Department of Electronic Engineering

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Small Hybrid Rat-race coupler

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

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Abstract

A broadband and compact size rat-race hybrid using multilayer technology is done in this project. It has some benefits over the conventional rat-race hybrid. Firstly, the size is reduced. The conventional rat-race hybrid is composed of three $\lambda/4$ sections and one $3\lambda/4$ section. Its total circumference is 1.5 wavelengths. By contrast, making use of the multilayer technology, the broadband compact rat-race hybrid occupies only about 33% of the conventional one.

Besides the size consideration, the performance is definitely taken into a deep consideration. The theory of the broadband rat-race hybrid and the factors relating to the performance are studied. Meanwhile, throughout the simulation and measurement process, desirable features can be identified.

Furthermore, it integrates one double-sided parallel-strip line (DSPSL) port and three microstrip line ports. Base on its extraordinary characteristic, this rat-race can facilitate circuit implementation. In this project, the broadband rat-race hybrid is combined with a passive antenna element on the same substrate. It is so-called active integrated antenna (AIA).

The work done in the project covers passive and active elements, the former is comprehensively examined in Chapter 3 and the latter is described in Chapters 4 and 5.
Chapter 1 Introduction

1.1 Fundamentals of Hybrid Couplers

Hybrid couplers are passive microwave components used for power division or power combining as a result of widely used in radio frequency circuits design. It is mainly divided into two categories “a three-port component” and “a four-port component”. In this project, the designated rat-race hybrid contains four ports and its characteristics are going to be reviewed.

Four-port network takes the form of directional hybrids or couplers. 90° hybrid and 180° hybrid are commonly used in microwave circuits. Generally, these two types of hybrids comply with several characteristics. The first one is that all ports are matched which means Snn=0 at each port. Moreover, the radio frequency (RF) power applied to any one port is split equally between two neighbouring ports. No output signal appears at the opposite port which is named as isolation port.

An ideal 180° hybrid coupler is shown in Figure 1. The phase difference between two output ports is either in phase (0° phase difference) or out of phase (180° phase difference) depending on which port is excited. For example, if a signal is applied to port 1, it will be split equally to port 3 and port 4 with 0 deg phase difference. On the other hand, if a signal is applied to port 1, similarly, it will be split equally to
port 3 and port 4. However, the phase difference between them is 180 deg phase
difference. Moreover, in this case, port 3 and port 4 are often called “the sum” and
“the difference” respectively. The names are attributed to the in-phase voltage
output at port 3 being proportional to the sum up of inputs port 1 and 2 while the
out-of phase voltage at port 4 being proportional to the difference of these two
inputs.

The scattering matrix of an ideal 180° hybrid is described in the following form
according to the above properties

\[
[S] = \begin{bmatrix}
0 & 1 & 1 & 0 \\
1 & 0 & 0 & -1 \\
1 & 0 & 0 & 1 \\
0 & -1 & 1 & 0 \\
\end{bmatrix}
\]

Figure 1 Ideal 180° hybrids
1.2 Conventional Rat-race Hybrid

Rat-race (ring hybrid) is one of the oldest and simplest designs for the fabrication of a 180° hybrid. As shown in Figure 2, it is a ring shape making of transmission lines which compose of three $\lambda/4$ line sections and one $3\lambda/4$ line section. The port impedances are all 50Ω. The quarter-wave length sections along to the circumference operate as a transformer which transforms the 50Ω loads on two output ports to 100Ω each at the isolation port. According to the input impedance equation,

$$Z_{\text{in}} = \frac{Z_4 + jZ_4 \tan \beta \ell}{Z + jZ_4 \tan \beta \ell}, \quad \ell = \frac{\lambda}{4}, \quad ZL=2 \text{ (because the load is the parallel combination of 50Ω)}$$

\[ \therefore \quad Z_{\text{in}} \approx \frac{Z_4^2 \tan \beta \ell}{2 \tan \beta \ell} = \frac{1}{2} Z^2 \]

The ring characteristic impedance is $50\sqrt{2}$. By constructing the ring hybrid based on the above specifications, the ports are all matched and the power form the source is split equally between two output ports.

![Figure 2 Top view of a microstrip rat-race hybrid](image-url)
To describe the operation, if port 1 is excited, the waves will be transmitted towards the neighbouring ports, port 2 and port 4, equally. The other port is isolated. Two identical waves are transmitted in clockwise and anti-clockwise direction respectively such that the waves are 180 deg out of phase at the interacting port 3. So, the voltages are cancelled out and become zero at this point. The isolated port lets the circuit become a three-port network. Due to the impedance of the rat-race ring being constant, the voltages are split equally to port 2 and port 4. However, the phase is not identical because the path from port 1 to port 2 is one-half wavelength which is longer than the path from port 1 to port 4. The phase difference between port 2 and port 4 is 180 deg. To infer, a table is constructed to illustrate the situations when different ports are excited. Refer to Figure 2, rat-race hybrid operation is summarised on the following table.

<table>
<thead>
<tr>
<th>Excited Port</th>
<th>Output Port</th>
<th>Isolated Port</th>
<th>Phase difference between two output ports</th>
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<tr>
<td>1</td>
<td>2 , 4</td>
<td>3</td>
<td>180°</td>
</tr>
<tr>
<td>2</td>
<td>1 , 3</td>
<td>4</td>
<td>180°</td>
</tr>
<tr>
<td>3</td>
<td>2 , 4</td>
<td>1</td>
<td>0°</td>
</tr>
<tr>
<td>4</td>
<td>1 , 3</td>
<td>2</td>
<td>0°</td>
</tr>
</tbody>
</table>

Table 1 Conventional rat-race hybrid operation
Chapter 2 Objective and Methodology

2.1 Criteria of Rat-race Hybrid

The project is to design a rat-race hybrid which operates at 4GHz. It is required to follow the basic functions and criteria of 180° hybrid described in Chapter 1.

1. All ports are matched.
   \[ S_{11}, S_{22}, S_{33}, S_{44} < -20dB \]

2. Power applied to anyone port is split equally between two other ports
   \[ S_{13} = S_{14} = -3dB \]
   \[ S_{23} = S_{24} = -3dB \]
   \[ S_{31} = S_{32} = -3dB \]
   \[ S_{41} = S_{42} = -3dB \]

3. The remaining port is isolated
   \[ S_{12}, S_{21} < -20dB \]
   \[ S_{34}, S_{43} < -20dB \]
2.2 Calculation of the Transmission Line

The rat-race hybrid is made by the microstrip line which can be fabricated by photolithographic processes and easily integrated with passive and active components. A conductor of width \( w \) is printed on a substrate of thickness \( d \) and relative permittivity \( \varepsilon_r \). These parameters are noticeable in RF circuits design. They relate to the characteristic impedance \( Z_0 \) and should be calculated carefully. Given that the characteristic impedance \( Z_0 \) equals to 50\( \Omega \), \( \varepsilon_r \) equals to 2.94 and \( d=0.762\text{mm} \), the \( w/d \) can be calculated as

\[
B = \frac{1}{Z_0} \frac{n_0 \pi}{2 \sqrt{\varepsilon_r}} \\
= \frac{1}{50} \frac{377 \pi}{2 \sqrt{2.94}} = 5.08
\]

\[
w = \frac{w}{h} = \frac{2}{\pi} \left( B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2 \varepsilon_r} \left[ \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r} \right] \right) \\
= \frac{2}{\pi} \left( 5.08 - 1 - \ln(9.16) + \frac{1.94}{5.88} \left[ \ln(4.08) + 0.39 - \frac{0.61}{2.94} \right] \right) \\
= 2.493
\]

\( w = 1.9\text{mm} \)

The effective dielectric constant of a microstrip line is given by

\[
\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \sqrt{\frac{1}{1 + \frac{12d}{w}}} \\
= \frac{3.94}{2} + \frac{1.94}{2} \sqrt{\frac{1}{1 + 12(2.493)}} \\
= 2.144
\]
The length of line, $\ell$, for a 90° phase shift is found as

$$\theta = \beta \ell = \sqrt{\varepsilon_e k_0 \ell}$$

$$k_0 = \frac{2\pi f}{c} = 83.77$$

$$\ell = \frac{\pi/2}{\sqrt{\varepsilon_e k_0}} = 12.8 \text{ mm}$$

### 2.3 Simulated Softwares

The calculation of the RF circuits is very complicated. The performance of circuits depends on many parameters. For simplicity and accuracy, simulated softwares are employed in this project.

(i) **High Frequency Structure Simulator (HFSS)**

HFSS is a simulated solution for RF passive circuit. This software is powerful that the S-parameters and the phase difference can be simulated accurately. After drawing the passive circuit layout at AutoCAD, the layout is directed to HFSS. The simulations of the hybrid and antenna proposed in this project can be done.

(ii) **Microwave Office**

Microwave office is used to simulate the active circuits which including active components such as inductors, capacitors and oscillators, etc. It can use the data simulated by HFSS. Therefore, the simulated hybrid data can be put into the microwave office to integrate an active integrated mixer.
Chapter 3 Broadband Compact Rat-Race Hybrid

3.1 Introduction of The Novel Rat-race Coupler Design

Since the hybrids are popularly using in microwave circuits such as mixers and phase shifters, much effort has been done to improve its performance. Size, isolation bandwidth, phase and amplitude balance are major concern in designing the hybrids. Isolation is the ratio of power at the isolated port to applied input port, normally expressed in decibels (dB). Phase balance is the deviation in phase from the ideal phase difference between any pair of outputs while amplitude balance is the difference in output amplitudes.

By using multilayer technology, the newly developed hybrid has a highly symmetric configuration. It consists of three types of transmission lines which are double-sided parallel-strip line (DSPSL), back-to-back microstrip line and microstrip line. DSPSL with an inserted conductor plane has a unique characteristic which combine out-of-phase signal and cancel out in-phase signal regardless of the frequency. Hence, this rat-race hybrid has the most obvious advantage of broadband and compact size.
3.2 Configuration of the Broadband Compact Rat-race Hybrid

Figure 3 Configuration of the rat-race hybrid (Top view)

Figure 4 Configuration of the rat-race hybrid (3D view)
3.3 Structure and Analysis of the Rat-race Hybrid

The configuration of the rat-race hybrid is shown in Figure 3 and Figure 4. It is constructed with the substrate on the top, middle and bottom layers. There are totally four ports including three microstrip line ports and one DSPSL port printed on the top layer and bottom layer. The middle metallization is inserted as a common ground plane which isolates the top and bottom layers circuits and converts the DSPSL line into two back-to-back microstrip lines. At the centre of the conductor plane, a short section called coplanar waveguide (CPW) is inserted. CPW contains two wheel holes. One of which is connected to the two back-to-back microstrip lines for power splitting, another is connected with the microstrip port (port 1) on the top side. On the opposite side, the DSPSL port which is composed of a pair of parallel strip lines is known as port 2.

The microstrip ports, port 3 and port 4, are fabricated on the top and bottom layer respectively. They are connected to the corresponding back-to-back microstrip lines. The lengths of the microstrip lines connected to port 3 and port 4 are not fixed but should be the same. As a result, the positions of ports are flexible for circuit layout in applications.

According to the structure using multilayer technology, the area of the rat-race is about $1/4 \frac{\lambda}{g} \times 1/6 \frac{\lambda}{g}$. Conventionally, the rat-race hybrid has a total circumference of $1.5 \frac{\lambda}{g}$. There is a great size reduction that it is only about 33% of
the conventional microstrip rat-race hybrid. Size reduction is the most advantage in this design when compared with conventional rat-race or even other novel rat-race which is published in recent years.

![Figure 5 Equivalent circuit of the rat-race hybrid](image)

Figure 5 shows the equivalent circuit of the rat-race hybrid. Here shows its operation. If port 1 which is a microstrip port is excited, the input signal voltages will be split into two waves that on the top and bottom strips. The phase does not change when the wave is transmitted from microstrip line to $1/4\lambda_g$ back-to-back microstrip lines. However, only a pair of out-of-phase waves can be transmitted from back-to-back microstrip lines to DSPSL as DSPSL is a kind of balanced transmission line. As a result, the junction connecting the back-to-back microstrip lines and DSPSL called open joint cancels out the incident in-phase waves. The position at the short joint is considered as open-
circuit point. The race-race hybrid is equivalent to three-port network shown in Figure 6.

This three-port network is realized as a Wilkinson Power Divider. By insisting that all ports be matched, the characteristic impedance of the quarter-wave lines can be evaluated. Like the section 1.2 proving, the characteristic impedance of 1/4λg back-to-back microstrip lines equals to \( \sqrt{2}Z_0 \). Thus, the input power at port 1 is split equally to port 3 and port 4. What’s more, according to the CPW transition without any phase changing as shown in Figure 7, the output voltage at port 3 and port 4 is in phase when port 1 is excited.

![Figure 6](image1.png)

Figure 6 Equivalent circuit of rat-race hybrid when port 1 is excited

![Figure 7](image2.png)

Figure 7 Side view of the E-field distribution
(a) Microstrip line    (b) Back-to-back microstrip lines
When port 2 is excited, the waves initially pass through the top and bottom striplines from the DSPSL port. After the point of the conductor plane is inserted, the waves then travel the $1/4 \lambda_g$ back-to-back microstrip lines. The conductor plane has no effect on the E-field distribution. Thus, the phase difference between the top and the bottom back-to-back microstrip lines is $180^\circ$ as shown in Figure 8. Afterwards, the wire connecting the top and bottom back-to-back microstrip lines combines the waves which are out-of-phase. It is known as a short-circuit point. Distance of $1/4 \lambda_g$ away from the short-circuit point is exactly the junction connecting the DSPSL with the back-to-back microstrip lines and the junction is therefore considered as an open-circuit point. The rat-race hybrid is equivalent to a three-port network shown as in Figure 9.

![Diagram of E-field distribution](image)

Figure 8 Side view of the E-field distribution
(a) DSPSL  (b) back-to-back microstrip lines

![Diagram of equivalent circuit](image)

Figure 9 Equivalent circuit of rat-race hybrid when port 2 is excited
As seen in the Figure 9, the characteristic impedance of the DSPSL ($Z_2$) is $2Z_0$. Therefore, the port is matched and equal power is distributed to port 3 and port 4 with low return loss. All in all, port 1 and port 2 are inherently isolated.

By reciprocal theory, as port 3 and port 4 get half power if port 1 or port 2 is excited, the port 1 and port 2 will also get half power if port 3 or port 4 is excited too. Similarly, port 3 and port 4 are isolated. Assuming that two waves are transmitted to port 3 (port 4), one of which passes through 180 degree electric length of two back-to-back microstrip lines and the other has the same phase with the original signal. As they are out-of-phase at port 4 (port 3), the signal will be cancelled out and thus isolation between port 3 and port 4 are recognised.

<table>
<thead>
<tr>
<th>Excited Port</th>
<th>Output Port</th>
<th>Isolated Port</th>
<th>Phase difference between two output ports</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>3, 4</td>
<td>2</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>3, 4</td>
<td>1</td>
<td>180°</td>
</tr>
<tr>
<td>3</td>
<td>1, 2</td>
<td>4</td>
<td>0°</td>
</tr>
<tr>
<td>4</td>
<td>1, 2</td>
<td>3</td>
<td>180°</td>
</tr>
</tbody>
</table>

Table 2 Novel rat-race hybrid operation
3.4 Simulated Results of S-parameters for the Conventional Rat-race and Proposed Rat-race

Figure 10 S parameters of the conventional rat-race hybrid when port 1 is excited (refer to the section 1.2)

Figure 11 S parameters of the conventional rat-race hybrid when port 3 is excited (refer to the section 1.2)
Figure 12: S parameters of the novel rat-race hybrid when port 1 is excited.

Figure 13: S parameters of the novel rat-race hybrid when port 2 is excited.
Figure 14 S parameters of the novel rat-race hybrid when port 3 is excited

Figure 15 S parameters of the novel rat-race hybrid when port 4 is excited
3.5 Simulated Results of Phase Difference Between the Sum and Difference Ports (Conventional Rat-race and Proposed Rat-race)

Figure 16 Phase difference of port 2 and port 4 at the conventional rat-race hybrid when port 3 is excited

Figure 17 Phase difference of port 2 and port 4 at the conventional rat-race hybrid when port 1 is excited
Figure 18 Phase difference of port 3 and port 4 at the novel rat-race hybrid when port 1 is excited

Figure 19 Phase difference of port 3 and port 4 at the novel rat-race hybrid when port 2 is excited
3.6 Analysis and Comparison of the Performance Between Conventional Rat-race and the Novel Rat-race Based on the Simulated Results

As the above sections mention that the function between the conventional rat-race hybrid and the novel one is the same, this section is going to corroborate the latter one having better performance based on the simulated results.

Real hybrids differ from the ideal hybrids in several ways: the most essential non-idealities are phase and amplitude balance, loss and isolation. This rat-race hybrid exhibits superiority of amplitude and phase balance performance and wider isolation bandwidth.

(i) Amplitude Balance Performance

Figure 10 and 11 show the S parameters when port 1 and port 3 of conventional rat-race hybrid is excited respectively. On the other hand, figures 12, 13, 14 and 15 show the S parameters when port 1 and port 2 of novel rat-race hybrid is excited. The better performance in amplitude balance, the closer of the ratio between two output ports does. Theoretically, the S-parameters of two output ports such as $S_{31}$ and $S_{41}$ are expected to equalise -3dB at the centre frequency. Clearly, the corresponding curves shown in Figure 10 and 11 does not as smooth as the curves shown in Figures 12, 13, 14 and 15 do. For the conventional rat-race, $S_{23}$ and $S_{43}$ fluctuated between -1 dB and 10dB at the
frequency range from 2GHz to 6GHz. Meanwhile, $S_{31}$ and $S_{41}$ of the novel rat-race is level off at -3dB at the same frequency range. As a result, it has a better amplitude balance performance than that of conventional one is proved.

(ii) **Isolation Bandwidth**

Isolation is usually frequency-dependent in most recent design. In this broadband compact rat-race hybrid, the isolation is attributed to cancellation at the short joint and open joint such that it does not depend on frequency. Also, refer to the same figures mentioned in (i), the curves of $S_{12}$ and $S_{21}$ reveal that the isolation curve is quite smooth and below 45dB. Not only does the bandwidth get wider, but also the isolation magnitude of the broadband compact rat-race reaches a surprisingly high level.

(iii) **Phase Balance Performance**

Figures 16, 17 show the phase difference of the sum and difference ports of the conventional rat-race. The curves increase gradually from -10 to 5 degree and -200 to -160 degree respectively at the frequency range from 3GHz to 5GHz. Suddenly, the curves dramatically fluctuate up and down at the frequency 5.5GHz. By contrast, the curves shown in Figures 18 and 19 are level off around 0.2 and 180 degree inherently. Therefore, the new rat-race has a better performance in phase balance compared with that of conventional one.
Chapter 4 Composition of Active Integrated Antenna

4.1 Introduction of Active Integrated Antenna

In this project, the rat-race hybrid integrates with the double-sided parallel-strip line (DSPSL)-fed quasi-Yagi antenna and singly balanced mixer to fabricate as an active integrated antenna. Active integrated antenna (AIA) signifies that the passive antenna elements and the active circuits are integrated on the same substrate. It has some advantages such as small size, low cost and low loss.

Many practical applicants such as beam switching, power combing and integrated oscillators are found in AIA. In this case, radio frequency signals are received by the DSPSL-fed quasi-Yagi antenna. Through the balanced mixer, radio frequency signals mixed with local oscillators. Finally, an intermediate frequency (IF) is generated. This operation is useful in millimetre-wave system application because microprocessor cannot usually analyse radio frequency signals.

To address the method and the mixer, chapter 4 is organised on the followings. First, a DSPSL-fed quasi-Yagi antenna which works as a load of the hybrid and radiation element is described. Secondly, the structure of the mixer based on the hybrid structure is introduced.
4.2. DSPSL-Fed Quasi-Yagi Antenna

Figures 20 (a) and (b) show the top view and side view of the DSPSL-fed Yagi antenna. Owning to the Yagi antenna integrating with the rat-race hybrid, it is composed of three layers used the same substrate ($\varepsilon_r = 2.94$, $h = 0.762$). The metallization is constructed on the top, middle and bottom layers. The top and bottom metallization have the same structure with mirror image. It contains one
The dipole element, 100 Ω DSPSL feed line. The middle metallization includes an inserted conductor plane and a director.

The functions of the elements in the antenna are going to be described briefly. The dipole element is to transmit and receive the radio frequency signal. The 100 Ω DSPSL feed line provides a path of 180° phase difference. By adding another 180° phase difference created by reflection, the phase difference between the received signal and the reflected signal is 0°. The received signal is therefore transmitted to the output port without any cancellation. Like the previous chapter mentioned, the conductor plane has no effect on electromagnetic field distribution of the DSPSL. Besides, the conductor plane works as a reflector element for the antenna as it is treated as a very large virtual ground plane. Therefore, the antenna radiates forward only and the front-to-end ratio should be good. The features indicate that the effective reflector for quasi-Yagi antenna appears as infinity for the rat-race hybrid. In terms of image theory, the inserted ground plane does not affect the operation of the rat-race hybrid.

Thanks to no accurate mathematical formulas derived, parameters of quasi-Yagi antenna are required to optimize. The optimization includes the lengths as well as the widths of the driver, director, reflector and the spacing between director and driver. However, the initial parameters are easily estimated. The
lengths of driver and director are around a half-wave-length at the centre frequency. Of course, the length of DSPSL feed line is one quarter-wavelength.

4.2.1 Objective of Simulation

As the hybrid is operated at 4GHz, the objectives of the simulated DSPSL-fed quasi-Yagi antenna are expected on the following areas.

1. Return loss is minimized at the centre frequency - 4GHz

   \[ S11 < -10\text{dB} \]

2. Input resistance and reactance should be matched and minimized respectively

   Input resistance \( \approx 100 \pm 30 \, \Omega \)

   Reactance impedance \( \approx 0 \pm 30 \, \Omega \)

3. Good front-to-end ratio of both E- and H-plane

   Front-to-end ratio > 15dB

4. Cross-polarization should be as least as possible

   Cross-polarization < -20dB
4.2.2 Comparison of Performance When Each parameter of Quasi-Yagi Antenna Changes

By setting the parameters as above suggested, the simulated result is revealed on Figure 21.

![Figure 21 Simulated return loss based on initial parameters](image)

Clearly, the return loss is not less than -10dB and the centre frequency is not centralised at 4GHz. The performance is unsatisfactory. According to lots of parameters affecting the performance, trial and error is the only way for designing the structure. A systematic analysis is necessary to show how parameters influence the return loss and the frequency shifting significantly. Afterwards, a table is constructed to record the simulated results. Based on the table below, the significant parameters can be optimized to obtain the best performance of the antenna.
### Table 3 Effect of return loss and centre frequency by changing parameters

<table>
<thead>
<tr>
<th>(S_{\text{fed}})</th>
<th>(W_{\text{dri}})</th>
<th>(L_{\text{dri}})</th>
<th>(W_{\text{dir}})</th>
<th>(L_{\text{dir}})</th>
<th>(S_{\text{dir}})</th>
<th>Return Loss</th>
<th>Centre Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>↓</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>↑</td>
<td>↓</td>
<td>←</td>
</tr>
</tbody>
</table>

- : remains unchanged  ↓ : decrease / lower  ↑ : increase  ← : shift to the left  → : shift to the right

By the above table, it is illustrated that the parameters of \(L_{\text{dri}}\), \(W_{\text{dir}}\), \(L_{\text{dir}}\), \(S_{\text{dir}}\) affecting the performance most significantly. Initially, the parameters are:

\[
\begin{align*}
W_{\text{fed}} &= 1.9\text{mm} ; L_{\text{gnd}} = 14\text{mm} ; L_{\text{dri}} = 17.89\text{mm} ; L_{\text{dir}} = 21.9\text{mm} ; \\
S_{\text{fed}} &= 13.44\text{mm} ; S_{\text{dir}} = 3.19\text{mm} ; W_{\text{dir}} = 5\text{mm} ; S_{\text{dri}} = 5\text{mm} ;
\end{align*}
\]

By trial and error, the parameters are optimized.

\[
\begin{align*}
W_{\text{fed}} &= 1.9\text{mm} ; L_{\text{gnd}} = 14\text{mm} ; L_{\text{dri}} = 18.17\text{mm} ; L_{\text{dir}} = 19.5\text{mm} ; \\
S_{\text{fed}} &= 12.14\text{mm} ; S_{\text{dir}} = 2.89\text{mm} ; W_{\text{dir}} = 3.5\text{mm} ; S_{\text{dri}} = 3.5\text{mm} ;
\end{align*}
\]
4.2.3 Simulated Results

Figure 22 Simulated return loss of the proposed DSPSL-fed quasi-Yagi antenna

Figure 23 Simulated input resistance and reactance of the quasi-Yagi antenna
Figure 24 Simulated radiation patterns (E-plane co-polar and cross-polar) at 4GHz

Figure 25 Simulated radiation patterns (H-plane co-polar and cross-polar) at 4GHz
4.2.4 Analysis of the Simulated Results of Quasi-Yagi Antenna

The simulated return loss of the quasi-Yagi antenna is shown in Figure 22. At frequency 4GHz, the simulated relative bandwidth of which the return loss is less than -10dB is about 30%. Across the 10-dB return-loss band, the simulated gain is 5.8-6.5dBi. Figure 23 shows the input resistance and reactance impedance of the antenna. Input resistance is equal to 100 Ω in ideal case; otherwise, the return loss would increase. Power consumption depends on the reactance impedance. Therefore, the reactance impedance should be as least as possible. When the frequency is between 3.5GHz and 5.5GHz, the input resistance is in the range of 110 ± 10 Ω and the reactance impedance is in the range of 20 ± 5 Ω. Moreover, the simulated patterns of E-plane and H-plane polarization are shown in Figure 24 and 25 respectively. Both E-plane and H-plane have a good front-to-end ratio which is better than 15dB and the cross-polarization has a great extent at the centre frequency too.
4.3 Mixer Design

4.3.1 Introduction

Usually, mixer is a three-port circuit included two inputs ports and one output port. It generates an output frequency which is equal or difference of two input frequencies or their harmonics. The selection of the output frequency relies on which kind of filters added. Basically, there are two frequency conversion processes. One is up-conversion in a transmitter, another one is down conversion in a receiver.

(a)

(b)

Figure 26 Frequency conversion process (a) Up-conversion in a transmitter (b) Down-conversion in a heterodyne receiver
For up-converters, the two input ports are excited by low intermediate frequency signal (IF) and local oscillator. Radio frequency is transmitted to output port. On the other side of the picture, two input ports are referred as radio frequency signal and local oscillator. The output port is called IF port.

Most mixers obey the principle of signal multiplication in time domain. For down converter, the mathematical formula is shown on the followings

Assuming there is a RF signal input: \(A \cos (\omega_1 t)\)

\[\text{LO input : } B \cos (\omega_2 t + \delta(t))\]

After mixing the signal by the mixer,

\[\text{IF Output} = A \cos (\omega_1 t) B \cos (\omega_2 t)\]

\[= \frac{AB}{2} \left[ \cos(\omega_1 t - \omega_2 t) + \cos(\omega_1 t + \omega_2 t) + \delta(t) \right]\]

The above equation shows that both high frequency and low frequency signals will be generated. To avoid the interference by different frequencies co-exist, some components are added to obtain the desired signal at a certain frequency.
4.3.2 Diode Mixers

To operate the up or down conversion, active components such as diode and FET are required to mix two frequencies up. In modern mixer circuit designs, Schottky diodes are commonly used. The reason of choosing them is that the switching speed is apparently higher and conversion loss is lower. Diodes will operate when a DC forward biasing is applied. That means it is necessary for the Local Oscillator (LO) provides a small DC current flows to the Schottky diodes.

Diodes are square-law devices which produce a strong mixing signal when excited within its operating frequency. For down converting mixer, the Local Oscillator (LO) is mixed with the wanted RF signal to generate IF signal. The theory behind is that when a small-signal voltage is applied to the diode, voltages as well as currents are generated in the junction at other sideband frequencies. These frequencies are called the small-signal mixing frequencies $\omega_n$. The relation of $\omega_n$ is given by

$$\omega_n = \omega_{RF} + n\omega_{LO}$$

where $n = \ldots -3, -2, -1, 0, 1, 2, 3 \ldots$

![Figure 27 Mixer spectral outputs](image-url)
4.3.3 Double Balanced Mixers

The previous section comments on how a diode plays an important role in mixing two frequencies. This section is going to describe the diodes integrating with the hybrid to compose a mixer.

For diode mixer circuit design, it is divided into two main streams – single-diode mixers and balanced mixers. Single-diode mixers are practical but they have some inevitable faults. Apparently, the most difficulty is that a filter diplexer is needed. On the other hand, balanced mixers deal with these faults and also have a better performance such as better power handling capabilities and reject spurious responses, LO noise, low conversion loss and spurious signals. Generally, singly balanced mixers based on 90-deg and 180-deg hybrids. According to the novel rat race being a kind of 180-deg hybrids, a singly balanced mixer using 180 deg hybrid is designed.

![Singly balanced mixer using 180-deg hybrid](image)

Figure 28 Singly balanced mixer using 180-deg hybrid

The block diagram illustrates the balanced mixer consists of two single-diode mixer. Two individual mixers connected to two isolated ports of the
hybrid. The remaining ports are used for the LO and RF inputs. LO-to-RF isolation of the mixer should be good such that the RF signal will not pass through LO ports causing signal loss. Based on Figure 26, the LO is applied the difference port while the RF is applied to the sum port. As a result, LO voltage has 180° and RF voltage has 0° phase difference at two diodes.

The direction of the diodes should be taken into consideration.

Figure 29 Normal operation of the balanced mixer

The arrows show the directions of RF voltage and LO voltage. To ensure the IF signal combines together, the direction of two diodes is reversed. The junction-conductance waveforms are in phase. The formula expressed in time domain for small-signal current is:

\[ i(t) = g(t) v(t) \]

where \( v(t) \) is the total small-signal voltage across the diode. As the applied RF voltage is in phase at the diodes, by the equation. The conductance waveforms are in phase. All signals including those at IF frequency are therefore in phase and hence, the IF currents combine at the diodes joint.
4.3.4 Low Pass Filter

Figure 25 shows the outputs containing spectrum with different frequency. In this case, radio frequency is set to be 4GHz and Local Oscillator is 3.99GHz. The objective of intermediate frequency is therefore 10MHz. As a result, a low-pass filter is added to eliminate other frequency spectrums.

Figure 30 Eliminated mixer spectral outputs by LPF

It is a five element low-pass filter. The length and width are optimized by the simulated software.

Figure 31 Schematic of microstrip LPF
The objective of the low-pass filter is to filter out the radio frequency. Therefore, there are two optimized goals in the simulation. The first one is that $S_{12}$ should be below -20dB around 4GHz. Truly, the 10MHz IF signal cannot be blocked. Thus, the $S_{12}$ is above -2dB below 10MHz.
4.3.5 Matching network

The purpose of the matching network added is to provide a maximum power is delivered from RF input to LO output. For the easiest way, microstrip line is integrated instead of the active components such as inductors and capacitors. The advantage of using microstrip line is low cost and easier to integrate that without any soldering.

4.3.6 Return Path for RF, LO and IF signals

For LO, RF signals, the diode is a load for these two signals. The design of mixer is to apply these two signals to the load. As a result, a return path for frequency around 4GHz is added in the mixer circuit. The way providing the return path is not the same as low frequency signal. A microstrip passive component is called “radial stub” which is realized a “short circuit” at the point where it is placed.

![Figure 33 Schematic of microstrip radial stub](image)
For IF signal, the diode serves as a generator instead of a load. The design is to provide this generator with a suitable load. Meanwhile, a return path for IF is needed. A $\lambda_{RF}/4$ short stub is implemented at the rat-race hybrid. This short stub not only supplies IF return path, but also it has no effect on RF and LO signals. An addition simulation of the rat-race hybrid is therefore required.
Figure 36 Simulated results of the rat-race hybrid adding $\lambda_{RF}/4$ short stub

Apparently, the performance is not affected by the additional $\lambda_{RF}/4$ short stub. The reason is that the $\lambda_{RF}/4$ short stub provides 180° path difference at the interact point and an additional 180° phase is added at the end of short stub through the via. Thus, the signal is in-phase between the transmitted and reflected.
Chapter 5  Design an Active Integrated Antenna Based on the Novel Rat-race Hybrid

5.1 Block diagram of the Balanced Mixer Using Novel Rat-race Hybrid

Port 1 is a microstrip port that connects to Local oscillator (LO) while port 2 is a DSPSL port that integrated with a DSPSL-fed quasi-Yagi antenna. Port 1 and port 2 are related that the waves which split from port 1 or port 2 are equally distributed to port 3 and port 4. Moreover, since two radio frequency signals split from port 2 are out-of-phase and two local oscillator signals split from port 1 are in phase, the mixer diodes(SMS 7621-079) added at port 3 (on top layer) and port 4 (on bottom layer) are reversed. Then, the intermediate frequency (IF) signals are in phase and they are combined using a via. By the properties of low-pass filter, only 10MHz IF is generated.
5.2 Simulated Results

Figure 38 Schematic of simulated balanced mixer

Figure 39 Simulated mixer loss
Figure 38 shows the schematic of the balanced mixer or active integrated antenna. Port 1 and port 2 is excited by LO and RF respectively. At port 1 of the rat-race hybrid, LO signal including power (5-10dbm) is applied for the mixer diodes operation. At port 2 of the rat-race hybrid, the “PORTF” is pretended to be an antenna and its power is -30dBm. In addition, matching network is joined between the mixer diodes and port 3 to eliminate mixer loss. Mixer loss is the majority consideration in mixer circuit designs. Usually, Mixer loss is acceptable at 7dBm. By the simulated result shown in figure 37, the mixer loss is estimated around 5dBm.

Parameters:

Matching network: width = 1.6 length = 4.2

Transmission line between the port and mixer diode: width = 0.6 length = 11.5
5.3 Configuration of Active Integrated Antenna

Figure 40 Configuration of the active integrated antenna (a) Top layer (b) middle layer (c) bottom layer
The composition of active integrated antenna is displayed in Figure 20. The functions of via, mixer diodes, radial stubs, LPF are described at chapter 4. Moreover, the DSPSL-fed quasi-Yagi antenna should be placed at the centre of the microstrip. Thus, the lower part of the microstrip exists although there does not contain any metallization.
Figure 42 Fabrication of active integrated antenna
Chapter 6 Measurement and Discussion of Active Integrated Antenna

After the fabrication, measurement is needed to prove the simulation whether it is accurate. The measurement is measured in near-field measurement system room.

Figure 43 Block diagram of the measurement system

The arrangement of the devices in the measurement room is shown in Figure 41. The RF generator connecting to the transmitter is set to be 4GHz with -10dBm power. The RF generator connecting to the LO port gives suitable power to the diodes so as to trigger off the active circuit. Distance between the RF transmitter and RF receiver is 3m. It is important to lengthen the distance accurately because it is useful for calculations. The mixer originally generates some harmonics current. By inserting the low-pass filter, only the intermediate
Frequency (10MHz) is brought out to the output port which is measured by spectrum analyser.

**Measurement equipments List**

**Standard Antenna Horn**

- To connect to the RF generator for operating as a transmitter. The antenna gain ranging from 2GHz to 8GHz must be provided on a datasheet.

**Agilent E4438C ESG Vector Signal Generator (250KHz - 6.5GHz)**

- To generate 4GHz signal frequency to the standard antenna (transmitter).

**IFR 2052 AM/FM RF Signal Generator Signal Generator (10KHz - 5.4GHz)**

- To generate 3.99GHz signal frequency to the hybrid. It is regarded as a Local Oscillator.

**HP 8593E Spectrum Analyser (9KHz – 26.5GHz)**

- To measure the power of the spectrum at 10MHz

![Figure 44 Display of the signal strength by the spectrum analyser at 10MHz](image)
6.1 Measurement One – Polarization Patterns of E-plane and H-plane

This measurement is to find the patterns of E-plane and H-plane polarization including both co-polar and cross-polar polarization.

The measurement arrangements are

1. Frequency of local oscillator is fixed at 3.99GHz with the power of 10dBm.
2. Frequency of RF generator is fixed at 4GHz with the power of -10dBm.
3. The values are taken each 5° rotating angle by the spectrum analyser at 10MHz.

<table>
<thead>
<tr>
<th>E-plane</th>
<th>Co-polar</th>
<th>Cross-polar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard antenna (Transmitter)</td>
<td>horizontal</td>
<td>horizontal</td>
</tr>
<tr>
<td>Active integrated antenna (Receiver)</td>
<td>vertical</td>
<td>horizontal</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>H-plane</th>
<th>Co-polar</th>
<th>Cross-polar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard antenna (Transmitter)</td>
<td>vertical</td>
<td>vertical</td>
</tr>
<tr>
<td>Active integrated antenna (Receiver)</td>
<td>horizontal</td>
<td>vertical</td>
</tr>
</tbody>
</table>

(b)

Table 4 Direction of the standard antenna and active integrated antenna to obtain the polarization pattern of co-polar and cross polar

(a) E-plane    (b) H-plane
Figure 45 Measured radiation pattern of the active integrated antenna at 4GHz
(a) E-plane  (b) H-plane
The measured co-polarization and cross-polarization patterns for the E-plane and H-plane at 4GHz are shown in Figure 43. The received cross-polarization patterns of E-plane and H-plane were around -20dB and -30dB respectively. They are both lower than the maximum co-polar patterns.

The measured front-to-end ratio is worse than that of the simulated result. For E-plane, the front-to-end ratio is -18dB. For H-plane, the front-to-end ratio is approximately -19dB. Practically, the performance is acceptable.
6.2 Measurement Two – Measurement the Signal Strength Variation When $P_{LO}$ Changes

The measurement is to show how the signal strength varies if the power given by local oscillator is changed. In addition, based on the data obtained, an optimum power of local oscillator can be decided. The optimum power decision depends on the signal strength and it should be as small as possible.

The measurement arrangements are

1. The frequencies of RF generators -transmitter and receiver are fixed at 4GHz and 3.99GHz respectively

2. The directions of both antennas are fixed and E-plane co-polar polarization is the reference of the measurement.

3. The power of transmitter is fixed while the power of LO changes.

4. The data is taken by recording the signal strength displayed on the spectrum analyser.
Figure 46 $P_{LO}$ verses $P_{if}$ ($P_{LO}$ ~ -10dBm to 10dBm)

Figure 47 $P_{LO}$ verses $P_{if}$ ($P_{LO}$ ~ 0dBm to 12dBm)
From Figure 46, it is obvious that the power of LO should not be lower than 2dBm. To examine the graph obtained accurately, Figure 47 reveals the IF signal strength for the frequency ranging from 0dBm to 10dBm. Also, it is the range of choosing the optimum power of LO generated. As the curve shown in Figure 5 is smooth, 7dBm of $P_{LO}$ is chosen. As a result, the power of LO is fixed on the following discussion.
6.3 Measurement Three – Active Integrated Antenna Gain Plus Mixer Loss

Mixer loss is a major concern of the active integrated antenna design. However, the gain of the active integrated antenna cannot be known in the measurement process. Only mixer loss plus active integrated antenna gain is evaluated.

By the formula,

\[ \text{Mixer Loss} + G_{AIA} = P_{IF} - P_{LO} + L_s - G_{\text{standard antenna}} + L_{\text{RF Line}} + L_{\text{IF Line}} \]

where \( G_{AIA} \) is the active integrated antenna gain,

\( P_{IF} \) is the IF power recorded by the spectrum analyser

\( P_{LO} \) is the power of the local oscillator generated

\( L_s \) is the transmission path loss

\( G_{\text{standard antenna}} \) is the standard antenna gain

\( L_{\text{RF Line}} \) and \( L_{\text{IF Line}} \) are the line loss at certain frequency

\[
L_s = 92.4 + 20 \log f (\text{GHz}) + 20 \log d (\text{km}) \text{ dB}
= 92.4 + 20 \log (4) + 20 \log (0.003)
\approx 54\text{dB}
\]

By setting \( P_{LO} = 7\text{dBm} \) and the frequency of LO sweep from 3 to 5 while RF sweeps form 2.99 to 4.99. The mixer loss plus antenna gain verses frequency is obtained.
The performance of the mixer loss is good. The curve shown in the graph is not fluctuated. This feature is contributed by the compact broadband rat-race hybrid having a wide isolation bandwidth. By the simulated result, the gain of DPSIL-fed quasi-Yagi antenna is around 6dB at 4GHz. The mixer loss is guessed to be -6dB. The insertion loss is relatively low.

Figure 48 Mixer loss plus antenna gain against frequency
6.4 Measurement Four – Inter-port Isolations Versus Frequency

![Graph showing inter-port isolations against RF frequency]

Figure 49 Measurement inter-ports isolation against RF frequency

Inter-ports isolation is important, otherwise, the signal radiated by the antenna will interfere with LO. Thus, RF should be isolated with LO, vice versa. Generally, it is desirable that the isolation is good among three ports. Figure 47 shows the measured inter-port isolations of the mixer. The LO-to-RF isolation is above 50dB from 3 to 4.5GHz. The RF-to-IF isolation is higher than 35dB at the same range of frequency. The LO-to-IF isolation is around 25dB which is lower than RF-to-IF isolation. It is because before the IF filter having additional rejection, the combing point will reject the out-of-phase RF signals but in-phase LO signals do not.
Chapter 7 Conclusion

To conclude, a novel compact broadband hybrid is reported. It has some extraordinary characteristics being a 180° hybrid. Chapter 3 demonstrates the proposed rat-race has the same function with the conventional one but it has a better performance. It is composed of three microstrip line ports and one DSPSL port by using multilayer technology. When compared with the conventional rat-race coupler, the most obvious advantage is the appearance. The proposed rat-race exhibits compact size which is only about 33% area of the conventional one. Moreover, the isolation bandwidth is independent of frequency between port 1 (microstrip port) and port 2 (DSPSL port) because of the conversion from the double-sided parallel-strip line to the back-to-back microstrip line. The symmetric structure improves the amplitude and phase balance which are greatly concern in designing hybrid. What’s more, it is easier to construct the circuit when different frequencies of circuits are needed. For example, if the hybrid is made to operate at 10GHz instead of 4GHz for the centre frequency, the parameters such as the width and circumference of the rat-race ring and spacing between four ports should be carefully calculated as well as fabricated. However, for the proposed one, there exists only one parameter for sweeping the centre frequency which is a pair of back-to-back microstrip lines.
Hybrids are always found in RF circuits such as mixers, power dividers, phase shifters and power divider. The broadband compact rat-race is also easy for circuit integration of both microstrip line port and DSPSL port. An active integrated antenna is designed by rat-race mixer integrating with DSPSL-fed quasi-Yagi antenna. The measurement of the active integrated antenna is taken to demonstrate the advantaged and feasibility of the rat-race. Inter-port isolation, mixer loss, compactness are improved when compared with the performances of conventional rat-race using in a mixer. Moreover, the characteristics of DSPSL-fed quasi-Yagi antenna are examined. In the E-plane and H-plane polarizations, the cross-polarization patterns are better than 15dB and 30dB which are lower than the maximum co-polarization patterns at 4GHz. The front-to-end ratio is good such that the antenna part is isolated to the mixer. As a result, an active integrated antenna based on compact broadband rat-race hybrid is done which has the advantages of low cost, low loss and small size.
Components List

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
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</thead>
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<tr>
<td>PCB Board ($\varepsilon_r = 2.94, h = 0.762\text{mm}$)</td>
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</tr>
<tr>
<td>Mixer Diode (SMS7621-079)</td>
<td>2</td>
</tr>
<tr>
<td>SMA Terminal</td>
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References


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I would like to thank Dr. Xue Quan who is my final year project supervisor. He gives me the guidance and support from the beginning of my final year project starting date until the end. The topic he provided to me is very interesting that the rat-race hybrid circuit design is unique in City University of Hong Kong. Moreover, he has requested team-mates and me having one presentation bi-week. This arrangement pushes my fyp progress forward and improves my presentation skills. I sincerely thank him for contributing extra time for us.

Secondly, I want to thank my fyp mentor, Jin Shi, too. At the beginning of my fyp, he taught me much technical knowledge in rat-race hybrid designs and demonstrates how to use the simulated softwares. He shows the patient, concern and endeavour to give me guidance.

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