Design of a Low Cost $4 \times 4$ Butler Matrix Fed Antenna Array
Partially Loaded with Substrate Integrated Waveguide (SIW)

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Abstract- A low cost $4 \times 4$ butler matrix fed antenna array has been proposed for Ku band applications. At high frequencies, the ohmic and dielectric losses are high and also the undesired feed radiation is more in the case of microstrip line feed, therefore substrate integrated waveguide (SIW) has been used to feed the antenna elements. The implementation of SIW technology improved the radiation performance of the antenna array system. More directive beams have been achieved than the conventional design. The gain improvement of $1.63$ dB and $0.9$ dB have been achieved for $2L$ and $2R$ beams respectively and the first nulls of all the four major beams have improved considerably. The proposed design is not realized completely either by microstrip or by SIW technique but it combines both the techniques to minimize the design complexity of SIW technique and to improvement in the radiation performance which degrades at high frequency for microstrip feeding network. The design also leads to symmetricity in the maximum gain values of the radiated major beams. FR-4 epoxy has been used as dielectric to build up the whole antenna array system, which makes the system less costly. The single layer implementation also makes the fabrication process simple. The measured results are in good agreement with the simulation.

Index Terms- butler matrix network, microstrip antenna, antenna array, substrate integrated waveguide (SIW), SIW transitions.

I. INTRODUCTION

In the recent years, research has focused on improving the capacity of satellite communication. Frequency reuse is one of the techniques to increase the capacity. Multiple directive beams at a single frequency can be used to achieve the frequency reuse. Beam forming network (BFN) is one of the frequently used techniques to achieve multiple directive beams. Several beam formers are available in the literature such as Blass matrix, Nolen matrix, Rotman lens and Butler matrix [1-4]. Due to design simplicity, wider bandwidth and low cost the butler matrix network is often used as the beam former. The antenna array fed by butler matrix network will produce multiple beams in different directions. Mostly, the rectangular patch microstrip antennas are used as the radiating elements due to their compactness, low weight and low cost. The microstrip technique is preferable in most of the cases to design the butler matrix network due to simple implementation. But at high frequencies the microstrip feeding network suffers from high ohmic and dielectric losses. Besides these, the undesired feed radiation also degrades the performance of the antenna array system. A rectangular waveguide can be used to overcome the problems associated with the microstrip feeding network. Waveguide has the ability to transmit the electromagnetic wave with low loss up to a very high frequency and also reduces the undesired feed radiation. But due to its non planar structure it is very difficult to integrate a waveguide with the planar circuits. To overcome this difficulty, the substrate integrated waveguide (SIW) technology has been proposed. It can be easily integrated with the planar structures and it preserves all the

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advantages of rectangular waveguide as well as it is compact, light weight and less expensive.

Earlier some researchers have worked to reduce the losses and improve the overall performance of the butler matrix network using SIW technology. Single layer and two layer butler matrix network using SIW technology are designed for the Ku band applications [5-7]. But the design complexity increases by using SIW in place of microstrip components. A small fabrication error can degrade the system performance. The radiation performance of the antenna array system can also be improved by using SIW to microstrip power divider [8-9]. So to avoid the design complexity and to improve the performance a tradeoff between these two conditions is necessary to achieve.

In this paper, initially a simple $4 \times 4$ butler matrix fed antenna array has been designed for Ku band applications using the microstrip technique. The output ports of butler matrix network feed the antenna elements to generate multiple directive beams. At high frequency the microstrip structure encounters several losses and also the microstrip feeding network is responsible for spurious feed radiation as discussed previously degrading the radiation efficiency of antenna array system. To minimize the losses and to improve the radiation performance the whole system can be realized by the SIW technology as described in [5-7]. But the design complexity is very high when the whole system is realized by SIW technique. To improve the radiation performance of the conventional system (realized by microstrip technique) substrate integrated waveguide (SIW) has been used for feeding instead of directly connecting the antenna elements to the output ports of butler matrix network. Here, instead of using the SIW technique to build up the whole beam forming network a small portion of the network is constructed using SIW. Microstrip to SIW and SIW to microstrip transitions have been used for compatibility. Most of the researchers developed the whole antenna array system either by microstrip technique or by SIW technique. This paper describes a different approach where both the techniques are combined to minimize the design complexity and also to improve the performance of the system. In [5-7] the radiation performance of the system is developed analytically. The proposed structure is realized practically and the radiation performance of the system is authenticated by measurements. It would be shown in the section IV that the performance of modified antenna array system is better than the conventional system. All the simulated and measured results are in good agreement. The above discussions convey that the proposed design is light weight, less expensive and easy to realize. The radiation performance of the proposed modified design is better than some of the previously published work and it is discussed in the last section of this paper.

II. DESIGN CONCEPT OF 4×4 BUTLER MATRIX FED ANTENNA ARRAY

A 4×4 butler matrix network is a stepping stone to achieve bigger networks of the order of 32×32, 64×64, 128×128 elements or more which can be used practically for the various frequency band applications. A $N \times N$ butler matrix network ($N = 2^n$) requires $2^{n+1} \log_2 2^n$ number of 3dB branchline couplers and $2^{n} \left( \log_2 2^n - 1 \right)$ number of fixed phase shifters [10-12]. 0dB coupler or crossover is used in the path crossing of the two transmission lines for the single layer implementation of butler matrix array. The output ports of butler matrix network feed the radiating elements A1, A2, A3 and A4. A basic block diagram of 4×4 antenna array system is shown in Fig.1.

![Basic block diagram of 4×4 butler matrix network with antenna elements](image_url)
According to the directions of main beams the input ports of the antenna array system are named as 1R, 2L, 2R and 1L (R: Right, L: Left). If the power is fed to port 1R then the major beam direction of antenna array system should be within $0^\circ$ to $30^\circ$. Similarly, when power is fed to other ports namely 2L, 2R and 1L then the major beam directions of the antenna array system should be in the range of $-30^\circ$ to $-60^\circ$, $30^\circ$ to $60^\circ$ and $-30^\circ$ to $0^\circ$ respectively. The pointing directions of the antenna beam can be calculated as follows [13]:

$$\theta = \cos^{-1}\left[\frac{\pm (2n-1)\lambda_0}{8d}\right]$$

Where $n = 1, 2, \ldots$ etc, $\lambda_0$ is free space wavelength and $d$ is the spacing between the antenna elements (in this case $d = 0.45\lambda_0$).

III. SUBSTRATE INTEGRATED WAVEGUIDE (SIW)

The substrate integrated waveguide (SIW) technology makes it possible to fabricate the rectangular waveguides in a planar form. The classical rectangular waveguides can easily be integrated with the planar structures using this technology. The SIW structures preserve the advantages of rectangular waveguides such as high Q factor and high power handling capability. SIW technology reduces the losses associated with the microstrip lines. SIW structures can be fabricated in the planar form by using periodic metallic via holes, air holes or holes filled with a different dielectric. The SIW made with air holes or holes filled with a different dielectric produces more leakage in comparison to the SIW with metallic via holes. The metallic pins shield the electromagnetic waves and these pins also connect the surface currents in order to preserve the guided wave propagation. Fig.2 shows a simple SIW structure formed by arrays of metallic vias.

The width ($w$) of SIW can be calculated as follows [14-16]

$$w_{\text{eff}} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w}$$

Where $d$ is the diameter of metallic vias, $w_{\text{eff}}$ is the equivalent width of SIW and $s$ is the center to center distance between the vias. If the conditions like $s/d < 2$ and $d/w < 1/5$ are followed to build up the SIW structure the leakage loss will be very small. The proposed structure of SIW including microstrip to SIW and SIW to microstrip transition is shown in Fig.3.

Using Eq.2 and the conditions mentioned above an SIW is designed for a cutoff frequency of 11 GHz. The dimensions are varied slightly to obtain good results. In the proposed design, $w = 8\text{mm}$, $d = 1\text{mm}$ and $s = 1.3\text{ mm}$. These parameters satisfy the previously stated conditions. Fig.3 shows that the microstrip to SIW and SIW to microstrip transitions have been used to integrate
the SIW structure with the butler matrix network. The transition is implemented by connecting the ground of microstrip line to the waveguide at a distance of $\lambda/4$ from the rectangular waveguide by grounding vias so that maximum field can be transferred to the waveguide [16-17]. The S-parameter characteristics of the proposed SIW structure is shown in Fig.4.

![Fig.4. Simulated S-parameter characteristics of SIW](image)

It is observed that the structure preserves the characteristics of a rectangular waveguide. The cutoff is achieved at 11 GHz as visible from the graph. The waveguide operates with good S-parameter values at 14.5 GHz which is the operating frequency of the design.

IV. DESIGN OF 4×4 BUTLER MATRIX FED ANTENNA ARRAY USING SIW TECHNOLOGY

The conventional structure of 4×4 butler matrix fed antenna array has been designed for the Ku band with the centre frequency of 14.5 GHz is shown in Fig.5.

![Fig.5. (a) Layout of the structure; (b) Fabricated structure](image)

The structure is fabricated on a single layer of material (FR-4 epoxy) with the permittivity of $\varepsilon_r = 4.4$, loss tangent ($\tan \delta$) = 0.02 and the thickness, $h = 1.6mm$. At high frequencies (Ku band), attenuation in the FR-4 substrate is quite high, hence this material is not a very good choice for Ku band application. But it is easily available and less expensive. In the present endeavor, FR-4 substrate is used to reduce the cost of the system. In some previous researches, FR-4 has been used for antenna design in Ku band [18-19]. It is responsible for surface wave
excitation, which is a major limitation of the microstrip antennas [20]. It degrades the radiation performance of antenna array and also increases the mutual coupling between radiating elements. Although the substrate has several limitations but its low cost and ease of availability makes it very useful.

Earlier RT Duroid 5870 ($\varepsilon_r = 2.33$, $\tan \delta = 0.0012$ and $h = 0.787$ mm) and Rogers 6002 ($\varepsilon_r = 2.94$, $\tan \delta = 0.0017$ and $h = 0.508$ mm) have been used as dielectric and the SIW technology is used to design the beam forming network [5-7] to improve the performance of the system at high frequency (Ku band). The substrates used in the previous designs are very costly and the SIW technology makes the system complex. In the proposed structure FR-4 epoxy has been used as a dielectric to lower the cost. Also the SIW technology has been used to form a small portion of the beam forming network to minimize the design complexity than the previously published structures [5-7]. In the previous research works [5-7], the radiating elements were not connected to the butler matrix network. The radiation patterns shown were developed analytically. But in the proposed work the radiating elements are also connected to the butler matrix network and complete experimental analysis has been carried out.

The individual components of the conventional 4 $\times$ 4 beam forming network are implemented using the microstrip technique. At high frequencies, losses are high in the microstrip lines. The SIW’s are used at the output ports of the butler matrix network to feed the antenna elements to reduce the losses occurring due to microstrip lines and FR-4 substrate. The transitions (shown in Fig. 4) (microstrip to SIW and SIW to microstrip) are used to connect the SIW with butler matrix network and the antenna elements. This SIW technique reduces the undesired feed radiation and also minimizes the mutual coupling between the array elements due to surface wave excitation. The layout and fabricated structure of the proposed design are shown in Fig.6(a) and Fig.6(b) respectively.

A. Simulated and Measured Results
Fig. 7. Simulated and measured reflection loss of conventional beam forming network: (a) For 1st port excitations; (b) For 2nd, 3rd and 4th port excitations.

Fig. 8. Simulated and measured reflection loss of proposed beam forming network: (a) For 1st port excitations; (b) For 2nd, 3rd and 4th port excitations.

Fig. 9. Simulated and measured normalized E-plane patterns of the conventional beam forming network at 14.5 GHz for different port excitations: (a) For 1st (1R) port excitations; (b) For 2nd (2L) port excitations; (c) For 3rd (2R) port excitations; (d) For 4th (1L) port excitations.
Fig. 10. Simulated and measured normalized E-plane patterns of the proposed beam forming network at 14.5 GHz for different port excitations: (a) For 1st (1R) port excitations; (b) For 2nd (2L) port excitations; (c) For 3rd (2R) port excitations; (d) For 4th (1L) port excitations

B. Discussions

All the simulations are carried out using commercial HFSS software. The measurement of reflection losses carried out using Agilent N5230A PNA-L network analyzer. The radiation patterns and the gain of different beams are measured using signal generator (SMR20, 1 GHz – 20 GHz) and spectrum analyzer (FSP, 9 KHz – 30 GHz). Fig. 7(a) and Fig. 8(a) represent the simulated and measured reflection losses of the conventional and proposed 4 × 4 beam forming network respectively for the 1st (1R) port excitation. The amplitude of the reflection loss both in simulation and measurement is below -10 dB at 14.5 GHz. The simulated and measured reflection losses (S11) of the conventional antenna array system are -40.35 dB and -25.9 dB respectively at the operating frequency and in the case of proposed structure, reflection losses of -40.8 dB and -19.8 dB have been achieved respectively in simulation and measurement, hence a good matching has been achieved. The matching for different ports of the conventional and proposed beam forming network are also quite good both in simulation and measurement as observed in Fig. 7(b) and Fig. 8(b) respectively.

The normalized E-plane patterns of the conventional design for different port excitations (1R, 2L, 2R and 1L) at the operating frequency are shown in Fig. 9(a), 9(b), 9(c) and 9(d) respectively. Previously, it has been stated that for each port excitation the radiated major beam direction should be in the specified angular region. The direction of the major beam is achieved in the angular range specified in section II. The first nulls of the major beams (1R and 1L) are not clearly visible as shown Fig. 9(a) and 9(d). To improve the radiation performance of the antenna array system a new design has been proposed. The radiation performance of the proposed structure for different port excitations (1R, 2L,2R and 1L) at the operating frequency are shown in Fig. 10(a), 10(b), 10(c) and 10(d) respectively. More directive beams are achieved for the 2nd (2L) and 3rd (2R) port excitations.
The 1R and 1L beams are also clearly visible. First nulls of the 1R beam are at -4.27 dB and -3.62 dB (Fig.10a) below the maxima whereas in the conventional design these levels were -1.7 dB and -2.77 dB (Fig.9a) below maxima. Similarly the first nulls of 1L beam are at -3.85 dB and -4.66 dB (Fig.10d) below maxima. The major beams (1R and 1L) of the proposed design can be easily distinguished from the side lobes. The first null point of 2L and 2R beam of the proposed design are at -9.8 dB and -9.6 dB below the maxima respectively (Fig.10b and Fig.10c respectively). In the conventional design these null point levels of 2L and 2R beams were at -4.3 dB and -5.0 dB below maxima respectively (Fig.9b and Fig.9c respectively). More directive beams (2L and 2R) have been achieved with an improvement in isolation of the main beam with other beams. The measured normalized E-plane patterns for both the conventional and proposed design are in good agreement with the simulated results as shown in Fig.9 and Fig.10 respectively.

The beam directions are +16.1°, -56.4°, +56.4° and -16.1° for the beams 1R, 2L, 2R and 1L respectively as calculated from Eq.1. The measured beam directions of the conventional design are listed in Table 1 and it is observed that they show some variation in comparison to calculated values, which may be attributed to practical testing errors.

### Table 1: Comparative analysis of measured beam directions of the conventional and proposed design for different port excitations

<table>
<thead>
<tr>
<th>Input ports</th>
<th>Conventional Design</th>
<th>Proposed Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured beam</td>
<td>Measured beam</td>
</tr>
<tr>
<td></td>
<td>directions in degree</td>
<td>directions in degree</td>
</tr>
<tr>
<td>1R</td>
<td>+22°</td>
<td>+18°</td>
</tr>
<tr>
<td>2L</td>
<td>-50°</td>
<td>-52°</td>
</tr>
<tr>
<td>2R</td>
<td>+58°</td>
<td>+54°</td>
</tr>
<tr>
<td>1L</td>
<td>-18°</td>
<td>-20°</td>
</tr>
</tbody>
</table>

The measured beam directions of the conventional and proposed beam forming network are similar to each other and also lie in the specified range.

A comparative analysis of gain for different beams (1R, 2L, 2R and 1L) of the conventional and proposed structure are given in Table 2. The gain of 2L and 2R beams of the conventional design is quite low as compared to the other two beams. The gain improvement of 2.16 dB and 1.07 dB in simulation and 1.63 dB and 0.9 dB in measurement has been achieved for 2L and 2R beams respectively by the modified antenna array system. An asymmetry is observed in gain of different beams of the conventional design. After implementing the SIW technology the asymmetry has been removed which is clearly visible from the data given in Table 2. The measured gains of the different beams for both the structures are in good agreement with the simulated values.

In comparison with [9] it is observed that more directive beams are achieved for 2L and 2R port excitation by the proposed structure (Fig. 10b and Fig. 10c). Also in [9] the 1R beam is widely spread between 0° to 30°, but comparatively narrower beam (1R) is achieved with the proposed antenna array system as shown in Fig. 10a. To reduce the mutual coupling and enhance the gain spiral EBG structures are introduced between the antenna elements of the beam forming network [21]. But a small gain enhancement of 0.25 dB has been achieved. In comparison with [21] a good gain enhancement has been achieved for 2L and 2R beams by the
proposed antenna array system as discussed earlier. At high frequency to improve the performance the whole butler matrix array is realized by the SIW technique [7]. The radiation performance of the system realized analytically, and it is observed that a very wide spread beam (2L) is achieved. The structure is more complex to fabricate. In comparison with [7] a simple structure is proposed in this paper to improve the radiation performance and it is also easy to fabricate. A good directive beam (2L) (Fig. 10b) is achieved compared to the beam (2L) shown in [7] by the proposed structure and also the radiation performance of the proposed design is verified by measurement. This directive beam will help to minimize the interference and also to make the frequency reuse technique to work properly.

V. CONCLUSION

The conventional 4 × 4 beam forming network suffers from undesired feed radiation, high ohmic and dielectric losses and these affect the radiation performance of the system. To reduce these losses and improve the radiation performance, substrate integrated waveguide has been introduced partially. A good and symmetric radiation performance has been achieved by a simple modified structure of beam forming network. The system is less expensive and easy to fabricate. The design can be extended to more number of radiating elements for practical applications.

REFERENCES

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