DOI 10.5162/SMSI2020/E1.2

SI Realization of the farad at LNE

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Summary:

This paper describes practical realizations of the farad in the revised SI at LNE. The latest developments on the new Thompson-Lampard calculable capacitor with target accuracy of one part in 10^8 for 1 pF are presented.

Keywords: impedance metrology, traceability, capacitance standard, Thompson-Lampard capacitor, precise mechanical positioning

I. Introduction

Within the revised SI and according to the Appendix 2 of the 9th SI Brochure (2019) [1], two practical realizations of the farad are indicated. The first method consists of using a calculable capacitor and the value of the electric constant ε_0 = 8.854 187 8128(13) pF/m [2]. On the other hand, the second method allows one to realize the farad by comparing the impedance of a known resistance, obtained using the quantum Hall effect (QHE) and the value of the von Klitzing constant R_K = 25 812.807 459 3045 Ω, to the impedance of an unknown capacitance using, for example, a quadrature bridge. Fig. 1 illustrates the implemented chain of the two ways of realization of the farad at LNE [3] and their relation.

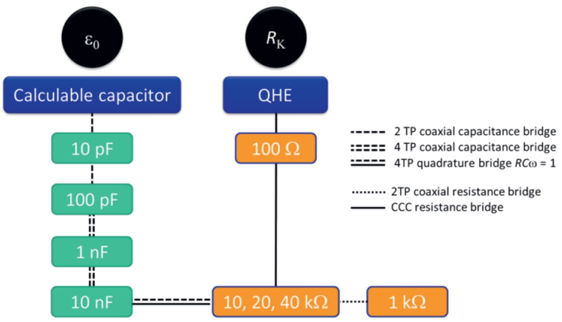

Fig. 1. Measurement chain linking ε_0 and R_K.

In practice, the two methods lead to measure 10 pF and 100 pF secondary capacitance standards. They are measured in terms of ε_0 using a 2-terminal-pair (TP) coaxial capacitance bridge or in terms of R_K by means of several other bridges and standards. This implies at first cryogenic current comparator (CCC) to measure in dc 100 Ω then 10 kΩ, 20 kΩ and 40 kΩ. The impedance of the resistors is then compared to that of 10 nF capacitors at 400 Hz, 800 Hz and 1600 Hz by mean of a 4 TP quadrature bridge. The frequency dependences of the resistors are measured with a 1 kΩ calculable resistance standard. The 10 nF capacitances are finally used to measure 1 nF then 100 pF and 10 pF.

This measurement chain has allowed LNE to determine R_K with a standard uncertainty of 5.3 parts in 10^8 [3]. The previous developed calculable capacitor revealed the two prevailing uncertainty components among those due to the mechanical imperfections of the capacitor. The first one is related to the cylindricity defects of the cavity due to the deviation of the electrodes' shape from perfect cylinders and to their mispositioning with respect to each other (2.5 parts in 10^8). The second one is related to the coaxiality defect between the capacitor axis and the trajectory of the moving guard (3 parts in 10^8). The target uncertainty of one part in 10^8 requires LNE to develop a new standard calculable capacitor keeping the electrodes' cylindricity and positioning defects below 100 nm and that of the movable guard trajectory to 100 nm or less. Hereafter, are presented the results of some recent tests carried out on the alignment of the electrodes of a new calculable capacitor.

II. The LNE calculable capacitor

The new LNE calculable capacitor is a Thompson-Lampard calculable capacitor constituted of five cylindrical electrodes (bars) in vertical position arranged at the vertices of a regular pentagon. It generates a calculable capacitance variation, proportional to the length of the displacement of a movable guard in its cross section, allowing linking the farad to the meter as it is shown in Fig. 2.

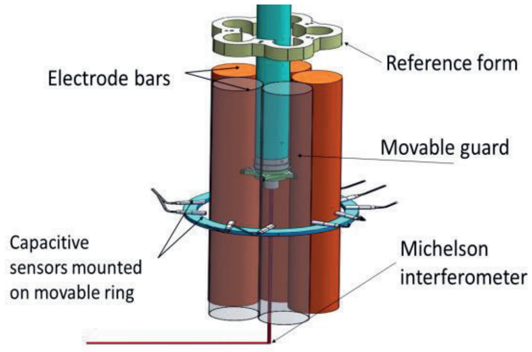

Fig. 2. LNE vertical five electrode-bar capacitor.

Cylindricity of new electrodes

Bars are made from non-magnetic stainless steel and are machined and grinded to obtain an initial cylindricity defect of about 1.5 µm. The surface roughness is then reduced to 100 nm by lapping and polishing electrodes manually. The measurement of the straightness and parallelism of the electrodes are carried out with an on-purpose built measuring machine [4].

Aligning electrodes in parallel

The alignment procedure is carried out in two steps. In the first step, the top and bottom of the electrodes are positioned at the vertices of a regular pentagon with an accuracy of 5 µm by aligning them with respect to the reference form (Fig. 2). The capacitive sensors mounted on a movable ring enable to measure the relative position of each electrode with a resolution of 20 nm to the corresponding vertices of the reference form. However, the absolute positions of the capacitive sensors are not known sufficiently in horizontal plane (few µm of displacement depending on movable rings' vertical position). Therefore, alignment of electrodes in parallel is not guaranteed at this stage. In the next step, one of the bars is chosen as a reference and the four other bars are aligned with regard to it by measuring their relative tilt. In such a scenario, the relative position of sensors to the reference electrode and thus to the others is perfectly known at any moment due to the construction provided that capacitive measurements are taken simultaneously. The relative tilt of each electrode is estimated from a scan of capacitive measurements along the length of the electrodes at orthogonal horizontal axis. Firstly, the error introduced from sensors' positions is corrected and then linear regression is applied to the moving mean of the corrected data. In Fig. 3 an example of alignment for one electrode axis is shown. The achieved alignment has uncertainty of 50 nm (k=1) on average for four electrodes in accordance with initially defined target uncertainty.

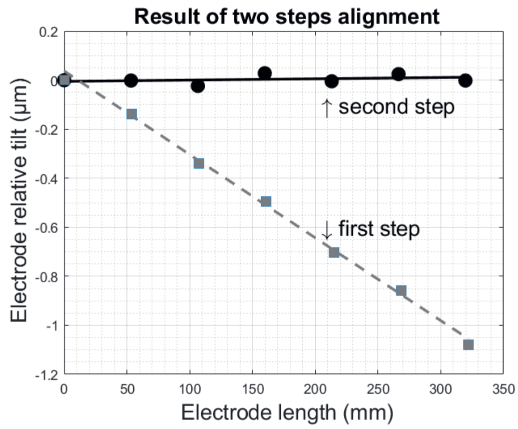

Fig. 3. Aligning an electrode in two steps.

III. Conclusion

The present status of the development of the new LNE calculable capacitor is briefly presented. The fabrication of the new set of electrodes and their sub-micrometric alignment system is finalized. Currently, tests related to the guard positioning is under progress. More details and results of these improvements will be given during the conference. In parallel to calculable capacitor development, improvements are made on the measuring chain linking the farad to the QHE to achieve an overall uncertainty lower than 1 part in 10^8. In the context of European project JRP GIQS (*Graphene Impedance Quantum Standard*, 2019-2022), the implementation of AC quantum Hall effect in Graphene to realize the farad is in preparation at LNE for the future.

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