A Passive Circulator for RFID Application with High Isolation using a Directional Coupler

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***Abstract* — In this paper, a newly invented circulator for T/R switch of UHF radio-frequency identification (RFID) application is proposed to overcome TX-to-RX leakage problem. A microstrip coupled-line directional coupler is used for this passive circulator and the isolation characteristic is drastically improved not by complex method such as compensating phase velocity, but by considering both directional coupler itself and imperfect input impedance of the employed antenna. The measurement result of the proposed circulator using modified microstrip coupled-line directional coupler with employed antenna shows excellent TX-to-RX leakage suppression in the 860 MHz − 960 MHz, more than 45 dB enhancement at the center frequency compared to the conventional coupler. Experimental verification using RFID system is also performed to prove the validity of the proposed circulator.**

***Index Terms* — Coupled line directional coupler, RFID, High Isolation, TX-to-RX leakage.**

I. INTRODUCTION

The range of application of RFID system has been expanded explosively from just simple replacement of barcode to sensor networking such as location sensing. RFID system still has enormous potential to be applied for more fields, even mobile application, by satisfying the requirement of low cost and small size and long detection range.

One of the most distinctive characteristic of RFID system compared to other transceivers is duplexing that is necessary for isolating the RX signal from TX signal. Neither FDD (frequency division duplexing) nor TDD (time division duplexing) is used in RFID system although it adopts full-duplex system. It transmits continuous sine wave and receives the back-scattered data from a tag at the same time, at the same frequency band. Therefore, a form of TX-to-RX switching is essential to guarantee good TX-to-RX leakage suppression, to be further applicable.

TX-to-RX leakage must be removed in the receiver since it could degrade the several performances of RFID system. Sensitivity and detection range are decreased due to the LNA saturation and lowered dynamic range. DC offset problem could be also caused by self-mixing of the mixer. Using dual antennas for the transmitter and the receiver makes system unattractive as the size and the cost are doubled even if it can isolate TX and RX fairly well. So a directional coupler has been widely utilized as RFID T/R switch, since it is competitive in aspect of the complexity, the isolation and the cost, compared with active CMOS circulator or ferrite material circulator.

A conventional microstrip coupled-line directional coupler has, however, inherent drawback of poor isolation caused by different modal phase velocity in inhomogeneous dielectric material such as microstrip substrate. The effect of phase velocity difference in microstrip coupled-line directional coupler has been carried out [1] and several techniques for compensating this difference of the even-odd mode velocity have been proposed: wiggly line coupler [2], lumped element compensation [3], dielectric overlay on microstrip line [4].

Although the isolation characteristic of the directional coupler itself is very satisfactory by above compensation technique, TX-to-RX isolation becomes poor if those directional couplers are employed with an antenna. This problem comes from imperfect input impedance of an antenna. In this p140
aper, an effective method is proposed to achieve high isolation by considering not only coupled-line directional coupler but also antenna input impedance. We propose a methodology based on reflected power canceller (RPC) using the idle port [5].

II. THE ANALYSIS OF THE PROPOSED METHOD

The use of the proposed directional coupler as a circulator in the RFID system with a single antenna is shown in Fig.1. The transmitted signal is transferred to the *through* port and radiated by the antenna, so the insertion loss of the transmitted signal is less than 1 dB in a coupled-line directional coupler. The insertion loss of the received signal is about 10 to 20 dB which is the coupling factor. This is because the received signal is delivered by the coupling of the directional coupler. In spite of the insertion loss of the received signal, a coupled-line directional coupler can perform the role of the circulator in RFID reader, since the LNA recover the insertion loss of the received signal enough and a RFID system operates within somewhat short distance of less than 10 m.

Three ports of the directional coupler are used in TX, RX, and antenna, respectively as shown in Fig. 1. The TX-to-RX leakage flows to the receiver mainly through two paths when a conventional coupler is adopted: imperfect isolation of the coupler itself and reflection by the input impedance of an antenna.

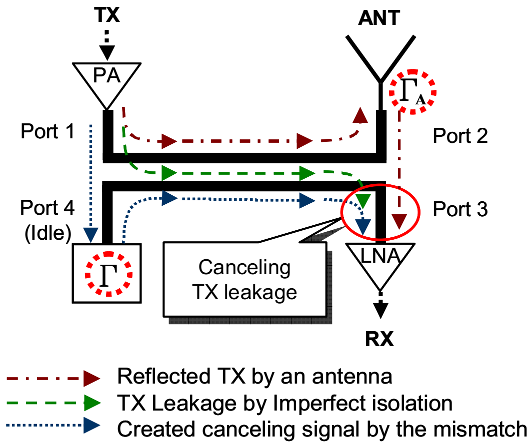

Fig. 1. The principle of the reflected power canceller using the proposed coupled-line directional coupler.

To increase isolation characteristic, these two leakage components must be removed and the proposed approach is canceling the leakage by canceling signal. The intended mismatch is introduced in the idle port to create the canceling signal as shown in Fig. 1. The reflection coefficient of the mismatch, therefore, is designed to make the canceling signal have same magnitude and anti-phase of the sum of the two leakage component. Then, the total leakage becomes zero by the canceling signal.

With above principle, the relationship among S-parameters of the conventional directional coupler and the input impedance of an antenna Γ_A and optimum reflection coefficient Γ of the idle port, is easily derived. S-parameters of the conventional directional coupler is

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & T & I & C \\ T & 0 & C & I \\ I & C & 0 & T \\ C & I & T & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \qquad (1)$$

where a_n represents an incident wave at the n-th port, and b_n represents a reflected wave from n-th port as shown in Fig. 2. The capital letters T, I, C are used for convenience, which represents the factors of *through, isolation, coupled.*

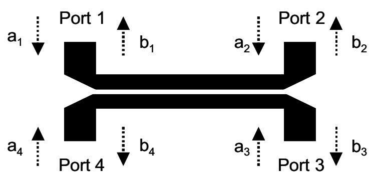

Fig. 2. Incident waves and reflected waves in a coupled-line directional coupler.

Since port 2 and port 4 of the proposed circulator are used for an antenna and mismatch load respectively as shown in Fig. 1, two more conditions are added, which is

$$a_4 = \Gamma b_4 , \qquad (2)$$

$$a_2 = \Gamma_A b_2 . \qquad (3)$$

By substitution of (2), (3) into (1), S-parameters of the proposed directional coupler can be expressed with the 2 x 2 matrix, considering only TX (port 1) and RX (port 3).

$$\begin{bmatrix} b_1 \\ b_3 \end{bmatrix} = \begin{bmatrix} C^2\Gamma + \frac{(T+C\Gamma I)^2\Gamma_A}{1-I^2\Gamma\Gamma_A} & (I+C\Gamma T)+\frac{(C+T\Gamma I)(T+C\Gamma I)\Gamma_A}{1-I^2\Gamma\Gamma_A} \\ (I+C\Gamma T)+\frac{(C+T\Gamma I)(T+C\Gamma I)\Gamma_A}{1-I^2\Gamma\Gamma_A} & T\Gamma^2 + \frac{(C+T\Gamma I)^2\Gamma_A}{1-I^2\Gamma\Gamma_A} \end{bmatrix} \begin{bmatrix} a_1 \\ a_3 \end{bmatrix} \qquad (4)$$

Since our goal is to isolate RX (port 3) from TX (port 1), S21 of (4) is to be zero as shown in (5), which is the form of the sum of the infinite geometric series.

$$(I+C\Gamma T)+\frac{(C+T\Gamma I)(T+C\Gamma I)\Gamma_A}{1-I^2\Gamma\Gamma_A} = 0 \qquad (5)$$

As shown in (5), Γ is very exact value because it considers the summation of infinite number of leakage paths from port 1 to port 3 but complicate to be solved. Equivalent equation of the (5) is

$$\begin{aligned}(I)+(C\Gamma T)+(T\Gamma_A C)+(C\Gamma I\Gamma_A C)+(T\Gamma_A I\Gamma T) \\ +(C\Gamma I\Gamma_A I\Gamma T)+(T\Gamma_A I\Gamma I\Gamma_A C)+......=0\end{aligned} \; . \qquad (6)$$

By simulation, however, obtained Γ with the five terms is found to be also valid, which leads to (7).

$$I+T\Gamma_A C+C\Gamma T+C\Gamma I\Gamma_A C+T\Gamma_A I\Gamma T=0 \qquad (7)$$

Thus, from (7), the required reflection coefficient of the idle port, Γ is given by

$$\Gamma = -\frac{I+T\Gamma_A C}{CT+CI\Gamma_A C+T\Gamma_A IT} . \qquad (8)$$

III. Design Procedure

The reflection coefficient of the mismatch, Γ can be obtained from both S-parameters of the conventional directional coupler and the input impedance of the antenna, as shown in (8). S-parameters of the conventional directional coupler are easily found by the simulation. In this paper, proposed structure is based on 15 dB conventional coupled-line coupler in 860 MHz ~ 960 MHz.

For the input impedance of an antenna, simple printed dipole antenna of 910 MHz was designed, which is composed of dipole arms, CPS line, and balun. All simulation is performed by Agilent ADS 2004A and Taconic TLX-9 substrate is used for all fabrication.

The reflection coefficient of the mismatch can consist of any types of structure, such as short stub or open stub, lumped capacitor, or inductor. It depends on the designer's preference and the value of the reflection coefficient of the mismatch.

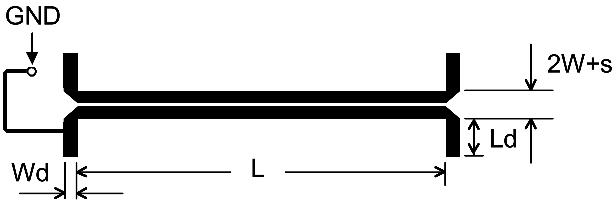

Fig. 3. The physical layout of the proposed circulator

Physical layout of proposed circulator is shown in Fig. 3. Detailed dimensions are (unit: millimeters): L = 57.7, Wd = 2.25, Ld = 6, W = 2.1, s = 0.45. The mismatch is located in idle port which is composed of 100 Ω short stub of 22.5 mm, 50 Ω series line of 0.7 mm.

IV. MEASUREMENT RESULT

Fig. 4 shows the measured data of the conventional directional coupler itself. The conventional directional coupler yields the isolation of 26.7 dB at frequency of 910 MHz which is poor as expected and the coupling of 15.1 dB. The proposed circulator is implemented based on these S-parameters at 910 MHz.

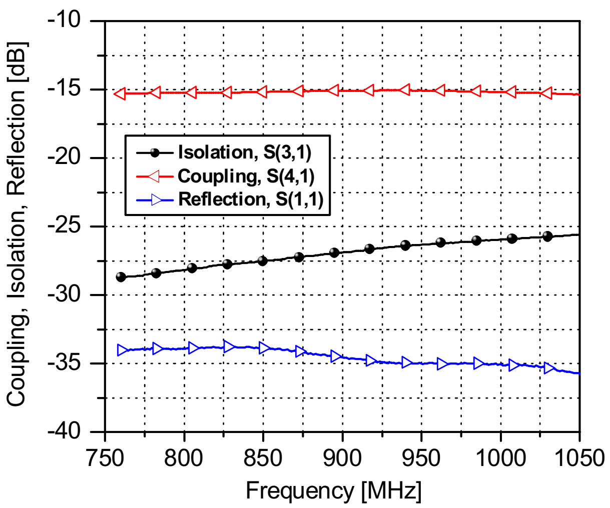

Fig. 4. Measured result of the conventional coupled-line coupler.

The input impedance of the designed printed dipole antenna is shown in Fig. 5. At 910 MHz, input impedance is about -16.7dB.

TX-to-RX leakage (S31) and TX reflection (S11) of the proposed and conventional coupler are shown in Fig. 6 when the designed dipole antenna is applied. TX reflection is mostly from input impedance of the dipole antenna, thus it is almost similar in both case. TX-to-RX leakage, however, shows remarkable difference in two cases. TX-to-RX leakage by the use of the conventional coupler is -23.5 dB, whereas the use of the proposed circulator exhibits -58.3 dB at 910 MHz. The maximum TX-to-RX leakage suppression of the proposed circulator is -68.8 dB at 908.5 MHz, which is improved more than 45 dB.

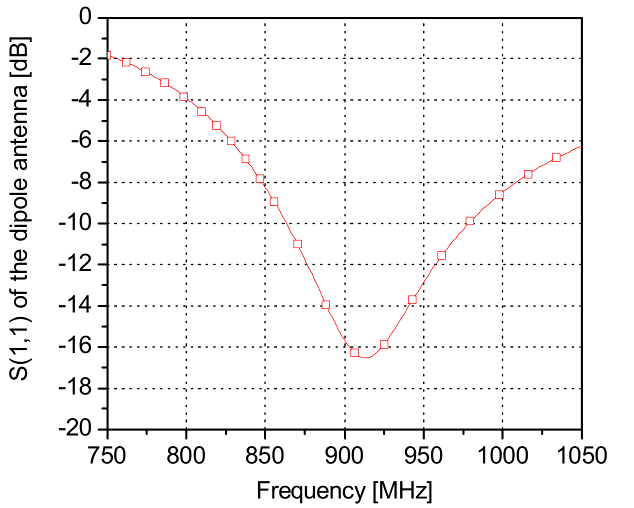

Fig. 5. The input impedance of the designed printed dipole antenna

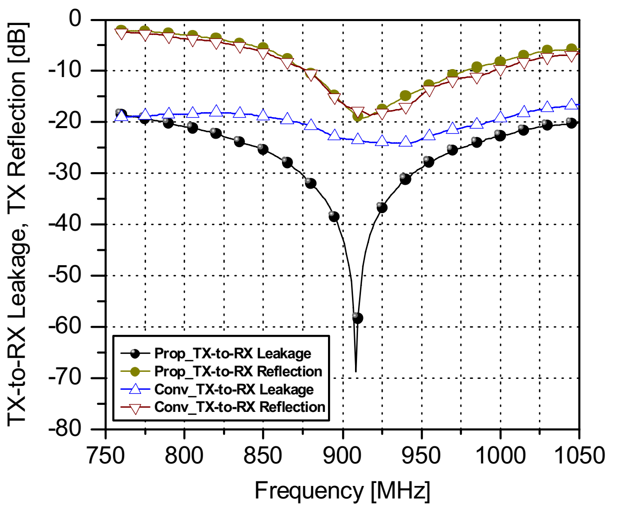

Fig. 6. Measured TX-to-RX leakage (S31) and TX reflection (S11) in the use of the proposed circulator and conventional directional coupler

V. EXPERIMENTAL VERIFICATION

To verify the validity of the proposed circulator, a test-bed is constructed as shown in Fig. 7. The experimental set-up includes the RFID reader board, a designed printed dipole antenna, a UHF class 1 Tag, and a spectrum analyzer for measuring the received power.

The transmitted signal of the RFID reader is continuous sinusoid wave with a power of 18 dBm at 910 MHz. A passive tag is located at 20 cm far from the antenna, responding the transmitted continuous wave.

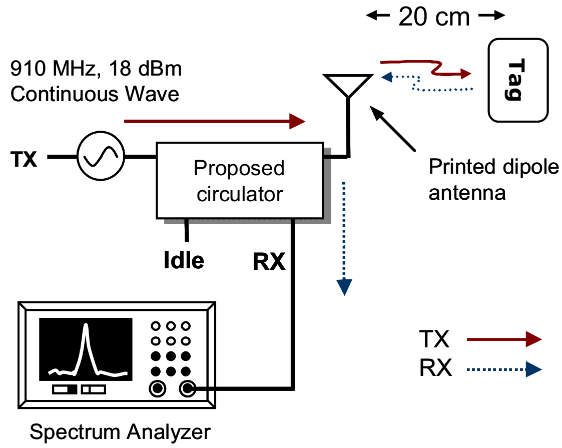

Fig. 7. Experiment configuration of the directional coupler and RFID system.

Fig. 8 shows the frequency spectrum of the received signal in the case of use of the proposed circulator and the conventional coupler. In both cases, ripples represented the back-scattered baseband information of the tag. Note that the magnitude is the same in both cases since the tag is located in the same distance from the reader. Nevertheless, peak is disappeared in Fig. 8 (b), which means strong TX-to-RX leakage is suppressed effectively by the use of the proposed circulator.

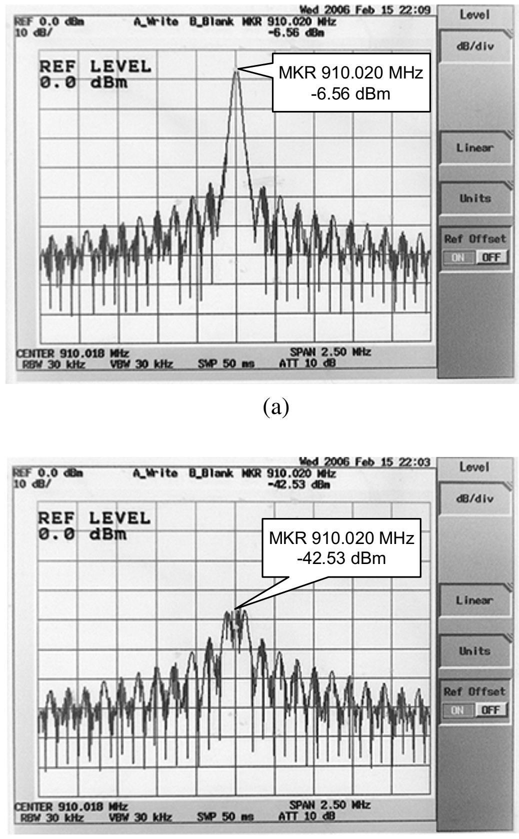

Fig. 8. Frequency spectrum of the received signal on the use of the conventional coupler (a) and the proposed circulator using a modified directional coupler (b).

VI. Conclusion

New approach for increasing isolation of a coupled-line directional coupler, especially operated as a circulator of RFID application, has been presented. The principle of the proposed circulator is based on the cancellation using the mismatch load implemented at idle port. The mismatch is designed by considering not only imperfect isolation of the coupled-line directional coupler itself but also input impedance of the employed antenna. TX-to-RX isolation is enhanced more than 45dB compared with the conventional directional coupler.

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