22.7 A Tunable Integrated Duplexer with 50dB Isolation in 40nm CMOS

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Modern RF duplexers rely on *frequency-selective filters* for isolation. The stringent isolation requirements prohibit the integration of RF duplexers on silicon and particularly in CMOS technology. However, CMOS technology offers superior tuning and calibration capabilities supported by the integrated digital baseband. This work presents the first integrated duplexer in CMOS technology with an adequate performance for full-duplex cellular applications such as WCDMA and HSPA. The proposed implementation is based on electrical balance of a *hybrid transformer* rather than frequency selectivity which unfavorably requires high-Q elements.

An integrated duplexer should perform two functions: first, it must provide concurrent matching for the antenna, the transmitter (TX), and the receiver (RX), and second it should attenuate the transmitted signal at the RX input to avoid saturation or desensitization. The attenuated transmitted signal can be filtered further using active RF filtering techniques presented in the past [1,2]. For the targeted UMTS-FDD application here, the isolation requirement for an integrated duplexer is set to better than 40dB. This attenuation is sufficient to reduce TX output of +24dBm to a tolerable level at the RX input, along with further active filtering at the LNA [1].

The duplexer as described above belongs to a class of networks called *maximum output* networks [3]. A well-known embodiment of a maximum output network is the Hybrid Transformer (HT), shown in Fig. 22.7.1 [4]. The HT has several peculiar characteristics: First, all HT ports can be simultaneously matched; Second, HT ports are *bi-conjugate*, that is, TX and RX are electrically isolated from each other, and so are the antenna and balancing resistor R_{bal}; and third, the incoming power from one port can be split in any ratio between the two receiving ports. The HT in Fig. 22.7.1 is a balun with three ports connected and matched to the RX, TX , and antenna. The fourth port, which is the center tap, is connected to the balancing resistor R_{BAL}. For the ideal balun to operate as an HT, the values of the port resistance should satisfy $R_{TX} = R_{RX} = 2R_{ANT}(N_1/N_2)^2$, $R_{BAL} = R_{ANT}(N_1/N_2)^2$. Once all ports are matched the balance is achieved, and the TX and the RX are perfectly isolated. As for the performance of the ideal balun, the Insertion Loss (IL) is 3dB for both the TX and the RX. A practical balun suffers additional ohmic loss as it is formed by coupling two separate inductors together. Thus, in a monolithic balun, the loss and the coupling trade off with each other. In order to achieve sufficient coupling, the ohmic loss of the balun is found to be around 2dB for the 6M 40nm technology used here, and the overall insertion loss of the RX is on the order of 5dB, which may not be acceptable for certain applications.

In order to reduce the ohmic loss of the HT, the *autotransformer*, implemented as a differential inductor as illustrated in Fig. 22.7.2 is found to be a better candidate. The simplicity of the implementation yields lower loss for the same coupling, which is about 1dB here. The center tap of the autotransformer is connected to the antenna. The RX and the TX are connected to the two sides of the autotransformer, and the balancing resistor is connected between the TX and RX. When the TX is active, it creates two in-phase currents, one in the balancing resistor and the other in the inductor connected to it. The inductor current induces an out-of-phase replica in the other inductor. By adjusting the value of the balancing resistor, the two opposing currents can be made to cancel each other completely. For the ideal autotransformer to function as a HT, the values of the port resistance should satisfy $R_{TX} = R_{RX} = 2R_{ANT}$, $R_{BAL} = 4R_{ANT}$. The insertion loss of the autotransformer duplexer is about 4dB for both the TX and the RX. Moreover, at balance all ports are matched.

In practice, the self inductance of the autotransformer has to be tuned with some capacitance as shown in Fig. 22.7.3. Consequently, the isolation frequency response resembles a notch at the resonance frequency. The depth of the notch is limited by the accuracy of the balancing resistor and by the bandwidth of the resonance of the LC circuit. An isolation of more than 50dB in a bandwidth of 5MHz is achievable with a balancing-resistor resolution of 5Ω. The frequency of the notch can be tuned over a wide frequency range of over 1GHz by changing the value of the tuning capacitor C_{TUNE}. The isolation and the insertion loss remain almost the same over the entire range.

For some applications, a tight noise-figure budget may require lower RX IL. To satisfy such a requirement, the autotransformer has to be modified. By simply changing the tap point towards the RX, the antenna will favor the RX. Therefore, this asymmetric autotransformer will achieve low IL for the RX but higher IL for the TX. The IL is given by: $RX\ IL=10\log(1+1/r)+loss$, $TX\ IL=10\log(1+r)+loss$, where r is the power split ratio, and is controlled by the location of the tap of the auto transformer. For an ideal autotransformer, r is the ratio of the number of turns in the two inductors.

For the proof of concept, two versions of the autotransformer-based integrated duplexer with an LNA have been implemented in 40nm CMOS technology (Fig. 22.7.3): a symmetrical version with moderate IL for both the TX and the RX, and an asymmetrical version with lower RX IL and higher TX IL. The LNA connected to the duplexer should have single-ended input with wideband matching to provide the desired termination over a wide frequency band. A common-source (CS) common-gate (CG) LNA is used (Fig. 22.7.3) to provide wideband matching with noise cancellation. To provide noise cancellation, the gains of the CG branch (M2, M4) and of the CS branch (M1, M3) are made unequal. The LNA of Fig. 22.7.3 is loaded with a symmetric differential inductor. Since the inductor is excited by current, the coupling between the two halves helps create a differential output. The antenna is connected to the tap of the autotransformer through the pad and the bond wire. No external matching network is needed.

The measured isolation for the asymmetric autotransformer, tuned for WCDMA Band II is shown in Fig. 22.7.4. The notch achieves better than 50dB of isolation in a 5MHz bandwidth. In the RX band, a rejection of about 25dB is measured, and thus to attenuate the TX noise further some kind of notch filtering in the TX chain is required [5]. Alternatively the duplexer notch could be tuned somewhat closer to the RX band, which still ensures more than 40dB of attenuation in the TX band, as well as 35dB in the RX band as a compromise. The measured and simulated gain and noise figure of the receiver are shown in Fig. 22.7.5. A summary of the simulated key parameters for both the symmetric and the asymmetric versions is shown in Fig. 22.7.6. The performance shown in Fig. 22.7.6 proves that the integrated duplexer presented in this work offers a comparable performance to the off-chip versions with two main advantages: first, full integration in CMOS technology, and second, tunability over a wide range of frequency bands. The die micrograph is shown in Fig. 22.7.7, which occupies an area of $0.2mm^2$, dominated by the two autotransformers.

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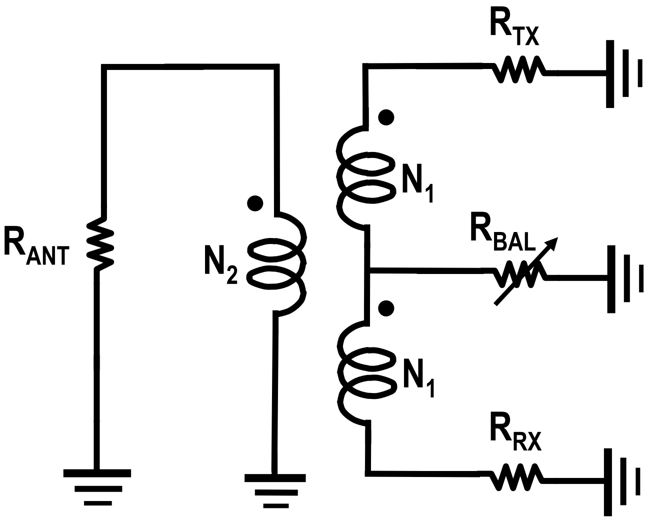


Figure 22.7.1: Balun as a hybrid transformer.

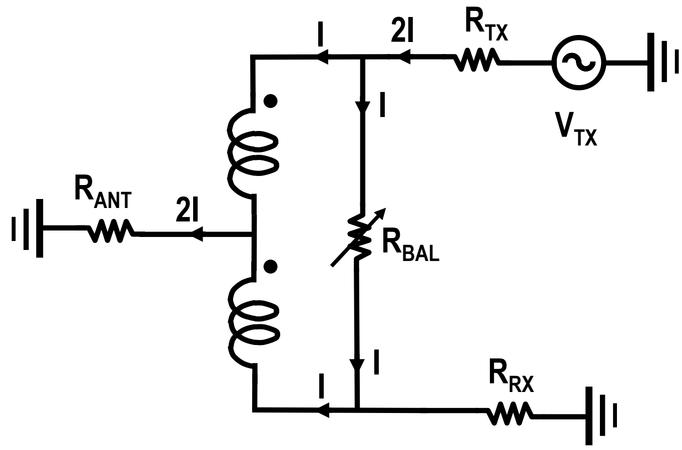
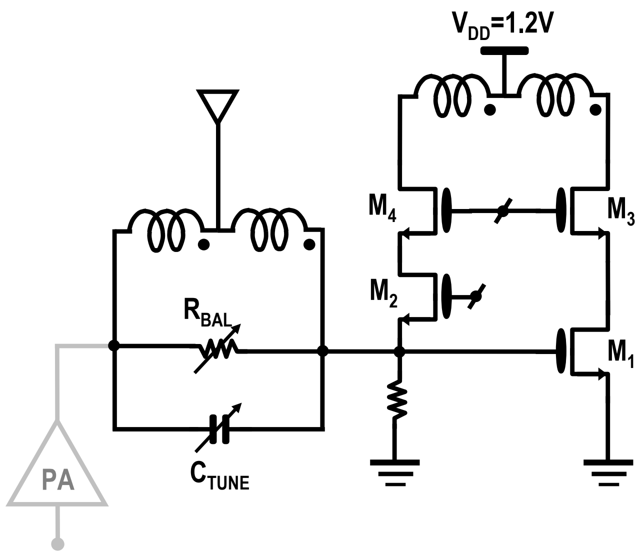


Figure 22.7.2: Autotransformer as a hybrid transformer.



22.7.3: Integrated duplexer with LNA.

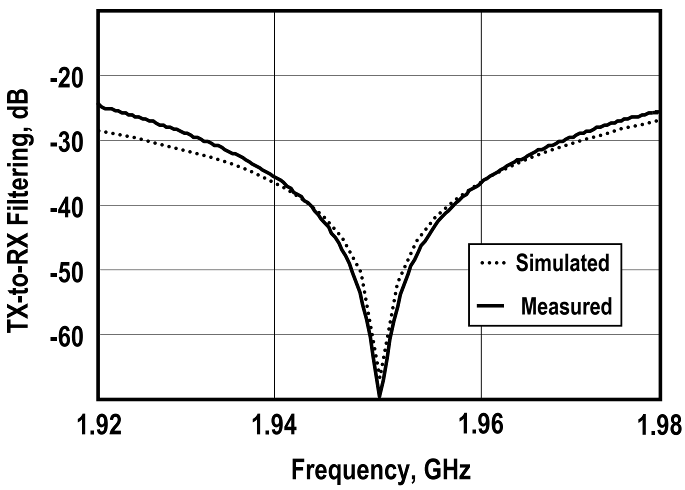


Figure 22.7.4: Measured isolation of the autotransformer.

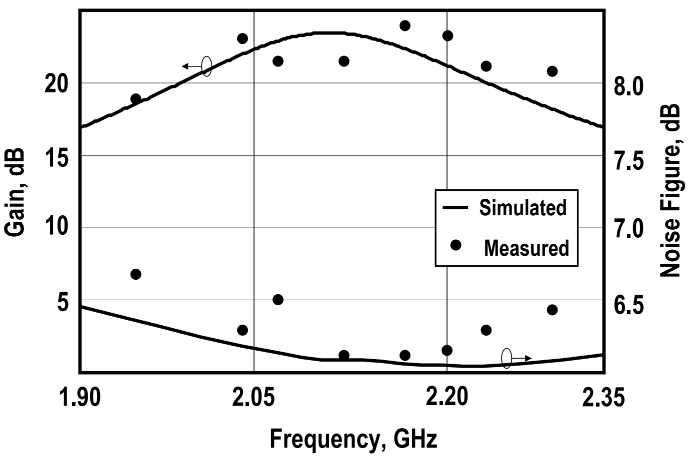


Figure 22.7.5: Measured gain and noise figure of the RX.

Parameter	Asymmetrical Autotransformer	Symmetrical Autotransformer
Duplexer RX IL (est.)	2.9dB	4.2dB
Duplexer TX IL	5.9dB	4.2dB
Isolation	> 50dB	> 50dB
Cascaded RX NF	6.1dB	7.4dB
Gain	23dB	24dB
Tuning Range	1.5 to 2.4GHz	1.5 to 2.5GHz
Current	7mA	6mA
Supply Voltage	1.2V	1.2V
Area	< 0.2mm^2	< 0.2mm^2

Figure 22.7.6: Measured performance summary.

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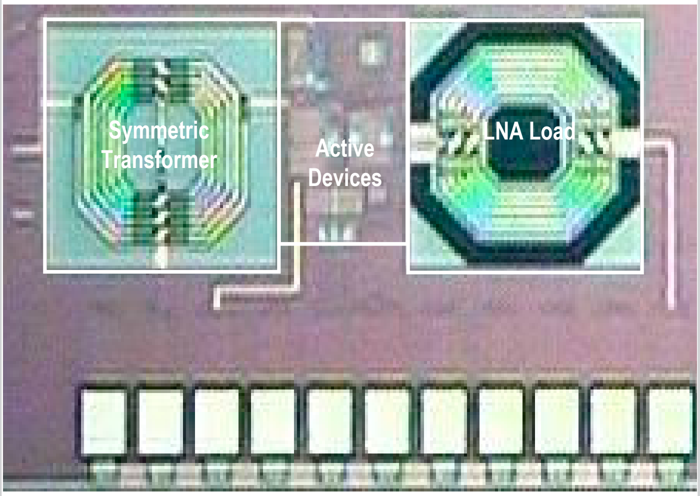

Figure 22.7.7: Die micrograph.

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