A Quadrature Signal Generator Using PLL Technique

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Abstract — A monolithic quadrature signal generator is presented, using PLL technique for automatic calibration. The quadrature signal generator consists of a quadrature signal generation block and a phase control loop to calibrate quadrature signals in real-time. The phase of a phase shifter is tuned by a control current from the phase control loop. The phase error of quadrature signals is detected by two phase detectors. A charge pump generates a feedback voltage to control the phase of the phase shifter. The quadrature signal generator operates at 1.76 GHz to 2 GHz in consistent accuracy of quadrature signals in measurement. The phase error is less than 0.3°, and the amplitude error is less than 0.062 dB over a 500 MHz sweep in simulation. The IC is fabricated in 0.5-μm SiGe BiCMOS, packaged in MLF 20-pin, and consumes less than 13 mA from 3-V supply.

I. INTRODUCTION

Exact quadrature signals are indispensable for direct conversion, image rejection receivers, single sideband mixing, I/Q down conversion, and so on. Especially, the direct conversion is a goal of RF receiver architectures and it grows necessity of the quadrature signals. For the performance of the above systems using quadrature signals depends on the phase and amplitude accuracy of the quadrature signals, the exact quadrature signals are essential. Quadrature signals are often generated using a frequency divider [1] or a polyphase filter [2]. Both methods have no tuning capability. The frequency divider needs a doubled frequency signal to be divided by two and the polyphase filter is susceptible to process gradients and tolerances.

This paper describes a monolithic quadrature signal generator fabricated in 0.5-μm SiGe BiCMOS technology. Designed for operation from a 3-V supply, the IC consists of a phase shifter, limiting amplifiers, phase detectors, low pass filters, op-amps, and a charge pump. The quadrature signals are generated by the quadrature signal generation block and they are tuned by a feedback voltage from the phase control loop automatically. This method needs no doubled frequency signal. The circuit is less susceptible to process gradients and tolerances, and provides precise quadrature signals over a wide frequency range.

II. CIRCUIT DESIGN AND OPERATION

A quadrature signal generator can be divided into two main blocks shown in Fig. 1. The first block is the quadrature signal generation block consisting of a balun, a phase shifter and limiting amplifiers. The remaining block, the phase control loop, generates the control current to tune the phase shifter using phase detectors, low pass filters, an op-amp, a tri-state selector, a charge pump and a V-I converter. Comparing the quadrature signal generator with a PLL, phase detectors, low pass filters and a charge pump come from the PLL. And the phase shifter replaces the VCO in the PLL.

The function of the quadrature signal generator is described in detail with Fig. 1. A balun is used to

![Fig. 1. Quadrature signal generator block diagram.](image-url)
generate differential signals to feed two amplifiers. One is a differential cascode amplifier to extract in-phase signals and the other is a phase shifter, which is modified from the differential cascode amplifier, to extract quadrature-phase signals (see Fig. 2). Two identical limiting amplifiers remove the amplitude imbalance introduced by the cascode amplifier and the phase shifter. Two XOR type phase detectors generate pulses whose widths are inverse to each other (see Fig. 3). The two pulses are low-pass filtered to produce two dc signals (see Fig. 4). When the two dc signals have the same dc level, the exact quadrature signals are obtained. The op-amp and the tri-state selector decide how the charge pump operates to generate a proper dc-level for phase tuning of the phase shifter. Using the phase control loop, exact quadrature signals are obtained.

All subcircuits are implemented on a monolithic chip except an input balun. The balun is an off-chip transformer for smaller phase error of the 180° phase different signals.

A. Phase Shifter Stage

A phase shifter stage consisting of a differential cascode amplifier and a phase shifter modified from the previous one is illustrated in Fig. 2 [3]. If a transconductance of the differential cascode amplifier is $g_m$, the phase shifter has a transconductance of

$$g_m' = g_m \frac{1 - sC / g_m}{1 + sC / g_m}$$

with the Miller feedback capacitance. The $g_m'$ results in 90° shifted characteristic from $g_m$ at $\omega = g_m / C$. The $g_m'$ is controlled by the bias current. Current controllability means that the output phase of the phase shifter can be controlled by the bias current. And the bias current is generated by the charge pump output voltage through the V-I converter. The next stage is a limiting amplifier stage to remove the amplitude imbalance introduced by the phase shifter stage. The output of limiting amplifiers can be used to drive LO switching pairs of direct conversion mixers.

B. Phase Detector And Low Pass Filter

The outputs of the limiting amplifiers are used as the inputs of the phase detectors. The phase detector shown in Fig. 3 is a symmetric XOR gate in [4]. It has advantages of simple structure, perfect symmetry and short delay. From Fig. 4, two inverse outputs, $X$ and $\overline{X}$, are obtained from a XOR gate and a XNOR gate respectively. The XNOR gate is another XOR gate which inputs, $IN_{0\text{deg}}$ and $IN_{270\text{deg}}$, are swapped. $Q_{15}$ is only on if both $IN_{0\text{deg}}$ and $IN_{90\text{deg}}$ are low, and $Q_{16}$ is only on if $IN_{180\text{deg}}$ and $IN_{270\text{deg}}$ are low. $IN_{0\text{deg}}$ and $IN_{270\text{deg}}$ are the differential signals of $IN_{180\text{deg}}$ and $IN_{270\text{deg}}$ respectively. Therefore, the output is equal to

$$IN_{0\text{deg}} \cdot IN_{90\text{deg}} + IN_{0\text{deg}} \cdot IN_{90\text{deg}} = IN_{0\text{deg}} \oplus IN_{90\text{deg}}.$$ 

After low pass filtering of $X$ and $\overline{X}$, two dc signals are achieved and the dc voltage levels are decided by the duty of the phase detector output pulse. If both $X$ and $\overline{X}$ have 50% duty pulses, the two dc signals have the same dc level and exact quadrature phase signals are obtained.

C. OP Amp

Using an op-amp, two dc signals can be compared to get the phase difference condition. The three conditions are 90°, shorter than 90° and longer than 90°. And the dc outputs of the three conditions are VCC/2, VCC and GND, while a positive supply voltage is VCC and a negative supply voltage is GND.
D. Tri-State Selector And Charge Pump

A tri-state selector consisting of two op-amps selects charge pump operation (see Fig. 5). As the fore op-amp output, the tri-state selector makes the charge pump charge, discharge or keep the present voltage level. The output voltage from the charge pump is converted to a current with the V-I converter and the current is the bias input of the phase shifter to tune the phase difference as shown in Fig. 1.

There is a precondition of \( V_{\text{ref1}} < V_{\text{CC}}/2 < V_{\text{ref2}} \). \( V_{\text{ref1}} \) and \( V_{\text{ref2}} \) are set by external voltage references. If the op-amp output is lower than \( V_{\text{ref1}} \), the charge pump charges the capacitor and the charge pump output voltage increases. If the op-amp output is higher than \( V_{\text{ref2}} \), the charge pump discharges and the output voltage decreases. If the op-amp output is between \( V_{\text{ref1}} \) and \( V_{\text{ref2}} \), the charge is kept consistent. To reduce the error range, \( V_{\text{ref1}} \) voltage and \( V_{\text{ref2}} \) voltage must be close to \( V_{\text{CC}}/2 \).

III. OPERATION TEST AND MEASUREMENT

First, the operation was checked with simulation waveforms. When the capacitor of the charge pump is large enough, the op-amp output is locked at \( V_{\text{CC}}/2 \) and the quadrature outputs show 90° phase difference (see Fig. 6). When the capacitor is small, the op-amp output is not locked and it is toggled to generate quadrature signals close to 90° phase difference (see Fig. 7). A sufficiently large capacitor must be used at the charge pump to be locked on the exact quadrature signal generation condition. Fig. 8 shows the measured output waveform at 1.927 GHz and the measured waveform shows the consistent accuracy of phase and amplitude of quadrature signals at 1.76 GHz to 2 GHz. Phase error cannot be measured precisely, because even the coaxial cable line difference can make phase error. In simulation, the phase error is less than 0.3°, and the amplitude error is less than 0.062 dB over a 500 MHz sweep.

The measured IC consumes less than 13 mA from 3-V supply, and the phase control loop consumes only 4.5 mA of total current 13 mA.
IV. CONCLUSION

A quadrature signal generator is implemented in a 0.5-μm SiGe BiCMOS technology that draws 13 mA from 3-V supply. The phase control loop consumes only 4.5 mA of total current 13 mA. The measured quadrature signals show the consistent accuracy of phase and amplitude at 1.76 GHz to 2 GHz. In simulation, the phase error is less than 0.3°, and the amplitude error is less than 0.062 dB over a 500 MHz sweep. Using PLL technique, the output quadrature signals are calibrated automatically.

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