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Nano-dimensional effect at planar inductance with "conducting film inside current ring"-technology

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Abstract — Properties of vortex current's positive planar inductance (PPI), executed by "conducting film inside current ring"-technology, are considered. The calculation method for frequency-independent inductive properties of conducting film for LF, HF, SHF and EHF frequency bands has been suggested. The existence of nano-dimensional effect, where vortex currents manifest their paramagnetic properties has been pointed out. It has been shown that inductance of film depends of geometric dimensions only and frequency band depends of resistivity. The medium frequency of PPI operational band increases with the growth of film's resistivity. The investigated nano-dimensional effect permits to increase the value of planar inductance at the square of 100x100 micron from 7 till 50 times.

Key words **—positive planar inductance (PPI), cylindrical film, current ring, nano-dimensional effect, LF (low frequency), HF (high frequency), SHF (super high frequency), EHF (extremely high frequency).**

I. Introduction

The planar inductances, which are realized at insulating base as multi-turns circular, spiral, square and more complex geometric forms, for example, orthogonal spiral, are widely used in modern devices for communication and telecommunications, in the structure of "system-on-chip" or "system-in-package" [1].

The methods of calculation of frequency-dependent inductance of solid conducting cylinder with vortex currents' azimuthal density have been proposed in papers [2-5].

The paper object is to suggest the method of calculation of frequency-independent microscopic planar inductance for its creation over breakthrough "conducting film inside current ring"-technology. The realization of this technology permits to increase surface density of inductance till the limit value of 10 H/m^2.

II. Construction of planar inductance with thin cylindrical film

At figure 1 the construction of inductance suggested, which uses well-known single-turn topology of its creation [1] has been adduced.

The additional thin film with $h_2 << h_1$ thickness and $R < R_1$ radius from material, which has given conductance and has no electric contact with the turn, has been introduced into internal area of the turn (current ring) from metal film with thickness h_1.

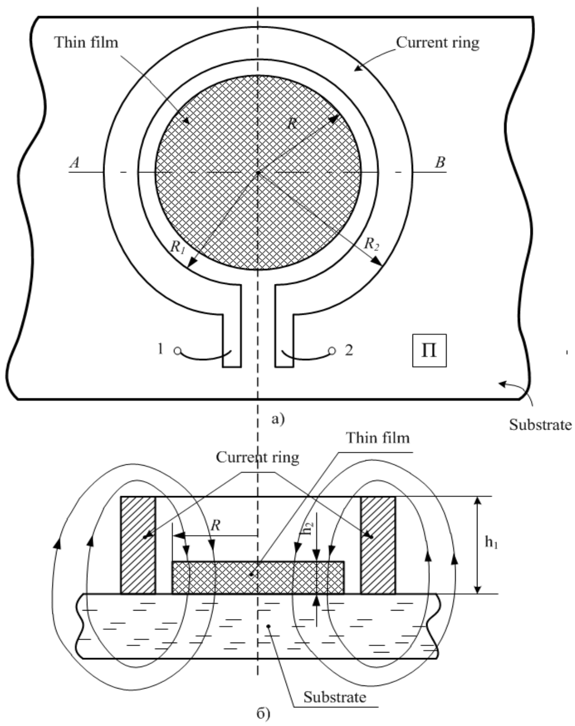

Fig. 1. The construction of inductance suggested (a) and its vertical section AB (б)

There are following designations at fig. 1, 2: R – the radius of additional thin film, h_2 – its thickness; R_1 – internal radius of the turn (current ring) from metal film with thickness h_1; R_2 – external radius of the turn; 1 and 2 are terminals of integral inductance to insert it into electronic circuit.

III. Method of calculation of conducting film's frequency-independent inductance

At fig. 2 the directions of main vectors of problem have been shown. The inductance of construction L (fig. 1) in regard to terminals 1 and 2 is summed from two components

$$L = L_c + L_F \tag{1}$$

where L_c – inductance of the turn (current ring), which calculation can be executed at the base of formulas and charts, represented in [1]; L_F – flux inductance of additional thin film h_2, which calculation has been represented below.

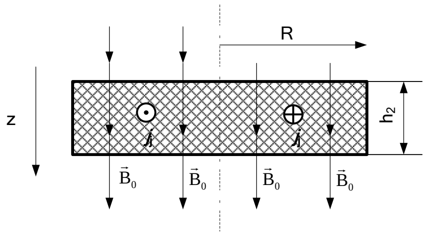

Fig. 2. The directions of main vectors of problem

Let's suppose that additional thin film (continuous, conducting, non-magnetic) at fig. 2 is in external homogeneous variable magnetic field, directed at axis *z*, which has the single component $\vec{B} = (0,0,B_z)$ only. This external magnetic field is created by the turn (current ring), but its dependence on time has a form

$$B_z = B_0 \cos \omega t . \tag{2}$$

We suppose for simplicity that homogeneous magnetic field B_0=*const* doesn't depend on cylindrical coordinates of system (r,φ,z) and has been limited in radial direction by external radius of thin film, and in axial direction – by the thickness of thin film, designated as h_2.

The variable magnetic field over such orientation will generate in the thin film the vortex electric field, which strength $\vec{E} = (0,E_\varphi,0)$ has the single component only [6].

The components of variable electromagnetic fields in conducting film at fig. 2 have been related between themselves by the first Maxwell equation, written in projections of cylindrical system of coordinates (r,φ, z)

$$\sigma(rot\vec{E})_z = -\frac{\partial B_z}{\partial t} , \tag{3}$$

where $\sigma = \pm 1$ – the refining sign factor. It involves in himself two possible orientations of vortex electric field's rotor in regard to original direction of vector B_0. As experiments, carried out by American technologists [7], show, the value $\sigma = -1$ appears in cylindrical films with the thickness of tens and hundreds nanometers. The Foucault currents in such ultrathin films form frequency-independent positive inductance L_F, which is brought to terminals 1 and 2 of integral inductance, manifesting its unexpected weak ferromagnetic properties.

Suppose in (3) that

$$\sigma E_\varphi = E_0(r) sin \omega t , \tag{4}$$

from equation (4) we get equation, connecting $E_0(r)$ and B_0

$$\frac{1}{r}\frac{\partial}{\partial r}(r\sigma E_0) = \omega B_0 , \tag{5}$$

where r – the radius of current observation point at cylindrical system of coordinates, which can varies in the band of $0 \div R$.

The solution of equation (5) for $E_0(r)$ has a form

$$\sigma E_0(r) = \omega B_0 r / 2 + C_1 / r , \tag{6}$$

where C_1 – the constant.

Let's remove singularity in the solution (6) under $r \to 0$ by suppose C_1=0. This condition under $B_0 = 0$ brings to $E_0 = 0$. It is seen from (6) that azimuthal vector's component of vortex electric field's strength is linear function of radius r with the scale

$$E_* = \omega B_0 R / 2 = \pi f B_0 R . \tag{7}$$

The relation $\omega = 2\pi f$ has been taken into account in the scale of strength. Then (6) in the view of (7) under $0 \le r \le R$ has a form

$$E_0(r) = \sigma E_* r / R . \tag{8}$$

The density of Foucault currents is calculated from differential Ohm's law

$$j_\varphi = E_\varphi / \rho , \tag{9}$$

where ρ – the electrical resistivity of additional thin film.

It is seen from (9) that density of Foucault current in homogeneous conducting medium ρ=*const* also is linear function of radius r and also depends on time as E_φ

$$j_\varphi = \sigma j_0(r) sin \omega t , \tag{10}$$

where $j_0(r)$ has been connected with the scale of current density

$$j_* = \pi f B_0 R / \rho \tag{11}$$

by relation

$$j_0(r) = j_* r / R . \tag{12}$$

The vortex current, inducted in the whole additional thin film, can be obtained from integration of current density at cylindrical coordinates

$$i = \int_S \vec{j} d\vec{s} = \int_0^{h_2}\int_0^{R} j_\varphi drdz = i_* \, sin \omega t , \tag{13}$$

where

$$i_* = j_* h_2 R / 2 = \pi f B_0 h_2 R^2 / (2\rho) \tag{14}$$

– the scale of inductive current.

The density of vortex Foucault currents (10) creates inherent magnetic field $\vec{B}_1$ in film's space.

The distribution of substance reply's magnetic field can be calculated from the second Maxwell's equation, written in cylindrical system of coordinate (r, φ, z):

$$(rot\,\vec{B}_1)_\varphi = -\frac{\partial B_{1z}}{\partial r} = \mu_0 j_\varphi\,. \qquad (15)$$

By integrating of (15) for initial condition $B_{1z}(0) = 0$ in the view of (10) we get

$$B_{1z} = -\sigma B_{1*}(r/R)^2 \sin\omega t\,, \qquad (16)$$

where

$$B_{1*} = \mu_0 j_* R/2\,, \qquad (17)$$

the scale of induction of substance reply's magnetic field. We can relate it with induction of external magnetic field by non-dimensional parameter β

$$B_{1*} = \beta B_0\,, \qquad (18)$$

which points to the influence of Foucault currents' magnetism:

$$\beta = \frac{\mu_0 \pi R^2 f}{2\rho} = \frac{f}{f_*}\,, \qquad (19)$$

where

$$f_* = 2\rho/(\mu_0 \pi R^2) \qquad (20)$$

– the scale of system's frequency.

Let's investigate the inductive properties of additional thin film and find its flux inductance from the relation:

$$<F> = L_F <i>\,, \qquad (21)$$

where $<F>$ will be considered as summary mean flux over the half-period. This flux crosses over conducting additional thin film and is formed by external variable magnetic field B_0 and substance reply's magnetic field B_1. We'll consider the mean value of one-directional alternating current over the half-period as value of $<i>$. Then the coefficient of proportionality (L_F) between them will play the role of mean flux inductance of additional thin film.

The flux of external homogeneous variable magnetic field has a form

$$F_0 = B_0 \pi R^2 \cos\omega t\,, \qquad (22)$$

and the flux of substance reply's magnetic field is calculated from the relation

$$\begin{aligned} F_1 &= \int_s \vec{B}_1 d\vec{s} = \\ &= -\sigma \int_0^{2\pi} d\varphi \int_0^R B_{1*} \sin\omega t \frac{r^3}{R^2} dr = -\frac{\sigma\pi R^2}{2} B_{1*} \sin\omega t \end{aligned}\,. \qquad (23)$$

The mean value of summary flux over the half-period has a form

$$<F> = <F_0> + <F_1>\,, \qquad (24)$$

where

$$<F_0> = \frac{2}{T}\int_0^{T/2} B_0 \pi R^2 \cos\omega t dt = 0\,, \qquad (25)$$

and

$$<F_1> = -\frac{2\sigma}{T}\int_0^{T/2} B_{1*}\pi R^2 \sin\omega t dt/2 = -\sigma R^2 B_{1*}\,. \qquad (26)$$

By substituting of (25) and (26) into (24) in the view of relation (21), we get

$$L_F = <F>/<i> = -\frac{\sigma\pi R^2 B_{1*}}{2 i_*} = \pm\frac{\mu_0 \pi R^2}{2 h_2}\,. \qquad (27)$$

It is followed from (27) that mean flux inductance L_F of additional thin film over the half-period doesn't depend on frequency and can be as a positive value so a negative one.

For the first time the frequency-independent positive microscopic inductance has been discovered in experiments of American technologists in 2009 [7]. The planar spiral inductor [8]-[10] has been used there.

The comparison of theoretic results obtained with experiments [7] for positive inductance gives satisfactory coincidence with an error of 20 percent. Besides, the comparison permits to ascertain the upper limits on values, which can be substituted into formula (27). The formula is applicable for microfilms with thickness less than 500 nanometers only. Notably, when nano-dimensional effect of Foucault currents, being in the state of strengthening of external variable magnetic field, is manifested.

If the thickness of thin film is h_2>1 micron and h_2<R condition has not been executed, then the film can be in the state of frequency-dependent dynamic inductance, which vanishes at the two characteristic frequencies [11].

The values of flux inductance L_F, calculated from (27), which can be realized at nano-dimensional effect for thin film with radius R=50 micron have been adduced in table 1.

Table 1

The dependence of thin film's flux inductance L_F from its thickness h_2

h_2, nm	50	100	150	200	250	300	350
L_F, nH	100	50	33,3	25	20	16,7	14,3

Herewith, the resistivity of the thin film does not influence at the value of inductance between terminals 1 and 2, but it varies the frequency band only, where such inductance will be permanent. The given frequency band can be estimated from the condition $0{,}1 f_* < f < 10 f_*$, where f_* - the scale of conducting film's frequency (20), represented in table 2.

Table 2

The frequency's scale of conducting film with radius of 50 micron

N Or/sqs	The substance	The resistivity, Ohm·m	The frequency's scale, Hz
1	copper	$15{,}5\cdot10^{-9}$	$3{,}14\cdot10^{6}$
2	aluminum	$25{,}0\cdot10^{-9}$	$5{,}0\cdot10^{6}$
3	tungsten	$48{,}9\cdot10^{-9}$	$10{,}0\cdot10^{6}$
4	nickel	$61{,}4\cdot10^{-9}$	$12{,}4\cdot10^{6}$
5	nichrome	$1{,}0\cdot10^{-6}$	$203\cdot10^{6}$
6	Electronic silicon (KEF)	$1{,}0\cdot10^{-3}$	$203\cdot10^{9}$

It is seen from tables 1 and 2, that application, for example, of aluminum under sputtering of additional thin film with radius R=50 micron and thickness of h_2=100 nm permits to obtain thin film's flux inductance L_F=50 nH. Such thin film will provide frequency-independent inductance at the frequency band from 0,5 till 50 MHz.

The estimations, represented in tables 1 and 2, affirm the ability of solution of given problem. Under change of film's thickness from 50 nm till 350 nm the inductance proposed varies in the band from 100 nH to 14 nH, that is more better (in7-50 times) than maximal inductance, which is known in traditional CMOS-technologies, attained in one layer at the same square [12].

IV. Conclusion

The construction and calculation of PPI with "conducting film inside current ring"- technology, being suggested, has significant advantages in comparison with classic single-turn solution. The nano-dimensional effect, which has been experimentally discovered in [7] and theoretically affirmed in this paper, permits to realize in 7-50 times higher values of microscopic integral inductances at the same square. The selection of resistivity's value of material, from which the thin film is created, permits "to shift" operational frequency band of suggested inductance into given frequency band.

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