Department of Electronic Engineering

FINAL YEAR PROJECT REPORT

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<Multiband Hybrid for WiFi>

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Bachelor of Engineering (Honours) in Electronic and Communication Engineering (Full-time)
Student Final Year Project Declaration

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Project Title: Multiband Hybrid

For WiFi

Student Name: CHEUNG KING YIN

Signature

Student ID:

Date:
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Abstract

Nowadays, there are many wireless communications systems with multiple standards. One of the example is the WiFi systems with IEEE802.11b/g for 2.4 GHz and IEEE802.11a for 5 GHz. For the integration of the circuitry in these systems, it is great interested to develop multiband microwave circuits that can operate at two or more arbitrary frequency bands. This report is targeted on the hybrid coupler which is with a wide range of application in RF and Microwave circle.

Two multiband hybrid couplers were simulated and fabricated for detail analysis. First, a branch line multiband coupler with open circuit stub covering frequency 2.45 GHz and 5.25 GHz was investigated. Second, a multiband hybrid coupler covering frequency 2.45 GHz, 5.25 GHz and 5.8 GHz was investigated. The multiband hybrid coupler employs rectangular disk hybrid coupler and open circuit stubs. In order to demonstrate the application of the hybrid coupler, a multiband butler matrix based on the rectangular disk hybrid coupler and Schiffman Phase Shifters are also fabricated for detail analysis. The butler matrix is a kind of beamforming network that can be used to feed the antenna array and build the multiport amplifier.
Chapter 1: Introduction

Objective of this project:

1. Design a multiband Hybrid coupler covering 3 frequency band of Multiband (2.4-2.485 GHz, 5.15-5.35 GHz and 5.725-5.85 GHz)

2. Design a Butler Matrix aimed to be used in the antenna system of the Multiband Access Points

Methodology

A set of procedures are designed to meet the objectives of this project. They are listed as shown:

Step1. Review the pass studies from the Literature

Step3. The structure are guessed base on the knowledge or similar structure from the literature.

Step2. The purposed structure is simulated by using CAD software. The dimensions are optimized by using the results from the simulation.

Step3. The optimized structures are fabricated. The S-parameter of the fabricated circuits is measured by Network Analyzer. After the measurement, the measurement results are compared with the simulation result. We adjust the situation method by the comparison to make the simulation result more accurate.
**The tools used in this project**

**CAD Software**

Several CAD Softwares are used in this project. Zeland IE3D was used to perform full full-wave EM simulation. The layouts of the circuits are drawn by AutoCAD. Txline is used to calculate the dimension of the microstrip line according to the Impedance and Electrical Length.

**Vector Network Analyzer**

Aligent 8753ES S-parameter Network Analyzer is used to measure the S-parameter of the circuits.

![Figure 1 Aligent 8753ES S-parameter Network Analyzer](image)

**Material used in this project**

The Dual band branch line coupler are fabricated on a substrate with permittivity of 2.65 and height of 0.5 mm. The multiband Rectangular disc hybrid, the phase shifter, Butler Matrix and other coupler are fabricated on a substrate with permittivity of 2.33 and height of 1.57 mm.
Chapter 2: Background

WiFi

WiFi is a set of standards for wireless local area network which are defined by WiFi alliance. The standards of Multiband are overlapped with 802.11 defined by Institute of Electrical and Electronics Engineers (IEEE). Computer, mobile phone and other portable electronic device can be connected to the internet in a wireless way with the area covered by a WiFi access point.

Advantage of WiFi

The Local Area Network can be deployed without connecting the client devices using WiFi instead of using cable. This will reduce the cost of deployment of the network. A LAN can be hosted in a wireless way by using WiFi in some area which is not possible to install cables. WiFi is a global set of standard. A device satisfied with WiFi standards can be operated anywhere around the world. [1]

Frequency Range of Multiband

The most common standards of Multiband are 802.11a , 802.11b , 802.11 and 802.11g.

Their corresponding frequency range is listed below:

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency range</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11</td>
<td>2.400 - 2.4835 GHz</td>
<td>LAN</td>
</tr>
<tr>
<td>IEEE 802.11b</td>
<td>2.400 - 2.4835 GHz</td>
<td>LAN</td>
</tr>
<tr>
<td>IEEE 802.11g</td>
<td>2.400 - 2.4835 GHz</td>
<td>LAN</td>
</tr>
<tr>
<td>IEEE 802.11a</td>
<td>5.150 – 5.350 GHz, 5.725 – 5.825 GHz</td>
<td>LAN/WAN</td>
</tr>
</tbody>
</table>
S-parameter (Scattering Matrix)

\[
\begin{pmatrix}
V_1^+
\end{pmatrix}
\begin{pmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{pmatrix}
\begin{pmatrix}
V_2^-
\end{pmatrix}
\]

\[
\begin{pmatrix}
V_2^-
\end{pmatrix}
\begin{pmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{pmatrix}
\begin{pmatrix}
V_1^+
\end{pmatrix}
\]

Figure 2 The power wave incident and reflect from a 2 port network

The characteristic of a N-port Microwave circuit is usually described by S-parameter. The S-parameter relates the voltage waves incident on the ports to those reflected from the ports.

\[
\begin{pmatrix}
V_1^- \\
\vdots \\
V_N^-
\end{pmatrix} = 
\begin{pmatrix}
S_{11} & \cdots & S_{1n} \\
\vdots & \ddots & \vdots \\
S_{m1} & \cdots & S_{mn}
\end{pmatrix}
\begin{pmatrix}
V_1^+ \\
\vdots \\
V_N^+
\end{pmatrix}
\]

The effect of the matrix, \( S_{ij} \) is measure by following procedures. All the ports in the network except port \( j \) and port \( i \) is terminated to a matched load. An incident wave of amplitude \( V_j^+ \) is inputted to port \( j \) and the amplitude of reflected wave \( V_i^- \) reflecting from port \( i \). The relationship is described by the below equation:

\[
S_{ij} = \frac{V_i^-}{V_j^+} \quad \text{for} \quad k \neq j
\]

Power dividers and directional couplers

Power dividers and directional couplers are passive circuit used for RF and Microwave application. They are used for dividing or combining 2 (or more) signals.

Figure 4 Power divider

Figure 3 Power coupler
Hybrid coupler

Hybrid coupler is a kind of power divider circuit in which the amplitudes of the 2 outputs are equal. There are many forms of hybrids. The quadrature 3 dB couplers are one of the popular forms of hybrid coupler. The amplitude of the 2 outputs of quadrature 3 dB coupler are equal and the phase difference between them are 90 degree.

![Figure 5 Hybrid coupler](image)

There are some terms to describe the property of the Hybrid coupler.

**Insertion Loss**

Insertion Loss\(=(1-\alpha)=10\log(P_1/P_2)=-20\log(S_{21})\)

P1 is defined as the power inputted at port 1 and P2 is the output power from the through port (port 3). It is related to S21 in dB. The requirement for insertion loss in Hybrid coupler is between 3 dB to 4dB.
**Coupling factor**

Coupling factor: \( \alpha = 10 \log \left( \frac{P1}{P3} \right) = -20 \log(S31) \) (0.1)

\( P1 \) is defined as the power inputted at port 1 and \( P3 \) is the output power from the coupled port (port 3). It is related to \( S31 \) in dB. The requirement for insertion loss in Hybrid coupler is between 3 dB to 4 dB.

**Isolation**

Isolation (dB)\( = 10 \log \left( \frac{P1}{P4} \right) = -20 \log(S31) \) (0.2)

In a hybrid coupler, the isolation is defined as the difference between the signal levels between the isolated port and the input port. It is related to \( S41 \) in the S parameter of the hybrid coupler. The requirement for isolation in Hybrid coupler is greater than 10dB.

**Return Loss**

Return Loss (dB)\( = -20 \log(S11) \)

The Return loss is describing the portion of power that is reflected from the input.

The Return loss is related to \( S11 \). For a hybrid coupler, the return should be less than -10dB.

**Directivity**

Directivity (dB) \( = 10 \log\left( \frac{P4}{P3} \right) = 10 \log(P4/P1)+10 \log(P3/P1) = -20 \log(S31/S41) \)

Directivity cannot be measured directly. Therefore, it is calculated from the measurement of isolation and coupling. It can be calculated as below:

Directivity (dB) \( = \) Isolation (dB) - Coupling (dB)  [2]
A single band branch line hybrid coupler

![Diagram of a single band branch line hybrid coupler](image)

Figure 6 single band branch line coupler

Fig2.1 A schematic of a single band hybrid coupler

At the frequency \( f_0 \), all the 4 branches are equal to 90 degree.

The single band branch line coupler will have the property shown below:

The S-parameter of a single band branch line hybrid coupler:

\[
S_{11} = 0
\]

\[
S_{41} = 0
\]

\[
S_{21} = -\frac{j}{\sqrt{2}}
\]

\[
S_{31} = -\frac{1}{\sqrt{2}}
\]

\[
S_{22} = S_{44} = S_{33} = S_{11} = 0, \quad S_{21} = S_{12}, \quad S_{31} = S_{13}, \quad S_{41} = S_{14}
\]
The S-parameter of the hybrid coupler can be proven using Even-odd Mode Analysis.

First, the circuit shown in figure 6 is normalized by $Z_0$. The normalized circuit is shown in Fig7.

By using odd or even excitation, the above circuit can be decomposed to a set of 2 decoupled 2 port network.

Even mode

Fig 2.3 show the circuit excited in even mode. 2 incident wave of amplitude equal to $1/2$ exciting port 1 and port 4 in even mode. Because of the symmetry of even excitation, the circuit is decomposed as shown in Fig8.

Figure 7 a hybrid coupler normalized with $z_0$

Figure 8 Hybrid coupler excited in even mode
Figure 9 decomposition of coupler in even mode
The admittance of the shunt open-circuited $\lambda/8$ stub, $Y = j \tan \beta l = j$

Therefore, the transmission matrix of the shunt open circuit stub is shown:

$$
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} =
\begin{pmatrix}
1 & 0 \\
0 & j
\end{pmatrix}
$$

The transmission matrix of the transmission line:

$$
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} =
\begin{pmatrix}
cos Bl & j \sin Bl / \sqrt{2} \\
j \sqrt{2} \sin Bl & \cos Bl
\end{pmatrix} =
\begin{pmatrix}
0 & j / \sqrt{2} \\
j / \sqrt{2} & 0
\end{pmatrix}
$$

The transmission matrix of the upper part of the circuit can be obtained by multiplying the above transmission matrices:

$$
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_e =
\begin{pmatrix}
1 & 0 \\
j & 1
\end{pmatrix}
\begin{pmatrix}
0 & j / \sqrt{2} \\
j / \sqrt{2} & 0
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
j & 1
\end{pmatrix} = 1 / \sqrt{2} \begin{pmatrix}
-1 & 0 \\
j & -1
\end{pmatrix}
$$

The transmission and reflection coefficient is then found:

$$
\Gamma_e = \frac{A + B - C - D}{A + B + C + D} = \frac{(-1 + j - J + 1) / \sqrt{2}}{(-1 + j + J + 1) / \sqrt{2}} = 0
$$

$$
T_e = \frac{2}{A + B + C + D} = \frac{2}{(-1 + j + j - 1) / \sqrt{2}} = -\frac{1}{\sqrt{2}} (1 + j)
$$

Odd mode:

Fig 2.5 shown, the circuit is excited in odd mode with 2 incident wave of amplitude equal to $1/\sqrt{2}$ and $-1/\sqrt{2}$. In Fig 2.6, the circuit is decomposed to 2 decoupled parts:
As the admittance of the shunt stub is shorted to ground. It's admittance $= \frac{1}{\tan \beta l} = -j$.

Therefore, the transmission matrix of the upper part of the circuit in odd mode:

$$
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_o = \begin{pmatrix} 1 & 0 \\ -j & 1 \end{pmatrix} \begin{pmatrix} 0 & j / \sqrt{2} \\ j / \sqrt{2} & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -j & 1 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}
$$

The transmission and reflection coefficient is calculated in a similar way to that in odd mode:

$$
\Gamma_e = \frac{A + B - C - D}{A + B + C + D} = \frac{(-1 + j - j + 1) / \sqrt{2}}{(-1 + j + j + 1) / \sqrt{2}} = 0
$$

$$
T_e = \frac{2}{A + B + C + D} = \frac{2}{(-1 + j + j - 1) / \sqrt{2}} = \frac{1}{\sqrt{2}} (1 - j)
$$

Superposition:
The above prove are reference to prove of Hybrid coupler in EE5601 notes. [3]

Butler Matrix

Butler Matrix is a kind of beamforming network for switch beam system. There are $2^n$ input port and $2^n$ output port in a $2^n \times 2^n$ Butler Matrix network. This network can be consist of $2^n \log_2(2^n)$ hybrid coupler and some phase shifter.

The input signal enter a NXN Butler Matrix will have N output. In the ideal case, the N output will have equal amplitude and a phase difference

$$\theta_k = \pm (2m-1)\pi / N, \text{ where } k = 1, 2, 3, \ldots, N / 2$$

Besides its use in antenna system, Butler can also be used to make the multiport amplifier.[4]
Chapter 3: Dual band branch line Hybrid couplers:

Design Methodology

A journal suggests that a single band branch line hybrid coupler can be made to become multiband by additional 4 open circuit stub.

The main ideal of the dual band branch line coupler is that the structure of figure 12 can be equivalent to structure in figure 13 at the 2 frequency by setting property value of $Z_A$ and $Y$.

A dual band hybrid coupler can be obtained by replacing the each branch of the single band hybrid by structure b as shown in Figure 14.
Figure 14

Z2, Z3 and Z1 in figure 14 can be obtained by using the below Formula:

\[
\Delta = \frac{f_2 - f_1}{f_2 + f_1}
\]

\[
Z_i = \frac{Z_0}{\sqrt{2}} \cos\left(\frac{\Delta \pi}{2}\right)
\]

\[
Z_2 = Z_0 \frac{1}{\cos\left(\frac{\Delta \pi}{2}\right)}
\]

\[
Z_3 = \frac{Z_0}{1 + \sqrt{2}} \frac{1}{\sin\left(\frac{\Delta \pi}{2}\right) \tan\left(\frac{\Delta \pi}{2}\right)}
\]

The above 3 equation can be proved by evaluating the transmission Matrix of the structure shown in figure 12 and figure 13
The detail proves can be found in the journal [5]

For $f_c=(5.25+2.45)/2 \, \text{GHz}=3.85 \, \text{GHz}$ and $Z_0=50 \, \text{ohm}$,

$$\Delta = \frac{5.25 - 2.45}{5.25 + 2.45} = 0.3636$$

$Z_1=42.0267 \, \text{ohm}$

$Z_2=59.43421 \, \text{ohm}$

$Z_3=70.0468 \, \text{ohm}$

All the length of the branch is equal to $\lambda/4$ at $f_c$.

The dimension of each branch line is found by using TX Line:

<table>
<thead>
<tr>
<th>Table 2 The impedance and dimension of the Dual band coupler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>$Z_1$</td>
</tr>
<tr>
<td>$Z_2$</td>
</tr>
<tr>
<td>$Z_3$</td>
</tr>
</tbody>
</table>

All the branch lines are connected according to the Figure a and The layout of the multiband hybrid coupler is obtained:
Figure 15 layout of multiband branch line hybrid coupler
Result and Analysis

Measurement Result of the multiband Hybrid coupler

![Graph showing S-parameter (dB) for 2.45 GHz and 5.25 GHz frequencies]

Figure 16 S-parameter (dB) of the branch line hybrid coupler

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>S11</th>
<th>S21</th>
<th>S31</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>-26.099</td>
<td>-3.1325</td>
<td>-3.3333</td>
</tr>
<tr>
<td>5.25</td>
<td>-22.506</td>
<td>-3.7083</td>
<td>-3.8583</td>
</tr>
</tbody>
</table>

Table 3 The S-parameter of the Hybrid coupler
Figure 17 the phase difference between port 2 and port 3 of the branch line hybrid coupler

Table 4 The phase difference of the hybrid coupler

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Phase (S2,1) (degree)</th>
<th>Phase (S3,1) (degree)</th>
<th>Phase difference (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>-162.95</td>
<td>106.26</td>
<td>90.79</td>
</tr>
<tr>
<td>5.25</td>
<td>85.913</td>
<td>-3.3714</td>
<td>89.2844</td>
</tr>
</tbody>
</table>

For frequency ranges from 2.3 GHz to 2.6 GHz and the 5.1 GHz to 5.4 GHz, S21 and S31 of the hybrid coupler are between -3 dB to -4 dB. The isolation and return loss are better than 10 dB in this frequency range. Also, the phase difference between the 2 output port are around 90 degree in the 2 frequency bands. Therefore, this coupler can cover 2 frequency band of WiFi. However, the upper bandwidth of the coupler is insufficient to cover the third frequency band of Wi-Fi. Therefore, a new design of multiband Hybrid coupler is needed.
Chapter 4: Multiband Rectangular Disc Hybrid coupler

Design Methodology

In 1994, Tadashi Kawai and Isao Ohta propose that by optimizing the parameters of a rectangular disc, a hybrid coupler can be obtained.[6]

The below figure show a single band rectangular disc hybrid proposed by them:

Figure 18 structure of rectangular disc hybrid coupler

By optimizing the value of S1, Sw, T, b, a in the above figure, a broadband patch hybrid coupler can be obtained in a desired frequency band.

There are 2 methods to optimize the circuit parameters.
First, it can be done by using segment method. The coupler is divided into 4 segments by line AA’ and BB’. The Z-parameter of each segment can be obtained by using Green function. However, this method will require a lot of complex calculation.

Another method is to optimize the parameter by using an evolutionary algorithm. The values of the S1, Sw, T, b for a wide band rectangular disc hybrid are obtained from the evolutionary algorithm. However, there should be some modification done on the values of the circuit make the patch hybrid suitable for dual band application.

<table>
<thead>
<tr>
<th>Table 5 The parameter of the hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
</tr>
<tr>
<td>SW</td>
</tr>
<tr>
<td>T</td>
</tr>
<tr>
<td>b</td>
</tr>
</tbody>
</table>

By adding 4 open circuits stub to the above circuit can making the patch hybrid become dual band.

The dimension and the position of the open circuit stubs on the hybrid are also obtained by optimization.

The position of the open circuit stub in the hybrid is represented by x in the below graph:
The local minimum point of $S_{11}$ of the hybrid indicates the centre frequency of operating frequency band. It is found that both local minimum point of lower and upper frequency band will shift to high frequency when the value of $X$ increases. That is, both upper and lower
frequency band will shift to the high frequency when the open circuit stub is move closer together. The optimizated value of the open circuit stub is x=10.6 mm. When the stub is at this location, local minimum point for lower frequency band and the upper frequency band is located at 2.45 GHz and 5.6 GHz.

The effect of the impedance of the open circuit stub:

Figure 21
Figure 22 The effect of the impedance of the open circuit stub

From the above graph, it seems that the impedance of the open circuit stub will affect the amplitude imbalance in the upper frequency band of the hybrid coupler.

However, it seems that the bandwidth of the upper frequency will decrease as the amplitude imbalance decreases. Therefore, we need to balance the amplitude imbalance and the bandwidth of the upper frequency band.

The impedance of the open circuit is chosen for the smallest amplitude imbalance in the upper frequency band with enough bandwidth to cover the frequency range of the IEEE 802.11a. The impedance of open circuit is chosen to be 98.0162 ohms and the corresponding width of the open circuit is 1.4mm.

The length of the open circuit stub
From the design ideal of dual band hybrid coupler, it is known that the Open circuit stub should be equal to \( \frac{\lambda}{4} \) at the middle frequency of the upper frequency and lower frequency. In our case,

\[
\frac{f_{\text{middle}}}{2} = \frac{f_{\text{lower}} + f_{\text{upper}}}{2} = \frac{2.45\,\text{GHz} + 5.8\,\text{GHz}}{2} = 4.125\,\text{GHz}
\]

By the calculation in the TxLine, the length of \( \frac{\lambda}{4} \) transmission line at 4.125 GHz is equal to 13.4 mm. Therefore, the length of the open circuit stub is equal to 13.4 mm. It is also found that if the length of open circuit stub is smaller than \( \frac{\lambda}{4} \). The centre frequency of upper and lower band will move away from each other. If the length is larger, the centre frequency of upper and lower band will move toward each other. The observation is shown in Figure 25.
By the result of the optimization, the position, the width and the length of the open circuit stub are found.

\[ W = 1.4 \text{mm} \]

Figure 25 the optimized position, length and width of the stub

The layout of the multiband rectangular disc hybrid is shown below:
Figure 26 the layout of the multiband disc hybrid

Figure 27 The photo of the multiband rectangular disc hybrid coupler
Result and Analysis

2.45 GHz
5.25 GHz
5.8 GHz

Figure 28 The simulation and measurement result of the S-parameter (dB) of the hybrid coupler

2.45 GHz
5.25 GHz
5.8 GHz

Figure 29 The simulation and measurement result of the phase difference of the hybrid
Table 6 S-parameter of the disc hybrid coupler

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>S21</th>
<th>sim(S(2,1))</th>
<th>S31</th>
<th>sim(S(3,1))</th>
<th>S11</th>
<th>sim(S11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>-3.7517</td>
<td>-3.342</td>
<td>-4.1404</td>
<td>-3.537</td>
<td>-17.8</td>
<td>-23.21</td>
</tr>
</tbody>
</table>

Table 7 phase different of the disc hybrid

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>Phase difference (degree)</th>
<th>Sim (Phase difference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>90.201</td>
<td>90.44</td>
</tr>
<tr>
<td>5.25</td>
<td>93.19</td>
<td>89</td>
</tr>
<tr>
<td>5.8</td>
<td>89.412</td>
<td>89.24</td>
</tr>
</tbody>
</table>

For the simulation result, the insertion loss and the coupling factor of the hybrid coupler are between 3dB and 4dB at the frequency ranges 2.4 GHz to 6 GHz and 5.15 to 5.8 GHz.

For the measurement result, the insertion loss and the coupling factor of the hybrid coupler are between 3dB and 4.2 dB at the frequency ranges 2.43 GHz to 2.55 GHz and the frequency ranges from 5.2 GHz to 6 GHz.

The return loss and the isolation are better than 10 dB in the frequency range 2.35 GHz to 3 GHz and frequency range 4.6 GHz to 6 GHz in both measurement result and simulation result.
The insertion loss in frequency greater than 5 GHz in the measurement result is larger than the simulation. It is due to high loss of the SMA connectors in the frequency greater than 5 GHz. The losses of SMA connector have been measured and the result has been put in the table 15 in the appendix.

**Further Work on the disc Hybrid**

**Lump capacitor**

The open circuit stub of the disc Hybrid can be replaced by the shorter microstrip line loaded with a lump capacitor.

![Open circuit stub](image)

Lump capacitor and a microstrip line

Figure 30

It is found that a microstrip line with open end is equivalent to shunt stub consists of a microstrip line section loaded with a capacitor. It is because the effect of fringe electric fields from the open end of the line to the ground plane is acting like a supplementary capacitor.
loaded at the end of the open circuit stub as shown in the figure below. Therefore, we can replace the open circuit stub with a transmission line section loaded with lump component capacitor as shown in Figure 30. There are 2 advantages of doing this. The lump capacitor will produce extra line extension to the microstrip line. Therefore, we can greatly reduce the length of the transmission line section by connecting a lump capacitor with a large capacitance at its end. As result, the total size of the stub can be greatly reduced. Second, placing capacitors with different capacitance in the end of the transmission line will have an effect of lengthening or shortening the length of transmission line section. Therefore, we can adjust the electrical length of the stub by loading different lump component capacitor in the transmission line. Finally, we can tune the frequency band of the coupler by change the capacitor.

Figure 31 the fringe electric fields in open end microstrip line [7]

In order to replace the open circuit stub in the hybrid, an equivalent microstrip line and lump capacitors is need to found. Therefore, an experiment is set up in RF circuit simulator ADS to found the equivalent lump capacitor and microstrip line. The experiment test what value of
dimension of transmission line section and lump capacitor will have same magnitude and phase of S11 in the frequencies 2.45 GHz, 5.25 GHz and 5.8 GHz.

From the experiment in ADS, it is found the width of the required microstrip line is 1 mm and its length is 5.05 mm. The required lump capacitor is around 0.5 pF.

Figure 32 the layout of the hybrid loaded with lump capacitor

Figure 33 The photo of the hybrid coupler load with lump capacitor
By using the 0.333 pF capacitor, a frequency response which is similar to that of the original hybrid coupler with open circuit stub is obtained. It is found that the operating frequency of
this kind of Hybrid can be tuned by changing the capacitors with different value at the end of the stub.

**Radial Stub**

In addition to the shunt stub consists of transmission line loaded with capacitor, the open circuit stub of the rectangular disc hybrid can also be replaced by the radial stub. [8]

In theory, radial stub have a larger fringing capacitance at the open end. It is believe that the radial stub have wider bandwidth than open circuit due to this reason.

However, up to now, the hybrid with open circuit only obtain a same bandwidth with the hybrid using open circuit stub.

The result is shown below:

![Figure 36 the photo of the circuit using open circuit stub](image-url)
Figure 37 layout of the hybrid using open circuit stub

![Figure 37 layout of the hybrid using open circuit stub](image)

Figure 38 The S-parameter of the hybrid using radial stub

Table 8 The S-parameter of the hybrid using radial stub

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>S31</th>
<th>S21</th>
<th>S11</th>
<th>S41</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.454969148</td>
<td>-3.6308</td>
<td>-3.5254</td>
<td>-16.866</td>
<td>-22.72</td>
</tr>
</tbody>
</table>
Figure 39 The phase difference between 2 port of the hybrid coupler using radial stub

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>2.45</th>
<th>5.25</th>
<th>5.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>phase difference (degree)</td>
<td>89.207</td>
<td>88.83</td>
<td>85.33</td>
</tr>
</tbody>
</table>

Table 9 the phase difference of 2 output of the hybrid coupler using radial stub
The potential Application

The multiband Hybrid coupler can be used in the balance amplifier to achieve good return loss, good isolation and higher 1 dB compression point as shown in Fig30.

Figure 40 a balance amplifier
Beside balance amplifier, the hybrid can also be used in the balance Mixer.[9]
Chapter 5: the Phase shifter

Design Methodology

A differential 45 degree Phase shifter is needed for the design of Butler Matrix.

A parallel Schiffman phase shifter is used in the design of 45 degree Phase shifter.

The design of the parallel Schiffman phase shifter is shown below:

![Figure 41 Schematic of the Phase shifter](image)

The parallel Schiffman phase shifter is consist of a coupled section and reference line.
The coupled section consists of 2 coupled line connected in parallel. The lengths of the coupled lines are equal.

The phase shift between the Phase shifter and the reference line is determined by the below equation:

$$\Delta \phi = k\theta - \cos^{-1}\left(\frac{\rho_{p1} - \tan^2 \theta}{\rho_{p1} + \tan^2 \theta}\right)$$

Where

$$\rho_{p1} = \rho_1 \rho_2 \frac{Z_{o11} + Z_{o22}}{Z_{o12} + Z_{o22}}$$

$$\rho_1 = \frac{Z_{o1}}{Z_{o12}} \quad \rho_2 = \frac{Z_{o2}}{Z_{o22}}$$

Differentiating (1) by $\phi$

$$\frac{d\Delta \phi}{d\theta} = k - \frac{2\sqrt{\rho_{p1}} (1 + \tan^2 \theta)}{\rho_{p1} + \tan^2 \theta}$$

$$\frac{d^2 \Delta \phi}{d\theta^2} = 4\sqrt{\rho_{p1}} (\rho_{p1} - 1) \tan \theta (1 + \tan^2 \theta) \quad (\rho_{p1} + \tan^2 \theta)^2$$

$$\frac{d^2 \Delta \phi}{d\theta^2} = 0 \text{ when } \theta = 90^0$$

Therefore, maximum bandwidth is obtained when $\theta = 90^0$
Put $\theta = 90^0$ into (0.3)

$$\Delta \phi = K \theta$$

For the differential phase shift is equal to $-45^0$

i.e. $\Delta \phi = -45^0 = 225^0$

$$K \theta_1 = \Delta \phi = -45^0 = 225^0$$

By using the Txline, the length of the coupled line, $\theta_1 = \theta_2 = 14$mm

The length of the coupled line, $K \theta_1 = 31.9355$mm

In theatrical approach, the value of $\rho_1$ can be found by solving the above equations. As the result, the values of $Z_{oo1}, Z_{oe1}, Z_{oo2}, Z_{oe2}$ can be found. The dimension of the coupled line can be found. [10]

However, it is different to find the dimension of coupled line according to $Z_{oo1}$ and $Z_{oe1}$ with high accuracy. Therefore, the dimension of the coupled line will be found by optimization.
Fig 4. The effect of the width (W) and gap (S) toward the phase difference

The value of width (W) and gap (S) which made the phase shifter to have smallest phase derivation is chosen. As the result, the gap of the coupler line=0.4mm and the width of the coupled line=1.2mm

The layout of the parallel Schiffman phase shifter:

The coupled section:

The reference line:
Result and Analysis

Figure 42 Layout of the phase shifter

Figure 43 photo of the phase shifter

Figure 44 the phase difference of the phase shifter
Figure 45 The insertion loss of the phase shifter

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>measured phase difference (degree)</th>
<th>simulated phase difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>46.76</td>
<td>45.3</td>
</tr>
<tr>
<td>5.25</td>
<td>44.86</td>
<td>44.04</td>
</tr>
<tr>
<td>5.8</td>
<td>45.16</td>
<td>45.3</td>
</tr>
</tbody>
</table>

Figure 46 The phase difference between port 2 and port 4 of the phase shifter

From the measurement result, the phase difference between port 2 and port 4 of the phase shifter at the frequency ranges from 2.4 GHz to 2.5 GHz is $45^\circ \pm 3^\circ$. In the frequency range 5 GHz to 5.9 GHz is $45^\circ \pm 1^\circ$.

The insertion of the phase shifter is quite high in the measurement result. The reason is that there is high loss in the SMA connector reference to table 15 in appendix. Moreover, it is found that the insertion loss in the phase shifter can be reduced by reducing the length of the port of the phase shifter.
Chapter 6: Butler Matrix

Design Methodology

A conventional Butler Matrix consists of hybrids, crossover, and phase shifters.

The topology of the conventional Butler Matrix is shown below:[11]

However, a new topology of Butler Matrix has been proposed [12]. This new topology of Butler Matrix eliminates the use of 0° crossover coupler which will increase the additional loss and increase the size of the circuit. The schematic of the Butler Matrix using the new topology is shown below:
Figure 48 the schematic of the new Butler matrix

The Butler Matrix is connected as shown below:

Hybrid coupler

Figure 49 the layout of the Butler Matrix
Figure 50 The photo of the Butler Matrix

Figure 51 the signal flow in the Butler Matrix (assume that there are no loss in the hybrid and phase shifter)
Table 10 the phase difference between difference ports of the Butler Matrix

<table>
<thead>
<tr>
<th></th>
<th>Port 3</th>
<th>Port 4</th>
<th>Port 7</th>
<th>Port 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>port 3</td>
<td>0</td>
<td>90</td>
<td>135</td>
<td>225</td>
</tr>
<tr>
<td>port 4</td>
<td>-90</td>
<td>0</td>
<td>45</td>
<td>135</td>
</tr>
<tr>
<td>port 7</td>
<td>-135</td>
<td>-45</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>port 8</td>
<td>-225</td>
<td>-135</td>
<td>-90</td>
<td>0</td>
</tr>
</tbody>
</table>
Result and Analysis:

**Figure 52** The simulation result of magnitude (dB) of the S-parameter of the Butler Matrix

**Figure 53** the Measurement result of the S-parameter of the Butler Matrix
### Table 11 The simulation Result of the Butler Matrix

<table>
<thead>
<tr>
<th>Freq[GHz]</th>
<th>dB[S(1,1)]</th>
<th>dB[S(3,1)]</th>
<th>dB[S(4,1)]</th>
<th>dB[S(7,1)]</th>
<th>dB[S(8,1)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>-17.76</td>
<td>-6.851</td>
<td>-7.425</td>
<td>-7.028</td>
<td>-7.166</td>
</tr>
<tr>
<td>5.25</td>
<td>-18.97</td>
<td>-7.656</td>
<td>-7.272</td>
<td>-6.864</td>
<td>-7.007</td>
</tr>
<tr>
<td>5.8</td>
<td>-27.18</td>
<td>-6.479</td>
<td>-6.885</td>
<td>-7.327</td>
<td>-6.917</td>
</tr>
</tbody>
</table>

### Table 12 The Measurement Result of The Butler Matrix

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>S3,1 (dB)</th>
<th>S4,1 (dB)</th>
<th>S8,1(dB)</th>
<th>S7,1(dB)</th>
<th>S1,1(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>-7.4653</td>
<td>-7.084</td>
<td>-7.7746</td>
<td>-7.7585</td>
<td>-12.037</td>
</tr>
<tr>
<td>5.25</td>
<td>-7.5557</td>
<td>-7.8411</td>
<td>-6.5352</td>
<td>-7.833</td>
<td>-11.672</td>
</tr>
</tbody>
</table>
Figure 54: The simulated result of the phase difference between each port of the Butler Matrix.

Figure 55: The measured phase difference between each port of the Butler Matrix.
Table 13 The simulation Result of phase difference

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>simulation phase difference (3,4)</th>
<th>simulation phase difference (3,7)</th>
<th>simulation phase difference (3,8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>89</td>
<td>226.41</td>
<td>135.81</td>
</tr>
<tr>
<td>5.25</td>
<td>91.8</td>
<td>222.02</td>
<td>133.12</td>
</tr>
<tr>
<td>5.8</td>
<td>86.97</td>
<td>223.05</td>
<td>132.15</td>
</tr>
</tbody>
</table>

Table 14 The measurement Result of the phase difference of Butler Matrix

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>measured phase difference (3,4)</th>
<th>measured phase difference (3,7)</th>
<th>measured phase difference (3,8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>93.998</td>
<td>223.267</td>
<td>133.267</td>
</tr>
<tr>
<td>5.25</td>
<td>97.98281</td>
<td>223.504</td>
<td>133.504</td>
</tr>
<tr>
<td>5.8</td>
<td>86.343</td>
<td>222.643</td>
<td>132.643</td>
</tr>
</tbody>
</table>

For the simulation result, it is found that the insertion loss of the Butler matrix is between -6 dB to -8 dB in the frequency ranges 2.4 GHz to 2.5 GHz and 5.2 GHz to 6 GHz. The phase errors are within 5 degree at the above 2 frequency range. Moreover, the isolation and the return loss of the Butler matrix are better than 10 dB at the frequency range 2.35 to 3 GHz and the frequency range 5 GHz to 6 GHz.

For the measure result, it is found that the insertion loss of the Butler matrix is between -6 dB to -8 dB in the frequency ranges 2.43 GHz to 2.52 GHz and between -6 dB to -8.3 dB in the frequency ranges 5.22 GHz to 5.3 GHz and between 5.55 GHz to 5.8 GHz. The isolation and the return loss are better than 10 dB in the frequency range 2.42 GHz to 2.9 GHz and 4.9 GHz to 6 GHz. The phase error is within 8° in the frequency range 2.3GHz to 2.53 GHz and the 5.2 GHz to 6 GHz. The measured insertion loss in the frequency greater than 5 GHz is high due to the high loss in the SMA connector. The Loss of SMA connectors are up to 0.4 to 0.6 dB in this frequency reference to fig1 and table1 in the appendix. If no SMA connectors are used, the insertion loss will be 0.4 to 0.6 dB lower.
The potential application of the Butler Matrix

We can implement a switch beam system by the Butler Matrix in the WiFi access point as shown in Figure 57.

Figure 56 the switched beam system

The switch beam system have several advantage over a simple antenna system. Multiple narrow beams can be produced by the system. The one with strongest signal level can be selected by the control units. As the result, the signal to interference ratio can be increase. The co-channel interference and the multipath interference can be reduced. The range of the antenna system can also be increase.[13]
Discussion

Work Review

There are many ways to make a hybrid coupler working in multiband. In this project, the multiband hybrid couplers are designed by using additional open circuit stubs. This approach has several advantages over other approach mention in the literature. One of the advantages is that other approaches such as using right hand left hand transmission line can only be applied to the branch line Hybrid coupler. The open circuit stub approach can be applied to both branch line hybrid coupler and disc Hybrid coupler.

In this project, a multiband branch line coupler and a multiband rectangular disc hybrid coupler have been fabricated. When comparing with the branch line hybrid coupler, the rectangular disc hybrid has a larger bandwidth and easier to be fabricated due to its simpler structure. On the other hand, the disc hybrid have disadvantage due to its larger shape.

Future Work

Some improvement can be done on the multiband rectangular disc hybrid. The size of the stub of the hybrid coupler can be reduced by replacing the open circuit stub with the transmission line section loaded by a capacitor. Moreover, the disc hybrid coupler can be modified to become a tunable structure by replacing the capacitor loaded by a varactor diode. The capacitance across varactor diode can be changed by varying the DC voltage
applied across it. As the result, the operating frequency of the hybrid coupler of this structure can change by DC biasing.

In addition, it may be possible to increase the bandwidth of the coupler by replacing the open circuit stub of the hybrid coupler with the radial stub. The dimension in the main part of the hybrid is also needed to be changed for the replacement of open circuit stub by radial stub.

Figure 57 a radial stub
For the Butler Matrix, a multiband antenna array which can cover the 3 frequency band of WiFi should be needed to design and fabricated in order to construct the switch beam system for WiFi.

Conclusion

A branch line multiband hybrid coupler covering 2 frequency band of WiFi and a rectangular disc hybrid coupler covering 3 frequency band have been designed and fabricated. Both of them have isolation and return loss better than 10 dB in their operating frequency band. They have acceptable insertion loss in their operating frequency band too.

The Butler matrix base on the rectangular disc hybrid coupler and Schiffman phase shifter have also been designed and fabricated. It is aimed to be used in the antenna system of the Multiband access point.
## Appendix

![Graph showing insertion loss vs. frequency](image)

**Figure 58** the insertion loss of the SMA connector

<table>
<thead>
<tr>
<th>frequency (GHz)</th>
<th>Insertion Loss of the SMA connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>-0.0378</td>
</tr>
<tr>
<td>2.425</td>
<td>-0.0478</td>
</tr>
<tr>
<td>2.45</td>
<td>-0.0176</td>
</tr>
<tr>
<td>2.475</td>
<td>-0.022</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.0355</td>
</tr>
<tr>
<td>2.525</td>
<td>-0.061</td>
</tr>
<tr>
<td>2.55</td>
<td>-0.0837</td>
</tr>
<tr>
<td>2.575</td>
<td>-0.0783</td>
</tr>
<tr>
<td>2.6</td>
<td>-0.0761</td>
</tr>
<tr>
<td>5.15</td>
<td>-0.5007</td>
</tr>
<tr>
<td>Value</td>
<td>Insertion Loss</td>
</tr>
<tr>
<td>-------</td>
<td>---------------</td>
</tr>
<tr>
<td>5.175</td>
<td>-0.556</td>
</tr>
<tr>
<td>5.2</td>
<td>-0.5205</td>
</tr>
<tr>
<td>5.225</td>
<td>-0.4022</td>
</tr>
<tr>
<td>5.25</td>
<td>-0.2962</td>
</tr>
<tr>
<td>5.275</td>
<td>-0.2551</td>
</tr>
<tr>
<td>5.3</td>
<td>-0.3724</td>
</tr>
<tr>
<td>5.325</td>
<td>-0.4946</td>
</tr>
<tr>
<td>5.35</td>
<td>-0.5432</td>
</tr>
<tr>
<td>5.375</td>
<td>-0.498</td>
</tr>
<tr>
<td>5.4</td>
<td>-0.4451</td>
</tr>
<tr>
<td>5.7</td>
<td>-0.3245</td>
</tr>
<tr>
<td>5.725</td>
<td>-0.4597</td>
</tr>
<tr>
<td>5.75</td>
<td>-0.5687</td>
</tr>
<tr>
<td>5.775</td>
<td>-0.6672</td>
</tr>
<tr>
<td>5.8</td>
<td>-0.6365</td>
</tr>
<tr>
<td>5.825</td>
<td>-0.55</td>
</tr>
<tr>
<td>5.85</td>
<td>-0.4086</td>
</tr>
<tr>
<td>5.875</td>
<td>-0.2903</td>
</tr>
<tr>
<td>5.9</td>
<td>-0.3242</td>
</tr>
<tr>
<td>5.925</td>
<td>-0.499</td>
</tr>
<tr>
<td>5.95</td>
<td>-0.7088</td>
</tr>
<tr>
<td>5.975</td>
<td>-0.7408</td>
</tr>
<tr>
<td>6</td>
<td>-0.5996</td>
</tr>
</tbody>
</table>

Table 15: Insertion loss of the SMA connector
Reference


[3] Chapter 8 of EE5601 notes


[6] Tadashi Kawai and Isao Ohta, Planar-Circuit-Type 3 -dB Quadrature Hybrids

[7] Chapter 2 of EE5601


[10] JosC Luis Ramos Quirarte, and J. Piotr Starski, Member, IEEE” Novel Schiffman Phase Shifters”


