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Plastic circuits and tags for 13.56 MHz radio-frequency communication

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A B S T R A C T

We discuss the design and implementation of 64-bit and 128-bit plastic transponder chips for radio-frequency identification tags. The 64-bit chips, comprising 414 organic thin-film transistors, are integrated into fully functional plastic radio-frequency identification tags with 13.56 MHz communication. The required supply voltage on the tag is generated from the AC input signal detected by the antenna, using a plastic double half-wave rectifier circuit. The tag is fully functional at a magnetic field strength of 1.26 A/m, which is below the minimum required radio-frequency magnetic field stated in the standards. We discuss the reading distance that can be achieved with our plastic rectifiers, and show that this reading distance is not limited by the performance of the plastic rectifier or transponder chip. The 128-bit transponder chip includes further features such as Manchester data encoding and a basic ALOHA anti-collision protocol. It employs 1286 organic thin-film transistors and generates the 128 bit sequence at 24 V supply voltage at a data rate of 1.5 kb/s. Data rates up to 2 kb/s could be achieved on chips with an 8-bit transponder chip.

1. Introduction

In the last decade, organic thin-film transistors (OTFTs) have gained considerable attention because of their potential for low-cost processing on flexible substrates [1–4]. A possible application of such TFTs is in radio-frequency identification (RFID) tags [5–8]. In a passive RFID tag, the power needed to bias the transponder chip is generated by the electromagnetic field emitted by the reader antenna at a certain standard base carrier frequency. In an inductively-coupled tag, the tag antenna is an LC (inductor–capacitor) tank designed to resonate at the frequency of this base carrier. The main base carrier frequencies available are 125 kHz (LF, low frequency), 13.56 MHz (HF, high frequency) or 869/915 MHz (UHF, ultra high frequency) [9]. A rectifier on the tag generates a rectified bias voltage as supply voltage for the transponder from the resonating voltage on the LC antenna of the tag. The value of the bias voltage depends on the magnitude of the magnetic field captured by the tag antenna, which decreases with distance from the reader antenna. To achieve a large reading distance, the transponder chip should operate at a low bias voltage, and the rectifier's power conversion efficiency should be high. Both these requirements are challenges in plastic electronics technology. Furthermore, a realistic tag for item-level identification must carry and read out the standard Electronic Product Code (EPC) consisting of 64 bits [10], which must be read out in 10–20 ms. These specifications set demanding requirements to the complexity of the chip and the clock frequency. In order to enhance the read out of the RFID tag more easily, the data should be encoded, for instance by Manchester encoding which allows the clock recovery at the reader. Furthermore, it is imperative to foresee an anti-collision protocol, to allow the read out of multiple RFID tags in the field of a single reader.

In 2007, Cantatore et al. [6] published a capacitively-coupled RFID system where a 64 bit code was read out at a base carrier frequency of 125 kHz. The 64-bit code generator was fully functional at a 30 V supply voltage. In that work, lower bit generators (up to 6-bit) could be read out using a base carrier frequency of 13.56 MHz by a capacitive antenna. The ability to use organic electronics for inductively-coupled systems has been shown by Böhm et al. [11], who demonstrated the read out of a ring oscillator using an inductive antenna. Ullmann et al. [12] demonstrated a 64 bit tag working at a bit rate exceeding 100 b/s at a base carrier frequency of 13.56 MHz. Recently, PolyIC has developed a 4-bit organic complementary RFID tag comprising n-type and p-type organic

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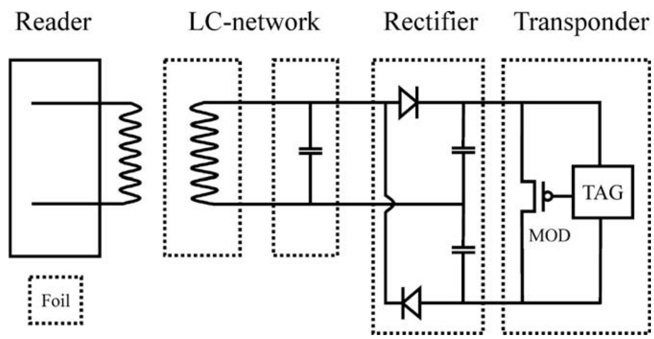


Fig. 1. Inductively-coupled organic RFID tag using DC load modulation.

field-effect transistors at 13.56 MHz [13]. In this work, we demonstrate major advances in both the digital transponder chip and the analog front-end of plastic RFID tags, and demonstrate that plastic electronics can result in a tag with a realistic code size, bit rate and reading distance at reasonable and allowed field strength. We also demonstrate significant increases in complexity of RFID transponder chips where the data have been Manchester encoded and a basic anti-collision protocol has been added that will allow the read out of multiple organic RFID tags in the field of a single reader at once.

The basic schematic of the RFID tag presented in this work is depicted in Fig. 1. It consists of four different foils: an antenna coil, an HF-capacitor, a rectifier and the transponder chip with an integrated load modulator. The coil and HF-capacitor match the resonance frequency of 13.56 MHz, and absorb energy transmitted by the reader and power the organic rectifier with an AC-voltage at 13.56 MHz. The rectifier generates the DC supply voltage for the organic transponder chip, which drives the modulation transistor between the on- and off-state with the code sequence. Fig. 1 depicts a general overview of the foils of our inductively-coupled RFID tags. For organic RFID tags, the load modulation transistor is preferably located at the output of the rectifier (DC load modulation), because when placed in front of the rectifier (AC modulation), it switches at the high "HF" frequency.

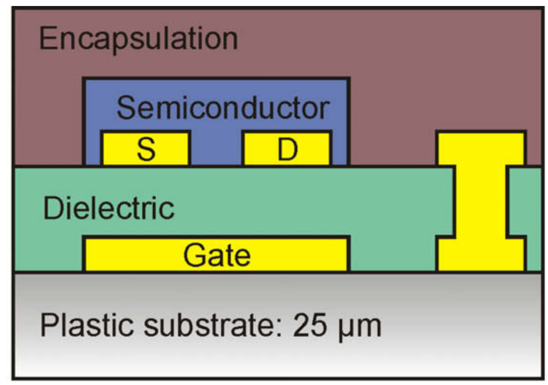
The small molecule pentacene is used as organic semiconductor material, which is deposited using two different methods. Evaporated pentacene is used for the rectifying diodes, creating vertical Schottky diodes which have been proven to be able to rectify at frequencies of 13.56 MHz and higher [14]. For the transponder chip, precursor pentacene is spin coated on the wafer and baked out, thus resulting in pentacene. The ability of integrating many OTFTs in a circuit with the precursor route has been shown before [15].

2. Manufacturing process

In this section we describe the manufacturing process of three of our modules, being the HF-capacitor, the rectifier foil and the transponder foil. The coil was manufactured by Hueck Folien GmbH, and is a thick etched Cu-layer on polyethylene terephthalate (PET) foil.

2.1. HF-capacitor

The HF-capacitor, or resonant capacitor, consists out of a metal–insulator–metal stack (MIM stack), processed on a 150 mm, 200 μm-thick flexible polyethylene naphthalate (PEN) foil. The insulator material used for this capacitor is Parylene diX SR and the metal layers consist of 30 nm Au.



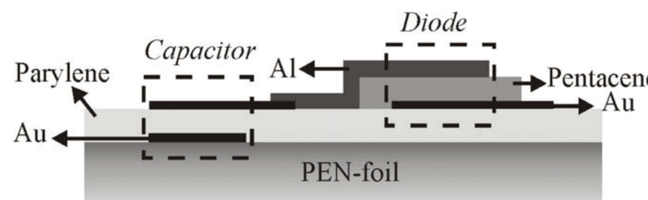


Fig. 2. Cross-section image of (top) an organic thin-film transistor and (bottom) a double half-wave rectifier.

2.2. Rectifier

The rectifier comprises two vertical Schottky diodes, and two capacitors in a so-called double half-wave rectifier configuration [16]. The schematic is depicted in Fig. 1. On a 150 mm PEN-foil, the MIM stack for the capacitors is processed in the same way as the HF-capacitor. On top of the MIM stack, pentacene is evaporated using HV-deposition through a shadow mask. Subsequently, an Al cathode is also evaporated through a shadow mask. As encapsulation layer, Parylene C and Al are deposited on top of the rectifier. A cross-section of the stack is depicted in Fig. 2.

2.3. Transponder chip

The organic transponder chips are made on a 25 μm thin plastic substrate using bottom-gate OTFTs. The organic electronics technology that is used, was developed by Polymer Vision for the commercialization in rollable active matrix displays and is described elsewhere [15,17]. The insulating layers and the semiconductor layer are organic materials processed from solution. A cross-section of the stack is depicted in Fig. 2.

3. Results and discussion

In this section, the electrical results of the transponder foils are discussed. After integration of the four foils (antenna, resonant capacitor, rectifier and transponder foil comprising load modulation transistor), the plastic RFID tag is measured in DC load modulation mode. Integration of the four foils was done on a PCB (Printed Circuit Board, only used for interconnects) for measurements, using sockets for every foil (see Fig. 3).

The reader setup conforms to the ECMA-356 standard for "RF Interface Test Methods". It consists of a field generating antenna and two parallel sense coils (Fig. 3), which are matched that they cancel out the emitted field. By this method, only the signal sent by the RFID tag is read out at the reader side. The detected signal is then demodulated by a simple envelope detector (inset Fig. 13), being a diode followed by a capacitor and a resistor, and shown on the oscilloscope.

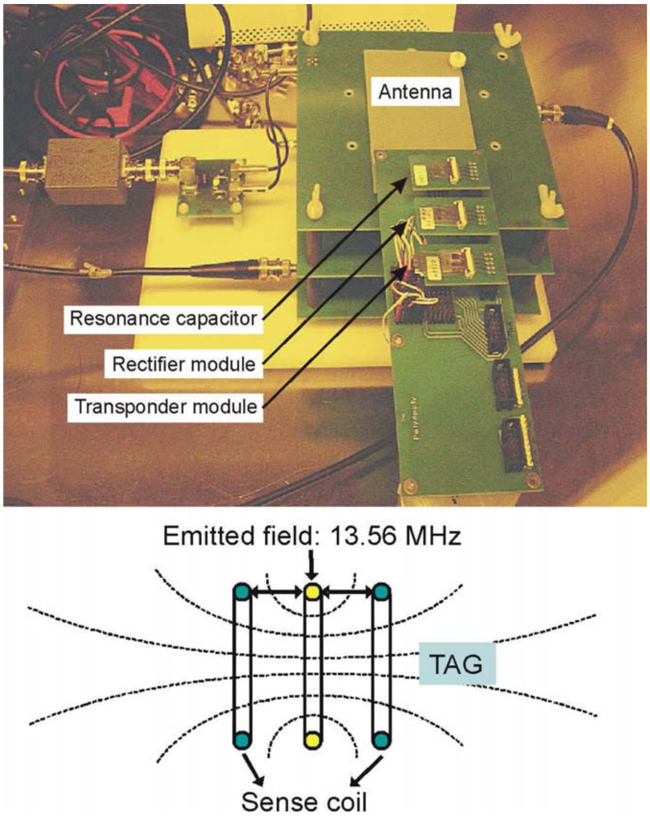


Fig. 3. (Top) overview of the reader and RFID tag measurement setup. Foils are placed in sockets to ease manipulation. (Bottom) schematic overview of the reader setup.

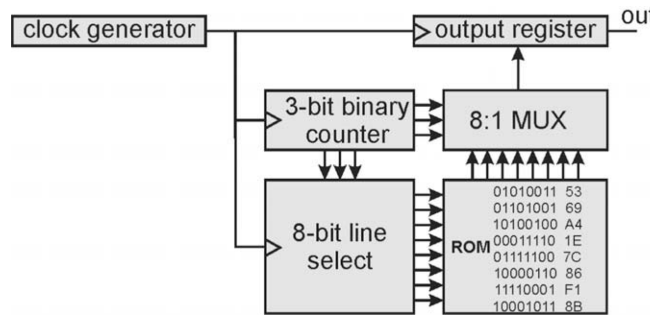


Fig. 4. Schematic overview of the digital logic part of the “generation 1” 64-bit transponder chip.

3.1. Transponder chips

The transponder chips are designed and fabricated in two different generations. The first generation comprises 8-, 16-, 32- and 64-bit transponder chips, whereas in the second generation 8- and 128-bit transponder chips were designed and fabricated. Also more functionality was integrated in latter transponder chips. Technology-wise, the two generations are very similar.

3.1.1. Transponder chips of generation 1

The design of the organic RFID transponder chips was limited to p-type only logic, since pentacene is a p-type semiconductor. The OTFTs, with a typical channel length of 5 μm, result an average saturation mobility of 0.15 cm^2/Vs. Logical gates, like inverters and NANDs, are therefore designed using zero V_{gs}-logic [6]. The gain of an inverter at the trip point, at supply voltages of 10 and 20 V is respectively 1.75 and 2.25. 19-stage ring oscillators are measured, yielding frequencies of 627 Hz at 10 V supply voltage and 692 Hz at 20 V supply voltage. Equivalent ring oscillators are used as clock generators in our RFID transponder foil.

The schematic of the transponder foil is depicted in Fig. 4. A 19-stage ring oscillator generates the clock signal when powered. This clock signal is used to clock the output register, the 3-bit binary counter and the 8-bit line select. The 8-bit line select has an internal 3-bit binary counter and a 3-to-8 decoder. This block selects a row of 8 bits in the code. The 3-bit binary counter drives the 8:1 multiplexer, selecting a column of 8 bits in the code matrix. The data bit at the crossing of the active row and column, is transported via a 8:1 multiplexer to the output register, which sends this bit on rising edge of the clock to the modulation transistor. The 3 bits of the 3-bit binary counter are also used in the 8-bit line select block for selecting a new row after all 8 bits in a row are transmitted. The 64-bit transponder foil comprises only 414 OTFTs. The design is made using only inverters and NAND-gates and is five times smaller than earlier reported. The challenge of designing complex circuits in present-day OTFT technology is the spread in parameters, in particular the threshold voltage [18]. To tackle this challenge in the design, we performed Monte Carlo simulations which took the spread of threshold voltages and mobilities into account.

Fig. 5 shows a micrograph image of the transponder foil. At 14 V supply voltage the 64-bit transponder foil generates the correct code at a data rate of 757 bits/s, which is depicted in Fig. 6.

Transponder chips with a lower number of bits are also designed, more specifically 8, 16 and 32 bits. The main difference in the design is the complexity of the line select. Fig. 7 shows the obtained code when these transponder chips are empowered.

3.1.2. Transponder chips of generation 2

In the second generation transponder foils, 8- and 128-bit transponder chips including more functionality, being data encoding and a basic anti-collision protocol were designed and fabricated. The mobility and threshold voltage of the single transistors are slightly higher, yielding a 33-stage ring oscillator of about 1.8 kHz at 15 V supply voltage. The speed of the ring oscillator, and therefore also the bit rate of the transponder chip, is faster compared to generation 1 due to the higher mobility and threshold voltage of the OTFTs. The choice for a 33-stage ring oscillator is determined during the design by a larger critical time path as a consequence of the added complexity.

The schematic overview of the 128-bit transponder chip can be seen in Fig. 8. The difference between the 128-bit and 64-bit transponder chip (generation 1) is the complexity of the line select, which is now a 16-bit line select. Also here, 128 bits are hardcoded in the chip. As mentioned earlier, the clock signal in the generation 2 transponder chips is a 33-stage ring oscillator.

Data-encoding is added to this generation 2 8- and 128-bit transponder chip, more specifically Manchester encoding. A zoom in the digital logic of the Manchester encoding block is depicted in Fig. 8. Manchester encoded data requires, besides the normal bit transitions, also a transition in the middle of the bit. A transition of 0–1 corresponds with a logic 0 and vice versa. In our design, every transition needs a rising edge of the clock. To include Manchester encoding to this scheme without losing data rate, a clock having double frequency is generated by the 33-stage ring oscillator. This clock is used to encode the data. The generation of this clock is done by an EXNOR behind stage 15 and 25, as depicted in Fig. 8. The two measured clock signals are shown in Fig. 9, whereby the speed of the Manchester clock (3.6 kHz) is double the speed of the system clock (1.8 kHz). The data is subsequently encoded by adding another EXNOR and NAND gate.

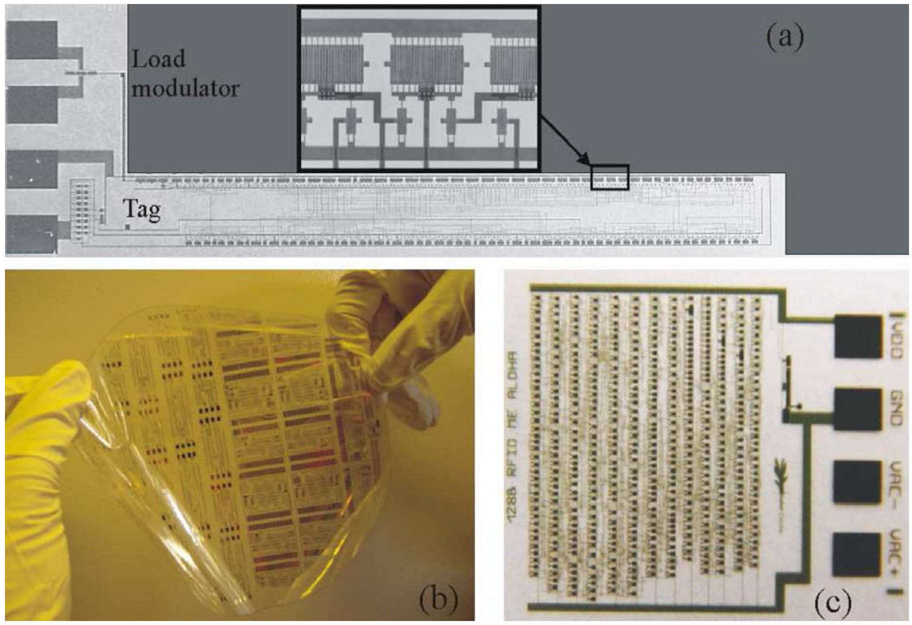


Fig. 5. Pictures of (a) the "generation 1" 64-bit transponder foil, (b) the 6" wafer comprising the transponder chips and (c) the "generation 2" 128-bit transponder foil whereby the functional area is about 1 cm^2.

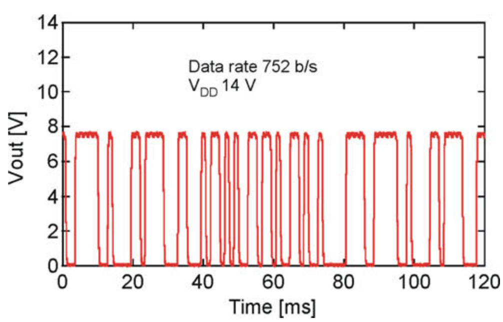


Fig. 6. Measured code of the 64-bit transponder chip at a supply voltage of 14 V.

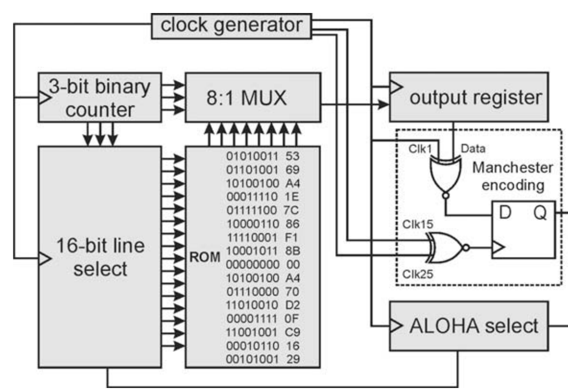


Fig. 8. Schematic overview of the digital logic part of the "generation 2" 128-bit transponder chip.

To enable the read out of multiple organic RFID tags at once, a basic anti-collision protocol is added to the plastic RFID transponder chip. The anti-collision protocol used is a basic version of ALOHA, which is a "tag talks first" protocol. A tag sends its code after which a silent period follows. The code is then retransmitted. During the silent period, another tag can be read out. If a tag transmits its code during the transmitting time of another tag, a collision occurs and the code is consequently not valid. A full ALOHA protocol should also allow the reader to acknowledge the successful detection of the code, after which the tag remains silent. This has not been implemented here due to the non-existent communication from the reader towards the tag.

In the implementation of this ALOHA protocol, a 1100 binary counter is used to select whether the data, coming from the Manchester encoder, should be sent out (value of the counter is 0000) or the supply voltage should be connected to the load modulator (all other values of the counter). The clock for this counter is

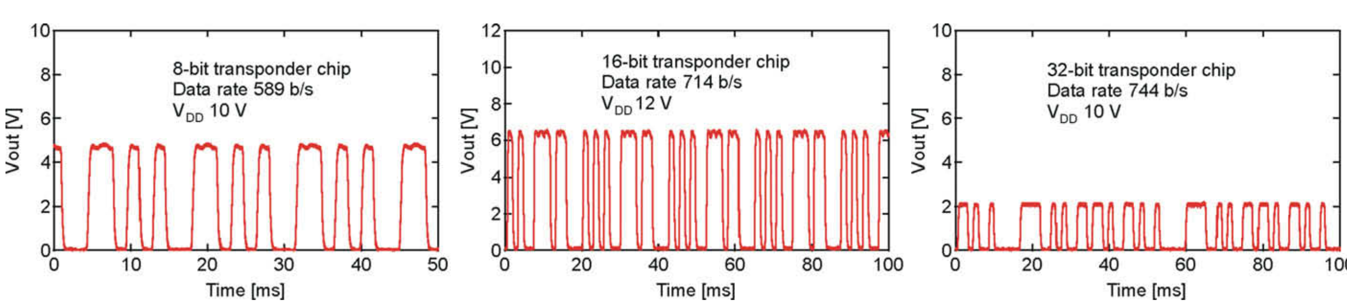


Fig. 7. Measured code of the (left) 8-bit transponder chip at a supply voltage of 10 V, (middle) 16-bit transponder chip at a supply voltage of 12 V and (right) 32-bit transponder chip at a supply voltage of 10 V.

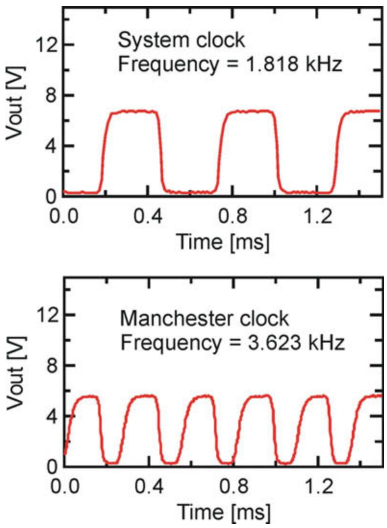


Fig. 9. Measured signal of (top) the 33-stage ring oscillator which is the system clock for the "generation 2" transponder chips and (bottom) the generated Manchester clock. The supply voltage for these clocks is 15 V.

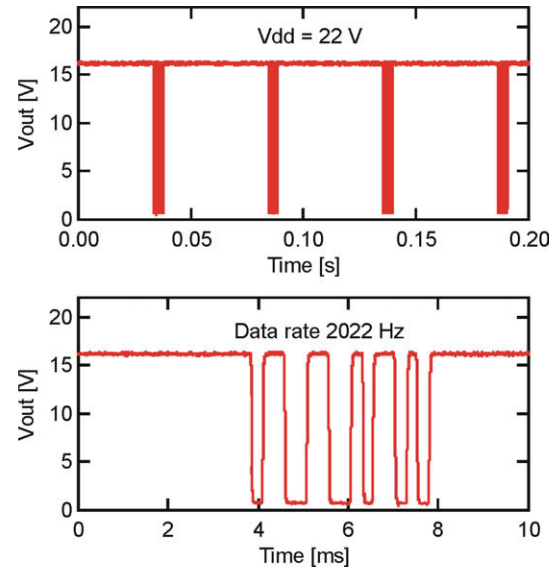


Fig. 12. Measured signal of the "second generation" 8-bit organic transponder chip with a power supply of 22 V (top) and a zoom of 1 period where the full code of the 8-bit organic transponder chip is shown (bottom).

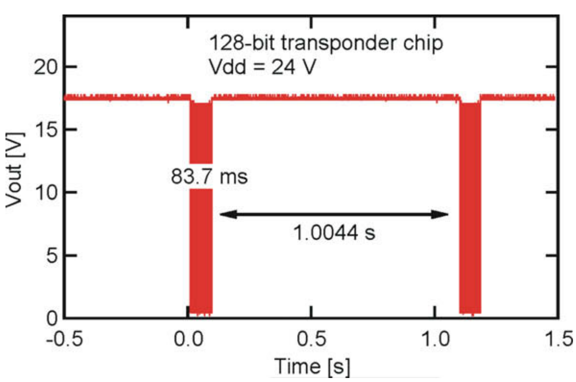


Fig. 10. Measured signal of the 128-bit organic transponder chip with a power supply of 24 V.

generated by the 3-bit binary counter and the 16-bit line select. In this way, the silent period takes 12 times the time necessary to stream out all data bits. Figs. 10 and 11 depict the measurement results of the 128-bit transponder chip, including Manchester encoding and the ALOHA protocol. This chip was powered with a supply voltage of 24 V and employs 1286 OTFTs. The 128 bits can be read out in 83.7 ms, i.e. a bit rate of 1529 Hz. Fig. 5 shows a picture of the 128-bit transponder foil.

The 8-bit transponder chip, including Manchester encoding and ALOHA protocol is fully operational at a supply voltage of 22 V with a data rate of 2022 Hz. This is depicted in Fig. 12. This data rate is a 10-times higher than the data rates reported earlier. A photograph of the 128-bit plastic transponder chip can be seen in Fig. 5.

3.2. Full organic RFID tag using DC load modulation

In this part, generation 1 transponder foils are integrated with the antenna coil, the HF-capacitor and the rectifier to form an organic RFID tag. In DC load modulation mode, the modulation transistor (W/L = 5040 μm/5 μm) is placed behind the rectifier, as can be seen in Fig. 1. 14 V DC can be obtained after rectification using a DC load modulation configuration and an RF magnetic field strength of 1.26 A/m [16]. This 14 V drives the transponder chip, which sends the code to the modulation transistor. The signal sent from the fully integrated, plastic tag is received by the reader and subsequently visualized using a simple envelope detector (see inset Fig. 13) without amplification. The signal measured at the reader side is depicted in Fig. 13. This shows the fully functional, 64 bit

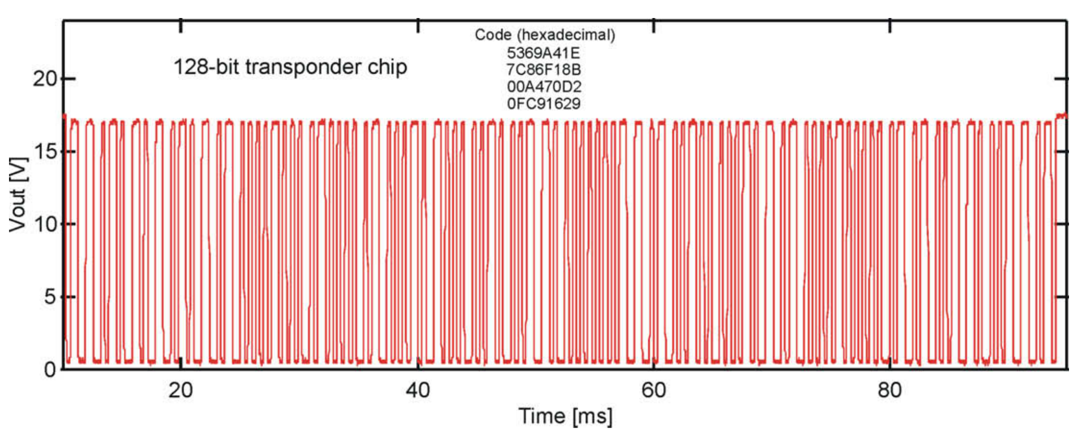


Fig. 11. Zoom of 1 period of Fig. 10 where the full code of the 128-bit organic transponder chip is shown.

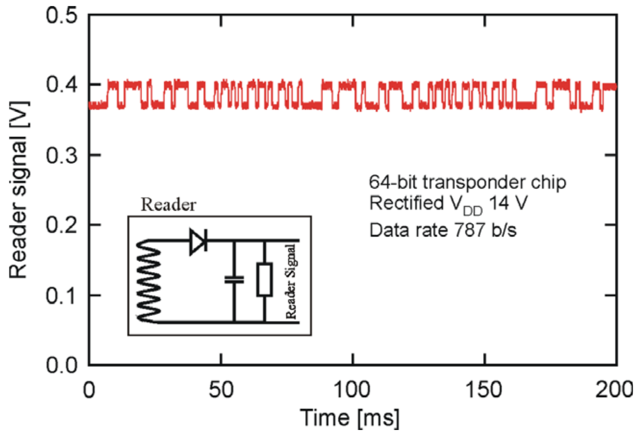


Fig. 13. Signal of the 64-bit RFID tag measured on the reader (unamplified reader signal). The envelope detector of the reader is depicted in the inset.

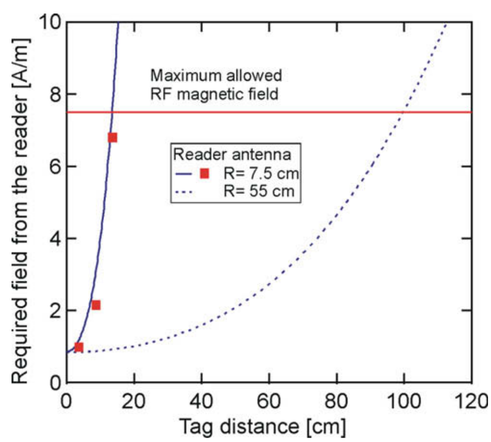


Fig. 14. Calculation and experimentally obtained date of the required RF magnetic field at the reader side as a function of the tag distance in order to generate the required RF magnetic field to operate the tag.

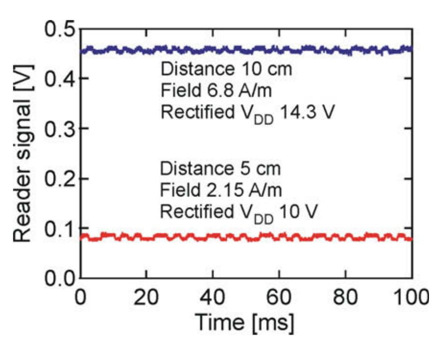


Fig. 15. Signal of the 8-bit RFID tag measured on the reader (unamplified reader signal) in DC load modulation mode at distances of 5 and 10 cm.

RFID tag using an inductively-coupled 13.56 MHz RFID configuration with a data rate of 787 b/s. With a 0.7 V drop over the diode at the reader (envelope detector), a tag-generated signal of about 1.1 V is obtained, from which 30 mV is load modulation (modulation depth $h = 1.4\%$).

Two of the reader standards at 13.56 MHz base carrier frequency are the proximity (ISO 14443) and vicinity readers (ISO 15693). The main difference in between them is the coil radius, being 7.5 cm for the proximity reader and 55 cm for the vicinity reader. This results in a maximum read-out distance of 10 cm and 1 m for the proximity and vicinity reader respectively. The standard (ISO 14443) states also that the tag should be operational from below minimum required RF magnetic field (1.5 A/m) while the maximum allowed RF magnetic field is 7.5 A/m. One can calculate the required magnetic field at the antenna centre in order to obtain the required field to operate at the tag. In our case, the required field for the 8-bit plastic RFID tag was 0.97 A/m. This is depicted in Fig. 14. The dots in this graph show the experimental data at distances of 3.75, 8.75 and 13.75 cm with respect to the field generating antenna. This graph shows that it is possible to energize our 8-bit plastic RFID tag at maximum read-out distances for proximity readers below maximum allowed RF magnetic field. The signal detected by the reader during the same experiment is depicted in Fig. 15 at distances of 5 and 10 cm with respect to the sense coil.

4. Summary and conclusions

In this work, we presented an inductively-coupled passive 64-bit organic RFID tag which is fully functional at a 13.56 MHz magnetic field strength of 1.26 A/m. This RF magnetic field strength is below the minimum required RF magnetic field stated in the ISO standards. The 64-bit transponder chip employs 414 OTFTs. It is internally driven by a supply voltage of 14 V generated by an organic, double half-wave rectifier. The obtained data rate is 787 b/s. Also an 8-bit transponder chip was measured in DC load modulation configuration and could be read out at a distance of 10 cm, which is the expected read-out distance for proximity readers. Subsequently we successfully integrated more complexity into the design of the transponder chips by addition of Manchester encoding to the data and of a basic ALOHA anti-collision protocol. The 128-bit transponder chip which includes the extra functionality employs 1286 OTFTs and generates the 128 bit sequence at 24 V supply voltage at a data rate of 1.5 kbit/s.

This work demonstrates that when taking proper care of the critical timing path in digital circuits to account for variability of parameters, state-of-the-art plastic electronics technology allows fairly complex digital circuits. Furthermore, the performance of high-frequency analog front-end devices such as rectifiers and load modulators are sufficient for a full plastic tag to match ISO standards in terms of allowed magnetic field and read-out distance.

Acknowledgements

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