MĀPAN-Journal of Metrology Society of India (March 2017) 32(1):17–22
DOI 10.1007/s12647-016-0186-0

ORIGINAL PAPER

Development of an Automated Precision Direct Current Source for Generation of pA Currents Based on Capacitance Charging Method at CSIR-NPL

B. Ehtesham*, P. S. Bist and T. John

LF HF Impedance and DC Standards, ALSIM, CSIR-National Physical Laboratory, New Delhi 110012, India

Received: 15 September 2015 / Accepted: 01 August 2016 / Published online: 19 August 2016

Abstract: The design and development of a direct current source for picoampere currents based on capacitance charging technique at CSIR-NPL is presented. A highly linear voltage ramp generator has been realized which can generate ramps with any rate between ±1 and ±100 mVs^{-1}. The ramp generator is computer controlled where the amplitude, slope and duration can all be controlled in software developed in LabVIEW which greatly simplifies the hardware configuration while providing great operational flexibility. The experimental evaluation of the current generator in the range from 1 to 100 pA indicates satisfactory performance. This work aims at developing a facility to ensure that CSIR-NPL can provide traceable calibration for picoammeters and electrometers.

Keywords: Capacitance charging; Current generator; Ramp generator; Calibration; Electrometer

1. Introduction

In recent years, electrometers, pico-ammeters, source-measure units (SMU) etc. have emerged as essential electrical test and measurement tools, particularly for probing and characterizing nano-materials and nano-devices. Associated with this development is the requirement for proper calibration of these instruments with traceability to the SI. Calibration of these instruments in the nano-ampere range and lower requires development of very high accuracy current generators. One technique that has been found quite suitable for accurate direct current generation below the 1 nA range is the capacitor charging method and several national metrology institutes have already implemented this technique or are in the process of implementing it for low current calibrations of nano-amperes and lower [1–6]. As the national metrology institute (NMI) of India, CSIR-National Physical Laboratory (CSIR-NPL) is working on developing such a facility at NPL to meet the requirements of users in this country. This paper presents the design and experimental evaluation of such a system at NPL.

2. The Capacitance Charging Method

The technique is quite simple and well established. When a linear ramp voltage is applied to a capacitor (C), a constant dc current (I) proportional to the slope $S = \dfrac{dV}{dt}$ of the ramp as $I = C \times S$ is generated [1]. This method has been successfully applied in producing very low DC currents down to pico-amperes and below values while neglecting the flaws caused by frequency dependence of the capacitor. The accuracy of current generation will depend upon the quality of the capacitor as well as the accuracy and stability of S. From quality point of view, only capacitors of gas or air dielectric are suitable for this application. Standard air capacitors are available in decade values from 1 pF to 10 nF, but normally capacitors of values higher than 1 nF are not recommended in this application because the higher value capacitors can cause instability for the input stage of the instruments to be calibrated. Even though the current generation depends on the slope S and not on the magnitude of the ramp voltage, from a practical point of view, both the amplitude (V) and duration (T) of the ramp are also important factors to be taken into account in the design of the system. This is because there is a limit on the maximum value of V possible by a given ramp generator and $T = V/S$ should be long enough for performing a useful measurement after

---

The original version of this article was revised: Few entries in Table 5 were incorrectly published.

---

*Corresponding author, E-mail: bushra3007@gmail.com allowing for instrument settling times. This will decide the maximum value for S than can be employed which is in the range of 100 mVs^{-1} with a ± 10 V ramp ($T = 200$ s). On the lower side a stable ramp of slope down to 1 mVs^{-1} is practicable. Given the range of C and S that can be selected, stable and accurate DC current generation over a range of values is theoretically possible.

3. Experimental Setup

The block schematic of the setup is shown in Fig. 1. The system is designed for automated operation with software developed in LabVIEW. The most important unit of the system is the ramp generator. The critical factor is the linearity of the ramp and earlier works have used both analog and digital ramp generators and in certain cases incorporated compensating circuits to rectify nonlinearity errors [1–4]. However, for the purpose of the present work we have chosen to use a simple design based on an analog integrator (without a compensating circuit) that can generate a ramp of ± 10 V amplitude. The basic circuitry of ramp generator is shown in Fig. 2. It is essentially an integrator in which the feedback capacitor is charged by a constant current to produce a linearly varying ramp voltage. The control voltage V(in) supplied by a programmable voltage source is used to produce alternating UP and DOWN going ramps which are applied across C to generate alternately a positive current and a negative current of the same magnitude. The ramp voltage is acquired separately by the DAQ, NI PCI-4461 (24 bit resolution) system with known time base and the slopes are derived from this data. Continuous sequence of UP and DOWN ramps is generated by reversing the polarity of V(in) which forces the ramp in the opposite direction when the ramp voltage reaches its positive maximum in UP direction and negative maximum in DOWN direction. This is done automatically by continuously comparing the instantaneous DAQ data with the value of ramp amplitude set in the software. For a given C, as I depend on S only and in order to generate currents over a range of values, it is necessary to produce ramps of different rates with precisely known values. This is achieved by changing the value of V(in). The design of the ramp circuit is such that by changing V(in) in the range of ± 0.1 to ± 10 V, ramps of any rate between ± 1 and ± 100 mVs^{-1} can be generated. The DAQ is calibrated in the range of -10 to $+10$ V which is also the maximum voltage of the ramp. We have used Fluke 5720A multifunction calibrator as a programmable voltage source for deriving the control voltage. This instrument has been chosen because it can be programmed to deliver very accurate voltages and that it is calibrated in DC voltage ranges with traceability to Josephson voltage standard at NPL. One reported problem with Fluke calibrator is the presence of high frequency spikes [7] at its output but this is not a cause for concern here because of the large time constant ($\tau = 100$ s) of the integrator. The integrator IC (AD549) is powered using ± 15 V battery pack to reduce power supply noise. The electrometer for current measurements is the Keithley 6430 sub-femtoampere remote source meter in its current measure mode. Both Fluke 5720A and Keithley 6430 are connected to the PC through GPIB interface.

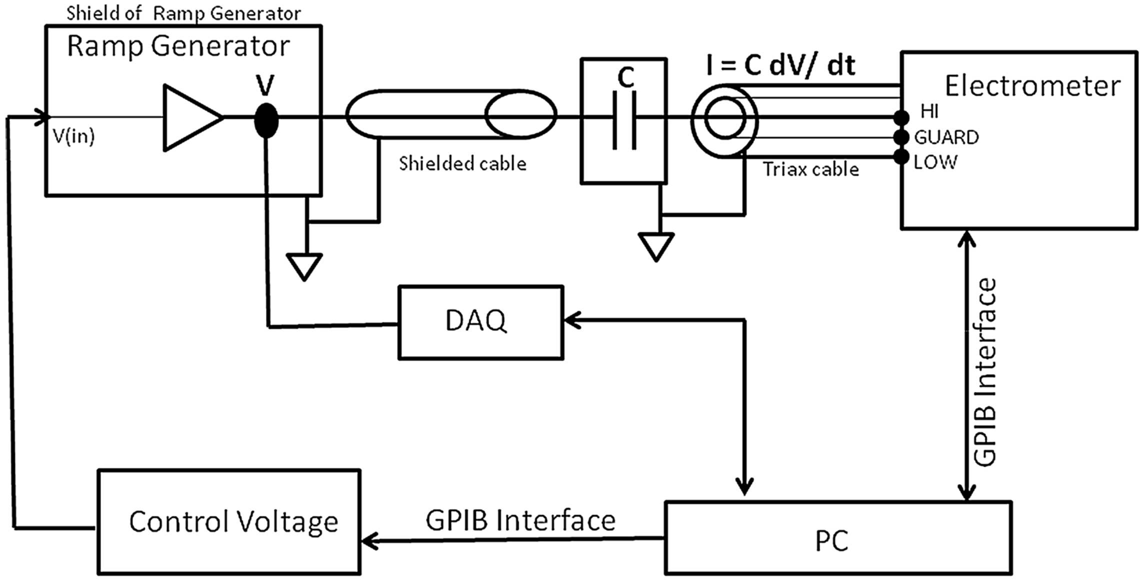
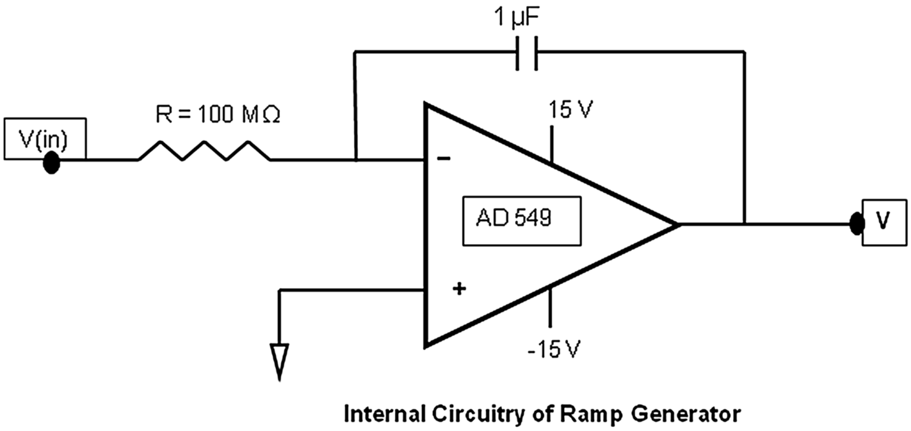


Fig. 1 Schematic block diagram of capacitance charging current source. The system is designed for automated operation. The amplitude, duration, slope and slope polarity of the ramp can be controlled by software

Fig. 2 Simplified circuit of ramp generator. Time constant is 100 s. ± 15 V battery pack is being used as power supply



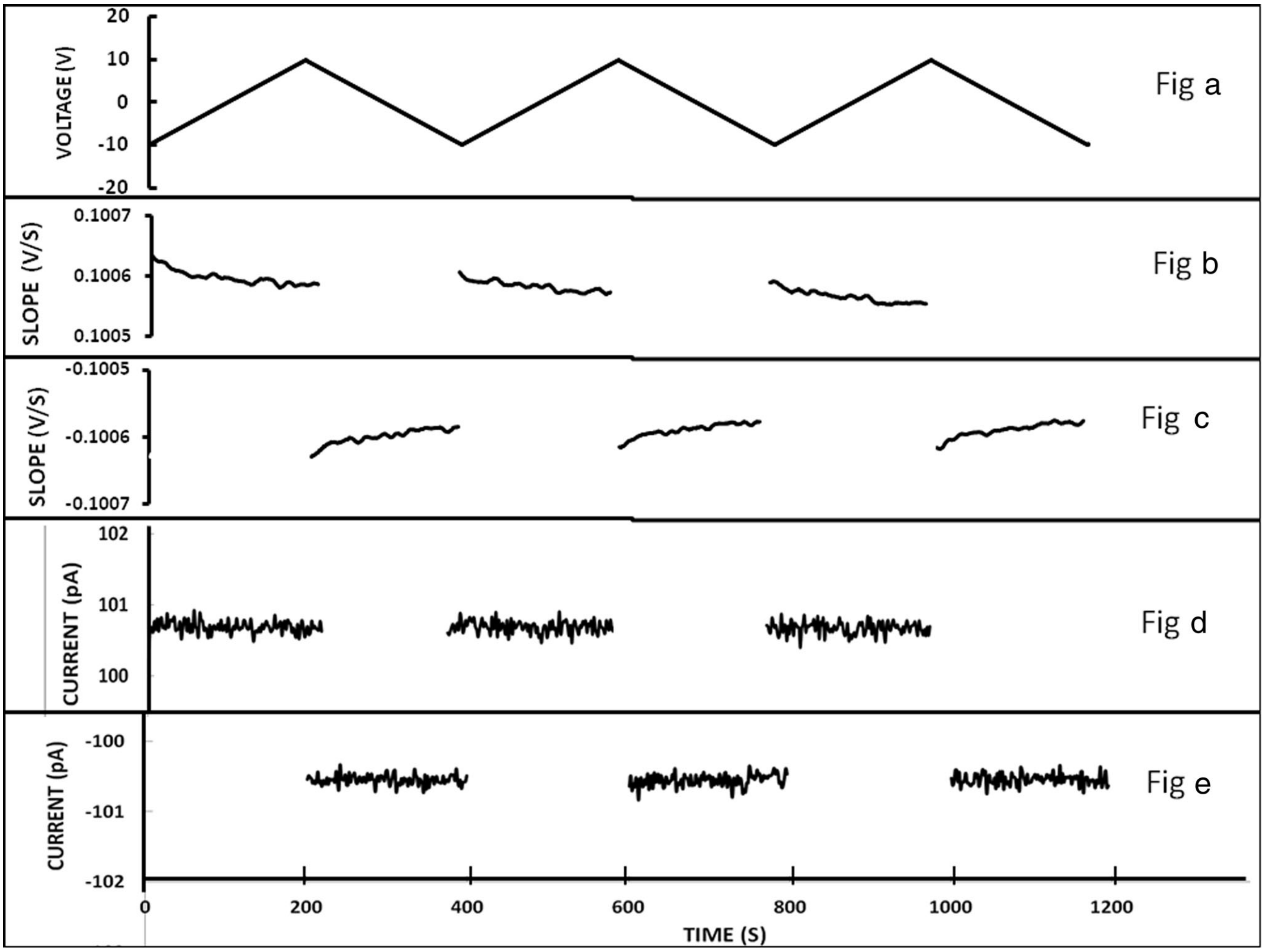


Fig. 3 Graphical display of the ramp waveform and the currents measured by the electrometer. The ramp is designed to generate alternately positive and negative currents of the same nominal value. The ramp sequence will repeat N times where N is a number set in the automation software. We have $N = 3$ in this example shown. Ramp amplitude and ramp rate are also programmable parameters. **a** UP and DOWN ramp sequence of duration 200 s each, **b** slope calculated using DAQ data (UP ramp), **c** slope calculated using DAQ data (DOWN ramp), **d** positive current corresponding to UP ramps, **e** negative current corresponding to DOWN ramps

The capacitor selected (C in Fig. 1) is the 1 nF air capacitor belonging to the 1404 series of Reference Standard Capacitors from IET Labs Inc. This capacitor has temperature coefficient of maximum 5 ppm/ °C and drift of <20 ppm/year. As an air capacitor, it can be assumed to have very low leakage and dielectric absorption errors. The capacitor is calibrated at 1 kHz on the capacitor bridge AH2700A with traceability to the national standards at NPL. The calibrated value of $C = (1000.0013 \pm 0.01)$ pF. The AC–DC difference in the capacitance value of this capacitor type is on order of 100 ppm [8].

4. Current Generation and Measurement

The setup is tested for current generation in the range of ±1 to ±100 pA. With the 1 nF capacitor, a current of 100 pA requires a ramp of $S = 100\,\mathrm{mVs}^{-1}$ and 1 pA requires a ramp of $S = 1\,\mathrm{mVs}^{-1}$ and this is done by adjusting the value of the control voltage through automation. As per design, the full scale variation available for the ramp is 20 V (−10 to +10 V) and as can be seen, one ramp time (*T*) for this will vary from 200 to 20,000 s. Since in one ramp time, measurement of current of only one value can be made, waiting for up to 20,000 s to complete one measurement is really unnecessary. The approach adopted here involves keeping the ramp duration and hence the measuring time fixed at 200 s for all ramp rates. This involves curtailing proportionally the ramp amplitude at all ramp rates that are slower than 100 mVs^{-1} and this is done through software. Duration of 200 s is good enough time for performing valid current measurements even at the lowest value of 1 pA.

The measurements are performed under a regulated environmental condition of temperature (25 ± 1) °C and relative humidity of (50 ± 10) %. In order to guarantee full instrument accuracies, the measurements are taken after providing sufficient warm-up time for the instruments. The readings by the electrometer are acquired through GPIB communication. As mentioned earlier the ramp is monitored independently by the DAQ. In each case 200 points are sampled in the available measurement time of 200 s and both the data are stored into the same computer file for analysis later. A sample display of the raw data obtained with a nominal ramp rate of ±100 mVs^{-1} is shown in Fig. 3. The fluctuations in the electrometer output indicate the presence of noise in the measurements. The accuracy and resolution of the current measurements are improved by averaging of the samples. For averaging, the first 20 samples are discarded to compensate for the response time of the electrometer and the remaining 180 consecutive samples are averaged to obtain one single value for each ramp. The results so obtained are presented in Tables 1, 2 and 3 for three measurement values, corresponding to nominal currents of 100, 10, and 1 pA respectively. The values presented in the Tables are from measurements repeated on 3 days. The measured values of the applied ramp rates are 100.6,10.06 and 1.007 mVs^{-1} respectively. The uncertainty in the ramp rates is of the order of ±5 $\mu\mathrm{Vs}^{-1}$.

Table 1 Measurement results for generated current 100 pA (nominal value)

Current measured (EM range used : 1 nA)		
+VE current (I^+, pA)	−VE current (I^-, pA)	Offset corrected current (I, pA)
100.724	−100.581	100.652
100.722	−100.554	100.638
100.719	−100.570	100.644
100.727	−100.579	100.653
100.731	−100.583	100.657
100.722	−100.584	100.653
100.708	−100.570	100.639
100.722	−100.564	100.643
100.725	−100.570	100.647
100.721	−100.560	100.640
Average		100.646
SD		0.00676
Current as per $I = C\frac{dV}{dt}$		100.6

The applied ramp rate is ±100.6 mVs^{-1}

Table 2 Measurement results for generated current 10 pA (nominal value)

Current measured (EM range = 100 pA)		
+VE current (I^+, pA)	−VE current (I^-,pA)	Offset corrected current (I, pA)
10.0486	−10.0811	10.0648
10.0488	−10.0809	10.0648
10.0492	−10.0806	10.0649
10.0507	−10.0842	10.0675
10.0487	−10.0840	10.0664
10.0497	−10.0837	10.0667
10.0508	−10.0809	10.0659
10.0570	−10.0877	10.0724
10.0558	−10.0874	10.0716
10.0504	−10.0878	10.0691
Average		10.0674
SD		0.002754
Current as per $I = C\frac{dV}{dt}$		10.0666

The applied ramp rate is ±10.06 mVs^{-1}

The current (I) corrected for the electrometer zero offset is obtained from the measured positive current (I^+) and negative current (I^-) as $I = \frac{(I^+ - I^-)}{2}$ and it agrees very well with the one expected for $I = C\frac{dV}{dt}$ in each case, thus indicating that the overall performance of the system complies with our requirement.

For comparison, we have also performed current generation using an alternative method i.e. constant voltage

Table 3 Measurement results for generated current 1 pA (nominal value)

Current measured (EM range = 10 pA)		
+VE current (I^{+}, pA)	−VE current (I^{-}, pA)	Offset corrected current (I, pA)
0.9932	−1.0205	1.00685
0.9925	−1.0213	1.0069
0.9929	−1.0212	1.00705
0.9922	−1.0221	1.00715
0.9938	−1.0210	1.0074
0.9939	−1.0199	1.0069
0.9927	−1.0220	1.00735
0.9917	−1.0216	1.00665
0.9916	−1.0226	1.0071
0.9923	−1.0204	1.00635
Average		1.00704
SD		0.000316
Current as per $I = C\frac{dV}{dt}$		1.00699

The applied ramp rate is ± 1.007 mVs^{-1}

method which employed pico-ampere current generation by applying voltage across standard Giga-ohm resistors. In those measurements, the resistances are maintained at a steady temperature of 25 °C inside an air bath. For a comparison with the capacitance charging method, measurements made for 10 pA (nominal value) by the constant voltage method is also plotted in Fig. 4. In this particular case, the current fluctuations are approximately an order of magnitude larger in the capacitance charging method. In spite of this large noise, the capacitance derived averaged values show very consistent results in repeated measurements indicating that the capacitance method has much lower offset and drift errors and also lower combined uncertainty viz., 26.7 fA compared to 40 fA in the case of the resistance method.

The noise in the measurements of current generation using capacitance charging method can come from both external and internal sources. In the design and operation of the current generator, we have taken necessary precautions to reduce noise interference from external sources using correct shielding and guarding, especially the capacitor and electrometer input terminals [9, 10] as well as remote operation. Comparing with the noise performance achieved in the constant voltage setup which used very similar procedures to suppress external interference, the occurrence of enhanced noise in capacitance setup could be from sources internal to the system. The variations of the voltage ramp have been observed to be less than 5×10^{-6} Vs^{-1} clearly indicating that the dominant source of uncertainty in the measurements should be other sources. Of the different noise sources, the noise component due to the current measuring electrometer may be determined separately by taking measurements without applying any input. The rms noise measured in the different sensitive ranges of current measurement of the Keithley 6430 is listed in Table 4. This noise is independent of all other devices in the setup and sets the noise floor and sensitivity limit of the electrometer in its respective measurement ranges. The noise level changes with the selected

Table 4 Electrometer noise measurements

Electrometer range	RMS noise
10 pA	0.7 fA
100 pA	1.8 fA
1 nA	6.1 fA

Fig. 4 Results obtained for 10 pA (nominal value) current generations by constant voltage and capacitance charging methods. These are measurements made in the 100 pA measurement range of Keithley 6430. The vertical error bars denote the observed fluctuations in the raw data about the mean values

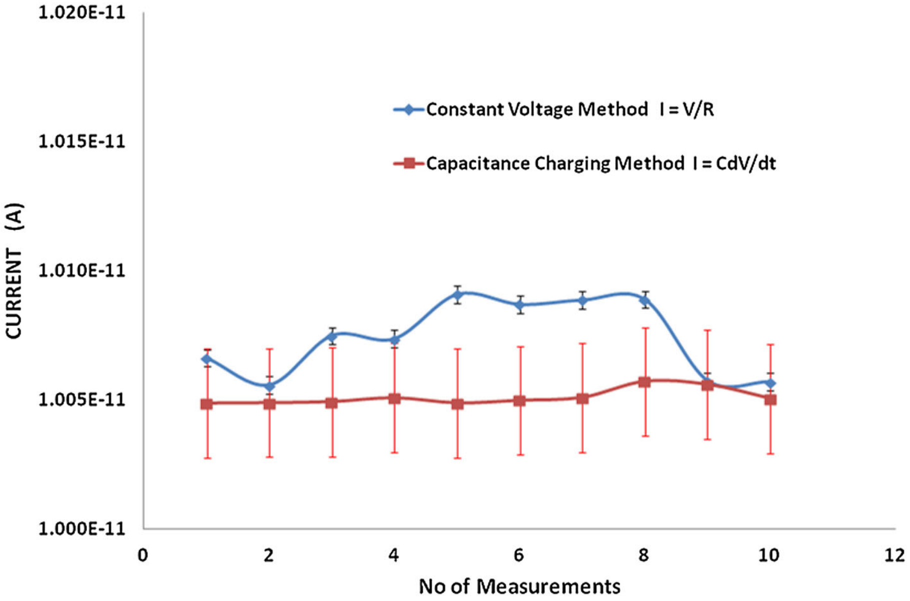


Table 5 Uncertainty evaluation

Uncertainty contribution in current measurement	100 pA	10 pA	1 pA
1. Due to ramp	10 fA	1 fA	0.1 fA
2. Due to differentiating Capacitor	0.5 fA	0.05 fA	0.005 fA
3. Due to electrometer	75.4 fA	13.6 fA	3.62 fA
4. Due to measurement repeatability	2.14 fA	0.9 fA	0.1 fA
Combined uncertainty	76.1 fA	13.6 fA	3.75 fA
Expanded uncertainty ($k = 1.96$)	149 fA	26.7 fA	7.36 fA

measurement range. In each range, the electrometer noise is more than one order of magnitude smaller than the total noise in the currents measured. Therefore improving the performance quality of the system requires reducing the noise contribution by the rest of the devices in the instrument setup. Kim et al. [11] have reported in their measurements that the 1404 series capacitor can be one source of enhanced noise. Presently we are unable examine this aspect as we do not have other type of capacitors that can be used for the measurements.

5. Uncertainty Calculation

Major contribution for uncertainty for current measurement is those due to the ramp, measuring electrometer, differentiating capacitor and Type A uncertainty from measurement repeatability. Type A uncertainty is calculated as the standard deviation of the measured offset corrected currents (column 3in Tables 1, 2, 3 respectively). The uncertainty components are presented in Table 5.

6. Conclusion

We have presented the development of a direct current generating setup using the capacitance charging method at CSIR-NPL aimed at creating a facility for providing traceable calibration for dc current parameter below 1 nA. We have developed a linear ramp generator with ample operational flexibility through software control. We have analyzed the performance of the designed system for current generation in the range of 1 to 100 pA. The overall performance of the setup in this current range is found to be satisfactory. A comparison made with constant voltage method which used standard resistors indicate that major source of uncertainty in the present setup is the noise. We have not considered the effect of possible ac–dc difference in the capacitance value. The noise performance of the system needs improvement for realizing currents of still lower values than those presently achieved.

Acknowledgments The authors would like to extend their gratitude to Dr. V.N. Ojha, Head Apex Level Standards and Industrial Metrology (ALSIM), NPL for his constant support and encouragement. Thanks are also due to director NPL for providing all the facilities. Authors would also like to express their gratitude to the anonymous referees for their valuable comments to improve the manuscript.

References

[1] G. D. Willenberg, H. N. Tauscher, and P. Warnecke, A Traceable Precision Current Source for Currents Between 100 aA and 10 pA, IEEE Trans. Instrum. Meas., 52 (2003) 436–439. DOI: 10.1109/TIM.2003.810051.

[2] H. E. van den Brom, P. de la Court,and G. Rietveld, Accurate Subpicoampere Current Source Based on a Differentiating Capacitor With Software-Controlled Nonlinearity Compensation, IEEE Trans. Instrum. Meas., 54 (2005) 554–558. DOI: 10.1109/TIM.2004.843127.

[3] L. Callegaro, V. D'Elia, and B. Trinchera, A Current Source for Picoammeter Calibration, IEEE Trans. Instrum. Meas., 56 (2007) 1198–1201. DOI:10.1109/TIM.2007.900128.

[4] G. D. Willenberg and H. N. Tauscher, Novel Digital Voltage Ramp Generator for Use in Precision Current Sources in the Picoampere Range, IEEE Trans. Instrum. Meas., 58 (2009) 756–760. DOI:10.1109/TIM.2008.2010675.

[5] L. Callegaro, P. P. Capra, V. D'Elia and F. Galliana, Generation of Reference DC Currents at 1 nA Level, with the Capacitance-Charging Method, IEEE Trans. Instrum. Meas., 63 (2014) 1779–1782. DOI:10.1109/TIM.2014.2298694.

[6] H. Scherer, G. D. Willenberg, D. Drung, M. Götz, and E. Pesel, Traceable Precision Generation And Measurement of Pa Direct Currents (2014), http://arxiv.org/ftp/arxiv/papers/1406/1406.4662.pdf.

[7] L. Callegaro,V. D'Elia,P. P. Capra and A. Sossco, Techniques for Traceable Measurements of Small Currents, IEEE Trans. Instrum. Meas., 56(2),April 2007. DOI:10.1109/TIM.2007.890800.

[8] S. P. Giblin, G. D. Willenberg, and N. E. Fletcher, Frequency Dependence Of Gas-Dielectric Capacitors Used In sub-nA Reference Current Generators, 2010 Conference on Precision Electromagnetic Measurements, Korea, 2010, pp. 318–319.

[9] M. F Gard, Electrometers, in Wiley Survey of Instrumentation and measurement, (Edited by Stephen A. Dyer), John Wiley and Sons (2004) 293–301.

[10] Keithley Instruments, Inc., Low level Measurements Handbook, Cleveland, 6th Edition, (2004) 2.15–2.73.

[11] W. S. Kim, M. S. Kim, D. bee Kim, Y. G. Kim and P. G. Park, A Precision DC Low-Current Source for Calibration of Electrometers in the Range Of 100 pA To 1 fA, http://www.imeko.org/publications/wc-2012/IMEKO-WC-2012-TC4-P20.pdf.