Rat-Race Based Microstrip Coupler With Differential Port to Realize Monostatic RF Systems

R-W. Jungmaier*, R. Feger†, B. Prammer*, H. Jäger‡, and A. Stelzer*,†
*Institute for Communications Engineering and RF-Systems, Johannes Kepler University, Linz, Austria
†Christian Doppler Laboratory for Integrated Radarsensors, Johannes Kepler University, Linz, Austria
‡DICE GmbH&Co KG, Linz, Austria

***Abstract*— In this work a rat-race based microstrip coupler, usable to realize monostatic RF systems, is presented. The coupler combines the two functions of separating the transmit (TX) and receive signal together with the conversion from a differential to a single-ended TX signal since two ports of the proposed five port coupler can be used as a differential port. The two functions are realized in a single microstrip structure, leading to decreased losses and a space-saving layout. Simulations and measurements at 79 GHz confirm the function of the coupler.**

***Index Terms*— Couplers, microwave devices, radar.**

I. Introduction

Rat-Race couplers are well known and used in microwave devices to transfer microwave power between the key-components like amplifiers, mixers and antenna systems [1]. In frequency-modulated continuous-wave (FMCW) radar systems couplers are typically used to receive (RX) and transmit (TX) simultanously using a single antenna. Fig. 1 shows a typical monostatic radar system consisting of an oscillator, an amplifier, a coupler, an antenna and a mixer.

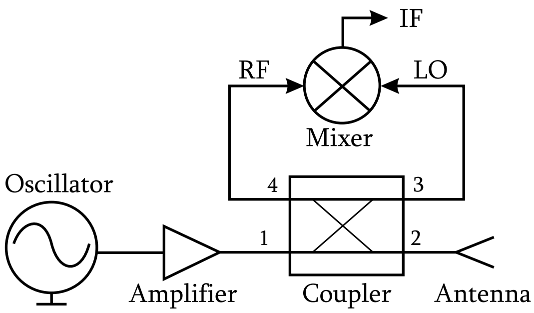

Fig. 1. A typical continuous-wave radar system making use of a coupler to realize a monostatic radar.

In Fig. 1 the oscillator in conjunction with the amplifier generates the TX signal. The coupler, consisting of four ports 1 to 4, delivers power from the input port 1 to the antenna (port 1→2) and to the mixer's LO port (port 1→3). In the reverse direction power is transferred from the antenna to the mixer's RF input (port 2→4). An important property is that port 4 is isolated from the TX signal on port 1 and its copies on port 3 and port 2 to avoid overdriving the mixer's RF input. Often RF signals are routed using single-ended microstrip transmission lines but typically RF ICs operating in mm-wave bands are realized using differential signals to allow a fully symmetic circuit design. Thus also transitions from chip to board are realized with differential signals. However, standard couplers on PCBs consist of single-ended transmission lines, which means that the differential signal has to be converted to a single-ended signal in order to allow a connection to standard microstrip structures. Fig. 2 shows a two coupler approach to facilitate the conversion between differential and single-ended signals (C1) and further feeding the rat-race coupler (C2) for separating TX and RX signals. The solution from Fig. 2 requires a large board area and introduces losses due to long microstrip lines. In this work an alternative solution is presented, which allows to realize a rat-race like structure capable of performing differential to single-ended conversion together with TX/RX separation.

II. Proposed Coupler Structure

The phase difference between the two lines of a differential signal should be 180°, which correspondens to the electric length of a transmission line of $\lambda/2$. The standard four port coupler C2 shown in Fig. 2 has a circumference of $3\lambda/2$. This coupler can be extended by an additional port with an offset of $\lambda/2$ with respect to P1 which leads to a single coupler as shown in Fig. 3. The proposed coupler from Fig. 3 provides one differential port P1n/P1p and three single-ended ports P2 to P4. Like a standard rat-race coupler the impedance of the port input lines is Z_0, while the impedance of the line forming the ring is $\sqrt{2}Z_0$.

The transmission lines between neighboring ports have a length of $\lambda/4$ except for the transmission line between the ports P1p and P1n with a length of $\lambda/2$. Assuming perfectly matched ports and an ideal differential signal (i.e. without a common-mode component) the introduced rat-race coupler from Fig. 3 can be described with a reduced scattering matrix. Ports P1p and P1n can be considered as a single differential port P1, thus the scattering matrix is reduced to a dimension of four by four. It is assumed that the signal at P1p is in phase with the signal at P1. Now the scattering matrix of the reduced five port rat-race coupler can be written as

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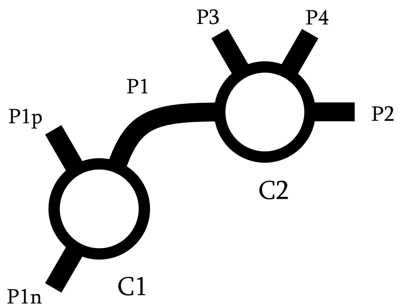

Fig. 2. Differential to single-ended coupler followed by a rat race coupler realizing differential to single-ended conversion together with TX/RX separation.

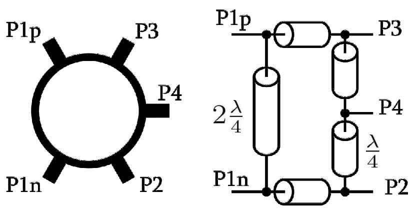

Fig. 3. Realization of the four port coupler with a single differential port P1p/P1n using the five port rat-race coupler.

$$[S] = \frac{\mathrm{j}}{\sqrt{2}} \begin{bmatrix} 0 & -1 & 1 & 0 \\ -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}. \qquad (1)$$

It can be seen from (1) that power from P1 is delivered to P2 and P3 whereas P4 is isolated and in the other direction power from P2 or P3 is delivered to P1 and P4. Finally P2 and P3 are isolated from each other.

III. Realization and Simulation

To employ the coupler in a radar system operating at 79 GHz an optimized layout was generated for the coupler from Fig. 3 using RF simulations in Agilent's ADS Momentum software. The layout was optimized for a 127 μm thick Taconic TLE-95 substrate. In Fig. 4 the simulation model of the coupler from Fig. 3 including a tapered transition to the bond pads is shown. The

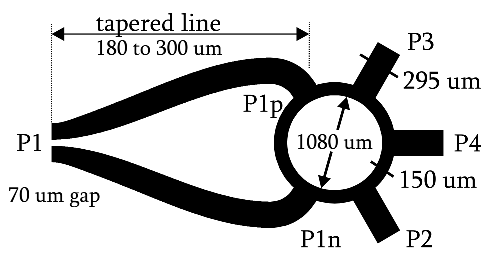

Fig. 4. Simulation model of the rat-race coupler with tapered transmission lines.

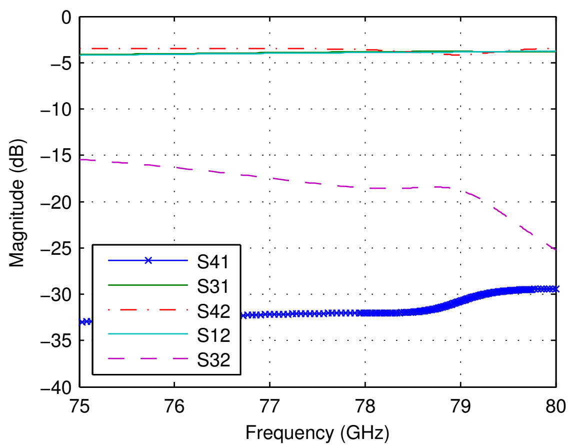

Fig. 5. Simulation results of the coupler including the tapered transition.

smallest dimensions of the coupler are the gap between the differential transmission lines and the width of the ring. To allow reliable manufacturing of the coupler the minimium achievable dimensions have been considered during simulation. The coupler was optimized with the constraints imposed by the manufacturing process to achieve a good isolation between the differential port P1 and P4 since P4 is intended to be connected to the RX mixer.

IV. Simulation Results

The simulations were performed assuming lossy substrate with a loss tangent of $\tan\delta{=}0.005$. The simulation results for the final coupler design are given in (2) and Fig.5.

$$|S| = \begin{bmatrix} -11.8 & -4 & -3.9 & -32.2 \\ -4 & -15.6 & -17.5 & -3.5 \\ -3.9 & -17.5 & -15.5 & -3.5 \\ -32.2 & -3.5 & -3.5 & -16.8 \end{bmatrix} \text{dB}. \qquad (2)$$

It can be seen that, as intended, power input into P1 is equally split between P2 and P3, whereas P4 is isolated from the TX power. In the reverse direction power from P2 is transferred equally to P1 and P4.

V. Measurement Setup and Results

To verify the simulations, the five port rat-race coupler was integrated into a 79 GHz monostatic radar system as it is shown in Fig. 6. A TX chip, comprising a VCO and a power amplifier, differentially feeds the coupler on P1 and provides the LO signal for the RX mixers. The TX chip's output is connected to P1, the antenna is connected to P2 and the mixers RF inputs are connected to P3 and P4. The baseband signals IF3 and IF4 are sampled by baseband hardware which allows to measure both the the RX signal received by the antenna via IF4 and the signal at P3 via IF3 to determine the isolation between P3 and P4. In a standard radar system the signal at P3 could be

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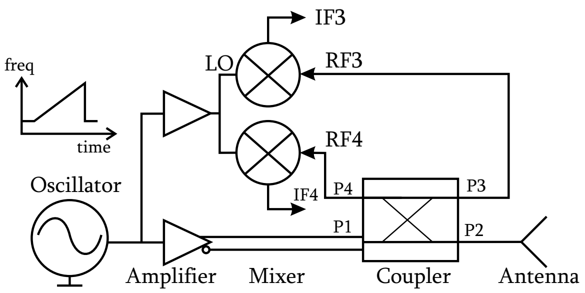

Fig. 6. Schematic of the realized hardware to test the coupler (DUT) in-system.

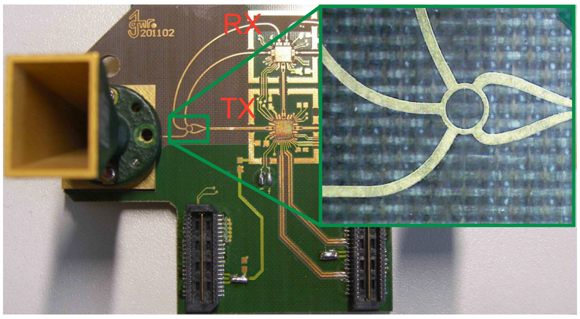

Fig. 7. Realized 79 GHz measurement system on 127 μm thick Taconic TLE-95 substrate.

used as LO input of the RX mixer. A photograph of the realized setup is shown in Fig. 7. The hardware consists of a three-channel TX IC with differential RF outputs and a four-channel single-ended receiver as presented in [2]. A horn antenna with a gain of 20 dBi was used in conjunction with a microstrip patch based transition from microstrip to WR12 waveguide. This setup was used to perform FMCW measurements with a frequency sweep from 79 to 80 GHz. In Fig. 8 the output spectra calculated from the signals IF3 and IF4 of a measurement using a single corner-cube as reference target are shown.

From Fig. 8 it can be seen that the isolation between P3 and P4 is approx. 15 dB which corresponds well with (2). According to the FMCW principle the copy of the TX signal being present at RF3 leads to a very low IF-frequency and is therefore suppressed by the IF filters in the baseband hardware. To avoid overdriving the input RF3 the FMCW measurement was carried out with reduced output power of -2 dBm. To test the forward path of the coupler the power at the waveguide transition was measured using a spectrum analyzer equipped with an external subharmonic mixer. For this measurement the full power available from the TX chip was used. A power of 7 dBm could be measured after the waveguide transition. This corresponds well with the 14 dBm available from the TX chip [2], if the 4 dB reduction due to the coupler according to (2) in conjunction with losses of 3 dB caused

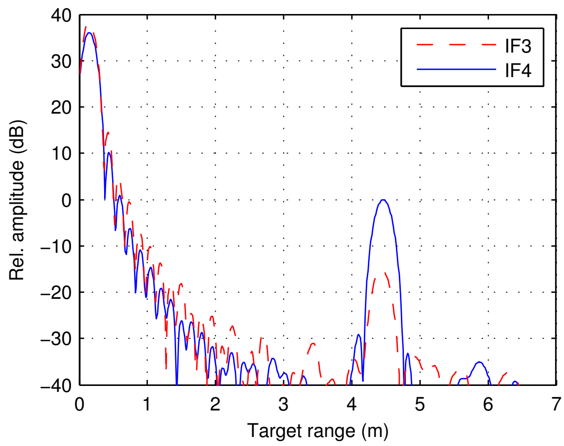

Fig. 8. Measurement results using a single corner-cube as reference target.

by the bond-wire interface, the waveguide transition, and the microstrip line with a length of 1 cm between TX chip and coupler are taken into account.

VI. Conclusion

In this paper a compact rat-race coupler with a single differential port has been presented. The differential port is realized by adding a fifth port to a classical rat-race coupler. Simulations showed that the function of conversion between differential and single-ended signals can be implemented together with the separation of TX and RX signal in a monostatic RF system with the proposed coupler. Compared to conventional solutions relying on multiple coupler the proposed solution leads to space-saving designs. The function of the coupler was verified using it in an FMCW system and by power measurements at the antenna port.

Acknowledgment

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