Introduction: Quadrature differential signals are used in a wide range of fields such as wireless communication and measurement. For example, quadrature oscillators are used to operate an I/Q (inphase/quadrature) mixer and to measure complex filter frequencies [1–3]. The generation of the quadrature differential signal is divided into two approaches: an active method and a passive method.

In the active method, a method using a differential oscillator or a divide-by-two divider is known [4–7]. However, since many active elements are used, problems such as an increase in power consumption and a decrease in linearity has been pointed out.

In the passive method, the number of active elements which behave as noise sources can be reduced, so that both an improvement of phase noise and a reduction in power consumption can be achieved. For example, an approach which combines two 90° hybrid circuits and one coupler has been introduced, but there is a problem in the circuit is large. In order to solve this problem, a ring resonator has been proposed, and this circuit succeeded in reducing circuit size and phase difference characteristics. However, it still remains a problem in that the insertion loss increases to 5.2 dB and the usable band is narrow [8]. The RC polyphase filter is a circuit that has good phase deviation characteristics and can generate quadrature differential waveforms in a wide frequency band, but because of the use of resistors, the insertion loss is as large as 7 dB in one stage [9]. Recent studies have reported polyphase filters that can control the center frequency by incorporating transistors in the circuit [10, 11]. A sequential-phase feeding network is small and the insertion loss is as small as 1.4 dB, while it has a large phase deviation characteristic [12]. On the other hand, six-port quadrature couplers with balanced and unbalanced ports can generate quadrature differential waveforms with a wide bandwidth, but this has a problem that the phase difference characteristics and bandwidth deteriorate at single ended input [13]. For this reason, this quadrature coupler is not suitable to be configured together with oscillators using GaAs-IC or discrete, which are advantageous for low phase noise. In the present letter, we propose a new six-port rat-race coupler that can obtain a high-precision quadrature differential waveform is used. Since Figure 1(b) is symmetric about the AA’ plane, the two-terminal pair circuit of port 1 and port 3 shown in Figure 2 can be obtained by applying even-odd mode analysis [14].

Circuit configuration and analysis: Figure 1(a) shows the configuration of the devised quadrature differential output six-port rat-race coupler. This circuit is composed of a 1/4 wavelength transmission line, a 1/2 wavelength transmission line, and a 3/4 wavelength transmission line, which each characteristic impedance is equal to the port impedance Z0. For ease of analysis, consider the circuit shown in Figure 1(b) in which the open stub and the 1/2 wavelength transmission line are removed and the only rat-race circuit path that has function of outputting a quadrature differential waveform is used. Since Figure 1(b) is symmetric about the AA’ plane, the two-terminal pair circuit of port 1 and port 3 shown in Figure 2 can be obtained by applying even-odd mode analysis [14].
Since an electric wall and a magnetic wall are assumed on the AA’ plane, 1/2 power is output to ports 1 through 3 and 1/2 power is output to ports 4 through 6.

Therefore, the transmission amount $|S_{21}|$ from port 1 to port 2 and the transmission amount $|S_{51}|$ from port 1 to port 5 are as follows:

$$|S_{21}| = \frac{1}{2} - |S_{11}|^2 - |S_{12}|^2 = \frac{1}{4}$$  \hspace{1cm} (9)

$$|S_{51}| = \frac{1}{2} - |S_{41}|^2 - |S_{61}|^2 = \frac{1}{4}$$  \hspace{1cm} (10)

$$S_{21}[\text{Fig. 1b}] = \frac{1}{2}$$  \hspace{1cm} (11)

$$S_{51}[\text{Fig. 1b}] = \frac{1}{2}$$  \hspace{1cm} (12)

Since ports 2 and 3 and ports 5 and 6 are connected by a 1/4 wavelength transmission line, each port has a phase difference of 90°. Therefore, the transmission coefficients $S_{21}$ and $S_{51}$ are as follows:

$$S_{21}[\text{Fig. 1a}] = \frac{1}{2}j$$  \hspace{1cm} (13)

$$S_{51}[\text{Fig. 1a}] = \frac{1}{2}j$$  \hspace{1cm} (14)

Next, the circuit of Figure 1(a) is analysed.

In Figure 1(a), there is an open stub, but the F matrix is an identity matrix because of the 1/2 wavelength, and the reflection coefficient and the transmission coefficient of each port are not affected at the center frequency.

Furthermore, in Figure 1(a), since ports 2 and 6 are connected to the 1/2 wavelength transmission line, they have a phase difference of 180°. Compared to ports 2 and 6 in Figure 1(b). Accordingly, the transmission coefficients $S_{21}$ and $S_{61}$ in Figure 1(a) are as follows:

$$S_{21}[\text{Fig. 1a}] = \frac{1}{2}j$$  \hspace{1cm} (15)

$$S_{61}[\text{Fig. 1a}] = \frac{1}{2}j$$  \hspace{1cm} (16)

Since the 1/2 wavelength transmission line connected to the ports 2 and 6 is assumed to be a lossless transmission line, the transmission coefficients other than those for ports 2 and 6 are the same as those in the circuit of Figure 1(b).

Based on Equations (5) through (7) and Equations (14) through (16), there is no reflection at port 1, no power is output at port 4, and the electric power input from port 1 is equally distributed to ports 2, 3, 5, and 6, and the phases are shifted to 0°, 90°, 180°, and 270°.

From the above, since the proposed circuit has the same port impedance and characteristic impedance, it can be designed simply by substituting the port impedance value for $Z_0$ in Figure 1(a).

Finally, the effects of the open stub and 1/2 wavelength transmission line are confirmed. As shown in Figure 1(b), there are two possible reasons why the six-port rat-race circuit generates phase errors: (1) the amount of phase change is different between the 1/4 and 3/4 wavelength transmission lines, and (2) a 1/4 wavelength transmission line between the output ports affects the amount of phase change between each port.

Figure 3 shows the phase characteristics of a 1/4 wavelength transmission line, a 3/4 wavelength transmission line, and a 1/4 wavelength transmission line connected to an open stub. The phase difference between a 1/4 wavelength transmission line and a 3/4 wavelength transmission line is 180° at the center frequency, but as the frequency moves away from the center frequency, the phase difference shifts significantly. On the other hand, the phase difference between the 3/4 wavelength transmission line and the 1/4 wavelength transmission line with the open stub connected remains close to 180° even away from the center frequency, indicating that the amount of phase change against frequency is uniform. As a result, by adding an open stub, it is considered that the phase difference characteristics between port 2 and port 6 and between port 3 and port 5 become uniform.

The phase change amount of a 180° transmission line with center frequency $f_0$, input, output, and characteristic impedance of $Z_0$ can be expressed as follows using frequency $f$ and phase difference $\theta$.

$$\frac{\partial \theta}{\partial f} = -\frac{\pi}{f_0}$$  \hspace{1cm} (17)

Equation (17) shows that when the 1/2 wavelength transmission line is connected to the output port, the amount of phase change becomes larger. Using this, the difference in the amount of phase change between ports 2 and 6 in Figure 4(c) becomes the bandwidth of the center frequency of 0.96 GHz was simulated using AWR Design Environment 13 ideal components.

The simulation results are shown in Figures 4(a–c). Figure 4(a) shows that the reflection loss and isolation are 15 dB or more within the band of 0.89–1.03 GHz, so that sufficient matching can be secured. Figure 4(b) shows that the transmission loss from the input port to each output port is less than 0.37 dB, and the input power is divided into four ways. Figure 4(c) shows that the phase shifts of ideal six-port rat-race coupler, (d) phase shifts of measured six-port rat-race coupler.

In order to confirm the principle, a quadrate differential output six-port rat-race coupler with a center frequency of 0.96 GHz was simulated using AWR Design Environment 13 ideal components.
Six-port quadrature
Sequential-phase feeding
Two-stage doubly polyphase filter
Sequentional-phase feeding network
Six-port quadrature couplers with balanced and unbalanced ports

shows the amount of phase shift from the input port to each output port when the amount of phase shift from port 1 to port 5 is 0°. Each output port is phase shifted to 0°, 90°, 180°, and 270° in a wide band. Thus, this circuit can obtain a quadrature differential waveform in a wide band.

Measurement results: Figure 5 shows the layout and a photograph of the prototype 0.96-GHz band six-port rat-race circuit. The rat-race circuit was formed on an FR4 substrate having a substrate thickness of 1.6 mm, a dielectric constant at 1 MHz of 4.5 to 4.9, and a dielectric loss tangent of 0.013 to 0.020. The characteristic impedance of the transmission line constituting this rat-race circuit is 50Ω.

Figures 4(a), (b) and (d) show the measurement results. In the 0.89–1.05-GHz band, the transmission loss from port 1 to ports 2, 3, 5, and 6 was 7.03±0.45 dB, and the reflection loss and isolation were found to be greater than 15 dB. When the phase shift amount from port 1 to port 5 is 0°, the wave shift amount from port 1 to ports 2, 3, and 6 is 90°±0.5°, 179.7±0.5°, and 268.4±1.7°, respectively, within the same band. The change of the phase shift amount of each port is within the range of ±1.7°. Therefore, the proposed rat-race circuit was confirmed to output a highly accurate quadrature differential waveform in a wide band. As the factor that causes the transmission loss to open, a circuit is formed on the basis of using lathe processing, and errors in the line width and line length are caused by the accuracy. Table 1 shows a comparison with circuits with similar roles. The proposed circuit is superior to the other circuits in terms of bandwidth, insertion loss, and phase error. (Note: In this letter, bandwidth defines the range where return loss and isolation are at least 15 dB.)

Conclusion: In the present paper, we proposed a quadrature differential output six-port rat-race coupler and showed through simulation and measurement that high-accuracy quadrature differential output with a low insertion loss and a simple configuration can be obtained.

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Table 1. Performance comparison with some reported quadrature phase generator

| Ref     | Technology                                      | Center frequency | FBW (15 dB) | Max insertion loss for FBW | Max phase error for FBW | Physical size (λg × λg) |
|---------|-------------------------------------------------|------------------|-------------|---------------------------|-------------------------|-------------------------|
| This work | Quadrature phase generation using a ring resonator | 0.96 GHz         | 16.7%       | 1.48 dB                   | 3.3°×1.25               | 0.75 × 1.25             |
| [8]      | Two-stage polyphase filter                      | 3 GHz            | 4.76%       | 5.2 dB                    | 5°×1.6                  | 0.16 × 0.16             |
| [9]      | Two-stage doubly polyphase filter               | 5.8 GHz          | N/A         | 14 dB(at 5.8 GHz)          | 6°(at 5.8 GHz)          | n/a                     |
| [12]     | Sequential-phase feeding network                 | 2.5 GHz          | 19.1%       | 1.4 dB                    | 17°×0.5                 | 0.25 × 0.25             |
| [13]     | Six-port quadrature couplers with balanced and unbalanced ports | 1 GHz            | 8.23%       | N/A                       | 7°×n/a                  | n/a                     |

*Simulated using AWR design environment 13 ideal components (Zg1 = Zg2 = 20Ω, type 2, single end).

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