

INDUCTORS

1. The purpose of the paper: Knowledge of the characteristic parameters of the constructive structure of various types of through hole and surface mount inductors; performing specific measurements.

2.Theoretical background:

2.1 Overview

The inductor is the component that, in an harmonic regime (sinusoidal current, voltage) has at its terminals a phase angle φ , of about 90° between the voltage and the current.

Ideally, the phase angle is $\varphi = 90^\circ$, but in fact $\varphi < 90^\circ$ (Fig. 1)

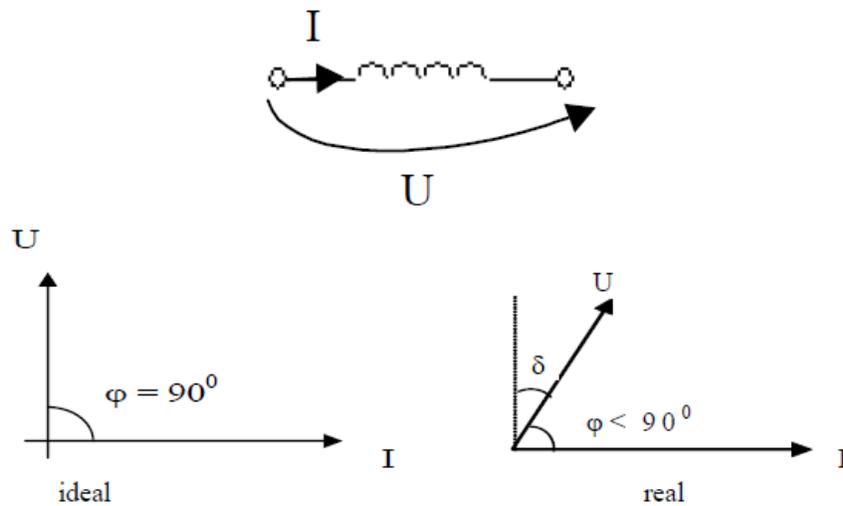


Fig. 1 Phasor diagrams of voltage and current for an inductor

Along with capacitors, which are able to accumulate power, inductors are passive components able to accumulate magnetic energy. Accordingly, under certain circumstances (a current must be passing through them), inductors are able to produce a magnetic field similar to that produced by a magnet.

A forward current of intensity "i" through a conductor arranged in certain manner creates a magnetic flux through the surface which stands onto the conductor wire. Between the two units there is a direct proportionality factor called inductance:

$$L = \frac{\phi}{i} \quad (1)$$

As the order of the magnetic flux, for a precise value of the current, depends on

the shape of the surface penetrated by the field lines generated by the current, it means that the inductance depends on geometrical factors on the one hand and on factors characterizing the magnetic properties of the environment on the other hand.

In this respect, the more permeable the environment to the magnetic field lines, the greater the magnetic flux; therefore for the same geometry of the conductive track of the current, the resulting inductance will be higher.

In the same time, corresponding to the same environment, as the same magnetic field lines pass several times through the surface onto which the conductive track stands the magnetic flux is higher and so is the inductance of the track which generated that area. In other words one can say that the inductance of a track of length “L”, with the shape of a circle, is higher than the inductance obtained from the same track placed in a different shape.

In the definition of the inductance no other physical effect was considered that could lower the magnetic flux caused by the electric current “i” and therefore this inductance is also called intrinsic inductance and is considered to be the inductance determined in DC or at low frequency.

With the increase of the current going through the conductive track, in the presence of other physical effects (capacitive and dissipative type), the magnetic flux is likely to be influenced by these effects and therefore the inductance might not remain constant from one frequency to another.

This dependence is higher or lower as the magnetic flux is influenced more or less by the aforementioned side effects, called parasitic effects.

In fact, these parasite effects lead to the representation of an inductor by means of an equivalent circuit which highlights its behavior in a certain frequency range. The equivalent electric circuit contains not only an inductance (the intrinsic one), but also highlights the capacitive effect (capacity) or dissipative effect (resistance), as shown in Figure 2.

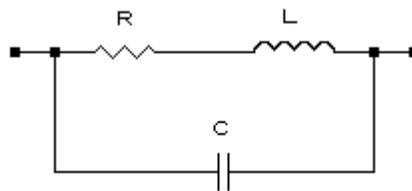


Fig.2 Equivalent circuit of an inductor

As such, the behavior of the inductor in the frequency range is determined by the dominating effect of one of the physical effects over the others. As the presentation shows that the inductive, the capacitive and dissipative effects are mainly present for an inductor, it implies that this electronic component can be an inductance, a capacity, a resistance or combinations of these elements.

Obviously for applications the primary inductive effect should be dominant; this requirement is satisfied in the range from DC (frequency zero) to the resonance frequency. The existence of this resonance can be explained if one takes into account the fact that, based on the physical effects taking place, the inductor could be considered to

be composed of an inductance and a parasitic capacity. This circuit implies the existence of its own resonance frequency, whose good approximation is specified by:

$$f_0 = \frac{1}{2\pi\sqrt{L \cdot C_p}} \quad (2)$$

where C_p is the parasitic capacity.

It is important to highlight the fact that, due to dissipative effect in the inductor, an active power appears. The active power losses of the inductor are characterized by the loss tangent (loss factor, dissipation factor), **tan δ** , which represents the ratio of between the active power and reactive power of an inductor.

$$tg\delta = \frac{P_a}{P_r} = \frac{I}{Q} \quad (3)$$

The inverse of the loss tangent parameter is the quality factor of the inductor. It is denoted by Q and it usually is preferred to **tan δ** when characterizing the losses of an inductor.

Based on the phasor's diagram of U and I at the inductor's terminals one could consider an equivalent circuit composed of two elements: inductive (L) and dissipative (R). This circuit can be series (L_s, R_s) and parallel (L_p, R_p). Since in most cases in electronics, it can be considered that the values of L_s and L_p are approximately equal, the inductance is by ' L ' and R_s by " r " and R_p by " R ". Substituting the expressions of active and reactive power, if one considers a series equivalent circuit, parallel respectively, the relations determining the quality factor results:

$$Q = \frac{\omega_r \cdot L}{r} ; Q = \frac{R}{\omega_r \cdot L} \quad (4)$$

$$r = R_s \quad R = R_p$$

where r is the series loss resistance and R , the parallel loss resistance (according to the notations above). The typical dependence of the quality factor with frequency is shown in Figure 3 (a). The shape of the plot can be explained by the fact that the frequency increases with increasing quality factor, based on formula 4, but so the losses increase too, highlighted by increasing the series resistance r . The increase of the resistance is explained by the skin effect which results in movement of the electrical current only to the exterior of a metal conductor at high frequencies. Often, at high frequency conductive silver is used and secondly tubes (pipes) could be instead of massive conductors. For the inductors with a magnetic core there is a further increase in losses due to high frequency losses in the magnetic core.

Based on the aforementioned aspects, it could be considered that in order to work properly an inductor, along with the inductance, the parasitic capacity and the quality factor should also be taken into account.

Measurements of inductors where inductance, the quality factor and the parasitic capacity had to be highlighted used to be made with a simple measurement device named Q-meter. Basically it is an electronic circuit consisting of a variable frequency voltage source that feeds the inductor connected in series with a variable capacitor. Currently the Q-meter was replaced with impedance analyzers, more complex measurement devices.

Since the inductance's value depends on the effects of capacitive type, respectively resistive type (parasitic effects) present at any inductor, at a certain frequency the inductor is characterized by an apparent inductance, L_a . As the parasitic effects are greater at high frequencies, at low frequency domain and DC the value of the inductance (denoted by L_{ech}) approaches the value of the intrinsic inductance (L). In general we consider $L_{ech} \sim L$. The apparent inductance of the inductor which highlights the presence of the parasitic capacity C_p , has the expression (5)

$$L_a = \frac{L_{ech}}{1 - \omega^2 \cdot L_{ech} \cdot C_p} \quad (5)$$

where:

ω is the angular frequency where L_a is computed;

L_{ech} - equivalent inductance (LF and DC inductance, when taking into account the ohmic and magnetic losses);

C_p - parasitic capacity.

The typical variation of the apparent inductance with frequency is shown in Figure 3 (b)

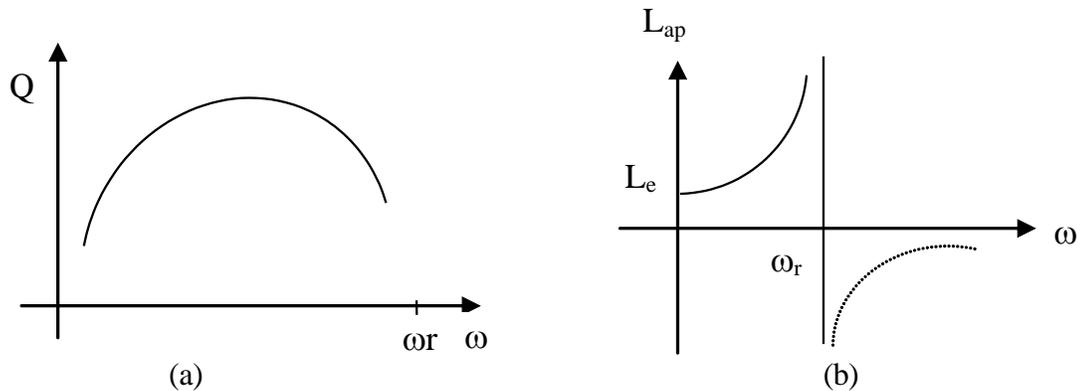


Fig. 3 Frequency dependence of the quality factor (a) and of the apparent inductance (b)

If the self-resonance frequency is exceeded, the apparent inductance becomes negative, i.e. inductor's character is predominantly capacitive. The frequency range where the inductor has to be used must be small enough compared to the self-resonant frequency and possibly in the area where Q has a maximum value.

The parasitic capacity can be estimated by various formulas, but the exact calculation is difficult, as it requires solving electromagnetic field equations on domains with complicated geometries. Usually the C_p effects are estimated by measuring and by determining its self-resonant frequency.

To reduce the parasitic capacity special wirewounds were made and we mention the honeycomb coil, pyramidal or shingle. [1].

For the components studied in the laboratory is particularly highlighted the useful induction and inductance in the sense that electronic components are studied where this effect is predominant and is, obviously, desirable. In practice, the realization of electronic equipment often leads to situations in which different structural elements of the circuit may have a more or less pronounced inductive effect. Therefore, the conclusions that will

be reached in understanding the concept of inductance issues will also be helpful in assessing situations where this effect is unwanted (parasitic). An example of a modified electric circuit due to the real structure (due to parasitic effects of dissipative, inductive and capacitive type) is shown in Figure 4.

The situation is presented because the design elements that interconnect the components in order to obtain an electrical circuit are considered null from the dissipative, inductive and capacitive point of view. In fact, due to physical effects involved during the working stage, the interconnection elements present to some degree the physical phenomena in question. The inductances which arise modify the structure of the designed electrical circuit. The equivalent electric circuits include, in addition to inductance, the resistance loss by conduction (ohmic) into the copper tracks and their parasitic capacities with respect to the ground level. Distributed parasitic capacity is a capacity that is due to the proximity of two conductors at different electrical potentials, in this case printed wiring tracks. This worsens the situation. Different filter structures are obtained that can lead to attenuation and distortion of useful signals transmitted on line. As the inductance obtained involuntarily through the wiring tracks may lead to the malfunction of the equipment, it is very important for the designer to seek the minimization of the inductive effect from an early phase in the development of interconnection structures.

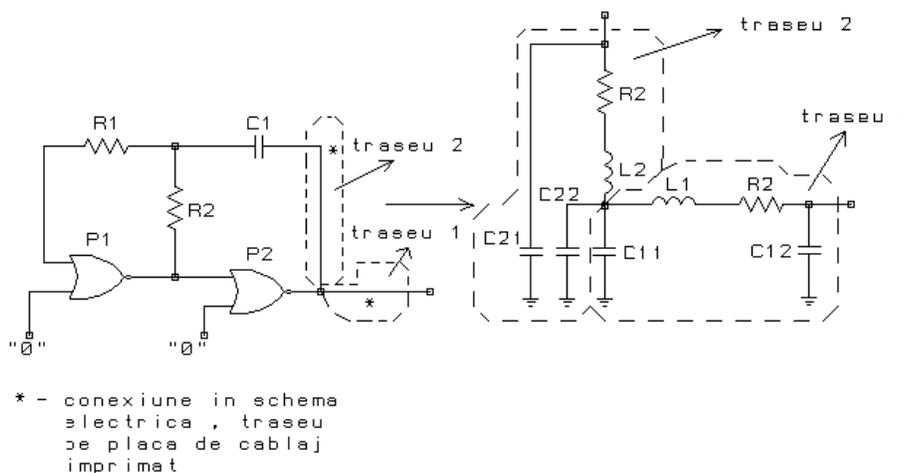


Fig. 4 Equivalent electrical circuit of an interconnection part according to the corresponding parasitic elements.

where:

- L^* - Parasitic inductance of a portion of the route;
- R^* - Parasitic resistance of a portion of the route;
- C^* - parasitic capacity (to ground) of a portion of the route, represented by the equivalent capacities at the ends of the route.

Similar situations (in terms of parasite induction) can be seen in terms of some components: the case of carbon-film resistors or metal spiral, wirewound resistors, stiroflex or electrolytic aluminum capacitors (see laboratory papers in question) . They

have a strong inductive behavior, a phenomenon which must be taken into account in the design stage.

2.2 Parameters of the inductors

The inductor, like any passive component is characterized by general parameters, specific to all passives: L_N rated inductance, tolerance t , the temperature coefficient α_T , range of temperature $[\theta_m, \theta_M]$, P_N rated power, tolerances t_j .

The rated inductance, L_N - depends on the physical dimensions of the inductor (coil), but also on the presence and type of the magnetic core onto which the coil is constructed, especially the frequency range of the inductor.

For different frequency ranges, large manufacturing companies provide series of rated values with the tolerance range of denominations $\pm 5\%$ and $\pm 20\%$, and with rated currents from tens of mA to several amps. These coils are built on a ferrite torus (closed magnetic circuit) or on ferrite rod (open magnetic circuit). They are small and are marked in code (possibly the color code) or clearly specified. The packages are through-hole or surface mount devices. For other values and/or frequency domains, manufacturers of electronic inductors offer custom designs, on demand.

For a cylindrical wirewound inductor with S-sectional area and diameter d , on a core with the relative permeability μ_r , with turns on one layer, with length $l \gg d$ (solenoid) the well-known formula to compute inductance can be used:

$$L = \mu_0 \mu_r \cdot \frac{N^2 S}{l} \quad (6)$$

This relation, although not very precise for other types of inductors such as those $l \approx d$ or the ones with more layers allows highlighting the factors that influence the inductance. Other parameters of the inductors are listed below:

- Rated current I_N represents the maximum rms value of the sinusoidal current that flows through the inductor during extended operation.

For some types of coils is given in the catalog the maximum DC component value that can be applied to coil system operating time.

- Self - resonance frequency, f_R , is given by:

$$f_R = \frac{1}{2\pi \cdot \sqrt{L_N C_p}} \quad (7)$$

where C_p is the parasitic capacity of the inductor; it depends on the structural design of the coil, the relative permittivity of the core and the insulating elements (layers of polish, paint, plastic case, etc.); in the equivalent circuit of the inductor it appears in parallel with the inductance.

- the inductor's quality factor, Q , is equal to the ratio of inductive reactive power occurring in the inductor at the working frequency and the active power dissipation in the inductor and is the inverse of the loss tangent $\tan \delta$:

$$Q = \frac{1}{\tan \delta} = \frac{\omega L I^2}{r_s I^2} = \frac{\omega L}{r_s} \quad (8)$$

where $\omega=2\pi f$, f =working frequency of the coil;

L = the inductance of the coil at frequency f ;

r_s = the series loss resistance of the coil at frequency f , due to conduction losses in the conductor of the coil's winding and the losses in the magnetic material of the core (the magnetization losses, by hysteresis, through eddy current and Foucault currents etc.) losses in the insulating materials (the insulation of the conductor, of the case of the protection element, of the impregnating varnish, etc.), losses in the electromagnetic screen.

δ = the complement of the phase shift angle between voltages and currents crossing the coil, called the loss angle.

In the datasheet the value of this factor is specified (the minimum guaranteed - Q_{\min} and Q value at a certain frequency or it is given the variation of the quality factor with respect to frequency). In terms of use in electronic circuits in order to achieve an oscillator or a filter, an inductor with a high quality factor provides a sharper amplitude-frequency characteristic than an inductor with a lower quality factor. It is stated that the circuit with a high Q inductor is more selective, meaning that it may favor (select) certain frequencies substantially better, over the same circuit made with a low Q .

• DC Resistance, R_{DC} is the coil's resistance measured at zero frequency and is mainly determined by the resistance of the wire that coil's conductor is made of;

• Rated voltage at the terminals of inductor U_N is determined by the rigidity of insulating materials used, by their insulation of winding wire and by the winding method that determines the relative distances between turns.

2.3. The structural design of the inductors

The structure depends on the inductor and is generally composed of:

- winding,
- magnetic core,
- insulation support (case)
- contact and terminal areas,
- protection element
- electromagnetic screen.

Some items may be missing from the structure or an element can perform two functions, for instance coils can be made directly on the insulating support which may be a ferrite core, which is electrically speaking an insulator or a ceramic material with low inductance.

Two examples of inductors made on circular cores, toroidal core respectively, are shown in Figure 5.

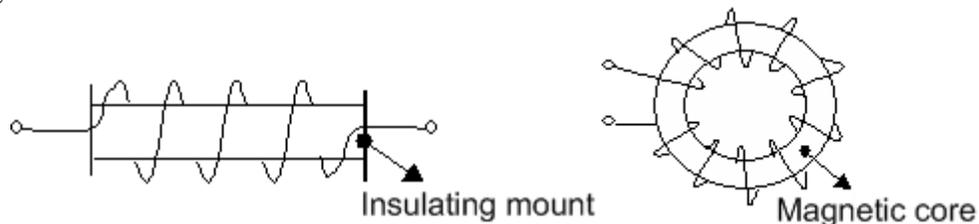


Fig. 5 Circular and toroidal inductor

Currently the vast majority of inductors used are made of ferrite magnetic core. Ferrite is magnetic material of metal-ceramic type with high relative permeability and with lower high frequency losses than the ferromagnetic materials. Like the latter, ferrites have a nonlinear character and present phenomena of saturation and hysteresis. However, they have a much lower saturation induction and also a smaller temperature range. Ferrite cores can be made in various formats: rod type, E + I type, E + I planar, pot type, toroidal, etc. In general for these cores the induction factor A_L (nH / turn²) is indicated and the resulting inductance $L = A_L \cdot n^2$, where n is the number of turns.

Rarely air coils are used for high frequencies or where the presence of the core can introduce distortions due to the nonlinear magnetic materials behavior, such as certain audio-frequency applications (filters for acoustic cases).

Surface mounted inductors are generally used in applications where high density is required for the equipment. In many high frequency applications, surface mounted inductors offer superior performance to the THT. SMD inductors most commonly used today are classic, with wire wound. There is a high frequency variation where a wire wounded on a non-magnetic core is used Figure 6 (a).

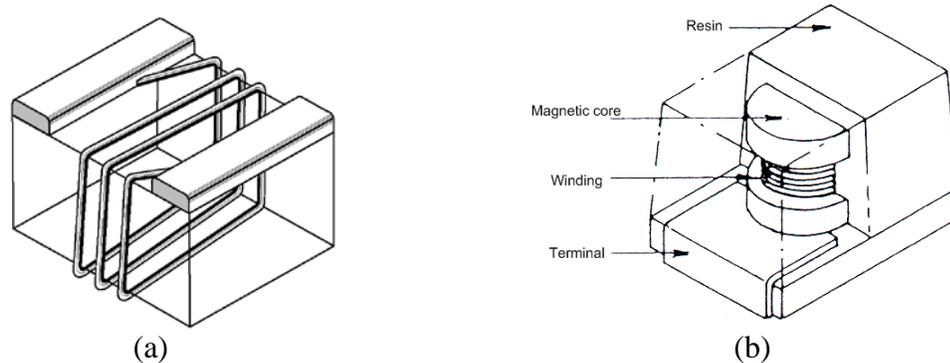


Fig. 6 The structure of SMD inductors (a) non-magnetic core, (b) magnetic core

Other medium and low frequency induction coil uses a ferrite core, the whole structure is then molded into a resin, the component being similar to tantalum capacitors, see Figure 6 (b).

Most inductors used in the laboratory are so-called high-frequency shocks. They are called so because they stop high-frequency currents and allow the passage of DC or low frequency AC. The shock inductor (coil) is connected in series with the electronic circuit and shock effect (block) is due to the higher impedance at high frequencies.

3. Work procedure

3.1. Identifying the parameters of the inductors

Proceed to the completion of Table 4 in Annex 1. For inductors L1-L15, shown in Figure 7, determine the marked and various other parameters which characterize these inductors using the datasheet. All data, both measured and determined are written in a table as the one given in Annex 1. Laboratory board is presented in Figure 7.

Procedure:

a) Identify the inductors based on the code in Table 1 and then, based on the data sheet, the parameters are identified and written in Table 4. For L1-L5 the marking in the color code is also verified, code similar to the one presented for resistors.

b) The inductance and quality factor are measured. At this point all measurements are made with the RLC bridge at the **frequency of 1 kHz**.

Inductors L1-L13 are all connected to a common ground GND, the other terminal being connected to the L_n termination, n the related order number. For inductors L14 and L15 the inductance is measured between terminals GH and I in order not to include in the circuit the shunt resistance R_s .

In the paper the t_m tolerance is computed resulting from the measurement, with:

$$t_{calc} = \frac{L_m - L_N}{L_N}$$

Where:

L_m - measured value of the inductance; L_N - the rated inductance.

Calculate the equivalent series loss resistance with: $R_{series} = \frac{\omega L}{Q}$.

Note: Some manufacturers specify the frequency at which the rated inductance is measured. Sometimes this may be the same frequency at which the quality factor Q is specified.

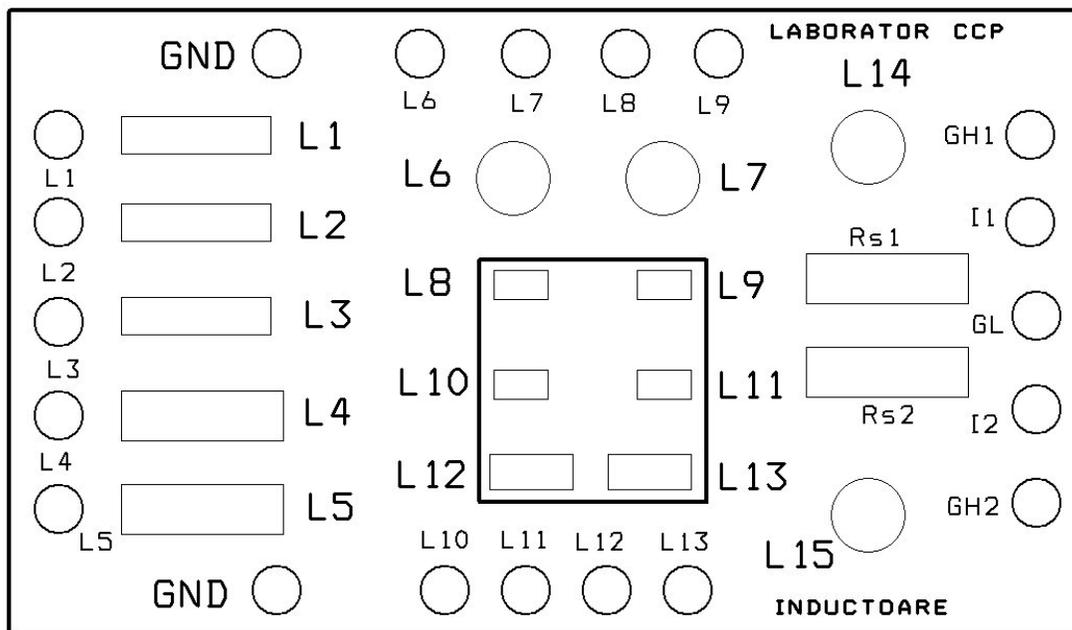


Fig. 7 Drawing of the board for the study of inductors

Table 1 : List and code for the components

Nr. ref.	Articol	Cod	Producător
L1	Axial Miniature Fixed Inductor 3x10mm	EC24-100k	CTC Coils
L2	Axial Miniature Fixed Inductor 3x10mm	EC24-221K	CTC Coils
L3	Axial Miniature Fixed Inductor 3x10mm	EC24-102K	CTC Coils
L4	Axial Miniature Fixed Inductor 5x14mm	EC46-222J	CTC Coils
L5	Axial Miniature Fixed Inductor 5x14mm	EC46-103J	CTC Coils
L6	Radial, Ferrite core fixed inductor 7,5x11mm	CH6080101K	CTC Coils
L7	Radial, Ferrite core fixed inductor 7,5x11mm	CH6080102K	CTC Coils
L8	SMD 1210 Molded Inductor	IMC1210U001	Vishay
L9	SMD 1210 Molded Inductor	IMC1210U004,7	Vishay
L10	SMD 1210 Ceramic Core Inductor	B82412 (SIMID1210-01)	EPCOS
L11	SMD 1210 Ferrite Core Inductor	B82412 (SIMID1210-01)	EPCOS
L12	SMD Molded Inductor	SMCM453232-470K	CTC Coils
L13	SMD Molded Inductor	SMCM453232-102K	CTC Coils
L14	Radial, Ferrite core fixed inductor 7,5x11mm	CH6080333K	CTC Coils
L15	Radial, Ferrite core fixed inductor 7,5x11mm	CH6080104K	CTC Coils

3.2 Frequency dependence of the quality factor

Determine the inductance and the quality factor at different frequencies available on the RLC bridge. Use inductors L3, L5, L7, L9, L13, L14, L15

Table 2 Variation of the inductance and the quality factor with frequency

f(kHz)		L3	L5	L7	L9	L13	L14	L15
0.1	L (mH)							
	Q							
0.12	L (mH)							
	Q							
1	L(mH)							
	Q							
10	L(mH)							
	Q							
100	L(mH)							
	Q							
200	L(mH)							
	Q							

Comment upon the results.

3.3. Inductors' behavior in AC

For this task it is intended to display on the oscilloscope screen the applied voltage at the terminals of the inductor signal generator and, simultaneously, the current through the inductor. In fact, the voltage drop on shunt-resistance, R_s , that will be

measured, is proportional to the current through the inductor, see Figure 8. So on the screen two sinusoidal signals will be shown for the corresponding voltage and current in the circuit.

The generator voltage is chosen up to 20 V_{pp} (peak-to-peak).

Frequency will be gradually increased. The current through the circuit will decrease with the frequency since $I=U/\omega L$. It is necessary to modify the vertical amplification of the oscilloscope in order to have comparable values for the voltage and assess the phase shift between the two signals. For a more accurate reading one can turn the oscilloscope cursors.

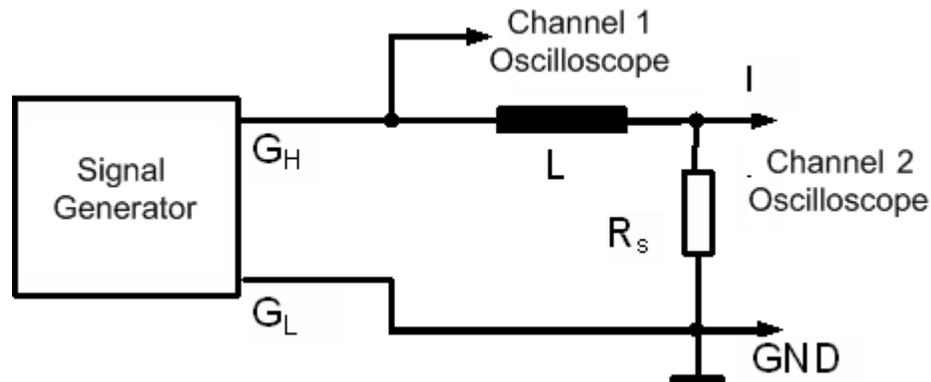


Fig.8 Setup for viewing voltages and currents through the inductor.

In low frequencies range, the current is shifted behind the voltage. Once we reach closer to the self-resonance frequency, the phase shift between voltage and current will decrease and we will see, after exceeding the self-resonant frequency that the current will pass before the voltage, i.e. inductor will present a capacitive character. The value of the current at resonance is very small, but once exceeded the self-resonance frequency the current begins to increase again. The display of the oscilloscope is shown in Figure 9.

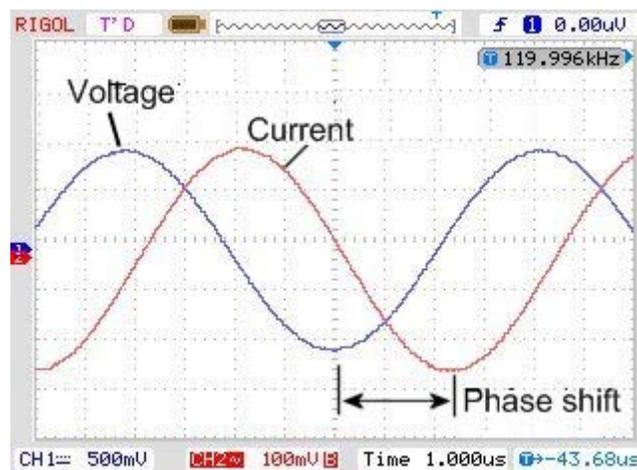


Fig.9 Oscilloscope display showing voltage and inductor current

The value of the self- resonance frequency will be marked for the two inductors. Knowing the low frequency inductance, the parasitic capacity can be computed with (2).

Another way to determine the parasitic capacity, if one cannot measure L_{ech} with the RLC bridge, is to conduct measurements of the apparent frequency dependence on inductance. So it is measured the voltage drop corresponding to the forward current through the inductor at different frequencies. The current is determined from the value of the shunt resistance $R_{s1} = R_{s2} = 10k\Omega$. The apparent inductance is calculated $L_a = U_G / \omega I$, where U_G is the voltage of the generator (also peak-to-peak). The frequencies are chosen corresponding to a logarithmic scale. In the vicinity of resonant frequency you will choose several measuring points.

$L_a(f)$ will be plotted which must be similar to the one in Figure 3b. Two frequencies are selected in ascending region of the graph, near the resonant frequency. The parasitic capacity is determined by the relationship:

$$C_p = \frac{L_{a2} - L_{a1}}{L_{a1} L_{a2} (\omega_2^2 - \omega_1^2)} \quad (9)$$

Table 3 will be completed for the two inductors L14 and L15.

Table 3 Behavior with respect to frequency

f(kHz)	U_I [V _{vv}]	$I = U_I / R_s$ [mA _{vv}]	$L_a = U_G / \omega I$ [mH]	
1				f1=..... f2=..... Cp=.....
2				
5				
10				
20				
50				
100				
.....				
fpr				

4. Questions, conclusions, data processing

4.1 Based on the data sheet and the laboratory board make a comparative study of the inductors' types: the main distinguishing elements, the constructive structure, main characteristics, the most important parameters, application areas.

4.2. Given the results in section 3.1 (Table 4) make a comparison of the inductors in terms of the parameters listed in the table. Discuss any differences between the measured quality factors and the values given in the datasheet.

4.3. Discuss the differences between the DC resistance value and the equivalent series resistance at the working frequency (1 kHz).

4.4. The data sheet does not state explicitly the rated power. How can you estimate the power dissipation capacity (DC) based on data from Table 4? Calculate power dissipation for inductors L1-L15. Discuss the results.

4.5. How do you explain the differences between the quality factors measured in 3.2? Discuss each type of inductor. Why are there different quality factors of inductors for the same rated inductance L3, L7 and L13?

4.6. Why the self-resonant frequency for inductors L14 and L15 is different? Which factors determine the parasitic capacity of the inductors?

4.7. If in section 3.3 two frequencies from the low frequency range are selected from the apparent inductance chart to determine the parasitic capacity, what results will be?

4.8. Near the resonant frequency the apparent inductance is high, apparently a positive thing. Why, however, working close to the self-resonant frequency is avoided?

5. Questions:

1. How does the inductance depend on the constructive elements of the inductor: length of winding, winding section, the number of turns, case, magnetic core, protection element, electromagnetic screen, etc.

2. Under what conditions the secondary capacitive effect of an inductor has less influence over its operation? What solutions exist to minimize this unwanted effect?

3. In which extent the case onto which the winding is made (winding mount) influences the inductor's parameters? Indicate which of them.

4. For what frequencies the inductor acts as a capacitor (due to the predominant capacitive effect)? Why?

5. What material or constructive parameters influence the DC resistance R_{CC} . What about the rated current?

6. Does a short linear inductor, basically a terminal of a component, have inductance?

7. Why are SMD components used more in the high frequency range?

8. Why should the inductances that appear accidentally (parasitic inductances) be taken into account in the analysis of the electronic circuits?

9. What effect does a brass core has over the inductance?

10. The parasitic capacity of a coil depends on:

- 1) winding wire insulation.
- 2) coil shape.
- 3) the distance between coil turns.
- 4) winding mount.

11. The equivalent electrical circuit of an inductor:

- 1) is a laboratory setup.
- 2) is a measurement circuit shown in datasheets.
- 3) represents an attempt of the manufacturers to minimize the parasitic effects that occur in high frequency.
- 4) is an equivalent electric circuit that models a real inductor.

12. The inductor:

- 1) tends asymptotically to the ideal inductor with increasing frequency.
- 2) deviates from the ideal inductor with increasing frequency.
- 3) manifests while working only as an element that dissipates energy.
- 4) has a leakage flux, ohmic losses and magnetic losses.

13. The apparent parallel inductance:

- 1) can be identified in DC with the equivalent inductance.
- 2) has a high absolute value close to the self-resonant frequency of the inductor.
- 3) is negative for frequencies higher than the self-resonant frequency.
- 4) has a fixed value that can be obtained by measuring the inductor with any LF

Bridge.

Content of the paper: The paper will contain all laboratory tables filled with the laboratory measurements and calculations, together with remarks, answers and conclusions. The graph will be plotted on millimetric paper for the variation of the apparent inductance in the frequency range

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Table. 4 Parameters of the inductors

No. crt.	Name ref.	L_N [mH] *	t [%]	Q	f_Q [MHz]*	T_m [°C]	T_M [°C]	SRF [MHz] *	I_N [mA]	Rcc [Ω]	L meas. [mH] *	Q meas	t calc. [%]	Rseries calc. [Ω]
1.	L1													
2.	L2													
3.	L3													
4.	L4													
5.	L5													
6.	L6													
7.	L7													
8.	L8													
9.	L9													
10.	L10													
11.	L11													
12.	L12													
13.	L13													
14.	L14													
15.	L15													

* The units of measure will be adequately used for each component