A tunable transformer-based CMOS directional coupler for UHF RFID readers

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Abstract: A tunable transformer-based directional coupler for UHF RFID readers is presented. Based on the current cancellation between inductively and capacitively coupled power through a non-inverting transformer and two coupling capacitors, respectively, the proposed directional coupler exhibits high isolation performance. In addition, by a tuning capacitor array and a terminal resistor array, the notch frequency of the coupler is tunable over the global UHF RFID band. The coupler is fabricated in a SMIC 0.18-µm CMOS process and the measured isolation is better than $-60$-dB from 840 MHz to 960 MHz. Besides, the transmission loss and the coupling factor at the notch frequency vary from $-0.86$-dB to $-0.7$-dB and from $-16.2$-dB to $-15.3$-dB, respectively.

Keywords: CMOS, current cancellation, directional coupler, isolation, transformer-based, UHF RFID

Classification: Electron devices, circuits and modules

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1 Introduction

In a passive UHF RFID system, the transmitter (TX) and the receiver (RX) of the reader operate at the same frequency simultaneously, resulting into a large leakage signal at the RF front-end of the receiver [1, 2, 3]. Usually, as Fig. 1 shows, a directional coupler is utilized to isolate the RX from the TX in case the RX front-end is saturated and the received backscattered signal is blocked [4, 5]. The input port, the direct port and the isolated port of the directional coupler are connected to the output of TX, the antenna and the input of RX, respectively. Transmission loss (TX to antenna), coupling factor (antenna to RX) and isolation (TX to RX) are used to characterize the directional coupler. The isolation performance is crucial for the sensitivity of the reader. Besides, the operating frequency of UHF RFID systems varies from 840 MHz to 960 MHz in different countries, such as 840 MHz to 845 MHz and 920 MHz to 925 MHz in China. Therefore, the directional coupler should be tunable for different frequency bands while maintaining high isolation performance.

![Fig. 1. A directional coupler isolating RX from TX in UHF RFID readers.](image)

In order for higher integration, lower cost and system complexity, the integration of tunable directional couplers in a standard CMOS process is essential [6, 7, 8,
This letter presents the topology of a tunable fully on-chip CMOS directional coupler which is based on the current cancellation between inductively and capacitively coupled power. Besides, the on-chip tuning of notch frequency over global UHF RFID band is realized by a tuning capacitor array and a terminal resistor array.

2 Proposed transformer-based directional coupler

Fig. 2 shows the circuit topology of the proposed transformer-based directional coupler consisting of a 1:1 non-inverting configured passive transformer, two coupling capacitors \( C_{C1} \) and \( C_{C2} \), a primary parallel capacitor \( C_P \), a secondary parallel tuning capacitor array \( C_S \) and a terminal resistor array \( R_T \). \( L_P \) and \( L_S \) are the inductance of the primary and secondary winding of the transformer, respectively. \( k \) is the magnetic coupling coefficient of the transformer. The primary tuning capacitor \( C_P \) is parallel to the primary coil of the transformer and the secondary tuning capacitor \( C_S \) is parallel to the secondary coil. The transformer plays the role of inductively coupling between two windings, and the coupling capacitors, i.e. \( C_{C1} \) and \( C_{C2} \), provide the capacitively coupling path.

In the proposed transformer-based directional coupler, it is the current cancellation between capacitively coupled current through coupling capacitors and inductively coupled current through the transformer that isolates the input port from the isolated port. Moreover, the current cancellation comes from the non-inverting configuration of the transformer. For non-inverting transformers, the two-port scattering matrix is

\[
S_{\text{non-inverting}} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},
\]
which means that no power is transferred \[11\]. In Fig. 1, the phase of the magnetically coupled current, i.e. \(I(L_S)\), tends to be opposite to that of the electrically coupled current, i.e. \(I(C_{C1})\), and the notch frequency of the coupler lies at the transmission zero from input port to isolated port where the capacitively and inductively coupled power cancel each other. Accordingly, assuming that \(L_P\) and \(L_S\) equal to \(L\), \(C_{C1}\) and \(C_{C2}\) equal to \(C_C\), and the terminal resistance is \(R_T\), the notch frequency \(\omega_0\) could be approximated as

\[
\omega_0 = \omega_a(1 - \gamma)^{0.5},
\]

where

\[
\omega_a = \sqrt{\frac{(1 - k^2)L + 2R_T^2(C_p + C_s + (1 - k)C_c)}{2(1 - k^2)R_T^2(L(C_pC_c + C_sC_c + 2C_pC_s))}}.
\]

\[
\gamma = \left(1 - \frac{\omega_f}{\omega_a}\right)^{0.5},
\]

\[
\omega_f = \sqrt{\frac{2kL + 4R_T^2C_c}{(1 - k^2)L^2C_c + 2R_T^2LC_c(C_p + C_s + (1 - k)C_c)}}.
\]

The on-chip tuning of the notch frequency is realized through tuning arrays of the secondary parallel capacitor \(C_s\) and the terminal resistor \(R_T\), both of which will not endure the high power of TX directly. Therefore, the directional coupler is capable of notch frequency tuning under high power operation.

3 Circuits design

The coupling capacitors \(C_{C1}\) and \(C_{C2}\) are implemented with the optimized parasitic capacitance between the primary and secondary coils of the transformer, and both are about 320-fF for enough capacitively coupling. Therefore, the transformer design in the proposed directional coupler is different from conventional transformer optimization where parasitic capacitance should be reduced as much as possible. Overlay winding configuration is chosen for the transformer in order for smaller area and easier coupling capacitors optimization by offsetting the stacked coils. The magnetic coupling coefficient of the transformer is 0.8, and the primary and secondary coils are implemented with Metal 6 and Metal 3, respectively. The inductance and peak quality factor of the primary coil are 14.5-nH and 8.3, respectively. For the secondary coil, they are 13.2-nH and 1.7. The co-design of the coupling capacitors and the transformer is carried out by EM simulations. \(C_p\) is a 10.5-pF on-chip MIM capacitor, and \(C_S\) is designed to be a 6-bit MIM-capacitor array with a step of 100-fF for notch frequency tuning. Besides, the terminal resistor is implemented as on-chip 4-bit poly-resistor array for 50-Ω tuning.

A trade-off exists between the transmission loss and the coupling factor due to the reciprocity of the directional coupler, i.e. higher coupling factor results into larger transmission loss. According to link budgets of UHF RFID systems \[1, 5\], the requirement of the transmission loss is much higher than that of the coupling factor. Therefore, the transmission loss is designed to be better than −1-dB for
higher system performance, which is guaranteed by the resonant frequency of \( L_P \) and \( C_P \) that is far below the UHF RFID bands.

4 Measurement results

The proposed transformer-based directional coupler was fabricated in a SMIC 0.18-\( \mu \)m 1P6M CMOS process. As shown in Fig. 3(a), the chip occupies an area of 0.81 mm \( \times \) 0.92 mm including bonding pads, and the core area is 0.70 mm \( \times \) 0.70 mm. The chip is directly bonded to an FR4 PCB, as shown in Fig. 3(b), for measurement with an Agilent network analyzer. Fig. 4 shows that the notch frequency can be tuned from 840 MHz to 960 MHz, which covers the main allocated UHF RFID band over the world, and the isolation at the notch frequency varies from \(-78.4\text{ dB}\) to \(-64.1\text{ dB}\). Accordingly, as shown in Fig. 5, the transmission loss and the coupling factor at the notch frequency vary from \(-0.86\text{ dB}\) to \(-0.70\text{ dB}\) and from \(-16.2\text{ dB}\) to \(-15.3\text{ dB}\), respectively. Performance comparisons between the proposed directional coupler and recently reported works are shown in Table I, exhibiting advantages in both area and isolation over a wide frequency range.
5 Conclusion

This letter presents a tunable transformer-based directional coupler that is feasible for CMOS integration. Measurement results of the directional coupler show that a transmission loss better than \(-0.9\text{-dB}\), an isolation level deeper than \(-60\text{-dB}\) and tunable notch frequency from 840 MHz to 960 MHz are achieved.

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