

# Portable Capacitance Standards

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## 1. Abstract

This paper describes capacitance standards made from NPO ceramic dielectric in the range from 100 pF to 1  $\mu$ F. The standards are encased in a two stage oven to achieve high temperature stability resulting in a low overall temperature coefficient which is less than 0.05 ppm/K (with typical stability of 0.01 ppm/h). The NPO ceramic is batch selected and trimmed to give close tolerance (better than 100 ppm) to the nominal value of the standard. The standards are designed to have good transport behaviour and have found many uses in AC bridge work. The design and manufacture of the capacitors will be discussed and results presented on their temperature coefficient, long-term drift, frequency dependence of capacitance and dissipation factor.

## 2. Introduction

The work to relate capacitance to the ac quantised Hall effect at NPL required a stable and transportable capacitance standard at 10 nF. It had been found that air capacitors at this value were not stable when moved from one laboratory to another so capacitors based on an NPO dielectric were developed[1]. This design has been enhanced so that selected values between 100 pF and 1  $\mu$ F can easily be constructed. A low temperature coefficient of capacitance is achieved by employing a simple temperature control circuit.

## 3. Multi-layer Ceramic Capacitors (MCC)

The NPO ceramic capacitors used in the production of the standards are of the surface mounting type and are available from a number of manufactures such as Phillips Components and Siemens with values in the range 10 pF to 10 nF of 5% tolerance with typical dimensions of 5.5mm x 5mm x 0.5 mm (2220 format). The small physical dimensions minimise the residual self-inductance and reduces the transitory changes of capacitance due to changing temperature gradients. The NPO ceramic capacitors usually show a temperature coefficient of  $0 \pm 30$  ppm/K. The type known as 'COG' made by some manufactures are similar to the NPO type. The 'G' represents the code for  $0 \pm 30$  ppm/K. The components of the NPO dielectric are  $\text{BaTiO}_2$  and  $\text{TiO}_2$  and are classified as Class 1 dielectric by the Electronic Industries Association (EIA), having the characteristics of low dielectric loss ( $\tan \delta < 0.002$ ), low permittivity ( $\epsilon < 100$ ) and low temperature coefficient. The MCC is composed of non-fired interlaced layers of ceramic and thin film metal electrode material. These are pressed and sintered to obtain a compact multi-layer structure.[2]

Thermal shock during soldering should be avoided by keeping the temperature differential between the component and the soldering temperature below 100 °C. Also, the chip capacitors should be handled with care to avoid contamination from perspiration and skin oils. Solder fluxes should be removed after soldering.

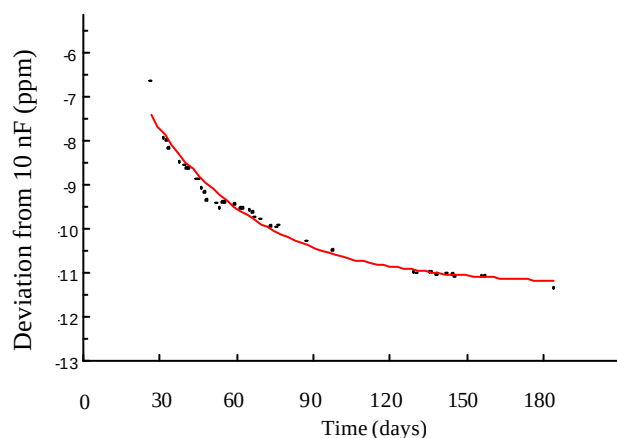


Figure 1 Ageing curve for a typical 10 nF Standard

Ceramic capacitors have a crystalline structure which re-orientates progressively after heating above the "Curie" point. The effect is that the dielectric constant and hence capacitance is at a maximum immediately after heating and there is then a predictable logarithmic decay of capacitance value, or ageing. Allowance must be

made for these variations when measurements are made soon after heating. For maximum accuracy, measurements should not be made within the first 10 hours. Note that the ageing is totally reversible by reheating at any time. Figure 1 shows a typical ageing curve of a standard.

#### 4. Construction of the Portable Capacitance Standard

The NPO ceramic capacitor chips are selected for capacitance tolerance from one large batch of 1000 capacitors from a single supplier. An initial temperature coefficient (TC) measurement is carried out using a hot air gun adjustable over the range 10 – 50 °C and a model 2500 Andeen-Hagerling Bridge.

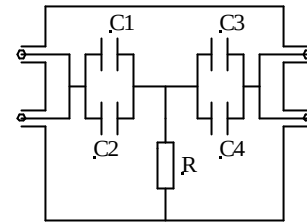


Figure 2 Capacitance cell.

The standard capacitance cell is made from four chip capacitors placed in a series/parallel configuration as shown in figure 2. The values are chosen to give a capacitance standard that is very close to nominal at an operating temperature of between 28 and 32 °C. The measurements of the capacitance values at a laboratory temperature of around 20 ± 1 °C and the initial temperature coefficient measurements are used to make the selection. A computer algorithm has been written to ease this task. The chip capacitors, despite being surface mount devices, are not mounted directly onto PCB material of the type FR4 as this has a temperature coefficient of expansion of around 10 ppm/K. They are instead attached to the ends of the coaxial inners with the high value resistor acting as an additional mechanical support. The resistor (approximately 10 MΩ) is used to trim the dissipation of the capacitor. The cell is enclosed in a copper jacket which forms a conducting screen and maintains the coaxial four terminal pair (4TP) definition [3]. (See figure 3).

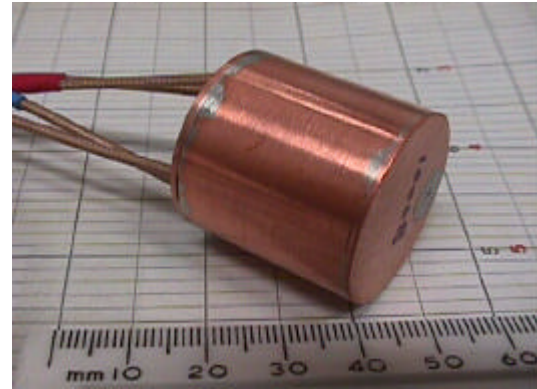


Figure 3 Conducting screen as the inner oven

A thermistor, a 100 Ω platinum resistance thermometer (PRT) and a heater are attached to the jacket and held in place by copper foil with an adhesive backing. The four coaxial cables (each 50 cm long) are wrapped around the cylinder once to provide a thermal anchor.

The inner cell is mounted in a second oven made of copper. The space between the inner cell and the second oven is filled with glass mineral wool. A further heater and thermistor are attached to this oven in a similar manner to that of the inner cell. The heater and thermistor connections from the two ovens are then connected to their temperature controller circuits shown in Figure 4. These controllers are on a single PCB that is mounted on the inner surface of the lid of a die-cast aluminium enclosure. The inner oven temperature is set with a single precision resistor in a bridge circuit to between 28-32 °C. The outer oven temperature is set just below that of the inner by typically 0.5 °C. The PRT connections are brought out onto two BNC connectors to provide a four terminal measurement. Standard PRTs which conform to BS 1940:1984 or DIN 4376:1980 class B are used which have a resistance change over 0 to 100 °C of 38.5 ohms which is referred to as the fundamental interval. Its characteristics can be expressed as a quadratic of the form:

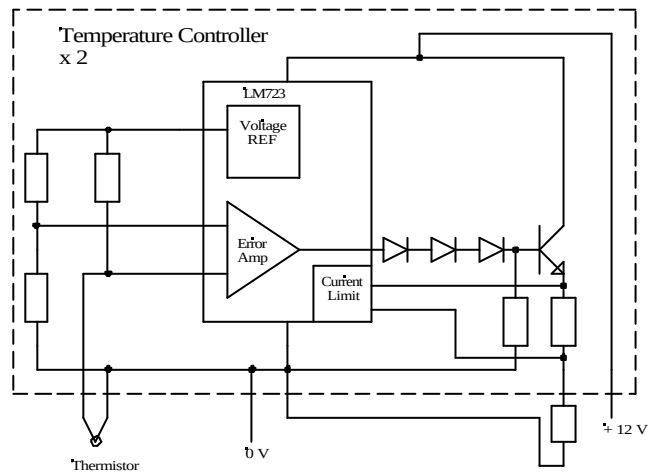


Figure 4 Circuit diagram of the temperature controller.

The PRT connections are brought out onto two BNC connectors to provide a four terminal measurement. Standard PRTs which conform to BS 1940:1984 or DIN 4376:1980 class B are used which have a resistance change over 0 to 100 °C of 38.5 ohms which is referred to as the fundamental interval. Its characteristics can be expressed as a quadratic of the form:

$$R_T = R_0[1 + aT + bT^2] \quad (1)$$

Where  $R_0 = 100 \Omega$  or  $25 \Omega$  depending on the PRT used,  $a = 0.003850 \text{ K}^{-1}$  and  $b = -5.775 \times 10^{-7} \text{ K}^{-2}$ .

This equation can be inverted to give an expression for the temperature in the terms of the of the resistance:

$$T = \frac{-a + \sqrt{a^2 - 4b \left(1 - \frac{R_t}{R_0}\right)}}{2b} \quad (2)$$

The two staged oven is mounted in a die-cast aluminium box with polystyrene insulation. The lid houses the temperature controller PCB, the four BPO connectors for the standard, two BNC connectors for the PRT measurement and two 4 mm sockets for the power supply connections typically  $12 \pm 0.5$  V DC.

## 5. Testing

The capacitors are soak tested for a period approximately 28 days. During this time the initial aging curve is observed and the start of the slow but predictable drift rates. Typical drift rates of 0.05 ppm/day have been observed. Our first batch of capacitance standards made over three years ago are now showing a rate of 0.001 ppm/day. Routine measurements of capacitance are carried out using the two terminal pair Andeen-Hagerling bridge. For more accurate measurement the four terminal pair bridge must be used. [4]

### 5.1 Temperature testing

The capacitance standards are tested in an environmental test chamber. The capacitance is measured between 15 and 25 °C with the ovens in the capacitor off and with the ovens on. The PRT measurements are made with an ASL Precision Thermometry bridge of the type F700. Figure 5 shows a typical temperature coefficient of 0.02 ppm/°C for this particular batch.

### 5.2 Frequency and dissipation

The frequency dependence of these standards has been found to be of the order of 90 ppm/decade change in frequency. For frequency dependence of the NPO dielectric capacitance to frequencies up to 1 MHz see [5]. In AC coaxial bridge systems, the frequency of energisation, typically 1kHz is very stable so the frequency dependence is not a limiting factor. However, it must be accounted for when making comparison measurements at different frequencies.

### 5.3 Voltage coefficient

The capacitance of the standard changes by less than 0.05 ppm for a factor of 10 change in the applied voltage[1].

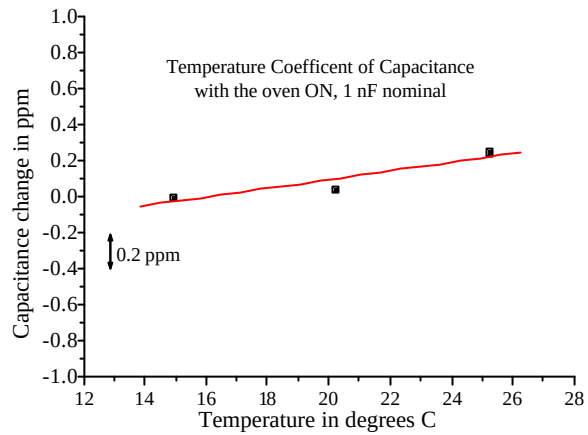


Figure 5 Temperature Coefficient of capacitance

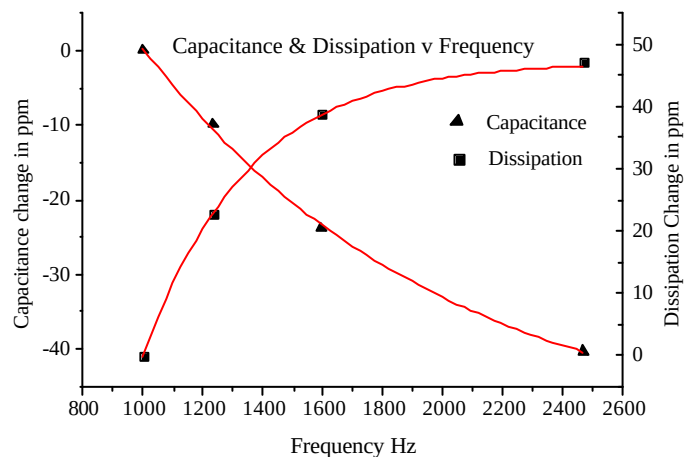


Figure 6 Capacitance & Dissipation dependence

## 5.4 Stability

The stability of the capacitance standard has been observed using a four terminal pair bridge and found to be better than 0.01 ppm/hour.

## 5.5 EMC

Normally passive components need not be subject to the relevant European Directive relating to emissions and immunity. However with the addition of an active temperature controller circuit employed in the standards, EMC tests were carried out in our GTEM<sup>®</sup> cell operated by the RF and Microwave Group at NPL. No levels were breached.

Figure 7 shows a complete 10 nF capacitance standard made using NPO dielectric and measures 125 mm depth, 123 mm width and 93 mm height. Selected values in the range 100 pF to 1  $\mu$ F are usually constructed to within 100 ppm of nominal value.

## 6. Conclusion

Capacitance standards made from the NPO dielectric have been found to be useful in AC Coaxial Bridge systems. The size, weight and capacitance stability to transportation of the standards are better suited than the gas dielectric standards. NPO dielectric capacitance standards were made typically to within than 100 ppm of nominal for selected capacitor value in the range 100 pF to 1  $\mu$ F and have regularly achieved 0.01 ppm/hour stability. These capacitors have predictable long term drift rate of the order of 0.005 ppm/day.

## 7. Acknowledgements

Advice and assistance from J.H. Belliss. B.P. Kibble for his advice and assistance in the production of the first batch of capacitors. S. Bryant for the four terminal pair measurements, formal calibrations of the standards and for writing a Pascal programme for capacitor selection. I.A. Robinson for his simple temperature control circuit. B. Loader for carrying out the EMC test to the latest European Directive. This work was supported by the Electrical Programme of the National Measurement System Policy Unit, Department of Trade and Industry, U.K.

## 8. References

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Figure 7 A complete 10 nF Standard Capacitor.

