# Design of Compact 4X4 X-band Butler with Lump Element Based on IPD Technology

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**Abstract—A X-band 4×4 Butler Matrix in IPD (Integrated Passive Device) technology is presented. Coupler and the phase shifter constituted by lumped circuits are utilized for Butler miniaturization. The compact chip area of implemented IPD Butler only occupies 2.12×2.07 mm$^2$ including all test pads. The result show the isolation of >12dB, the average loss of 3dB and the phase errors are within 5$^o$ at 9.5-10.5GHz.**

***Index Terms*—Lumped parameter, Butler matrix, IPD technology, X band**

## I. INTRODUCTION

In modern communication systems, multi-beam and beam-scanning antennas are crucial. Butler matrices are important components in beam-forming antenna systems. A lot of ways has been proposed to build up butler matrix. Micro-strip line and suspended strip-line were used to get butler respectively in[1]-[3]. SIW (substrate integrated waveguide) also has been used in the implementation of the butler[4]. In the above traditional methods, good performance but large chip area appeared.

Miniaturization methods also have been reported. Butler are realized by the distribution parameter in 0.18um CMOS and IPD respectively[5][6]. Sizes of them are in millimeter, while traditional one is in decimeter. The size reduced greatly. However, the distribution parameter circuit has advantage in high frequency but not in low frequency because of the size. The lump parameter circuit is used in low frequency instead of the distribution parameter circuit. In this paper it is put forward that the lumped parameter circuit in IPD technology is used to achieve miniaturization of the butler under circumstances of relatively low frequency.

In the paper, a X-band 4-ways Butler Matrix composed by the lumped parameter in IPD technology is demonstrated. As far as we know, this is the first demonstration of using lumped parameter in IPD for butler.

## II. DESIGN OF X BAND BULTER MATRIX

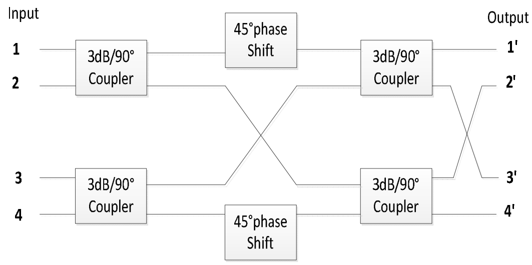


Figure1. The structure of 4×4 Butler

The general structure of 4×4 Butler is shown in Figure1. It consists of 3dB quadrature coupler and 45$^o$ phase shift. 4×4 Butler matrix is a circuit in which the input signal is equally divided among output ports, the adjacent phase shift between the output ports is equal and the value of the phase shift depends on the selected input port[1]. Table I presents retardation of each adjacent output signal when the signal from the four inputs, respectively.

TABLE I

OUTPUT PHASE DIFFERENCE

| Input port | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Retardation of adjacent output | -45° | 135° | -135° | 45° |

### *A. Miniaturized Coupler by Lumped Parameter*

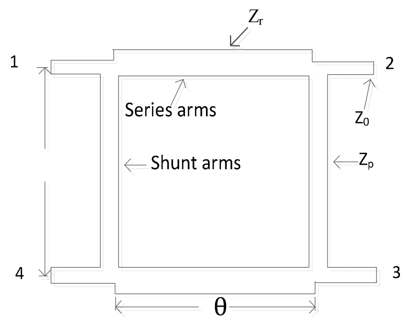


Figure 2(a). Branch line coupler

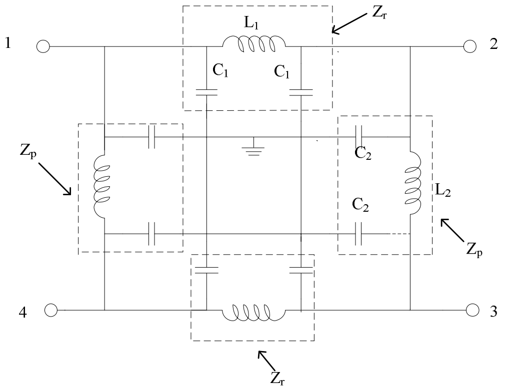


Figure 2(b). Coupler constituted of lumped parameter

Figure.2 (a) is the structure of branch line coupler and figure.2 (b) is the structure of lumped parameter coupler which is transformed by branch line coupler. Each transmission line can be equivalent to a π network. The conversion process is shown in following formula.

ABCD matrix of the transmission line[7],

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{bmatrix} \cos\theta & jZ_r \sin\theta \\ j\dfrac{1}{Z_r}\sin\theta & \cos\theta \end{bmatrix} \tag{1}$$

ABCD matrix of the π network can be obtained by the matrix multiplying of three lumped elements.

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{bmatrix} 1-\omega^2 L_1 C_1 & j\omega L_1 \\ j\omega C_1\left(2-\omega^2 L_1 C_1\right) & 1-\omega^2 L_1 C_1 \end{bmatrix} \tag{2}$$

By combining (1) and (2), (3) can be obtained

$$L_1 = \frac{Z_r \sin\theta}{\omega} \tag{3a}$$

$$C_1 = \frac{1}{\omega Z_r}\sqrt{\frac{1-\cos\theta}{1+\cos\theta}} \tag{3b}$$

$$L_2 = \frac{Z_p \sin\theta}{\omega} \tag{3c}$$

$$C_2 = \frac{1}{\omega Z_p}\sqrt{\frac{1-\cos\theta}{1+\cos\theta}} \tag{3d}$$

For traditional quadrature branch line coupler, $\theta$=90°, $Z_r = \frac{Z_o}{\sqrt{2}}, Z_p = \sqrt{2}Z_r$ and $Z_0$=50Ω. The initial value is easy to calculate with above formula.

*B. Phase Shift by Lumped Parameter*

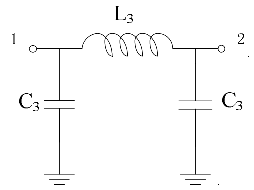


Figure3. The structure of 45°phase shift

Figure3 shows the 45° phase shift constituted of inductance and capacitance.

Due to the simple structure, circuits can be optimized by ADS software to get desired results.

TABLE II

THE ORIGINAL VALUE OF EACH PART COMPONENT

| $L_1$ | $C_1$ | $L_2$ | $C_2$ | $L_3$ | $C_3$ |
|---|---|---|---|---|---|
| 0.5627nH | 0.4502pF | 0.7985nH | 0.3183pF | 0.4204nH | 0.1685pF |

The original value of coupler and phase shift can be seen in Table II which comes from a series of calculation. The circuit simulation shows good performance with these original values. In the EM simulation component value will be further changed and optimized due to parasitic effects in the layout.

## III. IPD Technology Description and Application

*A. Description of IPD*

The IPD mentioned in this article is copper process based on high-resistivity silicon with $\varepsilon_r$=9.6. The structure of IPD is shown in Figure4. There are three metal layers (MCAP, M1 and M2) and two dielectric layers (PI-1and PI-2). M1 and MCAP are aluminum, M2 is copper and inductor is mainly produced in M2. The bottom and top plate of capacitors are respectively MACP and M1[8]. In order to reduce the area of inductors, M1 and M2 are combined to make it. M1 is right below M2.

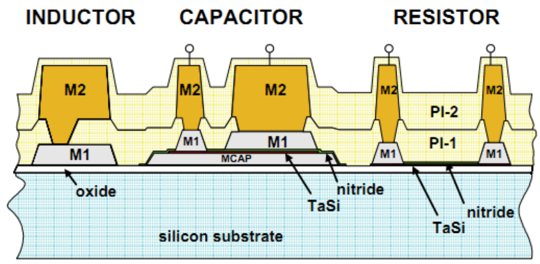


Figure4. Thin film Integrated Passive Device (IPD) structure [8]

*B. Butler in IPD*

After optimizing the circuit by ADS software, the layout of coupler can be seen in figure5 and the EM simulation result is in figure6. About 0.7dB insertion loss is produced because of dielectric loss and conductor loss. The phase difference between the port2 and port3 is 90° .

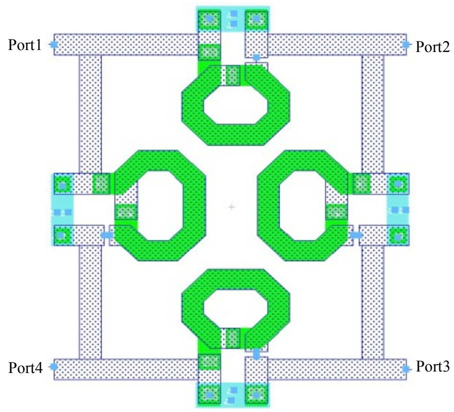


Figure5. The layout of coupler in IPD

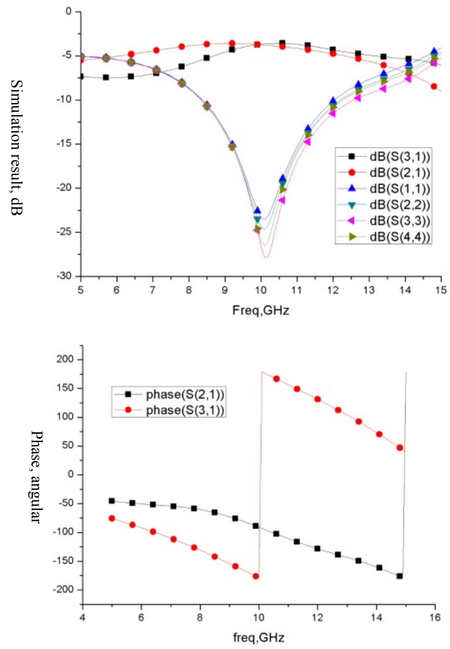


Figure6. The simulation results of coupler in IPD

Through tuning the layout of X-band butler matrix is obtained in Figure7. The area is 2.12mm×2.07mm. It contains four couplers and two phase-shifts. Multilayer structure achieves crossover simply and make the butler more compact. There are fourteen bumps in the IPD layout. The eight bumps on both sides are for input and output, the rest of six bumps are for electrical ground.

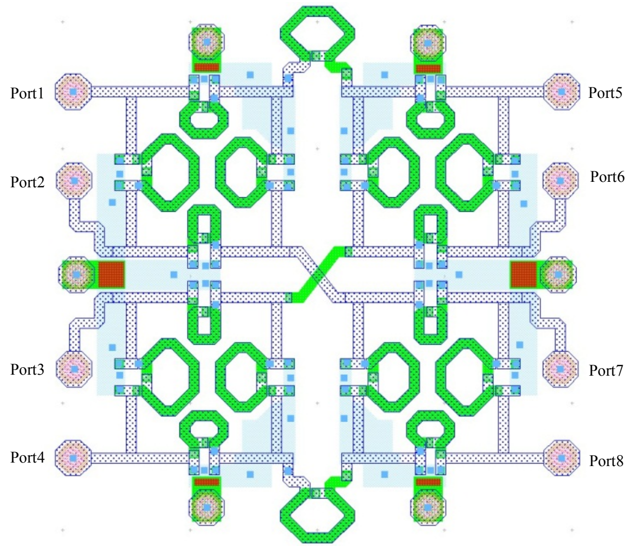


Figure7. The layout of desired Butler Matrix in IPD

EM simulation results for the layout is shown in Figure 8, in which, as an example, the port 1 is excited along with $45^o$ phase shift between adjacent output ports. The overall phase error is less than $5^o$ and the insertion loss is about 3dB within 9.5-10.5GHz.

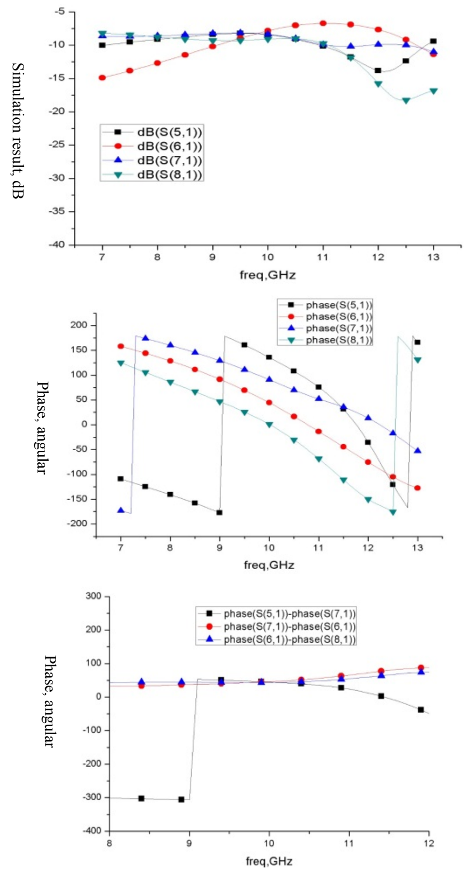


Figure8. Simulation results of desired Butler

## IV. Validation of Results by IPD filter

In order to verify the accuracy of the ADS simulation results in butler design, an IPD filter with the center frequency of 2.45GHz is presented in figure9. The filter was fabricated and measured. The photograph of filter is presented in figure10. The good agreement between ADS EM simulation and measurement results for the filter is shown in Figure11. Because the simulation setup in the filter design is same as that in our current butler design it indirectly verify the EM simulation of butler design in the paper.

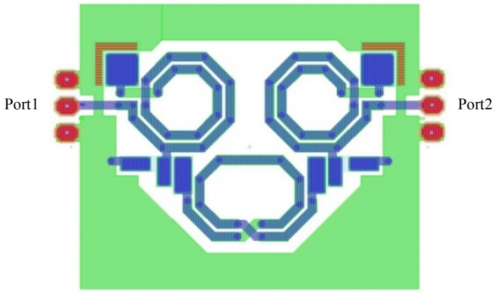


Figure9. The layout of filter in IPD

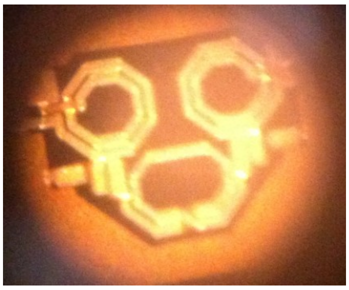

Figure10.Photograph of the IPD filter

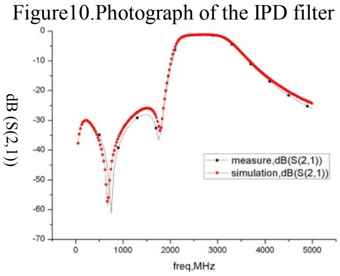


Figure11. Simulation result compared with measured result

## V. CONCLUSION

A lumped butler matrix is presented in the paper. The butler is achieved with passive lumped elements in IPD technology. The proposed butler matrix is much smaller than a classic design based on transmission lines so that big size reduction has been achieved. The insertion loss is not as good as distributed one and therefore further study should be carried out.

## ACKNOWLEDGMENT

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