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Design of 4 GHz 1-Bit Phase Quantized Beam Steering Transmitarray

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Abstract

A 4 GHz transmitarray is designed using 1-bit phase quantized U-slot patch element, which need only two switching elements per unitcell to control the transmission phase. The array consists of 22x14 number of 0.24λ_0 size unitcells. Beam scanning from -40° to +40° in the H plane and -20° to +20° is achieved with enhanced gain compared to the feed and SLL is 6 dB below the maximum. Peak gain of 15.3 dBi and SLL of 8.6 dB is observed for broadside radiation. Array is simulated using fullwave solver and radiation pattern results are shown for different scanning angles and frequencies.

1. Introduction

Transmitarray (TA) is a spatial fed array which is alternative to the phased arrays which requires large number of power dividers, phase shifters and lossy feed network. Due to its high gain, beam steering, space feeding capabilities TA found potential applications in wireless communication, remote sensing and THz imaging. A typical TA unitcell consist of coupled receiving (Rx) mode and transmitting (Tx) mode arrays. The Tx array is connected to the Rx array through phase shifter or simple via or aperture coupled. The Rx array is spatially illuminated by focal source, and Tx array is radiating collimated wave into space. To transform the spherical wave radiated by the focal source into a plane wave in the desired direction, the transmission phase in individual unitcell of the Tx array should be tuned. It can be done either by electronically controlling the phase shifter or reconfiguring phase of individual unitcell [1].

There are three major approached adopted in the beam steerable TA design, namely (i) tunable scatterer (ii) feed rotation & translation (iii) guided wave [2]. In tunable scatterer approach, individual elements of multi-layer FSS are electronically tuned using either varactor diodes or PIN diodes to adaptively synthesize antenna patterns. Limitation with this approach is significant side-lobes are produced at large angles, regardless of the aperture size and requires minimum two layers of FSS to meet the phase requirements of beam-forming [3-4]. In the feed rotation approach, beam steering in elevation is obtained through feed translation, while beam steering in azimuth requires the rotation of the full assembly [5].

Guided wave approach is the widely adopted approach in which, TA consist of two layers of antenna. One layer is spatially illuminated by the feed antenna and other layer radiates the planar phase front which forms the radiating aperture. The following literature are based on the above approach. In [6], TA operating at 5.7 GHz designed using 6x6 array in which, each unitcell consist of two microstrip patches on either side of a ground plane coupled by a small slot aperture all tuned by varactor diode. The gain of the feed horn is 17.6 dBi. Scanning of ±25° in both planes is reported with peak gain of 20.8 dBi in the broadside direction. MEMS switch based 34.8 GHz TA prototype is reported in [7], to steer beam ±40° in both planes using 22x22 unitcells with maximum gain of 9.2 dBi. An 8x8 reconfigurable transmitarray which operates at 5.4 GHz with ±60◦ beam steering in both planes with peak 17 dBi gain at two orthogonal polarization is reported in [8]. Here the unitcell is four-layer structure comprises of Rx patch, phase shifter, polarization configurable Tx patch. The gain of the feed horn is 19.7 dBi at 5.4 GHz. In [9], reconfigurable TA at 12 GHz band using phase shifter with beam steering capability of 9° is designed with 16 dBi gain. The feed gain is not reported. A wideband 20x20 array TA using 1-bit phase quantized U/O slot patch based $\lambda/2$ unitcell is reported in [10]. Two PIN diodes in O slot patch is used to configure two phase states of the unitcell. Maximum gain of 22.7 dBi at broadside and beam scanning of ±70° and ±40° in H and E plane is reported, which has better radiation performance compared to other TA design approaches. 11.1 dBi horn is used as feed source.

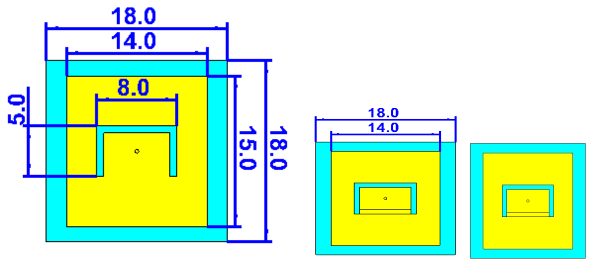
In this paper, TA is designed at 4 GHz using 1-bit phase quantized U/O-slot patch element to steer beam in both planes. The design flow consists of three steps: (i) designing of 1 bit phase quantized unit cell (ii) calculating the required phase on the array (radiating aperture side) (iii) full array design with each element phase controlled by configuring the switches.

2. Trasmitarray Design

2.1. Unitcell Design

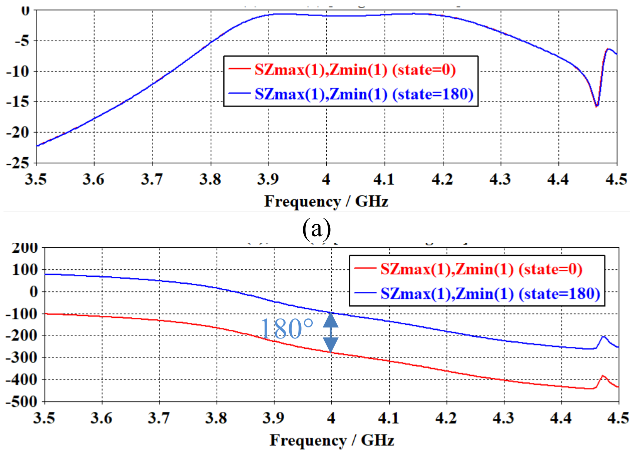
In TA unit element design, the objective is to have 360° phase control and close to 0 dB magnitude transmission coefficient at all the required phase states. Continuous 360°

phase tuning range is desired, but this is not feasible for implementation with switching devices. So, in this work, 1-bit phase quantized unitcell is designed, where the required phase of -90° to +90° will be quantized to 0° and remaining with 180° [10]. The designed unit radiating element shown in Figure 1 is 0.24 λ_0 square unit cell of size (18x18 mm), which consists of rectangular patch (15x14 mm). The patch is loaded by a U-slot on one side and a patch of the same size loaded by an O-slot on the opposite side. The two patches are connected using via. The unit cell is fabricated on RO4003 substrate. Depending on the bias, the incident field is transmitted in phase or with a 180° rotation, resulting in a 1-bit differential phase shift. In the simulation, instead of equivalent lumped parameter of diode ON and OFF cases, short and open are used. The designed unit cell possess less than 2 dB of insertion loss and 180° phase difference for both phase sates with 11% fractional 3-dB bandwidth, as shown in Figure 2.



(a) (b) (c)

Figure 1. Unitcell (a) front side (Rx) patch with U slot, and back side (Tx) (b) 180° phase state / short on top side of O slot (c) 0° phase state / short on bottom side of O slot [All dimensions in mm]



(a)

(b)

Figure 2. Transmission coefficient (a) Magnitude in dB (b) phase in degree for 0/180° phase state

2.2. Phase Distribution for Beam steering

The phase required at each unitcell on the radiating aperture is calculated to steer the beam in a specific direction. The electromagnetic field incident on each transmitarray element at a certain angle can be locally considered as a plane wave with a phase proportional to the distance from the phase center of the feed source to each element [1]. In this paper, the feed source is kept at a distance, 0.7 times the larger dimension of array to get maximum gain and directivity. TA coordinate system is shown in Figure 3, where focal source is kept in the z axis at distance F.

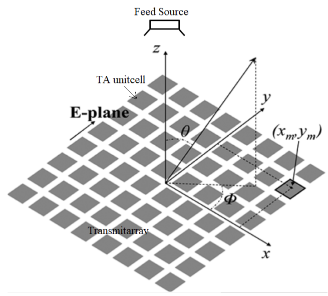


Figure 3. TA coordinate system

Phase shift that need to be introduced at each unit cell, with compensating the spatial phase delay from the feed to that element is

$$Ph(S_{21}^{m}) = \Phi_m(\theta_0,\phi_0) + k_0\sqrt{F^2 + x_m{}^2 + y_m{}^2} \quad (1).$$

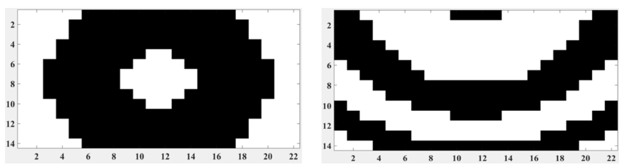
Where phase required at unitcell (m) to steer beam in desired direction (θ_0, ϕ_0) is

$$\Phi_m(\theta_0,\phi_0) = k_0(-x_m \sin\theta_0 \cos\phi_0 - y_m \sin\theta_0 \sin\phi_0) \quad (2).$$

Then 1-bit phase quantization rule is applied as

$$Q(Ph(S_{21}^{m})) = \begin{cases} 0^\circ & -90 \le Ph(S_{21}^{m}) < 90 \\ 180^\circ & otherwise \end{cases} \quad (3).$$

The phase distribution for the rectangular array (22x14) calculated using above equations are shown in Figure 4 for few scanning angles. The black and while squares represent 0 and 180 phases at each unitcell.



(a) (b)

Figure 4. Quantized phase for (a) $\phi_0 = 0°$; $\theta_0 = 0°$ (b) $\phi_0 = 90°$; $\theta_0 = -30°$

2.3. Transmitarray

The feed source used with the design is a high gain wideband patch antenna with flat gain of 11.78 dBi in 3.5 to 4.4 GHz band [11]. Rectangular TA of 22x14 array of size 400 x 250 mm is constructed, since the feed source beam is not symmetry in both planes. The array with the feed source is simulated with CST Microwave Studio, shown in Figure 5. For each beam steering case, the switches in the individual unitcell is configured using the calculated phase shown if Figure 4.

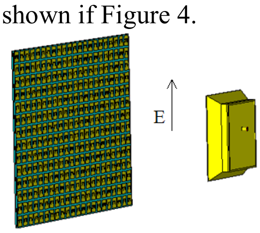


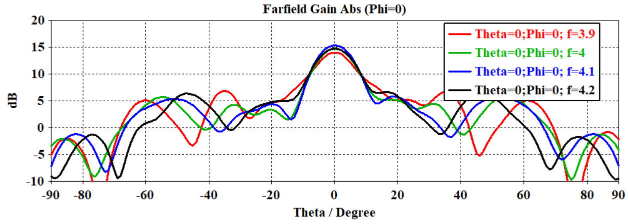
Figure 5. CST model of TA and feed source

Table 1. Beam Scanning in ϕ_0=0° plane

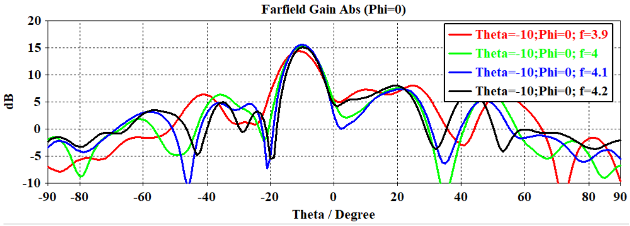
θ_0	**Gain (dBi)**				**3 dB BW in Degrees**				**SLL (dB)**			
	(f in GHz) 3.9	*4*	*4.1*	*4.2*	*3.9*	*4*	*4.1*	*4.2*	*3.9*	*4*	*4.1*	*4.2*
0	14	14.7	15.3	14.7	13.1	12.5	12.3	12.9	7.1	8.6	8.6	8.1
-10	14.4	15.2	15.6	15.1	11.6	10.5	9.7	9.1	6.4	7.7	8.2	7.1
-20	14.6	13.5	13.2	12.9	13.2	13.8	13.8	13.3	6.6	6.4	5.6	6.3
-30	13.3	12.1	13.2	14.4	20.5	17.2	13	11.1	2.1	4.7	4.3	6.1
-40	14.3	13	12.2	14.8	11.8	10.3	11.7	15.6	4.5	3.1	3.1	6.4
-60	12.2	14.2	10.6	9.4	13.4	11.6	11	11	1.2	4.7	5.4	2.2

3. Results

Radiation characteristics such as gain, -3 dB beamwidth and SLL for different scanning angles from 3.9 to 4.2 GHz is shown in Table.1. Radiation pattern for different frequencies in H plane for θ_0=0 to -60°is shown in Figure 6.



(a)



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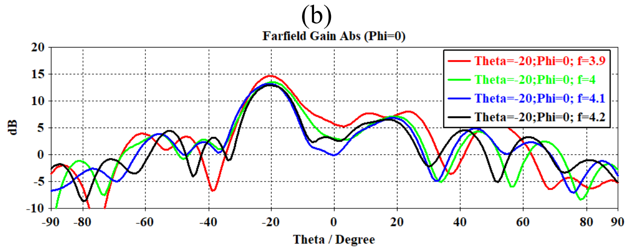

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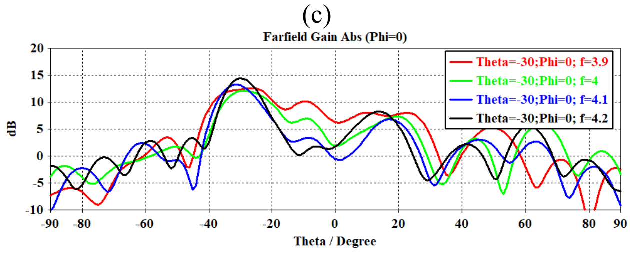
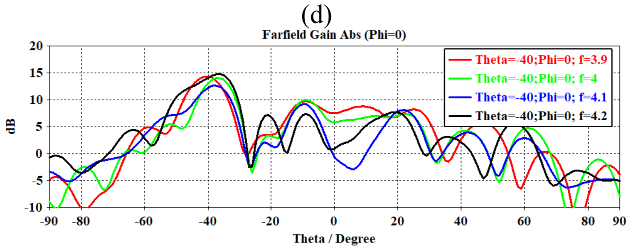


(d)



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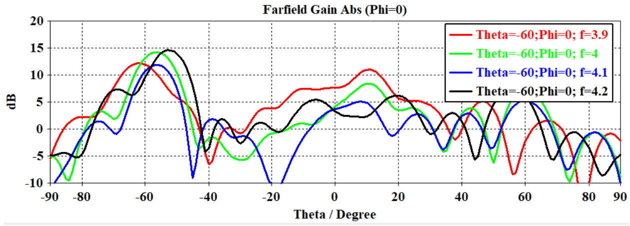
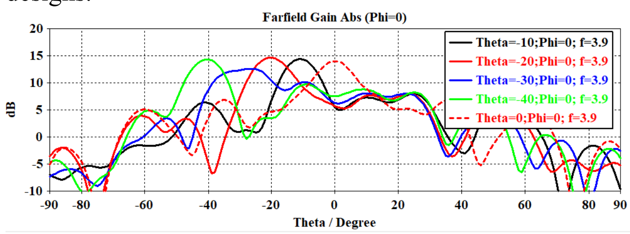


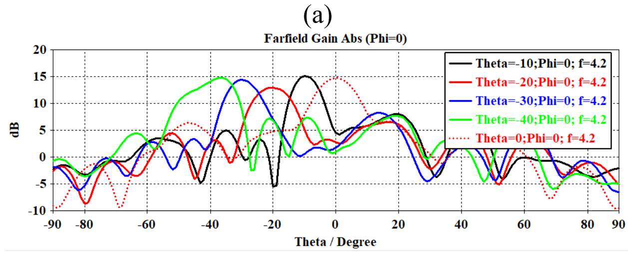
(f)

Figure 6. Radiation pattern of TA at different frequencies for beam at ϕ_0=0° and (a) θ_0=0° (b) θ_0=-10° (b) θ_0=-20° (b) θ_0=-30° (b) θ_0=-40° (b) θ_0=-60°

Since the beam of the feed source is symmetry in H plane, the designed TA beam will be symmetrical in -θ_0 and +θ_0. From Table I it is observed that gain and beamwidth decreases and the side lobes come closer to the main beam as scanning angle increases. It is due to the quantization of phase. Figure 6(a) shows gain variation of the broadside beam is within 1.3 dB at different frequencies. For the broad side beam, peak gain of 15.3 dBi is noted at 4.1 GHz with SLL of 8.6 dB. It is observed that SLL is above 6 dB for scanning upto ±40° at 4.2 GHz. But at other frequencies SLL is increasing, which will be controlled in the future designs.



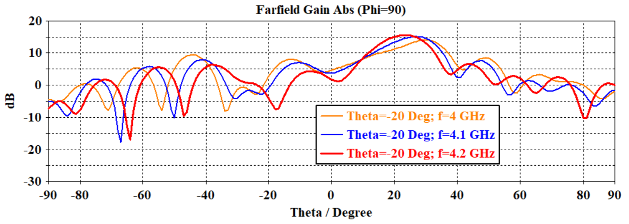
(a)



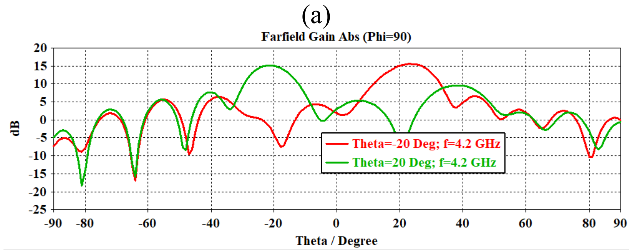
(b)

Figure 7. Radiation pattern of TA for scanning angle upto θ_0=-40° in H plane at (a) f=3.9 GHz (b) f=4.2 GHz

For the scanning angle upto 40° the gain variation is within 1.3 and 2.2 dB at frequencies 3.9 and 4.2 GHz respectively, which are shown in Figure 7(a-b).



(a)



(b)

Figure 8. Radiation pattern of TA in E plane (a) θ_0=-20° and f=4 to 4.2 GHz (b) θ_0=-20 and +20° at f=4.2 GHz

Beam scanning in the E plane (ϕ_0=90°) at θ_0=20° shown in Figure 8(a). Except at 4.2 GHz, the beam is squinted due to less number elements in E plane of the TA. Figure 8(b) shows the scanning at θ_0=-20° and +20° at the E plane. The θ_0=-20° beam squinted to 23° and θ_0=+20° is not squinted, since the beam of feed source is not symmetry in the E plane. The overall area of the 4 GHz TA is 1.1 times larger when compared with the X band TA reported in [10]. Gain reduction in 4 GHz TA compared with X band TA is expected, as gain reduces with frequency.

4. Conclusion

In this paper, 4 GHz beam steering Transmitarray is designed using 22x14 array with steerable beam of ±40° in H plane and ±20° in E plane. The small unitcell size (0.24λ_0) helps to reduce the overall array size (5.3λ_0 x 3.3λ_0). Gain variation is within 2.2 dB for the scanning ±40° and SLL is above 6 dB at 4.2 GHz.

5. Acknowledgements

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6. References

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