Design of Lumped Rat-Race Coupler in Multilayer LTCC

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Abstract — This paper proposes a compact lumped rat-race coupler configuration. Combining the advantages of lumped elements – low spurious problem and predictable response – with multilayer low-temperature co-fired ceramic technology, circuit layouts can be integrated vertically to realize a miniaturized rat-race coupler. The proposed coupler uses high-pass and low-pass lumped models to replace the transmission line sections of the conventional design. A new structure with enhanced bandwidth is achieved by increasing the order of the $270^\circ$ transmission line section. Measurement results are shown to validate the design and theoretical prediction, demonstrating 98.63% area reduction compared to conventional rat-race coupler and a 50% fractional bandwidth.

Index Terms — Low-temperature co-fired ceramic, lumped circuit, rat-race coupler.

I. INTRODUCTION

Recently, the need of RF circuits with high performance and compact size has attracted much attention in wireless and mobile communication systems. Rat-race coupler is a kind of power divider or combiner and serves as a core component in many RF modules, e.g. balance mixers, balance amplifiers and feeding networks of antenna arrays [1]. The circuit configuration of a conventional 3-dB rat-race coupler [2] is shown in Fig. 1. It is composed of one $3\lambda/4$- and three $\lambda/4$-line sections. A signal applied to a sum port or a difference port is equally split at two output ports with in-phase and out-of-phase responses, respectively, while the sum and difference ports are isolated to each other.

However, conventional rat-race coupler usually suffers from large real estate, especially in low frequency applications. Many approaches have been proposed to miniaturize the coupler size, such as using the slow-wave artificial transmission lines [3], [4], the quarter wavelength coupled lines [5], [6], the left-handed artificial transmission lines [7], and the lumped elements [8]-[10].

In this paper, a lumped rat-race coupler is developed to achieve not only size miniaturization but also bandwidth enhancement. In section II, the transmission line sections of the conventional rat-race are replaced by lumped II-networks. Besides, a higher order lumped model is adopted to realize the $270^\circ$ section and to improve the bandwidth. In section III, the lumped circuits are realized by low-temperature co-fired ceramic (LTCC) technology, exploiting its multilayer three-dimensional layout capability for the size reduction. The simulation and measurement results are presented. Finally, brief conclusions are drawn in Section IV.

II. LUMPED RAT-RACE COUPLER DESIGN

In general, a transmission line of electrical length $\theta$ can be replaced by an equivalent lumped II- or T-network at the design frequency. It is accomplished by equating the ABCD matrix entries for the transmission line segment to the entries for the equivalent lumped element networks. To achieve the equivalence at a wider frequency band, the transmission line can be replaced by $n$ cascaded II- or T-networks, each with the electrical length $\theta/n$.

From [11], The ABCD matrix of a II-shaped equivalent circuit model shown in Fig. 2 is

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
1 + \frac{Y_2}{Y_1} & \frac{1}{Y_3} \\
\frac{Y_1 + Y_2 + Y_3}{Y_1} & \frac{1 + Y_1}{Y_3}
\end{bmatrix}
$$

(1)

where $Y_1$, $Y_2$ and $Y_3$ denote the admittance of the elements. Comparing the ABCD matrix of a transmission line section...
Fig. 3. (a) Transmission and reflection frequency responses of 90° phase advanced transmission line replaced by single and cascaded Π-cells. (b) Phase differences of 270° transmission line, single Π-cell and cascaded Π-cell versus 90° transmission line.

and the Π-cell, the admittance of the elements in Fig. 2 are represented by

$$Y_1 = Y_2 = j \frac{1}{Z_o} \cos \theta$$

$$Y_3 = \frac{-j}{Z_o} \sin \theta$$

(2)

$Z_o$ and $\theta$ are the characteristic impedance and the electric length of the transmission line segment. For lossless circuit, the susceptance elements of the Π-cell can be realized by lumped inductors or capacitors.

Hence, according to (2), the quarter wavelength transmission line in the conventional rat-race coupler can be replaced by a Π-cell with one series inductor and two shunt capacitors. On the other hand, the 270° section can be substituted by a 90° phase-advanced transmission line [12]. The substitution results in a smaller slope parameter of the frequency-dependent electrical length and therefore leads to a broader operation bandwidth. It needs one series capacitor and two shunt inductors in the Π-cell to take the place of the 90° phase-advanced section. The phase-advanced section can also be realized by cascading two Π-cells with electric length equal to -45° as shown in the inset of Fig. 3(a). Basically, such a circuit has the high pass response. The reflection and transmission frequency responses of the single and cascaded Π-cells plotted in Fig. 3(a) show that the cascaded configuration can shift the cut-off frequency to a lower frequency and increase the operating frequency range. The phase differences of 270° transmission line, single Π-cell and cascaded Π-cell versus 90° transmission line is plotted in Fig. 3(b). The cascaded Π-cell one has a flattest phase difference response, which will results in a broader operation bandwidth.

Fig. 4(a) shows an equivalent lumped circuit model of a rat-race coupler with the 270° section replaced by two cascaded highpass Π-cells for bandwidth enhancement, whereas three 90° transmission line sections are realized by three single lowpass Π-networks. To reduce the number of lumped elements, the two inductors $L_2$ in the highpass section are shunted and so do the capacitors $C_1$ in the lowpass cell. Besides, the parallel LC tank, $L_2$ and $C_1$, connected to port 2 and port 4 are replaced by a capacitor $C_3$ with the same admittance at center frequency of the coupler. Therefore, only ten lumped elements are needed to realize the rat-race coupler and the implement of large inductors, e.g. $L_2$, can be avoided.

III. RESULTS

The proposed lumped rat-race coupler is implemented in a multilayer LTCC substrate by three-dimensional arrangement to further reduce the circuit size. The relative dielectric
The constant of the substrate is 7.6 with the loss tangent of 0.005. The coupler is realized in the top six layers of the LTCC substrate. Each dielectric layer has thickness of 50 μm and the metal patterns on the layers are formed by 13μm-thick silver. The design frequency of the 3-dB rat-race coupler is 2.4GHz and the reference impedance $Z_0$ of the coupler is 50 Ω. By (2), the corresponding values of the lumped elements can be obtained as $L_1 = 4.69\text{nH}$, $L_2 = 11.3\text{nH}$, $C_1 = 0.93\text{nH}$, $C_2 = 1.32\text{nH}$, and $C_3 = 0.55\text{nH}$.

The physical configuration of the lumped rat-race coupler is shown in Fig.5. It uses three-turn stacked inductors and parallel plate capacitor in the LTCC substrate to realize the lumped elements. The circuit area is about $2.71\times2.33\text{ mm}^2$, i.e. $0.06\times0.052\lambda^2$, where $\lambda$ is the wavelength in the substrate. Fig. 6 shows the photograph of the fabricated coupler. The frequency response of the coupler is verified by full wave simulator, HFSS [13]. The measurement is carried out using Agilent N5230A and by on-wafer probe.

Fig. 7 shows the simulation and measured results of the fabricated circuit. If 14dB return loss is referred, the measured data indicate that the bandwidth at ports 1 and 4 is 52.3% and 60.8%, respectively. At the design frequency, the measured insertion loss $|S_{21}|$, $|S_{31}|$, $|S_{24}|$ and $|S_{34}|$ are -3.06 dB, -3.56 dB, -3.5 dB and -3.2 dB, respectively. For a 20-dB reference, the measured isolation has the bandwidth of 66.8%. Fig. 8 plots
the magnitude and phase imbalance. The bandwidth of a ±10\(^\circ\) deviation is about 65.3\% and the bandwidth with ±1dB imbalance is about 50.2\%. The comparisons between fabricated rat-race coupler and the conventional design are listed in Table I.

### IV. CONCLUSION

In this paper, a lumped rat-race coupler is developed and fabricated in multilayer LTCC technology. The distributed transmission line is substituted by equivalent II-shaped circuit model to achieve size reduction. The 270\(^\circ\) section is replaced by 90\(^\circ\) phase advanced transmission line and substituted by two cascaded II-cells to improve the operation bandwidth. Compared with the conventional rat-race coupler, the developed coupler in this paper can achieve 98.63\% size reduction. The operation bandwidth is improved to about 50\%.

### REFERENCES


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### TABLE I

Comparison between Proposed Rat-Race Coupler and Conventional Rat-Race Coupler

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<thead>
<tr>
<th></th>
<th>This work</th>
<th>Conventional design</th>
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<tr>
<td>Return loss (14 dB)</td>
<td>52.3 %</td>
<td>42 %</td>
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<tr>
<td>Isolation (20 dB)</td>
<td>66.8 %</td>
<td>31 %</td>
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<tr>
<td>Magnitude imbalance</td>
<td>50.2 %</td>
<td>31 %</td>
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<td>(±1 dB)</td>
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<tr>
<td>Phase imbalance</td>
<td>65.3 %</td>
<td>31 %</td>
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<td>(± 10(^\circ))</td>
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