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# Beam Switching Cylindrical Array Antenna System for Communication

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**ABSTRACT**

The beam switching cylindrical array, which is a unique system, has been designed and developed to cover 360° in azimuth plane by generating 16 beams with specified elevation coverage. In this design, the concept of fast aperture selection (4 x 4) in microseconds from the total cylindrical array has been realised successfully to meet the requirement of point-to-multipoint communication. The components of the array, viz., radiating elements, powder dividers, switches, etc., are designed in printed circuit type, and hence, objectives of lightweight and ease of reproducibility are achieved. The lightweight of the array makes it accessible for easy mounting at a specified height for achieving longer communication range. Finally, a low-loss radome is incorporated to protect the array from environmental conditions. The various parameters, viz., return loss, gain, and switched-beam radiation patterns were measured over a bandwidth of 300 MHz in L- band and typical measured results are presented in this paper.

## 1. INTRODUCTION

In a point-to-multipoint communication system, an antenna is essentially required to transmit and receive over the specified frequency bandwidth. For communication to various locations, the coverage in azimuth plane should be 360°. Usually, such requirements can be met by designing wide-beam antennas, and by using few numbers, it is possible to cover 360°. In this approach, radiation of energy in undesired directions takes place and hence becomes susceptible for jamming or interferences. This problem can be solved, if the narrow beam is switched fast. In view of this, circular or cylindrical array becomes the obvious choice as it exhibits 360° coverage and negligible degradation in beam shape while scanning[1,2]. The scanning of beams is of two types: (i) to switch the beam at fixed angular intervals over 360° (simpler to implement), and (ii) beam scanning is nearly continuous by using the phase shifters, which makes the antenna system complex and costlier[3]. As the requirement of scanning is to generate a fixed beam in azimuth and also narrow beam in elevation planes, the cylindrical array with 64 elements arranged in 4 rows and 16 columns (4 x 16) is considered, which provides moderate gain. A software for uniform distribution was developed to study the effect of interelement spacing of cylindrical array, which reveals similar results[4]. Finally, the cylindrical array covering 20 per cent bandwidth in L-band has been designed and developed. The mutual coupling effects were also studied experimentally[5]. The concept of fast selecting aperture in co-phasal condition for appropriate beam is implemented successfully. The antenna is housed in a low-loss, lightweight sandwich radome and is evaluated in azimuth and elevation planes in small steps of

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frequency; and the measured 16 switched-beam patterns are presented.

## 2. THEORETICAL APPROACH

There are $n$ elements equispaced around the circumference of a cylinder and pointed along the radius vector and such $m$ circular arrays are stacked along the height of the cylinder as shown in Fig. 1. The total radiation from cylindrical array can be considered as product of radiation from circular array and linear array[6]. Hence, the total radiation $E(\theta,\phi)$ from cylindrical array can be written as

$$E(\theta,\phi) = E^c(\theta,\phi) \times E^L(\theta,\phi) \quad (1)$$

where

$E^c(\theta,\phi)$ Radiation due to circular array

$E^L(\theta,\phi)$ Radiation due to linear array

The radiation from circular array can be written as

$$E^c(\theta,\phi) = \sum_{p=1}^{n} I_p\, g(\theta,\phi-\alpha_p) \exp\left(j\frac{2\pi}{\lambda}R\cos(\phi-\alpha_p)\right) \quad (2)$$

where

$I_p$ Current distribution for $p^{th}$ element

$\lambda$ Operating wavelength

$R$ Radius of cylinder

$\alpha_p$ $2\pi p/n$

$g(\theta,\phi)$ Element pattern in azimuth plane

The radiation from linear array can be written as

$$E^L(\theta,\phi) \quad \sum_{q=0}^{m-1} I_q\, g'(\theta,\phi) \exp\left(j\frac{2\pi}{\lambda}qd\sin\theta\right) \quad (3)$$

where

$I_q$ Current distribution for $q^{th}$ element

$d$ Interelement spacing between two circular arrays

$g'(\theta,\phi)$ Element pattern in elevation plane

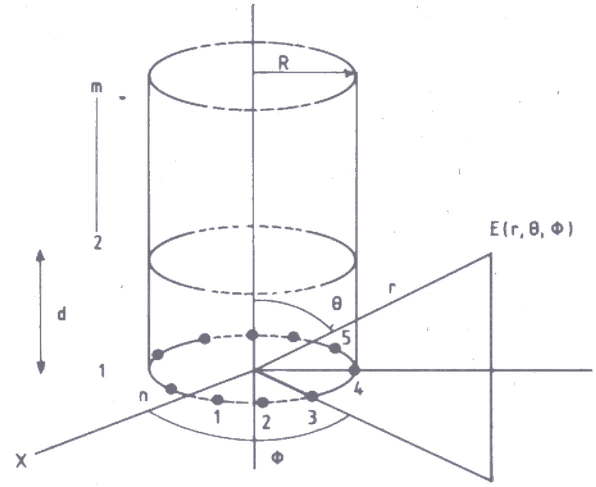


**Figure 1. Geometry of cylindrical array**

In this paper, 16 elements around circumference and 4 such circular arrays are stacked to produce the symmetric beam in both planes. The beamwidth in azimuth and elevation planes is considered to be 25° and 20°, respectively. The array is required to be scanned in azimuth plane by switching the appropriate aperture. Thus, the aperture for required beamwidth becomes 4 x 4. Hence, the Eqn. (2) for $i^{th}$ discrete scanned beam can be written as

$$E^c(\theta,\phi) = \sum_{p=i}^{i+3} I_p\, g(\phi-\alpha_p) \exp\left(j\frac{2\pi}{\lambda}R\,[\cos(\phi-\alpha_p)-\cos(\phi_o-\alpha_p)]\right) \quad (4)$$

where

$i$ is an integer $1 \le i \le 16$, and

for $i+3 > 16$, $i+3 \cong$ modulo 16

$$\phi_o = \frac{\alpha_{p+3}+\alpha_p}{2}$$

By proper selection of $i$, the fixed 16 beams can be generated. The first beam will be along 56.25°, if first element is placed at 22.5° from X-axis as shown in Fig. 1. All the subsequent beams will be at an interval of 22.5°. However, the first beam can be aligned to 0° by physical rotation of the cylindrical array to -56.25° in azimuth plane.

A software was developed to study the spacing between elements of circular array, and it was found that the spacing of half wavelength is optimum for uniform distribution. The element pattern is taken as cardioid type pattern given by

$$g(\phi - \alpha_p) = \left[\frac{1}{2}[1 + \cos(\phi - \alpha_p)]\right]^2 \tag{5}$$

Using Eqns (4) and (5), the beam patterns in azimuth plane with uniform distribution have been computed and it was observed that 16 beams are adequate for 360° azimuthal coverage.

From Eqn (3), it was found that the spacing should be 0.7λ for optimum gain and the element pattern was considered as

$$\begin{aligned} g'(\theta) &= \sin\theta \quad & 0 \le \theta \le \pi \\ &= 0 \quad & \pi < \theta \le 2\pi \end{aligned} \tag{6}$$

The elevation plane pattern is computed by taking four elements as linear array with a 7 dB amplitude taper and found that the 3 dB beamwidth variation is 20° ± 2° over the complete band with low side lobe level.

## 3. CONFIGURATION OF CYLINDRICAL ARRAY

It is evident from the computations that 16 elements are required to be mounted around the cylinder which acts as a ground plane. For controlling the radiation in elevation plane, four circular arrays are required to be used with 0.7λ spacing at the highest frequency. At a time, 4 elements in azimuth and 4 in elevation (4 x 4), i.e., 16 elements in total will be excited to generate the beam. Subsequent beams will be generated by selecting the next appropriate aperture through switching network. The switching network consists of four SP4T and two transfer (DPDT) switches. These switches are controlled by beam switching unit (BSU) to provide radio frequency (RF) interconnections to the specific elements, as desired. The complete configuration of the cylindrical array with beam switching mechanism is given in Fig. 2.

## 4. DEVELOPMENT OF BEAM SWITCHING CYLINDRICAL ARRAY

The development of beam switching cylindrical array system consists of the following sub-assemblies listed in order:

- Development of metallic cylinder
- Radiating element
- Elevation and azimuth power dividers
- SP4T and transfer switches
- Beam switching unit
- Radome

### 4.1 Development of Metallic Cylinder

Theoretical study reveals that the spacing between elements in circular geometry should be ≤ 0.5 λ. This has been selected at the highest frequency, which inherently satisfies the lower frequency. Similarly, the spacing for vertical stack of elements has been chosen as 0.7 λ at the highest frequency as there is no scanning involved. Hence, the diameter $D$ with 16 radiators around the cylinder is

$$D = 16 \times \frac{0.5\,\lambda_H}{\pi} = \frac{8\lambda_H}{\pi} \tag{7}$$

where $\lambda_H$ is wavelength at the highest frequency. The height of cylinder is 4 x 0.7 $\lambda_H$ = 2.8 $\lambda_H$. The cylinder is fabricated in 16 facets for mounting the 64 elements accurately. Each facet is used to mount four elements vertically with 0.7 $\lambda_H$ interelement spacing.

### 4.2 Printed Dipole Radiating Element

As lightweight and compact antenna is desired a printed dipole radiating element has been opted. Printed antennas have advantages such as low-profile, ease of fabrication and integration with feed lines. The designed antenna is printed dipole radiator which works over 20 per cent bandwidth at L-band. The radiator is fed by means of a microstrip balun[7]. The schematic of the printed dipole antenna with integrated balun is shown in Fig. 3.

The electrical parameters of the substrate used for etching the printed dipole are:

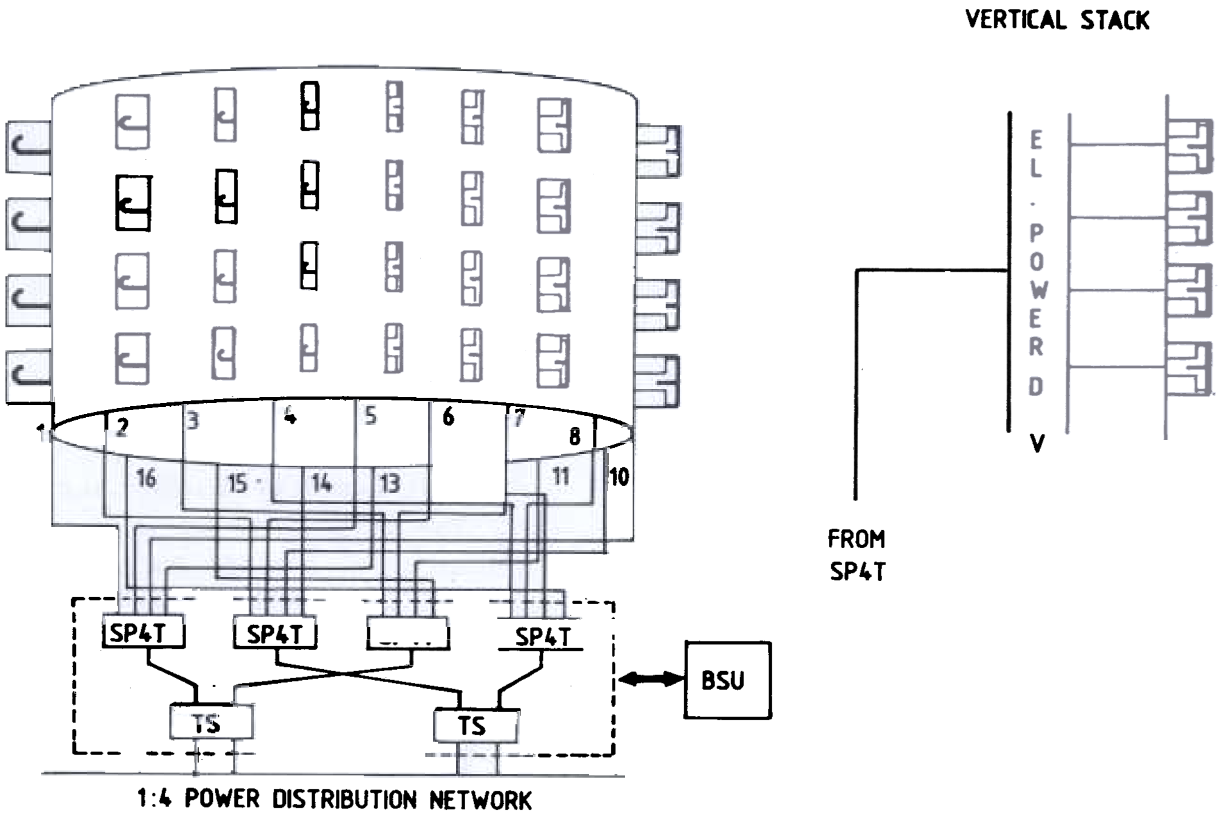


**Figure 2. Configuration of cylindrical beam switching array**

| | |
|---|---|
| Type of substrate | RT/Duroid 5880 |
| Relative dielectric constant | 2.2 |
| Substrate thickness | 1 .6 mm |
| Loss tangent, tan δ | 0.0009 |

The designed parameters of the printed dipole are:

| | |
|---|---|
| Length of the dipole, $L$ | $0.4\ \lambda_o$ |
| Width of the dipole, $W$ | $0.05\ \lambda_o$ |

where $\lambda_o$ is resonant wavelength of the dipole.

The calculated feed point resistance at resonance is approximately 80 Ω. By properly selecting the length of the microstrip line $\theta_b$ and the balanced line $\theta_{ab}$ (Fig. 3), the impedance matching between the feed and dipole is achieved. This element works in conjunction with a ground plane and in the present application, the body of the cylinder acts as a ground plane. The spacing between the element and the ground plane is taken as quarter wavelength for the impedance matching over the complete band of frequencies.

A set of 64 radiating elements was printed using photolithographic techniques and each radiator was connected with an end-launch connector (Omni Spectra, OSM 2070-5068- 02) . The return loss of radiating element was < - 10 dB over a 20 per cent bandwidth. The printed dipole element had a minimum gain of 5.5 dB with ground plane and the 3 dB beamwidths in $E$-plane and $H$-plane were 105° and 95°, respectively at the centre frequency. The cross polarisation of the antenna was < - 20.0 dB. The return loss and pattern tracking of the radiating elements was within ±1.0 dB, which is an important parameter for array configuration.

### 4.3 Power Dividers

In the beam switching cylindrical array, it was required to generate a directional beam by exciting

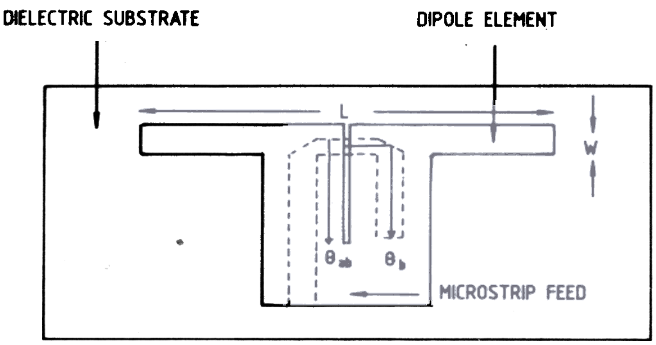


**Figure 3. Printed dipole radiating element**

four consecutive vertical stacks mounted on the circumference of the cylinder. For this, a 1:4 azimuth power divider was required. As there were 16 vertical stacks, each stack required a 1:4 power divider, therefore this was referred to as vertical or elevation power divider. Uniform amplitude distribution for azimuth power divider was used, whereas elevation power divider edge ports were 7.0 dB below those of centre ports. This was considered to reduce the side lobes in elevation plane.

### *4.3.1 Azimuth Power Divider*

A nonreactive type power divider using hybrid rings was used for azimuth power distribution. This is less sensitive to its output mismatches and offers in-phase and out-of-phase outputs. For realisation of a 4-way power divider, three hybrid rings were required. Since the power distribution to be implemented is uniform, 3 dB ring hybrids in microstrip version were used. Ring hybrid with 1.5 $\lambda_g$ circumference used in this work was designed as per procedure given in the paper[8]. Care was taken to get equal phase distribution at the output ports. The substrate used had the following parameters:

| | |
|---|---|
| Type of substrate | RT/Duroid 6010 |
| Dielectric constant | 10.2 |
| Substrate thickness | .27 mm |
| Loss tangent, tan δ | 0.01 |

Microstrip line widths for the realisation of required impedances and the effective dielectric constant were computed using quasistatic approximation given by Wheeler[9] The power divider with three ring hybrids etched on RT/Duroid 6010 material was assembled with Omni Spectra, OSM 2052-3123-00 jack connectors and electrical evaluation was carried out. A minimum return loss of 18 dB at the input port was obtained over the frequency band of interest. Power distribution was uniform within ± 0.3 dB and phase tracking was within ± 10° over the frequency band.

### *4.3.2 Elevation Power Divider*

Vertical power divider (1:4) was designed for the power distribution such that edge ports were 7.0 dB below the centre ports. This was implemented in strip-line configuration using reactive power division concept. The length of the power divider was so designed that additional cables were avoided to connect this to the radiating elements and had better reliability.

The details of the substrate used are

| | |
|---|---|
| Type of substrate | RT/Duroid 5880 |
| Relative dielectric constant | 2.2 |
| Thickness of the substrate | .6 mm |
| Loss tangent, tan δ | 0.0009 |

Strip-line widths required to realise the desired amplitude distribution was computed based on the procedure[10]. The power divider was developed precisely to get uniform phase distribution across the outputs of the power divider. A total of 16 such power dividers were developed and connected with plug end launch connectors (Omni Spectra, OSM 2071-5018-02) at the outputs, and jack end launch connector (Omni Spectra, OSM 2070-5068-02), at the inputs. The selection of such connectors provide direct interconnection of power dividers with the radiating elements. The measured phase and amplitude tracking was within ±10° and ± 0.25 dB, respectively over the complete frequency band.

### 4.4 SP4T & Transfer (DPDT) Switches

The selection of beam from cylindrical array was performed in few microseconds by switching the aperture through four SP4T and two DPDT switches. The formation of beam takes place if the co-phasal condition is achieved. This implies that all the components being used from the input of azimuth power divider to all the radiating elements are phase-matched, and hence, the phase matching is essentially required for SP4T and DPDT switches also. The amplitude and phase matching is required to be within the window of ± 0.25 dB and ± 5°, respectively. The other parameters, such as return loss < -15 dB, isolation > 40 dB and insertion loss < 0.8 dB, and switching speed of 0.20 microseconds was considered. Hence, SP4T switches (from Robinson, USA) and DPDT switches (from Elisra, Israel) which meet the above specifications have been used in configuring the system. The selection of a particular port within the switch is controlled by means of BSU.

### 4.5 Beam Switching Unit

The BSU of beam switching cylindrical array is used to switch the beam in any desired azimuth direction covering complete 360°. It consists of two parts, namely, code distribution box and remote control unit. The remote control unit is connected to code distribution unit via specified length of multi core cable to cater for driving requirement of RF switches mounted inside antenna at a certain height above the ground. The BSU takes beam number as input and generates necessary control command to RF switches via RS 422 serial link with suitable line drivers and line receivers. It has built in test equipment (BITE) facility to test the functioning of complete BSU hardware involving RF switches and also to fault diagnosis during checking.

### 4.6 Radome

To house the beam switching cylindrical array with the associated electronics, a lightweight sandwich radome has been designed and fabricated. The radome protects the array from severe environmental conditions and is almost transparent to electromagnetic radiation. To make the radome lighter with good electromagnetic transparency, an A-sandwich type of cylindrical radome wall construction is employed in the design. The A-sandwich radome consists of two high density skins separated by a low density core material. The skin and the core thicknesses are selected by computing the power transmission through the radome over the frequency band of interest by employing optical ray tracing technique[11]. The power transmission of > 90 per cent is achieved over the complete frequency band.

## 5. MUTUAL COUPLING STUDY & INTEGRATION OF ARRAY

The 16-faceted cylinder has been used to mount 64 radiating elements accurately. Before integrating 64 elements with various power dividers, switches, etc., the mutual coupling between elements was measured experimentally using element-by-element approach[5]. One element was selected as reference and was connected to one port of the vector network analyser HP 8722C and an adjacent element was connected to the second port of network analyser in transmission ($S_{21}$) mode to measure the coupled power. During this measurement, all other elements were terminated with 50 Ω load. It was observed that the coupled power was < - 20 dB. When alternate elements were measured in a similar way, it was about - 30 dB, which is much less than adjacent elements. This shows that the mutual coupling effect is only due to adjacent elements which does not drastically effect the radiation pattern. Moreover, the element pattern was also measured in array environment and it was found that there was no significant degradation from isolated radiation pattern.

After the above study was completed, 16 elevation power dividers were integrated with four radiating elements in each stack. Four SP4T switches were interconnected to input ports of 16 elevation power dividers by 16 phase-matched cables. The order of interconnection to each SP4T is clearly indicated in Fig. 2. Any deviation in interconnection can lead to nonexistence of the beam. The four outputs of 1:4 azimuth power

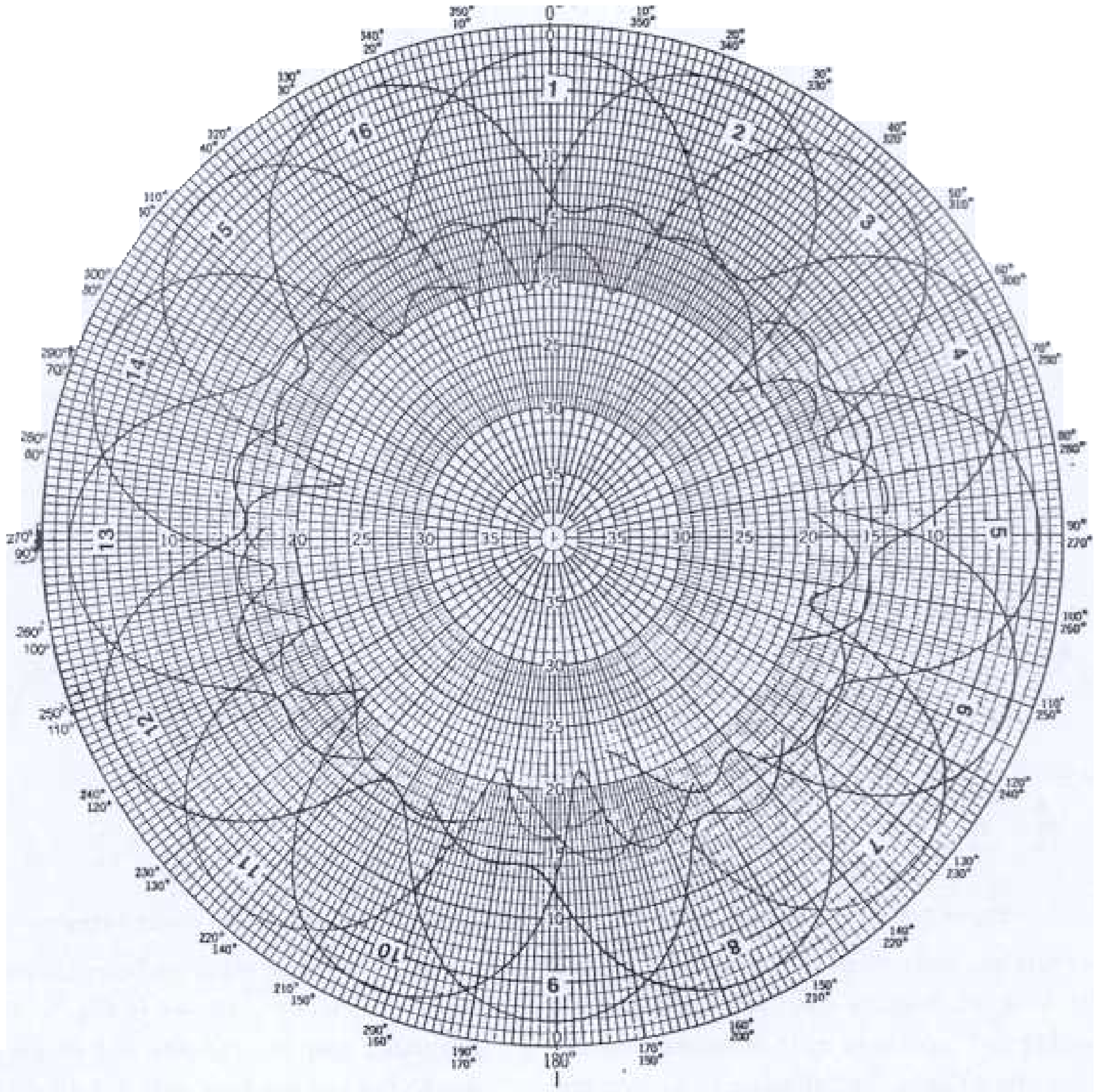


**Figure 4. Measured switched beams of cylindrical array at the centre frequency**

divider were connected to input ports of two DPDT switches through two sets of flexible cables which could meet the co-phasal condition for any four sets of successive elements of cylindrical array. The requirement for beam formation was to excite any successive four vertical stack of elements in-phase, and it was achieved by incorporating the phase-corrected transmission lines developed using Eqn (4). The four outputs of the two DPDT switches were in turn connected to the four inputs of the four SP4T switches through phase-matched cables. The SP4T and DPDT switches were integrated with BSU which sends the control data to switches for selection of any required beam.

## 6. EVALUATION & RESULTS

The Beam switching cylindrical array was enclosed in a radome and was evaluated for the following parameters:

- Return loss
- Radiation pattern
- Gain

By sending the control data through BSU for all the 16 beams one after the other, the return loss was measured by using HP 8722C network analyser. The return loss was about - 10 dB or less for all switched beams.

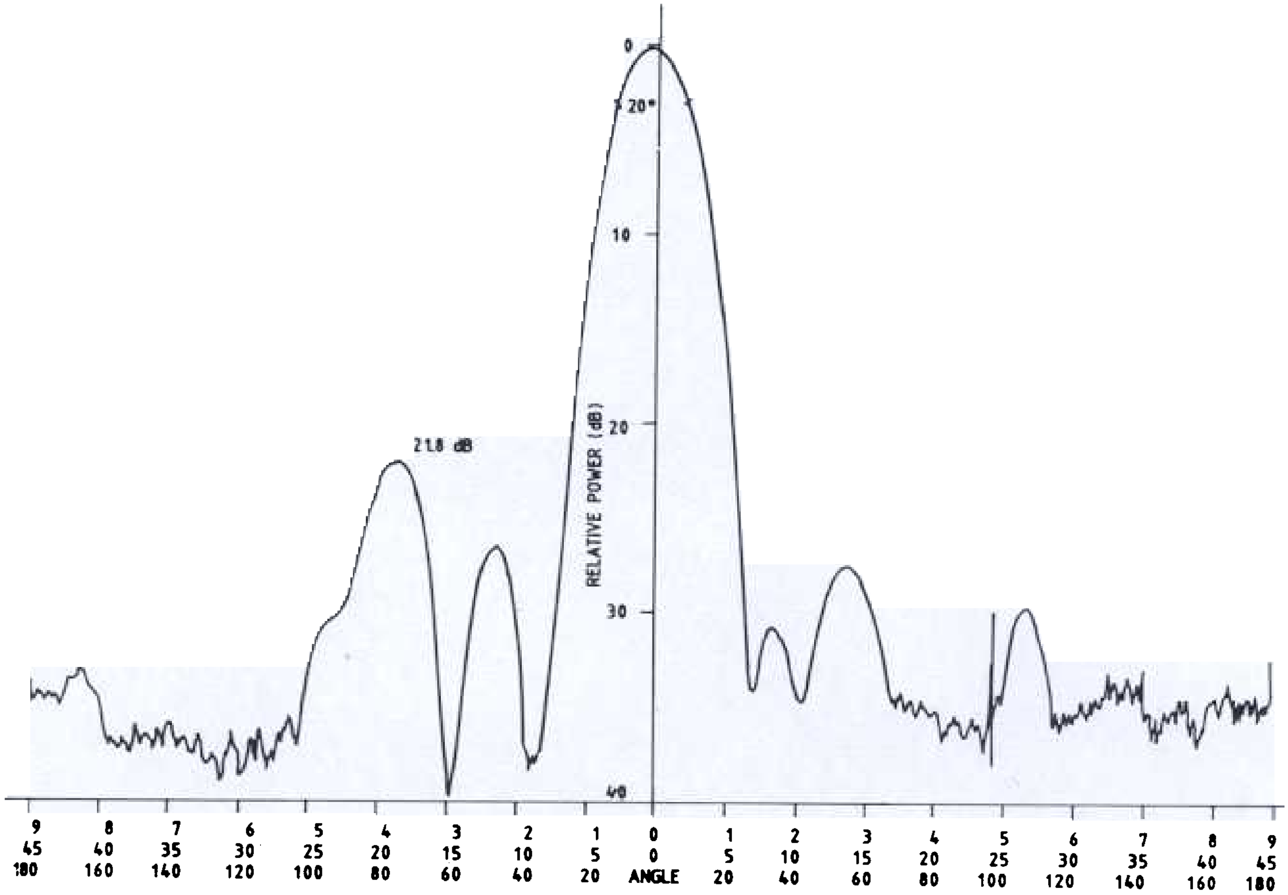


**Figure 5. Measured elevation pattern of beam switching cylindrical array at the centre frequency**

The radiation patterns of cylindrical array were measured in a rectangular anechoic chamber by using antenna measurement instrumentation from. Scientific Atlanta. Radiation patterns over the complete band with frequency interval 100 MHz were recorded for all 16 beam positions by sending the appropriate control data from the BSU. The typical measured radiation pattern at the centre frequency for all 16 beam positions is shown in Fig. 4. For the sake of clarity, all the beams were plotted only up to first side lobe levels on either side of the main beam. However, the far off side lobes are better than the first side lobe level. It was observed that the 3 dB beamwidth variation was $28^\circ \pm 2^\circ$ in azimuth plane and average side lobe level was < about - 9.0 dB. The elevation patterns were also measured and it was found that the beamwidth variation was $20^\circ \pm 2^\circ$ with side lobe < -15 dB. Typical measured elevation pattern at the centre frequency is shown in Fig. 5. The array was evaluated with the radome and found that the loss due to the radome was only 0.2 dB on bore sight.

The gain of the array for each beam position was measured in the anechoic chamber by using gain comparison method. It was observed that the gain of the array varied from 10 dB to 12 dB over the entire bandwidth. This includes the losses incurred due to various components used to configure the system. The gain variation for all the 16 switched beam positions was within ± 0.25 dB and it was due to phase errors resulting from various components in each transmission path.

## 7. CONCLUSION

The cylindrical array consisting of 64 elements covering 300 Mhz bandwidth has been designed and developed successfully for generating 16 switched beams to cover 360° with low side lobes in elevation plane. The achieved performance is in good agreement with theoretical computations. Similar approach can be adopted for any other frequency band without much experimentation. The fast switching of beams finds application in point-to-multipoint communication with the least interferences caused either by reflection or through external sources. The entire array system is lightweight and hence can be mounted at the highest point easily for increasing the communication range.

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