Inductance

The inductance of 31 µH, measured with a conventional LCR measuring bridge, is really rather surprising. The inductance arises from the 2 $^1/_2$ turns through the ferrite body. However, as the ferrite material causes the decoupling of the windings already mentioned, a high impedance is achieved over the whole frequency range up to 500 MHz, which has no resonant points. This component is mainly suited to power supply applications.

5.3 Ferrite Bridge

Ferrite bridge

A type of ”choke array“ should not go unmentioned: The ferrite bridge (Figure 2)

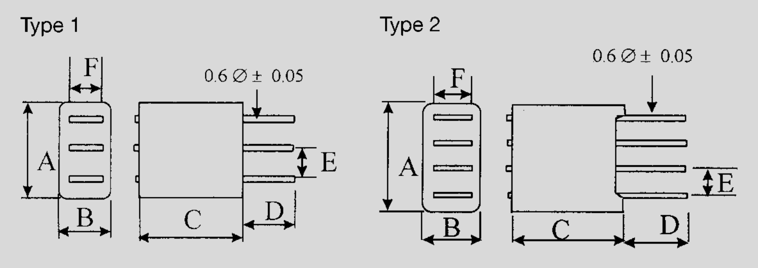


Fig. 1: Electrical parameters of some ferrite bridges.

Ref. no.	Name	A	B	C	D	E	F	Impedance (Ω) 25	100	Type
		mm	mm	mm	mm	mm	mm	MHz	MHz	
742 730 01	Ferrit bridge 3-lines	7,62	5,08	10	5,8	2,54	2,54	212	264	1
742 730 02	Ferrit bridge 4-lines	10,88	5,49	10	3,19	2,54	2,54	209	249	2
742 730 021	Ferrit bridge 4-lines	11,2 max	11,2 max	6	5	2,54	7,62	136	170	2
742 730 022	Ferrit bridge 4-lines	11,2 max	11,2 max	9	2,5	2,54	7,62	208	248	2
742 730 023	Ferrit bridge 4-lines	11,2 max	11,2 max	11	5	2,54	7,62	292	334	2

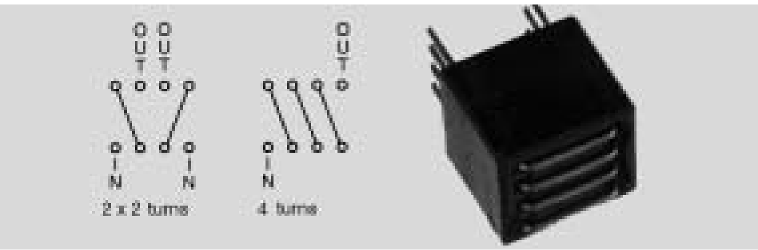


Fig. 2: Possible switching options of the ferrite bridge (layout design)

Mutual inductance

The ferrite bridge has three or four chambers depending on the type. A 0.6 mm cross-section wire passes through each chamber. The coupling or mutual inductance L_μ of the chambers with one another is lower than that of ribbed cores. They were wound according to test 2, due to the ferrite found between the individual conductors. The mutual inductance L_μ also falls from chamber to chamber, i.e. L_μ is greater between chamber 1 and chamber 2 than between chamber 1 and chamber 3 (Figure 3).

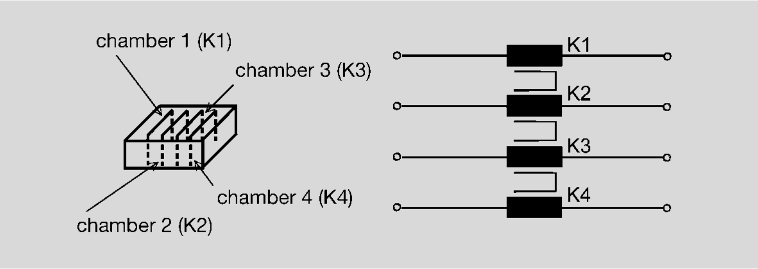


Fig. 3 *Schematic representation of the ferrite bridge.*

Damping characteristics

Common mode choke

Comparing the damping characteristics of the ferrite bridge in Figure 4 with the parameters from section 3. ”Current compensated chokes“, Figure 7, (1st test with the ribbed core choke), it is apparent that this component can be used as a common mode choke.

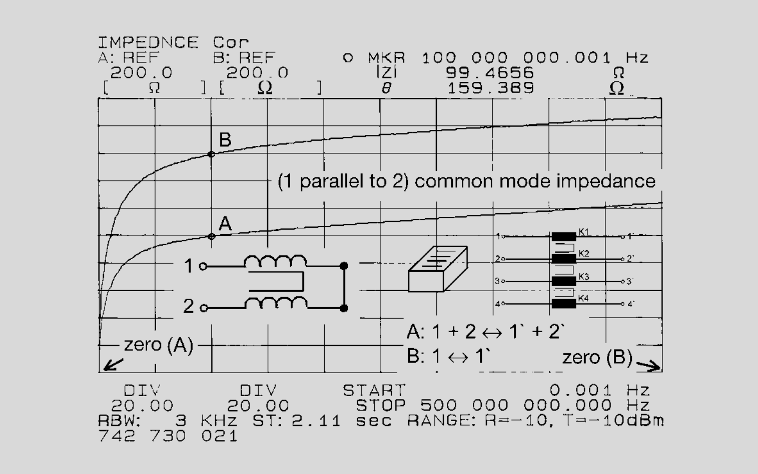


Fig. 4: *Impedance graph for the ferrite bridge in different configurations.*

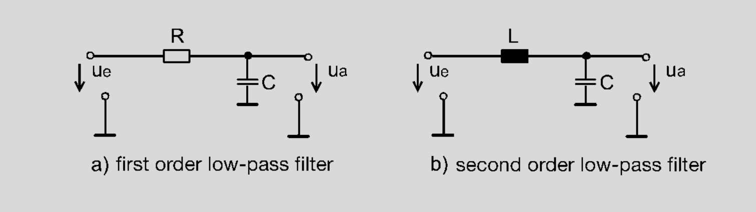
Impedance

Advantages of this common mode choke are high current loading capacity up to 4 A and its damping up to 1000 MHz without resonance. The choke is therefore particularly suited for use in power supply applications and in signal transmission in a signal bandwidth ‹ 5 MHz. The impedance of a chamber is represented by curve B in Figure 4, curve A is the signal insertion damping, the differential mode impedance.

Low-pass filter

2. The low-pass filter

The low-pass filter is the most commonly used filter circuit in EMC. However, to improve understanding and to evaluate the effectiveness of the filter, some detailed observations may be helpful. The observation should be made on the basis of the two most commonly used low-pass circuit varieties (Figure 1).



a) first order low-pass filter

b) second order low-pass filter

Fig. 1: Low-pass filters of first and second order.

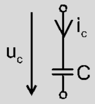
Laplace transformation

The converted form of the Laplace transformation is used to improve the mathematical representation of filters or quadrupoles in the frequency domain. The so-called Laplace transformation in the complex variable domain results, with

$$F_p = \int f(t) \cdot e^{-pt} dt$$

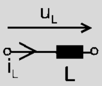
Frequency response

the transformed function in the frequency domain, i.e. from a technical viewpoint the circuit's frequency response. So-called functions in the complex variable domain can be found using some mathematical rules from basic time domain functions. For example, for



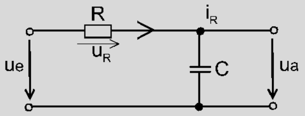
$$i_C = C \cdot \frac{du_C}{dt} \rightarrow u_C = \frac{1}{Cp} \cdot i_C$$

and for



$$u_L = L \cdot \frac{di_L}{dt} \rightarrow i_L = \frac{1}{Lp} \cdot u_L$$

Calculation table:



$$ue = u_R + ua$$

$$ua = \frac{1}{Cp} \cdot i_R \qquad \left(i_C = \frac{du_C}{dt} \right)$$

$$i_R = ua \cdot Cp$$

$$ue = i_R \cdot R + i_R \cdot \frac{1}{Cp}$$

$$ue = ua \cdot Cp \cdot \left(R + \frac{1}{Cp} \right)$$

$$ue = ua\,(RCp + 1)$$

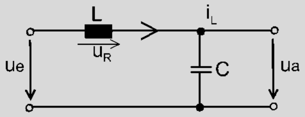
$$\boxed{\frac{ua(p)}{ue(p)} = \frac{1}{RCp + 1}}$$

$$\text{with } \tau_1 = R \cdot C = \frac{1}{2\pi f}$$

$$\text{and } f_0 = \frac{1}{2\pi RC}$$

$$\Downarrow$$

$$F_1(p) = \frac{1}{\pi_1 p + 1}$$



$$ue = u_L + ua$$

$$ua = \frac{1}{Cp} \cdot i_L \qquad \left(ua = L \cdot \frac{di_L}{dt} \right)$$

$$i_L = \frac{ua}{Lp}$$

$$ue = u_L + ua = L \cdot p \cdot i_L + i_L \cdot \frac{1}{Cp}$$

$$ue = L \cdot p \cdot \frac{ua}{Lp} + \frac{ua}{CLp^2}$$

$$ue = ua\left(CLp^2\right) + ua = ua\left(CLp^2 + 1\right)$$

$$\boxed{\frac{ua(p)}{ue(p)} = \frac{1}{CLp^2 + 1}}$$

$$\text{with } f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$\Downarrow$$

$$F_2(p) = \frac{1}{p^2C^2 + 1}$$

Both functions can be presented graphically (Figure 2).

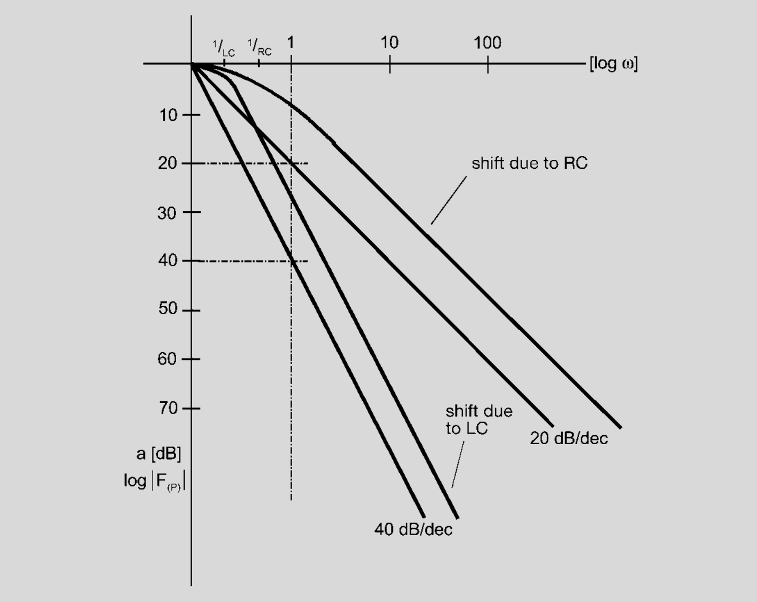


Fig. 2: Transfer function $F_x(p)$ against angular frequency.

Attenuation

As p is to the first power in $F_1(p)$, the filter shows an increase in attenuation of 20 dB/dec; the filter with the complex variable function $F_2(P)$ has, with a p of second power, an attenuation response of 40 dB/dec. Shifts of the angular frequency axis depend on time constants. At ω_o ($\omega_1 : F_1(P)$) there is an attenuation of 3 dB for $F_1(P)$ and an attenuation of 6 dB for $F_2(P)$.

Resonance point

In contrast to the RC filter, the LC filter has a resonance point. The resistive losses (see part 1) of the inductor must be taken into account to describe the series resonance. This results in the equivalent circuit in Figure 3.

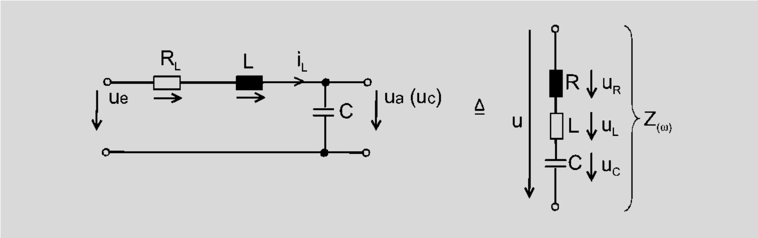


Fig. 3: Simplified equivalent low-pass filter circuit taking resistive coil losses into account.

Impedance

The impedance Z(w) is given by

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

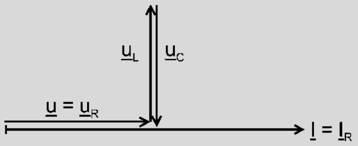
Resonance occurs if the imaginary component is 0, i.e.

$$\omega L - \frac{1}{\omega C} = 0 \quad \Rightarrow \quad \omega L = \frac{1}{\omega C}.$$

It follows that:

$$\omega^2 = \frac{1}{LC} \quad \Rightarrow \quad f_r = \frac{1}{2\pi\sqrt{LC}} \qquad \text{(Resonanzbedingung).}$$

Furthermore, at resonance



$$\underline{u}_R = \underline{i}_C \cdot R_L = \underline{u}$$

$$\underline{u}_L = j\omega_r \cdot L \cdot \underline{i}_R$$

$$\underline{u}_C = \frac{1}{j\omega_r C} \cdot \underline{i}_R$$

Amplitude response
Phase response

The amplitude and phase responses of the filter in Figure 3 are presented graphically in Figure 4.

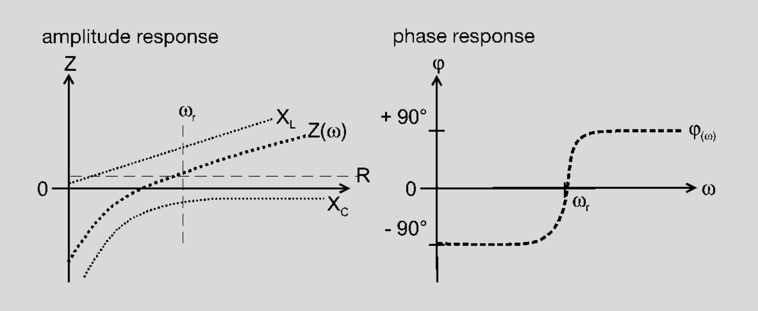


Fig. 4: Amplitude and phase response of the filter in Figure 3.

In practice this means that

Resistive part of impedance

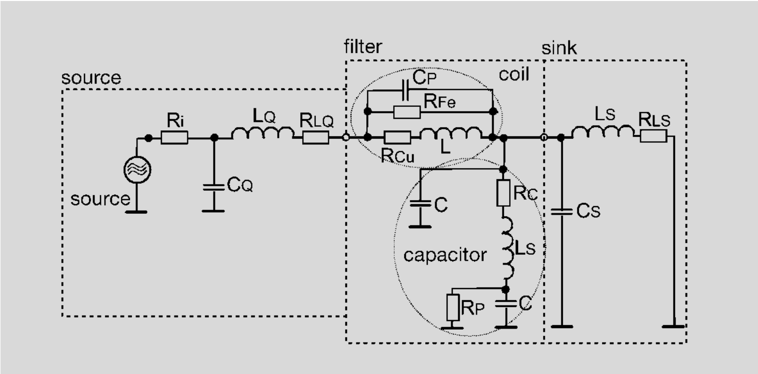
Resonant frequency
Capacitor

Linear phase response

Source and sink impedance

- the choke must have a constant high resistive impedance component over the required filter bandwidth to keep the resonant amplitude as low as possible and its bandwidth as broad as possible.
- both the useful and the noise signal frequencies should lie below the resonant frequency of the low-pass filter.
- quality factor and loss values of the capacitor generally play a lesser role if the resistive components of the choke are high.
- broadband, critical useful signals must lie within the linear phase response of the filter (far below resonance) to avoid distortion.
- additional resonance phenomena occur due to each additional parasitic element.
- source and sink impedances must also be taken into account with the filter properties.

The result is e.g.: a network with source, filter and sink as in Figure 5.



Parasitic impedance

Fig. 5: Example of a network, taking parasitic impedances of the components into account.

3. Filter circuitry

LC low-pass

Filters are frequency dependent voltage dividers, consisting of a combination of resistors or inductors and capacitors. Frequency dependence means a change in the electrical properties with frequency. The most commonly used filter, the LC low-pass, works on the basis that the impedance of the inductor rises with increasing frequency and the impedance of the capacitor falls with increasing frequency. This would solve most EMC problems in theory, were it not for some side-effects, which reduce the filter function, sometimes even negating it altogether.

3.1 Filter ground reference

3.1.1 Weaknesses of filter reference grounds

Ground

One of the most important conditions for useful function of an LC filter is the capacitor's "ground reference" (Figure 1).

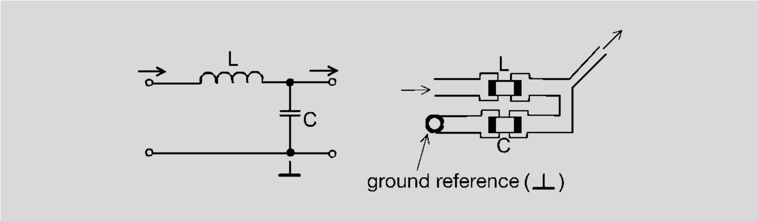


Fig. 1: Circuit diagram and faulty construction of an LC low-pass filter.

Every additional impedance in series with the capacitor, whether of parasitic origin "inside" the capacitor (see section Components, Capacitors), caused by layout or construction, reduces the effectiveness of the filter. Long connections between the capacitor and ground are additional unwanted series inductances – regardless of whether the inductance comes from the connecting legs of the capacitor, the conductor tracks or bolts on the component group fixture. Designers and layout specialists are often faced with seemingly almost insoluble problems in this regard, as restrictions such as the space availability within the component group, number of con-

4. Filtering an external AC/DC interface

Supply voltage

Supply voltages, whether AC or DC, often have to be routed via interfaces out of devices to supply other external peripheral devices or sensory systems. Here we will restrict ourselves to low voltage supply ‹ 60 V_{DC} or ‹ 25 V_{effAC}, the reason being that the required protection against accidental contact under VDE0100 part 410 does not need to be observed, rendering design simpler. The product-specific regulations under low voltage directive, the medical product law or other statutory or normative restrictions must of course be satisfied. These will not however be covered here as the physical and electronic principles explained here in the examples apply just the same.

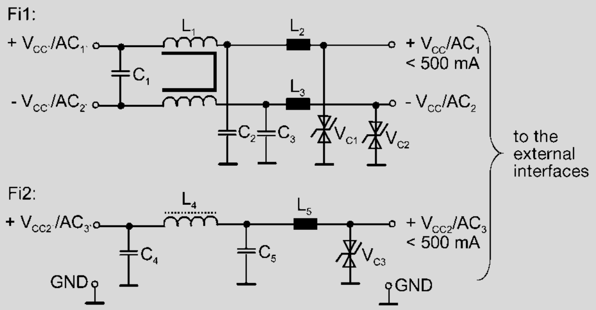
Symmetrical filter
Asymmetrical of filter

Figure 1 shows the circuit diagrams of a symmetrical and an asymmetric filter, suitable for connection of external device interfaces. Care must be taken in the treatment of external device interfaces for the following EMC reasons:

Interference

- External interface cables can emit high-frequency interference from the interior of the device,
- Noise can easily be picked up in external interface cables, which can then penetrate inside the device.

For the reasons given, external interfaces of IT systems and telecommunications end devices is subject to numerous tests of interference immunity according to the product norm EN 55024 to prove CE conformity.



L_1: 742 794 53 (noise suppression choke)
L_2: 742 792 63 (SMD ferrite)
L_3: 742 792 63 (SMD ferrite)
L_4: 742 794 04 (noise suppression choke)
L_5: 742 792 63 (SMD ferrite)

C_1: 100 nF
C_2: 100 nF
C_3: 100 nF
C_4: 100 nF
C_5: 100 nF

V_{C1}: VC060309A200
V_{C2}: VC060309A200
V_{C3}: VC060314A200
for V_{CC} = 12 V

multilayer varistors: AVX Karlsfeld

Fig. 1: Circuit diagrams of a symmetrical and an asymmetric AC/DC power supply filter for use on external interfaces (AC_{eff} ‹ 25 V, DC ‹ 60 V).

Transient voltage
Multilayer varistor

RF capacitor

Symmetrical interface

Through the multilayer varistors V_{C1}, V_{C2} and V_{C3}, the filters offer protection against transient voltage (bursts) capacitively induced via the cables. The multilayer varistor consists of zinc oxide layers separated by metal electrodes. Diffusion takes place as a result of the sinter process arising during manufacture, which converts each zinc oxide grain into a Schottky diode (PN junction). A sizeable capacitance (typ. 500 pF–1000 pF) is created through the parallel connection of many Schottky junctions, which can be used as a RF capacitor, as the parasitic inductance is of the order of less than 1 nH as a result of the small construction (e.g.: 0603). A very fast response time of typ. 0.2 ns–0.4 ns is the result. If the voltage applied to the varistor reaches or exceeds the Zener point of the PN junction, the current rises dramatically to flow from the electrodes to the counter electrodes from where it flows away to the system ground. As the component is in the breakdown state, the many million PN junctions contribute to energy absorption, causing leakage current ratings of 30 A to 120 A and even up to 500 A (standard pulse 8/20 µs) for the 1210 component size. Both reverse breakdown voltage values, seen as signal voltages, are added in the symmetrical interface. Therefore varistors can be chosen with small reverse breakdown voltages. A low-pass filter working in the 50–1000 MHz range is created with the SMD chokes L_2, L_3 and L_5 from the very low impedance multilayer varistors. For 100 MHz, the attenuation is given in Figure 2.

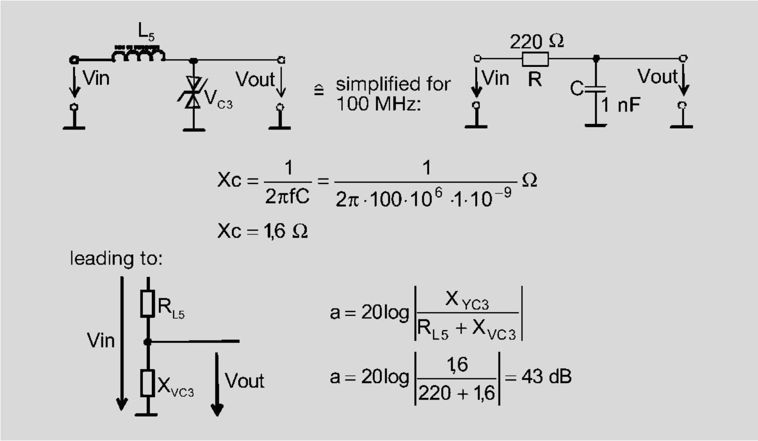


Fig. 2: Functional analysis of the effect of the first filter stage in Figure 1 (asymmetric).

The second filter stage ensures high attenuation in the frequency range below 50 MHz. The attenuation in Figure 3 is given for 50 MHz:

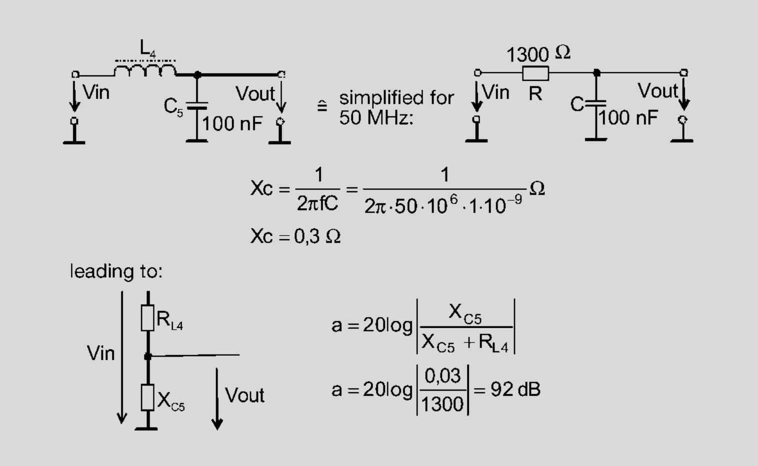


Fig. 3: Functional analysis of the second filter stage in Figure 1 (asymmetric).

Functional analysis

Asymmetric noise

The actual attenuation is found to be lower, due to the parasitic inductances and capacitances (see Part II Components). The input capacitor C_4 was not considered in the functional analysis, as it must be seen in association with the noise source, whose internal resistance is usually unknown. In the case of the symmetrical filter, C_1 does not have any effect on the common mode noise. Instead, C_1 ensures that the asymmetric noise components are reduced.

Decoupling

Shield connection wire

A RF compatible construction is indispensable for the proper function of a filter. Figure 4 shows a layout with the associated mechanical cable connections. Special attention must be paid to the decoupling between filter input and filter output for filters with a required attenuation range above 500 MHz. The interface connectors must be shielded if necessary or located on the other side of the filter (solder side). If connection wires between the filter component group and the peripheral connector are necessary, they must be shielded and the shield connected to ground at both ends. Depending on the length of the shield connection wire from the cable shield to ground (for lengths of 10 mm and more), the attenuation of the filter is reduced by at least 20 dB–30 dB in the high-frequency range. The design must therefore be well planned at the outset.

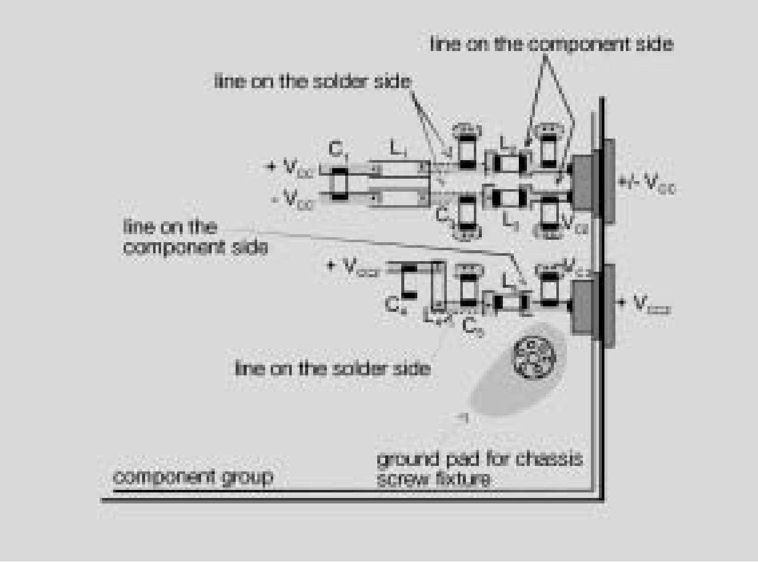


Fig. 4: Layout of the filter in Figure 1.

Through-contacts
Ground layer

The multilayer varistors must each be provided with 2 through-contacts to the ground layer. The conductors between L_1 and L_2 and between L_4 and L_5 are routed on the solder side; the supply and GND layers lie between the two signal layers. If only 2 layers are available, the region of the conductor between the coils in the ground layer must be left free. The layout is only problematic if just 1 layer is available. The only viable option is then to have a continuous ground area around the conductors; RF properties like those of the multilayer construction are however not to be expected.

5. VHF/UHF broadband amplifier

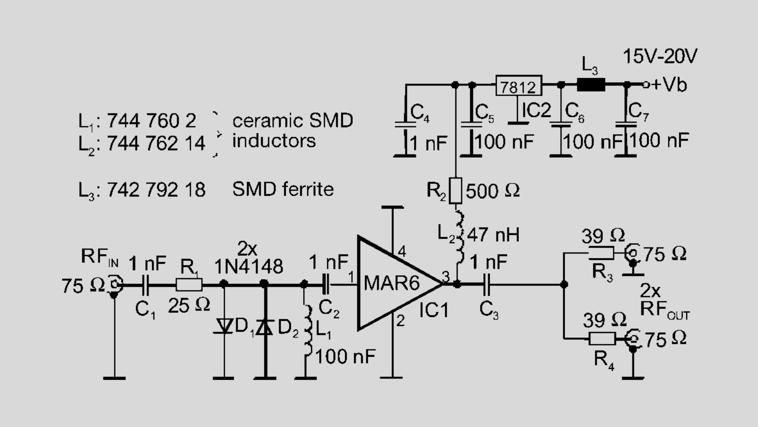


Fig. 1a: VHF/UHF amplifier circuit.