A 200 GHz 16-pixel Focal Plane Array Imager using CMOS Super Regenerative Receivers with Quench Synchronization

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Abstract **— We have realized a 200GHz 4x4 focal plane array (FPA) by using super-regenerative receiver (SRR) pixels made of 65nm CMOS for mm-wave imaging applications. With 16 pixel elements constructed on PCB, the FPA consumes 215mA under 1V power supply. Such realization is made possible by carefully analyzing the super-regenerative interference (SRI) commonly observed in close-spaced SRRs and applying a newly developed quench synchronization scheme to suppress the undesired SRI.**

I. INTRODUCTION

Since their introduction by RCA in 1928, super regenerative receivers (SRRs) have provided a means to non-coherently receive and demodulate an RF signal with a very simple architecture that offers comparable performance to that of a super-heterodyne or homodyne (direct conversion) receiver. The original motivation behind super-regeneration was to reduce the total number of vacuum tubes needed to build an AM band receiver, as each tube greatly increased the physical size and cost of the radio set. Tubes also consumed significant power and made ownership of the radio more costly and complicated as the tubes would burn out periodically and require replacement.

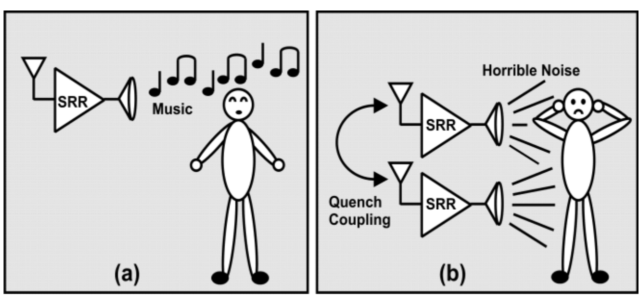

Fig. 1. (a) An early super-regenerative receiver with a listener. (b) Two super-regenerative receivers placed close together would create undesirable noise.

An interesting phenomenon of super regenerative receivers first observed in the 1930s was that when more than one SRR radio set were placed together on the same display shelf in the store, they stopped receiving properly and horrible "squeaking noises" would be emitted from both radio sets as illustrated in Fig. 1. Store employees quickly noted that the Radiola model 60 (A super-heterodyne based competitor of the RCA SRR) did not exhibit the same problem, and rendered a solution by placing SRR radios at the opposite ends of each display shelf with the super-heterodyne radios sitting in between. This phenomenon became known as the effect of "Super Regenerative Interference" or SRI [1].

Super-regenerative receivers (SRRs) have recently gained interest for use as receivers in CMOS mm-wave imaging systems and offer several major advantages over its LNA based counterparts including lower noise equivalent power (NEP), higher responsivity, lower power consumption, and a smaller die area [2,3]. For focal plane array (FPA) based imaging where the pixel receiver power and area are inflated by the number of pixels in the array, these characteristics become even more attractive than that of larger and power hungry III-V based receivers. One major concern for an SRR based FPA however, is the same super regenerative interference (SRI) effect seen on the shelf in the 1930 radio store will occur within the closely placed FPA receivers, and would either degrade the performance or inhibit the functionality. In this paper we first investigate the problem of super-regenerative interference and propose a solution to eliminate such interference based on quench synchronization.

II. SUPER REGENERATIVE INTERFERENCE

Several excellent attempts were made in the past to quantify the behavior of super-regenerative receivers, but their harsh non-linearity and time-varying nature had limited detailed analysis to the linear mode of operation only. While the linear mode of operation is desirable for communications, the logarithmic mode is actually preferable for mm-wave imaging as the soft compression improves pixel contrast and extends the available dynamic range. In general a super-regenerative system can be modeled by the diagram shown in Fig. 2.

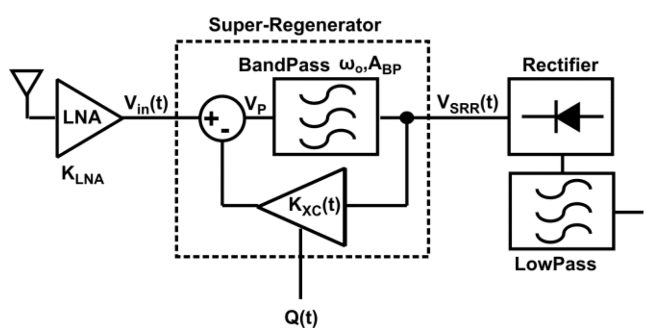

Fig. 2. Simplified model of a super-regenerative receiver with an amplifier $K_{XC}(t)$ whose gain alternates between positive and negative to model the effect of oscillator quenching.

In this model, the input signal $V_{in}(t)$ is fed into a super regenerator from an LNA. A band-pass network (typically considered a two-pole network) is used to model the oscillator tank with a peak gain of A_{BP} and center frequency ω_o, while an amplifier $K_{XC}(t)$ is used to model the quenching action. When

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the quench Q(t) is positive, the feedback element gain $K_{XC}(t)$ is also positive and the system is stable (quenched). When Q(t) is negative, the SRR enters oscillation. The output of the oscillator $V_{SRR}(t)$ is then rectified and filtered to capture the envelope. The model can be reduced to a time varying differential equation to provide a general expression of the SRR's response,

$$\frac{d^2V_{SRR}}{dt^2}+2\zeta(t)\omega_o\frac{dV_{SRR}}{dt}+\omega_o{}^2V_{SRR}=A_{BP}2\zeta_o\omega_o\frac{dV_P}{dt} \quad (1)$$

where ζ_o is the open loop dampening coefficient of the band pass network and $\zeta(t)$ is the instantaneous closed loop dampening coefficient when the feedback amplifier changes the sign. Reference [4] presents the solution details of the above expression to describe K_{RR}, the super-regenerative gain of the receiver to a CW input tone as

$$K_{RR}=\zeta_o\omega_o\int_{ta}^{tb}s(\beta)d\beta, \qquad s(t)=e^{\omega_o\int_0^t\zeta(x)dx} \quad (2)$$

where s(t) is defined as the sensitivity function which describes the instantaneous sensitivity of the receiver to the input signal. The function s(t) is strongly dependent on to the slope of $\zeta(t)$ at its zero-crossing. For practical SRRs s(t) begins at unity and decays rapidly as the instant t=0 ($\zeta(t)$'s zero-crossing) is departed from. Note that the output swing of the regenerative oscillator $V_{SRR}(t)$ is inversely related to s(t) as depicted in Fig. 3 and remains identical within each quench cycle.

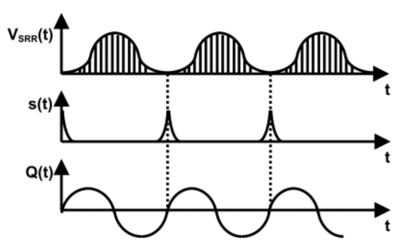

Fig. 3. Time domain graphs of super-regenerative quench Q(t), stage output voltage $V_{SRR}(t)$, and sensitivity function s(t).

Next we consider that the LNA placed in front of the super-regenerator has some finite isolation $S_{12}(\omega_o)$, and an output impedance $Z_{22}(\omega_o)$ at the oscillating frequency ω_o. The power re-radiated out of the receiver's antenna $P_{RR}(t)$ due to the oscillator's amplitude will then be,

$$P_{RR}(t)=\frac{V^2{}_{SRR}(t)}{|Z_{22}(\omega_o)|}|S_{12}(\omega_o)|A_{ANT} \quad (3)$$

Where A_{ANT} is the antenna gain of the receiver. For both a CMOS mm-wave receiver and tube based AM band receiver the LNA operates near f_t (device gain cutoff frequency), so that the reverse isolation is quite limited, typically only 5-10dB for a single stage amplifier. SRI can then be explained as follows: The quench signal of an SRR is typically generated internally by a free-running oscillator. For this reason the quench frequency of two closely placed SRRs will have some frequency variation and the maximum sensitivity window of one receiver will periodically coincide with the maximum re-radiation window of the other as shown in Fig. 4.

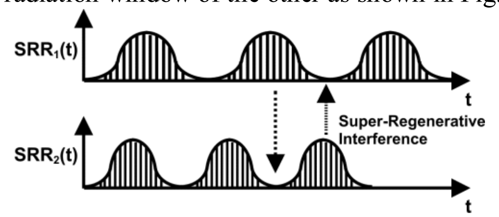

Fig. 4. Regenerative waveforms of two receivers with different quench frequencies showing the mechanism of Super-Regenerative Interference.

If the two SRRs have the same gain, the resulting SRI tone at the output of either receiver can be expressed as

$$SRI(t)=P_{RR}A_{RR}K_{RR}\alpha\sin[(\omega_{Q1}-\omega_{Q2})t] \quad (4)$$

Where α is the path loss between both receivers, and ω_{Q1} & ω_{Q2} are the quench frequencies of each receiver. It is interesting to note that if we operate both SRRs from the same quench signal ($\omega_{Q1}=\omega_{Q2}$) without a phase shift then no SRI tone should be produced, which thereby overcomes the problem of super regenerative interference.

III. MEASUREMENTS

To verify this experimentally, two CMOS SRRs (SRR1 and SRR2) operating at 200 GHz with on-chip antennas are bonded on a PCB in close proximity (<10 wavelengths) with separate 1GHz quench inputs as revealed in Fig. 5. The SRRs used are the same as those demonstrated and described in detail in [5].

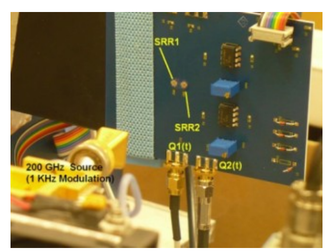

Fig. 5. Two 200 GHz CMOS SRRs bonded on a PCB with different quench feeds. The two SRRs are then illuminated by a 200 GHz source.

Fig. 6 shows the time domain output of both SRRs when the quench signals are first set to different frequencies (Fig.6(a)) and then when both SRRs are driven by the same quench (Fig.6(b)) when driven by a square chopped CW source at 200GHz. The sinusoidal SRI tones superimposed on the chopper output signal are clearly visible in the capture.

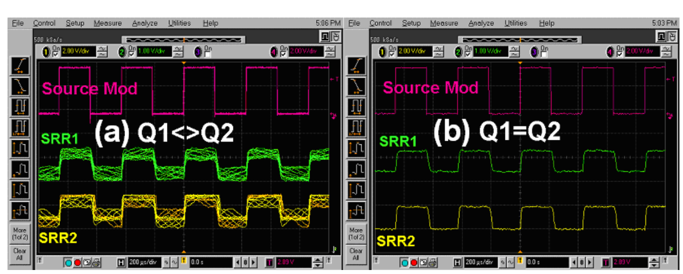

Fig. 6. Time domain captures of SRR1 and SRR2's outputs along with the modulation source signal when (a) quench signals are at different frequencies (Q1<>Q2) and (b) identical frequencies (Q1=Q2).

An alternative way to characterize the effect of SRI is to measure the unity SNR sensitivity (the input power level for 0 dB SNR) of either receiver while considering the SRI tone as part of the receiver's noise. In this way the degradation of the SRR's sensitivity due to the SRI interference can be measured directly. Fig. 7. plots the unity SNR sensitivity as the quench phase between SRR1 and SRR2 is varied.

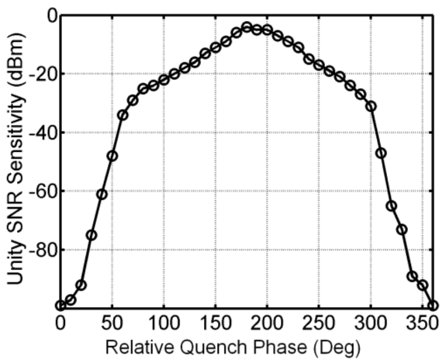

Fig. 7. Unity SNR sensitivity of SRR1 as the quench phase between SRR1 and SRR2 is varied. The SRI tone is counted as part of the receiver's noise floor.

It is interesting to note that while a large difference in quench phase greatly desensitizes both SRRs, a small phase error of 3-5 degrees only affects the receiver sensitivity by a few dB. This suggests that standard techniques for managing clock skew in digital circuits should be sufficient to align the quench signals for constructing a full focal plane array, and suppress the SRI interference between pixels inside the array. To demonstrate the effectiveness of this approach, an entire focal plane array is implemented on a PCB with 4x4 CMOS receiver pixels spaced at 5 wavelengths as shown in Fig. 8. The quench is provided by a single input and distributed with an H-tree (a typical technique for digital clock distribution).

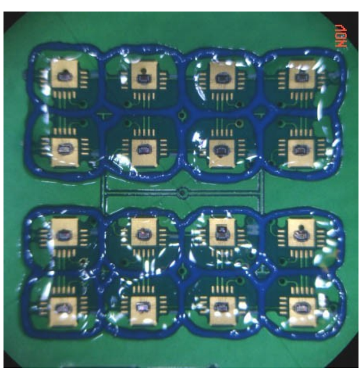

Fig. 8. A 4x4 focal plane array of 200 GHz SRRs implemented on a PCB board. The quench is distributed by an H-tree to make sure the phase is well-aligned between receivers.

A transmission mode imaging test setup is constructed as shown in Fig. 9(a) using an X-Y mechanical scanning stage with the X and Y step size calibrated to match the pixel-to-pixel pitch of the FPA for image re-assembly. The target is illuminated from a 20mW Backward Wave Oscillator (BWO) through a single Teflon lens at a target distance of 1 meter to provide 0.5mW/cm^2 of spatial power density incident on the focal plane array.

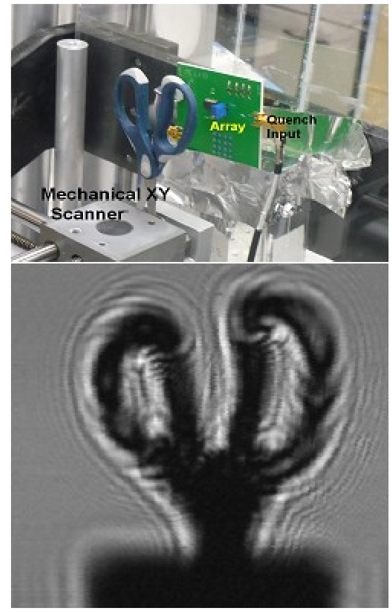

Fig. 9. (a) Transmission Image capture setup and (b) captured image of a pair of scissors with the full 4x4 focal plane array imager.

Also shown in Fig. 9(b) is an image of a pair of scissors captured by the 200GHz CMOS SRR FPA. Note that the handle section is totally plastic and does not contain any metallic component. The entire array consumes 215mW (13.4 mW per pixel).

IV. SUMMARY

We have analyzed the root cause of SRI (super-regenerative interference) and devised a quench synchronization method to prevent SRR receivers placed at close proximity within a common focal plan array (FPA) from being desensitized by SRI. Consequently, a 4x4 FPA has been successfully demonstrated by using 16X 200GHz CMOS SRR receiver pixels, which clearly opens the door for implementing practical large scale mm-wave imaging focal plane arrays based on cost-effective CMOS super-regenerative receivers.

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