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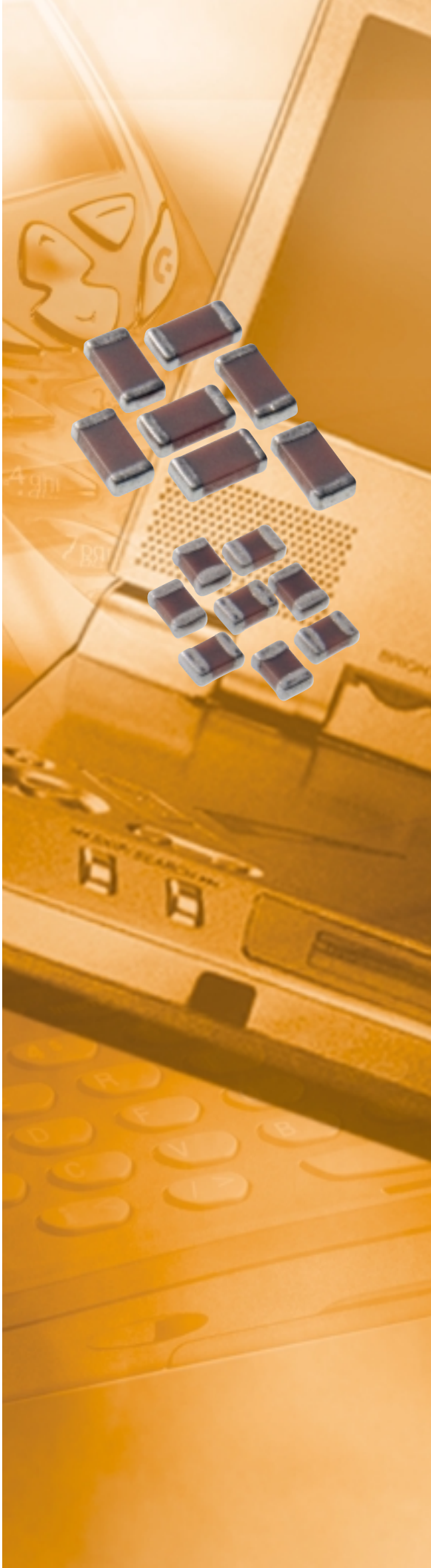
MLCC replacements for tantalum capacitors



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MLCC replacements for tantalum capacitors

SUMMARY

For certain capacitance values, many circuit designers who traditionally use tantalum capacitors might well find that their application is now better served by MLCCs. Moreover, the ever higher production levels of MLCCs coupled with new developments such as the introduction of base-metal electrodes have greatly reduced the unit production cost of MLCCs. This means on price too, they can now compete with tantalum capacitors in many applications.

The past 5 to 10 years have seen increases of between 10 and 100 fold in capacitance per unit volume for both ceramic multilayer capacitors and solid tantalum capacitors (Refs 1 and 2). Figure 1 shows this increase for ceramic capacitors. As a result, the application areas for MLCCs have gradually extended into those formerly dominated by tantalum capacitors and these, in turn, have extended into even higher capacitance application areas formerly occupied by, for example, electrolytics.

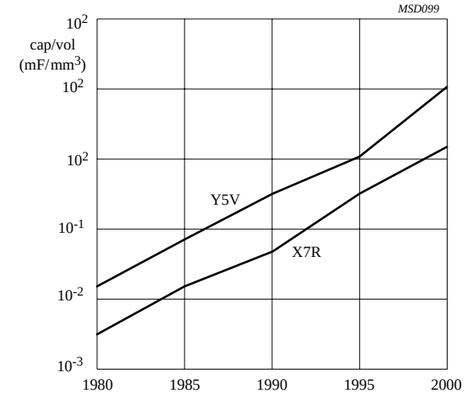

Fig. 1 MLCC capacitance per unit volume increase

In the area of overlap between 0.1 µF and 100 µF, therefore, the two technologies compete and many circuit designers who traditionally use tantalum capacitors might well find that their application is now better served by MLCCs. The ever higher production levels of MLCCs (currently 600 billion annually compared with 25 billion for tantalum capacitors) coupled with new developments such as the introduction of base-metal electrodes have also greatly reduced the unit production cost of MLCCs, which means on price too, they can now compete with tantalum capacitors in many applications.

Figure 2 gives a schematic view of the price decrease between 1985 and 1995 for 1 µF capacitors in ceramic multilayer and tantalum technology. In 1990, Y5V MLCC prices reached the tantalum level and since 1995 X7R types too have reached the price levels of 1 µF tantalum capacitors.

In this graph the cheapest solutions in both technologies are compared based on equal nominal capacitance. In this publication, however, it will be shown that instead of comparing costs of equal nominal capacitance it is better to compare costs of capacitance/size combinations which give equal electrical performance.

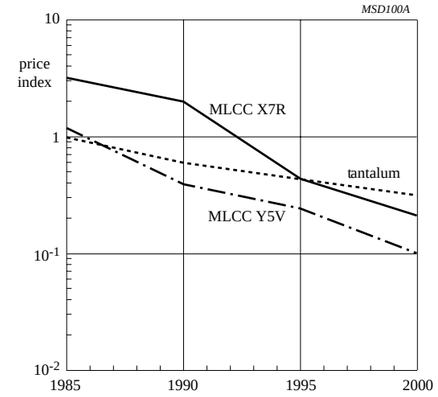

Fig. 2 Cost reduction for 1 µF capacitors.

Since in each application area the requirements of electrical performance differ, it's necessary to make a comparison per functional application area. In this publication, therefore, we shall compare two typical application areas in which MLCCs and tantalum capacitors compete: *decoupling* and *smoothing*.

First, however, let's look at the general differences in specification and performance of tantalum capacitors and MLCCs.

General comparison of specifications

A general problem in comparing capacitors made by different technologies is that in nearly all relevant specification points there are small or larger differences (see Table 1).

Table 1 Comparison of specifications: MLCCs versus tantalum capacitors

	MLCC	**tantalum capacitor**
capacitance measurement conditions	1 kHz, 1 V AC	120 Hz 0.5 V AC
size: 0603 0805	1.6 x 0.8 mm 2.0 x 1.25 mm	1.6 x 0.85 mm 2.0 x 1.35 mm
life-test conditions	max. temperature 2 x U rated	max. temperature U rated

These differences originate from the early days of capacitor development in which specifications were set more by the performance inherent to the specific manufacturing technology than by common customer needs. Ceramic capacitor manufacturers, therefore, set up their specifications to provide comparisons with other capacitors of similar technology, as did

manufacturers of tantalum capacitors, electrolytics and capacitors in other technologies.

Bearing this in mind we start comparing basic performance characteristics of MLCCs and tantalum capacitors by looking at major categories such as capacitance/volume per case size, rated voltages and temperature characteristics.

Capacitance per unit volume
Based on nominal specifications, tantalum capacitors offer the highest maximum capacitance at rated voltage of 2 to 4 V. For higher rated voltages, however, i.e. between 6 and 10 V, there is little difference in maximum capacitance between 0603, 0805 and 1206 Y5V MLCCs and tantalum capacitors.

In contrast, X7R MLCCs offering the same maximum capacitance are at least one and sometimes two case sizes larger than their counterparts in Y5V or tantalum.

Rated voltage
For tantalum capacitors, the rated voltage is close to the breakdown voltage and is clearly to be interpreted as more or less the maximum voltage at which the capacitors can operate. In the interests of reliability, therefore, designers commonly derate tantalum capacitors to operate at voltages between 20% and 50% below their rated voltage.

In contrast to tantalums, the rated voltage of MLCCs is far less than their breakdown voltage and is usually determined by the performance in dry endurance tests. A point worth noting here is that in order to comply with EIA and EIAJ standards, MLCCs are required to undergo long-term reliability testing *at twice their rated voltage*.

The obvious conclusion of this is that in circuits where either type may be used, to get the same circuit reliability it would be necessary to choose a tantalum with roughly twice the rated voltage of the equivalent MLCC.

Temperature characteristics
In the temperature range 0 to 85 °C, tantalum capacitors offer a relatively flat temperature characteristic.

MLCCs, on the other hand, come in different temperature classes defined by their dielectric, such as Y5V, Z5U, Y5U, X7R, and X5R. As a general rule one can say that for MLCCs, temperature characteristic can always be improved at the expense of capacitance per unit volume.

In general, X5R and X7R specifications are comparable to those of tantalum in the temperature range 0 to 85 °C. This does not mean, however, that in comparing tantalum capacitors with MLCCs, one should consider only X5R or X7R products. As we'll show later, Y5V MLCCs despite their strong temperature dependence can offer attractive alternatives to tantalum capacitors in certain areas.

Other general specification items
There are many other differences between the general specifications of MLCCs and tantalum capacitors. Table 2 gives a survey of these differences many of which may, in particular cases, be decisive in deciding on which technology to choose.

Table 2 General comparison of MLCCs and tantalum capacitors

characteristic	Y5V MLCC	X7R MLCC	solid Ta
capacitance range	++	+	++
bipolarity	++	++	-
resistance to pulse voltage	++	++	+
lifetime at T > 85 °C	+/-	+	-
high-frequency performance	+	++	-
breakdown voltage	++	++	-
voltage dependency (DC)	-	+/-	+
product height	++	++	+
SMD compatibility	++	++	+
reliability	++	++	+

In many instances, the criteria in Table 2 may make the choice between MLCC and tantalum clear. In other instances, however, to make a proper choice we need to look further at the influence of frequency, temperature and bias voltage on the more fundamental properties of *impedance, ESR and ESL*.

Comparison of impedance
Figure 3 gives a comparison of room-temperature impedance as a function of frequency for 1 µF capacitors in tantalum and Y5V MLCC technologies.

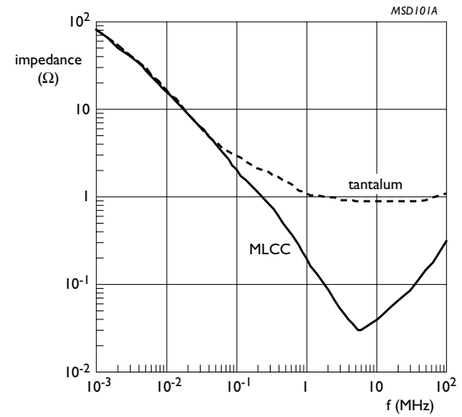

Fig. 3 Impedance as a funcion of frequency for a 1 µF tantalum capacitor (16 V) and a 1 µF Y5V MLCC

Since decoupling performance, in particular, is often determined by the capacitor's impedance, the lower impedance of the MLCC for frequencies above 100 kHz in this case makes it the preferred choice.

Influence of temperature on impedance.
The influences of temperature on the decoupling performance should also be taken in account. For the 1 µF capacitors in the example above, Fig.4 shows the temperature dependence of impedance between 0 and +85 °C.

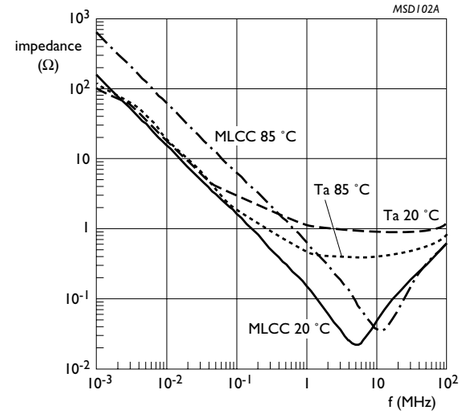

Fig. 4 Impedance as a function of frequency and temperature for a 1 µF 16 V tantalum capacitor and a 1 µF 16 V Y5V MLCC

From this figure we see that at low frequencies the impedance of a 1 µF Y5V MLCC roughly doubles its value between room temperature and 85 °C. Chiefly because of this, the frequency at which the impedance of the Y5V capacitor becomes lower than that of the tantalum capacitor of the same values shifts from approximately 60 kHz to 200 kHz. Although this suggests that the frequency range over which the tantalum capacitor competes with the MLCC is extended at these higher temperatures, most modern applications in, for example, EDP and power supplies operate at frequencies well in excess of 100 kHz which means that even with this relatively high dependence of impedance on temperature, the Y5V MLCC is usually still preferred.

X7R/X5R MLCCs
For X7R and X5R MLCCs, the low frequency impedance up to 10 kHz is approximately the same as for tantalum capacitors. Above this frequency, however, these MLCCs show rapidly decreasing impedance relative to tantalum and this impedance remains lower over the whole frequency range above 10 kHz.

X7R and X5R capacitors show hardly any variation in impedance with temperature so that with increasing temperature, the difference in impedance between a tantalum and X7R/X5R capacitor stays approximately the same.

Influence of DC-bias on impedance
A well-known feature of tantalum capacitors is that their capacitance remains relatively unchanged when DC-bias voltage is applied.

In contrast, the capacitance of class 2 MLCCs falls with DC bias voltage. The magnitude of this fall depends both on the dielectric material and on the applied field strength. It therefore differs for X7R and Y5V and for each rated voltage.

For X7R MLCCs, this effect is limited. A typical 16 V type will lose a maximum of 20% of its capacitance when a 16 V bias is applied.

For a 16 V Y5V MLCC, the effect is relatively large, a capacitor losing over 80% of its impedance when a 16 V bias voltage is applied.

Figure 5 shows the influence of this change on the impedance of the capacitor. Again we see that, despite the large dependence on bias voltage, for frequencies above 100 kHz the impedance levels of the MLCC are much lower than those of the tantalum capacitor. In the 1 to 10 MHz region, the difference is a factor 10.

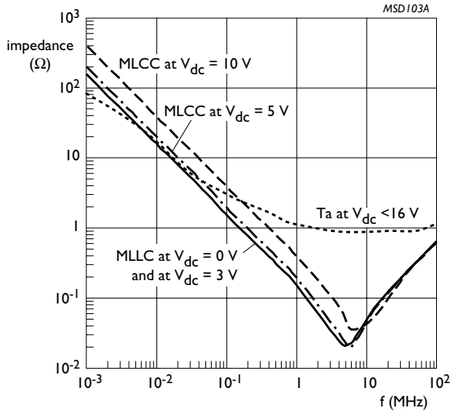

Fig. 5 Impedance as a function of frequency and DC voltage for a 1 µF 16 V tantalum capacitor and a 16 V Y5V MLCC

Effective capacitance

Besides the variations of capacitance with temperature and bias voltage just described, variation of capacitance with frequency must also be taken in account since the two technologies (MLCC and tantalum) show some marked differences in this area.

Figures 6 and 7 illustrate the general trend. Figure 6 shows that the capacitance of X7R MLCCs remains relatively constant with frequency and Fig.7 shows that the capacitance of Y5V MLCCs increases at higher frequency. Both figures show that the capacitance of tantalum capacitors falls strongly at higher frequency. It's worth noting, however, that these effects are all much smaller than those due to variations in temperature and bias voltage.

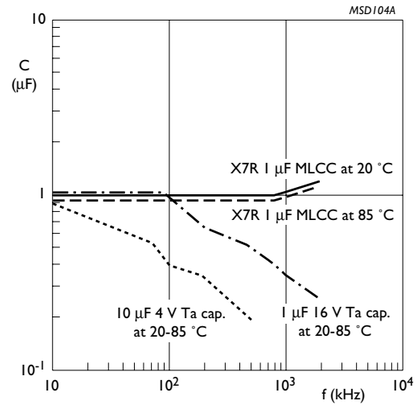

Fig. 6 Capacitance as a function of frequency for X7R MLCCs and 16 V tantalum capacitors

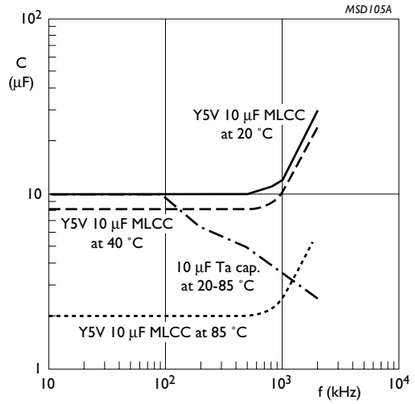

Fig. 7 Capacitance as a function of frequency for Y5V MLCCs and 16 V tantalum capacitors

For tantalum capacitors the effect of capacitance reduction with increasing frequency depends on the construction of the capacitor. In general, versions with lower rated voltages start losing capacitance at lower frequencies: a 4 V type, for example, loses approximately 80% of its capacitance at 500 kHz, while a 16 V type loses about 50% at 500 kHz.

Equivalent series resistance (ESR)

Here we speak of ESR of a capacitor not as the minimum value but as a function of frequency. ESR is also a function of temperature but its dependence on frequency is far greater.

Because of the differences in their construction, the value of ESR for MLCCs and tantalum capacitors differs greatly. Fig.8 gives an example for 10 µF capacitors.

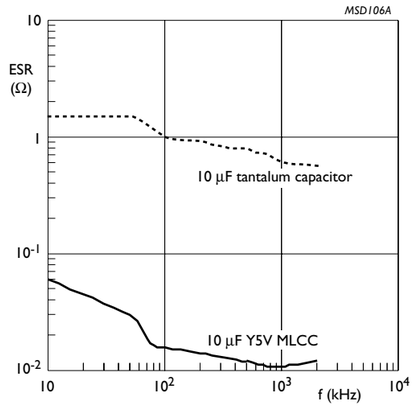

Fig. 8 ESR as a function of frequency for 10 µF MLCCs and tantalum capacitors

In practice, this means that for tantalum capacitors the minimum frequency from which the impedance is determined by the ESR is much lower than it is for MLCCs.

If a tantalum capacitor with a lower ESR is required, it's possible to select a type with the same capacitance but with a higher rated voltage or one with a larger capacitance. It is often also necessary to choose a larger case size.

Equivalent Series Inductance (ESL)

When a capacitor discharges into an IC, the series inductance impedes the process in two ways. First, the series inductance of the discharge path, which a second order effect, reduces the discharge speed. Second, the current change induces a voltage across the series inductor which adds to the ripple voltage. The primary variable in ESL is the size of the capacitor.

For both tantalum capacitors and MLCCs, the inductance is in the region of 1 to 3 nH but the intrinsic design characteristics of MLCCs and their greater possibilities for miniaturization both offer greater possibilities to reduce ESL.

Though ESL considerations can be important for decoupling HF signals, in view of the similarities between the capacitor technologies in this respect and the fact that ESL usually becomes important at frequencies that are so high that MLCCs are preferred in any case, we shall not consider this parameter further in the publication.

Functional performance per application area

In any design decision, electrical performance is not the only criterion. Component cost too must be taken into account. For each application area such as *decoupling, smoothing* and *noise suppression* the requirements on functional performance differ. We shall therefore compare the functional performance of tantalum capacitors and MLCCs per electrical function.

Major application areas are decoupling and smoothing. Table 3 makes a comparison between a set of typical tantalum capacitors and MLCCs considering both electrical performance and cost.

Table 3 Type selection for comparison of tantalum capacitors and MLCCs. A: 3.2 *x* 1.6 mm (1206) C: 6.0 *x* 3.2 mm D: 7.3 *x* 4.3 mm

Type	Size	Cap (µF)	Rating (V)	Cost Index
MLCC Y5V	0805	0.1	25	15
MLCC Y5V	0805	1	16	30
MLCC Y5V	1206	10	6	152
MLCC X7R	0805	0.1	25	23
MLCC X7R	0805	1	10	76
MLCC X7R	1206	2.2	10	121
Tantalum	A	1	16	100
Tantalum	A	10	10	100
Tantalum	A	22	4	107
Tantalum	C	33	4	150
Tantalum	D	100	4	303

Y5V and X7R/X5R type MLCCs were selected for the comparison because the performance of Z5U and Y5U capacitors, in general, falls between that of an X7R /X5R and Y5V types.

To assess the electrical performance, one must in fact look at different frequencies, operating temperature ranges and bias voltages. The present comparison is limited to the conditions as given in Table 4.

Table 4 Frequency, temperature and bias voltage for the comparison of Table 3

parameter	selection
frequency	100 kHz, 200 kHz 500 kHz, 1 MHz
temperature	40 °C, 60 °C, 85 °C
DC bias	5 V

For the capacitor types in Table 3 and the parameters in Table 4, the minimum effective capacitance, impedance and ESR values have been determined. The effect of temperature dependence on ESR has not been taken into account since the effects are relatively small. For both technologies ESR decreases with temperature over this frequency and temperature range (Ref.3).

With this set of data, electrical performance per application is simulated to provide meaningful comparisons between the two technologies.

Smoothing

Smoothing is one of the important application areas in which MLCCs and tantalum capacitors often compete.

One of the most common areas for smoothing is found in switched-mode power supplies (SMPS) which cover a very broad spectrum of output powers and ripple

currents. Even so, design constraints such as maximum operating temperature, capacitance required and high-frequency switching requirements of modern SMPS designs often make the choice of capacitor technology clear. In those areas where the choice is not clear, however, it is sensible to make a cost-performance analysis.

For this we use what's known as a *spice model* (Ref.3) to compare the smoothing performances of the products in Table 3. The simulation circuit consists of a full-wave rectifier bridge excited by a 10 V sine-wave voltage source with an internal resistance of 1 Ω. The rectifier bridge is smoothed by either an MLCC or an tantalum capacitor. The circuit is loaded with a 100 Ω resistor. The capacitor models are basically RLC-models with the values properly chosen as a function of frequency, temperature and bias voltage. This approach is valid because the circuit is simulated for a single frequency.

Based on the cost index as given in Table 3, the smoothing performance is translated into cost-performance diagrams. Figures 9, 10 and 11 are examples of these diagrams.

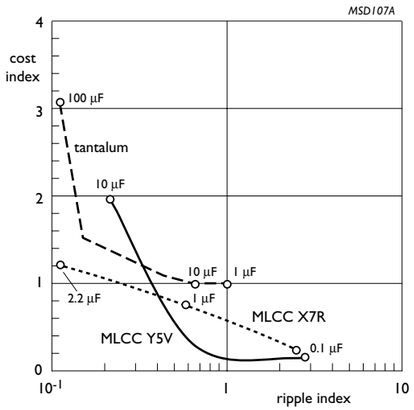

Fig. 9 Cost-performance diagram at 40 °C, 100 kHz, 5 V bias for smoothing

In the cost-performance diagram, both cost and performance are given relative to the tantalum 1 µF level. Good performance corresponds to low ripple index.

The lines in the figure connect the data for the types from Table 3 manufactured in the same technology. For all 3 series the performance improves with increasing capacitance.

From Fig.9, the following conclusions can be drawn:
- Within the MLCC range, a cheaper solution can be found for all performance levels
- For low and medium performance levels, a Y5V MLCC is the most cost-effective solution
- For high performance levels (including the best level) an X7R MLCC is always the best choice.

In a next step we look at the effects of an increase of operating temperature. The results are summarized in Fig.10 which gives the cost-performance at 60 °C, 100 kHz and 5 V bias.

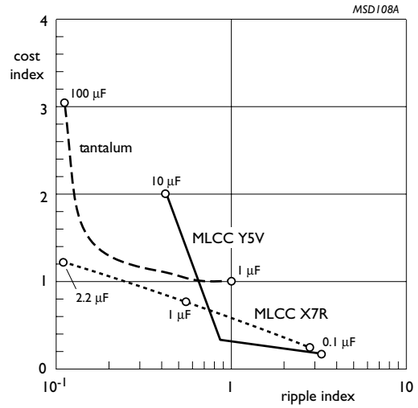

Fig. 10 Cost-performance diagram at 60 °C, 100 kHz, 5 V bias for smoothing

Basically at 60 °C the conclusions differ little from those drawn from Fig.9. The main difference is that the Y5V MLCCs are less competitive as a result of their reduced effective capacitance.

Figure 11 illustrates the influence of both a further temperature and frequency increase. The Y5V MLCC has been omitted here because it is no longer competitive at these high temperature.
One further conclusion can be added:
- At 1 MHz the competitive position of the X7R MLCC improves due to the tantalum capacitors' reduced effective capacitance and high ESR.

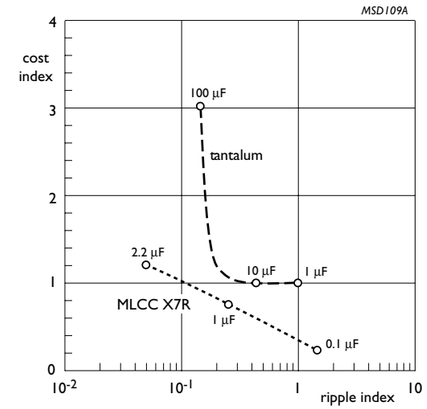

Fig.11 Cost-performance diagram at 85 °C, 1 MHz, 5 V bias for smoothing

Influence of the DC-bias levels
These results have all been simulated with parameters based on a DC-bias level of 5 V. When reducing the bias level to 3 or 1.5 V, the performance of tantalum capacitors stays the same, but the performance of MLCCs improves. In this respect it's worth noting that the performance of the Y5V MLCCs improves more since it is more sensitive to DC-bias. *As a result, Y5V MLCCs become more cost effective at lower circuit voltages.*

Decoupling
When looking at local decoupling one has to assess the amount of charge required by the IC to perform its state change without causing excess voltage ripple. The voltage ripple can seriously degrade IC performance. The capacitor, therefore, has to respond as a *low-impedance* charge source.

To assess the capacitors' behaviour in this respect, the performance of 0.1 to 10 µF MLCCs and 1 to 100 µF tantalum capacitors from Table 3 were investigated in the 100 kHz to 1 MHz frequency range. In the initial tests, the capacitors were subjected to a 100 kHz square wave and in the later tests they were subjected to a 1 MHz sine wave. The influence of temperature and intermediate frequencies was simulated using a general decoupling model.

Figures 12, 13 and 14 show typical cost-performance diagrams. As with smoothing, performance was seen to improve with increasing capacitance.

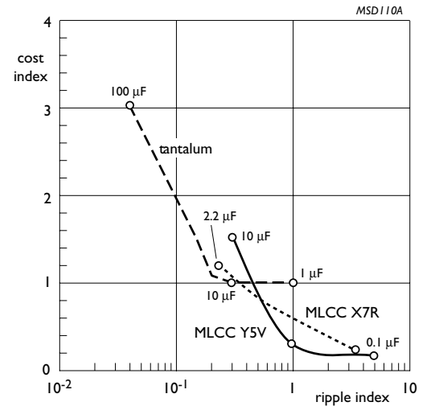

Fig.12 Cost-performance diagram at 40 °C, 100 kHz, 5 V bias for decoupling

From Fig.12 it's evident that at 100 kHz and 40 °C, a 1 µF MLCC offers a more cost effective solution than a 1 µF 16 V tantalum but does not perform as well as the 10 µF tantalum capacitor. The 33 µF in case size C and 100 µF in case size D achieve even better performance levels at, it should be noted, considerably greater cost. Additionally, since the size of these components is much greater, a designer may well consider using more than one MLCC in preference to a larger tantalum capacitor.

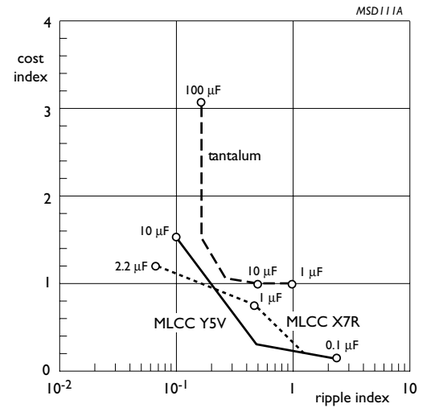

Fig.13 Cost-performance diagram at 40 °C, 1 MHz, 5 V bias for decoupling

Figure 13 shows the influence of increasing the decoupling frequency to 1 MHz. Here the situation has changed. We see now that at this frequency the 1 µF X7R MLCC offers a more cost-effective solution than even the 10 µF tantalum capacitor. Moreover, the cost effectiveness of the Y5V capacitor has also improved. Both effects come from the reduced need for effective capacitance at this frequency and the increased importance of low ESR.

We also notice that despite the high nominal capacitance, the 33 µF and 100 µF tantalum capacitors no longer offer the best performance. In this example, the 2.2 µF X7R MLCC is, in fact superior to these capacitors.

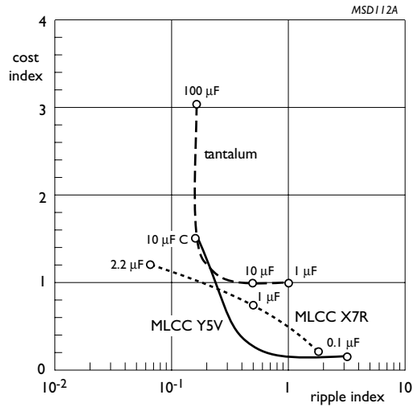

Fig.14 Cost-performance diagram at 60 °C, 1 MHz, 5 V bias for decoupling

Figure 14 shows the influence of increasing the operating temperature to 60 °C. Compared with the situation of Fig.13, the major change here is the increased cost effectiveness of the X7R MLCCs. In fact, under these conditions X7R MLCCs are unique in their ability to achieve the best performance.

From the simulation results it can be concluded that MLCCs with nominal capacitance both in X7R and Y5V dielectric offer cost-effective alternatives to equivalent tantalum capacitors over a large frequency and temperature range.

For frequencies up to 500 kHz, it is possible to improve the decoupling performance in tantalum technology by choosing a larger capacitance. Since the ESR of this larger capacitance is lower, the impedance will also be lower over a large proportion of the frequency range. Usually, however, a larger value tantalum capacitor has the disadvantages of a lower rated voltage or a larger case size and a poorer performance at higher frequencies. This can give additional problems if EMC regulations have to be taken into account.

Moreover, it is often possible to use a much smaller capacitance in MLCC technology to achieve the same decoupling performance. This is because in tantalum technology it is always necessary to choose a larger capacitance to reduce ESR and compensate for loss of capacitance at higher frequencies.

Future developments

In both technologies, developments continue towards further increase of capacitance per unit volume and smaller sizes (Refs 2, 3 and 4). In addition, both technologies are introducing products with lower ESR levels. In tantalum technology, new series like the Neocapacitor (Ref.5) and the dedicated Low ESR series are finding their application segments. Likewise, in MLCC technology increased numbers of layers and greater effective capacitances are leading to reduced ESR levels (Ref.6).

First indications based on extrapolations of Figs 1 and 2 lead to the expectation that MLCCs will further penetrate the tantalum area and that tantalum capacitors will strengthen their position in the high capacitance area (currently dominated by electrolytics).

Conclusions

- MLCCs and tantalum capacitors have been compared on general and functional specifications
- A detailed understanding of the behaviour is needed to predict the performance in relation to circuit demands
- Cost-performance diagrams can help in selecting the optimal capacitor.
- Both in smoothing and in decoupling, MLCCs have been shown in most cases to be more cost effective than tantalum capacitors
- The cost effectiveness of MLCCs improves with frequency
- Y5V MLCCs are most cost effective at low bias voltage, medium performance levels and temperature up to 40 to 60 °C
- X7R MLCCs are most cost effective at high performance levels and higher temperatures
- The battle between MLCC and tantalum capacitor technologies will continue.

More information

For more information and data, contact your local Yageo sales representative or visit our web site on **http://www.yageo.com**.

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