Balanced Directional Coupler Structure with Insensitive Isolation for Load Impedance

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Abstract—**In this paper, a balanced directional coupler structure with lumped elements is presented as a new method to solve Tx-to-Rx leakage problem. An analysis for the characteristics of the balanced directional coupler is performed to introduce that the proposed structure is insensitive for varying load impedance. The balanced directional coupler structure consists of two Wilkinson power dividers and two contra-directional couplers implemented with lumped elements. The validity of the proposed structure is confirmed by comparisons with the measured results obtained from a single contra-directional coupler. The fabricated balanced directional coupler has 58 dB of isolation for matched load impedance and less than 45 dB for mismatched load impedance at 910MHz, the center frequency of UHF RFID.**

Index terms—**Directional coupler, Tx leakage, Front-end, UHF RFID, Isolation.**

I. INTRODUCTION

In microwave circuits, components such as circulators and directional couplers have been used to guarantee the isolation between transmitter and receiver [1], [2]. Because the reading range should be as long as a few meters in the UHF RFID system, the isolation between a transmitter and a receiver which operates simultaneously at the same frequency has always been an important issue. However, conventional components provide insufficient isolation around 25 dB and this feature is also sensitive for a mismatched load, especially antenna. Hence, diverse methods have been studied [3]-[4].

In this paper, we propose the balanced circulator with high isolation for varying load impedance, as shown in Fig. 2. The basic principle of the balanced structure is to cancel the direct coupler leakage signal (denoted as *I* in Fig. 1) by adding 180˚-delayed (anti-phase) signal to Rx port through the compensation circuit (shaded region of Fig. 2). Therefore, we approved this principle through theoretical and experimental verification for variant possibilities of load impedance change. In addition, the proposed structure can take advantages of the low-cost and light-weight characteristics from implementing with lumped elements.

For many practical applications, the balanced antennas, such as dipole antenna, quadrifilar spiral antenna, and
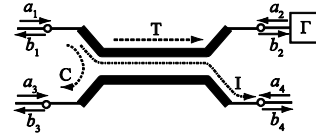

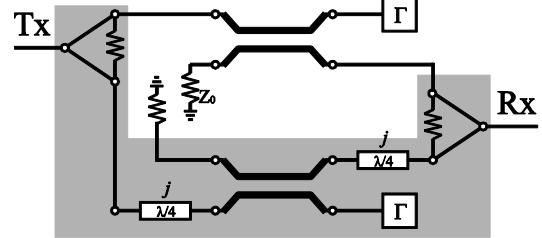Fig. 1. Conventional contra-directional coupler with mismatched load.

Fig. 2. Proposed balanced directional coupler structure.

quadrifilar helix antenna [4], can be connected with the proposed balanced circulator.

II. RELEVANT THEORY

A. Isolation

In Fig. 1, the single contra-directional coupler is connected to the mismatched load. The scattering matrix of this conventional coupler is represented in (1).

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

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

If we assume that the reader antenna has mismatched load and the port 3 is connected to a 50 Ω terminal, the total Tx leakage of a single directional coupler is
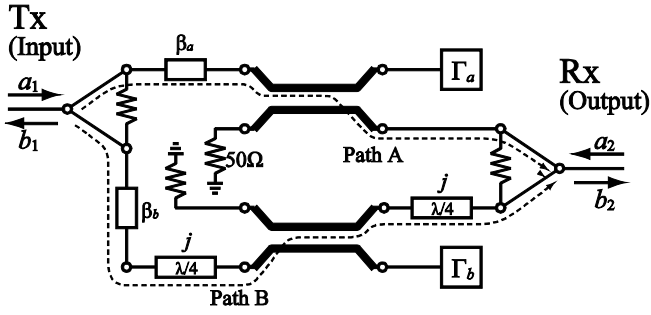
Fig. 3. Equivalent circuits of the balanced coupler with mismatched load and path error.

$$b_4 / b_1 = I + T \cdot C \cdot \Gamma \qquad (4)$$

, which implies that the isolation characteristic is affected by both the isolation of directional coupler and the reflection coefficient of the reader antenna.

Fig. 3 shows the equivalent circuits of the balanced directional coupler, which have two directional couplers, two power dividers and two load connections. β_a and β_b indicate the amplitude and phase errors of the compensated circuits in path A and B, respectively.

For the balanced directional coupler with mismatched load, the scattering matrix is given in (5).

Therefore, the Tx leakage of the balanced directional coupler with the mismatched load is,

$$\frac{b_2}{a_1} = \frac{1}{2}\left(TC\left(\beta_a\Gamma_a - \beta_b\Gamma_b\right) + I\left(\beta_a - \beta_b\right)\right),$$

$$\frac{b_2}{a_1} = \frac{1}{2}T \cdot C \cdot \left(\Gamma_a - \Gamma_b\right), \text{ for the ideal case}$$

, where Γ_a and Γ_b are reflection coefficients of antenna ports. In above equation, the Tx leakage can be considered for two cases. The first case is that the path A and B are not equal and the antennas are balanced ($\Gamma_a = \Gamma_b$). Second, the antennas are unbalanced and the path A and B are equal ($\beta_a = \beta_b$). The Tx leakages for above-mentioned cases are given in (6), respectively.

$$\frac{b_2}{a_1} = \frac{1}{2}T \cdot C \cdot \beta \cdot \left(\Gamma_a - \Gamma_b\right), \qquad \text{for } \beta_a = \beta_b = \beta \quad (6)$$

$$\frac{b_2}{a_1} = \frac{1}{2}\left(T \cdot C \cdot \Gamma + I\right) \cdot \left(\beta_a - \beta_b\right), \text{ for } \Gamma_a = \Gamma_b = \Gamma$$

From the above equations, it is noted that high isolation can be achieved whenever one of these two factors (β and Γ) is in balance although the other one is somehow unbalanced. The calculated isolation characteristics are shown in Fig. 4 for two cases.
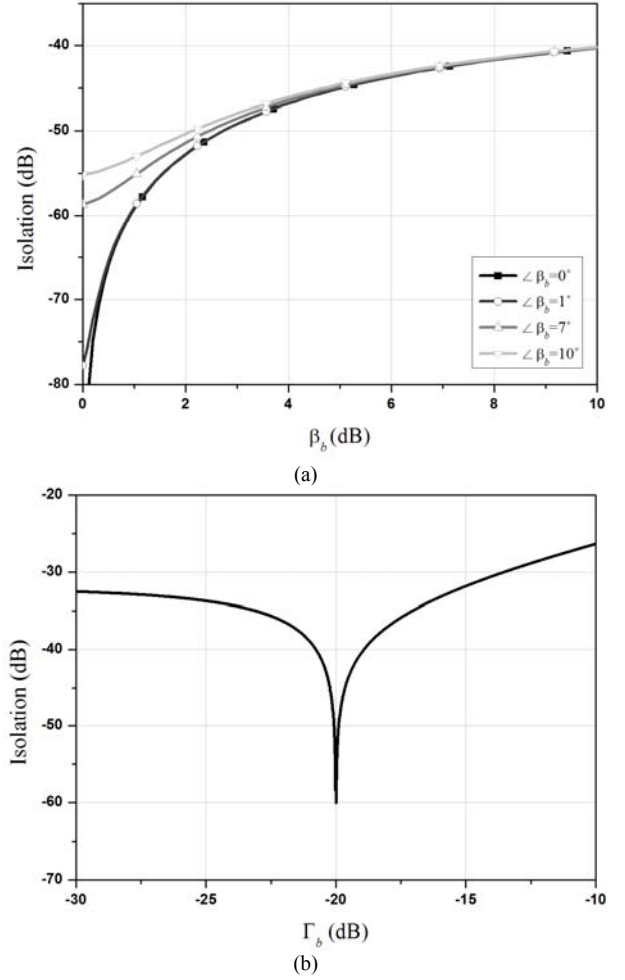

(a)

(b)

Fig. 4. Calculated isolation characteristics for the proposed structure. (a) Unbalanced path error with balanced antenna. (b) Balanced path error with unbalanced antenna.

In case (a), the error from the path B (β_b) varies in magnitude for given phase errors while the antennas are balanced ($\Gamma_a = \Gamma_b = -20$ dB). In case (b), mismatched load impedance are applied on the proposed structure with the balanced path ($\beta_a = \beta_b = 1 \angle 0°$). It is noted that the proposed structure shows isolation characteristics which are robust for varying load impedance and path loss and relatively better than that of a single directional coupler.

III. MEASUREMENT RESULT

To implement the balanced directional coupler structure using lumped elements for UHF RFID system, the design of Wilkinson power dividers and π-type 12 dB contra-directional couplers, the dominant composers of the proposed structure is preceded, based on conventional method as in Fig. 5 [5], [6].

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} T^2(\beta_a^2\Gamma_a - \beta_b^2\Gamma_b) & TC(\beta_a\Gamma_a - \beta_b\Gamma_b) + I(\beta_a - \beta_b) \\ TC(\beta_a\Gamma_a - \beta_b\Gamma_b) + I(\beta_a - \beta_b) & C^2(\Gamma_a - \Gamma_b) \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad (5)$$
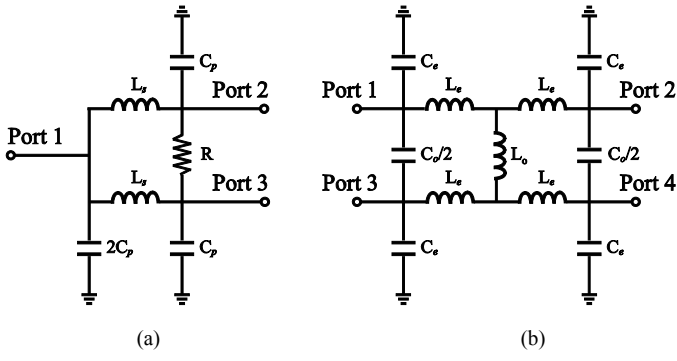
Fig. 5. Schematics of (a) Wilkinson power divider and (b) contra-directional coupler.

$$C_e = \frac{Y_{0e}}{\omega}\tan\frac{\theta}{2}, L_e = \frac{Z_{0e}}{2\omega}\sin\theta \qquad (7)$$

$$C_o = -\frac{Y_{0o}}{\omega}\cot\frac{\theta}{2} + \frac{1}{\omega^2 L_e} - C_e$$

$$L_o = \frac{1}{\omega^2\left(C_e + C_o\right) - \omega Y_{0o}\tan\frac{\theta}{2}}$$

Using the above equations, the detailed component values can be calculated: C_p=2 pF, L_s=12.4nH and R=100 Ω for the Wilkinson power divider, C_e=2.7 pF, L_e=2.7nH, C_o=3.6 pF and L_o=3.3 nH for the 12 dB contra-directional coupler, operating at UHF RFID frequency. The fabricated Wilkinson power divider on FR4 substrate (ε_r=4.6) with 0.6 mm thickness showed -3.4 dB for both S21 and S31 at 910 MHz. Also, the implemented 12 dB contra-directional coupler had about -0.8 dB, -12.5 dB and -38 dB at 910 MHz for S-parameters of the *through, coupled* and *isolation* port, respectively. The balanced directional coupler circuits are also fabricated on the FR4 (ε_r=4.6) substrate with 0.6-mm thickness.

The measured results of the isolation characteristics for the single contra-directional coupler in varying load impedance condition (25 Ω, 50 Ω, 75 Ω and 100 Ω) are shown in Fig. 6. In perfectly matched case, about 38.9 dB of isolation is obtained at 910 MHz (black solid line with filled triangles). As the load impedance varies, the isolation is measured from 22.1 dB to 25.4 dB (dark gray and light gray solid lines). The isolation characteristic of the proposed structure at the UHF RFID frequency band is shown in Fig. 7.

When there is no reflection from the antenna load, the isolation feature is measured about 58.1 dB at 910 MHz (black solid line with filled triangles). Also, the proposed structure provided about 45.4 dB of isolation for 100 Ω of mismatched load (light gray solid line with inverted triangles), which is about 20 dB better than the results of the conventional directional coupler.

In this structure, the Tx power are about -4.3 dB at two antenna ports. If we employ two-port balanced antenna, the Tx power will experience about -1.3 dB of propagation loss.
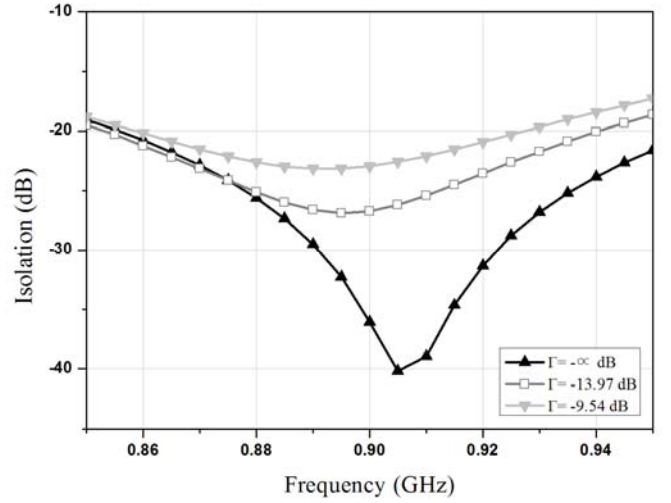

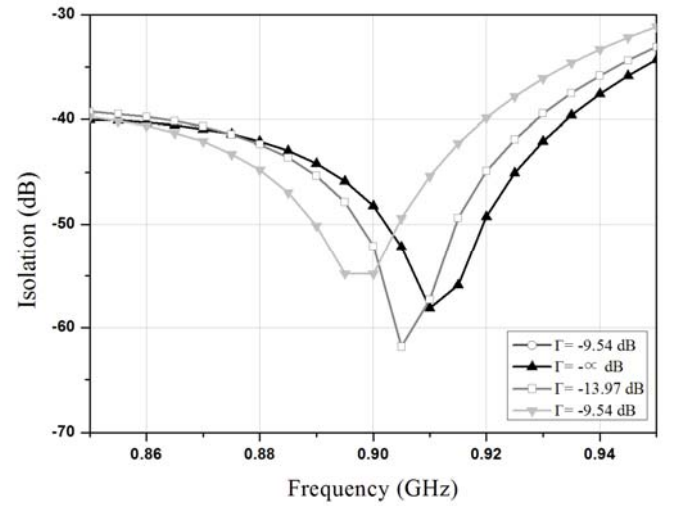Fig. 6. Measured isolation characteristics of conventional directional coupler with mismatched load.

Fig. 7. Measured isolation characteristics of balanced directional coupler with mismatched load.
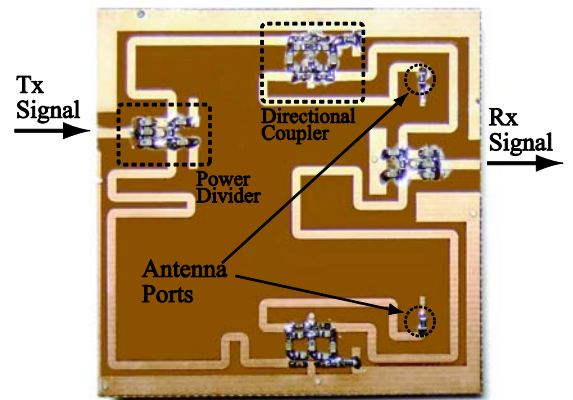

Fig. 8. Fabricated prototype of the balanced directional coupler.

IV. Conclusions

In this paper, we proposed a balanced directional coupler structure with high isolation and load-insensitive characteristics. This improved isolation characteristic is achieved by employing two power divider and two contra-directional coupler to cancel the Tx leakage signal. These features can contribute for the performance of RFID reader.

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