# *A Survey of Millimeter Wave RF Design Approaches for 5G Cellular Communications*

*Vivekanandh Elangovan*
Wireless @ Virginia Tech
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

*Dinesh Datla*
Harris Corporation, Lynchburg, Virginia

*Jeffrey H. Reed*
Wireless @ Virginia Tech
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

***Abstract*—Industry and academia have started discussions on the vision for 5G cellular communications. Millimeter wave communication technology is a strong potential candidate for 5G communications given the vast attention that it has received from industry and academic research institutions, and given the vast potential for expanded spectrum access. Although millimeter wave technology is considered as an innovation in the cellular world, it has been commonly used in satellite communications, radar, backhaul and biomedical applications. Broadly speaking, the literature on millimeter wave design discusses the application of heterodyne, superheterodyne, and direct conversion architectures for signal transmission and reception. This paper has two objectives: (a) to survey existing approaches for millimeter wave RF design and to evaluate their suitability for 5G communications; and (b) discuss the drawbacks of employing existing cellular RF design approaches for 5G millimeter wave communications, where the RF design is expected to be power efficient and robust. The paper's scope is limited to system level design aspects of RF signal reception and transmission. In order to address the second objective, the paper presents simulation results of the performance of a reference superheterodyne receiver design.**

***Keywords—60 GHz; RF front end design***

## I. Introduction

Over the past decade, the demand for high data rate mobile communication has been increasing rapidly. Cellular industry has been working to address the demand by evolving the wireless systems over several years. 4G LTE is now being deployed worldwide. As the spectrum is getting crowded, industry is exploring novel spectrum options with the objective of discovering usable spectrum that can provide the wide bandwidth that is required for multi giga bit per second data rates. Spectrum ranging from 3 to 300 GHz is currently being utilized minimally and, hence, serves as a good candidate for hosting wide bandwidth and high data rate wireless services. Millimeter wave communication is a promising enabling technology that is being explored for utilizing this spectrum for 5G cellular communications. Although millimeter wave technology is considered as an innovation in the cellular world, it has been commonly used in satellite communications, radar, backhaul and biomedical applications. Meteorological satellites, such as the MTSAT, operate in the ka band (uplink of 27–31GHz). Popular commercial applications include body scanners used by airport security which operate close to sub-mm wave frequencies. Airplane navigation support radars operate in the 31 – 36 GHz band. Broadly speaking, the literature on millimeter wave design discusses the application of heterodyne, superheterodyne, and direct conversion architectures for signal transmission and reception. Although this technology exists, there are challenges to be addressed before this technology can be used for 5G cellular communications. In 5G cellular communications, the RF design is expected to be power efficient and robust (low phase noise), with relatively less emphasis on spectral efficiency.

This paper has two objectives: (a) to survey existing approaches for millimeter wave RF design with focus on system level design aspects of RF signal reception and transmission and evaluate the suitability for 5G communications; and (b) discuss the drawbacks of employing existing cellular RF design approaches for 5G millimeter wave communications. The rest of the paper is organized as follows. Section II discusses existing 60 GHz RF front end designs and presents their drawbacks when used for 5G. Section III presents a simulation study of the use of the superheterodyne receiver for millimeter wave communications and compares its performance with a reference cellular RF front end system.

## II. Current Millimeter RF Designs

This section discusses some existing classical and specialized transceiver designs that have been explored for possible implementation in millimeter wave frequencies. The aim is to identify their drawbacks when employed at millimeter wave frequencies.

### *A. Classical designs*

The following are some fundamental transmitter front end designs that have been explored for 60 GHz front end operation: (a) impulse radio transmitter; (b) direct conversion transmitter; and (c) two step transmitter. In the impulse radio the transmitter transmits impulses of finite duration which requires a wide bandwidth. When implemented at millimeter wave frequencies, the pulse width is much shorter thereby introducing challenges in pulse generation and timing. This makes the monocycle impulse design not a viable option for millimeter wave systems. The use of a impulse radio direct conversion transmitter at 60 GHz has been explored by Badalawa et al. [2] and Deparis et al. [3]. The application of the direct conversion design to 60 GHz systems has been explored by Ellinger [4] and Wicks et al. [5]. The direct conversion design, in general, allows greater flexibility in the generation of signal waveforms as most of the signal processing occurs in software that runs on a digital baseband processor. However, as pointed by Ellinger [4], the direct conversion transmitter suffers from injection pulling which occurs due to the fact that the power amplifier's band of operation is centered on the same frequency as that of the VCO. In the case of the two step transmitter [6], injection pulling is not a major concern, however image rejection can be a major challenge.

In a millimeter wave transmitter front end architecture, some of the key factors that have to be considered are phase noise, load pull and adjacent channel rejection. In order to avoid phase noise a multiple level up conversion method can be employed. A phase locked loop with voltage controlled oscillator generates a frequency that is higher than that of the oscillator's reference source. When the generated frequency is higher than that of the reference source, the phase noise is low. Phase noise can be reduced by operating the local oscillator (LO) at a lower frequency and using a multiplier to realize the required frequency. This approach allows a logarithmic increase of phase noise with increase in frequency, which is better than the linear increase in phase noise caused when employing a high frequency LO. In order to minimize load pull and increase the isolation between the oscillator and its varying load, more number of buffer amplifier stages with attenuators between them need to be used. Good isolation is required in the power amplifier as any feedback might affect the adjacent channel rejection ratio which is a key transmitter performance metric. Good isolation can be realized by using a good ground and a short path to the ground. At millimeter wave frequencies, the short path is really short and realizing it can be a challenge.

The following receiver architectures are explored for 60 GHz front end design: (a) non-coherent receiver; (b) coherent impulse radio receiver; (c) super heterodyne receiver; (d) direct conversion receiver; and (e) image rejection receiver. The non-coherent receiver is the simplest receiver architecture, but suffers from the drawback that it has a high noise figure. The coherent impulse radio receiver is better than the non-coherent receiver, but when implemented at 60 GHz this architecture will have issues in meeting the stringent timing requirements of coherent receivers [7]. In the case of the super heterodyne receiver, the main drawbacks are apparent with image rejection and adjacent channel rejection [8]. The direct conversion receiver design, on the other hand, is not concerned with image rejection. The main drawbacks of direct conversion, however, are DC offset, LO leakage, noise and I/Q mismatch. LO leakage can result in injection pulling in a direct conversion receiver. A 60GHz image rejection receiver [9] provides a good solution for image rejection at the cost of a complex circuit implementation.

A classical example of the super heterodyne architecture is the channel sounder. Treyer [13] implemented a channel sounder that was used to measure channel characteristics at 58 GHz. As per the design presented in Figures 1 and 2, the channel sounder operates with a 5.8 GHz intermediate frequency. In order to generate a 52 GHz LO signal, the transmitter uses a 13 GHz oscillator that is phase locked to a 10 MHz clock and a cascade of multipliers that increase the frequency to the required one. An LO amplifier is used in cascade with the multipliers to boost the LO signal and compensate for the loss introduced by the multipliers. The front end design includes an edge coupled microstrip bandpass filter with edge coupled half wave resonators. This setup has a low passband insertion loss at frequencies ranging from 56.6 to 58.6 GHz, and a high stopband attenuation at the LO and the image frequency which is very critical for millimeter wave design. This design was used for channel sounding purposes and is not suited for cellular communications.

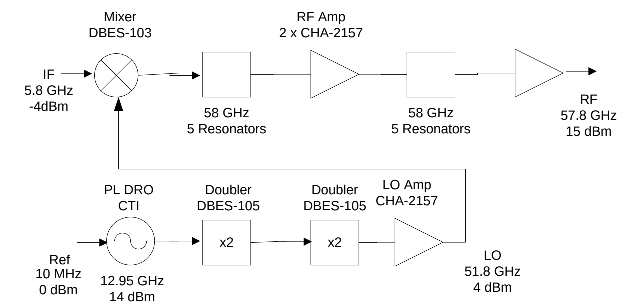


Fig 1. 58 GHz channel sounder Transmitter section (adapted from [13])

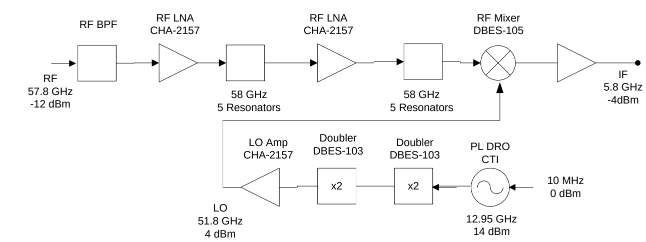


Fig 2. 58 GHz channel sounder Receiver section (adapted from [13])

At the receiver end, some of the key design issues are phase noise and image rejection. In order to avoid the phase noise issue, a multiple level down conversion method is used and a similar architecture to transmitter for phase locked loop is used. Meeting the stringent requirements of the image rejection filter at high frequencies is a challenge.

### B. *Current state-of-the-art in millimeter wave radio design*

This section discusses some of the specialized designs that were proposed for millimeter wave systems. In the adopted direct conversion front-end design [10] (Figure 3 and 4), the in-phase and quadrature components are differential so that the baseband circuits do not suffer from common mode interference or noise. Next, a phase shifter is used so that the I and Q signals are 90 degree out of phase with each other. Two mixers are used in the transmitter and receiver designs for up conversion and down conversion, respectively. In the transmitter design, the frequency synthesizer is a differential and the fundamental frequency VCO oscillates in the millimeter wave frequency. Due to differential signal, this design leads to decrease in power efficiency of the front-end which increases power consumption. Another interesting design is the multiport circuit based transceiver design [11]. While classical designs are implemented using discrete components, this low cost approach implements the transceiver in the form of a multiport circuit that is based on 90 degree hybrid couplers. The multiport quadrature down conversion approach [11] provides improved results in terms of conversion loss; excellent isolation between the multiport RF inputs; and very good suppression of harmonics and spurious products at the mixer. The multiport circuit also requires a lower LO power compared to classical approaches.

The intermediate frequency (IF) section is an important part of the RF front end as it enhances the desired signal while eliminating undesired signals. Bao et al. [12] implemented an IF circuit for a 60 GHz linear frequency-modulated continuous wave (LFMCW) radar system. The design achieves a 120 dB gain with a pre-amplifier and an auto-gain amplifier design that is implemented as a cascade of low noise amplifiers and voltage controlled gain amplifiers. This design, however, doesn't address the image rejection issue which is a key criterion for millimeter wave designs.

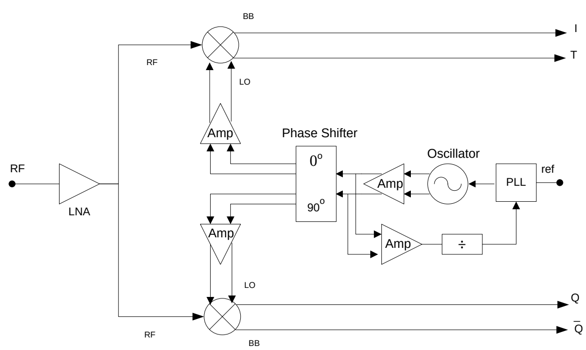


Fig 3. Block diagram of adopted direct conversion receiver (adapted from [10])

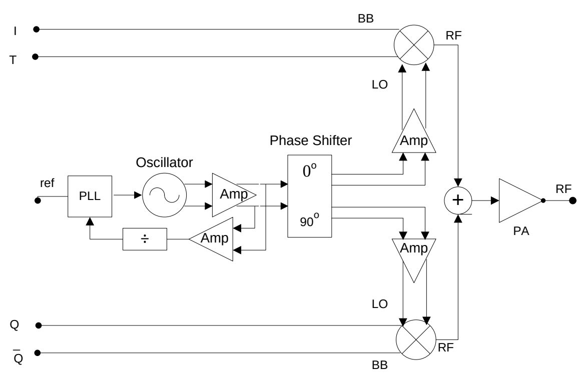


Fig 4. Block diagram of adopted direction conversion transmitter (adapted from [10])

The direct conversion design approach eliminates the need for image rejection filters and synthesizing the Local oscillator is very critical and difficult to implement. A sub-harmonic downconverion has been sudied in [16]. The VCO and the dividers run at the sub-harmonic of the received signal and there is no intermediate frequency and image frequency. The sub-harmonic also avoids the direct conversion issues such as DC offset and leakage which is a concern with direct conversion architecture.

Traditionally, a 60 GHz tranceiver is not considered for low power system design due to various reasons such as component power consumption, high transmission loss and other reasons. But by operating at a low duty cycle and by lowering the number of bits transmitted the system can be designed for low power transmission [14]. In this approach, a local oscillator is implemented as a co-planar waveguide transmission line based on negative resistance oscillator. This eliminates the need for a PLL as frequency accuracy is not a critical issue, thereby reducing the turn-on power.

In higher frequency systems, it is typical for power efficiency to decrease as the RF frequency increases. The Power Amplifier (PA) poses a huge issue as the frequency increases the efficiency and the output power decreases. However, as fabrication technology is improving PA efficiency is improving. This can be seen with existing wireless technology such as WCDMA, where the efficiency increases over time as shown in Figure 5 which has been surveyed over different product available in the market over the period of years.

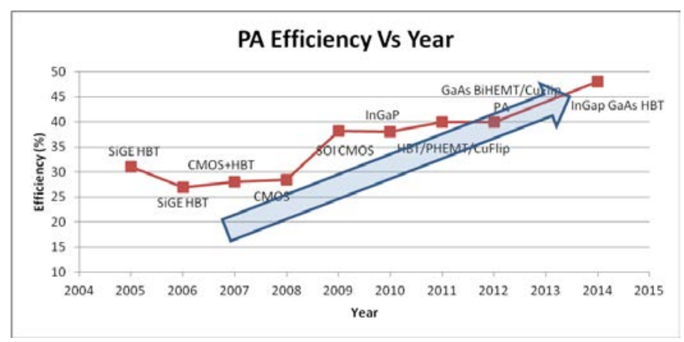


Fig 5. WCDMA Power Amplifier trend

Operating at higher frequency requires scaled technologies with low breakdown voltages, limiting the output power that can be generated from a single PA where the efficiency is limited by active and passive losses. With the various ongoing researches on the PA in mmwave technology the efficiency and output power would improve which is shown as a trend in Figure 6 collected over [23, 24, 25, 26]. From figure [6] it can be noted that with standard CMOS it is hard to attain the high efficiency similar to cellular frequency (WCDMA). With SOI CMOS (Silicon on Inductor CMOS) the efficiency can be increased at higher frequency. And as the technology grows over the years the efficiency at higher frequency can be attained similar to current cellular frequency

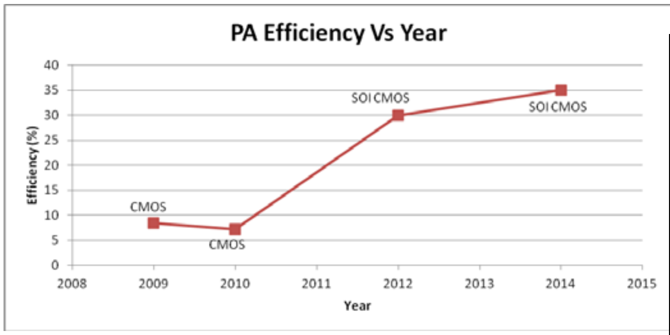


Fig 6. mmWave Power Amplifier trend

## III. Simulation Study

A superhetrodyne receiver (Figure 7 and 8) is considered for simulation and a comparison is made between the current RF front end design at 782 MHz and millimeter wave at 60 GHz. A channel bandwidth of 10 MHz is considered and therefore the SAW filters are designed for a bandwidth of 10 MHz with the stop band attenuation at 70 dB. LNA with a typical gain of 13 dB are designed for the RF front end and a mixer with a conversion gain of 6 dB is considered for this simulation. The IF circuit (Figure 8) would be identical for both the 782 MHz and 60 GHz with the 1$^{st}$ IF at 70 MHz and the 2nd IF at 2.16 MHz. Two IF amplifiers are designed with a fixed gain of 16.5 dB and 20 dB with conjunction with IF filter centered at 70 MHz which is usually considered as image rejection filter. The components used for simulation are shown in table 1 and 2.

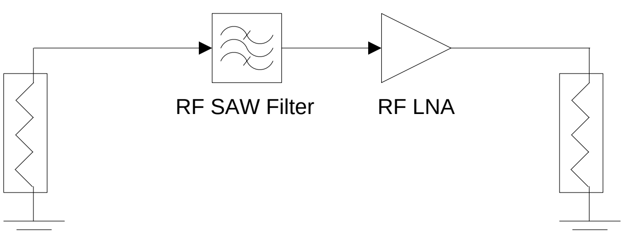


Fig 7. RF section design for ADS simulation

| Components | 782 MHz | 60 GHz |
|---|---|---|
| **RF SAW Filter** | Triquint 856844 [17] | ADS Custom BPF Chebychev Filter |
| **RF LNA** | Freescale MML09211HT1 [18] | Triquint TGA4600 [19] |

Table 1: Components considered for simulating RF front end

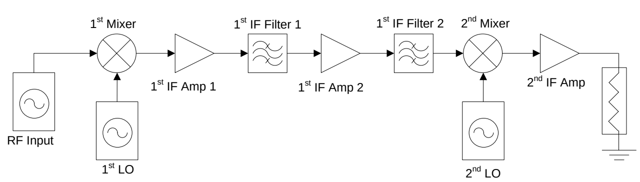


Fig 8. IF section design for ADS simulation

| Components | 782 MHz | 60 GHz |
|---|---|---|
| **RF Input** | 782 MHz @ 0 dBm | 60 GHz @ 0 dBm |
| **1$^{st}$ LO** | 712 MHz @ 10 dBm | 59.930 GHz @ 10 dBm |
| **1$^{st}$ Mixer** | ADS Mixer | ADS Mixer |
| **1$^{st}$ IF Amp 1** | Analog Devices ADL5536 [20] | Analog Devices ADL5536 |
| **1$^{st}$ IF Filter 1** | SAWTEK 854665 [21] | SAWTEK 854665 |
| **1$^{st}$ IF Amp 2** | Analog Devices ADL5536 [22] | Analog Devices ADL5536 |
| **1$^{st}$ IF Filter 2** | SAWTEK 854665 | SAWTEK 854665 |
| **2$^{nd}$ Mixer** | ADS Mixer | ADS Mixer |
| **2$^{nd}$ LO** | 67.84 MHz @ 10 dBm | 67.84 MHz @ 10 dBm |
| **2$^{nd}$ IF Amp** | Analog Devices ADL5530 | Analog Devices ADL5530 |

Table 2: Components considered for simulating IF section

The simulation result for the 2$^{nd}$ IF amplifier is shown in Figures 7 and 8 considering the entire RF front end are matched to 50 ohm and with an input of 0 dBm for the received signal. The matching components and the RF SAW filter play an important role determining the output level. At 60 GHz since the wavelength is very small and hence there would be more attenuation through the traces and the components used for matching have to be chosen carefully. The simulation results shown in Figure 9 and 10 shows the difference in output power level between 782 MHz and 60 GHz as there is more attenuation in 60 GHz due to the matching components and SAW filter. The simulation is considered only for the RF section and a perfect image rejection filter is considered for the IF section to avoid any image issues in the receiver. The phase noise is considered the same for both 782 MHz and 60 GHz simulations which masks any phase noise issue for the receiver at 60 GHz simulation.

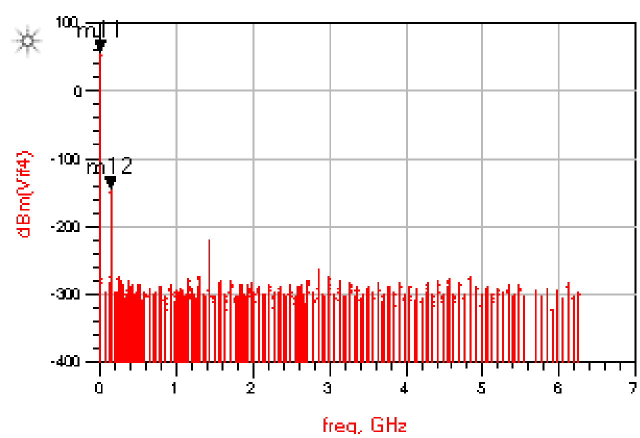


Fig 9. 2nd IF amplifier output for 782 MHz

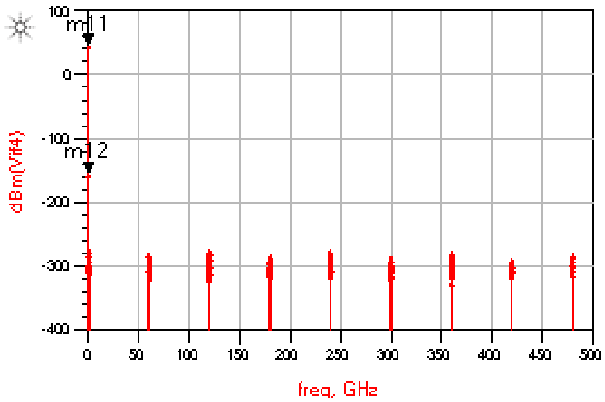


Fig 10. 2nd IF amplifier output for 60 GHz

Theoretically speaking when the RF is centered at 782 MHz, the 1st IF Image falls at 637 and 647 MHz and the 2nd IF image falls at 772.68 and 782.68 MHz whereas when the same IF is used at 60 GHz, the 1st IF image falls at 59.855 and 59.865 GHz and the 2nd IF image falls at 59.99068 and 60.00068 GHz. The image frequencies reflect that at 60 GHz the image rejection would be really critical and also care should be taken on the phase noise where the phase noise can be avoided by using a lower LO and using a multiplier for the IF frequency.

## IV. Conclusion

Different transceiver architectures lead to different issues in millimeter wave systems. The overview of transmitter designs presented in this paper sheds light on the various issues such as power amplifier efficiency, Adjacent Channel Power Rejection (ACPR) as well as issues in the receiver, namely image rejection and phase noise. As pointed out in the simulation results, current architectures used in cellular systems cannot be directly implemented for millimeter wave design as they do not properly perform well at extremely high frequencies. Various best practices and architectures have to be combined together to achieve a good RF front end design for 5G millimeter wave communication. SOI CMOS technology offers great benefits over discrete components and can be considered as an excellent alternative for 5G millimeter wave RF font end design.

## References


[1]. T. S. Rappaport, J. N. Murdock, and F. Gutierrez, ``State of the art in 60 GHz integrated circuits & systems for wireless communications," Proc. IEEE, vol. 99, no. 8, pp. 1390_1436, Aug. 2011.

[2]. B.B.M.W. Badalawa and M. Fujishima. "60 GHz CMOS pulse generator," Electronics Letters, vol. 43, pp. 100-102, Jan 18 2007.

[3].N. Deparis, A. Boe, C. Loyez, N. Rolland and P. Rolland, "60 GHz UWB-IR transceiver with pulsed-injected locked oscillator," European Conference on Wireless Technologies, 2007, pp 280-283, 2006.

[4]. F. Ellinger. *Radio Frequency Integrated Circuits and Technologies*, Springer Berlin Hidelberg New York, 1st edition, 2007.

[5].B.N. Wicks, C.M. Ta, F. Zhang, P. Nadagouda, B. Yang, Z. Liu, Y. Mo, K. Wang, T. Walsh, G. Felic, R.J. Evans, I. Mareels and E. Skafidas,, "60 GHz direct conversion transceiver on 130 nm CMOS with integrated digital control interface," European Microwave Integrated Circuit Conference, 2009, pp 41-44.

[6]. D. Dawn, P. Sen, S. Sarkar, B. Perumana, S. Pinel and J. Laskar," 60 GHz integrated transmitter development in 90 nm CMOS,"Vol. 57, No.10, IEEE October 2009 pp 2354-2367.

[7]. M. Kraemer, A. Lecointre, D. Dragomirescu, and R. Plana, "Architecture consideration for 60 GHz pulse transceiver front-ends," CAS 2007, Vol. 2, pp 425-428.

[8]. B. Razavi. RF microelectronics, Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1998.

[9]. J. Kim, W. Choi, Y. Park, and Y. Kwon, "60 GHz broadband image rejection receiver using varactor running," RFIC 2010

[10].M.M. Kraemer, "Design of a low-power 60 GHz transceiver front-end and behavioral modeling and implementation of its key building block in 65 nm CMOS", University of Toulouse, January 2011 [online: https://tel.archives-ouvertes.fr/tel-00554674/document].

[11]. S.O. Tatu, E. Moldovan and S. Affes, "Low-Cost Transceiver Architecture for 60 GHz Ultra Wideband WLAN's," International Journal of Digital Multimedia Broadcasting, vol. 99, article ID 382695.

[12]. Y. Bao, Z. Shi and K. Chen, "Intermediate Frequency Circuit Design for a 60 GHz LFMCW Radar," Proc. ICMMT 2010

[13]. D. Treyer, R. Vogt, W. Bachtold, "58 GHz Front Ends for a channel sounder," 0-7803-8246-1/04 IEEE 2004 pp 95-100

[14]. X. Li, P. Baltus, D. Milosevic, W. Deng, P. Zeiji, N. Bird, A. Roermund "Wireless Wire-the 60 GHz Ultra-Low Power Radio System," 978-1-4244-2699-7, IEEE 2009, pp 215-218

[15]. Yu, Y Baltus, P.G.M. Smulder, P.F.M., "System and Architectures for very High Frequency Radio Links", proc. 2007IEE Advances in Analogue Circuit Design Workshop.

[16]. F. Svelto, A. Mazzanti, M. Sosi, M. Repossi, "A CMOS Sub-Harmonic Architecture for Signal Down-Conversion at Ka-Band", IEEE December 2007, pp 179-182

[17]. Triquint semiconductor Data Sheet SAW Filter [online: http://www.triquint.com/products/d/DOC-A-00000654]

[18]. Freescale semiconductor Technical Data [online: http://cache.freescale.com/files/rf_if/doc/data_sheet/MML09211H.pdf]

[19]. Triquint semiconductor product data sheet [online: http://www.triquint.com/products/d/DOC-A-00000888]

[20]. Analog Devices data sheet [online: http://www.analog.com/static/imported-files/data_sheets/ADL5536.pdf]

[21]. Sawtek data sheet [online: www.triquint.com/products/d/DOC-A-00000423]
[22]. Analog Devices data sheet [online: http://www.analog.com/static/imported-files/data_sheets/ADL5536.pdf]
[23]. A. Valdes-Garcia, IBM, "Principles of Silicon mmWave PA Design," Columbia University, April 2009 [online: http://pasymposium.ucsd.edu/docs/RAB_PAsymp2014_v1.pdf]
[24]. Y. He, D. Zhao, L. Li, P. Reynaert, "Design considerations for 60 GHz CMOS power amplifiers," Proceedings of Asia-Pacific Microwave Conference 2010
[25]. Ogunnika, Olumuyiwa Temitope, MIT [online: http://dspace.mit.edu/handle/1721.1/78455]
[26]. R. Bhat, A. Chakrabarti, H. Krishnaswamy, "The path to Efficient-yet-Linear Watt-class mmWave CMOS Pas: Device Stacking, Switch-mode Operation, Power Combining and Linearization," Columbia University, PA Symposium 2014 [http://pasymposium.ucsd.edu/docs/RAB_PAsymp2014_v1.pdf]