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A NOVEL PRECISION DC CURRENT SOURCE IN THE pA RANGE

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Abstract

We present a novel technique to generate an accurate dc current in the pA range. This source works by the charging of a capacitor using a voltage ramp with a precisely controlled slope. We generate this ramp with a precalculated Δ-Σ modulation sequence. The accuracy is limited by the voltage stability of the arbitrary wave generator used to generate the pattern.

Introduction

With the development of accurate instruments to measure small currents at the pA scale and lower, there is an increasing need for calibrations at this level. The traditional way of generating accurate currents is to apply a known voltage over a calibrated resistor. However, this is impractical for currents smaller than a few tens of pA, because the high resistances required, 10 GΩ and upwards, are unstable and measurements are very sensitive to disturbances. For these reasons several national metrology institutes have developed traceable current sources based on the charging of a capacitor at a constant rate [1, 2, 3, 4] according to (1). These systems generate the voltage ramp indirectly by charging another capacitor and then measure the resulting voltage ramp.

$$I = C\frac{dV}{dt} \tag{1}$$

We present another approach, where we generate the voltage ramp directly using a Delta-Sigma modulated signal and a low-pass filter. The advantage of our approach is that the linearity of the voltage ramp is linked to the time base and the calibration of a small number of dc voltage levels which is done beforehand using a voltmeter. We also need only one high quality capacitor. The Delta-Sigma signal is provided by a low noise arbitrary wave generator (AWG) which can generate waveforms of about a million samples with an accurate time base.

Delta-Sigma modulation

The Delta-Sigma technique [5] has been around since the 1960s and can be easily integrated in electronic circuits to construct powerful analog-to-digital and digital-to-analog converters. In our application we simulate the Delta-Sigma modulator in a computer and use the simulated signal sequence to program an arbitrary wave generator (AWG).
Digital-to-analog (DA) conversion inevitably introduces quantisation errors since not every value can be generated exactly. These errors result in distortion and noise. The idea of the Delta-Sigma technique is to modulate the signal in such a way that the quantisation noise occurs at

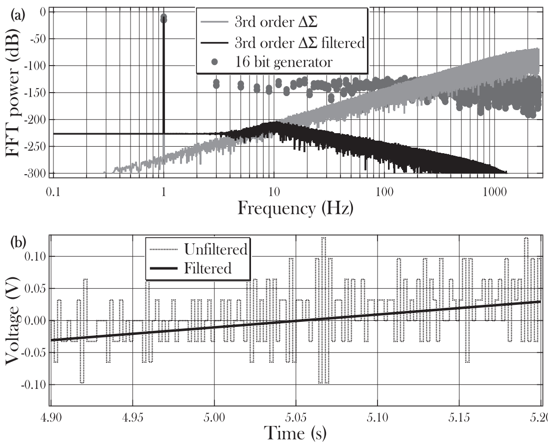

Figure 1. The power of Delta-Sigma modulation. Simulation. (a) A 1 Hz sinusoidal signal is generated with a sample rate of 5 kS/s. The spectrum of the 3rd order Delta-Sigma modulated signal (6 bits) has very low noise at low frequencies. The noise at high frequencies can be filtered with a low pass filter. As a comparison a direct 16 bit DA converted signal has more than 50 dB higher noise in the form of distortion at odd harmonics. (b) A voltage ramp generated by the Delta-Sigma generator before and after filtering.

frequencies considerably higher than the signal of interest. The modulated signal can then be low pass filtered to produce very accurately the desired signal. Fig. 1a illustrates the point.
There are many ways to construct the modulator. In our application we simulate a 3rd order modulator in a computer in order to generate the modulation sequence. An example of the output from this model is displayed in Fig. 1b together with the filtered signal. We have constructed a program which takes the list of calibrated voltage levels, the calibrated value of a capacitor and the desired output current, and calculates a Delta-Sigma modulated sequence which will generate this current.

Calibration procedure

Fig. 2 shows an overview of the system. The procedure consists of three steps. First we decide which voltage levels will be used in the modulated sequence. These levels are then generated as DC levels and measured with a calibrated voltmeter.
The next step is to calculate the modulated sequence using the measured voltage levels. We used $10^5 - 10^6$ samples with good results. This sequence is then transferred to the AWG (using the original levels in the first step, not the measured levels).
Third we connect the output of the AWG to the filter-

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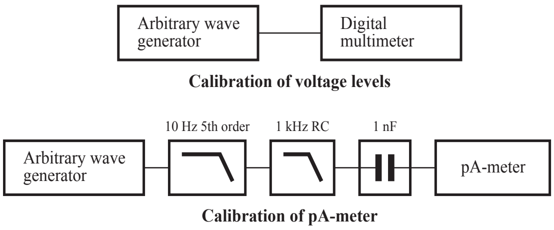

Figure 2. The measurement setup. First the AWG is connected to an accurate DMM to calibrate a small number of voltage levels. These voltages are then used to calculate a Delta-Sigma modulated sequence in a computer, which is transfered to the AWG. The resulting AWG signal is filtered in two stages and then connected to the calibrated capacitor. The current from the capacitor is used to calibrate the pA-meter under test.

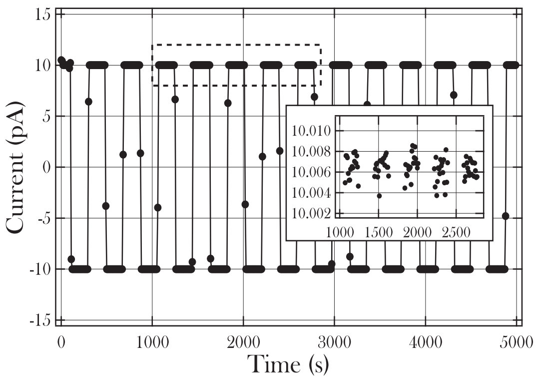

Figure 3. Current measurement with 200 s voltage ramps on a 1 nF capacitor. Each measurement point is integrated for 10 s. The inset shows the measurement noise of five of the positive ramps.

ing circuit and the filter output to the calibrated capacitor. We implemented a 5th order 10 Hz Butterworth filter and added a 1 kHz RC low pass filter to the output. The calibrated capacitor should be a gas or vacuum dielectric capacitor in order to minimise the leakage currents. If there is some measurable leakage current it will average out because the voltage ramp used is symmetrical around 0 V. The current from the capacitor is then used to calibrate the pA-meter. The zero offset should be measured by grounding the input of the capacitor, in order to compensate for possible polarisation currents from the capacitor. (We noticed some capacitors with polarisation currents up to a few hundred fA. This current can be reduced considerably by grounding the output terminal for a few days.)

Measurements

In order to test the current generator we used an accurate pA-meter to compare currents at 10 pA using the Delta-Sigma method and using a calibrated 10 GΩ resistor with a DC voltage. We tested the system at the 10 pA level because it is possible to compare it with the traditional resistor method with reasonable accuracy. An example of the measurement is shown in figure 3. The voltage ramp was repeated several times for positive and negative current and the average current during each 200 s ramp was recorded. The zero level was also measured by grounding the input of the filter and recording the value. The estimated standard uncertainty of twelve readings was 0.16 fA.

We then measured the current with a calibrated 10 GΩ resistor and $\pm$100 mV DC voltage. We needed to take into account the offset voltage of the pA-meter in this measurement which was approximately 80 μV as measured with an external voltmeter. The result deviated from the Delta-Sigma method by +6.8 fA and -4.1 fA for the positive and negative currents respectively, with a standard uncertainty of 8 fA. This shows that the methods agree well within the measurement uncertainty. A comprehensive uncertainty analysis will be presented at the conference.

This system will be used for calibrations at SP for currents from 10 fA to 100 pA using 10 pF to 1 nF air gap capacitors with different ramp rates. A bilateral comparison with PTB in Germany is planned in order to verify the accuracy of this method.

Conclusion

We have developed a current source based on charging a capacitor at a constant rate. By using a small number of calibrated voltage levels and Delta-Sigma modulation the linearity of the voltage ramp is ensured to within the stability of the voltage source.

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