application note
Philips Passive Components

Ceramic multilayer capacitors for high-frequency communication equipment

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Summary

Philips Components has developed a range of narrow-tolerance NP0 ceramic multilayer capacitors for precise impedance matching, blocking and filtering in HF communications equipment. The series also offers series resonant frequencies up to 8 GHz in both 0603 and 0402 case sizes. Philips has also made detailed ESR measurements on this new series and is currently the only CMC supplier providing this information to equipment manufacturers to assist them in the design phase of their equipment.

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Ceramic multilayer capacitors for high-frequency communication equipment

At very-high (e.g. gigahertz) frequencies, the value of capacitors used in, for example, transceiver front-ends becomes ever more critical and production spreads can, if too great, lead to significant deviations in transceiver characteristics. For these circuits, therefore, narrow tolerance on capacitance is as crucial as good high-frequency characteristics, low dissipation factor and low drift. Formerly, however, narrow-tolerance (±0.1 pF) CMCs were several times as expensive as their ±0.25 pF counterparts, so to avoid using these more expensive components, system manufacturers often resorted to trimming their circuits to get consistent performance characteristics.

Recent advances by Philips in, for example, screen printing and electrode manufacture have led to the development of a new narrow-tolerance CMC series offering excellent price/performance ratio.

The new series offers tolerances of just ±0.1 pF for capacitances below 2.7 pF. Tolerances of ±0.05 pF are also available on special request. The capacitors moreover offer the important benefits of high reliability and high stability with regard to voltage and temperature variations.

Supplied in sizes 0402 and 0603 in tape on reel or Bulk Case, the capacitors are available with NiSn or AgPd terminations suitable for reflow or wave soldering. Rated voltage is 50 V.

HF behaviour of CMCs

Modern high-frequency transceiver front-ends such as that shown in Fig.1 contain a large number of CMCs in blocking, filtering and matching functions. The high frequencies at which these circuits operate, i.e. up to several gigahertz, mean that the DC capacitance of these components must be relatively low (often less than a picofarad) in order to limit their reactance at the operating frequency of the circuit.

Standard ‘low-value’ capacitors, however, are usually available with tolerances of ±0.25 pF which can be around 10% and in some instances even 50% of the value of the capacitance. As the following section explains, such wide tolerances can seriously affect overall circuit characteristics.

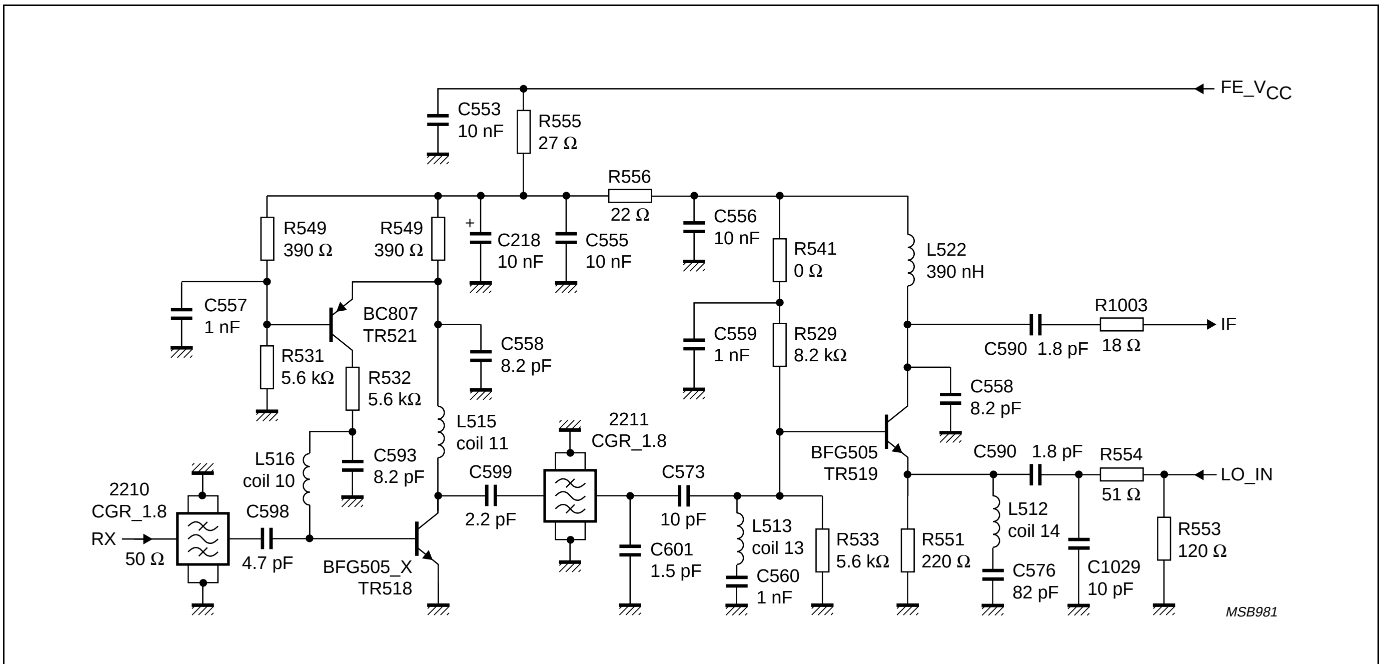


Fig.1 A modern HF front-end circuit contains many CMCs in blocking, filtering and impedance matching functions

Effect of parasitic elements

Though closely approximating the 'ideal' capacitor, CMCs contain parasitic capacitive, resistive and inductive elements that become important at higher frequencies (see Fig.2). The impedance of an ideal capacitor decreases monotonically with frequency, i.e. as frequency increases, impedance steadily falls as shown by the broken line of Fig.3. At gigahertz frequencies, however, the reactance of the parasitic elements becomes significant, causing the capacitor to behave as a resonant circuit with series and parallel resonant frequencies indicated by the unbroken line of Fig.3. In this figure, SRF and PRF are only the first series and parallel resonances, others may occur at higher frequencies.

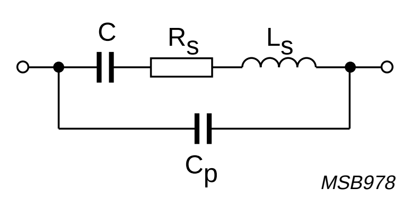


Fig.2 Equivalent circuit of a CMC at high frequencies: C = primary capacitance, L_S = parasitic series inductance, R_S = equivalent series resistance (ESR), C_P = parasitic parallel capacitance

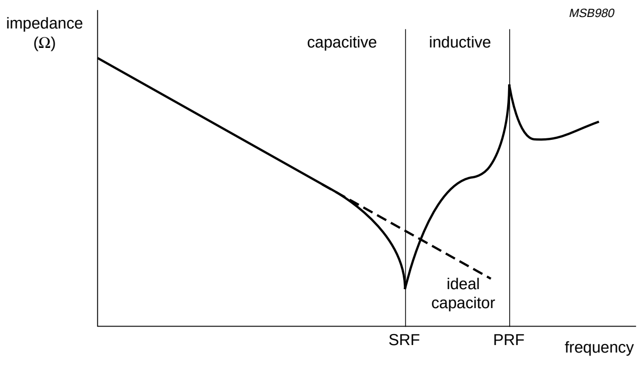


Fig.3 At gigahertz frequencies, parasitic components cause the 'ideal' capacitor to exhibit series and parallel resonances

Series resonance occurs when the reactance of the parasitic series inductance (L_S in Fig.2) equals that of the capacitor. At frequencies below series resonance, the impedance is mainly capacitive, above series resonance it's mainly inductive. Since it is the capacitive properties that are required in the blocking, filtering and matching functions referred to earlier, it is obvious that for these functions the capacitor should be operated below its series resonant frequency. In the blocking function, for example, where the capacitor is connected in series with the line to block DC and transmit HF signals, the inductive nature of the capacitor above its series resonant frequency causes it to exhibit gradually higher insertion loss and hence high-frequency roll-off of its transmission response.

Capacitor tolerance

Series resonant frequency is therefore a crucial factor influencing the selection of CMCs for high-frequency circuits like that shown in Fig.1. But since this frequency depends strongly on the primary capacitance (the capacitance measured at 1 MHz), it's clear that tolerance on capacitance critically affects circuit behaviour.

As stated earlier, the capacitance of a standard CMC with a tolerance of ±0.25 pF, may deviate by up to 50% from its specified value. This leads to a significant deviation in the series resonant frequency from its predicted value and may, in worst-case condition, result in the resonant frequency approaching the operating frequency of the circuit. So since it is never possible to predict individual component deviations, circuit manufacturers have in the past been compelled to individually trim each circuit to ensure predictable behaviour. The alternative, to use narrow-tolerance microwave capacitors, was unattractive owing to the relatively high cost of these components.

Recent developments by Philips Components, however, have led to a new range of 0402 and 0603 narrow-tolerance CMCs suitable for HF blocking, filtering and matching applications at a price comparable with that of standard ranges currently available. The standard tolerance of the new series: ±0.1 pF for capacitances below 2.7 pF is, in fact, comparable with that of Philips' microwave CMC series.

New narrow-tolerance CMCs

In developing the new range, attention was focused on optimizing electrode design (using finite-element-analysis techniques) to allow for tighter control of capacitance during manufacture. The analysis was directed at electrode geometry and dielectric material and resulted in a design featuring fewer electrode layers and greater overlap than the earlier design. Recent advances in screen printing and dielectric ceramics also assisted the development of this new electrode structure.

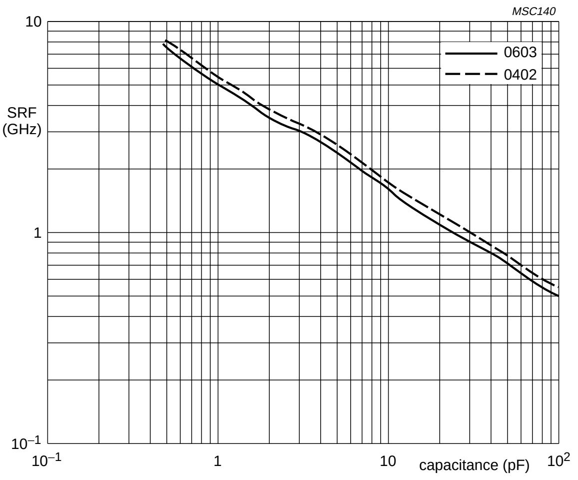


Fig.4 Relation between series-resonant frequency (SRF) and capacitance for Philips' new narrow-tolerance CMC series

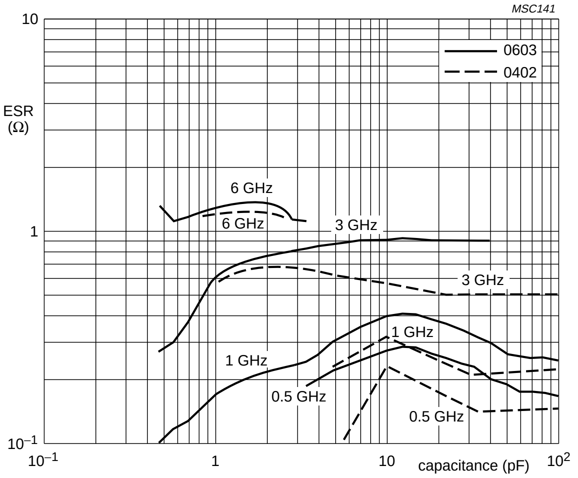


Fig.5 Relation between ESR and capacitance for Philips' new narrow-tolerance CMC series

Figure 4 shows the relation between series resonant frequency and capacitance for Philips' new narrow-tolerance series. As the figure shows, the 0603 series exhibits series resonant frequencies up to around 8 GHz and the 0402 series exhibits even higher resonant frequencies − approaching 9 GHz. But the major benefit of the new design is that it gives a more clearly defined SRF/capacitance characteristic which means that circuit manufacturers can rely on the reproducibility of this characteristic when optimizing their designs for volume production.

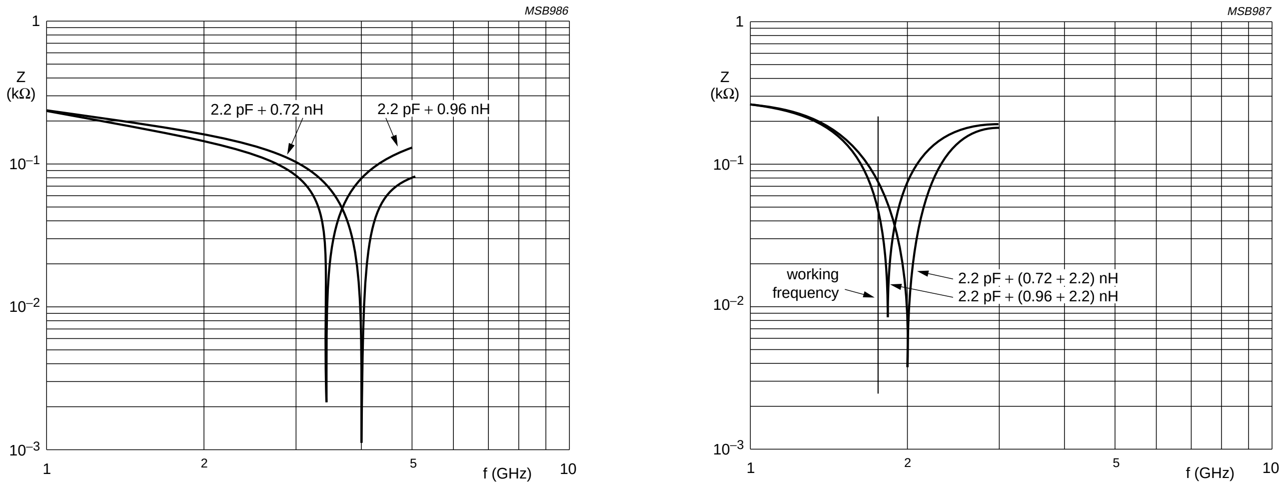
Figure 5 shows the measured relation between ESR and capacitance for the new series. Details of these measurements are given in the Appendix. An interesting fact emerging from these measurements is that the ESR of the 0402 series is lower than that of the 0603 series for a given series resonant frequency. ESR values for both new series are, however, generally higher than for Philips' microwave CMC series. This is not normally a serious disadvantage but for circuits in which low ESR is critical (where reduction of phase noise is important for example), circuit designers might consider using products from the microwave CMC series. The table on page 8 gives an overview of the high-frequency CMC series currently available from Philips Components.

Effect of parasitic inductance

The high-frequency performance of capacitors is strongly related to geometry and material properties. At gigahertz frequencies, the inductive effect of each lead and every current path inside the capacitor becomes important and the effects of differing electrode structures cannot be ignored. This means that capacitors from different suppliers with identical capacitance, dissipation and voltage rating may perform quite differently in a high-frequency transceiver circuit such as that shown in Fig.1.

This is illustrated in Fig.6(a) which compares the series resonant frequencies of two apparently equivalent 0603 CMCs with a capacitance of 2.2 pF and an ESR of 0.3 Ω. As the figure shows, the difference in parasitic series inductance (0.72 nH in one case, 0.96 nH in the other) leads to a shift of more than 0.5 GHz in series resonant frequency. This effect is somewhat exaggerated since it ignores the inductive contribution of the PC board tracks (around 1 nH per mm of track). To emulate this, Fig.6(b) shows the effect on the resonant frequencies of the same two CMCs in series with a 2.2 nH inductance. Though the difference is now clearly reduced, the figure nevertheless illustrates the critical effect a capacitor's parasitic series inductance can have on the performance of a high-frequency circuit.

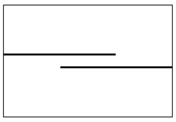
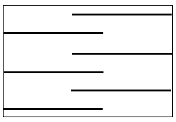
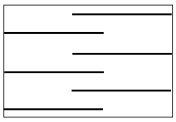
Parasitic inductance is at present not specified in the data sheets of any CMC manufacturer. Philips Components, however, is currently investigating the effects of parasitic inductance on high-frequency performance. These investigations are still at an early stage but the aim eventually will be to include parasitic series inductance in the specifications of our narrow-tolerance CMC series.



(a) *(b)*

Fig.6 (a) Series resonant frequency of two 0603 CMCs from different suppliers: capacitance 2.2 pF, ESR 0.3 Ω; (b) as (a) but with capacitors in series with a 2.2 nH inductance

Philips Components' high-frequency CMC range

Narrow-tolerance range	**Microwave range**	
±0.1 pF tolerance	5% tolerance	1% tolerance
		
■ high-frequency ■ low cost	■ high-frequency ■ low ESR ■ medium Q	■ high frequency ■ low ESR ■ high Q
Applications		
communications	power supply circuits	oscillators

Appendix

Series resonant frequency measurements

The series resonant frequency measurements of Fig.4 were made on a Hewlett Packard network analyzer with the CMCs soldered onto a 50 Ω SMA-type connector, Fig.A1. An HP 8753B network analyser was used for capacitances above 4.7 pF and an HP 8510 for lower values. The setup was calibrated using the HP calibration kit provided with the network analyser. Calibration points were obtained with the connector initially open-circuited and subsequently short-circuited (by means of a stub connected between the centre contact and the outer conductor of the SMA connector). Using the ‘stretch’ function on the network analyser, the effect of the SMA connector was de-embedded so that the mounting plane of the connector became the reference plane for measurement.

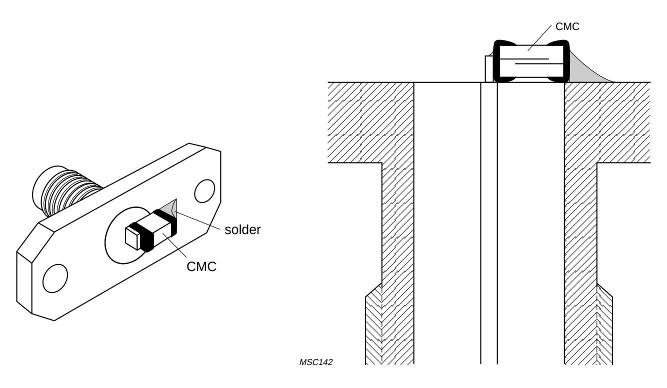


Fig.A1 CMC mounted on SMA connector

The ESR measurement setup

The main problem with the measurement of ESR of a capacitor is that the resistive component of the total complex impedance is relatively small compared with the reactance. The lower the capacitance (i.e. the higher the reactance), the greater this problem becomes. To avoid significant errors therefore, the large reactive part of the impedance of the capacitor must be tuned to zero at some resonant frequency. At this frequency, the resulting low impedance comprises only the real part, which is the ESR.

The measurement of such low impedances in an SMA-connector setup (which is a one-port reflection measurement) has, however, been found to lead to significant errors. Instead, experience indicates that a two-port parallel setup such as that shown in Fig.A2 gives more reliable results. Moreover, from a detailed accuracy analysis, it has been found that the network analyser measures low impedances in a parallel setup most accurately by means of the transfer response S_{21}.

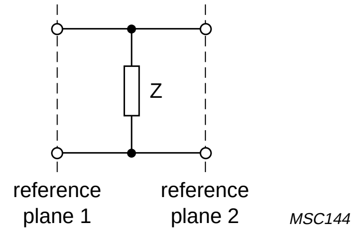


Fig.A2 Parallel measurement setup

For the configuration shown in Fig.A2, the impedance Z follows from the S_{21} measurement with the network analyser by

$$Z = \frac{Z_0 S_{21}}{2(1 - S_{21})}$$

A measurement setup therefore had to be implemented that:

- closely resembled the setup of Fig A2
- allowed the reactive part to be tuned to zero
- exhibited low losses with respect to the expected ESR of the CMC

The setup used for the ESR measurements was implemented in microstrip line on Duroid with characteristic impedance $Z_0 = 50\ \Omega$. This is shown schematically Fig.A3.

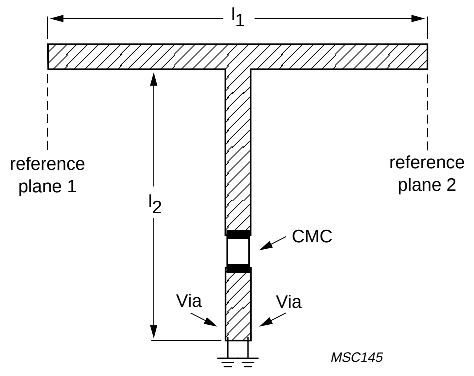


Fig.A3 Parallel measurement setup implemented in microstrip line

It was assumed that losses in the microstrip line and vias were small compared with those in the CMC. The shunt branch of the transmission line from reference plane 1 to reference plane 2 was modelled in terms of Kirchoff network elements for frequencies up to the first resonant frequency f_{res} of the shunt branch (see Fig.A4).

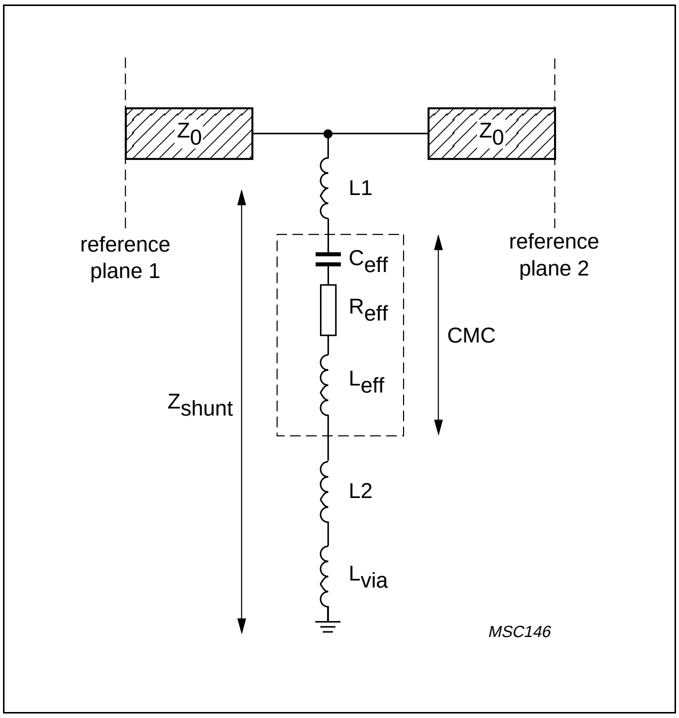


Fig.A4 Analysis of parallel measurement setup in terms of Kirchoff network elements

In Fig.A4, the lines of the shunt branch and the vias are modelled as inductors at resonant frequency. At the first resonant frequency f_{res} the transfer parameter $|S_{21}|$ is at a minimum. The impedance then becomes:

$$Z_{shunt} = R_{eff}$$

and it can be shown that at resonant frequency f_{res}, R_{eff} is related to S_{21} by

$$R_{eff} = \frac{Z_0|S_{21}|}{2(1 - |S_{21}|)}$$

Furthermore:

$$R_{eff} \geq ESR$$

and the equality sign holds when the losses of the measurement setup become negligible.

Remarks:

- R_{eff} can be measured at different frequencies if different lengths are chosen for the microstrip line in the shunt branch
- The length of the microstrip-line from reference plane 1 to reference plane 2 is not important (except for the losses in the line) because R_{eff} is related to the absolute value of S_{21}.