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Lumped directional coupler with a varactor tuned reflector for RFID applications

Moon-Que Lee[a)]
School of Electrical and Computer Engineering, University of Seoul, Siripdae-gil 13, Dongdaemun-gu, Seoul 130–743, Korea
a) *mqlee@uos.ac.kr*

Abstract: In this paper, a lumped directional coupler with a tunable reflector is proposed for an UHF passive RFID front-end system in which the sensitivity is limited by the isolation between transmitter and receiver. The proposed directional coupler can tunably eliminate TX-to-RX leakage caused by both the imperfect isolation of a directional coupler and the mismatch of antenna impedance which may be changed due to near-field environment. The measured result shows excellent TX-to-RX isolation above 70 dB at 910 MHz and 55 dB over Korean UHF-RFID band.

Keywords: RFID, directional coupler, tunable, isolation, antenna mismatch

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

In the concept of *hardware*, a RFID reader receiving passive tag's response can be understood as full-duplexing system. This is because the reader transmits CW *without* information for the tag to backscatter while listening for the tag's response. However, commercially used frequency-division duplexers cannot be used to isolate TX signal from RX port since the received tag's signal has the essentially same frequency with the reader's signal. Thus, in the passive RFID system, isolation problem between the transmitter and the receiver becomes a limit factor on the reader's receiver sensitivity.

Two approaches to the isolation problem have been known [1]: (1) using two antennas separated in space, called by a bi-static configuration and (2) using a circulator or a directional coupler, called by a mono-static configuration. The former approach uses separate TX and RX antennas to transmit CW and receive the tag's response, respectively. Spatially separated antennas can more improve the isolation between TX and RX compared with that of single antenna configuration. However, the use of two antennas is not proper solution to compact-sized or low-cost applications.

In a mono-static configuration, the receiver input will be exposed to a substantial CW signal from the transmitter, due to the reflection from antenna and the inherent isolation of a circulator or a directional coupler. As shown in the following section, the antenna mismatch is generally more important than the inherent isolation of the directional devices in practical cases.

In this paper, a compact directional coupler with a tunable canceler is proposed as a device for TX-to-RX isolation in the mono-static passive RFID application in which antenna's reflection coefficient can be changed with the near-field environment.

2 Directional coupler in RFID applications

Compared to the use of circulator, the use of directional coupler has advantage of low cost, while gives rise to high noise figure or RX signal reduction in RX path corresponding to coupling ratio. In some reader system, RF front-end optionally requires low noise amplifiers to boost up the RX signal required at the mixer.

Fig. 1-(a) shows the signal flows in an ideal directional coupler used in RFID front-end in which antenna is assumed to be perfectly matched to the coupler. The RX port is connected to the port isolated from the transmit port and coupled from the antenna port. Path-(1) and path-(2) denote the transmit signal-flow and the receive signal-flow, respectively. Here, it is noted that the port coupled from the transmit port is not used, that is an idle port. In the practical situation, non-ideal leakage may exist at RX port shown

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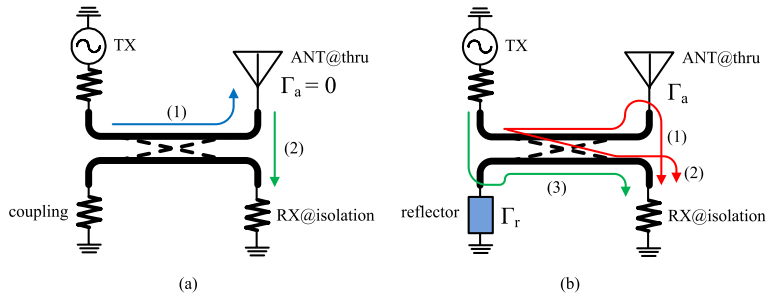

Fig. 1. Signal flows in the directional coupler applied in passive RFID front-end. (a) transmit and receive signal flows in the ideal directional coupler and perfectly matched antenna, (b) TX leakage flows and the proposed leakage-canceling flow at RX port in a practical application.

in Fig. 1-(b) [2, 3]: Path-(1) and path-(2) indicate TX-leakage components due to antenna mismatch Γ_a and the isolation characteristic in directional coupler, respectively.

These two leakages are vector-summed at RX port. For convenience, let's denote through, coupling and isolation of directional coupler as T, C, and I, respectively. Then, leakage path-(1) and (2) in Fig. 1-(b) can be written as:

$$L_{ant} = T\Gamma_a C \tag{1}$$

$$L_{isol} = I. \tag{2}$$

It is worth to compare which one is more dominant in total leakage. In Eq. (1), transmission T is almost 1 for loose couplers and isolation I of Eq. (2) is the sum of directivity D and coupling C. Thus, the dominant leakage is determined by comparing the directivity D and antenna return loss Γ_a. In practice, it is generally accepted that the return loss of above 12 dB and directivity of about 20 dB. Hence, in most practical applications, antenna mismatch becomes the dominant factor to limit the sensitivity of receiver.

In Fig. 1-(b), in order to cancel the vector-summed leakage at RX port caused by path-(1) and (2), canceling signal can be generated by coupling TX signal and properly reflecting it, denoted by path-(3). Taking into the effect of the reflector at the idle port coupled from TX port, the total signal at RX port is written as:

$$L_{leakage} = I + (T\Gamma_a C) + (C\Gamma_r T) + H.O.T. \tag{3}$$

where Γ_r is the reflection coefficient of reflector at the idle port.

In above equation, the third term in the right side means the canceling signal, path-(3) shown in Fig. 1-(b). The higher-order terms contain multiple reflections between the reflector and imperfect antenna mismatch. Thus, they are assumed to be very small compared with the first, second, and third terms. Therefore, the reflection coefficient Γ_r of reflector to cancel out TX leakage at RX port can be calculated from Eq. (3).

$$\Gamma_r = -\frac{I}{CT} - \Gamma_a \tag{4}$$

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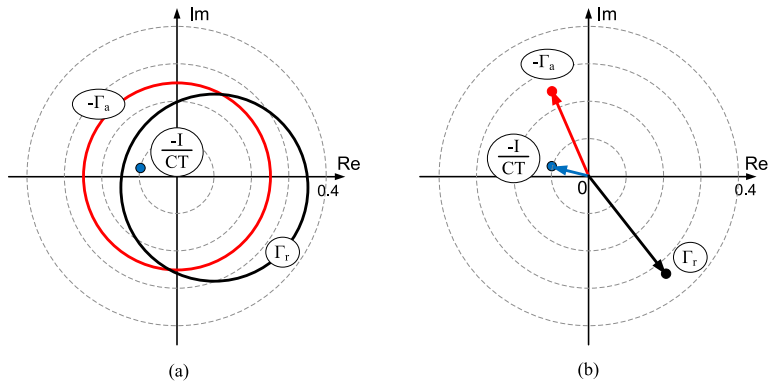

Fig. 2. Vector sum diagram on the Γ_r plane: (a) trajectories for antenna return loss of 12 dB and directivity of 20 dB, (b) a specific example to show TX leakage canceling.

Fig. 2 shows the vector-sum diagram on the Γ_r complex plane, in which the required Γ_r to eliminate $L_{leakage}$ is shown for return loss Γ_a of 12 dB and directivity of 20 dB. If Γ_a is susceptible to the near-field objects surrounding antenna, Γ_r should be variable in order to cancel out the TX leakage related with Γ_a.

3 Lumped directional coupler with a varactor tunable reflector

There are a variety of lumped directional couplers [4, 5, 6, 7]. For some schematics, they have theoretically infinite directivity [7]. As described in previous section, however, the infinite directivity of coupler or circulator in RFID front-end applications does not mean no TX leakage at RX port. As a criterion to select the lumped coupler schematic, circuit simplicity is more important than its own directivity. The selected schematic here is a simplified lumped forward directional coupler shown in Fig. 3-(a), which has a finite directivity because of the difference of even- and odd-mode velocities. Lumped-element values of the equivalent circuit for loose coupling are given by

$$C_T = \frac{1}{\omega_o Z_o}, \tag{5}$$

$$L_T = \frac{Z_o}{\omega_o}, \tag{6}$$

$$C_C = \frac{C_{coup}}{\omega_o Z_o}, \tag{7}$$

where Z_o, ω_o, and C_{coup} are the characteristic impedance, operating angular frequency, and coupling ratio, respectively.

It is noted that the mismatched antenna causes dominant leakage to RX port and its input impedance may vary with the near-field environment. Hence, it is important to design RF front-end by taking into account the variation of antenna impedance. As a tunable reflector, the schematic shown

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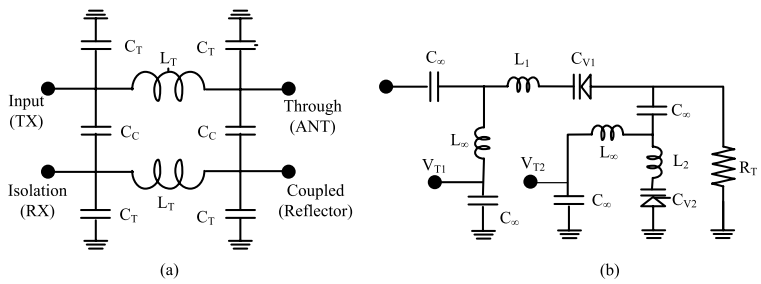

Fig. 3. (a) A simplified lumped directional coupler and (b) varactor tunable reflector.

in Fig. 3-(b) is adopted in this paper. Here, assuming C_∞ and L_∞ are large enough to be neglected, the input impedance of reflector is given by

$$Z_r = \frac{G_T}{G_T^2 + B^2} + j\left(X - \frac{B}{G_T^2 + B^2}\right). \tag{8}$$

where G_T is a termination conductance $1/R_T$, $X = \omega L_1 - 1/\omega C_{V1}$, and $B = 1/(-\omega L_2 + 1/\omega C_{V2})$. Tuning V_{T1} and V_{T2} and choosing a proper R_T, the required Z_r corresponding Eq. (4) can be implemented.

4 Measurement

A directional coupler with a tunable reflector was designed at Korean UHF-RFID band allocated over 908.5 to 914 MHz. The lumped directional coupler with the coupling factor of 20 dB shown in Fig. 3-(a) was implemented using Murata's chip capacitors and inductor libraries on FR-4 substrate with 0.8 mm thickness. The calculated lumped capacitance and inductance are $C_T = 3.50$ pF, $L_T = 8.74$ nH, and $C_C = 0.35$ pF. Simulated directivity of the lumped coupler is 20.04 dB at 910 MHz. The directivity of the designed schematic results from the difference of even and odd mode velocities of the schematic shown in Fig. 3-(a).

Patch antenna MP9026CPR from MAXRAD company was employed for verifying the design. The adaptive tuning reflector to cancel TX leakages was implemented using a varactor diode 1SV285 which has 6.5 pF to 1.5 pF over from 0 to 10 volt tuning voltage.

Fig. 4 shows the measured characteristics of the designed coupler. As described in previous section, TX-to-RX isolation using a conventional lumped directional coupler without a reflector is predicted as the sum of the antenna return loss and coupling factor of coupler. For a typical example of 12 dB the antenna return loss and 20 dB coupling factor, TX-to-RX isolation of 32 dB is predicted. From Fig. 4, the proposed coupler with a reflector exhibits over 55 dB over from 908.5 to 914 MHz, which is enhanced result by 23 dB than that of coupler without reflector.

5 Conclusion

In this paper a directional coupler with a varactor tuned reflector has presented for passive UHF RFID in which an excellent TX-to-RX isolation is

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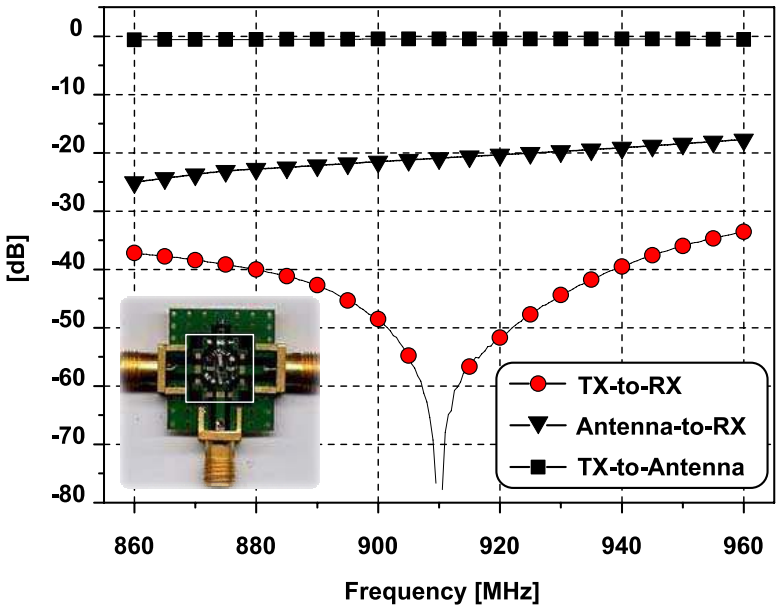

Fig. 4. Measurement of the designed directional coupler with a varactor tuned reflector.

required. The proposed directional coupler has a tunable TX-to-RX leakage canceling feature, which is very useful in the practical RFID environment that the input impedance of antenna may be sensitively varied with respect to the near-field environment. The measurement shows good TX-to-RX isolation of above 55 dB in the Korean UHF RFID frequency band.

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