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A Steerable 8 Element 73 GHz Transmitting Time Modulated Array

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***Abstract*—The Time Modulated Array (TMA) is a type of phased array rarely seen applied, though it has advantages over other approaches. A TMA produces a set of radiated beams that are harmonically related to a set of digital control signals. In this paper the first mmWave beam steerable prototype TMA operating at 73 GHz, using bespoke GaAs integrated circuits, is presented. The beam steerable system consists of RF hardware and an FPGA controller. Laboratory radiated tests show good agreement to theoretical expectations. A beam steering of 24 degrees is reported (i.e. +/- 24 degrees total achievable range) for the TMA first harmonic beam, and 44 degrees for the second harmonic beam. The peak measured radiated array gain is -5 dBi. The maximum capable radiated power is +21.9 dBm. An increased level of integration on-chip, based on the existing architecture, could provide an array gain of +3 dBi.**

***Index Terms*—antennas, time modulated arrays, mmWave circuits, pattern measurements.**

I. Introduction

Antenna phased array based transmission systems have commonly been realised using phase shifter chips or vector modulators. An alternative strategy that uses time-controlled RF switch functionality is called the Time Modulated Array (TMA) [1], [2], [3], [4]. The TMA has been demonstrated at microwave frequencies, though with only a few examples of hardware. Published examples include [5] and [6] operating at circa 5.8 GHz, and [7] operating at circa 2 GHz. The first mmWave 73 GHz TMA phased array demonstrator was reported by us in [8]. Now, in this paper, we present new 73 GHz results with enhanced beam steering. The only other mmWave system we are aware of is [9], operating at 73 GHz - but using a fixed beam and addressing physical layer security rather than beam steering for phased arrays.

Future mobile communication systems are now exploring mmWave frequencies [10], [11]. Steerable beams at mmWave frequencies (where the channels often have negligible reflections) can thus make use of phased arrays. Therefore, new approaches are needed, for future power efficient mobile handsets and other applications.

The basic conceptual operation of a TX TMA can be considered as a set of N RF switches, all fed from a shared RF input, and each in turn feeding an antenna, as shown in Fig. 1.

By periodic control of the switches between on and off states, they each implement an equivalent phase shift on the input RF signal. This can be deduced straightforwardly through Fourier analysis of the controlling switch signals [5] and leads to a set of complex Fourier coefficients representing the switching effects. The periodic waveform (period Tp) controlling switch k (out of a total of N) is fully described by an element-specific on duration T_k and turn on delay T_{0k}. The resulting Fourier coefficient for TMA element k is multiplied with harmonic n of the switching frequency ω_p (where $\omega_p = 2\pi/Tp$) and up converted to the carrier frequency ω_c. This results in a steered beam at ($\omega_c + n\,\omega_p$) from the array. The resulting TMA array factor (AF) at beam evaluation angle θ can be expressed by (1) [5]. Term $e^{j\varphi_k}$ is an element-specific phase shift and is a function of evaluated beam angle and the spacing between radiating elements [5].

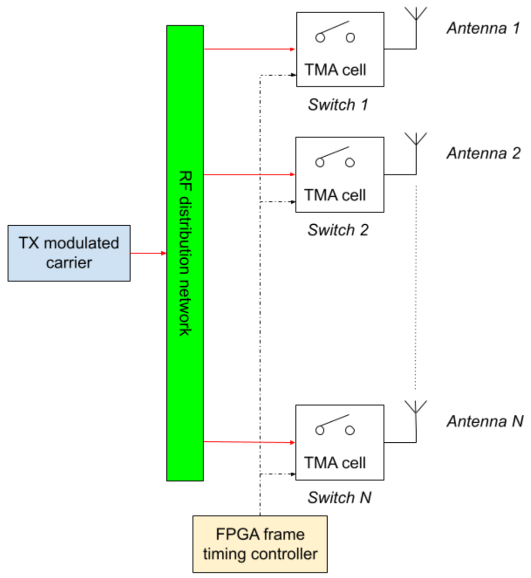


Fig. 1. Conceptual model of a TX TMA.

$$AF(\theta,n,t) = e^{j[\omega_c + n.\omega_p]t} \sum_{k=1}^{N} e^{j\varphi_k} \frac{\sin\left(n\pi \frac{T_k}{T_p}\right)}{n\pi} e^{-jn\pi\left(2\frac{T_{0k}}{T_p} + \frac{T_k}{T_p}\right)} \quad (1)$$

Practical TMA implementations may use elaborate RF circuitry to create the required switching function, such as multi-state switches or gain control. Such circuitry will have a gain per TMA switching cell (G_{cell}). The peak radiated gain of the TMA can then be predicted using (2) and (3) [12].

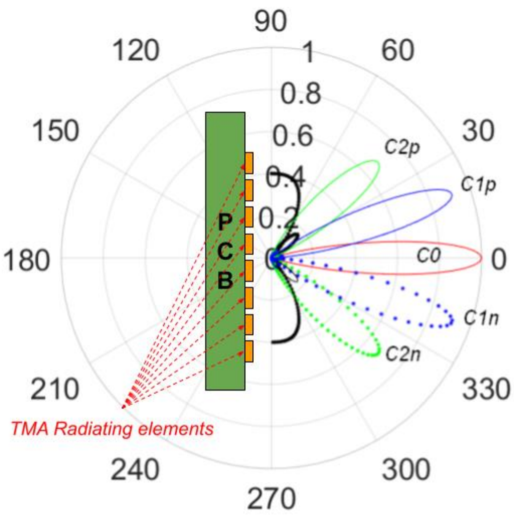


Fig. 2. An example of a TMA set of TX beams, including C0 boresight beam and first (C1p) and second (C2p) harmonic beams.

$$G_{TMA} = 10 \log_{10}(N) + G_{cell} + G_{ave} \text{ dBi} \tag{2}$$

$$G_{ave} = 20 \log_{10}\left(\frac{T_{ave}}{T_p}\right) \text{ dB} \tag{3}$$

The average on time, T_{ave}, of all the TMA hardware cells affects the overall achieved array gain. From (3) an 8-element TMA using a first harmonic beam steered to 12 degrees would produce a $T_{ave}/T_p = 0.32$, leading to a G_{ave} of -10 dB. This can be comparable to the insertion loss of a conventional phase shifter. G_{cell} is the sum of the RF hardware gain of one TMA cell (as measured conducted to antenna input) and gain of a single antenna element serving that TMA cell. An example of a beam pattern from a TX TMA is shown in Fig. 2.

One problem with many conventional TX TMAs is their emission on boresight (C0 beam), which cannot be steered-potentially representing wasted energy. In our early work [5], we identified a technique to null out this beam, through use of signal processing and dedicated RF hardware more complex than a simple switch. This earlier RF hardware employed a 0 / 180 degree phase shift switch and a 2 discrete gain control states, operating at 5.8 GHz [5].

In this paper, we present new laboratory test results from our bespoke mmWave 73 GHz TMA TX system [8]. The system incorporates our custom MMICs and hardware, to implement the required RF switching functions to steer the beam and also cancel the C0 boresight beam [8].

II. MMIC Overview

To realise a fast, simple, RF switch in high mmWave frequencies is difficult, with no suitable commercial parts available. Additional complexity is required to implement the C0 cancelling function. Therefore, we set out to design our own MMIC to incorporate amplification and a two-phase fast RF switch [13]. The MMIC includes a 0 / 180 degree phase shifter for the transmitted signal and a fast 10 dB gain change control. These functions are required for use in C0 beam cancellation and beam steering.

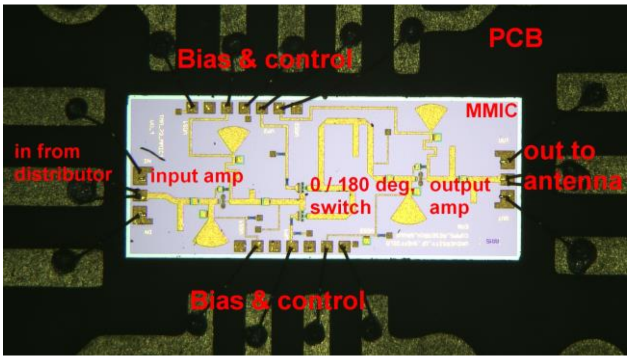


Fig. 3. A 73 GHz MMIC on the TMA PCB, showing amplifier stages and the phase inversion switch.

The design was created in Keysight ADS using the UMS Ltd PH10 design kit, and 20 GaAs MMICs were manufactured. All MMICs were lab tested at the University of Sheffield [14]. A photograph of one of the chips after attaching and wire bonding to the TMA RF PCB is shown in Fig. 3. Each MMIC is controlled by only 2 digital lines (hence 16 in total for an $N = 8$ array), representing a significant simplification over conventional phased array phase shifter approaches. The measured gain of the chips was 4.4 dB and the phase switch range was 183 degrees [13].

III. Hardware Demonstrator System

An 8 element PCB demonstrator system was created to host the MMICs and control them [8]. Analogue interface electronics was created to interface the MMICs to an FPGA platform (Intel MAX 10 EK-10M50F4840). The analogue control circuitry was required to translate from the 2.5 V logic levels of the FPGA to the analogue levels required by the MMICs (in ranges 0.8 V / -0.8 V), implemented using a dedicated interface PCB, shown in part in Fig. 4.

The RF platform included a set of series fed arrays (SFAs) as the radiating elements, with each MMIC feeding its own dedicated SFA. The RF PCB consisted of a composite of 0.2 mm Rogers 4003C outer layers and a central FR4 core, overall

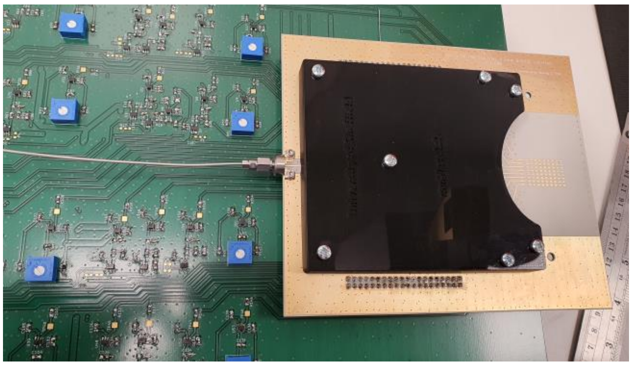
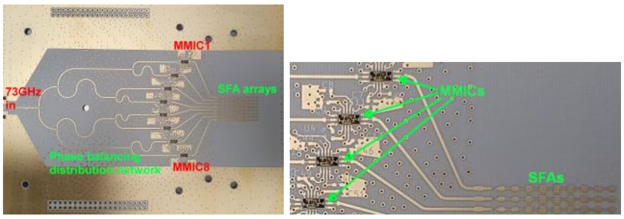


Fig. 4. The assembled TMA showing baseband and analogue controller PCB (green) and RF PCB (gold, top). The MMICs are under the black cover of the TMA RF PCB. The 8 SFAs are visible on the right of picture).



(a) (b)

Fig. 5. TMA RF PCB. (a) showing phase balancing input distribution network, 8 mounted MMICs in an arc and 8 SFA sub arrays, (b) close up of upper 4 MMICs and their 3 adjacent SFAs.

forming a 4-layer board, 1.6mm thick. The 73 GHz RF PCB for the TMA is shown in Figs. 5a and 5b.

IV. Laboratory Test Results

The TMA is employed by selecting a desired harmonic beam (n) to be used and then calculating the timing control waveforms for each switch function to implement the required beam steer. This is simple to implement in the FPGA controller as a set of repeating digital patterns (16 lines in total to control the 8-element array) with pattern repetition frequency ω_p.

After initial setup and over the air calibration was completed (to phase align the signals from each MMIC and its associated SFA) the full beam control was assessed. Radiated tests used a Keysight Smart Mixer M1971E, with standard gain horn, connected to a Keysight PXA N9030B. The transmitted signal was generated using a Rohde & Schwarz SMM100A feeding a VNAX 1591 x6 multiplier, then feeding the TMA, as shown in Fig. 6

The beam patterns and gains were measured for the TMA's first (C1p) and second (C2p) harmonic beams and then compared to theoretical expectations using (2) and (1).

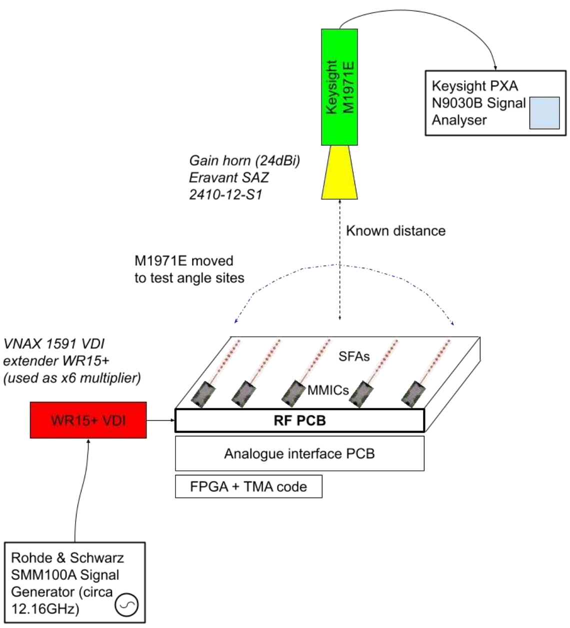


Fig. 6 The laboratory TMA TX radiated beam measurement system.

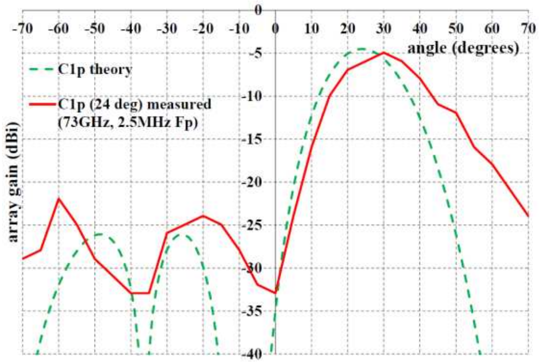


Fig. 7 The measured radiated gain pattern for first harmonic beam (C1p) when steered to 24 degrees ($Fp = 1/Tp$).

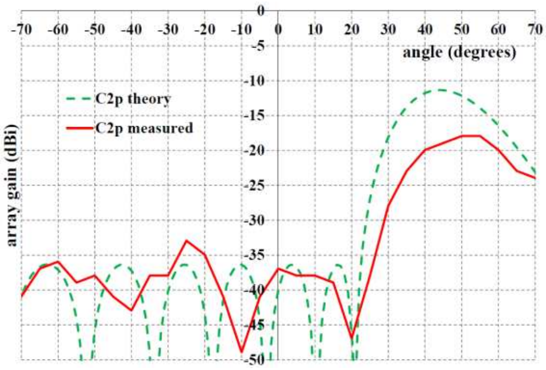


Fig. 8. The measured radiated gain pattern for second harmonic beam (C2p) when steered to 44 degrees.

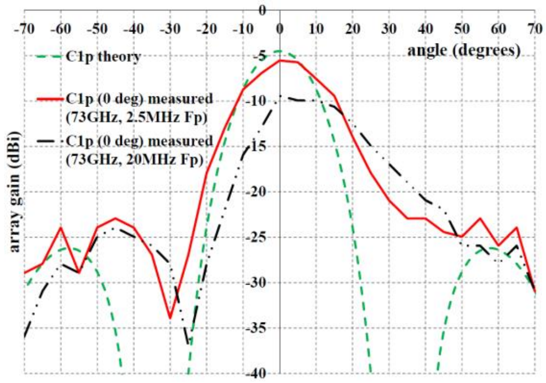


Fig. 9 The measured radiated gain pattern for first harmonic beam (C1p) when steered to 0 degrees, comparing gains for Fp = 2.5 and 20 MHz.

The measured radiated patterns when the array is steered to +24 degrees (C1p beam) and +44 degrees (C2p beam) are shown in Fig. 7 and Fig. 8 respectively. Fig. 9 shows the beam pattern when the first harmonic beam is steered to 0 degrees (i.e. boresight), comparing different Fp switching rates *(Fp = $1/Tp$)*.

During testing it was identified that the PCB input phase balancing distribution network imposed an insertion loss of 20 dB, which is 11 dB more than the 9 dB loss that would be expected from a set of three *idea lossless*, cascaded power dividers. This extra loss is mainly due to real-world tracking losses from the physical size of the PCB microstrip network used (overall RF PCB is 146 mm x 124 mm).

TABLE I. COMPARISON TO OTHER TMA WORKS.

Ref.	Carrier (GHz)	Array Gain (dBi)	Elements (*N*)	Control Interface	Beam Steering Range (deg)
This work	71-73	-5 (PCB & chips)	8	16 digital lines	C1p: +/-24 C2p: +/-44
[8]	71-73	-2 (PCB & chips)	8	16 digital lines	C1p: +/-12 C2p: +/-30
[9]	71-76	-	2, 4	4 digital lines	Not steerable
[5]	5.8	2	6	12 digital lines	C1p: +/-18
[6]	4.7-5.9	-	1	2 digital lines	Not steerable
[7]	1.5-2.5	-	8	15 digital lines per element	+/- 45

A simple improvement to recover some of this loss would be to not use input phase balanced lines and so use shorter lines, then accommodating phase trimming in the TMA timing design, as identified in [8].

This may also suggest that an on-chip input distribution network (with all TMA active circuits also on the same chip) could result in a gain increase of up to 11 dB (ignoring chip implementation losses). If additional on-chip tracking losses are a pragmatic estimated 3 dB, then the resulting array gain on the first harmonic beam (C1p) could increase from the measured -5 dBi here to +3 dBi, based on our present MMIC.

The present MMICs have a conducted measured gain of +4.4 dB, output 1 dB compression point of +2.8 dBm and output saturated power (P_{SAT}) of +9.8 dBm [13]. Driving the MMIC harder, or redesigning it to include a higher gain preamplifier, could boost radiated TX power, though with increased DC power draw. With the present system, the P_{SAT} defined TX radiated power is +21.9 dBm [8]. Additional input amplification MMICs could be included onto an updated PCB design. Finally, higher gain radiating elements could also be used, replacing the sub-array SFAs presently employed.

V. CONCLUSION

We present a design overview and new lab radiated gain measurements of a 73 GHz TX TMA system, extending our work in [8]. The system steers the TMA C1p beam to +24 degrees, with a gain of -5 dBi and expected radiated P_{SAT} of +21.9 dBm. It has demonstrated steering the second harmonic beam to +44 degrees. This implies a total steerable range of +/- 24 degrees for C1p and +/- 44 degrees for C2p.

A fully on-chip version of the same system, but still with the same SFA off chip antennas, could provide an array gain of +3 dBi. If required, higher array gain may also be achieved by redesigning the MMIC amplifier stages.

Extending the work in [8], to the authors' best knowledge, this new work is the first mmWave demonstration of a wider steering TMA TX system at 73 GHz - representing a significant step forward in TMA operational frequency capability. Other recently published TMA transmitters are compared to this work in Table 1, confirming the novelty of our system in steering a beam at mmWave using the TMA approach. It is proposed that the TMA could be a useful technique for low-complexity, low-cost future mmWave phased arrays.

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