

A Low-Power, Subharmonic Super-Regenerative Receiver toward a Massive Multichannel FMCW Radar Close to Cut-Off Frequency

Leonhard Hahn, Martin Vossiek, Christian Carlowitz

Institute of Microwaves and Photonics (LHFT), FAU Erlangen-Nürnberg, Germany

leonhard.hahn@fau.de

Abstract—This paper reports for the first time on an entirely new subharmonic super-regenerative receiver (SRR) concept. Unlike in conventional SRRs, the local oscillator signal is additionally used for non-linear downconversion, enabling phase-coherent amplification. An experimental concept verification is done with a 24 GHz FMCW radar transceiver implemented using planar microstrip technology. It is shown that the subharmonic SRR down-conversion allows to significantly increase the maximum operating frequency and bandwidth. In addition, the LO power requirements are considerably reduced compared to what is typically needed in passive mixer approaches. Operated with a sinusoidal quench signal, the fabricated SRR achieves a gain greater than 60 dB with a power consumption of only 24 mW. It is explained that the concept allows also for operation near the semiconductor cutoff frequency. Due to this, and because of its simplicity, this novel concept is especially suited for scaling to integrated circuits with a high number of receive channels at very high, several 100 GHz, carrier frequencies.

Keywords—super-regenerative receiver, phase-coherence, subharmonic mixing, FMCW radar.

I. INTRODUCTION

To further improve the performance of modern radar systems, the exploitation of increasingly higher frequencies and bandwidths up to THz frequencies is essential. However, the realization of efficient coherent receivers for such systems is challenging due to high propagation losses and the frequency limit of active semiconductor devices, especially in the technologically limited range of high frequencies. Massive multi-channel systems based on common homodyne or heterodyne receivers therefore typically exhibit large sizes and high complexity and electrical power consumption, such that circuits in this frequency range become disproportionately expensive, large and inefficient. The subharmonic super-regenerative approach proposed in this paper represents a promising way to realize efficient and compact radar receivers for low-power applications, although the technological cutoff frequency of the underlying transistors is reached or even exceeded. The basis for this is the super-regenerative oscillator (SRO) [1], which has been thoroughly investigated in [2] and successfully used in various applications as a receiving technology, for example as an active backscatter tag for RFID localization [3], for high data rate communication [4] or as an amplifier in the mmW range with phase coherence [5] or high sensitivity [6]. The demonstrated principle is based on the injection of a low-power, high-frequency RF signal into the feedback loop of the SRR, which is centered around a

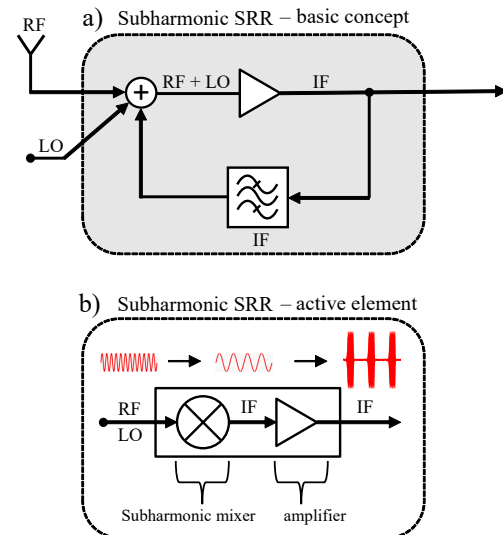


Fig. 1. a) Basic concept of the SRR b) Task of the active element: simultaneous downconversion and amplification of high-frequency injection signals.

transistor-based amplifier with its output fed back to its input. Therefore, repetitive positive feedback will cause oscillation, which can be used to amplify the injected RF signal. To process signals close to or inside the technological limit, the nonlinearity of the transistor is used. With the addition of a suitable LO signal, simultaneous downconversion and amplification of the originally high-frequency input signal is possible, see Fig. 1 a) and b). This concept of boosting the reception frequency by intermodulating the SRR was already successfully demonstrated for incoherent, CW-based THz imaging in [7]. By recurrently starting oscillations using an external quench signal that periodically switches the underlying amplifier on and off rapidly, the SRR performs a phase-coherent sampling of its injection signal during the sensitivity period of the super-regenerative sampling process. This was already theoretically and experimentally proven in earlier publications, see [8] or [9].

II. SYSTEM CONCEPT

The proposed system relies on the use of a single FMCW transmitter generating a frequency ramp at 8 GHz with bandwidth B_s at a power close to 20 dBm. The synthesizer is only needed once and provides power not only for transmission signals, but also for a possibly large number of LO channels. In contrast to diode-based passive

mixers, the SRR downconversion process needs considerably less LO power, which allows for multichannel scaling. For subharmonic downconversion and coherent regeneration of the transmitted signal, the SRR requires the injection of an RF and LO-signal. Therefore, the fundamental frequency is tripled to 24 GHz (RF) and doubled to 16 GHz (LO), which significantly exceeds the recommended frequency range of 12 GHz of the used transistor (CE3514M4) and therefore sets the RF signal into the range of the transistors cutoff frequency. By periodically switching the SRR with the square

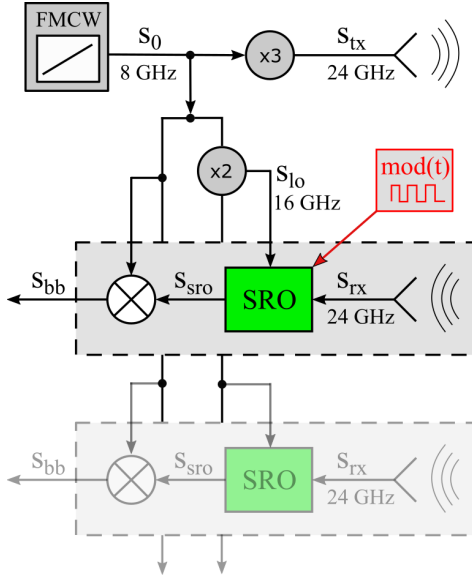


Fig. 2. Subharmonic super-regenerative reception of high-frequency FMCW-signals with the implied possibility of massive multichannel scaling.

wave signal $mod(t)$, sampling of the down-mixed injection signal and phase-coherent regeneration is performed, i.e. each pulse starts with the phasor sampled from the injected and downconverted signal. For the generation of the beat signal a baseband mixer is used for final de-chirping of the remaining frequency modulation. A block diagram of the system concept is shown in Fig. 2. In case of CW excitation, RF and LO can be described as follows:

$$s_{TX}(t) = A_0 \cos(3 \cdot \omega_0 t) \quad (1)$$

$$s_{LO}(t) = A_0 \cos(2 \cdot \omega_0 t). \quad (2)$$

Due to propagation and reflection, the received RF signal after transit time τ can be derived as:

$$s_{RX}(t) = A_{RX} \cos(3 \cdot \omega_0(t - \tau)). \quad (3)$$

After bandpass filtering at each input, the injection signal $s_{inj}(t)$ is generated after subharmonic downmixing:

$$\begin{aligned} s_{inj}(t) &= s_{RX}(t) \cdot s_{LO}(t) \\ &= A_0 A_{RX} [\cos(3\omega_0(t - \tau) - 2\omega_0 t) + \cos(3\omega_0(t - \tau) + 2\omega_0 t)]. \end{aligned} \quad (4)$$

Due to its own natural oscillation frequency ω_{srr} , the SRR is sensitive to an injection as long as s_{inj} is within the oscillator's

input bandwidth. Assuming this frequency-limiting behavior, the second, upmixed term at $3\omega_0 + 2\omega_0$ from (4) is suppressed, simplifying (4) to

$$s_{inj}(t) = A_{inj} \cdot \cos(\omega_0 t + \varphi_{inj,0}), \quad (5)$$

with an injection amplitude of $A_{inj} = A_0 \cdot A_{RX}$ and all phase offsets caused by τ being summed up in $\varphi_{inj,0}$. For SRR modulation, $mod(t)$ is assumed to be a rectangular function with period T_{mod} and frequency f_{mod} , pulse width T_{on} and duty cycle D_{mod} . Including the SRR's sampling operation, the output signal can be derived as

$$\begin{aligned} s_{srr}(t) &= \sum_{n=0}^{\infty} A_{srr} \cdot \cos[\omega_{srr}(t - nT_{mod}) + \varphi_{inj}(nT_{mod})] \\ &\cdot \text{rect}\left(\frac{t - nT_{mod} - T_{on}/2}{T_{on}}\right). \end{aligned} \quad (6)$$

The phase value $\varphi_{inj}(nT_{mod})$ equals the current phasor of the injected RF signal at every oscillation start-up, the oscillator is assumed to sample this phasor as initial vector of oscillation, but still oscillating at its own natural frequency ω_{srr} . The amplitude A_{srr} is significantly stronger than A_{inj} due to the regeneration process. According to [8], the corresponding magnitude spectrum can analytically be described with

$$\begin{aligned} |s_{srr}(f)| &= A_{srr} \cdot D_{mod} \cdot \text{si}[\pi T_{on}(f - f_{srr})] \\ &\cdot \sum_{n=0}^{\infty} \delta[(f - f_0) - n f_{mod}]. \end{aligned} \quad (7)$$

From $s_{srr}(f)$, it can be seen that the SRR output spectrum has Dirac impulses exclusively at the injection frequency f_0 , which are periodically repeated in the spectrum with f_{mod} due to undersampling caused by the quenching signal, which is of much lower frequency than the injection signal. The sinc-shaped envelope results from periodically sampling the injection signal with an ideal square wave window and has its maximum at ω_{srr} . In the extended case of slowly modulated FMCW excitation, the injection frequency f_0 from (7) can be replaced after downmixing by the following expression:

$$f_0 = f_{start} + \frac{B_s}{T_s}(t - 3\tau). \quad (8)$$

The previous bandwidth tripling thereby generates a likewise tripled delay-related frequency shift τ . The baseband signal is created by the additional downconversion mixing step using the synthesizers FMCW frequency $f_0 = f_{start} + (B_s/T_s) \cdot t$. This finally results in:

$$|s_{bb}(f)| = A_{bb} \cdot E(f) \cdot \sum_{n=0}^{\infty} \delta[(f + \frac{B_s}{T_s} 3\tau) - n f_{mod}]. \quad (9)$$

Due to the propagation delay τ , the Dirac pulses and their aliases are shifted with the beat frequency f_{beat} . $E(f)$ denotes the SRR's sinc-shaped envelope function from (7). Distance measurements are possible by estimation of the beat frequency f_{beat} , as in conventional FMCW systems:

$$f_{beat} = \frac{B_s}{T_s} 3\tau = 3 \cdot \frac{2B_s}{cT_s} \cdot d. \quad (10)$$

III. IMPLEMENTATION

In order to verify the functionality of the the proposed system concept, a demonstrator is designed, see Fig. 3. The core component of the resulting microwave circuit is the oscillator, which is based on a commercial off-the-shelf transistor (CE3514M4) and implementing a positive feedback loop from drain to gate. The oscillation frequency ω_{SRR} of the SRR is set by the bandpass resonator's center frequency as well as by the open loop's phase, which is set to 360° to fulfill Barkhausen's oscillation criterion. ω_{SRR} must be in good agreement with the desired injection frequency due to the limited SRR bandwidth. For subharmonic downconversion and generation of the injection signal, the required RF and LO signals are combined at the gate of the JFET using a triplexer. The designed triplexer acts as signal crossover and additionally closes the feedback loop. Stubs are used to improve matching and suppress unwanted signal components. Transistor biasing and DC divert are provided by two bias tees. A branchline coupler optimized for low insertion loss is used to decouple the output signal. The suppression of unwanted harmonic signal components is achieved by a bandstop filter at the demonstrator's output port. Particularly noteworthy is the low power consumption of only 24 mW, which enables scaling to massive multichannel applications.

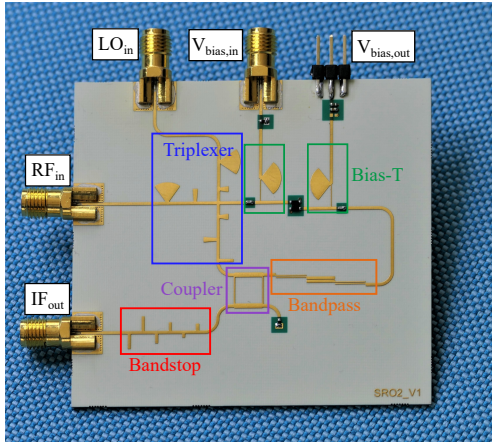


Fig. 3. Microwave circuit for evaluation and demonstration of the proposed concept's functionality.

IV. MEASUREMENTS

To verify the proposed SRR, the IF output signals and its relevant parameters are determined during operation with a sinusoidal quench of 15 MHz. The captured IF signal shown in Fig. 4 a) illustrates SRR's capability to periodically start recurring oscillations in response to its quenching signal, causing injection signals to be periodically sampled and to receive significant amplification due to the oscillator's high output power. Evidence of phase-coherent sampling is obtained from the IF spectrum, see Fig. 4 b), which reveals the formation of Dirac pulses in accordance with the theoretical expectation from (7). The formation of such pulses located exactly at the underlying injection frequency, including

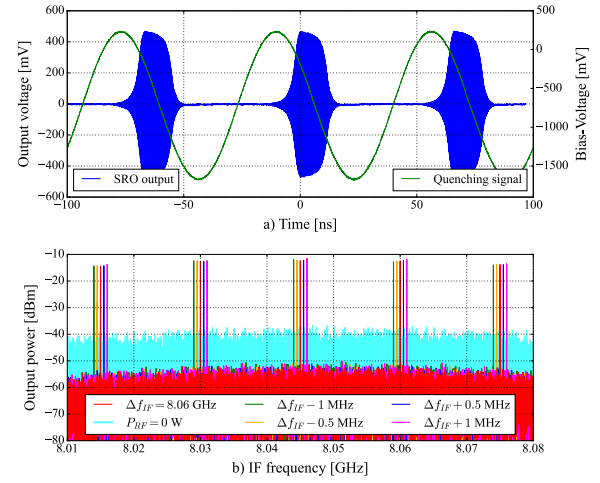


Fig. 4. IF output of the quenched SRR in time (a) and frequency domain (b) as reaction to a -50 dBm injection at 8 GHz and $P_{\text{LO}} = -20$ dBm.

repetition according to the alias effect, is already sufficient evidence for coherent sampling according to [8]. This also becomes clear if one considers the case of an absent excitation of the SRR, which means that the oscillation starts from noise, i.e. it produces random phases resulting in wideband noise in spectrum, see Fig. 4 b), the cyan-colored curve. For extended verification, a slight variation of the injection frequency is applied to verify coherence to the input signal. The SRR responds with an equivalent shift of the Dirac comb, which supports the theoretical assumption from (7). After

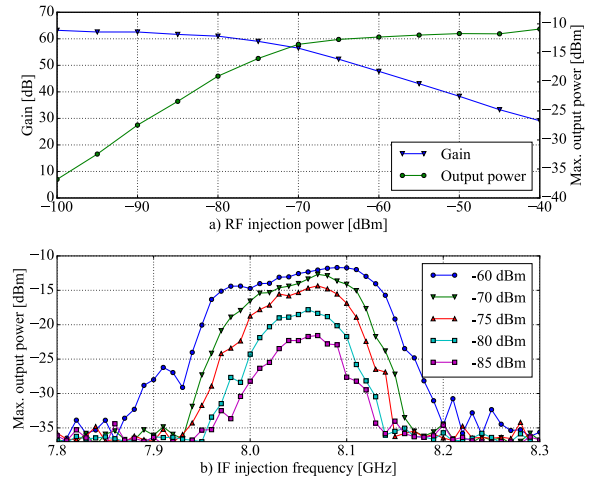


Fig. 5. a) Maximum output power and gain of the SRR circuit b) Evaluation of available bandwidth for different reception power levels.

verification of basic SRR functionality, the measurement setup can be further used to quantify output power and gain of the microwave circuit as shown in Fig. 5 a). Due to the underlying oscillation processes, the SRR provides significant gain of more than 60 dB, especially for low-power input signals. For coherent SRR operation, a LO power down to -20 dBm was used and has proven to be sufficient. High

sensitivity becomes clear, since a coherent sampling can be observed at close to -100 dBm signal power (Spectrum-RBW 7.5 kHz). Further of importance is the supported bandwidth of the SRR circuit, especially in respect to its planned use for FMCW radar applications, in which resolution is directly proportional to bandwidth. Therefore, the frequency response of the IF output power versus the swept injection frequency is observed in Fig. 5 b). The achieved bandwidth relies heavily on the SRR's operation mode. In linear operation, there is a strong dependency on the injection power P_{RF} . This relation is lost in logarithmic operation due to saturation of the oscillator's output power. The IF bandwidth is tripled due to the usage of multipliers, resulting in a 10-dB bandwidth of at least 600 MHz at -60 dBm or 400 MHz at -85 dBm. With broadband resonators, even higher SRR-bandwidth is possible, as proposed in [10] for UWB pulse reception.

To finally verify the overall presented concept of the SRR for radar applications (Fig. 2), the originally separated RF and LO signal sources are replaced by a single, PLL-stabilized VCO, which is used to generate both CW or FMCW signals as proposed in Fig. 2. Regarding FMCW excitation ($\Delta f_{RF} = 900$ MHz, $T_s = 2$ ms), Fig. 6 shows the beat spectrum after baseband mixing with a corner reflector at four different distances. With increasing distance, a clear movement of the baseband peaks is detected, which indicates functionality and therefore serves as a successful proof of concept.

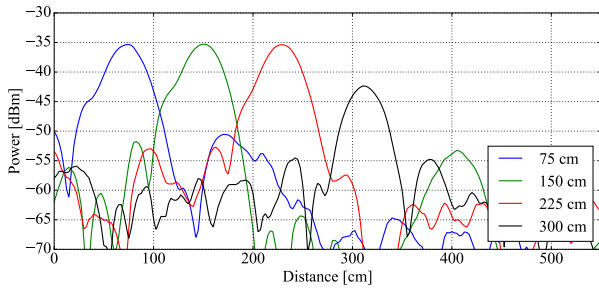


Fig. 6. Beat spectrum after dechirping the SRR's output signals in case of FMCW excitation for range estimation.

V. CONCLUSION

The proposed concept presents a promising alternative to conventional receivers, especially in terms of its complexity and energy efficiency. Inherently implemented downmixing allows for phase-coherent regeneration, even in the range of technological cutoff frequency. This is of particular interest for FMCW applications, which have been successfully demonstrated in this paper. Despite its minimal complexity and ultra-low power consumption of 24 mW, the designed demonstrator offers significant gain greater than 60 dB, while maintaining high sensitivity of nearly -100 dBm and bandwidths of 400 to 600 MHz. For downmixing, LO power down to -20 dBm has proven to be sufficient, thereby outperforming conventional passive mixers. The proposed concept is scalable to higher frequencies and massive multi-channel topologies.

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