Proceedings Paper:

Ball, E.A. orcid.org/0000-0002-6283-5949 and Tennant , A. (2017) Antenna Beam Steering Without Phase Shifters – an 'Old' Technique Revisited. In: Proceedings of Automated RF & Microwave Measurement Society (ARMMS). Automated RF & Microwave Measurement Society (ARMMS) Conference, 13-14 Nov 2017, Wyboston Lakes, Wyboston. Automated RF & Microwave Measurement Society (ARMMS) .

Antenna Beam Steering Without Phase Shifters – an ‘Old’ Technique Revisited

Eddie Ball (Reader in Wireless Communications) & Alan Tennant (Professor of Applied Electromagnetics)

Communications Research Group, University of Sheffield.

Abstract

Antenna arrays are of perennial interest and relevance to RF wireless system designers, indeed the rise of 5G is showing their importance is only growing. Most implementations of linear arrays use phase shifters to feed the array and hence form the main-lobe beam. In the 1960s, a technique using RF switches and Fourier analysis was discovered to be a viable alternative to phase shifters - called the Time Modulated Array (TMA). Little modern research has been conducted in this area, despite its likely cost-effective implementation and technical relevance.

This paper presents a brief overview of the TMA, followed by our work into prediction and control of the RF harmonic levels in TMAs. The effect of RF ramping on the switching waveform is analysed first, followed by a novel way of reducing the carrier fundamental (due to the Fourier DC term) produced by TMAs. Finally, a novel RF transistor cascode fast switch is introduced, using 3 gain states, to pragmatically implement the reduction of the carrier fundamental. The transistor cascode in the TMA utilizes binary logic control interfaces, rather than analogue control interfaces, for hardware efficiency. Early simulation results are included.

Index Terms

Antenna phase shifters, Fourier DC term removal, RF Cascode Switch, Time Modulated Array.

1 Introduction

There is today much ongoing research into hybrid beamforming techniques for use in next generation 5G communications, with a focus on mmWave radio for mobile applications [1]. From a future mobile device’s perspective, it can be argued that only a single active beam may be required; significantly relaxing the technical challenge and cost in implementing a radio using beamforming. This is particularly beneficial at mmWave, due to the present high cost of implementation and DC power draw.

The Time Modulated Array (TMA) [2], [3] can be used to generate a beam at a desired angle without the use of vector modulators or phase shifters, though it seems rarely used in practice. TMAs create a steerable beam, using only RF switching elements and can create beams carrying different modulated data [4]. Increased beam steer angles often require the use of higher order harmonics, for realizable switching timings. The TMA also offers a novel way of creating a harmonic fan-beam pattern which may be used to illuminate a space for radar applications.

In this paper we first briefly introduce the concept of TMAs and then go on to predict the magnitude of a harmonic beam as a function of RF switch ramping time between on and off states (due to slew rate). We then propose a way of controlling the fundamental beam harmonic level using a bipolar (i.e. inverting and non-inverting) gain stage. We go on to show a new RF switch topology with three gain states and phase inversion, based on a transistor cascode, to implement the required bipolar gain. The RF cascode is a well-known circuit topology that supports high RF bandwidth and is a good candidate for implementing RF switches, though is rarely seen used in this application. Finally, we simulate a three-stage RF cascode at a 5GHz carrier frequency, as a switching element for use in a TMA offering control of carrier fundamental emission.

Therefore, the contributions of this paper are threefold: 1) simple mathematical model for the prediction of harmonic levels in TMAs due to RF switching slew; 2) a hardware-efficient technique to null out the TMA fundamental without affecting the harmonic beam directions and 3) a pragmatic, fast-switching cascode transistor circuit with defined gain states, to implement the control of fundamental level and harmonic beam direction, within a TMA.

2 Harmonic Levels in Time Modulated Arrays

We will now proceed to show how the harmonic energy in a particular direction can be predicted.

2.1 TMA with RF Switching Slew

The Array Factor (AF) for an array of *N* isotropic radiating elements in a TMA can be described by (1) as in [5], where $F_n[U_k(t)]$ is the Fourier coefficient of the *n*th harmonic of the time domain control switching waveform *U* on the *k*th element.

$$AF(\emptyset, t) = e^{j[\omega_c + n\omega_p]t} . \sum_{k=1}^{N} F_n[U_k(t)] \, e^{j\emptyset_k} \quad (1)$$

The time modulation of the RF signal at element *k* can be represented as a series of Fourier coefficients multiplied with harmonics of the switching frequency ω_p up-converted to the carrier ω_c. Term $e^{j\emptyset_k}$ is an element-specific phase shift, due to antenna element spacing and beam angle, as defined in [5]. In the rest of this paper, we refer to the *n*th Fourier coefficient of the switching waveform for a particular element *k* as $C_{nk} = F_n[U_k(t)]$.

Although there has been some prior research into deliberately shaping the switching waveform $U_k(t)$, such as [6], AF TMA models commonly assume an infinite slew rate on the transition of the RF signal from radiating element *k* 'on' state to element 'off' state. In this ideal case, the fundamental (DC) term C0 can be represented by (2), where *Tk* is the element on-time and *Tp* is the switching period. (Also noting the relationship $\omega_p = \frac{2\pi}{T_p}$).

$$C_{0k} = \frac{T_k}{T_p} \quad (2)$$

In practical systems, an RF switching ramp time of zero seconds is not achievable. Fig. 1 shows a more typical waveform for *Uk(t)*, with period *Tp* and on-time *Tk*.

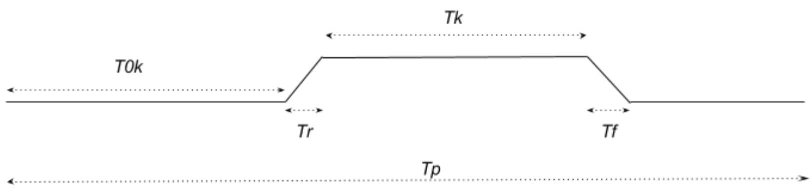

Fig. 1. *Uk(t)* example time domain form, including ramping *Tr* and *Tf*.

Next are presented the equations for the Fourier coefficients that include the effect of RF switching slew: *Tr* 'off-to-on' and *Tf* 'on-to-off' transitions.

Equation 3 describes the C0 term and (4) the Cn term, for a particular element *k* in the TMA.

$$C_{0k\_ramp} = \frac{T_r}{2T_p} + \frac{T_k}{T_p} + \frac{T_f}{2T_p} \quad (3)$$

From (3), the *n*th Fourier coefficient C0 for the *k*th element can be seen to include the zero-ramping expression of (2) and additional terms associated with the ramping slew.

$$C_{nk\_ramp} = \left\{\frac{e^{-jn\omega_p T_{0k}}}{T_p T_r n^2 \omega_p^2}\left[e^{-jn\omega_p T_r} - 1\right] + \frac{je^{-jn\omega_p (T_{0k}+T_r)}}{2\pi n}\right\} + \left\{\frac{1}{n\pi} e^{-jn\pi\left(\frac{2T_{0k}}{T_p}+\frac{T_k}{T_p}+\frac{2T_r}{T_p}\right)} sin\left(\frac{n\pi T_k}{T_p}\right)\right\} + \left\{\frac{e^{-jn\omega_p (T_{0k}+T_r+T_k)}}{n^2 2\pi\omega_p T_f}\left[1 - e^{-jn\omega_p T_f}\right] - \frac{je^{-jn\omega_p (T_{0k}+T_r+T_k)}}{2\pi n}\right\} \quad (4)$$

Hence equations (4), (3) and (1) allow the prediction of the directional harmonic levels as a function of switching ramp times *Tr* and *Tf*. Fig. 2 shows the AF for a 9 element Dolph-Chebyshev weighted array, designed for -20dB side lobes on the first harmonic and with *Tp* set to 1us, *Tr* and *Tf* set to 1ns (i.e. 0.1% of switching period *Tp*). The switch timings were designed to achieve a first harmonic beam pointing at 10 degrees, using the technique described in [5].

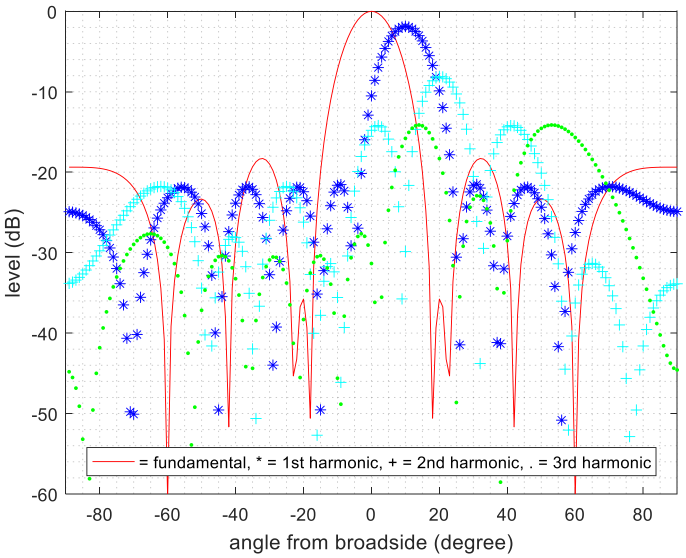

Fig. 2. TMA AF for fundamental and positive harmonics 1 to 3.

As an example of the effect of switching slew, let *Tr* and *Tf* now increase to 200ns (20% of *Tp*); the magnitude of the 2nd and 3rd harmonic levels predicted by (4) are significantly reduced, as shown in Fig. 3 below.

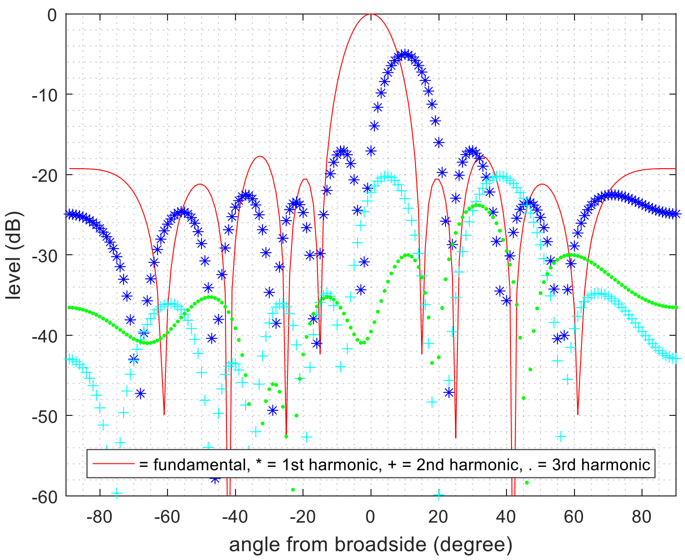

Fig. 3. TMA AF for fundamental and positive harmonics 1 to 3.

From Fig. 2 and Fig. 3, the effect of RF switching slew can be seen to reduce the harmonic energy, as would be anticipated. In some circumstances it may be desirable to control the magnitudes of the harmonic beams: control of switch ramping times is one way this could be achieved. This is explored further in [6].
The dominant, non-steerable, beam due to Fourier C0 component is also evident on Fig. 2 and Fig. 3. In section 2.3 we go on to consider how the C0 component emission may be reduced.

2.2 Radar Applications
If the TMA switches are configured to a sequential activation pattern then the emissions from the array will contain significant energy on all harmonics. Figure 4 below shows such a radar timing sequence and Fig. 5 the resulting harmonic beam pattern, with *Tr* and *Tf* set to 1.5% of *Tp*.

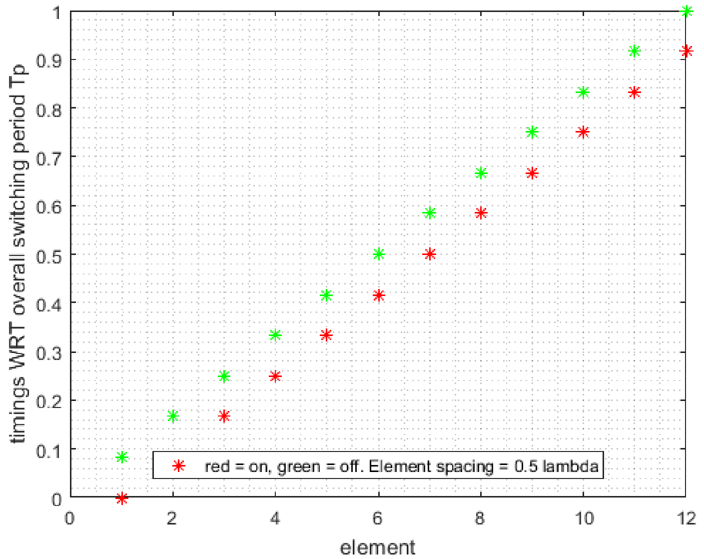

Fig. 4. Radar application sequential element switching times, normalised to *Tp*.

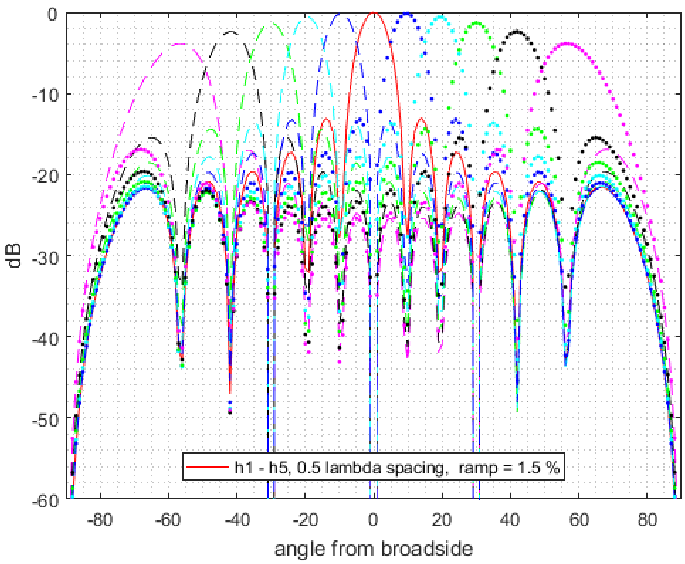

Fig. 5. Radar application for TMA: AF for fundamental, negative and positive harmonics 1 to 5.

A simple bistatic radar system could be envisioned consisting of a TMA illuminated target and a wide beam width antenna used to receive reflected energy -the incoming reflection angle is identified by energy being received at the corresponding harmonic beam frequency.

2.3 Use of Bipolar Uk(t) to Reduce Fundamental Carrier Emission due to C0

It will be noticed from (2) that since DC coefficient C0 can never be zero for practical array timings, there will always exist a strong emission on array boresight. This is undesirable in many communications beam steering system. One way to remove the C0 contribution at each element is to arrange for a two-state amplifier with gains chosen such that the combined average of $U_k(t)$ over 1 cycle of *Tp* is zero. Let the *k*th element amplifier have gain states *ra* (positive) and *rb* (negative) at the antenna element *k*. The resulting equations for the C0 Fourier coefficient at element *k* in this bipolar gain scenario is shown in (5).

$$C_{0k} = \frac{T_k}{T_p}(ra_k - rb_k) + rb_k \qquad (5)$$

The *n*th Fourier coefficient for the *k*th element can be derived and represented as a scaled version of the representation in [5], as shown in (6).

$$C_{nk} = \left(\frac{ra_k - rb_k}{\pi n}\right) e^{-jn\pi\left(\frac{2T_{ok}}{T_p}+\frac{T_k}{T_p}\right)} sin\left(\frac{n\pi T_k}{T_p}\right) \qquad (6)$$

If C0k is set to 0 in (5) then a relationship between *ra* and *rb* can be obtained for the *k*th element, as shown in (7).

$$\frac{ra_k}{rb_k} = 1 - \frac{T_p}{T_k} \qquad (7)$$

Simulation of the AF resulting from Fourier coefficients (5) and (6) and use of element specific gains *ra* and *rb* from (7) applied to (1) are shown in Fig. 6 below (assuming *Tr* and *Tf* are zero). Fig. 4 clearly shows the desired cancellation of the fundamental emission compared to Fig. 2.

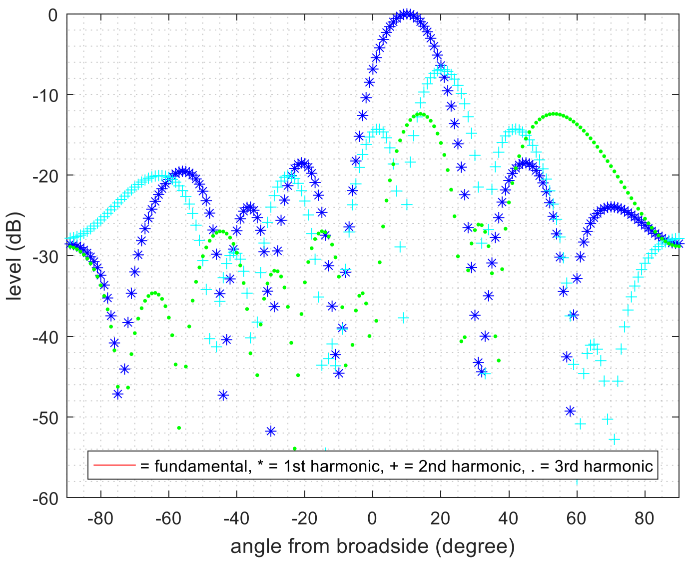

Fig. 6. TMA AF for fundamental and positive harmonics 1 to 3. Fundamental carrier component cancelled, desired 1st harmonic beam at 10 degrees.

Key attractions of the TMA are its low cost and low implementation complexity, in contrast to phase shifters or vector modulators commonly used in antenna arrays. It is therefore proposed that calculating and controlling gain *rb* (assuming *ra* is fixed) on a per-element basis is highly unattractive, due to the complexity of element RF hardware; hence a pragmatic approach is required. The ideal values of *rb* vary per element, but it is found that their average across the array is constant, regardless of beam pointing angle. Furthermore, it is found that values of *rb* can be quantised to a subset of 2 values (*rb1*, *rb2*) and still support cancellation of the fundamental to better than -10dB whilst steering the beams of the first 3 harmonics. Our initial test of this concept, again using the method in [5] to define element timings, show reduced nulling of the fundamental emission and an increase in fundamental side lobes, compared to those seen with ideal element-specific control of *ra* and *rb* (Fig. 6), but still offers useful reductions (10dB below first harmonic beam).

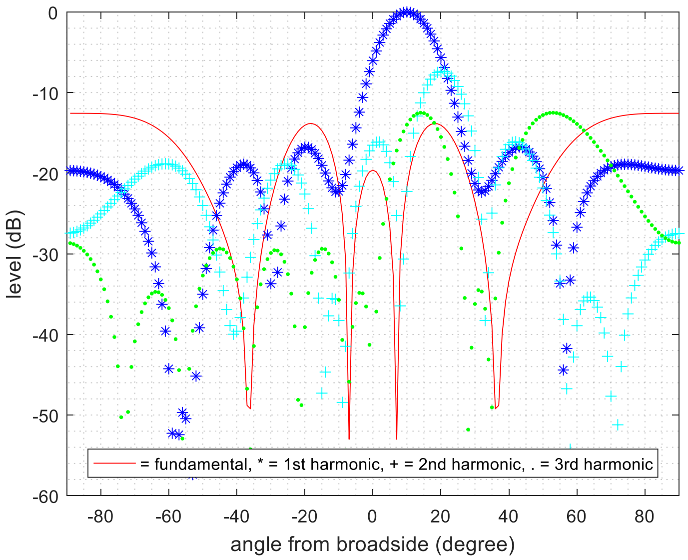

Fig. 7. TMA AF for fundamental and positive harmonics 1 to 3, 1st harmonic beam at 10 degrees.

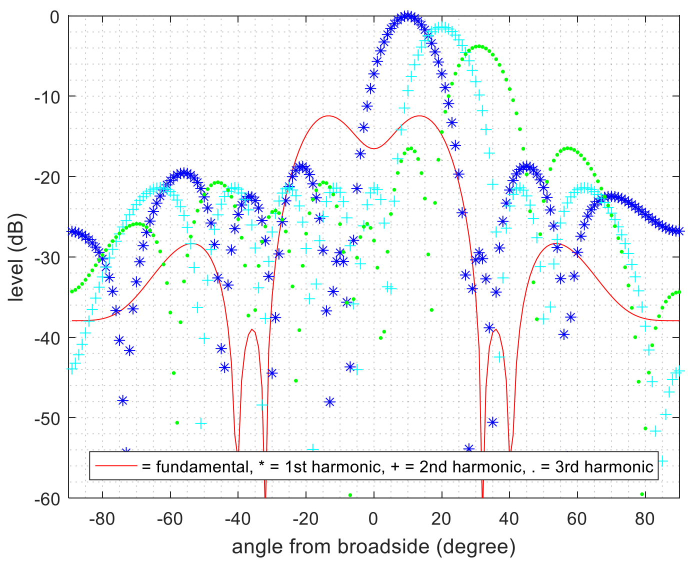

Fig. 8. TMA AF for fundamental and positive harmonics 1 to 3. Fundamental reduction, 2nd harmonic beam pointing at 20 degrees. Fundamental term below -10dB. TMA bipolar gain quantized to *ra, rb1, rb2*.

Figures 7 & 8 above show the AF results for the use of fixed gains *ra*, *rb1,* and *rb2* when used at all elements (in all cases *Tr* and *Tf* were set to zero).

Hence, it is therefore suggested that by use of RF switches with fixed gain states in the TMA, the fundamental carrier (un-steered) emission can be reduced as well as maintaining beam steering across the remaining harmonics. Work is still required to further control other harmonic levels.

3 TIME MODULATED ARRAY TRANSMITTER USING RF CASCODE SWITCH

TMAs generally require fast RF switching, with a slew rate significantly faster than the switching frequency. The effect of this slew on harmonic energy levels has been shown in equations (3) and (4). To obtain harmonic beams with a wide spectral spacing requires a high switching frequency.

3.1 Fast RF Cascode Switch with Three Amplification States

The RF cascode transistor amplifier is widely used in RF design as a high bandwidth amplifier, but appears to have only recently been applied to RF switching [7]. A key advantage of the cascode for our application is its ability to amplify as well as switch fast, hence simplifying the RF front-end hardware in the proposed transmit TMA. As described so far, we propose to modify the TMA Uk(t) waveform to be bipolar, with a single fixed positive gain state (ra) and two fixed negative gain states (rb1, rb2) used at each element. In our example application, the proposed values for each gain state at all elements are ra = 5.555, rb1 = -2.611, rb2 = -1.0. From (7) it is clear that the ratio of gains are key, hence the absolute gains can be scaled to practical values. The proposed 3 gain-state RF cascode to implement the required gains is shown in Fig. 9, using Infineon BFP420 RF transistors and ideal transformer models.

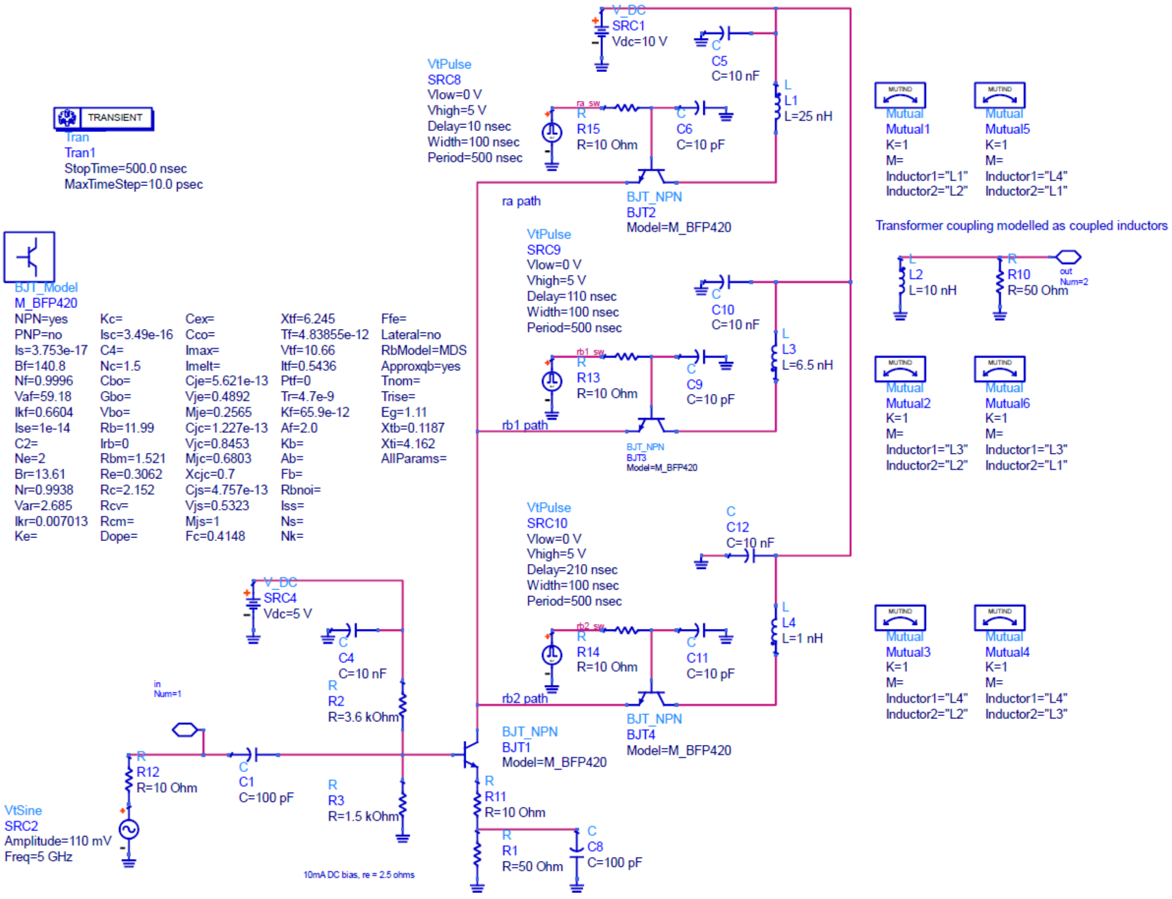

Fig. 9. Switched cascode amplifier with 3 selectable gain states (*ra*, *rb1*, *rb2*) for 1 element of TMA. Phase inversion is provided via output transformer coupling.

The gain is defined by the cascode transconductance and the specific winding ratio of the output transformers for each gain path, driving the 50 ohm (antenna element) termination. The inversion for *rb1* and *rb2* is provided by the winding phase of the (ideal) transformers. Keysight ADS simulations of both the gain and switch change-over delay (indicative of ramping slew) are shown in Fig. 10 - Fig. 13 as time-domain plots for operation at a 5GHz carrier. The *ra* output power obtained is 4.4dBm.

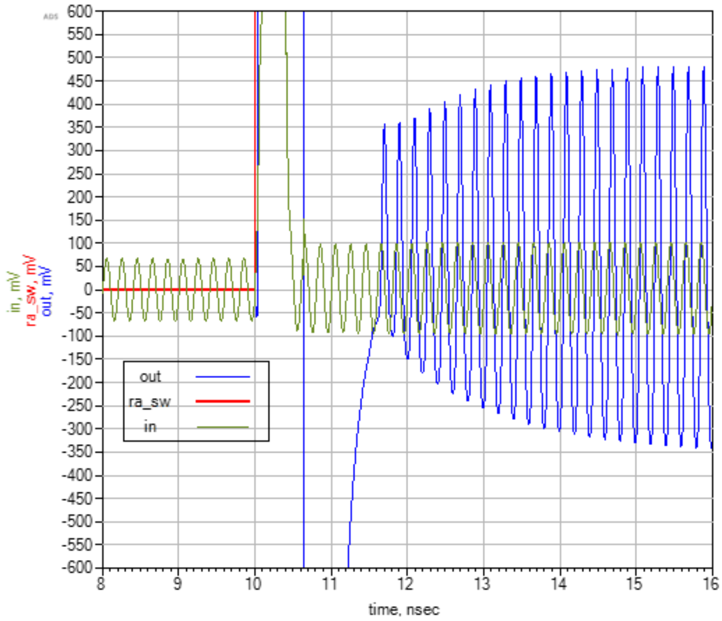

Fig. 10. *ra* turn on delay.

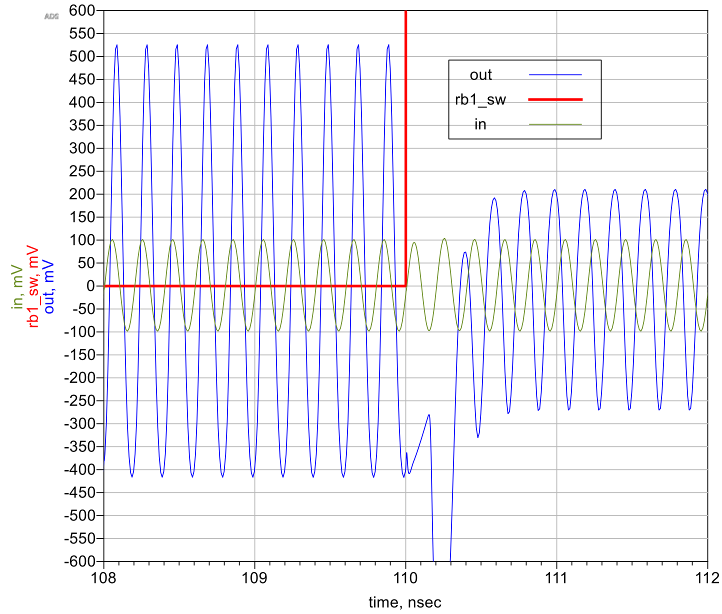

Fig. 11. *ra* to *rb1* transition, note required gain change and phase inversion is obtained after changing from *ra* to *rb1*.

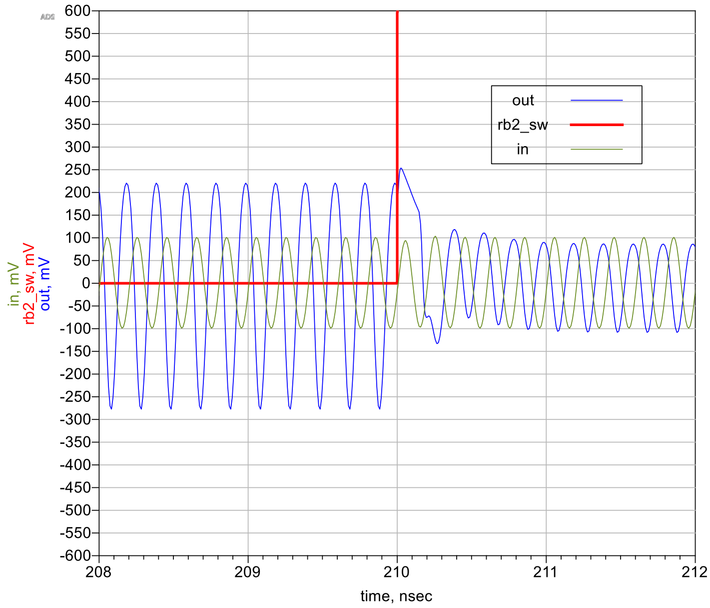

Fig. 12. *rb1* to *rb2* transition, note required gain change obtained (phase also remains inverted).

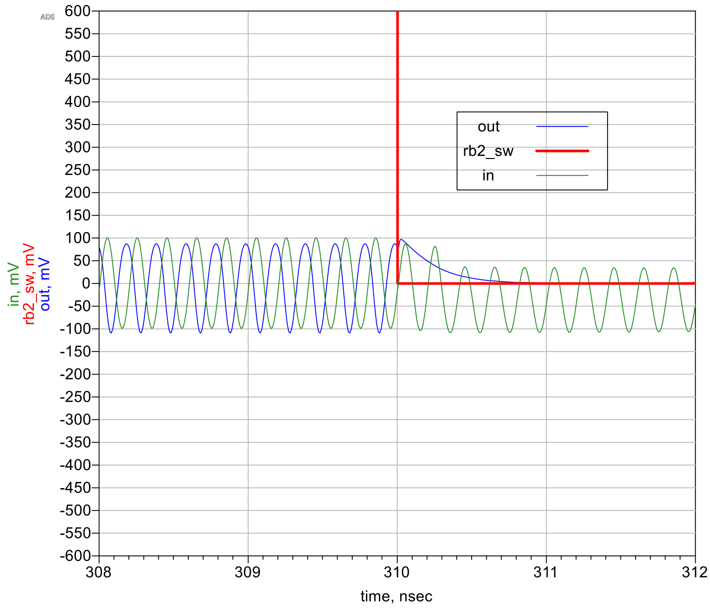

Fig. 13. *rb2* turn off delay.

From Fig. 10 and Fig. 13, it is clear that the element turn-on and turn-off times are less than 2ns (though some further amplitude ramping is seen at turn-on, due to the transistors re-biasing). In this paper's proposed TMA bipolar gain application the cascode is never in an all-off state, hence these delays will not be experienced during normal operation.
From Fig. 11 and Fig. 12 the delay when switching between operational gains (*ra*, *rb1*, *rb2*) can be seen to be less than 1ns, representing the normal operation in the proposed TMA. The required phase inversion between output from *ra* and *rb1* or *rb2* is also apparent. These results demonstrate both the switching speed benefit of the cascode, when used as a low-cost switch for TMAs, and also its suitability for element bipolar gain control.

4 Conclusion & Next Steps
There is currently much interest in beam steering for future 5G mobile systems. To be commercially viable, such systems must be cost-effective and power-efficient. The TMA techniques described in

this paper may be applicable to handset mmWave antenna arrays constrained to point traffic to only a single base station at any given instant.
If required, a single harmonic beam could be selected, from all generated, by appropriate use of both a high switching frequency and frequency-agile RF carrier oscillator (modulated with user data) driving the array with frequency selective filters placed before each antenna element (or with suitably narrow-band elements) to select the desired harmonic. However, this technique would waste the energy on the unwanted harmonic beams. An alternative and elegant solution could use the harmonic optimisation approach in [8], where the structure of the switching waveform is constructed of sub-pulses that are optimised to increase energy for a desired harmonic whilst suppressing unwanted harmonics.
Although this paper has focused on a transmitter TMA, the concept of the 3 gain state cascode switch could also be applied for receiving arrays, using cascode LNAs, or indeed in a transceiver array.

The cascode amplifiers require use of phase inversion; for convenience modeled in this paper as an (impractical) ideal transformer and subsequent combining and feeding into a radiating element. We anticipate conducting further research around these phasing, combining and antenna functions to form a single radiating structure -taking feeds directly from an element's cascodes.

Alternatively, rather than trying to suppress the harmonic beams, they could be fully employed in a simple bistatic radar system as discussed, which is a particular focus of our future work.

Thus, we intend to further explore the TMA in both communications and radar applications, via demonstrator PCB systems designed at X-band.

References
[1] S. Kutty and D. Sen, "Beamforming for Millimeter Wave Communications: An Inclusive Survey," *IEEE Communications Surveys & Tutorials,* vol. 18, p. 25, second quarter 2016 2016.
[2] W. H. Kummer, A. T. Villeneuve, T. S. Fong, and F. G. Terrio, "Ultra-Low Sidelobes from Time-Modulated Arrays," *IEEE Transactions on Antennas and Propagation,* pp. 633-639, 1963.
[3] Y. Tong and A. Tennant, "Simultaneous Control of Sidelobe Level and Harmonic Beam Steering in Time-Modulated Linear Arrays," *Electronics Letters,* vol. 46, p. 200, 2010.
[4] Y. Tong and A. Tennant, "A Two-Channel Time Modulated Linear Array With Adaptive Beamforming," *IEEE Transactions on Antennas and Propagation,* vol. 60, pp. 141-147, 2012.
[5] G. Li, S. Yang, Y. Chen, and Z. Nie, "A Novel Beam Scanning Technique in Time Modulated Linear Arrays," *Antennas and Propagation Society International Symposium, 2009. APSURSI '09. IEEE,* 2009.
[6] E. T. Bekele, L. Poli, P. Rocca, M. D'Urso, and A. Massa, "Pulse-Shapping Strategy for Time Modulated Arrays - Analysis and Design," *IEEE Transactions on Antennas and Propagation,* vol. 61, p. 13, 7 July 2013 2013.
[7] M.-K. Cho, I. Song, J.-G. Kim, and J. Cressler, D., "An Active Bi-Directional SiGe DPDT Switch With Multi-Octave Bandwidth," *IEEE Microwave and Wireless Components Letters,* vol. 26, pp. 279-281, 2016.
[8] L. Poli, P. Rocca, F. Viani, and A. Massa, "Advanced Harmonic Radiations Design in Time-Modulated Antenna Arrays," presented at the 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, Canada, 2015.