

A 28GHz, 4-channel Phase Adjustable Power Amplifier IC for 5G front-ends

Stuart Glynn and Liam Devlin

Plextek RF Integration, London Road, Great Chesterford, Essex, CB10 1NY, UK;
(liam.devlin@plextekRFI.com)

Abstract

5G communications promises to offer the user the perception of near infinite capacity. This will require a step change in data rates, which will be facilitated by a move to higher transmission frequencies where wider bandwidths are more readily available. New innovative components will be required to allow the design of suitable hardware, such as the 4-channel 28GHz (27 to 29.5GHz) phase adjustable Power Amplifier (PA) IC described here. Each channel of the IC includes a PA with an integral 4-bit, digitally controlled phase shifter offering a compact means of providing beam steering as an integral part of the PA. The output power capability of each channel is +30dBm (at 1dB compression) with an IP3 of +38dBm. The phase shifters include TTL compatible control and have an rms phase error of 2.3°.

Introduction

An enormous amount of research effort is currently being devoted to developing 5G technology with the aim of roll out by the year 2020. The details of the 5G standard are yet to be defined but a common vision for this new standard is that as well as providing much higher data rates it must also allow for extremely low latency (less than one millisecond) and uniform coverage over a wide area. As well as providing improved performance for existing applications, for example allowing the download of several HD movies in a second, the technology will enable and encourage the development of new markets, technologies and applications.

Although there is still much debate about the precise form that 5G will take, there is a degree of consensus that the standard will frequently require large chunks of contiguous spectrum. This can only be found by utilizing frequencies much higher than the current cellular frequencies of around 3GHz and below. Therefore, as well as the use of current cellular frequencies, a key component of the new 5G radio interface will be the use of mm-wave frequencies where there is greater spectral availability.

Until recently mm-waves have been viewed as a rather inappropriate choice for mobile applications due to their unfavourable propagation characteristics. However, recent research, involving extensive propagation measurements at several mm-wave frequencies around metropolitan areas in both the United States [1] and South Korea, has shown that the issues can be addressed and overcome. Such research included the investigation of more sophisticated antenna schemes employing phased arrays of antennas to optimise the transmitted and received beams at both the base-station and the mobile device. The fact that wavelengths are small at mm-wave frequencies allows such arrays to be incorporated into a small mobile form factor. It also allows the implementation of compact base-stations which will facilitate regular deployment around metropolitan areas.

Bands within 27 to 29.5GHz are strong candidates for the new 5G radio interface and much of the research undertaken to date has been conducted at around 28GHz [2]. This paper describes the design of a 4-channel transmitter IC with each channel containing a PA with integral 4-bit phase shifter. The IC is designed using a commercially available 0.15 μ m GaAs pHEMT process and is intended to be housed in a low cost SMT package suitable for volume production.

28GHz 5G Transmit RF Front End Architecture

The architecture of an RF Front-End (RFFE) using the 28GHz transmit IC is depicted in Figure 1 below. It shows a 4 element antenna array, where each element is driven by one of four parallel phase adjustable power amplifiers. It is likely that some degree of filtering would be implemented immediately after each power amplifier for harmonic rejection and suppression of receive band noise and unwanted spurious outputs. The 4 channels are each driven in-phase from a common RF input via a 4-way splitter.

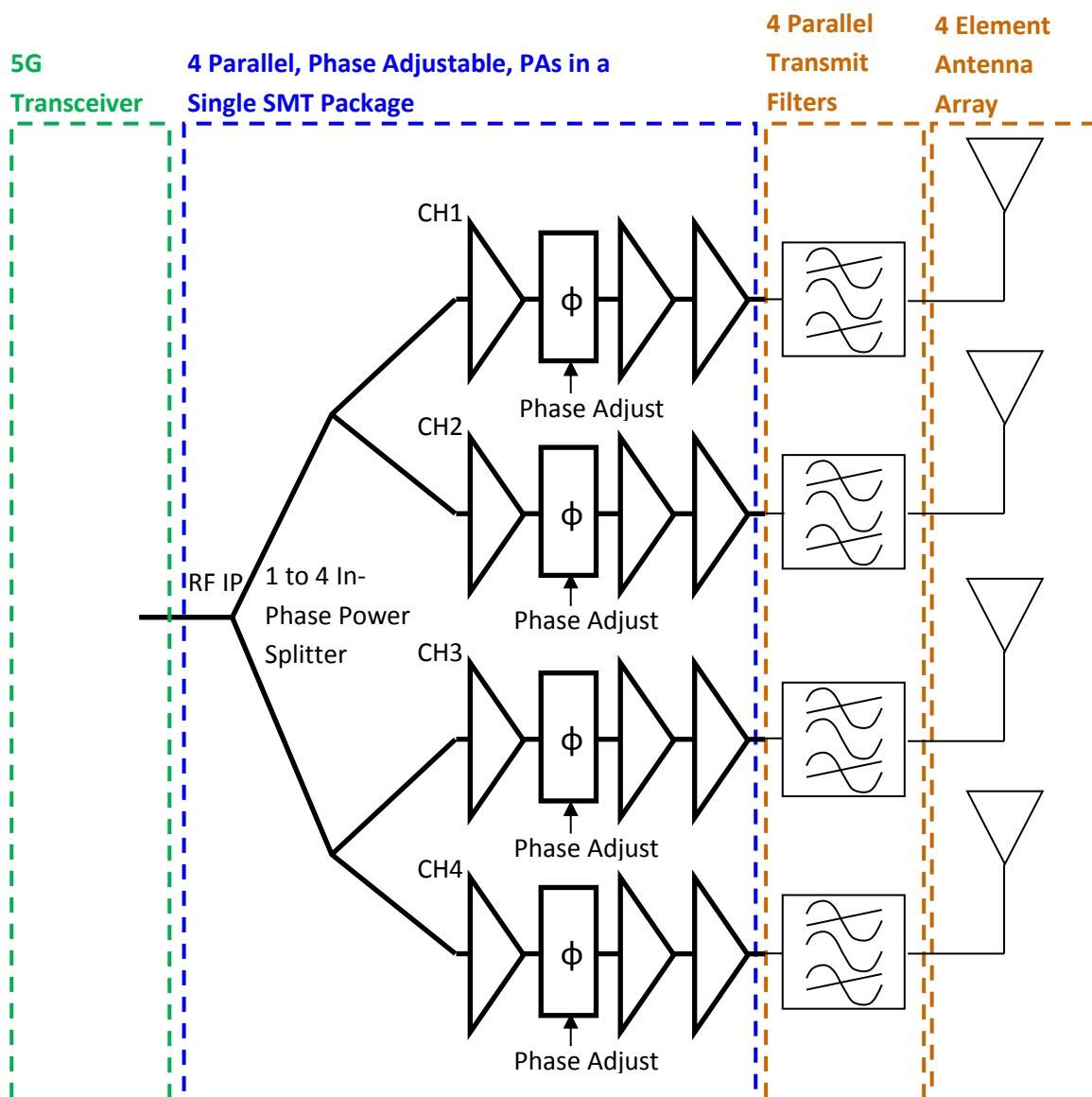


Figure 1: Architecture of the 4-channel transmitter IC

The IC itself is a 4-channel part but if a particular architecture required a higher number of elements in the antenna array, say 16, then multiple ICs could simply be used in parallel.

A layout plot of one channel of the transmitter IC is shown in Figure 2; this is a stand-alone test-chip – the transmitter IC itself comprises 4 separate channels with an in-phase splitter at the input. The test chip measures 3.8mm x 1.84mm.

The PA output (to the right of the layout image) comprises 4 power combined transistors, driven from 2 transistors of the same size. The 4-bit phase shifter is positioned before this with an input stage of amplification that is a modified version of the 2 transistor driver stage. The drain supplies for the power amplifier are Vd1, Vd2 and Vd3 and they are nominally set to +6V. Vg1 sets the quiescent bias current in the first stage and Vg23 sets the quiescent bias current in the second and third stages.

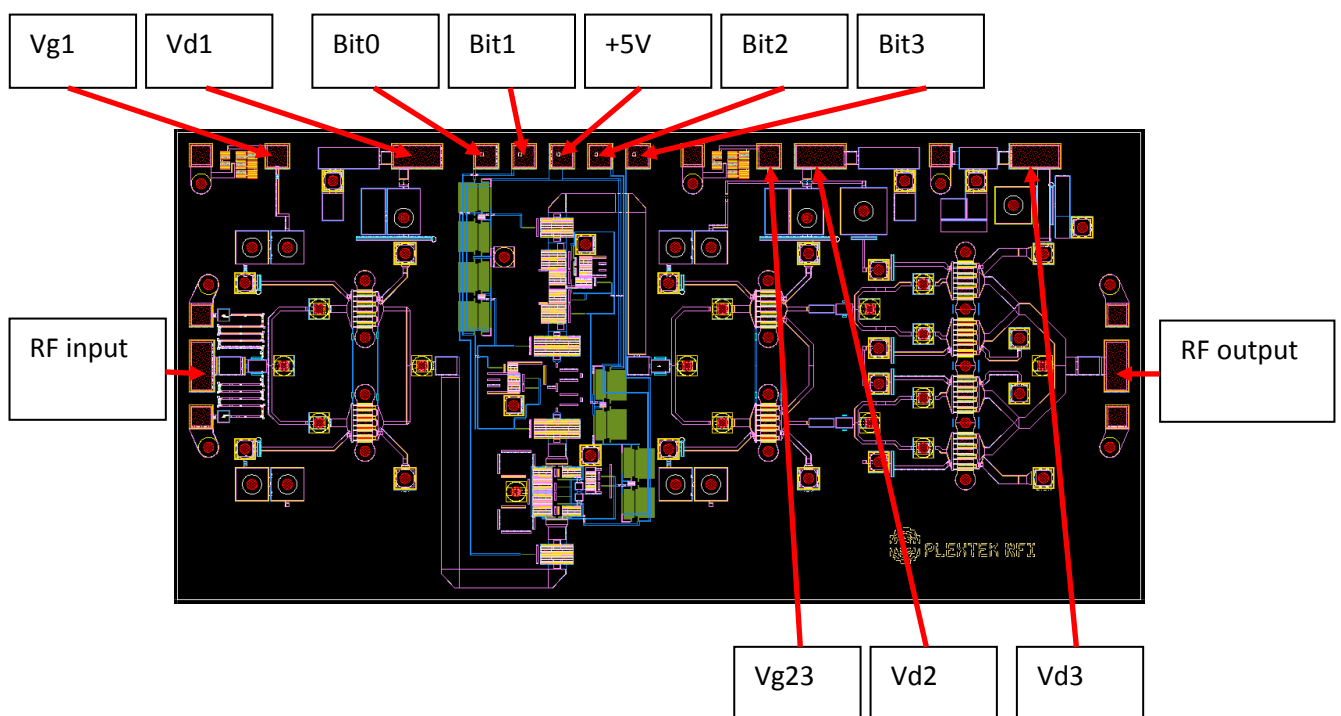


Figure 2: Layout plot of one channel of the transmitter IC

The phase state of each bit of the integrated phase shifter is controlled by a single-ended TTL compatible control line. All of the control logic required to shift the levels to those needed for the phase shifter bits is included on-chip. The truth table for the integrated phase shifter is shown in Table 1 below.

Bit0	Bit1	Bit2	Bit3	Relative Phase Shift (nominal)
0V	0V	0V	0V	0°
+5V	0V	0V	0V	22.5°
0V	+5V	0V	0V	45°
+5V	+5V	0V	0V	67.5°
0V	0V	+5V	0V	90°
+5V	0V	+5V	0V	112.5°
0V	+5V	+5V	0V	135°
+5V	+5V	+5V	0V	157.5°
0V	0V	0V	+5V	180°
+5V	0V	0V	+5V	202.5°
0V	+5V	0V	+5V	225°
+5V	+5V	0V	+5V	247.5°
0V	0V	+5V	+5V	270°
+5V	0V	+5V	+5V	292.5°
0V	+5V	+5V	+5V	315°
+5V	+5V	+5V	+5V	337.5°

Table 1: Truth table for phase setting of each channel

Single Channel Performance

The performance plots presented below are at room temperature, nominal bias across the frequency range 26 to 30GHz.

The 4-bit phase shifter is based on a switched high-pass/low-pass filter topology [3]; it allows the insertion phase of each channel to be independently set with 22.5° resolution. The most significant bit (180°) uses two Single Pole Double Throw (SPDT) switches to route the RF signal through either a low pass or a high pass filter, as depicted in Figure 3. The high pass filter exhibits a phase advance compared to the low pass filter with the phase difference being relatively constant over a reasonable bandwidth. Optimisation of the component values is required to obtain the desired phase difference with an acceptable amplitude difference. The lower order bits make use of re-configurable phase shifter bits, such as that depicted in Figure 4, which offers the benefit of lower insertion loss.

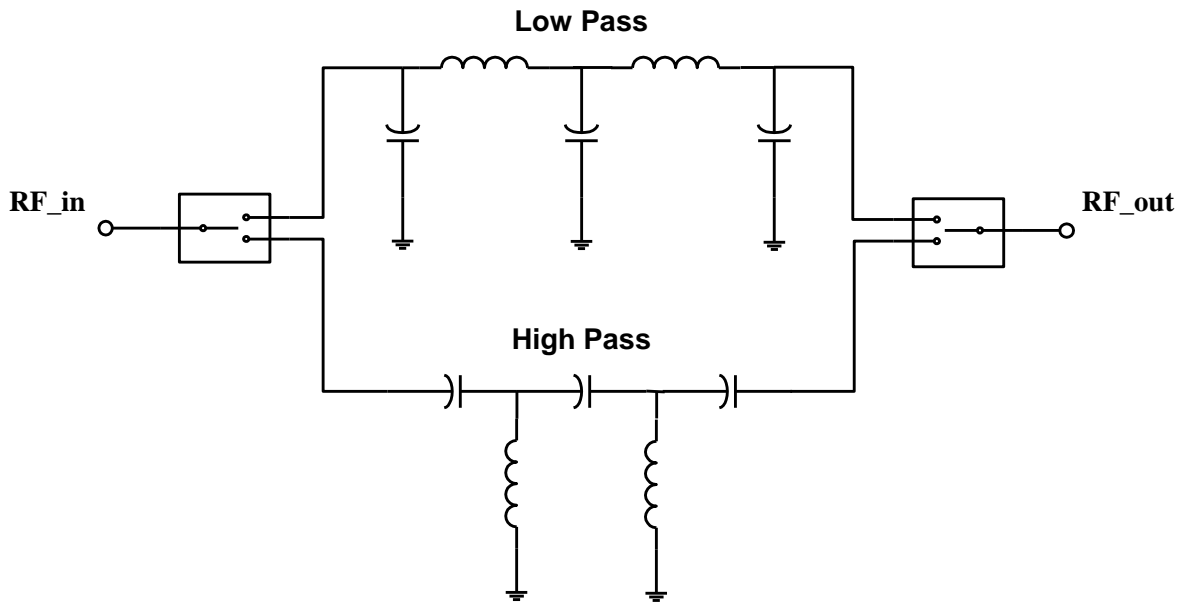


Figure 3: Switched filter phase shifter bit

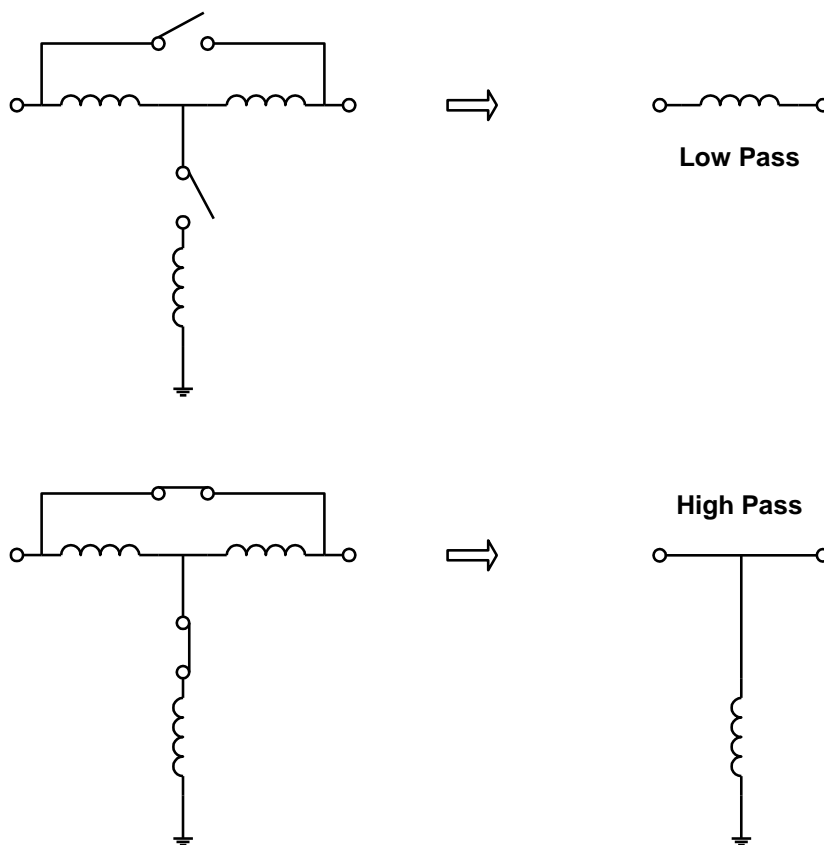


Figure 4: Re-configurable phase shifter bit

A plot of the simulated phase shift versus frequency for each of the 16 states of a single channel, including the PA, is shown in Figure 5; a flat phase shift versus frequency response is clearly evident.

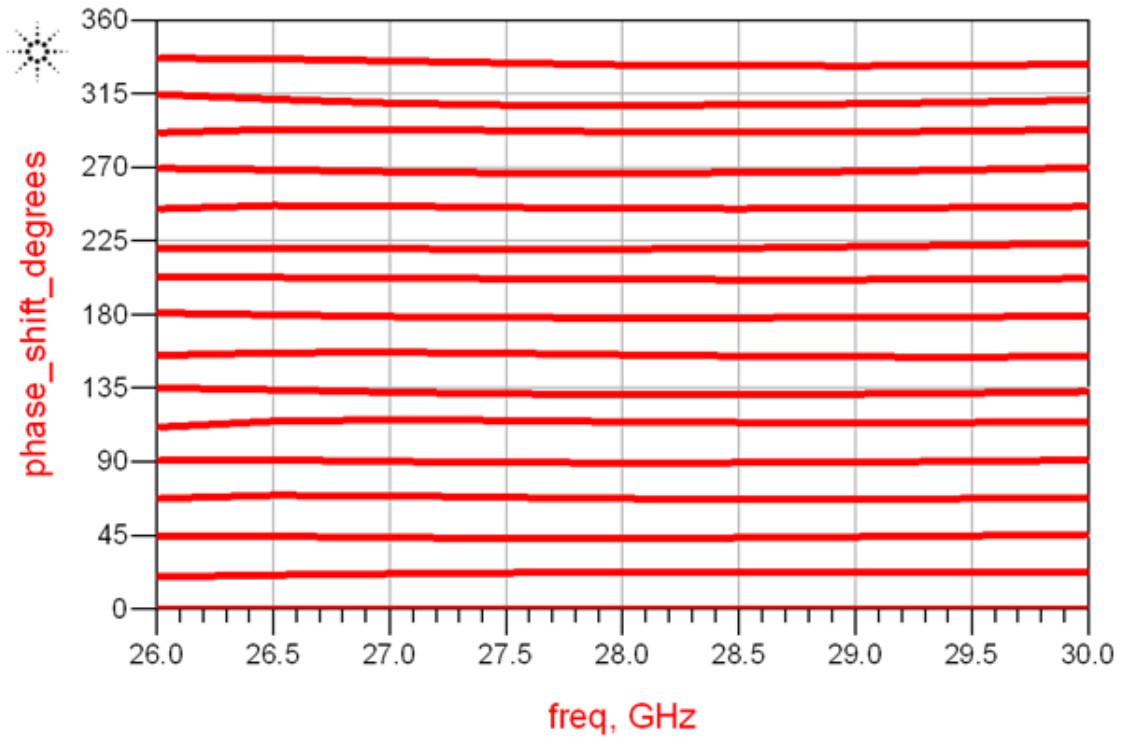


Figure 5: Phase shift versus frequency for a single channel

The phase shift actually produced by the phase shifter in each phase state always differs slightly from the ideal phase shift that would be produced if each bit were perfect. The rms phase error is a statistical measure of this deviation used to quantify the accuracy of the phase setting and is plotted against frequency in Figure 6 showing a worst case of 2.38° occurring at around 27.5GHz.

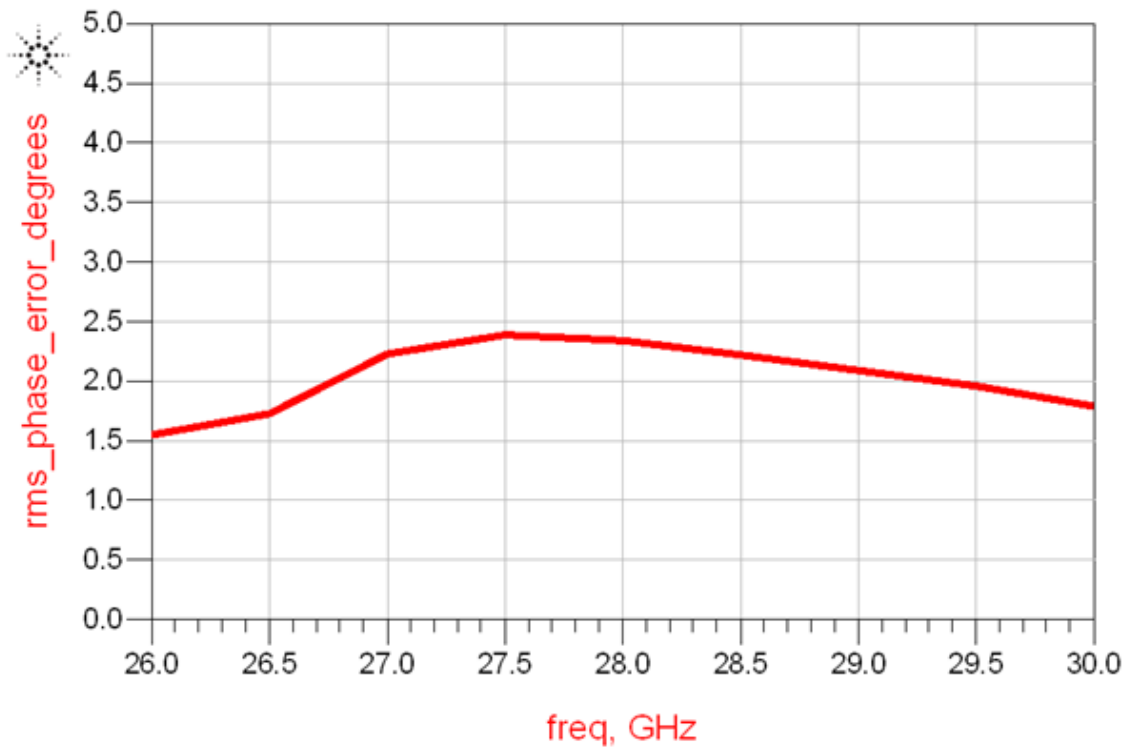


Figure 6: RMS phase shift error versus frequency for a single channel

Each channel of the transmitter IC has a nominal gain of just over 20dB (excluding the splitting losses of the 4-way in-phase splitter). Figure 7 shows the gain versus frequency of a single channel in each of the 16 phase states, at 28GHz the gain variation with phase state is ± 0.6 dB. The total gain variation with both frequency (over 26 to 30GHz) and all phase states is ± 1.5 dB.

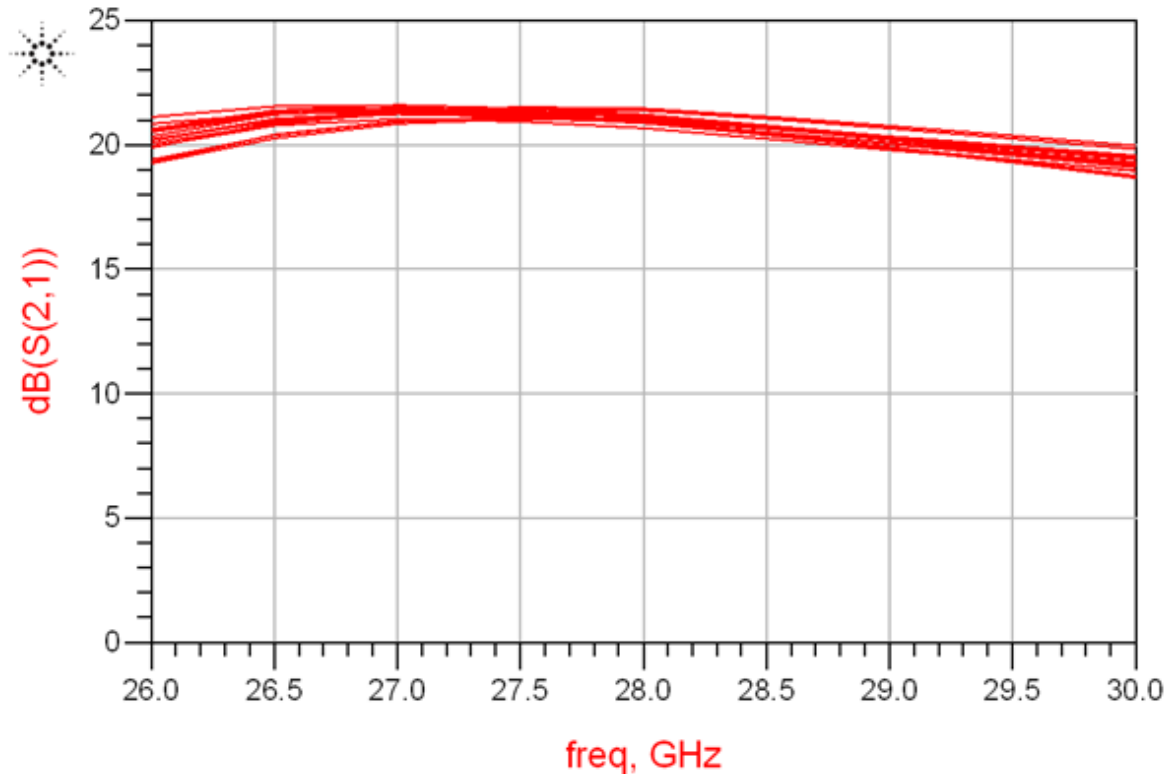


Figure 7: Gain versus frequency for a single channel, all phase states

An ideal phase shifter would have an amplitude response that did not change with phase state. In reality there will always be some change in amplitude associated with a change in phase state. The rms amplitude error across all phase states is plotted versus frequency for one channel of IC in Figure 8. At 28GHz the rms amplitude error is just 0.2dB; the maximum rms amplitude error is 0.53dB occurring at 26GHz.

As the phase state of the phase shifter changes the reflected waves from each bit experience different phase shifts. Sometimes the reflected waves add constructively, so degrading return loss at the input, sometimes they add destructively, improving return loss at the input. All multi-bit phase shifters tend to exhibit significant variation in return loss with phase state [3]. The input and output return losses versus frequency are plotted for a single channel in all phase states in Figure 9. Although significant variation is evident the worst case return loss is still good. The worst case return losses across the 26 to 30GHz range occur at 26GHz. At the input the worst case return loss is 13.4dB and at the output it is 14.9dB.

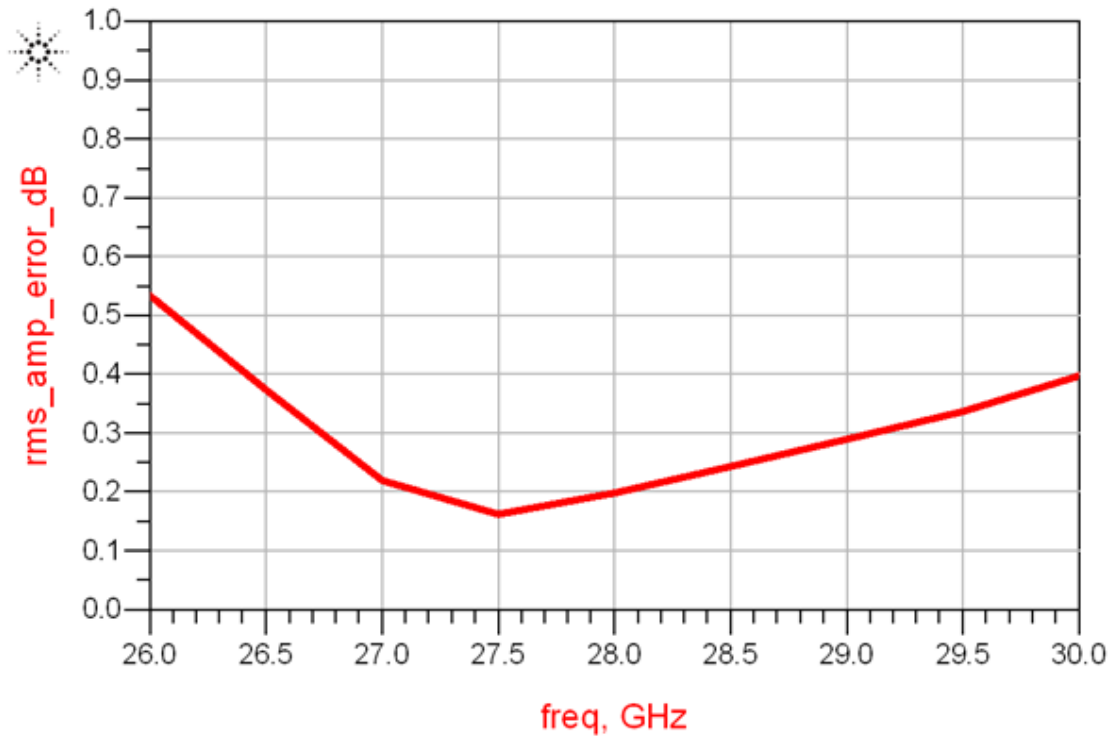


Figure 8: RMS amplitude error with phase state versus frequency for a single channel

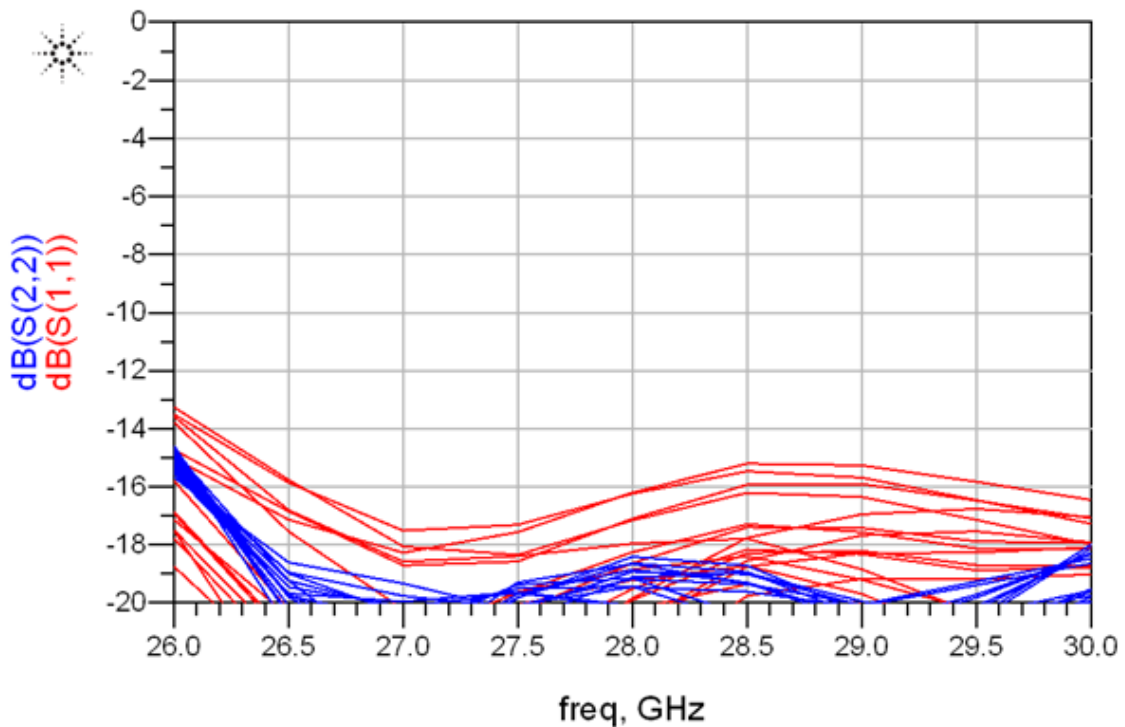


Figure 9: Input and output match versus frequency for a single channel, all phase states

The quiescent bias current of the complete 3-stage PA is 626mA from +6V, which provides an RF output power at 1dB gain compression (P-1dB) of 30dBm at 28GHz for each channel. The output power (at P-1dB) versus frequency is plotted in Figure 10 below for the 0° (reference) phase state. It is nominally +29.5dBm with a variation of $\pm 1\text{dB}$ across the 26 to 30GHz band.

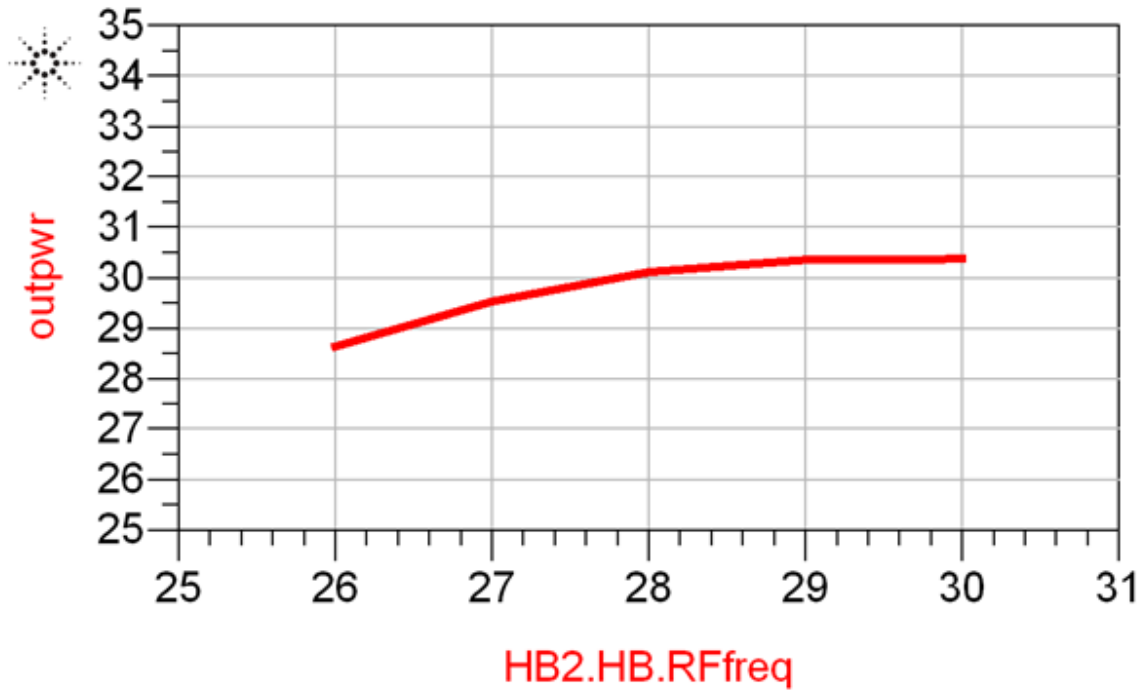


Figure 10: P-1dB versus frequency for a single channel, reference phase state

The corresponding Power Added Efficiency (PAE) for one PA channel operating at 1dB gain compression is shown in Figure 11. At 28GHz the PAE is 24%, across the full 26 to 30GHz simulated range it is nominally 21.5% and varies $\pm 3\%$ across the band. 5G systems will operate with modulation schemes with high peak to average power levels. It is therefore likely that the PA will be operated backed off from P1dB at a lower average output power level to preserve modulation fidelity.

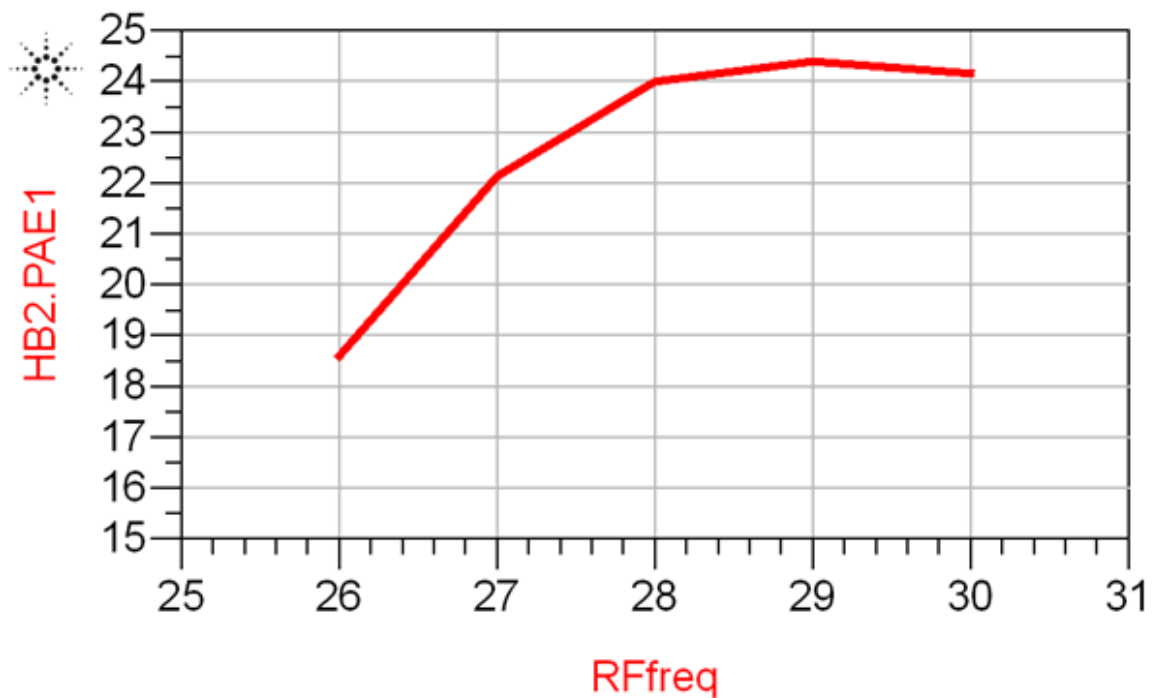


Figure 11: PAE versus frequency for a single channel at P-1dB, reference phase state

The traditional metric for linearity of microwave amplifiers is the output referred third order intercept point (OIP3). This parameter is plotted against frequency in Figure 12 for a single channel set to the 0° relative phase shift state. In this simulation the total average input power is set to 0dBm i.e. the power in each input tone is -3dBm and the nominal power in each output tone is around +17dBm. The simulated OIP3 for each channel is +38.8dBm ±0.7dB across the band.

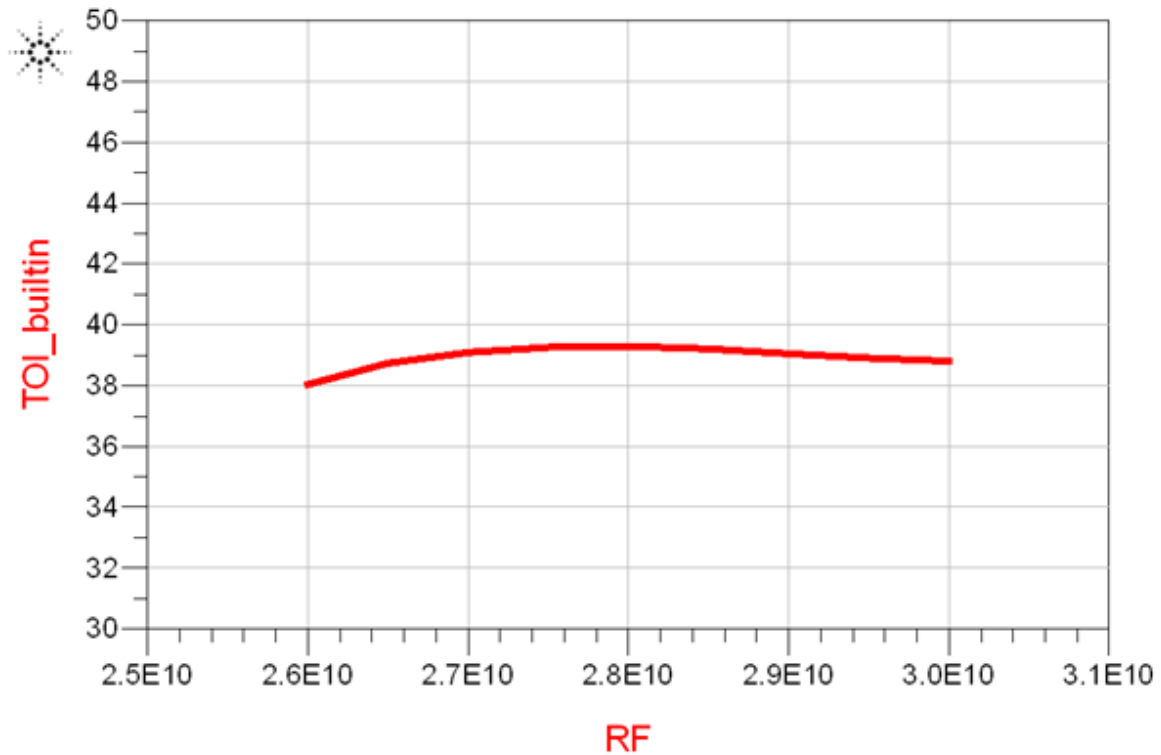


Figure 12: Output referred IP3 versus frequency for a single channel, reference phase state

A summary of the simulated performance of each channel of the phase adjustable PA is presented in Table 2.

Parameter	Min	Max	Units
Frequency Range	26	30	GHz
RMS Phase Error		2.38	°
RMS Amplitude Error		0.53	dB
Gain	18.5	21.5	dB
Min Output Return Loss	14.9		dB
Min Input Return Loss	13.4		dB
P1dB at 0°	28.5	30.5	dBm
PAE at P1dB at 0°	18.5	24.5	%
OIP3 at 0°	38.1	39.5	dBm

Table 2: Performance summary of each channel of the 4-channel phase adjustable PA

Simulations of a Four Channel Array

Simulations were undertaken to show the antenna pattern produced by a linear array of 4 omnidirectional (0dB gain) antennas spaced by a half wavelength ($\lambda/2$) at 28GHz when driven by the 4-channels of the phase adjustable PA MMIC. The results are presented below in the form of polar plots showing the normalised antenna responses in dB versus azimuth angle in degrees. The absolute gain of a 4 element array of 0dB gain elements would be 6dB ($10 \cdot \log_{10}(N)$, where N is the number of elements). In practise the individual elements would have some level of gain and the boresight gain of the array would be augmented by this.

Figure 13 shows the boresight pattern when the relative phase shift in each channel is set to 0° . The plots include the effects of the systematic gain and phase errors in each channel.

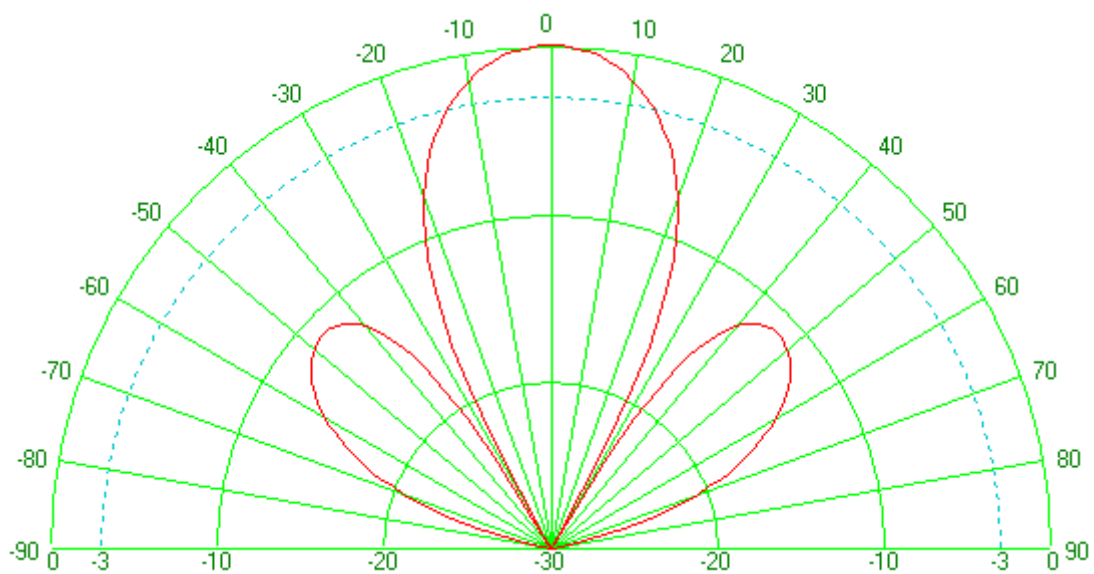


Figure 13: Beam pattern produced with all channels set to the 0° reference state

Figure 14 shows the simulated antenna pattern when the beam is steered to -38.68° . This is achieved by applying an incremental phase shift of -112.5° per element. The ability to electronically steer the antenna is one of the benefits of using a phased array approach.

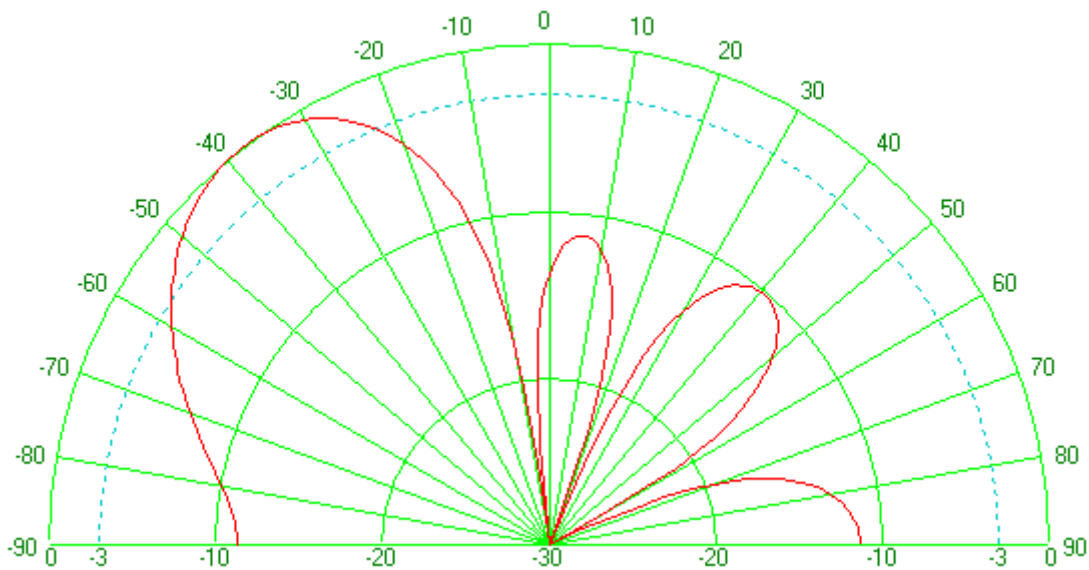


Figure 14: Beam pattern produced with phase states of the 4 channels set to steer the beam to -38°

Concluding Remarks

This paper describes the design of a 4-channel 28GHz (27 to 29.5GHz), transmitter IC. Each channel of the IC includes a power amplifier with an integral, independently controllable 4-bit digital phase shifter. The IC is intended for use in the transmit chain of a 5G RF Front-End (RFFE) module in either a mobile device or a base-station. It has been designed using a commercially available $0.15\mu\text{m}$ GaAs pHEMT process and is suitable for assembly in to a single SMT package.

Details of the layout of a test chip for evaluating the performance of a single channel were presented along with simulation results of key performance parameters including rms phase error, rms amplitude error and OIP3. Antenna pattern simulations for four channels driving four elements in a linear array were also given showing the potential for beam steering using the 4-channel MMIC.

It was noted that although this paper has focused on a four element array, the solution can be extended to larger antenna arrays. For example if the number of elements in the antenna array was 16 then this would require four of the 4-channel phase adjustable power amplifiers in parallel.

References

- [1] Theodore S. Rappaport, NYU Wireless, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!", IEEE Access 30th May 2013
- [2] Wonbin Hong, Samsung Electronics, "Design and Analysis of a Low-Profile 28GHz Beam Steering Antenna Solution for Future 5G Cellular Applications", IEEE MTT-S International, June 2014
- [3] Liam Devlin, "The Design of Integrated Switches and Phase Shifters", Proceedings of the IEE Tutorial Colloquium on "Design of RFICs and MMICs", Wednesday 24th November 1999, pp 2/1-14