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A SiGe Frequency Quadrupler for M-QAM Carrier Recovery

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Abstract—In this paper a frequency quadrupler circuit, integrated with a commercially available SiGe HBT technology ($f_T/f_{max} \approx 80/90$ GHz) is presented. The quadrupler consists of two Gilbert cell mixers stacked as squarers. The measured maximum conversion gain is 0.6 dB for an input level of -9 dBm. The circuit is optimized for M-QAM carrier recovery, and the performance was tested by applying QPSK and 16QAM modulated signals with 4 Gbit/s data rate at the input. Both experimental and simulated results are presented. The fully integrated chip is operated from a single 2.5 V DC supply and draws 22.3 mA current.

Index Terms—HF receivers, Millimeter wave communication, Quadrature phase shift keying, Demodulation, Synchronous detection, Bipolar analog integrated circuits.

I. INTRODUCTION

One of the most challenging issues of achieving multi-gigabit wireless transmission is realizing analog to digital converters (ADC) with high enough sampling rate and quantization steps [1]. ADCs with sufficient sampling rates typically consume several watts of power and relatively large chip areas [2], [3]. Consequently, ADCs tend to become the bottleneck of ultra-high data rate wireless communication systems in terms of cost and power consumption, especially for applications targeting battery-operated, hand-held devices.

In a current project targeting 10 Gbit/s transmission at 60 GHz, we suggest to realize the demodulation completely in the analog domain, thus reducing the ADC block to a simple sample and hold circuit. In order to realize such a communication link, a carrier signal needs to be recovered by the analog circuitry for synchronous demodulation. Therefore the modulation format needs to be kept relatively simple in order to allow analog recovery schemes to be applicable. We present a carrier recovery circuit, designed for a heterodyne receiver architecture with a 5 GHz intermediate frequency (IF). The modulation format under consideration is quadrature phase shift keying (QPSK), which constitutes a good trade-off between spectral efficiency and simplicity.

This paper is organized as follows. In Section II a brief description of the carrier recovery concept, chosen for the receiver design is given. In Section III the designed

frequency quadrupler is described and measured performance is presented. The carrier recovery experiments are presented in Section IV.

II. THE CARRIER RECOVERY METHOD

It is possible to remove the modulation from an M-QAM signal by generating a 4th harmonic, through a non-linear operation [4]. As an example, a QPSK modulated signal can be expressed as [5]

$$S_{QPSK} = A_C(t) \cos[\omega_C t + \frac{\pi}{4}(2m - 1) + \theta_{in}(t)], \quad (1)$$

where $A_C(t)$ is the amplitude function depending on the pulse shaping filter, $\theta_{in}(t)$ is the time-dependent arbitrary unknown signal phase and $m=0, 1, 2, 3$. In this case, the bandpass component at the quadruple carrier frequency would be

$$S_{QPSK}^4 = A_C(t)^4 \cos[4\omega_C t + \pi(2m - 1) + 4\theta_{in}(t)]. \quad (2)$$

As it can be seen from (2), for any value of m , the modulated phase becomes an odd multiple of π , which reduces in the end to π , since cosine is an even function. Therefore we can rewrite this signal as

$$S_{QPSK}^4 = -A_C(t)^4 \cos[4\omega_C t + 4\theta_{in}(t)]. \quad (3)$$

The result is the carrier signal at the quadruple input frequency with the 4th power of the input amplitude function $A_C(t)$. This example can be generalized to any M-QAM, but here it is limited only to QPSK, which is the modulation type of interest.

The recovered carrier in this way can be used in two principal configurations. One approach would be in a closed loop configuration, where the recovered carrier would be compared with a reference signal in order to generate an error feedback. A generalized study of such systems can be found in [6]. Although using a closed loop approach stabilizes the recovered carrier in a phased-locked-loop (PLL), it is not obligatory to follow this approach. The other approach would be using the recovered carrier in a feedforward architecture (or openloop), by directly using it for demodulation after dividing by four, without any feedback. Such systems were frequently used

in the recent years in very high data rate optical communication systems [7]-[10]. The feedforward approach makes use of the fact that the recovered carrier contains the incoming unknown phase, including phase noise, as was seen in equation (3). This feature makes feedforward carrier recovery approach tolerant to phase noise, provided that the time delays in the signal and carrier recovery paths are similar [10].

III. THE CIRCUIT DESCRIPTION

In order to realize the frequency quadrupler, two Gilbert cell mixers were used as frequency doublers by connecting their two inputs together [11], [12]. A Gilbert cell mixer as a frequency doubler requires much less input drive for saturated gain in comparison to other types of frequency multipliers. On the other hand, it suffers from a strong DC offset at the output, which causes unbalanced operation [13].

Fig. 1. Simplified Schematic of the Frequency Quadrupler

For the purpose of carrier recovery, the frequency quadrupler was optimized for an input frequency of 5 GHz and an output frequency of 20 GHz. To maximize gain and reduce power consumption, the mixers were designed with the tuned amplifier principle by using LC matching networks as loads. The schematic of the designed circuit is shown in Fig. 1. The bias circuitry is omitted for simplicity. As seen in the figure, the output of the first mixer stage is matched to the input of the second stage, and the output of the second stage is matched to a 100 Ω differential load. By this means a relatively narrow band operation is achieved, which helps to improve the suppression of unwanted spectral components appearing around the recovered carrier signal. A low supply voltage of 2.5 V can be used due to the reactive loads and by skipping the common current sources at the differential pair tails which, on the other hand, leads to a poor common mode rejection ratio (CMRR) and thereby well balanced input signals are required for proper operation. Finally, several on-chip DC-block capacitors are used to separate the operating points of the upper-quad and lower-pair transistors, and

in order to separate the DC-operating points of preceding and following stages.

Fig. 2. Photograph of the Fabricated Quadrupler Chip

The frequency quadrupler chip is fabricated using Telefunken SiGe2RF technology [14]. SiGe2RF is a low cost Si/SiGe HBT process with a minimum effective emitter size of $0.5 \times 1.1 \mu\text{m}^2$. The SIC-npn transistors (with selectively implanted collector) have a f_T of 80 GHz. The photograph of the fabricated chip can be seen in Fig. 2. Including the pads, the used chip area is $730 \mu\text{m} \times 710 \mu\text{m}$. The power consumption is 55.7 mW.

Fig. 3. Measured Conversion Gain versus Input Power at 5 GHz Input Frequency

The circuit was characterized on wafer. An external ultra-wideband BALUN was used at the input for differential stimulus, and the output was taken single-endedly while terminating the other output port with a 50 Ω load. Fig. 3 shows the measured conversion gain for swept input power at an input frequency of 5 GHz, and an output frequency of 20 GHz. It can be seen that the optimum input level is around -9 dBm. The given input power is the available power at the probe tips and the conversion gain is given with respect to this value.

Fig. 4. Measured Conversion Gain versus Input Frequency for -9 dBm Input Power

Fig. 4 shows the conversion gain for swept input frequency. The available input power was set to be -9 dBm at the probe tips. The output is taken at the quadruple input frequency. From the figure, it can be seen that the maximum conversion gain is 0.6 dB and is achieved for an input frequency of 5.1 GHz. As the input frequency gets lower or higher, the conversion gain drops sharply, which indicates that the intended power matching is achieved. The circuit shows a 3 dB bandwidth of 3.6 GHz at the output.

IV. CARRIER RECOVERY EXPERIMENTS

In order to determine the ideally expected carrier recovery performance, some simple simulations were performed by mathematically quadrupling QPSK modulated signals.

Fig. 5. Normalized Simulated Quadruple Spectrum of a 4 Gbit/s QPSK Signal

Fig. 5 shows the results of such a simulation for 4 Gbit/s data rate. The simulation was performed for a duration of $1 \mu\text{s}$, using a pseudorandom (PN) bit sequence, an ideal root-raised-cosine (RRC) pulse shaping filter with a roll-off factor of 0.35 and a carrier frequency of 5 GHz. It is

seen from the figure that a rich spectrum is generated by quadrupling the QPSK signal, with distinct components at $(4 \cdot f_C)$ and at $(4 \cdot f_C \pm f_S)$, where f_C is the carrier frequency and f_S is the symbol rate.

The quadrupler circuit was also tested by applying QPSK modulated signals at the input, and observing the output with a spectrum analyzer. The input signal was generated with Tektronix AWG7122B signal generator, using a 5 GHz carrier frequency, a PN bit sequence and a RRC pulse shaping filter with a roll-off factor of 0.35. The average modulated power at the input was around -4 dBm, which was the maximum available power from the signal generator. The generated broadband spectrum was slightly asymmetric due to the limited bandwidth of the digital to analog converter outputs of the signal generator, with a drop of around 5 dB at higher frequencies.

Fig. 6. Measured Quadrupler Output Spectrum for a 4 Gbit/s QPSK Input

Fig. 6 shows the measured output spectrum of the quadrupler circuit, for a 4 Gbit/s QPSK input. The recovered carrier power corresponds to -15.2 dBm after compensating for the measurement setup losses. The recovered carrier power is in well agreement with the expected value from circuit simulations.

The ideally simulated and the measured spectrum in Fig. 5 and Fig. 6 are both plotted with a 1 MHz relative bandwidth and a span of 5 GHz. Therefore a direct comparison between them is possible, although it should not be forgotten that the simulated power levels are arbitrary and are normalized to one. It is clear from both figures that the recovered carrier needs to be filtered if it is to be used as a reference signal. On the other hand, the strongest spurious components rise up at a distance equal to the symbol rate, which makes the filtering easier and the carrier recovery concept better suited for higher data rates. Therefore, for high data rate systems the spurious components at the close vicinity of the recovered carrier are of highest importance. As seen in (3), the spectrum rising up around

the carrier can be treated as an amplitude fluctuation caused by the fourth power of $A_C(t)$. The magnitude of these fluctuations should be kept low enough, in order to prevent a fading of the recovered carrier. Therefore the suppression of the spurious spectrum around the recovered carrier is very important, which in the end determines the bandwidth of the bandpass filter that would be needed for filtering the recovered carrier. The suppression of these components was found to be 23.3 dB and 21.7 dB for the simulated and measured case, respectively. The measured suppression is very close to the simulated one, as the difference is well within the measurement and simulation accuracy.

Fig. 7. Measured Quadrupler Output Spectrum for a 4 Gbit/s 16QAM Input

The quadrupler circuit was also tested with higher order modulation types. Fig. 7 shows the measured output spectrum of the quadrupler circuit, this time for a 4 Gbit/s 16QAM input having the same conditions. Similar to the QPSK case, a rich spectrum is generated with components at $(4 \cdot f_C)$ and $(4 \cdot f_C \pm f_s)$. Although the spectral efficiency is doubled, the suppression of the spurious spectrum around the recovered carrier is much worse having a value of only 13 dB. These results indicate a much sharper bandpass filter requirement for the carrier recovery with higher order modulation types.

V. CONCLUSION

In this work, a circuit capable of M-QAM carrier recovery using frequency quadrupling was presented. The circuit was fabricated using a low-cost SiGe HBT process. It was shown by comparing measured and simulated results that the designed frequency quadrupler performs similar to the ideal case for QPSK carrier recovery. Furthermore, the circuit is operated from a low supply voltage of 2.5 V, it requires low input drive for saturated gain and has a narrow band characteristic which acts as an inherent filter. All these features make the designed frequency quadrupler

very suitable to be used in compact, low-cost, high data rate systems.

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