to ensure controlled-impedance transitions between the connectors and the RF traces and is supported by ground pads and via stitching. HMC6505A RF mixer IC (U1) and HMC981LP3E bias controller IC (U2) are the main active circuits, and are modeled by elaborated schematic circuits which explicitly indicate functional groupings of pins. Their footprints are always based on the land patterns recommended by the manufacturers to maintain the optimum RF performance, grounding and thermal dissipation. The standardized symbols and well-chosen footprints allow us to reduce the risk in the manufacturing process and enhance the RF mixer usage.

PCB STACK UP

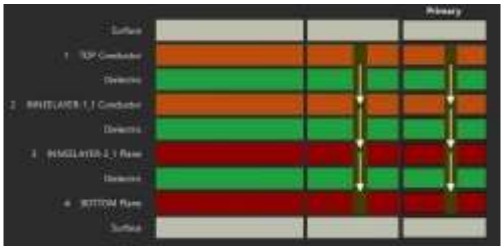


Fig: PCB Stack Up

The FR 4 PCB stack up is based on four-layer stack up that provides high frequency and isolation of a RF mixer at low cost and manufacturability. The uppermost layer is in planar which carry critical RF, LO, and IF signals and conduct lines of controlled- impedance trace, inner layers divide power, control, and grounding in order to reduce noise coupling. Good internal ground plane offers low impedance return path, port isolation and it also removes EMI in favor of good via stitching. The base layer helps in distributing power in a stable manner, decoupling as well as providing further shielding. The multilayer FR 4 structure, in general, guarantees the reliability of frequency conversion, good signal integrity, and sound RF performance.

GERBER DATA

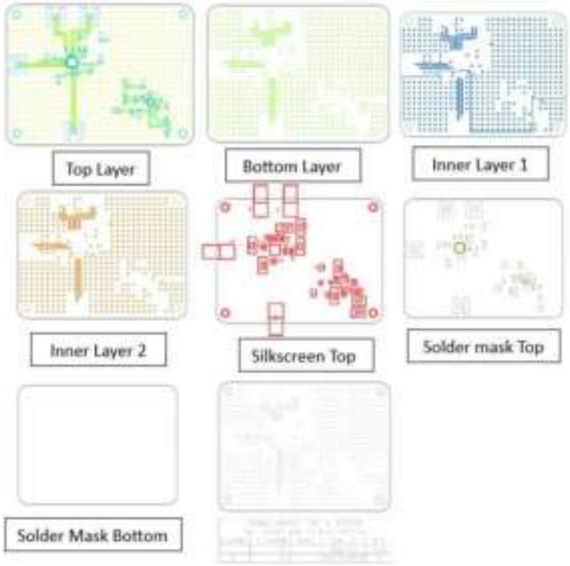


Fig: Gerber data

The Gerber data of the four-layer RF PCB is used to fully describe the physical implementation of RF mixer design. The uppermost layer has all the active and passive components having controlled-impedance microstrip routing which links centrally located RF ICs to edge mounted SMA connectors through short traces which are symmetric and short to reduce loss and reflections.

Inner Layer 1 is applied as a split power plane to convey individual bias in addition to lowering noise coupling, whereas Inner Layer 2 is applied as a continuous solid ground plane to give low-impedance RF return path, higher shielding, and higher signal integrity due to a massive via stitching.

The secondary ground and low-frequency routing layer are the bottom layer which is used to provide additional grounding and EMI suppression. Dense plated vias are used in drill data to provide interlayer connection and grounding and non-plated mounting holes to provide mechanical stability. Silkscreen layer offers easy identification and orientation of components to be assembled correctly whereas top and bottom solder mask layers also safeguard unused copper, guarantee good solder joints and also add long-term reliability to the PCB without compromising on the RF performance.

Fabrication of PCB

Fig: PCB Fabrication

This diagram explains the four-layered RF PCB design that was applied to the HMC6505A RF mixer and HMC981LP3E RF bias controller. The uppermost layer has all active and non-active elements, and RF, LO and IF traces are executed using short and controlled-impedance traces of microstrip to edge-mounted connectors as possible to reduce loss and reflections. Good signal integrity, isolation, and EMI are guaranteed by matching networks, DC-blocking capacitors and dense via stitches. The second is a split bias plane between VDD and VGG in order to avoid noise coupling and enhance bias stability. The third one is a solid ground plane continuously covering the ground plane that offers a low-impedance RF return and high-strength electromagnetic shielding. The base plate is an extra ground plane which makes it isolate better, dissipate thermal energy and be more robust. A combination of the structure results in low-noise, stable and reliable microwave RF performance.

RF OSCILLATOR

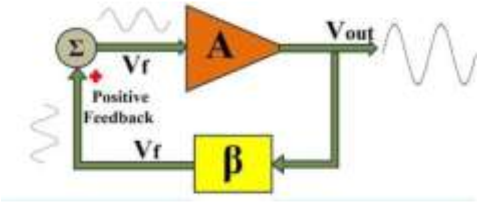


Fig: RF Oscillator

RF oscillator: This is an RF or microwave sinusoidal signal of constant amplitude and constant period. These are the signals you will encounter in the centre of radio systems playing the role of the primary carrier or as a local oscillator. Before it even gets to important system characteristics such as phase noise, frequency stability and spectral purity, the performance of an RF oscillator directly influences the key system specifications. Designers boost the frequency to reach such high frequencies by means of feedback, frequency multiplication or mixing. However, it is not only about the circuit itself but the specifics of PCB do matter. Proper routing, grounding, effective shielding, and decent decoupling of power-supplies can all serve to ensure that phase noise is minimized, reduce unwanted.

Schematic

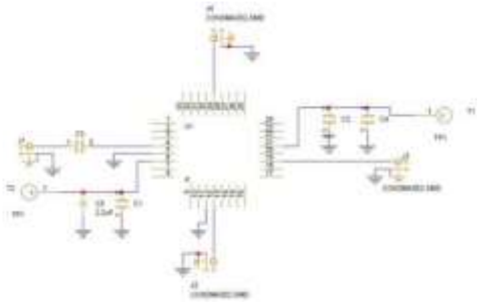
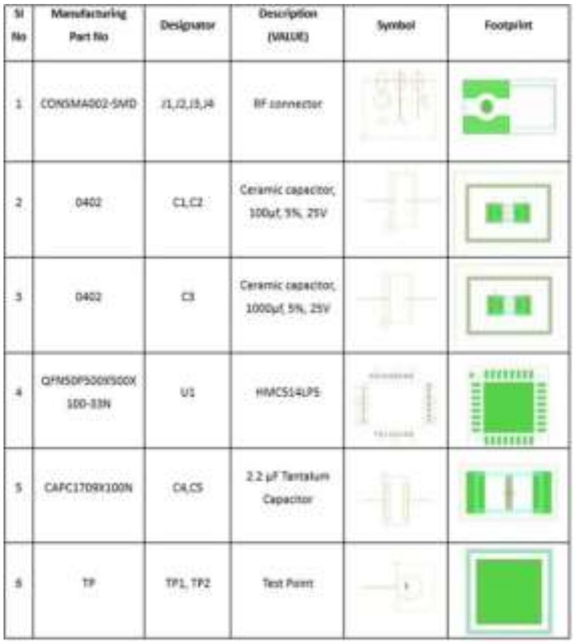


Fig: Schematic of RF Oscillator

The schematic represents RF oscillator module that is to be used in the generation of microwave signals. The design consists of the HMC514LP5 broadband VCO, the core of which produces X/Ku -band frequencies under the control of the VTUNE voltage The RF output is passed to an SMA connector through controlled impedance transmission lines so as to ensure signal integrity. Optional 2 and 4 divider out deliver flexible lower frequency LO signal.

The use of decoupling and bypass capacitors has been used very carefully to make sure that the VCO and the buffer stages receive low noise and constant power.

SYMBOLS AND FOOTPRINT

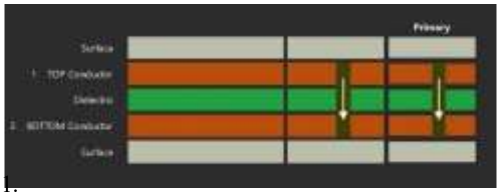


Sl No	Manufacturing Part No	Designator	Description (VALUE)	Symbol	Footprint
1	CONSMA002-SMD	J1,J2,J3,J4	RF connector		
2	0402	C1,C2	Ceramic capacitor, 100uf, 5%, 25V		
3	0402	C3	Ceramic capacitor, 1000µf, 5%, 25V		
4	QFN50P500X500X100-33N	U1	HMC514LP5		
5	CAPC1709X100N	C4,C5	2.2 µF Tantalum Capacitor		
6	TP	TP1, TP2	Test Point		

Schematic symbols and PCB footprints are very well defined in the RF oscillator PCB design to be a representation of electrical functionality and physical realization. Circuit connectivity is represented by symbols like J1-J4, C1-C5, TP1, TP2, and U1 and footprints provide them with their correct position and manufacturability. SMA connectors provide controlled-impedance RF interfaces, SMD footprints with ground pads and stitching via to reduce reflections and inductive return-path through each interconnection. Capacitors are utilized to decouple high-frequency, mid-frequency and bulk supply so as to suppress noise and provide stable oscillator operation over a broad frequency spectrum.

The active device, U1 (HMC514LP5 VCO), is depicted as a schematic symbol with detailed terminals in which RF outputs, tuning voltage, supply and ground pin are perfectly identified. Its QFN footprint also adheres to lands patterns recommended by manufacturers and it has an exposed ground pad to facilitate efficient grounding and thermal dissipation which are essential in low phase noise and frequency stability. To allow the safe probing of the tuning and supply nodes, test points are added to permit testing and validation. On the correct mapping of symbols to footprints and good layouts practices will guarantee better assembly, constant frequency generation.

PCB STACK UP



1.

Fig: PCB Stack Up

The PCB stack up is a two-layered high-speed design that is carried out with Roger's dielectric substrate so as to have better RF performance. Components are placed on the top and microstrip routing of sensitive RF signals is controlled at impedance and microstrip of sensitive RF signals, using the short trace paths and direct trace paths to reduce the insertion loss, reflections and phase distortion at the microwave frequencies.

Its dielectric core offers a constant dielectric core and low loss tangent which offers predictable impedance and lower attenuation. The lowermost is a continuous ground plane, which is in effect a low impendence return path and increased electromagnetic shielding. The two-layer Rogers stack up in general offers a cost- efficient, low-loss, and stable solution to RF oscillator implementation as well as to the implementation of microwave circuits.

GERBER DATA

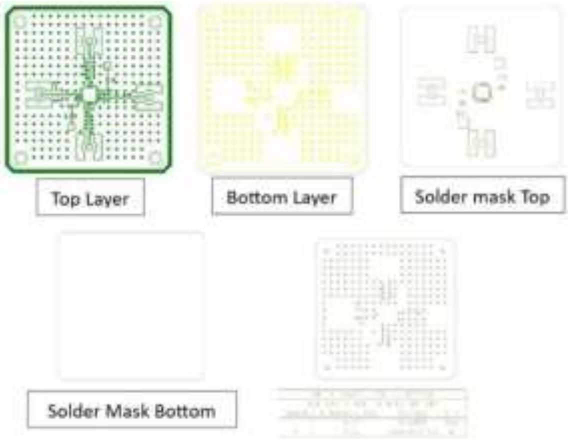


Fig: Gerber Data

The Gerber data on two-layer RF PCB design. The top layer has all the active and passive elements and routing using controlled-impedance microstrip and centrally mounted RF IC to edge-mounted SMA connectors, which are conductively stitched together by dense via, to provide good grounding and electromagnetic shielding. The bottom layer is used as a continuous solid ground plane thereby providing a low-impedance return path and reducing the noise coupling due to minimal routing.

The top solder mask forms exact openings representing the IC pads, passive components, connectors and test points whereas the bottom solder mask totally covers copper layer to offer insulation, protection against oxidation and mechanical strength. The data of the drill consists of the densely spaced 0.3mm plated vias in the interlayer connectopies and RF return and non-plated holes of mounting to provide mechanical integrity. All these properties assure a good signal of integrity, stable high- frequency behavior.

IV. RESULTS AND DISCUSSION

The RF mixer PCB fabrication proves the assertion that the dedicated mixer layout and the multilayer stack-up is highly efficient to frequency-conversion applications at high frequencies. The FR4 structure of 4-layer with a solid internal ground plane gives a good return path to RF and LO and enhances the isolation and reduces the parasitic effects. Signal routing and bias network separation assure there is a reduced interference between the RF paths and the mixer biasing circuitry that is vital in the stable and predictable operation of the mixer.

Also, the RF mixer PCB, which was fabricated, illustrates the possibility of the realization of a small, multilayer RF front-end module with a standard FR4 material. Proper achievement of the SMA interfaces, controlled-impedance traces and grounding vias fact that the design can be made, and the component assembly and testing is ready

V. CONCLUSION AND FUTURE WORKS

Conclusion

Two major RF subsystems, namely RF mixer and RF oscillator, were also designed on a printed circuit board in this work up to various phases of realization. The RF mixer PCB has been designed with the multilayer FR4 stack-up and fabricated to bare PCB level that verified the layout, stack-up planning, grounding strategy, and manufacturability. The inclusion of dedicated ground layer, controlled- impedance RF traces as well as separated bias routing proves that the proposed mixer PCB design can be used in high-frequency operation and offers a stable base on which to further assemble and test.

Simultaneously, the RF oscillator PCB was completed to Gerber file generation point, and this confirmed that the schematic, footprint assignment and layout rules had been correctly applied to RF application. Even though fabrication was not performed on the oscillator board, the final Gerber data reflects an indication of readiness to undertake manufacturing and has the right RF layout behavior including short signal paths, effective decoupling and grounding behavior. In general, this creates practical design of RF PCB starting with conception of the circuit, up to the documentation that is fabrication-ready.

Future Work

The next step in work will consider the assembly and experimental testing of the produced RF mixer PCB through the mounting of active and passive devices and the RF tests of the conversion loss, isolation, Return loss and noise performance of the mixer. These measurements will enable the comparison of the simulated and measured results directly, which will give more information about the efficiency of the PCB layout and the choice of material. The mixer circuit can also be experimented under various operating conditions in order to study thermal behavior and long- term reliability.

In the case of the RF oscillator, the second step is to assemble the PCB using the produced Gerber files and the assembly of the oscillator IC and other related parts. The design of the oscillator will be completely validated by subsequent characterization of output frequency, phase noise, tuning range and stability. In the next generation, RF substrates with higher performance like Rogers materials can also be considered in order to minimize dielectric losses at microwave frequencies and the mixer and oscillator boards can be combined to form an RF front-end module to be tested and tuned as a system.

VI. REFERENCES

[1]. T. Kared, H. Silaghi, M. Rudolph, A. Silaghi, U. L. Rohde – “Design of a Fixed IF Down-Conversion Double-Balanced Mixer for UHF Band Applications”, Sensors, vol. 25, no. 608, January 2025.

[2]. Sukju Yun, J. Jeong, D. Cho, S. Lee – “A 2.4/5 GHz Dual-Band Low-Noise and Highly Linear Receiver with a New Power-Efficient Feedforward OPAMP for WiFi- 6 Applications” – Analog Integrated Circuits and Signal Processing, 2023.

[3]. S. Chrisben Gladson et al. – “RF Received Front- End Employing IIP2-Enhanced Techniques” – 2022/2023.

[4]. S. Chrisben Gladson, P. Siva Prasad, B. Manickam – “A 223-µW Single-to- Differential RF Mixer with 8.6 dBm IIP3 using Current-Bleeding and Body-Effect for Sub-6 GHz 5G Applications” – Analog Integrated Circuits and Signal Processing, 2021.