Compact Switched-Capacitor Power Detector With Frequency Compensation in 65-nm CMOS

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\section*{ABSTRACT}
This work presents a compact switched-capacitor power detector (PD) with frequency compensation technique in a 65-nm CMOS process. Utilizing self-biased MOSFET as switches, the PD works both at the positive and the negative cycle to increase the dynamic range (DR). The output of traditional power detectors usually change with the variations of input frequencies which make the measurement of PD more difficult. In this design, by adding a feed-forward frequency detection circuit, the load resistors of the power detector are changed according to the input frequencies. Thus, the effect of input frequency variation is minimized. The measured operation frequency of the power detector is from 3 GHz to 5 GHz with a dynamic range of 20 dB with an error of \(\pm 2\) dB. The variations of the output voltage are reduced from more than 4 dB to \(\pm 0.5\) dB, achieving a variation of less than \(\pm 0.25\) dB/GHz. To the authors’ knowledge, it is the first power detector with input frequency compensation. The core of the power detector occupies an area of 0.014 mm\(^2\) and consumes 2.04 mW static power.

\section*{INDEX TERMS}
CMOS power detector, dynamic range, frequency compensation, self-biased MOSFET.

\section*{I. INTRODUCTION}
In a radio frequency (RF) integrated circuit (IC) system, power control is essential for the power amplifier to maintain reliable communications and extend battery life in mobile devices. In transmitter systems, the power detector is usually used to adjust transmission power, increasing the capacity and quality of the network. Supporting multi-band is a trend in modern communication systems. However, for different frequency bands, the outputs of PD varies with input frequencies. This variation can be up to several dB, which requires calibration on these frequencies, making the measurement of input powers difficult. To solve this problem, the frequency compensation technique is required. Besides, since modern systems have a large peak-to-average power ratio, this demand the investigation of power detector with wide dynamic range. Also, the power detector should have a compact size and low power consumption to be integrated into the whole system.

Although the frequency compensation technique in PD is not discussed in the previous works before. Several techniques are introduced to increase the dynamic range (DR) and bandwidth of the PD [1]–[4]. A PD consists of HBTs in cascode configuration with diode connected PMOS transistor load in a SiGe BiCMOS technology is reported in [1]. The cascode configuration is used to provide wide-band input matching independent of input power level. The DR of the PD is improved by implementing diode connected PMOS transistor load to reduce the load impedance for high DC currents. However, the linearity of this PD is not good enough, so the high dynamic range is realized by increasing the error of the detected power. Cascading gain amplifiers and squaring circuits are utilized to achieve wide DR using the power level segmented detection method in [2]. The frequency response is enhanced by gain amplifiers with a cross-coupled NMOS structure. The power level is divided into several segments
and each segment is detected separately. In [3], a capacitor attenuation array and seven stage CMOS rectifiers with auxiliary capacitors are utilized for a wide dynamic range PD. The attenuation capacitors reduce the input signal for rectifiers so the PD can detect input power precisely. Auxiliary capacitors are introduced to improve the DR by making the rectifier maintain the transfer characteristic at the saturation region. However, these circuits are complicated and difficult to realized. Switched-capacitor balanced diode structure is employed in [4]. It is designed with PN junction diodes working at both positive and negative cycle to increase the linearity. The switched-capacitor structure can reduce the voltage drop across the diodes over the entire period, improving the dynamic range of the PD. Although the DR is increased but the minimum detectable power is too large to be used in wireless communication applications. These reported PDs do not have frequency compensation considerations, so the variations of output voltages can be up to several dB/GHz, making the measurement of input power at different frequencies more difficult.

In this paper, we demonstrated a power detector with reasonable DR and frequency detection circuits to compensate the effect of input frequency variations by changing the load resistances. The PD employs self-biased P-type and N-type MOSFETs as switches and utilized a balanced structure to increase the DR of the PD. The measured DR is 20 dB with a small chip area and 2.04 mW static power. The output voltage variation is within ±0.5 dB, achieving a variation less than ±0.25 dB/GHz, which makes this PD more suitable for integrated multi-band RF transmitter systems.

II. DESIGN OF FREQUENCY COMPENSATED POWER DETECTOR

A. DESIGN OF POWER DETECTOR

The proposed power detecting circuit is shown in Fig. 1. It consists of two N-type and two P-type MOSFETs, two input capacitors as DC blockers, two feedback resistors for self-biasing of the MOSFETs, a variant load resistor controlled by digital signals, and a second order RC low-pass filter network to obtain the output DC voltage.

The structure of the proposed power detector is similar to the one published in [4], replacing the diodes used in [4] with self-biased MOSFETs. There are two reasons that the self-biased MOSFET is preferred to diode switch in this design. Firstly, since the PN-junction diode has a higher threshold voltage, the power supply could be much lower using MOSFET switches. This will reduce the power consumption. Secondly, the self-biased MOSFET is more sensitive to small signals compared to the diode. This may be due to the \( I_{ds} - V_{gs} \) curve of the MOSFET has a sudden change of slope from the cut-off region to the saturation region when the \( V_{gs} \) increases gradually. However, for diode device, the slope of I-V curve changes gradually. Therefore, for the same voltage increase, the MOSFET will conduct more current than the diode.

In this structure, the four MOSFETs work as four switches. With proper supply voltage, the N-type and P-type MOSFETs are just biased below the saturation region. When a positive cycle RF input signal is applied to the Port1, the N-type MOSFET \( M_{n1} \) is closed, while the P-type MOSFET \( M_{p1} \) is open. At the same time, a negative cycle input signal is applied to the Port2, the P-type MOSFET \( M_{p2} \) is closed.
while the N-type MOSFET $M_{n2}$ is open. The capacitor $C_1$ is discharged through the load resistance and $C_2$ is charged by the supply voltage. When a negative cycle input signal is applied to the Port 1 and a positive cycle signal is applied to the Port 2, switch $M_{p1}$ and $M_{n2}$ are closed, while the switch $M_{p2}$ and $M_{n1}$ are open. Then the capacitor $C_1$ is charged by the supply voltage and $C_2$ is discharged through the load resistance. The charging and discharging currents depend on the average voltages applied on terminals of the MOSFETs in one cycle.

### B. DESIGN OF FREQUENCY DETECTION CIRCUIT

In the proposed PD, we innovatively compensate the variations of input frequencies by adding a frequency detection circuit. As shown in Fig. 1, the frequency detection circuit is composed of an inverter chain, two true single-phase clock (TSPC) dividers, a clock generator, a frequency-to-voltage converter (FVC) and a 2-bit ADC. The inverter chain is used to amplify the input signal and to convert the input sinusoidal signal to a square wave signal. If the input signal is large, the inverter chain works as a limiter to protect the following stage. Two series TSPC dividers are utilized to divide the input frequency by 4 to generate the clock for the next stage. Dividing the frequency of the input signal by 4 allows the FVC to work at higher frequency.

The schematic of the clock generator and FVC are shown in Fig. 2 and Fig. 3. The working principles of these two circuits are similar to the work published in [5]. The clock generator provides three control signals $S_1$, $S_2$, and $S_3$, controlling transistors $M_1$, $M_2$, and $M_3$ as shown in Fig. 3. The input and output signals of the clock generator are presented in Fig. 4. It is composed of a D flip-flop, a non-overlapping circuit, two NANDs, and eleven inverters. The input frequency is divided by two to generate the signal $S_1$. With the non-overlapping circuit and NANDs, we can obtain two non-overlapping signals $S_2$ and $S_3$ whose frequency is half of the input signal.

These three control signals are with the same frequency. The general operation of the FVC is to charge capacitors $C_3$ and $C_4$ by the current mirror when signal $S_3$ is high. The capacitor $C_3$ is discharged when signal $S_2$ is high. The charge in $C_4$ is held constant to provide an output voltage corresponding to the frequency of the control signals. In the negative period $T_1$ of signal $S_1$, all transistors $M_1$, $M_2$, and $M_3$ are turned OFF and the charge in $C_4$ is held constant. During the positive period $T_2$ of signal $S_1$, transistor $M_1$ is turned ON. In this period, when signal $S_2$ is at a low voltage level and $S_3$ is high, capacitors $C_3$ and $C_4$ are charged by the current mirror. There is a charge redistribution in capacitors $C_3$ and $C_4$ at the beginning of this period when the charge of these two capacitors is not equal. Once the charge of these two capacitors equals, the redistribution procedure stops. When signal $S_2$ is at a high voltage level and $S_3$ is low, capacitor $C_3$ will be discharged and the voltage of $C_4$ is held constant. Since $C_3 = C_4 = C$. If the input frequency of the PD and the clock generator is $f_{in}$ and $f_{cg}$, then the frequency of the signal $S_3$ is $f_{cg}/2 = f_{in}/8$. We have:

$$V_{out} = \frac{I_c}{2C} T_4 = \frac{I_c}{2C} \left( \frac{2}{f_{cg}} \right) = \frac{I_c}{2C} \left( \frac{8}{f_{in}} \right)$$

(1)
So the output voltage of the FVC is reversely proportional to the input frequency. The charging and discharging procedure of this FVC is different from the one published in [5]. In [5], capacitor $C_3$ is charged firstly and then the charge of $C_3$ and $C_4$ are redistributed which makes the whole procedure slower. In the proposed FVC, the redistribution procedure is accelerated by injecting the current of the current mirror at the same time. So the working frequency of this FVC is higher and the time for the FVC to reach a steady state is faster. The output voltage versus input frequency of the FVC is shown in Fig. 5.

To compensate the variation of input frequencies, output voltage versus input power relationship with different input frequencies in an uncompensated PD are shown in Fig. 6. In this figure, simulation results of the PD working at 2 GHz-9 GHz are shown, so a clearer trend of output voltage variation while increasing input frequency can be observed.

From the simulated results, we can see that with the increase of input frequency, the output voltages of PD also increase with the same input power. This is because with the frequency of the MOSFET switches turning ON and OFF increased, the charging and discharging frequency also increase, resulting in a higher output voltage. So to eliminate the effect of this charging current increase, we could reduce the load resistance instead. Simulation results for an uncompensated PD are shown in Fig. 7 that with a higher load resistance, the output voltage also increases. If we can reduce the load resistance while increasing the input frequency, the voltage-power curve may remain the same with different input frequencies.

To verify this idea, the output voltage of the FVC is digitized by a 2-bit ADC firstly in this design. For simplicity, the structure of the ADC is a basic flash ADC using a resistor-constructed voltage ladder and comparators. The resistors in the ADC are tuned to not to be linear for the best performance. The output digital signals control the switches to short resistors as shown in Fig. 8. With higher frequency, more resistors are shorted to ground, reducing the load resistance of the power detector. The resolution of the ADC can be increased if higher accuracy is needed. With proper load resistance, we can obtain the same performance of the PD for different input frequencies. In this PD, the load resistance is designed...
III. MEASUREMENT RESULTS

The proposed frequency compensated power detector has been designed and fabricated in GlobalFoundries 65-nm CMOS process. Fig. 9 shows the micrograph of the fabricated chip. The area of the power detector is only 200 µm x 70 µm. With a 1.2 V supply voltage, the current consumption of the switched-capacitor power detector is 1.7 mA. Cascade Elite 300 probe station is used to measure the power detector as shown in Fig. 10. Keysight E8257D signal generator providing continuous-wave (CW) signal is first connected to an amplifier and a hybrid coupler to convert to the single-ended signal to the differential. Then differential signals are applied to the input of the power detector. To de-embed the effect of the amplifier and coupler, before the measurement of the PD, the gain of the amplifier and the loss of the hybrid coupler and coaxial cables are measured at target frequencies. So after measurement of the PD, the actual input power of the PD can be calculated to obtain accurate measurement results. The losses of the RF probes are also de-embedded using the S-parameters provided by Cascade. Keysight 34401A multimeter is used to measure the output voltage of the PD.

In this design, since the resolution of ADC is only 2-bit, five different load resistance values can be obtained by changing the output voltage of the FVC. In the measurement results, two of the five load resistances didn’t compensate input frequency well. Therefore, only three frequency points which are well compensated are shown in these figures. Fig. 11 and Fig. 12 show the output voltages and maximum voltage difference versus input power at different frequencies with and without frequency compensation. The maximum voltage difference is calculated by the output voltage difference of PD in a frequency range from 3 GHz to 5 GHz at the same input power. It is shown that the with the frequency compensation circuit, the PD output voltage is more consistent at various input frequencies. However, with the frequency compensation circuit, the lowest detectable power is increased, and the dynamic range is also decreased. We think the possible reason maybe is the increased parasitic and the loading effect of the frequency compensation circuit. The proposed frequency compensated power detector has
TABLE 1. Comparisons with previous power detectors.

| Reference | Frequency Compensation | Variation of Output Voltage (dB/GHz) | Dynamic Range (dB) | Operating Frequency (GHz) | Power Consumption (mW) | Active Area (mm²) | Process |
|-----------|------------------------|--------------------------------------|-------------------|--------------------------|------------------------|-------------------|---------|
| [1]       | NO                     | 52                                   | 7-20              | 7.2                      | 0.42                   | 250-nm BiCMOS    |         |
| [2]       | NO                     | >40                                  | 0.7-4             | 5.8                      | 0.15                   | 28-nm CMOS       |         |
| [3]       | NO                     | 42                                   | 0.3-10            | 0.55                     | 0.113                  | 180-nm CMOS      |         |
| [4]       | NO                     | <1.5*                                | 30                | 0.7                      | 0.0036                 | 65-nm CMOS       |         |
| [5]       | NO                     | 43                                   | 2-14              | 35.2                     | 1.75                   | 130-nm CMOS      |         |
| [6]       | NO                     | 40                                   | 0-20              | -                        | 0.385                  | 180-nm BiCMOS    |         |
| [7]       | NO                     | 29                                   | 1.8               | 16                       | 0.48                   | 180-nm CMOS      |         |
| [8]       | NO                     | 40                                   | 0.9-8             | 70                       | 0.98                   | 180-nm CMOS      |         |
| [9]       | NO                     | 21                                   | 0.3-20            | 0.12                     | 0.083                  | 130-nm CMOS      |         |
| [10]      | NO                     | 20                                   | 0.125-8.5        | 0.18                     | 0.0126                 | 130-nm CMOS      |         |
| [11]      | NO                     | 20                                   | 3.1-10.6         | 3.8                      | 0.36                   | 180-nm CMOS      |         |
| [12]      | NO                     | 20                                   | 3-5              | 2.04                     | 0.014                  | 65-nm CMOS       |         |
| This work | YES                    | <0.25                                | 20                | 3-5                      | 2.04                   | 0.014            | 65-nm CMOS      |

*Estimated from measurement results.

FIGURE 13. Measured error of the PD with frequency compensation.

An operating frequency range from 3 GHz to 5 GHz. The variations of the output voltage are reduced from more than 4 dB to ±0.5 dB. The measurement results indicate that the power detector has more than 20 dB dynamic range. The error of the frequency compensated PD is within ±2 dB as shown in Fig. 13. Compared with previous published PDs (Table 1), this PD features at frequency compensation technique with low power consumption, a compact area, and a reasonable DR.

IV. CONCLUSION

In this work, we have verified the idea of the input frequency can be compensated by changing the load resistance of the PD by designing an input frequency compensated, low power consumption, reasonable DR power detector with an area of 0.014 mm² in a 65-nm CMOS process. The measurement results show that with a static power consumption of 2.04 mW, the dynamic range is more than 20 dB in the frequency range of 3-5 GHz. Applying frequency detection circuits, the variations of the output voltage are reduced from more than 4 dB to ±0.5 dB, achieving a variation less than ±0.25 dB/GHz. With low power consumption, small area, and input frequency compensation technique, the proposed power detector is suitable for multi-standard wireless communication on-chip applications.

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C. Li et al.: Compact Switched-Capacitor PD With Frequency Compensation in 65-nm CMOS

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