Enhancing Wake-up Receiver Sensitivity Beyond –68 dBm Without Additional Power Consumption

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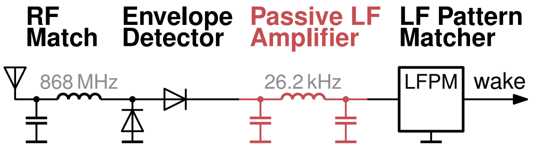

Idea: LC resonance circuit at 26.2 kHz

Results:

- 6.1 dB passive amplification
- WuRx sensitivity: –62.5 dBm → –68.6 dBm
- Low latency: 13.5 ms
- Constant power consumption: 10.3 µW

***Abstract*—Wake-up receivers (WuRxs) enable wireless, low-latency communication with greatly improved power efficiency. However, this efficiency comes at the cost of reduced sensitivity and communication range. Improving WuRx sensitivity without increasing power consumption remains a major challenge. Many existing approaches introduce RF amplifiers, but these typically require power in the milliwatt range. Only a few designs have achieved sensitivity values better than –65 dBm with a passive RF front-end. In this contribution, we propose a passive LF amplifier based on an inductor-capacitor resonance circuit. Using this method, we improve the sensitivity of the WuRx prototype from –62.5 dBm to –68.6 dBm, while keeping the power consumption constant at 10.3 µW and maintaining a low latency of 13.5 ms. To the best of our knowledge, this is the most sensitive WuRx reported that uses a passive RF front-end from 434 MHz–2.45 GHz with such very low latency.**

***Index Terms*—Wake-up receiver, wireless sensor network, ultra-low power, low-frequency receiver, AS3933, on-demand communication, LC resonator.**

Wake-up receivers (WuRxs) are special RF receivers that enable always-on listening for sleeping battery-powered sensor nodes. While modern RF transceivers usually require at least 10 mW, these specialized WuRxs consume much less power and help maintain a continuous communication link [1].

Therefore, WuRxs extend the battery life of sensor nodes and allow tasks that would otherwise not be possible [2].

Many articles focus on the development and use of WuRxs. Typical power consumption is in the range of 10 µW. WuRxs require special RF packets, as they use simpler modulation schemes and slower data rates. These wake-up packets (WuPts) usually last around 10 ms [3]. One disadvantage of WuRxs is their lower sensitivity compared to the main radio. Improving sensitivity and communication range remains an active area of research.

The WuRx literature includes designs based on application-specific integrated circuits (ASICs) and those using commercial off-the-shelf (COTS) components. We focus on COTS-based WuRxs because they are simpler, and are easier to reproduce and to adapt [2], [4], [5]. In a broad literature survey, we found out that about half of the COTS prototypes use low-frequency pattern matchers (LFPMs). LFPMs are special ICs that detect low-frequency signals, perform pattern matching, and consume very little power. These ICs integrate most required functions into one device and enable reliable WuRx communication [6].

Previously, we published a WuRx operating at 868 MHz, achieving a sensitivity of −61.6 dBm at a power consumption of 5.71 µW and a latency of 9.02 ms [6]. The prototype presented in this letter builds upon that design.

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I. STATE OF RESEARCH

The majority of COTS WuRxs rely on a passive radio-frequency envelope detector (RFED) to down-convert the RF signal. As a result, these WuRxs depend on amplitude-based modulation schemes such as on-off keying (OOK) [3]. This article focuses on WuRxs that incorporate low-frequency pattern matchers (LFPMs). LFPMs were typically designed for keyless car entry systems. They operate in the LF range of 15–150 kHz. Combined with a passive RFED, they enable the design of highly sensitive, reliable, and low-power WuRxs with addressing capabilities. Only a few additional components are required [6].

LFPM-based WuRxs require specially structured WuPts to meet the input requirements of the LFPM. These requirements are shown in Fig. 1. Both the RFED and the LFPM act as envelope detectors. Thus, the WuPt is amplitude-modulated both in the RF and LF domains. Our prototype operates with an RF frequency of 868 MHz and an LF signal around 25 kHz [6]. The RF carrier is turned on and off repeatedly to generate the LF carrier. Meanwhile, the envelope of the LF carrier contains the preamble and address information of the WuPt [6].

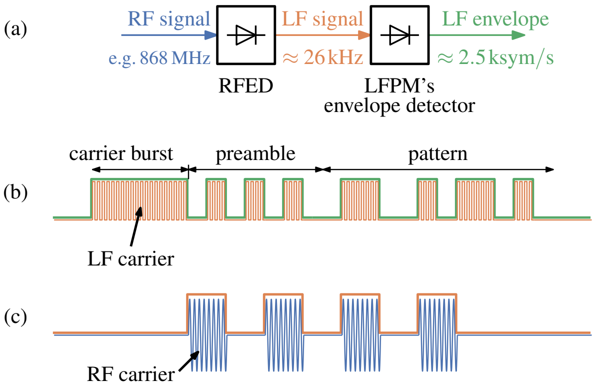

Fig. 1. Requirements on the WuPt for LFPM-based WuRxs. (a) Simplified reception path containing two envelope detectors. (b) LF envelope and LF signal of the WuPt. Visualization of the different components of the WuPt. (c) LF signal generated by the envelope of the RF signal.

This double amplitude modulation is used mainly for LFPM-based WuRxs. Most other COTS WuRxs rely on comparators for quantization and use microcontrollers or digital circuits for pattern detection [3], [4]. These typically apply direct OOK, where the address information appears directly at the output of the RFED. The passive LF amplification approach presented in this letter depends on a constant LF value and is therefore mainly suitable for LFPM-based WuRxs. It is not applicable to WuRxs using direct OOK.

Bdiri et al. [7] achieved one of the highest sensitivity values, −90 dBm, with a COTS-based WuRx at 868 MHz. This WuRx uses an RF amplifier in front of the passive RFED, increasing sensitivity by 35.5 dB. However, the amplifier consumes about 1 mW, making it unsuitable for always-on use.

Several other WuRxs also rely on active RFEDs or RF amplifiers to achieve sensitivity values beyond −70 dBm [8]–[11]. However, these designs typically require high operating current or rely on duty cycling. Duty-cycled systems are more complex, require additional components, and may suffer from high power consumption in the event of false wake-ups. Such wake-ups can occur due to interference or heavy channel traffic, potentially draining the sensor node's battery quickly unless proper safeguards are implemented.

The only always-on WuRx found in our literature survey that achieved −70 dBm sensitivity with low power consumption was proposed by Kazdaridis et al. [12]. Their design uses a passive RFED working at 868 MHz, opamp-based LF amplifier, comparator, and microcontroller for address decoding. Since only one opamp is used to amplify the LF signal, we expect the symbol rate to be low. We estimate a symbol rate of 47 sym/s, which would result in a 337 ms WuPt for 16 symbols.

In this letter, we present an LFPM-based WuRx with a passive RFED and passive LF amplification. Our WuRx achieves a sensitivity of −68.5 dBm, consumes 10.3 µW, and operates with WuPts of 13.5 ms. According to our literature survey, this is the most sensitive LFPM-based WuRx reported so far. The only exception is the prototype by Pflaum et al. [11], which uses both an RF amplifier working at 868 MHz and active LF amplification. This WuRx achieved −71 dBm sensitivity but consumed 183 µW and had a latency of 1000 ms due to duty cycling.

Köble et al. [13] proposed another LFPM-based WuRx with −63.4 dBm sensitivity and 8.7 µW power consumption working at 434 MHz. Their design includes a passive RFED, LF amplifier, and comparator. A crystal oscillator network converts the 4.68 kHz LF signal to 32.8 kHz to match the LFPM's requirements. No latency or data rate values were reported, but we expect higher latency due to the low LF value and the need for multiple signal periods to excite the oscillator network.

The idea of passive voltage amplification using resonance circuits was also explored by Gamm et al. [14]. They used a crystal oscillator to amplify the signal and reported a 25% increase in output voltage. However, no tests were performed using an LFPM, and loading effects on the oscillator were not discussed. Furthermore, no sensitivity measurements were reported.

II. MODELING

The passive LF amplifier proposed in this letter is based on an LC resonance circuit. The circuit amplifies the voltage signal from the RFED and forwards it to the LFPM. Proper tuning of the resonance frequency, handling of loading effects, and ensuring a high quality factor are important for effective operation. To analyze the circuit in SPICE, we created an equivalent model of the LF section of the complete WuRx. This model includes the output impedance of the RFED, the input impedance of the LFPM, and the parasitic properties of the inductors.

In [6], we introduced a voltage-doubler-based RFED using the Schottky diode SMS7630, operating at 868 MHz. The full schematic, which includes a LC-based RF impedance matching, is shown in the graphical abstract. In [15], we measured the video resistance of the RFED by connecting different load resistors and observing the voltage drop. The video resistance was found to be 11.7 kΩ. A low-pass capacitor of 47 pF is placed at the RFED output to filter high-frequency components.

In [6], we also used the AS3933 as the LFPM and studied its behavior in different configurations. According to the datasheet [16], the AS3933 has an input impedance of 2 MΩ. However, we could not verify this value experimentally. Using the RCL meter PM6306, we measured an input capacitance of 33 pF instead. This value was confirmed by observing a 50% voltage drop when adding this capacitance in series.

The LFPM includes internal tuning capacitors ranging from 1–31 pF in steps of 1 pF. These capacitors are used to adjust the resonator's frequency response to the desired center frequency. Their actual values were verified using the RCL meter.

A high-valued inductor is required because of the high output resistance of the RFED and the low LF carrier frequency of the LFPM. Only a few commercially available inductors reach the necessary inductance of over 100 mH. In our final prototype, we obtained the best amplification results using multiple inductors connected in series.

The inductor used for the passive LF amplification circuit has a nominal inductance of 100 mH and the part number B82144A2107J. We measured its impedance and phase using the RCL meter. The measured impedance curve is shown in blue in Fig. 2. We successfully modeled this inductor by adding a series resistance of 390 Ω and a parallel capacitance of 12 pF. The resulting modeled impedance curve is shown in orange.

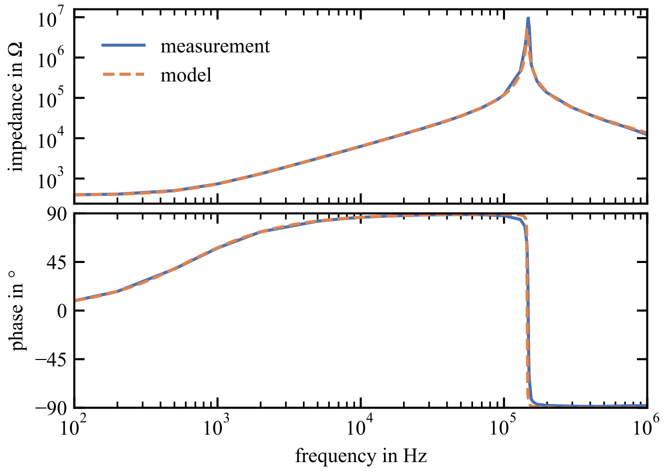

Fig. 2. Impedance curve of B82144A2107J inductor in blue, model with 100 mH inductance, 390 Ω series resistance, and 12 pF parallel capacitance in orange.

The complete equivalent circuit used in our SPICE simulations is shown in Fig. 3. Simulation results indicate that the resonance circuit has a sufficiently high quality factor to provide a voltage gain of up to 10 dB. Multiple inductors in series are required to tune the resonance frequency to 25 kHz. This LF was selected based on earlier measurements, which showed the best sensitivity of the LFPM at this value [6]. Adding external capacitors to achieve the same resonance frequency as with one or two inductors reduced the quality factor and voltage gain.

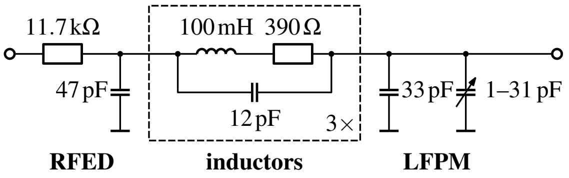

Fig. 3. Low-frequency equivalent circuit of RFED, inductors, and LFPM. Three of the displayed 100 mH inductors were utilized in series.

III. Results

For testing and validation of the circuit design, we manufactured a test PCB that includes the passive RFED and the LFPM. The LFPM is externally connected to a microcontroller. Our method for measuring and defining sensitivity is described in detail in [6], including calculations of the measurement error. By generating the WuPt using an RF signal generator, precise RF levels can be set, and errors are minimized. We estimated the packet error rate (PER) by transmitting 100 WuPts and counting the number of packets successfully received at different RF power levels. The sensitivity level was defined as the average power of the WuPt at which a 30% PER is observed. As a reference, we first performed a sensitivity measurement without the passive amplification circuit. The sensitivity of this PCB was −62.5 dBm.

Fig. 4 shows a photograph of the test PCB. The three 100 mH inductors are clearly visible on the right side of the image.

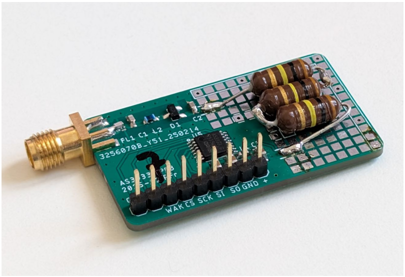

Fig. 4. Test PCB with passive RFED, three 100 mH inductors, and LFPM.

As a first test, we measured the frequency response of the passive LF amplifier. We applied a continuous amplitude-modulated signal to the RFED and probed the input of the LFPM. An ultra-low input capacitance probe was required for this measurement. Standard oscilloscope probes have significant input impedance and would affect the circuit behavior. Our probe consists of a custom PCB using the opamp LTC6268 as a pre-amplifier. The LTC6268 has an input capacitance of only 0.45 pF and input bias currents of just ±20 fA. By varying the modulation frequency of the RF signal, we recorded the frequency response. Measurements were repeated with different tuning capacitances of the LFPM: 0 pF, 15 pF and 31 pF, and with one, two, or three inductors in series. Fig. 5 shows the resulting frequency responses of the passive LF amplifier.

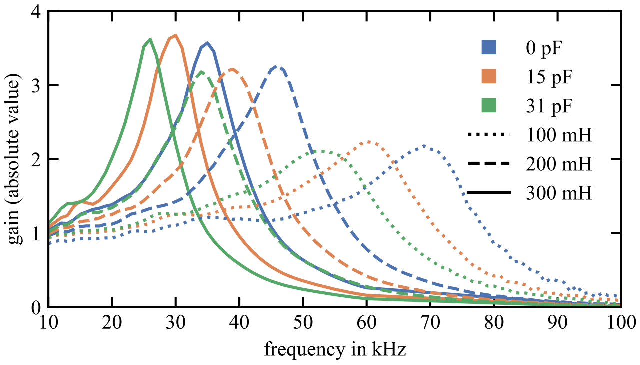

Fig. 5. Frequency response of passive LF amplifier for different tuning capacitances and one, two, or three inductors in series.

The frequency responses clearly show the band-pass behavior and resonance of the circuit. As the simulations showed, higher inductance values resulted in a higher quality factor. The tuning capacitances of 15 pF and 31 pF resulted in the highest voltage amplification, reaching a factor of 3.7. In [6], we found that the LFPM performs best at a LF of approximately 25 kHz. Therefore, we used three inductors and the tuning capacitor of 31 pF. The highest peak for this capacitor was observed at an LF of 26 kHz.

In [6], we also showed that the LFPM is sensitive across a wide frequency range. However, setting the correct symbol rate is critical. Due to the double amplitude modulation, the symbol rate and LF carrier are linked by the LF modulation ratio β_{LF}. We selected $\beta_{\mathrm{LF}} = 12$ to ensure that enough signal periods are present for the passive LF amplifier to settle.

The WuPt used in this prototype operates at an RF of 868 MHz, an LF of 26.2 kHz and achieves a symbol rate of 2.18 ksym/s. Referring to Fig. 1, the WuPt includes a carrier burst of 3.05 ms, a preamble of 3.20 ms, and 16 symbols. Using Manchester coding and a separation sequence for univocal addressing, 7 usable address bits are freely available for addressing [17]. Based on our definitions from [6], we estimate the sensitivity level of this configuration to be -68.6 dBm.

IV. Conclusion

Wake-up receivers (WuRxs) drastically reduce power consumption during RF reception by up to three orders of magnitude, making them a key technology for ultra-low-power sensor nodes. However, due to the use of simplified circuit designs and modulation schemes, WuRxs typically exhibit limited sensitivity. Improving sensitivity without increasing power consumption or latency remains a major challenge in research.

In this work, we present a WuRx design working at 868 MHz that employs passive LF amplification using an inductor-capacitor resonance circuit. This approach improves the sensitivity from -62.5 dBm to -68.6 dBm, corresponding to a 6.1 dB gain, which is sufficient to approximately double the communication range. Our design is fully based on COTS components and uses an LFPM for low-frequency signal detection.

When compared to existing work, only a few COTS WuRx designs reach similar sensitivity levels. Most high-sensitivity receivers rely on active RF front-ends with amplifiers, which significantly increase power consumption [7], [9], [11]. Kazdaridis et al. [12] achieved -70 dBm without active RF amplification, but their design appears to require a very low symbol rate and extended WuPt durations of over 300 ms. Such a high latency renders this design unpractical for many real-time applications.

The passive resonance circuit proposed here provides several advantages. It does not require any additional power, as it is energized entirely by the signal from the RFED. Its sharp band-pass characteristics enhance the desired LF signal while attenuating noise and out-of-band interference, effectively improving the signal quality at the input of the LFPM. The circuit integrates well with the impedance characteristics of the LFPM and can be tuned to match the desired resonance frequency by adjusting internal and external capacitors.

Nevertheless, this approach also presents certain limitations. As illustrated in Fig. 4, the through-hole inductors used in the prototype are large compared to other components. Although a few smaller inductors with similar inductance values are available, they often exhibit higher parasitic losses and lower quality factors. Therefore, this approach may not be suitable for applications that require very small PCBs or lightweight components. Additionally, the use of inductors can increase the receiver's susceptibility to external magnetic fields, which may reduce reliability in certain environments, such as industrial settings or areas near electric motors [18, p. 397]. The circuit was tested in a typical office environment, with multiple Wi-Fi networks and nearby mobile communication towers.

The prototype requires 12 LF periods per symbol to allow the passive amplifier to settle, resulting in a total WuPt duration of 13.5 ms. The total current consumption of the circuit is 3.43 µA at 3.3 V, as shown in [6], and can be reduced to 7.44 µW when the LFPM is supplied with 2.4 V.

In conclusion, the proposed passive amplification technique significantly improves WuRx sensitivity without increasing power consumption or latency. Future research may explore the use of compact or high-Q inductors, to further reduce the circuit footprint and enhance robustness against magnetic pickup.

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