# A wideband feedback compensated quadrature generator

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***Abstract*—A novel quadrature generator is presented in this paper that exhibits a 40% operating frequency bandwidth. Current circuits do not generally provide quadrature signals over such a wide fractional bandwidth and they are often susceptible to variances in component values, which can shift their operating frequency. In this work, this is resolved with the use of a negative feedback network including a pair of phase shifters and two variable gain amplifiers to actively compensate the imbalances over a large frequency range. Experimental results show a 2 GHz bandwidth centered at 5 GHz while maintaining a phase error below 8° and less than 1.5 dB in amplitude error. The circuit, without bonding pads, uses an area of only 0.28 mm$^2$.**

## I. INTRODUCTION

In transceivers, quadrature signals are produced using a variety of techniques. One prevalent approach is to use a quadrature oscillator in which two LC-tank oscillators are cross-coupled in order to achieve a quadrature output [1] [2]. Since this method requires the use of two identical oscillators, each one using one or perhaps even two spiral inductors, the result is often a physically large circuit with a typically small operating bandwidth.

Another method that has become standard is to use a differential oscillator operating at twice the desired frequency and then to use a divide-by-two frequency divider to generate the quadrature signals [3]. This approach has the firm advantage of producing quadrature signals with low phase error, yet it is not very well suited for wideband operation. For instance, in order to generate a quadrature signal over a 2 GHz bandwidth this method would need a VCO with a 4 GHz tuning range, which is difficult to achieve at the lower microwave frequencies ($\leq$15 GHz).

An RC-CR or a polyphase network [4] [5] can actually produce quadrature signals over a wideband. However, their limitation is that they cannot maintain the amplitude balance between the quadrature signals over frequency. In this paper, we remove this limitation by using a pair of variable gain amplifiers in a dual negative feedback loop to balance the amplitudes of the output signals. This novel approach results in a very wideband quadrature signal generator with a 40% bandwidth at 5 GHz.

## II. CIRCUIT DESCRIPTION

A functional block diagram of the proposed design is depicted in Fig. 1. By leveraging the ability for an RC-CR network (Fig. 1a)) to provide a constant 90° phase shift irrespective of the frequency, we can use a combination of variable gain amplifiers (VGA) to compensate the gain (Fig. 1b)) and significantly expand the bandwidth of the network. The correct control signals (e$_1$(t) and e$_2$(t)) in order to adjust the VGA's gain the appropriate amount is determined with an amplitude detector and comparator circuit (Fig. 1c)).

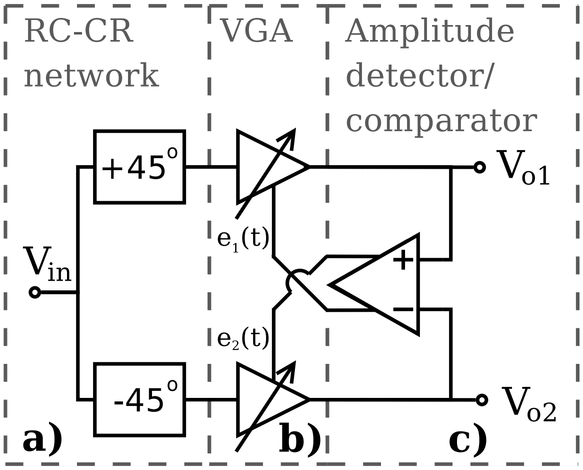
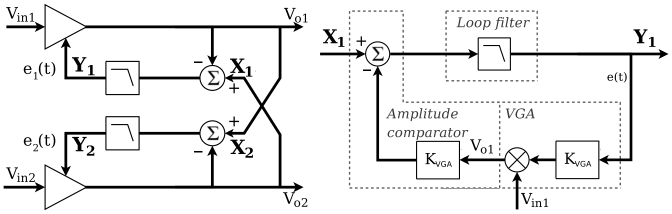


Fig. 1. Block diagram of feedback quadrature generator



(a) Simplified control system perspective of the circuit

(b) Rearranged feedback path

Fig. 2. Control system version of the block diagram

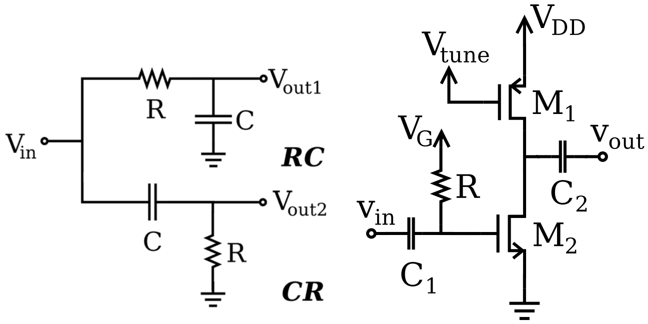
Fig. 2a) depicts a simplified block diagram of the same system if this circuit is viewed from a control system perspective. Portions of the actual circuit such as the quadrature generation have been omitted for clarity. Ignoring the quadrature generation for the moment, this system can be viewed as a simple circuit in which two signals $V_{o1}$ and $V_{o2}$ are desired to be of equal amplitude. Fig. 2b) shows only the feedback path of this system and is rearranged into a more familiar format.

This figure now depicts a simple negative feedback system that compares and adjusts for the amplitudes.

### *A. RC-CR Network & VGA*

For this system, a 90° RC-CR phase shifter is implemented followed by the use of a VGA. The generic RC-CR network is depicted in Fig. 3a). As mentioned previously a 90° phase difference between the two circuits is maintained over all frequencies. However the amplitude balance between $V_{out1}$ and $V_{out2}$ only occurs at $\omega = \frac{1}{RC}$

The VGA is then placed at the outputs of the RC-CR network and the gain control is determined by the amplitude detector and comparator network.

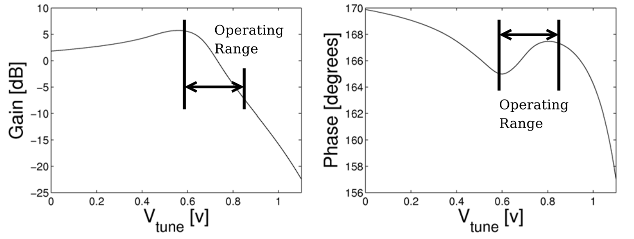


(a) Schematic of RC-CR network (b) Schematic of VGA

Fig. 3. Schematic of various subcircuits

As with any VGA design, an amplifier with a large tuning range and frequency bandwidth is required. However for this system, an additional requirement is that the phase must not vary along with the gain. If the phase changes in relation to the tuning voltage, the result is that the amplitude feedback system will no longer produce outputs that are 90° apart.

The VGA that was chosen is a common source configuration with the transistor $M_1$ in the drain and using its gate voltage to control the current and is shown in Fig. 3b).



(a) Gain (b) Phase

Fig. 4. Phase and gain for the variable gain amplifier as $V_{tune}$ is swept at 2 GHz

The selected area of operation for $V_{tune}$ will vary the gain from 0 to 6 dB. The operating region was chosen to maximize the amount of gain that can be varied while minimizing phase variation.

### *B. Amplitude Detector and Comparator Feedback Network*

The expanded block diagram depicting all the stages of the amplitude detector and comparator is shown in Fig 5. When the signals exit the variable gain amplifier at the output of the previous circuit, they are 90° apart. Because the comparator that is used is essentially a subtractor, subtracting two voltages ($V_{o1}$ and $V_{o2}$) do not produce any significant results. In order to properly compare the amplitudes of the two outputs, the signals need to be aligned.

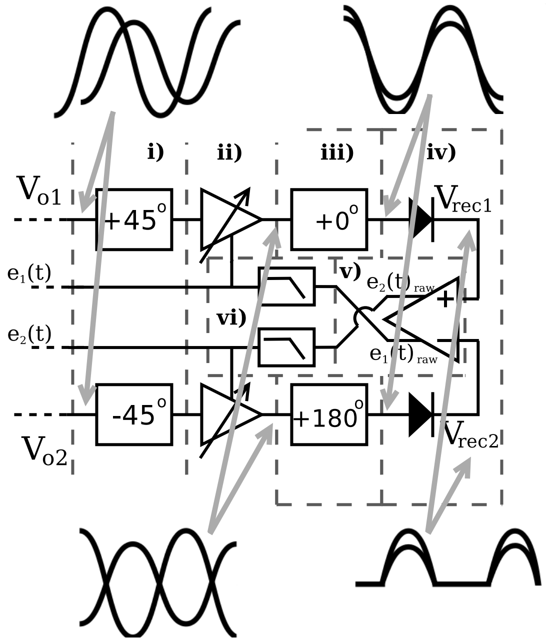


Fig. 5. Expanded block diagram of amplitude detector

The first step to align the signals is that another 90° RC-CR phase shifter is employed to shift the signals a further 90° out of phase (Fig. 5 i)).

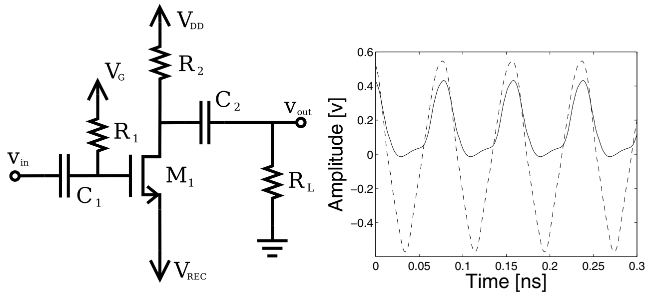
The signals are then passed through another VGA (Fig. 5 ii)) which will compensate for the amplitude imbalance caused by the previous RC-CR network. The signals are now 180° from each other. These signals are then passed through two circuits that produce 0° and 180° phase shifts (Fig. 5 iii)). At the outputs of this stage, the signals will now be perfectly aligned.

At this point, if the two different amplitude signals are subtracted from each other, another sinusoid will result. A rectifier circuit (Fig. 5 iv)) will need to be employed to remove the negative half of the signal. Once this has taken place, the signal can now be subtracted from each other. This process is done using another differential amplifier (Fig. 5 v)).

A low pass filter (Fig. 5 vi)) that also functions as the loop filter is then used to smooth out the resulting wave to produce a DC signal. This DC signal is the gain control for the VGA to adjust the amplitudes.

*1) Differential Pair:* For Fig. 5 iii)), a circuit is required to produce a 180° phase. A differential pair is one such circuit that can provide both a 0° and 180° phase shift. This is accomplished by exciting each differential pair single endedly at opposite sides. In this manner both 0° and 180° phase shifts will be created. Because both differential pairs on each of the branches are the same, they will exhibit the same gain properties across the frequency bandwidth.

*2) Rectifier Circuit:* Once the signals are aligned, the signal will need to be rectified (Fig. 5iv)) in preparation for the comparator stage. The ideal rectifier is a diode with a 0 V threshold voltage. This is particularly difficult to implement because the cutoff voltage for this technology is 0.7 V which is approximately the same signal levels used in RF circuits.



(a) Schematic of rectifier circuit (b) Simulations of before and after the rectifier

Fig. 6. Schematic and simulated results of the rectifier circuit

The use of a modified common source amplifier was employed. By biasing the transistor so that it is on the edge of turning on, then when the input is in the negative region, the output will remain at 0 V. But when the input is positive, the transistor turns on, and the signals is passed. The dashed line is the original wave and the rectified wave is the solid line.

*3) Comparator:* The final stage of the feedback loop is composed of an analog comparator circuit in which the two aligned waveforms are subtracted from each other. The output is connected to the VGAs through an RC filter and is shown in Fig. 7.

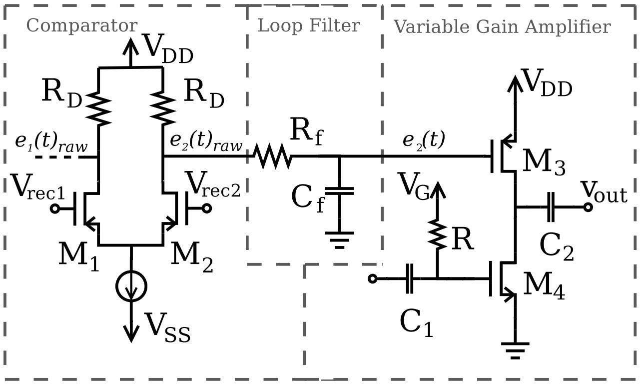
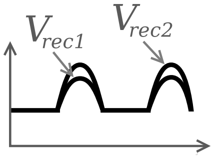


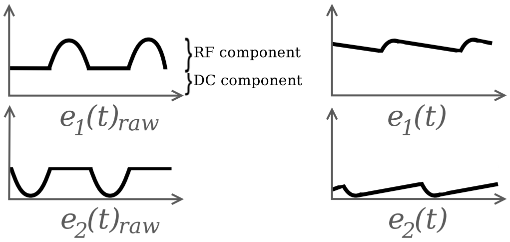
Fig. 7. Final stages of the feedback loop depicting the interface between the comparator and the VGA

This system is designed as a dual feedback network in which both branches are both compensated at the same time. Two signals are thus required to compensate the VGAs that adjust the $v_{+45}$ branch and another opposing set of signals to compensate the VGAs at the $v_{-45}$ branch.

A differential pair is used because it can also function as an analog subtractor. The two rectified signals $v_{rec1}$ and $v_{rec2}$ are then connected to the input of the differential pair and subtracted from each other. Fig. 8 depicts the input signals and the corresponding output signals before and after the RC filter. The outputs after they have been subtracted is then directly coupled to the VGA.



(a) Input Signal



(b) Comparator output (c) Filter output

Fig. 8. Signals associated with comparator stage

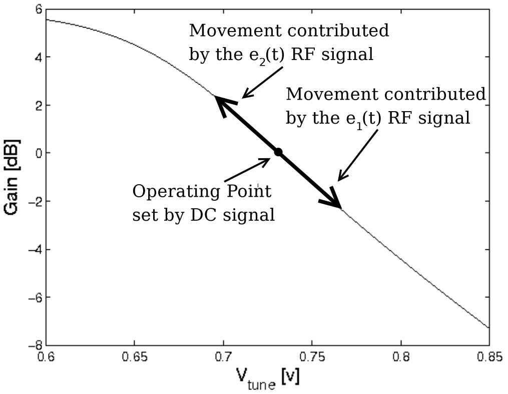


Fig. 9. Movement on VGA gain curve contributed by both DC and RF signal

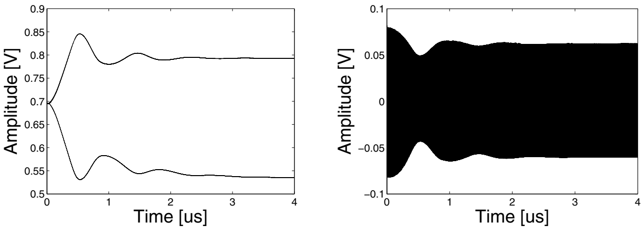
The DC component is set so that it will provide the starting operating point on the gain curve for the VGA. The additional RF component is then smoothed out using a basic RC low pass filter will then be used to move the gain up and down from the starting point. The RC low pass filter functions both to smooth out the half sine waveform and also as a loop filter that is used to adjust the settling time of the system. Because the differential output provides two signals that is the reciprocal of each other, one signal will increase the gain for one branch while the other will decrease the gain. Fig 9 illustrates the combination of DC and RF signals that move the gain of the VGA.

## III. RESULTS

### *A. Simulated Time Domain Results*

Typical time domain simulations are shown in Fig. 10. The results of the DC voltage for the dual feedback loop that adjusts the variable gain amplifier's gain is depicted in Fig. 10a).

As the circuit starts up, a typical underdamped response is clearly seen. After a period of approximately 4 $\mu$s, the system settles into a steady state producing the final compensated response. The result from the output of one of the VGAs as its gain is modified through the feedback loops is shown in Fig. 10b).



(a) DC feedback path that for VGA

(b) Resulting gain adjustment at the output of the VGA

Fig. 10. Simulated time domain results depicting the feedback settling time of the quadrature generator

### B. Measured Results

The device was fabricated to verify the circuit using conventional 0.18 $\mu$m CMOS technology and occupies 0.28 mm$^2$ without bonding pads and 0.62mm$^2$ with bonding pads. A micro-photograph of the fabricated circuit is found in Fig. 11.

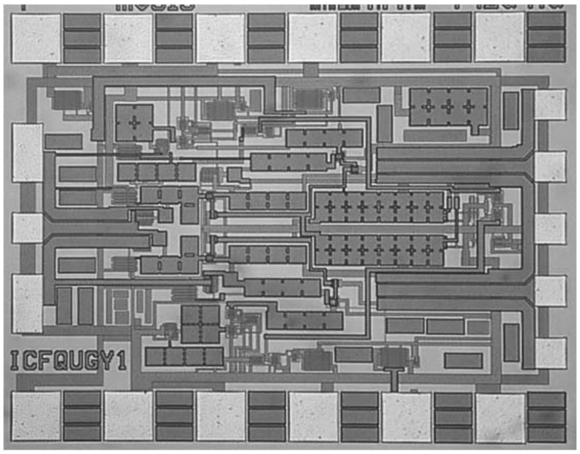


Fig. 11. Micro-photograph of feedback quadrature generator

A vector network analyzer was then used to measure the magnitude and phase at each output. The DC power consumption is found to be 69 mW.

The measured difference between the two outputs is shown in Fig. 12. The bandwidth of the system is found to be 2 GHz with a phase error of 8°. The amplitude error does not increase more than 1.5 dB.

The overall insertion loss for both outputs is 12 dB. The RC-CR network itself produces a -6 dB loss because of the input impedance mismatch. The additional 6 dB loss is produced by the high frequency rolloff from the VGAs.

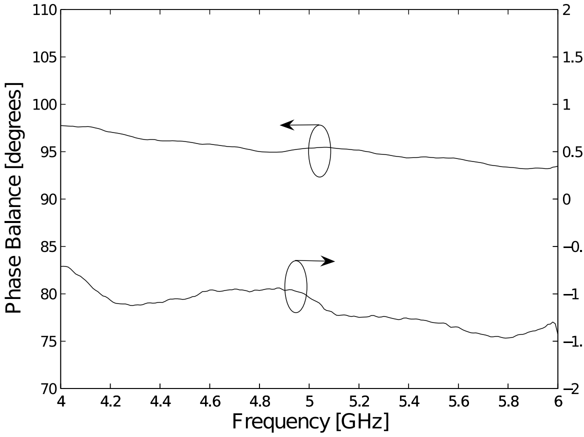


Fig. 12. Measured amplitude and phase balance

## IV. CONCLUSIONS

In this paper a quadrature wideband balun compensated through a feedback network is presented. The basic RC-CR network used in many circuits lack the ability to function over a large frequency range. This new circuit demonstrates the ability to compensate for an amplitude imbalance through the use of a novel amplitude detector to determine and compare the amplitudes of the two branches. The amount of compensation is then fed back into the variable gain amplifiers and the result is that this circuit now has the ability to significantly extend the bandwidth of the original RC-CR network. The experimental results show a device that produces a 2 GHz bandwidth while maintaining a maximum of 8° and a 1.5 dB phase and amplitude imbalance.

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