

Hybrid Transformer-Based Adaptive RF Front End for UHF RFID Mobile Phone Readers

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Abstract—We introduce hybrid transformer-based adaptive RF front end for UHF RFID readers. Small, narrow band antennas with high radiation efficiency can be utilised with an adaptive tuning of the antenna. The adaptivity also increases immunity to environmental changes, like detuning of the antenna by user hand. The hybrid transformer-based front end provides high isolation from TX to RX and eliminates the need for a cumbersome and expensive circulator. The small size of the module including the antenna enables integration to mobile phones.

I. INTRODUCTION

In UHF RFID readers the linearity of the receiver is of high importance [1]. The high transmitted power, even up to 33 dBm, should be isolated from the receiver still keeping the sensitivity reasonably high. The received signal power from the tag can be as low as -60 dBm. In addition to designing the receiver sensitive for the signal, also high carrier power level has to be taken into account.

In addition to the requirement of the high receiver linearity, the total power consumption should be as low as possible in handset devices. The complete system including the electronics and the antenna should also be very limited in size and mass productable with extremely low price. The size problem has been addressed by integrating as much as possible of the transmitter and receiver in integrated circuits [2], and designing small antennas for mobile phone readers [3].

There are two design alternatives: The active components in the receiver can be designed to tolerate high input power, but this is near impossible without degrading the sensitivity of the receiver too much. The other possibility is to introduce high isolation between the transmitter output and receiver active components. The latter solution is often realised with circulators or directional couplers, which provide 20 – 30 dB isolation. The problem with circulators, in addition to high price and large size, is incapability to eliminate the reflected power from the environment. This is not very important in the gate readers but highly important in the handsets.

Reflected power changes in time, especially in handsets, where user hand may be very near the antenna. This reflection can be eliminated by measuring it through receiver and adding a signal in antiphase to the input of the receiver. This kind of a reflection canceller circuits have been used for example within frequency modulated continuous wave (FMCW) radars [4], [5].

In this paper we introduce an UHF RFID reader front end, which offers low power consumption and high power

isolation from the TX output to RX input. The system eliminates the reflected power even from the nearby objects, and it is based on the reactive hybrid transformer dividing the power into two branches. One of the branches feeds the antenna, and other feeds an adjustable load. The ratio of the currents in the branches can be changed by varying the transformer coil inductances in the branches. The modulated signal from the tag is detected with an external coil in the transformer. The antenna is kept in resonance by tuning it with a varactor. In order to optimise the power consumption, the power amplifier is operated in the saturated mode and its output is connected directly to the antenna.

II. RFID READER BASED ON THE REACTIVE HYBRID TRANSFORMER

The basic concept of the reader is given in Fig. 1. The power amplifier (PA) having a low output impedance is directly connected via a series resonance circuit to the antenna. Neglecting the parasitic elements, the radiated power depends on the output voltage of the PA, the real part of the antenna feeding point impedance and the radiation efficiency of the antenna. The antenna is kept in resonance, i.e. its imaginary part is zero, by adjusting the varactor diode in the antenna.

If the power amplifier is operated in the saturated mode, the transmitted power can be give as

$$P_{TX} = \eta \left(1 + \frac{R_{PA} + R_{lc}}{R_{ant}} \right)^{-2} \frac{V_{PA}^2}{R_{ant}} \quad (1)$$

where η is the antenna radiation efficiency, R_{PA} is the output resistance of the PA, R_{lc} describes the losses of the series resonance, R_{ant} is the antenna input resistance, and V_{PA} is the PA output voltage.

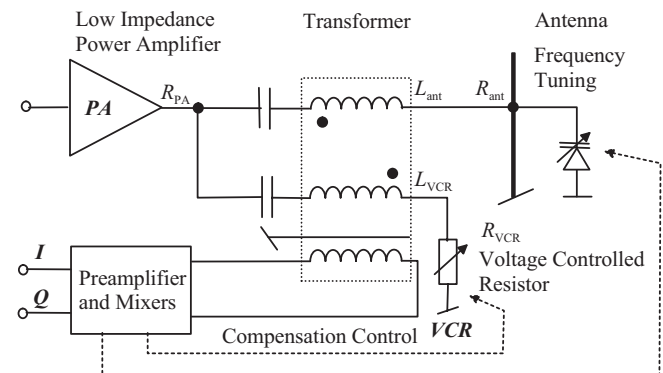


Fig. 1. Schematic of the RF front end module.

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The idea here is not to maximise the output power by matching the PA into the antenna but optimizing the total power efficiency of the system. Equation 1 shows that the efficiency can be optimised by maximising the antenna input resistance and minimising the PA output resistance. To keep the series losses as low as possible, the wiring from the PA to the antenna should be minimised and low inductance values in the transformer should be used.

In addition to the varactor for frequency tuning, the system includes a voltage control resistor (VCR), which is used to compensate for the changes of the real part of the antenna input impedance. If the ratio of the currents in the antenna and VCR branches is n , i.e. $n = I_1/I_2$, and the signal are in phase, the resistance of the VCR has to be n times that of the antenna including the other losses feeding the antenna. In the ideal case the loss in power is $1/n$. This means that in practice n has to be 3 - 6 in order keep the total power consumption as low as possible. There is no reason to make the ratio too high, since then the losses of in the power amplifier and the antenna will definitely dominate. In practice the maximum efficiency of the power amplifier could be 80 % and the efficiency of the small antenna 60 %. This means that we loose at least half of the power because of the PA and the antenna only. Consequently, the power ratio in the power divider more than 4 cannot be justified.

The VCR can be realised in different ways. We have tested here a FET and a PIN diode here as a tunable resistor. The VCR requires a sophisticated design to keep it real across the whole RFID bandwidth and for all resistance values. A PIN diode is an easiest component for this purpose but it dissipates more power than a FET.

To keep the currents in phase and in right ratio, the system has to be controlled. The outputs of the dual mixer stage control both the VCR and the varactor in the antenna. In principle, the imaginary part controls the varactor and the real part the resistance. Of course, the phase could be disturbed by the bridge and the delays from transmission lines and thus the controller has to be designed to combine I and Q signals for the right control. The bandwidth of the control has to be fast enough to compensate for the reflections but slow enough not to deteriorate the modulation from the tag. In practice, an ordinary PI controller providing feedback gain up to 1 kHz is sufficient.

The dynamic range of the compensation depends on the application. The most difficult situation is in a handset where a hand may cover the antenna or a large metallic object can be close to it. The retuning of the antenna by the nearby objects can be minimised by a proper antenna design. Since the whole UHF frequency band is so wide that the tuning range covering this is also sufficient to keep an antenna real near all the circumstances. This is, of course, valid only for antennas not too sensitive to nearby objects, e.g. electric dipole close to the cover is extremely sensitive to dielectric objects. The real part of the input impedance of a well designed antenna with a high radiation efficiency (e.g., 60 %) is hardly never halved and thus an octave is sufficient for VCR tuning range. As seen from Eq. 1, the lowered

antenna impedance leads to the higher radiation power. This is a good feature, since it helps to track a tag even with a hand touching the antenna.

III. ANALYSIS OF HYBRID TRANSFORMER

In this chapter, the hybrid transformer is studied theoretically by solving network equations. The model of the transformer is shown in Fig. 2. Port 0 stands for TX output, Port 1 is the antenna, Port 2 is the voltage controlled resistor (VCR) and Port 3 the RX input.

The network equations for the model are presented in Eq. 2. Here we have used standard definition for mutual inductance $M_{ab} = k_{ab}\sqrt{L_a L_b}$.

A. Isolation and TX attenuation

Solving Eq. 2 for isolation between TX and RX ports, i.e. $I_3 = 0$ with $V_1 = V_2 = V_3 = 0$, we get

$$\begin{aligned} & -\omega^2 M_{23} \left(L_1 - M_{12} - \frac{1}{\omega^2 C_1} \right) \\ & + \omega^2 M_{13} \left(L_2 - M_{12} - \frac{1}{\omega^2 C_2} \right) \\ & + j\omega (R_1 M_{23} - R_2 M_{13}) = 0, \end{aligned} \quad (3)$$

which includes two requirements for the isolation, one for real part and one for imaginary part. The equation for the real part includes two resonance relations, which can be individually tuned to zero.

The imaginary part of Eq. 3 gives a rather intuitive condition for the load resistances

$$\frac{R_1}{R_2} = \frac{M_{13}}{M_{23}} = \frac{k_{13}}{k_{23}} \sqrt{\frac{L_1}{L_2}}. \quad (4)$$

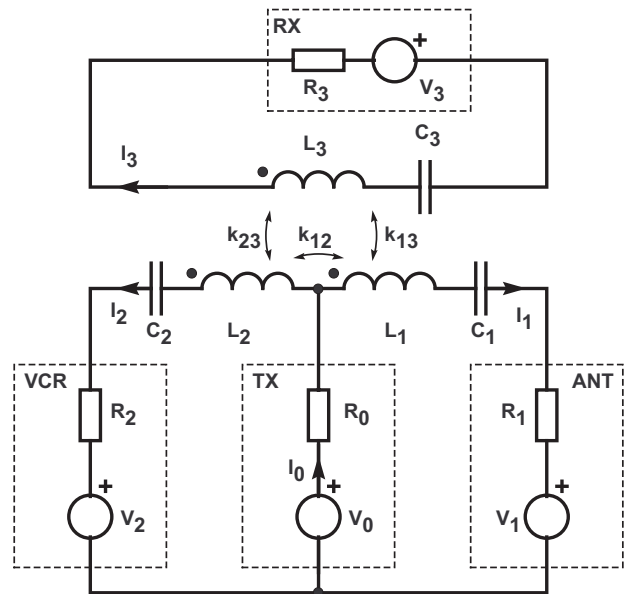


Fig. 2. The model of the hybrid transformer.

$$\begin{bmatrix} R_0 + R_1 + j\omega L_1 + \frac{1}{j\omega C_1} & R_0 + j\omega M_{12} & j\omega M_{13} \\ R_0 + j\omega M_{12} & R_0 + R_2 + j\omega L_2 + \frac{1}{j\omega C_2} & -j\omega M_{23} \\ j\omega M_{13} & -j\omega M_{23} & R_3 + j\omega L_3 + \frac{1}{j\omega C_3} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_0 - V_1 \\ V_0 - V_2 \\ V_3 \end{bmatrix} \quad (2)$$

This gives also the ratio of the currents I_1 and I_2 . Hence we define the current division ratio $n = R_2/R_1$. This is also roughly proportional to the the ratio of turns in coils L_2 and L_1 , because the inductance of a tightly wound coil is proportional to the square of the turns.

In resonance and isolation, the current distribution is determined by the load resistances, which leads to power ratio

$$\frac{P_1}{P_2} = \frac{R_2}{R_1} = n. \quad (5)$$

Hence the current division ratio can also be named as the power division ratio.

It can be seen from the above equations that hybrid transformer can deliver isolation between the TX output and the RX input. The power ratio scales as the load resistances, in the square root of hybrid coil inductance. The power ratio can also be expressed as gain G_{TX} from TX output to the antenna. The TX gain is

$$G_{TX} = \frac{P_1}{P_0} = \left(1 + \frac{R_1}{R_2}\right)^{-1} = \left(1 + \frac{1}{n}\right)^{-1}. \quad (6)$$

B. RX gain and noise figure

The gain from antenna to RX port, or the RX gain G_{RX} , can be calculated in a similar manner. To simplify the equations, we use we use Q-values of the series resonators: $Q_a = \omega L_a/R_a$. An interesting relation for the Q_1 and Q_2 holds in isolation:

$$\frac{Q_2}{Q_1} = \left(\frac{k_{23}}{k_{13}}\right)^2 n. \quad (7)$$

With incoming power $P_1 = V_1^2/R_1$ at port 1 in the network equation, we get for $n \gg 1$

$$G_{RX} = \frac{P_3}{P_1} \approx \frac{1}{Q_1 Q_3} \left(\frac{k_{23}}{k_{13}}\right)^4 \frac{1}{n^2}. \quad (8)$$

The RX gain degrades in the square of ratio n , and the TX gain increases directly proportional to n ratio. For high n , the loss in RX power is significant and in this respect very high values of n should not be used.

Let us also derive an equation for the sensitivity, i.e. the degrading in signal-to-noise ratio inherent to the hybrid. The signal-to-noise ratio for powers can be written as

$$\begin{aligned} SNR_{Out} &= \frac{I_3^2 (V_1 = V_{signal})}{I_3^2 (V_1 = V_{noise,1}) + I_3^2 (V_2 = V_{noise,2})} \\ &= \frac{P_1}{4k_b T \Delta B} (1+n)^{-1} \\ &= (1+n)^{-1} SNR_{In}. \end{aligned} \quad (9)$$

Here we have used $P_1 = V_{signal}^2/R_1$ as the signal power, and thermal noise of the resistors as noise sources. It is to be noticed, that SNR degrades directly proportional to the ratio n .

To calculate the noise figure NF of the hybrid, we need to take into account also the loss of signal, which was showed to be proportional to n^2 . Thus the noise figure becomes

$$NF \propto n^3 \quad (10)$$

As noise figure rapidly increases with n , very high value for n is not feasible. For low read range, $n = 4$ can still be feasible, if a good LNA is used. Numerical values for the attenuation as a function n of are presented in chapter IV.

C. Bandwidth

We have shown that the reactive bridge with a PA directly connected to an antenna provides an attractive UHF RFID reader concept. The drawback, however, is that the reactive arms limit the bandwidth. The bandwidth of the VCR arm is simply the ratio between its resistance and the impedance of the transformer stray inductance. Thus the relative bandwidth ΔB of the VCR arm can be approximated from the Q -value to be

$$\frac{1}{Q} = \frac{\Delta B}{\omega_0} = \frac{R_1}{n\omega_0 L_1 (1 - k_{12}^2)} \quad (11)$$

To keep the coupling constant high enough we easily end up with a rather high inductance. The total power efficiency of the system increases with increasing n , but the bandwidth may become too narrow. The compromise has to be done. If assuming $n = 4$, $R_1 = 10 \Omega$, $L_1 = 6$ nH, and $k_{12} = 0.7$, we get $\Delta B \approx 0.15\omega_0$. Using the above values the bandwidth could be about 150 MHz which is just enough covering all the UHF frequencies used for RFID applications around the world. The lowest frequency is 865 MHz used in Europe and the highest 950 MHz used in Japan. The inductance can be lowered by using a planar coil where the loops are set in parallel. In this way, a coil having diameter of 4 mm and 4 loops in parallel could have an inductance of the order of 3 nH or even less. The third coil used for detecting the modulation can also limit the bandwidth.

If the reactive hybrid with loading enables high enough bandwidth for all UHF RFID bands, the antenna bandwidth has to cover the information bandwidth only. The maximum information bandwidth is in USA being 1 MHz and thus the quality factor of the antenna has to be smaller than 100 without deteriorating the modulation. If aiming at highly efficient small sized antenna, the Q -value becomes easily very high. Since the reflection is compensated for by using the varactor in the antenna, it enables us to work with a narrow banded antenna.

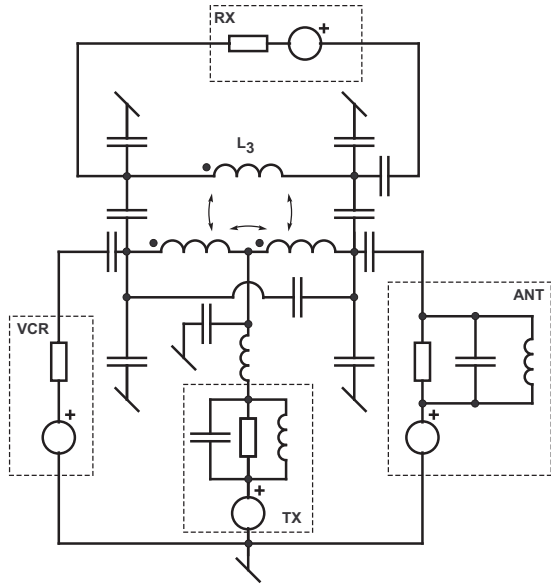


Fig. 3. Simulation model of the hybrid transformer: Antenna is modelled as a parallel resonator, PA matching and biasing circuits are added to the TX port and capacitive coupling and parasitics are modelled within the hybrid.

IV. SIMULATIONS

As seen in the previous chapter, analytical solution of three-mesh network leads to complicated equations. In this chapter, commercial simulator software APlac has been used to study the hybrid RF front end further. With this powerful tool, a more precise model of the actual realised front end can be used. The model is presented in Fig. 3.

The model has two main differences to the analytically examined model. First, all ports have been loaded with more realistic loads: The antenna is presented as a parallel resonator, and the TX input port takes into account the PA matching circuit. Second, the hybrid model has a lot of parasitic components, both capacitive and inductive, which have been derived from measurements.

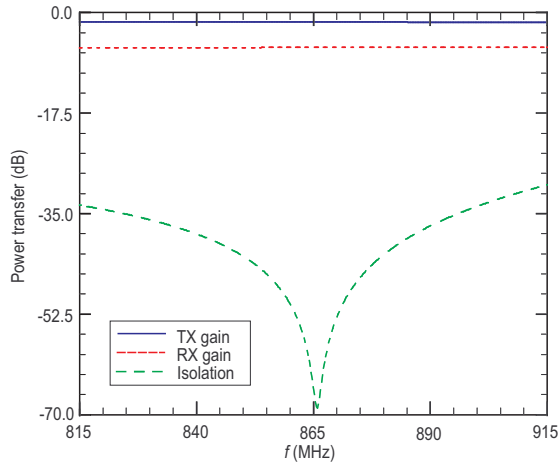


Fig. 4. Simulation results of the isolation, power transfer to antenna, and sensitivity with $n \approx 3$.

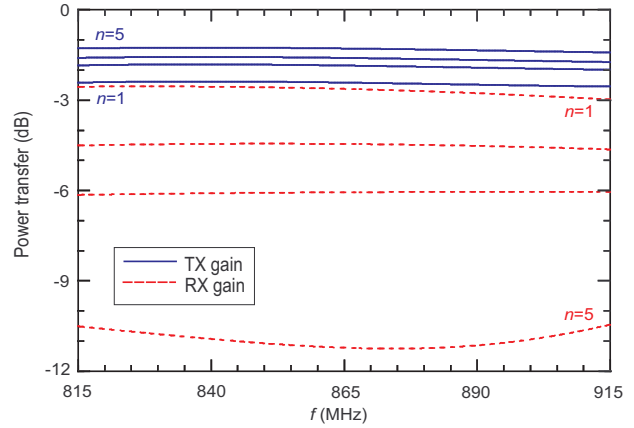


Fig. 5. Simulation results of the power efficiency and sensitivity with several values of the current ratio n .

The basic functionality of the hybrid is presented in Fig. 4. The isolation forms now a negative peak. At the same time, TX and RX gains are at maximum, but they are very wide band compared to the isolation.

To optimise the sensitivity and power efficiency of the hybrid, one would like to see the effect of power ratio n to TX and RX gains. The simulation results of the system with several values of the ratio n are presented in Fig. 5.

Clearly the dependence of sensitivity and power efficiency are against each other and the theoretically solved relations hold approximately: Sensitivity degrades twice the amount power is saved through the increasing of R_2 . The optimum ratio of the load resistances is a compromise that may vary in different applications.

Another interesting thing is to show, how the varactor tuned antenna can be used to tune the whole RF front end in frequency. In this case, the antenna parallel capacitor is varied to emulate parallel varactor. As seen in Fig. 6, the isolation is tuned smoothly over the European RFID band of 862-869 MHz by changing the antenna varactor capacitance.

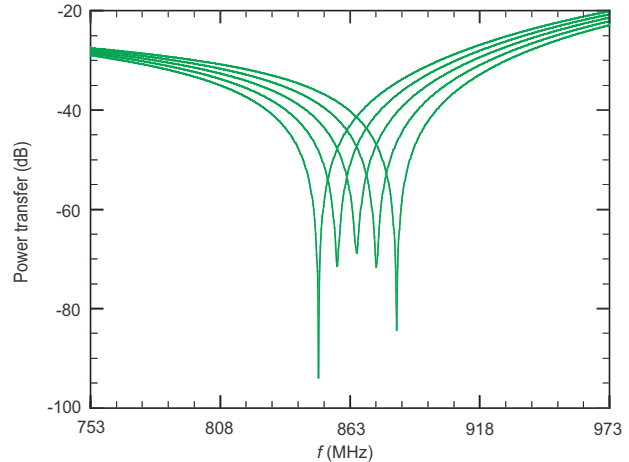


Fig. 6. Simulated isolation with different capacitance values of the antenna tuning varactor.

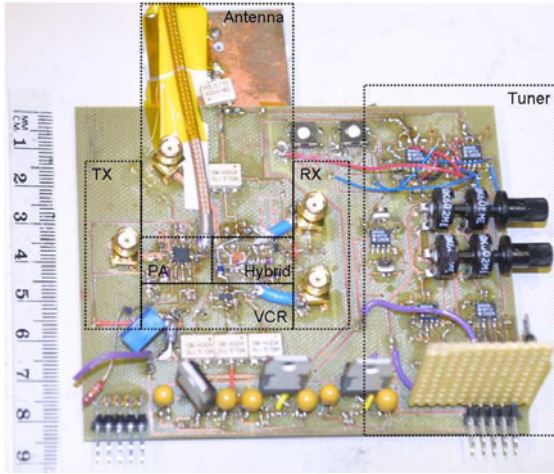


Fig. 7. First prototype of the RF front end.

V. MEASUREMENT RESULTS

After excessive analysis and simulations, a prototype of the hybrid RF front end was fabricated. The prototype consists of the hybrid transformer with ratio $n \approx 3$, a commercial power amplifier (PA), VCR, and a PIFA-type antenna on the opposite side of the PCB board. The antenna is small and narrow-banded, about $50 \times 30 \times 3 \text{ mm}^3$, and bandwidth of 10 MHz. The antenna can be made small, if tuning is provided. The RF front end was accompanied with a low frequency analog tuner, that took care of the tuning of the VCR and varactor. The prototype is presented in Fig. 7

The main difference between the realised prototype and the simulations as well as the theoretical analysis, is that parasitic series inductances from hybrid to antenna and VCR are not modelled. Also RX loop reactances are not considered in the previous analysis. Both of these lead to increased reactances of the system, and hence to narrower band of the system. Also the realised antenna is narrower than simulated ($Q \approx 50$), making the antenna the limiting component for the bandwidth.

The actual RF front end was first demonstrated with vector network analyser (VNA). The measurement setup is pre-

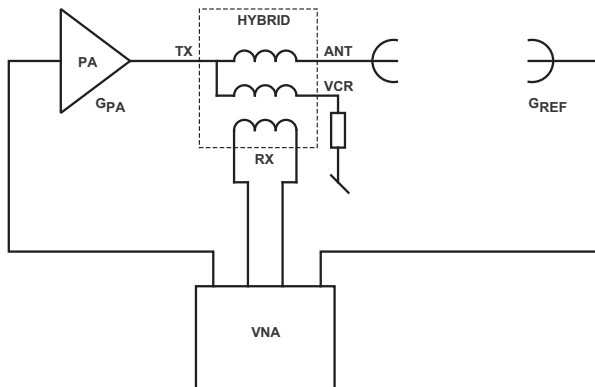


Fig. 8. Measurement setup of the prototype.

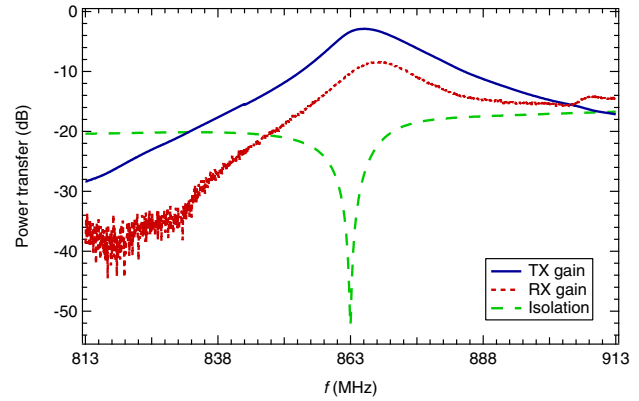


Fig. 9. Measurement of the prototype isolation and TX and RX gain.

sented in Fig. 8. The coupling to the antenna port is achieved with a reference antenna that is situated to a known distance of the antenna coupled to the RF front end. By knowing both antenna gains, the measurements of the antenna port are reduced to the power delivered to the antenna of the module. When similar calculation is made to take into account the power amplifier gain, the measurement results can be directly compared to the simulated and theoretical results. However, the PA gain is quite problematic to measure, as its gain depends on the output load. Hence error of 1 - 2 dB is to be considered for the measured results. The isolation and RX and TX gains of the RF front end are presented in Fig. 9.

In resonance, i.e. at 863 MHz, the isolation of even -50 dB is seen. The isolation is narrower than simulated, because the antenna of the prototype was narrower. Also VCR parasitics were not well enough included in the simulations. The TX gain is about -2.7 dB, and RX gain -7.0 dB, which are both a decibel less than simulated with $n = 3$. This probably due to the series losses, which were insufficiently modelled. In general, the shape and level of measured values comply well with both simulations and theoretical analysis.

The tuning of isolation over the European RFID band is shown in Fig. 10. The tuning range of the varactor capacitance is about one octave.

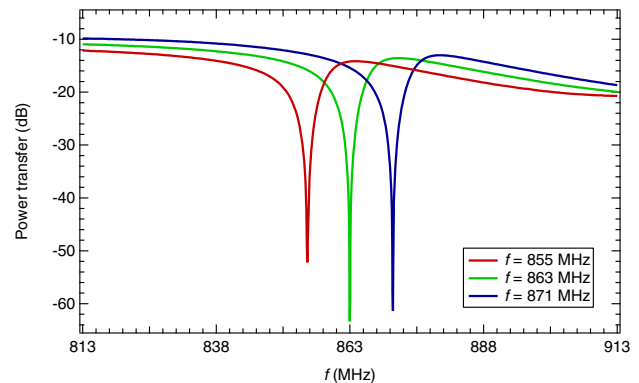


Fig. 10. Measurement of the isolation with different capacitance values of the antenna tuning varactor.

The RF front end was also tested with a RFID transceiver chip. The tuner used the output of quadrature mixers to tune the hybrid for maximum isolation. Here a reading distance of about 30-40 cm was achieved with transmit power of about 100 mW eirp regardless of the user hand or metal near the reader antenna.

VI. CONCLUSION

We have presented a hybrid transformer based RF front end for mobile UHF RFID readers. The solution has three main advantages: 1) power efficiency due to direct matching of antenna to PA output and narrow-band antenna; 2) small size, as circulator is not needed, and tunability allows a small, narrow-band antenna; 3) tunability delivers compensation for environmental reflections due to user hand near reader antenna, which increases read reliability.

The analysis and measurements show, that the solution is technically feasible. The hybrid delivers even -50 dB isolation between TX output and RX input. TX and RX gains depend from the ratio of VCR and antenna loads, i.e. the ratio $n = R_2/R_1$: The TX gain $G_{TX} \propto (1 + 1/n)^{-1}$ and RX gain $G_{RX} \propto 1/n^2$. Hence the more power is saved in the transmission, the more power is lost in the reception. These results were justified by theoretical analysis, simulations and measurements. Theoretically it was also shown, that the noise figure of the receiver increases as n^3 .

The bandwidth of the system has several limits. The fundamental, maximum bandwidth of the system, is limited by the reactance of the hybrid branches. Theoretically a maximum relative bandwidth of about 0.3 is achievable. In this demonstration the toroidal coil having 6 nH/turn was used. Owing to this reasonable high inductance the maximum bandwidth was limited to about 100 MHz, which is just enough for covering the whole RFID UHF band tuning the antenna only. The bandwidth of antenna, which is about 20 MHz, is more than enough for 1 MHz data bandwidth used in UHF RFID.

The system includes also an RFID transceiver chip, and a analog tuner, that uses the output of the quadrature mixers to tune the hybrid for highest isolation. When using the prototype with the about 100 mW eirp transmit power, a reading distance of 30 - 40 cm was achieved regardless of the user hand or metal near the reader antenna.

The analysis, simulations and measurements show that a very power effective RFID reader can be realised by using a reactive power divider with a low output impedance PA directly connected into an antenna. The tunable antenna enables optimizing the antenna radiation efficiency and, in addition, it can be used to compensate for the reflections. Our first demonstrator clearly indicates its potential but further optimization of the whole system is still needed.

VII. ACKNOWLEDGMENTS

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