A 4.6-5.35GHz Transceiver with 38dB On-Chip Self-Interference Cancelation at 10kHz Offset Frequency

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***Abstract*—A 4.6-5.35GHz transceiver with active self-interference cancelation is reported. The active cancelation circuit cancels up to 38dB of TX leakage at 10kHz offset from the RX signal. It increases the interference P1dB from -25dBm to -8dBm, and RX gain by 15dB. When the transceiver is utilized in a magnetic resonance spectroscopy system, the SNR improves by 15dB. Furthermore, in addition to the traditional method of B_0-sweep, for the first time, the method of frequency-sweep is demonstrated.**

***Index Terms*—Transceiver, self-interference cancelation, full-duplex, Silicon, SiGe, EPR, ESR, spectroscopy.**

I. INTRODUCTION

Interference-resilient transceivers, where the receiver (RX) is able to operate without performance degradation under a large interference power, are often required in many applications, including full-duplex wireless communication, magnetic resonance and dielectric spectroscopy, and full-duplex radar. Existing interference-resilient transceivers can be characterized into two categories: (1) Reject the interference at IF with little voltage gain at RF (mixer-first) [1-3]. (2) Reject the interference at RF using a high-Q filter [4,5]. Unfortunately, method 1 suffers from large $1/f$ noise contributed by mixers and baseband circuitries at low IF, due to the lack of voltage gain at RF; while method 2 has a low interference P1dB when the frequency offset between the interference and desired RX signal is small, due to the low quality factor of the RF filter. In order to achieve both low noise and high linearity, it is desirable that the interference be removed at RF without using a filter.

In this work, we make the observation that, for many applications, the interference signal results mostly from the transmitter (TX) leakage (self-interference). As the transmitted signal is generally known, it is possible to generate a cancelation signal and cancel the interference at RF. Utilizing this observation, in this paper, we propose the first single-chip transceiver with active self-interference cancelation. The proposed transceiver reduces the TX leakage by up to 38dB at RF at 10kHz offset frequency. Unlike prior work [4, 5], where the interference rejection is limited by the filter quality factor, the proposed transceiver does not require an RF filter. Thus, the cancelation can be achieved at an arbitrary small frequency offset between the interference and the desired RX signal. For 30dB voltage gain at RF, the active cancelation increases the interference P1dB from -25dBm to -8dBm. Due to the strong voltage amplification at RF, the $1/f$ noise from mixer and baseband circuitries is significantly suppressed, improving the noise figure (NF) of the RX.

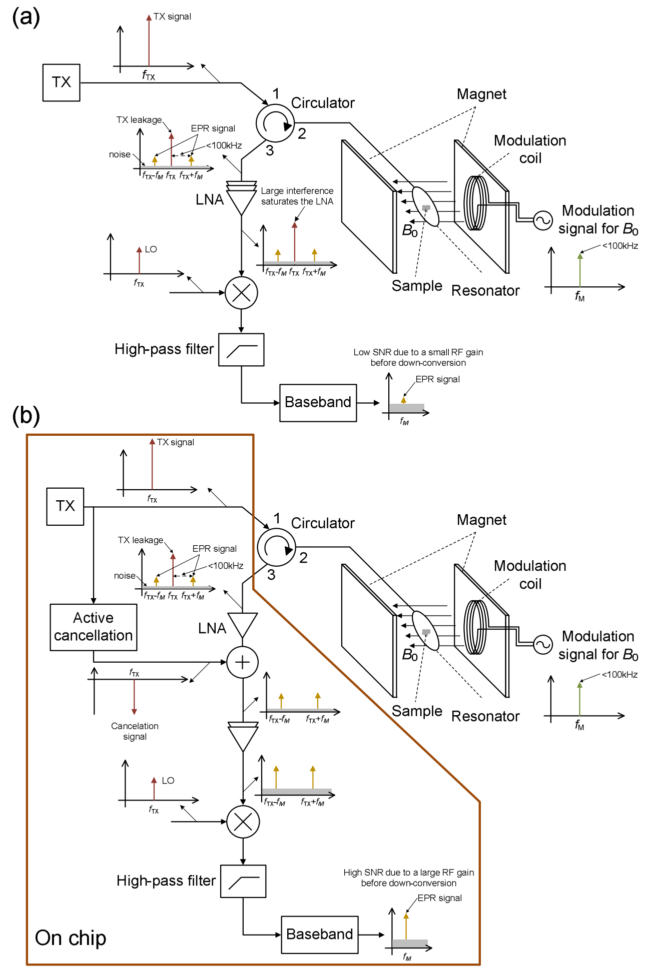

Fig. 1. Architecture of the (a) conventional and (b) proposed EPR spectrometer. The components in the highlighted box in (b) are implemented on-chip.

In order to demonstrate the advantage of active cancelation in real-world applications, in this work, we built and tested a spectrometer based on the proposed transceiver for Electron Paramagnetic Resonance (EPR) spectroscopy. EPR is in concept highly similar to nuclear magnetic resonance (NMR), except that EPR spectroscopy detects magnetic moments generated by unpaired electrons instead of the nucleus. EPR spectroscopy has a broad range of applications, including cancer research (tumor pO_2 mapping) [6], direct measurement of Nitric Oxide generation in the ischemic heart, magnetic nanoparticle detection, and biomedical sensing [7]. However, the design of a single-chip transceiver for EPR spectroscopy has been extremely challenging. In EPR spectroscopy, the interference is caused by the power leakage from the TX, which operates at GHz frequencies, and can easily reach -10dBm. Moreover, the frequency offset between the TX and the desired RX signal, as well as the frequency of the IF signal, is less than 100kHz. Under such stringent conditions, conventional interference-resilient architectures cannot satisfy both noise and linearity requirements, simultaneously. In the proposed transceiver, it is demonstrated that 15dB improvement in SNR can be achieved compared to the previous work [8]. Furthermore, in addition to the traditional method of magnetic-field sweep, for the first time, the method of frequency-sweep in EPR spectroscopy is demonstrated.

II. CIRCUIT ARCHITECTURE

The architecture of a conventional EPR spectrometer is shown in Figure 1(a). In this architecture, the TX transmits an excitation signal at frequency f_{TX} to a sample. The reflected signal is captured by the RX to extract the EPR response. To avoid low-frequency $1/f$ noise, the magnetic field B_0 is modulated at a frequency f_M, which is typically limited to less than 100kHz due to the constraints imposed by the modulation coil and the sample. The received EPR signal is down-converted to f_M for baseband amplification and digitization. During the measurement, a portion of the TX power leaks to the input of the RX through three mechanisms: (1) the finite isolation of the circulator, (2) the reflected TX power from the resonator, which rises drastically as the TX frequency deviates from the resonance frequency of the resonator, and (3) electromagnetic coupling between the RX and TX. The TX leakage appears as a large interference with frequency offset of f_M from the RX, prohibiting a strong amplification at RF and deteriorating the SNR.

In this work, we propose to insert an active cancelation block between the TX and RX, as shown in Figure 1(b). This block generates a precise cancelation signal with the same amplitude but inverted phase as the TX leakage, and combines it with the RX signal after the LNA. Therefore, the TX leakage is canceled and removed from the RX. Furthermore, as the cancelation signal mitigates the TX leakage, the TX noise is reduced by the same amount. This further improves the RX sensitivity. In Figure 2, the

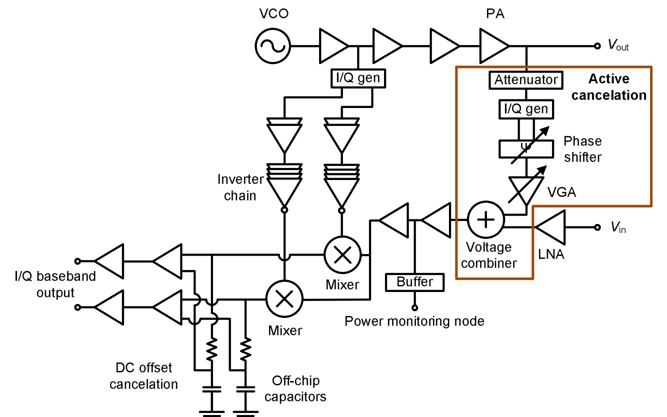

Fig. 2. The architecture of the single-chip transceiver. The active cancelation block is shown in the highlighted box.

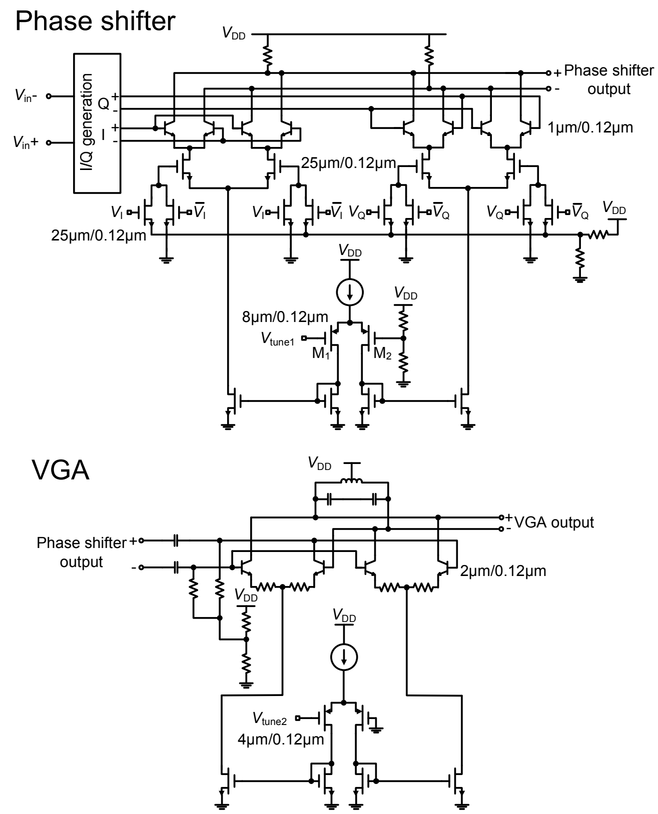

Fig. 3. Schematic of the phase shifter and the VGA (used in the active cancelation block).

architecture of the proposed transceiver is presented. The active cancelation block consists of an attenuator, an I/Q generator, a phase shifter, and a variable-gain amplifier (VGA). The attenuator attenuates the TX output to maintain linear operation of following stages. The I/Q generation is realized using a RC-CR network. The **I** and **Q** signals are passed to a Cartesian phase shifter, as shown in Figure 3. V_I, V_Q, and V_{tune1} can be adjusted to achieve a 0º-360º phase shift. The VGA has a variable gain from -25dB to +20dB, which is adjusted by V_{tune2}. It can

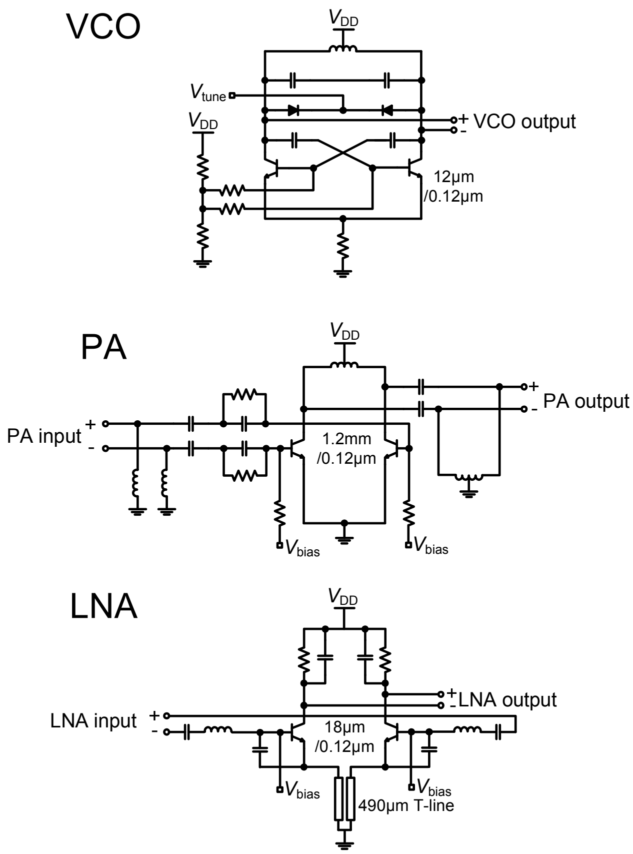

Fig. 4. Schematic of the VCO, PA, and LNA.

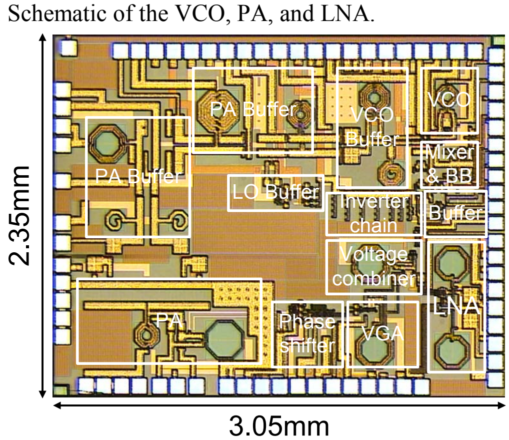

Fig. 5. Chip image. Major blocks are labeled in the figure.

generate a cancelation signal with a simulated maximum amplitude of 850mV at the cancelation frequency. Figure 4 presents the schematics of major blocks in the transceiver. The VCO frequency is tunable from 4.6GHz to 5.35GHz. The measured phase noise is -121dBc/Hz at 1MHz offset frequency. The differential PA generates a maximum power of 22dBm with a drain efficiency of 33% in the measurement (after power combining using an off-chip balun). The LNA has a simulated gain and NF of 12dB and 2.7dB, respectively. In the proposed transceiver, the cancelation signal is combined with the RX signal

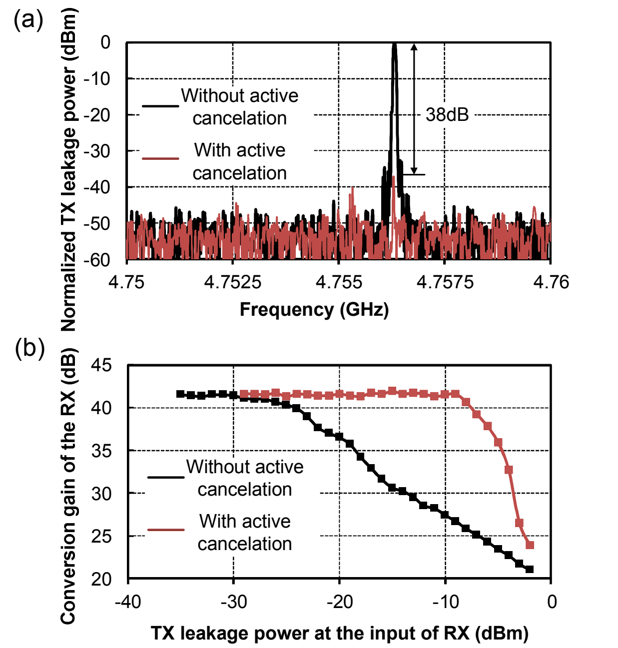

Fig. 6. (a) Normalized TX leakage power with and without active cancelation. (b) The conversion gain of the receiver with and without active cancelation.

after the LNA to minimize the noise contribution from the active cancelation block. After combining, the RX signal is further amplified by 18dB before down-conversion.

III. Measurement Results

The micrograph of the chip is presented in Figure 5. The chip is fabricated using IBM 0.13μm SiGe BiCMOS process. It occupies an area of 3.05mm by 2.35mm.

Figure 6(a) presents the signal spectrum measured at the monitoring node under a TX leakage of -20dBm. It is observed that 38dB cancelation of the TX leakage can be achieved. Figure 6(b) plots the conversion gain of the RX at various TX leakage power levels. The active cancelation improves the interference P1dB from -25dBm to -8dBm, and increases the RX gain by up to 15dB. During this measurement, the TX output is sent to the RX input through an external variable-gain attenuator to mimic the TX leakage. The leakage power is adjusted by tuning the attenuation value. The TX leakage power at the power monitoring node in the RX is measured to evaluate the effect of cancelation and guide the tuning of the VGA and phase shifter in the active cancelation block. During the tuning, both V_{tune1} and V_{tune2} are tuned from 0V to 1.2V with a step resolution of 10mV. Since RX adopts an on-chip VCO as the LO, due to the phase noise and frequency instability of the VCO, an accurate measurement of NF at 10kHz IF is unavailable. The simulated NF of the RX at 10kHz IF improves by 5.2dB when active cancelation is enabled. To the best of the authors' knowledge, this is the first demonstration of a fully-integrated transceiver with an active TX leakage cancelation structure.

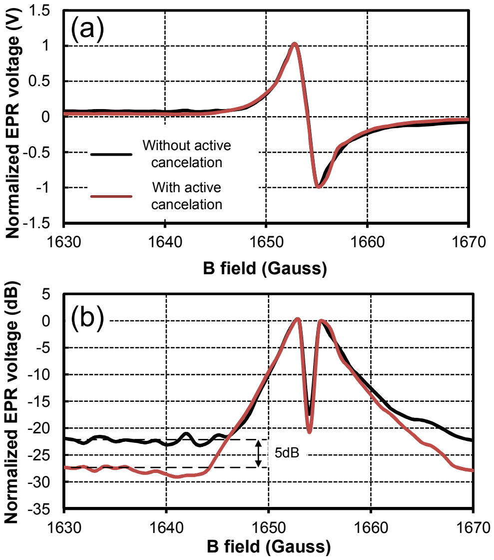

Fig. 7. The measured EPR response of 10mg DPPH powder using the B_0-sweep method in (a) linear scale and (b) log scale.

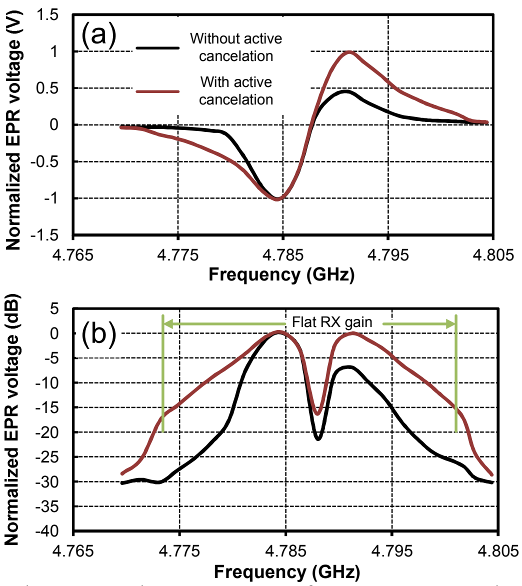

Fig. 8. The measured EPR response of 10mg DPPH powder using the frequency-sweep method in (a) linear scale and (b) log scale.

Figure 7 and Figure 8 plot the measured EPR response for 10mg 2,2-Diphenyl-1-Picrylhydrazyl (DPPH) powder. The sample is placed on a resonator with a Q of 30. B_0 is modulated at 10kHz. Figure 7(a) and 7(b) plot the measurement results using the method of B_0-sweep. In this measurement, the VCO frequency is fixed and deliberately off-tuned from the resonance frequency of the resonator to mimic the impacts of nonidealities, such as impedance mismatch caused by the sample and process/temperature variation. The measured TX leakage is -10dBm. With active cancelation, the sensitivity of the system improves by 5dB. Compared to the previous work [8], the SNR of the spectrometer in this work increases by 15dB while measuring the same DPPH sample. Furthermore, the reported spectrometer can tolerate 16dB lower TX-RX isolation compared to the previous work [8].

In addition to the method of B_0-sweep, for the first time, the method of frequency sweep is successfully performed in the EPR spectroscopy. The results of this measurement are shown in Figure 8(a) and 8(b). This measurement is very challenging in conventional EPR spectrometers because, as the frequency deviates from the resonance frequency of the resonator, the reflected TX power saturates the RX, alters the conversion gain, and distorts the EPR response. However, it is demonstrated that the active cancelation keeps the RX gain flat, even when the frequency deviates from the resonance frequency of the resonator by more than 10MHz. This feature reduces the distortion by up to 15dB, which is sufficient to capture the EPR response of samples with a narrow line-width, including DPPH.

IV. Conclusion

In this work, we report the first fully-integrated transceiver with active TX leakage/noise cancelation. The single-chip transceiver is utilized to build a complete EPR spectrometer. The transceiver is capable of performing both B_0-sweep and frequency-sweep EPR spectroscopy. In the B_0-sweep, an SNR improvement of 15dB compared to previous work is achieved. Furthermore, for the first time, the method of frequency-sweep is performed in EPR spectroscopy.

References

[1] D. Murphy et al, “A Blocker-Tolerant, Noise-Cancelling Receiver Suitable for Wideband Wireless Applications,” IEEE J. Solid-State Circuits, vol. 47, pp. 2943-2962, 2012.
[2] J. Zhou et al, “A Blocker-Resilient Wideband Receiver with Low-Noise Active Two-Point Cancellation of >0dBm TX Leakage and TX Noise in RX Band for FDD/Co-Existence,” Proc. ISSCC, pp. 352-353, 2014.
[3] Z. Ru et al, “A software-defined radio receiver architecture robust to out-of-band interference,” Proc. ISSCC, pp. 230-231, 2009.
[4] V. Aparin et al, “An Integrated LMS Adaptive Filter of TX Leakage for CDMA Receiver Front-Ends,” IEEE J. Solid-State Circuits, vol. 41, pp. 1171-1182, 2006.
[5] J. Borremans et al, “A 40nm CMOS 0.4-6 GHz Receiver Resilient to Out-of-Band Blockers,” IEEE J. Solid-State Circuits, vol.46, pp. 1659-1671, 2011.
[6] M. Krishna et al, “Electron Paramagnetic Resonance Imaging of Tumor pO2,” Radiation Research, vol. 177, pp. 376-386, 2012.
[7] B. Gallez et al, “In vivo EPR: when, how and why?,” NMR in Biomedicine, vol. 17, pp. 223-225, 2004.
[8] X. Yang, P. Seifi, and A. Babakhani, "A Single-Chip Dual-Mode CW/Pulse Electron Paramagnetic Resonance Spectrometer in 0.13μm SiGe BiCMOS," in IEEE Int. Microwave Symposium, 2013.