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Magnetic Flow Scattering in Ferrite Rings

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Abstract

It is shown that, contrary to the prevailing opinion, the scattering of the magnetic flux, even in ferrites with high magnetic permeability, is very large. A description of the technique for measuring the parameters of ferrites and inductors on ferrite rings is given. The results of experimental measurements of parameters for various grades of ferrites and various values of magnetic permeability are presented. Recommendations on the design of high-frequency transformers and inductors on ferrite rings are given.

Keywords: ***Scattering of the magnetic flux, ferrite ring, ferromagnetic, transformer.***

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I. Introduction

Optimal designing of radio equipment nodes is impossible without a clear understanding of physical phenomena and processes. In particular, the understanding of physical processes when using ferromagnetics is complicated by the fact that the theory is “overloaded” with complex mathematical issues. Only for a few simple tasks a strict solution was found. The applications of the theory for practical problems are virtually absent. In this paper, an attempt has been made to experimentally investigate phenomena in order to give a clear understanding of the features when using ferrite ruts. The obtained qualitative conclusions will be useful to those who design elements of radio engineering circuits using ferrite rings, based on experience and intuition.

It is usually considered that the entire magnetic flux is concentrated in the cross section of the ferrite ring and practically the scattering of the magnetic flux is small. The reason for this approach is the fact that the relative magnetic permeability of ferrites used in radio engineering devices amounts to tens to thousands. For example, the formula is valid if the relative magnetic permeability of the ring ferrite core μ>2000.

$$L = \frac{\mu\mu_0}{2\pi} hN^2 \ln\frac{D}{d}, \ldots (1.1)$$

Where μ is the relative magnetic permeability, μ_0 is the magnetic permeability of vacuum, N is the number of turns of the winding. The designations of other quantities appearing in expression (1.1) are shown in Fig. 1.

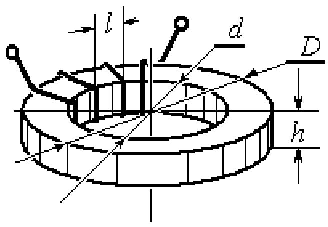


Fig.1

At high radio frequencies (over 10 MHz), ferrite rings with low magnetic permeability μ<500 and single-layer inductance winding are used. Magnetic flux scattering at small values of magnetic permeability can be significant.

Magnetic flux scattering is due to a demagnetizing factor. A ferromagnetic has a domain structure with a spontaneous magnetization of domains. When exposed to an external magnetic field, a change in the orientation of the magnetization vector in the domain and a change in the structure of the magnetic flux near the domain and “pushing” a part of the magnetic flux from the ferrite (“demagnetization”).[1,2,3&4]

The demagnetizing factor is a dimensionless tensor quantity, which depends on the shape and geometry of the device. The theory of calculating the demagnetizing factor is complex. Strict solutions were obtained only for a few special cases (ellipsoid, ovoid, etc.).[5] Therefore, in engineering practice, even approximate results are rarely used.

In this paper, we propose a different approach to describing the scattering flux in devices on ferrite rings. The article describes the methods for measuring the flux of scattering, the results of experimental studies and some practical recommendations.

II. The Method of Measuring Magnetic Coupling Coefficient

Initial relations. Consider a perfect lossless transformer on a ferrite ring. One of the variants of such a transformer, its equivalent circuit and designations are given in Fig. 2.

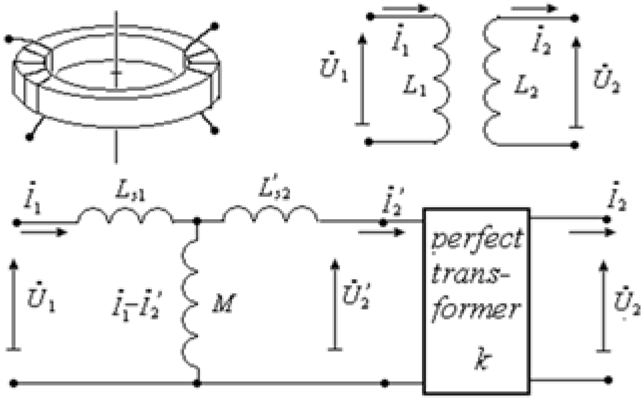


Fig. 2 L_1 and L_2 are inductances of primary and secondary windings, L_{s1} and L_{s2} are inductances of scattering windings, M is the mutual induction coefficient, $\dot{I}_1$ and $\dot{I}_2$ are currents of primary and secondary windings, $\dot{U}_1$ and $\dot{U}_2$ are voltages on the transformer windings, $L'_{s2} = L_{s2}/k^2$, $\dot{I}'_2 = \dot{I}_2/k$, $\dot{U}'_2 = \dot{U}_2 k$, $k = \sqrt{L_1/L_2}$.

Now we write the equations for complex amplitudes.

$$\dot{U}_1 = j\omega L_1 \dot{I}_1 - j\omega M \dot{I}_2 \, ; \, \dot{U}_2 = -j\omega M \dot{I}_1 + j\omega L_2 \dot{I}_2 \, . \qquad (2.1)$$

We introduce the following notation:

1. The transformation coefficient $k = \sqrt{L_1/L_2}$
2. The transformation coefficient of magnetic coupling $= M/\sqrt{L_1/L_2}$.

Taking into account the introduced notation, the equations will take the form

$$\dot{U}_1 = j\omega L_1 \left[\dot{I}_1 - \dot{I}_2 \frac{\eta}{k}\right] ; \, \dot{U}_2 = j\omega L_1 \left[-\dot{I}_1 \eta + \frac{\dot{I}_2}{k}\right]. \qquad (2.2)$$

For an *ideal transformer*, the following relationships are true.

$$\dot{I}'_2 = \dot{I}_2/k \, ; \, \dot{U}'_2 = \dot{U}_2 k \, . \qquad (2.3)$$

Taking these relations into account, we can bring the equivalent replacement circuit to the primary winding and highlight the ideal transformer in the circuit, as shown in the bottom diagram of Fig. 2. Now we can write the following system of equations for the equivalent circuit of a transformer with a transformation coefficient of 1: 1.

$$\dot{U}_1 = j\omega L_1 [\dot{I}_1 - \eta \, \dot{I}'_2] \, ; \, \dot{U}_2 = j\omega L_1 [-\dot{I}_1 \eta + \dot{I}'_2] \, . \qquad (2.4)$$

Now it is necessary to bring the resulting equations to a final form.

$$\dot{U}_1 = j\omega L_1 [(1-\eta)\dot{I}_1 + \eta(\dot{I}_1 - \dot{I}'_2)] \, ; \, \dot{U}_2 = j\omega L_1 [-\eta(\dot{I}_1 - \dot{I}'_2)\dot{I}_1 + (1-\eta)\dot{I}'_2] \qquad (2.5)$$

The system of equations fully corresponds to the equivalent transformer circuit (1: 1) shown in Fig. 2. Now one can decipher the notation.

1. The inductance of the primary winding of the transformer L_1.
2. The inductance of the secondary winding of the transformer $L'_2 = L_1 = L_2/k^2$
3. Mutual inductance $M = L_1 \eta$.
4. Inductances of scattering windings $L_{s1} = L_{s2} = L_1 (1-\eta)$.

Main settings. As can be seen from the obtained equations to determine the parameters of the transformer (having no losses and not containing containers), it is enough to know three parameters:

1. Ideal transformation coefficient k.
2. Magnetic coupling coefficient η.
3. The inductance of the primary winding L_1.

Primary winding inductance and transformation coefficient are measured using conventional methods. As for the magnetic coupling coefficient, here it is most convenient to use the "***idle and short circuit***" method.

Method of idling and short circuit. We set out the essence of the method.

1. At idle (the secondary winding of the transformer is open "***idle***"), the inductance of the primary winding is measured $L_{\text{id}} = L_1$.
2. Then we measure the inductance of the primary winding, provided that the secondary is short-circuited ("***short circuit***")L_{sc}.
3. The magnetic coupling coefficient, we can calculate by the formula

$$\eta = \sqrt{1 - L_{\text{sc}}/L_{\text{id}}} \,. \qquad (2.6)$$

Here we have a simplified approach. The strict approach should take into account losses in ferrite and losses in wires. However, in the presence of small losses all the relations remain fair. So, it is enough to make two measurements to calculate the magnitude of the magnetic coupling coefficient between the transformer windings.

III. Measurement Results

The above method for measuring the magnetic coupling coefficient can be successfully used to measure the magnetic flux dispersion of ferrite rods, rings and other products.

A coil of 5 turns is wound on a ferrite ring with a thin wire (diameter 0.06 mm). The coils overlap tightly to reduce the initial scattering of the flux of the magnetic field.

Measured inductance of idling. Then a short-closed ring, which can be moved across the torus, is tightly mounted on the ferrite torus (see Fig. 2). Measurements of inductance are carried out in the presence of a short-circuited ring at different angular distances of this ring from the coil winding.

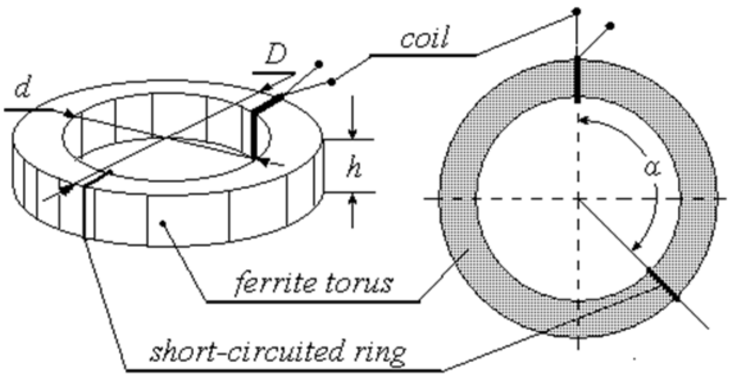


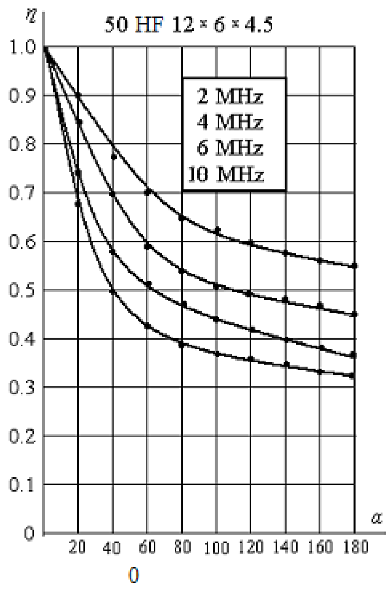
Fig.3

We will count the distance in angular units (angle α), as shown in Fig. 3. This is convenient because it is not related to the size of the ferrite torus. Obviously, the minimum magnetic coupling between the coil and the s.c.-wind (Fig. 3) will be at an angular distance of 180°, and the maximum - at an angle close to zero.

Measurement results. The measurements were carried out on various sizes of ferrites. When measurements were taken into account losses. The measurements were carried out with an angular displacement of a short-circuited ring by 20°. Typical results are shown in the graphs below (Fig. 4 and Fig. 5).

Brands, for example, Russian ferrites have the following designations (for example, 2000 HM 16×10×4.5):

1. 2,000 (initial magnetic permeability);
2. NN; NM; HF, etc. - material grade;
3. 16×10×4.5 - dimensions of the ferrite ring – $D \times d \times h$ (mm)



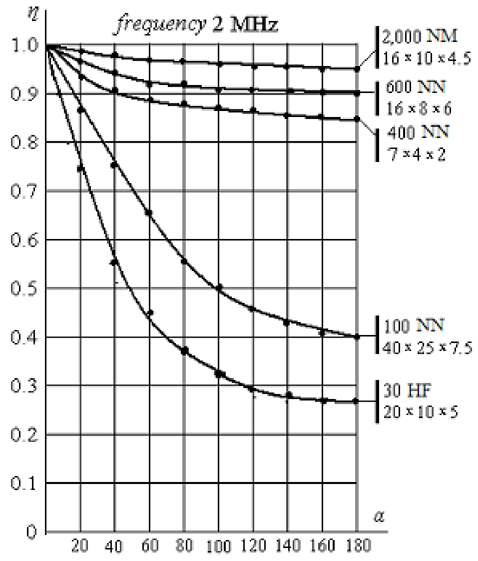


Fig.4 Fig.5

From the figures it is clear that

1. The scattering of the magnetic flux increases with increasing angle α, i.e. from the distance between adjacent turns. This is an obvious result.
2. More interesting and important is the increase in scattering with decreasing magnetic permeability. For example, at a frequency of 2 MHz (Fig. 4) for ferrites with a magnetic permeability of less than 400, the magnetic flux falls on the diametrically opposite side of the coil to 30-50 percent.
3. Scattering also increases with increasing frequency (Fig. 5).

All this must be considered when calculating transformers and coils on ferromagnetic rings.

IV. Single Layer Inductive Coil

Single-layer coils on ferrite rings are used at high frequencies. Here, the following requirements may be important: high quality (small losses), low magnetic flux dispersion (transformers, etc.)

Above, we cited formula (1.1) for calculating the inductance of a coil. This formula is valid if the demagnetizing factor has practically no effect on the scattering of the magnetic flux. In the presence of magnetic flux scattering, this formula can give a big error. We consider the effect of magnetic flux scattering for short coils occupying no more than $\frac{1}{4}$ of the ring length.

In this case, we can approximate this dependence $\eta = f(\alpha)$ by an exponent

$$\eta = e^{-b\alpha} \quad \left(0 < \alpha < 90^{\circ}\right), \qquad (4.1a)$$

where b is the scattering factor, and η there is a dependence of the magnetic coupling coefficient on the angular distance, measured from the wound test coil.

Data b for various grades of ferrites are shown in Table 1.

Table 1

Ferrite brand	Scattering factor b (1/*degr*)
2,000 HM 16×10×4.5	0.00075
600 HH 16×8×6	0.0015
400 HH 7×4×2	0.00275
100 HH 40×25×7.5	0.00675
30 HF 20×10×5	0.0175

In the presence of scattering, formula (1.1) requires clarification. In the formula (1.1) you must enter the correction factor $F(N, \eta_0)$

$$L = \frac{\mu\mu_0}{2\pi} hN^2 \ln\frac{D}{d} F(N, \eta_0), \qquad (4.1)$$

where N is the number of turns of a single-layer coil, η_0 is the coefficient of magnetic coupling between adjacent turns. The relationship between adjacent turns is determined by the formula

$$\eta_0 = e^{-2b\alpha_0}, \qquad (4.2)$$

Where $\alpha_0 = 104l/d$ is the angular distance between adjacent turns, expressed in degrees, and η_0 there is a coefficient of magnetic coupling between adjacent turns of a single-layer coil.

If a single-layer coil is wound on a small part of the ferrite torus, then the correction factor can be calculated by the formula (without deducing)

$$F(N,\eta) = \frac{1}{N^2}\left[N + 2\eta\frac{(N-1) - N\eta + \eta^N}{(1-\eta)^2}\right]. \qquad (4.3)$$

In this formula, the assumption is made that the mutual connection between the coils decreases exponentially. For small coil lengths, this assumption is valid. The values of the function $F(N,\eta_0)$ for different values of N and η_0 are shown in Table 2 and Fig.6.

Table 2 The values of the function $F(N,\eta_0)$ for some values of N and η_0

N	η_0 = 0,95	η_0 = 0,90	η_0 = 0,80	η_0 = 0,70
3	0,956	0,913	0,831	0,753
4	0,939	0,881	0,774	0,678
5	0,923	0,852	0,724	0,616
6	0,907	0,824	0,680	0,563
7	0,893	0,798	0,641	0,518
8	0,878	0,773	0,605	0,479

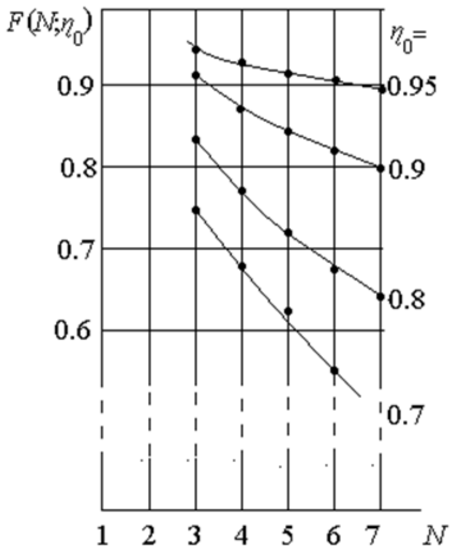


Fig.6

The dependency graphs are shown in Fig. 6. This data is sufficient for some conclusions. For example, if there are no strict requirements for the dimensions of the device, then it makes sense to use ferrites of large cross-section. This will reduce the number of turns, reduce the losses in the wires and reduce the scattering of the magnetic field.

Transformer. Obviously, the primary and secondary windings need to be closer to each other in order to minimize the leakage inductance. As an example, let us consider a transformer with a transformation ratio of 1:1 and the number of turns of the primary and secondary windings equal to 2. Different versions of the arrangement of turns are shown in Fig. 6a.

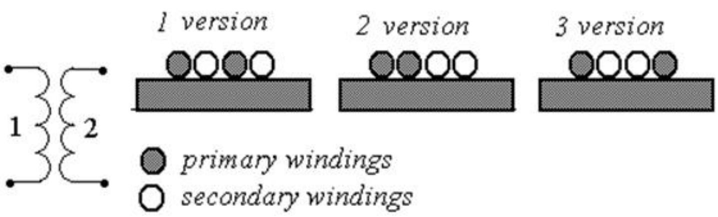


Fig. 6a

We write the expressions for the inductance of the primary winding, the secondary winding, the mutual inductance and the coupling coefficient of the windings.

First version

$$L_1 = 2L_0(1+\eta_0^2);\ L_2 = 2L_0(1+\eta_0^2); M = L_0\eta_0(3+\eta_0^2);\ \eta = \eta_0\frac{(3+\eta_0^2)}{2(1+\eta_0^2)}.$$

Second version

$$L_1 = 2L_0(1+\eta_0);\ L_2 = 2L_0(1+\eta_0);\ M = L_0\eta_0(1+\eta_0)^2;\ \ \eta = \eta_0\frac{(1+\eta_0)}{2}.$$

Third version

$$L_1 = 2L_0(1+\eta_0);\ L_1 = 2L_0(1+\eta_0^3); M = 2L_0\eta_0(1+2\eta_0);$$

$$\eta = \eta_0\frac{(1+2\eta_0)}{\sqrt{(1+\eta_0)(1+\eta_0^3)}}$$

A comparative evaluation of the magnetic coupling coefficients is given in Table 3.

Table 3

η_0		0,95	0,9	0,85	0,8	0,7
1 version	η	0,961	0,920	0,876	0,829	0,728
2 version	η	0,926	0,855	0,786	0,720	0,595
3 version	η	0,973	0,943	0,910	0,873	0,788

The considered example shows how important it is to choose the correct distribution of turns of the primary and secondary windings to minimize the leakage inductance or increase the magnetic coupling of the transformer windings.

V. Methods to Reduce Magnetic Flux Dispersion

The main problem of designing HF transformers using ferrite magnetic cores is the problem of minimizing the scattering of magnetic flux. Obvious ways are the choice of magnetic conductors (magnetic wires) with the highest possible relative magnetic permeability. However, at high frequencies, large losses limit the use of high-grade μ ferrites. Another way is the maximum tight winding of inductances and the maximum possible convergence of the secondary and primary windings. The third is the distribution of turns of the secondary winding relative to the primary so as to ensure the maximum possible magnetic coupling between them.

There is another way to reduce the scattering flux – internal shielding.

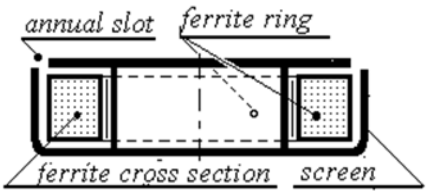


Fig.7

As shown by experimental studies, an effective way is the "screening of the ferrite ring". Its essence is simple. If you cover the ferrite with a conductive layer, then the entire HF magnetic flux will be inside the ferrite. Currents of Foucault will not let him off the screen. However, with this method, the windings wound on top of such a system will not be able to excite the magnetic flux in the ferrite.

Way out of this situation is quite simple. A ring is cut through the circumference in the screen, as shown in fig. 7. With this method, the screen is no longer a closed loop. The experimental dependence η on the angle α for ferrite without a screen and for ferrite with a screen is shown in Fig. 8. As can be seen from the graphs, the screen significantly reduces the scattering of magnetic flux.

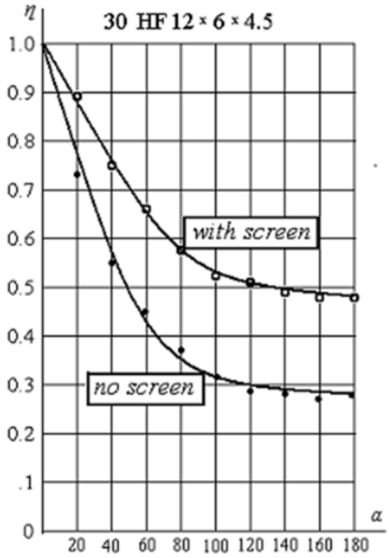


Fig. 8

The screen (metal coating of the ferrite surface) can be applied in various ways (chemical, electrochemical, etc.). Metal is plastic. With such processing, the metallized surface of the torus does not possess pronounced abrasive properties. This allows coils to be wound directly on a metal surface. For ordinary ferrite surface, this method is unsuitable. The surface of the ferrite before winding the coils should be covered with any material to protect the insulation of wires. And this, in turn, increases the scattering of the magnetic flux, i.e. reduces magnetic coupling between coils.

VI. Conclusion

So, we gave a description of the methodology for measuring the basic parameters of inductances and transformers using ferrite rings. We led to illustrate the results of experimental measurements, which allow a competent approach to solving design problems. We can draw the following conclusions.

1. If there are no strict requirements for dimensions, it is possible to improve the quality of the product by using large ferrites.
2. It is advisable to use tight winding of the coils to increase the interconnection between the coils.
3. Shielding a ferrite ring is a good method for reducing the magnetic field flux and the possibility of using ferrites with minor losses, which have a very small value μ.

The described method of measuring the magnetic flux coefficient can be used for cylindrical ferrite rods, etc. The results will be useful to those who design elements of radio engineering schemes using ferrite rings, relying only on experience and intuition.

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