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

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***Abstract* — In radio-frequency identification (RFID) system, a directional coupler has been used to isolate RX from TX due to its simplicity and low cost compared with a circulator. Nevertheless, a conventional microstrip directional coupler has inherent drawback of poor isolation due to unequal phase velocity between even and odd mode. In this paper, a newly proposed circulator using a microstrip directional coupler is proposed to achieve good isolation between TX and RX. The proposed circulator is used for UHF band RFID reader with a single antenna, of which the operating frequency band is 860 MHz – 960 MHz. The measurement of the fabricated circulator using a modified directional coupler exhibits excellent isolation of 64 dB and directivity of 49 dB in its frequency band. The validity of the proposed circulator is demonstrated by comparing the TX leakage at the RX port of RFID reader system with that of a conventional directional coupler.**

***Index Terms* — Circulator, RFID, Directional Coupler , High Isolation, High Directivity.**

I. Introduction

Recently, the uses of RFID system such as replacement for barcode of products, location sensing, smart card as electronic cash, are increased. For more applications, the RFID systems should be low cost and of long and reliable detection. Some difficult technical problems arise from TX-to-RX leakage because the RFID reader transmits continuous wave (CW) and receives back-scattered data from tags in the same frequency band simultaneously. The strong TX leakage in the receiver side degrades the RFID performance such as the sensitivity of the receiver and detection range of the tag. For the more detail, the low noise amplifier (LNA) of the receiver can be saturated by this strong TX leakage, decreasing the dynamic range of LNA. DC offset problem is also caused by self mixing in the mixer of receiver.

To alleviate these problems the strong TX signal should be separated from the RX signal as much as possible to achieve high performance of RFID reader. The simplest solution is to employ two separated antenna for TX and RX, however the size and the cost become double. A circulator of ferrite material or an active CMOS circulator may ease this difficulty, however the cost is not competitive and furthermore, isolation of circulators is not very satisfactory indeed.

A directional coupler can be, therefore, better choice rather than those circulators thanks to its simplicity and low cost. So far, conventional directional couplers are widely utilized to isolate between TX and RX of RFID system. However, owing to the unequal phase velocity between even and odd modes in inhomogeneous dielectric material such as microstrip lines, a conventional coupled-line directional coupler suffers from low isolation. 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 have been proposed: wiggly line coupler [2], lumped element compensation [3], dielectric overlay on microstrip line [4].

In this paper, an effective method is proposed to achieve high isolation. The fundamental concept of the proposed approach is based on reflected power canceller (RPC) using the idle port in a directional coupler [5]. The wave of the same magnitude and anti-phase of the TX leakage is created by the mismatch at the idle directional port, and added to TX leakage at isolation port (RX). As a result, these two waves can be canceled out. Accordingly, the proposed directional coupled-line coupler effectively isolates RX from TX leakage, behaving like passive circulator in RFID reader system.

II. The Principle 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 of the coupling factor. This is because the received signal is delivered by the coupling of the directional coupler. Despite of the insertion loss of the received signal, a coupled-line directional coupler can behave as a circulator in a RFID reader, because the LNA can recover the insertion loss of the received signal enough and a RFID system operates within somewhat short distance.

To increase isolation characteristic, the proposed approach is to mismatch the idle port (port 4) as shown in Fig. 1.

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Because of the mismatch, the coupled TX power is reflected at idle port and transferred toward RX port (port 3).

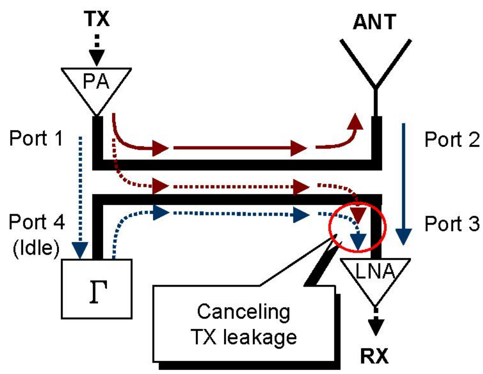


Fig. 1. The principle of the proposed coupled-line directional coupler.

Basically, the proposed technique adopts the RPC to enhance isolation, which makes TX leakage removed by canceling loop. The reflected wave at the idle port due to the mismatch travels toward RX port, and it cancels out the TX leakage at RX port. The reflected wave should have the same magnitude and the opposite phase of TX leakage at RX port. In this way, increased isolation at port 3 can be obtained in the proposed directional coupler.

With this principle, the relationship between optimum reflection coefficient Γ of the idle port and S-parameters of a conventional directional coupler can be easily derived. Whole S-parameters of the proposed circulator is derived through substituting the idle port of a conventional directional coupler as the mismatch load and reducing the 4 x 4 matrix to a 3 x 3 matrix.

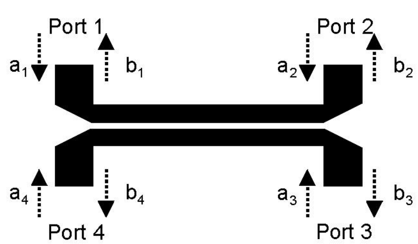


Fig. 2. Incident waves and reflected waves in a coupled-line directional coupler.

S-parameters of the conventional directional coupler is

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

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 each of elements, the capital letters T, I, C are used for convenience, which represents the factors of through, isolation, coupled. All of diagonal terms are assumed to be zero under the assumption of all port matching.

Because of existence of the mismatch at the idle port of the proposed directional coupler, one more condition is added, which is,

$$a_4 = \Gamma b_4 . \tag{2}$$

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

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} C^2\Gamma & T + C\Gamma I & I + C\Gamma T \\ T + C\Gamma I & I^2\Gamma & C + T\Gamma I \\ I + C\Gamma T & C + T\Gamma I & T^2\Gamma \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \tag{3}$$

Since the goal is to isolation of RX port from TX leakage, S31 of (3) should be zero,

$$I + C\Gamma T = 0 . \tag{4}$$

Thus, the required reflection coefficient of the idle port, Γ is given by

$$\Gamma = -\frac{I}{TC} . \tag{5}$$

III. Design Procedure

Before the design of the proposed structure, first of all, the coupled section of the conventional directional coupler should be simulated for the calculation of the optimum reflection coefficient Γ given by (5). The dielectric substrate with 0.5 mm thickness, 2.5 of the relative dielectric constant is used in the fabrication. S-parameters of the conventional directional coupler are obtained using a commercial EM analysis tool, Agilent ADS 2004A.

In this paper, proposed structure is based on 15 dB conventional coupled-line coupler and the frequency band of the RFID system, where this coupler is used, is 860 MHz ~ 960 MHz.

These simulated results of the coupled section of the conventional directional coupler can be applied to (2) to find the optimum reflection coefficient directly for the proposed structure. The reflection coefficient of the mismatch at idle port may consist of some short stub, or open stub, or series, shunt line. It depends on value of the reflection coefficient and designer's preference. And this mismatch may be fabricated with lumped elements or distributed elements.

Fig. 3 shows the physical layout of the proposed coupled-line directional coupler. The reflection coefficient at the idle port includes two distributed elements in this layout: the short stub, and the series line between the coupled section and the short stub.

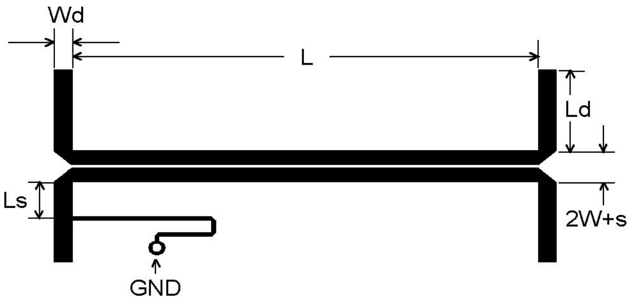


Fig. 3. The physical layout of the proposed coupled-line directional coupler.

Detailed dimensions are (unit: millimeters): L = 57.7, W = 2.1, s = 0.45, Wd = 2.25, Ld = 14. The mismatch is located at idle port which is composed of short stub of 0.5 mm width with 27.25 mm length, 50 Ω series line of 5 mm (Ls).

IV. Measurement Result

Fig. 4 shows the measured data of the conventional directional coupler. The conventional directional coupler yields the isolation of 25.1 dB at frequency of 910 MHz which is poor as expected and the coupling of 13.7 dB, little less than 15 dB. So by the definition of directivity, directivity of the conventional directional coupler exhibits 11.4 dB.

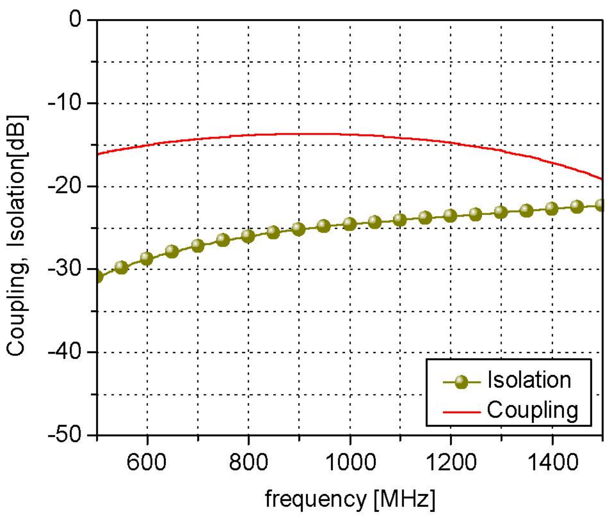


Fig. 4. Isolation (S31) and coupling (S32) of the fabricated conventional directional coupler.

The isolation (S31) and the coupling (S32) of the proposed circulator are shown in Fig. 5. The coupling is almost similar with that of the conventional coupler shown in Fig. 4, on the other hand, deep notch is founded in isolation. In Fig. 5, the isolation is measured about 60.4 dB at frequency of 910 MHz and maximum value, 64.6 dB at frequency of 915 MHz. Also, the isolation is over 40 dB in 860 MHz - 960 MHz band as shown in Fig. 5. Since the coupling is about 14.9dB, the maximum directivity of the proposed directional coupler is about 49.7 dB indicating excellent improvement more than 38dB, compared with that of the conventional directional coupler.

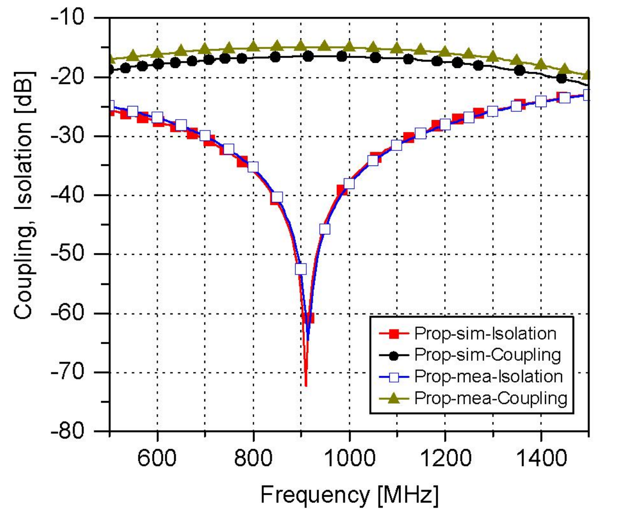


Fig. 5. The simulated and measured isolation (S31) and coupling (S32) of the proposed coupled-line directional coupler.

V. Experimental verification

To verify the validity of the proposed circulator, a test-bed is constructed as shown in Fig. 6. The experimental set-up includes the RFID reader board, a 900 MHz antenna, a UHF class 1 Tag, and a spectrum analyzer for measuring the received power.

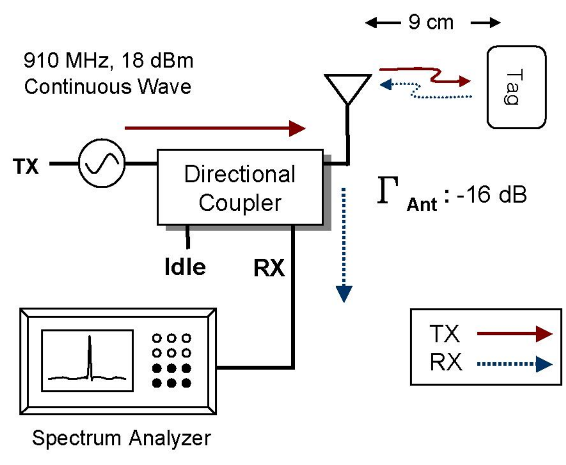


Fig. 6. Experiment configuration of the directional coupler and RFID system.

The transmitted signal of the RFID system is continuous sinusoid wave with a power of 18 dBm at 910 MHz. A passive tag is located at 9 cm far from the antenna, responding to the transmitted continuous wave. Thus the receiver picks up three different signals: TX leakage (S31), reflected TX power from the antenna (S32·S21) and the back-scattered power from the tag. Fig. 7 shows the photograph of the manufactured RFID reader test-bed. The power spectrum of the received signals in the cases of the use of the conventional directional coupler and the proposed circulator are shown in Fig. 8 (a) and (b), respectively. Ripples of the power spectrum of the received signal represent the back-scattered signal which is the tag's information. Note that the magnitude of back-scattered signal is almost same in both cases. Peaks of the power spectrum of the received signal represent mainly direct TX leakage and the reflected TX power from the antenna due to imperfect isolation of the circulator and low VSWR of the antenna, respectively.

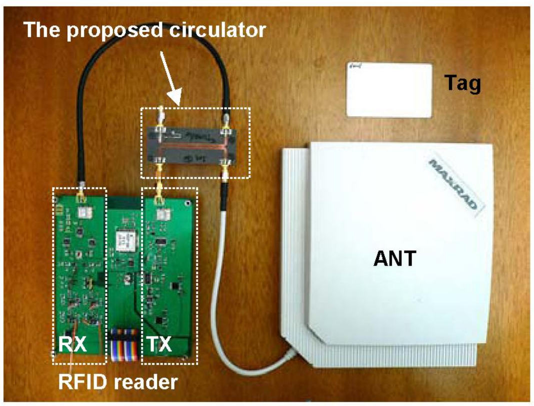
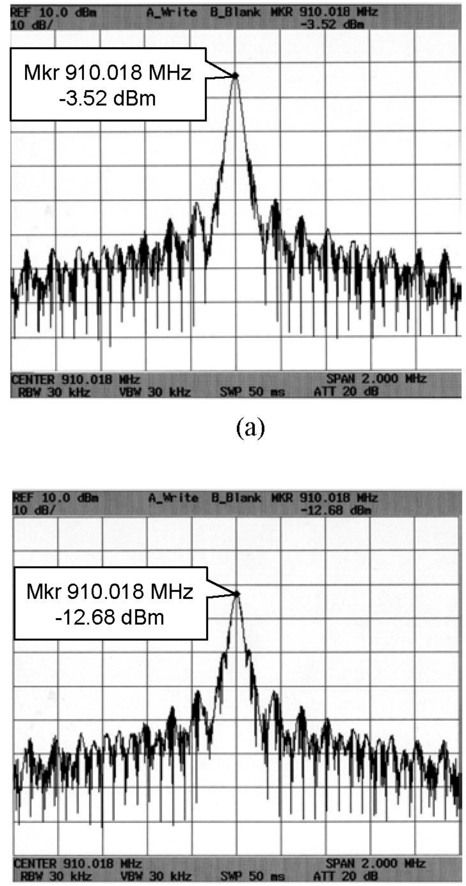


Fig. 7. The test-bed of the RFID reader system.

As shown in Fig. 8, the TX leakage power of the test using the proposed circulator is -12.68 dBm which is lower about 9 dB than that of the test using the conventional coupler. However, this difference is much lower than 38dB difference expected in shown in Fig. 4 and Fig. 5. The difference is attributed to the mismatch of the antenna, of which S11 is about -16dB. If the antenna mismatch as well as the imperfect isolation of the directional coupler itself is considered in the design of the circulator, TX leakage would be much more reduced in the received signal.

VI. Conclusion

New approach for increasing isolation of a coupled-line directional coupler, especially operated as a circulator of RFID system, has been presented. The principle of the proposed circulator is based on the cancellation using the mismatch load implemented at idle port. The proposed circulator achieves a good isolation of 64.6 dB at 915 MHz. The proposed method is successfully applied to RFID reader with a single antenna, significantly improving the sensitivity of the receiver by isolating the strong TX leakage effectively.



(a)

(b)

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

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