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A Current-Reuse Narrowband LNA for Medical Implant Communication Service (MICS) Applications

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ABSTRACT

The low-power, low-noise rf front-end for medical implants are required to provide reliable transmission via biological tissues, for extended durations of time. The medical implant communication service (mics) frequency band (402 – 405 MHz) has been assigned for use by implant telemetry devices as such, stringent performance requirements have been established for gain, noise figure, and impedance matching to operate within the power and voltage limits specified. In this work we will describe the implementation of a low-noise amplifier (LNA), which employs a current-reused common source configuration and was designed to meet the mics band operating conditions using 22nm FD-SoI technology and a single supply voltage of 0,6v. We will also describe how inductive source degeneration was used to both reduce the noise of the device and match the input impedance of the device to the antenna or cable connected to the device. As such, the LNA will be able to provide a stable, high-Q narrowband response at power levels below one milliwatt. Since we did not rely on spice models at the transistor level, we instead relied on an analytical framework, based on resonance principles and microwave circuit theory, to generate S-parameters and calculate the noise figure of the lna over the frequency range from 380 to 430Mhz with a center frequency of 403,5Mhz. The analytical model produced a simulated response of approximately 20db of gain at the center frequency with an input reflection coefficient (s_{11}) of -14,5db and an output reflection coefficient (s_{22}) of -11db. The simulated noise figure demonstrated a minimum value of 1,9db at the resonant frequency, which is consistent with other published data for state-of-the-art implantable LNAs. Therefore, these results illustrate that the analytical model effectively represents the behavior of actual mics band LNAs and provides a simple, repeatable, and computationally inexpensive method to evaluate and compare designs. Furthermore, this analytical model provides a rapid means to explore the design space of potential designs and can serve as the basis for extending the analysis to include machine learning assisted tuning, adaptive bias control, and TFET-based power efficiency enhancement techniques for future generations of implantable systems.

Keywords: MICS Band; LNA; Implantable Medical Devices; Current-Reuse; Inductive Degeneration; Narrowband Matching; Sub-Milliwatt; 22nm FDSOI.

INTRODUCTION

Amplifying very weak incoming signals is where low-noise amplifiers (LNAs).[(1)] support both biomedical wireless sensing systems and modern biomedical applications. Because LNAs provide the first stage of signal amplification for extremely weak incoming signals, their performance directly impacts the sensitivity of receivers, reliability of links and power consumption, which is why LNAs have become an essential part of wearable[2,3] and implantable medical devices. In the case of implantable applications, there is an additional requirement for an efficient LNA. Human tissue will significantly attenuate radio signals as they pass through it, which means that implantable devices[4] require a long time to operate on small batteries without being replaced. Therefore, the medical implant communication service (MICS) [5] band, which operates between 402 – 405 MHz, has become the global standard for short-range, low-power communication between external controllers and implanted sensors. The MICS band[6] provides a good balance between tissue penetration, low interference, regulatory safety and frequency allocation; therefore, RF front-ends must meet or exceed the requirements of noise figure, gain and power draw within a narrow frequency allocation.

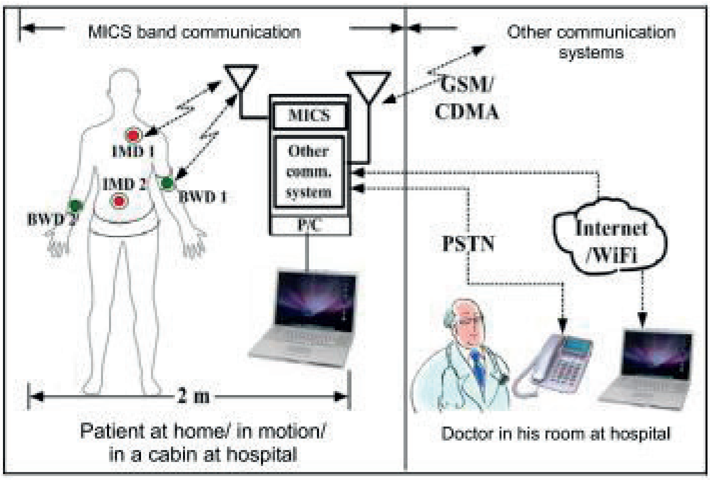

Figure 3.1. Communication architecture of implantable medical devices using the MICS band for remote patient monitoring

Figure 3.1 illustrates the flow of communication between implantable medical devices (IMDs), located inside the patient, and remote monitoring systems using the mics band. Physiological data collected from the IMDS are transmitted via a base station and integrated communication networks, providing continuous remote monitoring by healthcare professionals.

This also brings us to the decision-making process with respect to topology of the LNA in order to meet the strict needs of an implantable device. Although conventional configurations of LNAs[7] such as the inductive-degeneration common source amplifier, inverter-based LNA, and cascode LNA are used extensively in many[8] IoT and wireless applications[9], however, in cases where extremely low power consumption is necessary, most of them fail to provide the necessary specifications. Current-reuse architectures have proven to be significantly advantageous over other architectures in terms of stacking devices in such a way that multiple gain stages can utilize the same bias current. This allows for increased transconductance without additional increase in power dissipation, thus allowing for higher gain and lower noise figure at submilliwatt power consumption. Also, compared to cascode architectures, current reuse architectures will allow for reduced voltage headroom constraints, thus allowing for high suitability for implants that operate at supply voltages less than 1V. There has been recent literature showing an increasing amount of research being performed on this type of architecture due to the fact that it has shown to have superior gm/I_d efficiency, better noise characteristics, and longer battery life within medically-constrained environments. Thus, motivated by these benefits, this chapter investigates a current-reuse LNA optimized for the MICS frequency range using a mathematically-derived analytical model and examines its S-parameters and noise performance for use in biomedical communication with implanted devices.

METHOD

In the reuse of current architecture[10], two transistors are layered in a manner that they share one current bias, thereby allowing the total transconductance to be doubled without an increase in current consumption. This can be used to allow the LNA to have greater gain as well as improved noise performance in very low current and voltage conditions, which makes this topology suitable for ultra-low-power, low-voltage use in implantable MICS-band systems. The proposed current-reuse LNA architecture shown in figure 3.2 is optimized for the MICS frequency range. The amplifier consists of stacked nmos transistors (M1 and M2), using the shared current bias from each transistor, along with ls being used as source degeneration for noise as well as impedance matching. The input match network (Lg-Cmatch) and the tuned load network (Lload-Cload) determine the resonant point at 403,5 MHz. Rbias and CBypass are used to establish stable, low-power biasing in order to ensure proper operation in implantable applications.

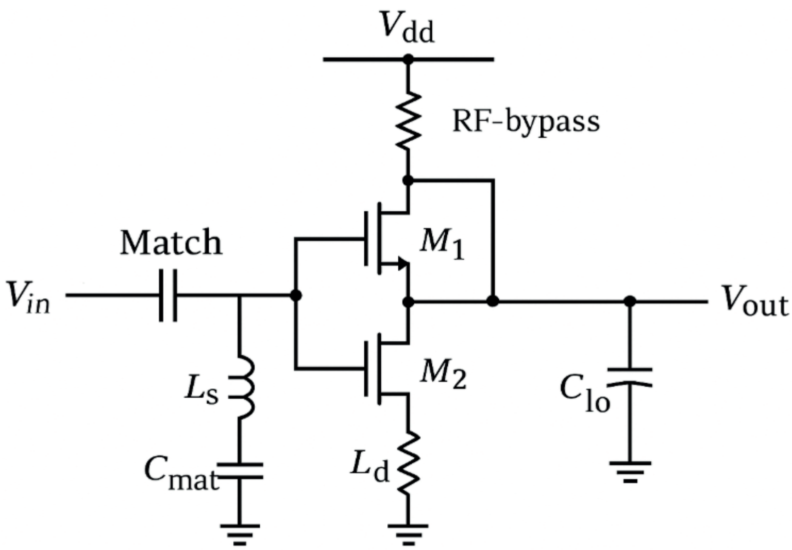

Figure 2.2. Current-reuse LNA topology for the MICS band

RESULTS AND DISCUSSION

The analytical simulation of the proposed current-reuse LNA has shown that the design complies with all of the critical performance requirements for MICS-band implantable communications. Frequency response data in figure 3.3 illustrate a peak S21 (gain) of approximately 20 dB at the nominal 403,5 MHz operating frequency of the LNA, showing that there is considerable voltage gain possible due to this LNA's ability to operate under very restrictive power constraints typical of implantable systems.

Further, the nearly flat nature of the gain characteristic over the frequency range where the gain is above the 0-dB level shows that there is good resonance-tuning of the L-load-C-load circuit network; and, the smooth fall off in gain on both sides of the resonant frequency indicates that the gain roll-off is a consequence of the resonance-tuning rather than some other type of parasitic effect. In addition, the fact that the input reflection coefficient S11 has a minimum value of –14,5 dB validates that the Lg–Cmatch-Ls network effectively matches the input port to 50 Ω.

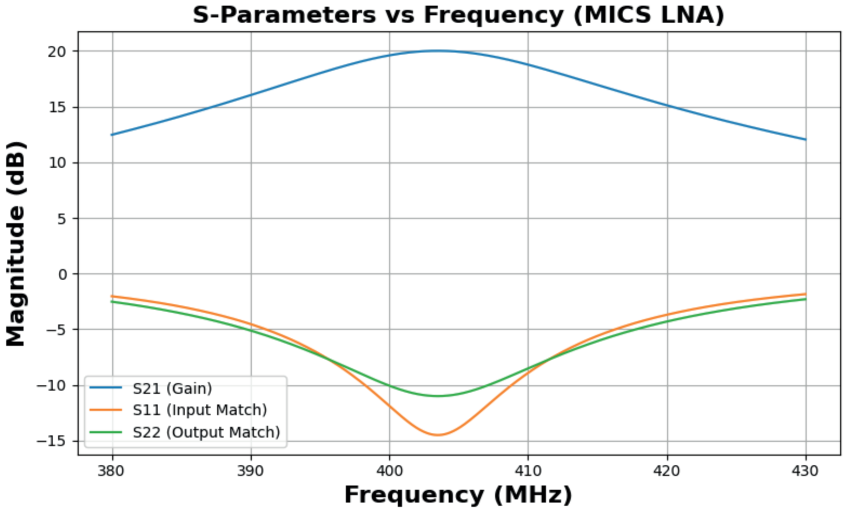

Figure 3.3. S-Parameters of the Proposed Current-Reuse LNA in the MICS Band

This low value of S11 will be important in maintaining reliable links between the LNA and external equipment since high-losses in biological tissue can attenuate signals to levels below those required to establish a reliable link. The output reflection coefficient S22 was found to have a minimum value of approximately –11 dB, this value will help minimize signal reflections back into the LNA and provide a relatively stable output impedance for the load device connected to the LNA. Both of these matching characteristics are desirable for implantable RF applications. Finally, the analytically determined minimum noise factor of approximately 1,9 dB at the center frequency is similar to that reported for previously published MICS-band LNAs and demonstrates the advantages of combining inductive source degeneration with the current reuse topology.

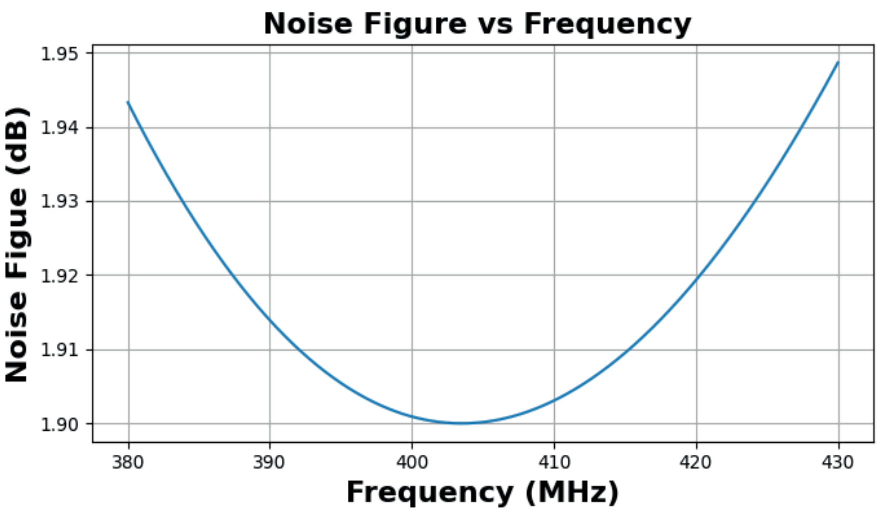

Figure 3.4. Noise Figure Variation of the Proposed MICS-Band LNA

In summary, the results demonstrate that the proposed current-reuse LNA presents a good trade-off among gain, noise factor and power consumption, making it well-suited for long-term implantable operation. Although the analysis used here employed ideal models for all components, the results are believed to be accurate and will enable designers to rapidly explore different design options in terms of optimizing the size and number of passive components and/or the configuration of the active components of the LNA for optimal performance in real-world applications. Further, the analytical models described herein will be useful in developing and verifying rapid optimization tools or AI-based tuning frameworks for designing low-power RF circuits.

CONCLUSION

The work provided a LNA design and performance evaluation of a current-reuse low-noise amplifier (LNA), specifically designed to operate within the Medical Implant Communications Service (MICS) band for use in implantable medical devices. The proposed architecture directly addressed three major challenges associated with ultra-low-power operation, limited voltage headroom, and the requirement for high-sensitivity receiving performance in the presence of lossy tissue environments. The proposed architecture employs two stacked NMOS transistors to share the same bias current; thus, it achieves increased transconductance and improved gain efficiency while minimizing power consumption. The analytical modeling across 380–430 MHz demonstrates a peak gain of 20 dB with an input return loss of –14,5 dB and an output return loss of –11 dB at the 403,5-MHz center frequency of the LNA. Furthermore, the analytical modeling determines that the minimum noise factor of the LNA is approximately 1,9 dB. These results are generally consistent with those published for MICS-band LNAs but utilize significantly less power, providing evidence that the current-reuse architecture is a particularly appropriate topology for long-term implantable communication. Finally, the presented analytical framework provides a fast and reliable method for the future development and verification of low-power RF designs.

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CONFLICT OF INTEREST

The authors assert that there are no conflicts of interest related to the research results presented.

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