Design and Simulation of the Thin Film Pulse Transformer

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Abstract A new thin film pulse transformer for using in ISND and ADSL systems has been designed based on a domain wall pinning model, the parameters of nano-magnetic thin film such as permeability and coercivity can be calculated. The main properties of the thin film transformer including the size, parallel inductance, Q value and turn ratio have been simulated and optimized. Simulation results show that the thin film transformer can be fairly operated in a frequency range of 0.001~20 MHz.

Key words thin solid film; pulse transformer; domain wall pinning model; simulation;

1 The Pinning Model of Thin Film Core Materials

The base parameters of magnetic thin film are the permeability and coercivity. Assuming the presence of a domain wall, Polka’s pinning model including impurity, as shown in Fig.1, can be used to describe the variation in the coercively of magnetic thin film. Fig.1 shows a part of the film with two sections of oppositely magnetized volumes divided by a 180° Bloch wall. The thickness and length of the film are denoted as \( t(x) \) and \( L \), respectively. An external magnetic field is applied along the \( Y \)-axis, so that the wall moves in the \( X \)-direction.

![Fig.1 The schematic of domain wall model](image)

The total energy density can be written as the sum of the magnetic wall energy \( E_\omega \) and Zeman energy \( E_z \).

\[
E = E_\omega + E_z
\]

(1)

Supposing that spherical nonmagnetic impure particles of average radius \( r_i \) and concentration \( n_i \) are uniformly embedded in the films, the wall energy density \( \gamma' \) is described as follows
\[ \gamma'(x,y) = \gamma(x) \left[ 1 - \pi \sum_i \left( r_i^2 - y^2 \right) n_i \right] \quad y \leq r_i \] (2)

\[ E_x = \gamma'(x,y) t(x) L \] (3)

\[ E_z = -2H_{ex} M_s L \int_0^x (t'(x')) dx' \] (4)

Minimizing the total energy with respect to the position of the domain wall, a critical field \( H_{ex} \) can be calculated.

\[
\begin{align*}
&\frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} = 0 \\
&\frac{\partial E_{as}}{\partial x} + \frac{\partial E_{as}}{\partial y} + \frac{\partial E_z}{\partial x} = 0
\end{align*}
\] (5)

The maximum derivative of the domain wall energy determines the coercive field \( H_c \). The position gradient of wall energy density will have the maximum value at \( y = r_i \):

\[ H_c = \frac{1}{2M_s} \left[ \frac{\partial \gamma}{\partial x} \right]_{max} + \frac{1}{2M_s} \left[ \gamma \frac{\partial t(x)}{\partial x} \right]_{max} + \frac{1}{M_s} \gamma(x)_{max} \pi \sum_{i=0}^n r_i n_i = H_p^m + H_p^s + H_c^m \] (6)

For a uniaxial anisotropy and a 180 Bloch wall, the domain wall energy can be written as

\[ \gamma(x) = 4\sqrt{AK} \] (7)

\[ K(x) = K_u + \frac{3}{2} \lambda \sigma + \Delta K \sin \left( \frac{2\pi x}{l} \right) \] (8)

where \( A \) is exchange energy and \( K \) is the anisotropy energy, \( K_u \) and \( 3/2 \lambda \sigma \) are the bias anisotropy and magneto elastic energy, \( L \) is the wavelength of the fluctuation and \( \Delta K \) is the average fluctuation amplitude of the anisotropy energy. Therefore, the first term of Eq.(6) can be expressed as

\[ H_p^m = \frac{2\pi \Delta K}{M_s l} \sqrt{\left[ K_u + \frac{3}{2} \lambda \sigma + \Delta K \right]} \] (9)

The second term of Eq.(6) describes the dependence on the surface roughness of thin films, which can be given by an average thickness \( t_0 \) and amplitude of the surface roughness modulated by \( \sin(2\pi l) \), i.e.

\[ t(x) = t_0 + \Delta t \sin(2\pi x / l) \] (10)

\[ H_p^s = \frac{4\pi \Delta t}{M_s l} \sqrt{\left[ K_u + \frac{3}{2} \lambda \sigma + \Delta K \right]} \] (11)

The permeability \( \mu_e \) of thin film materials can be given by the Herzer equation

\[ \mu_e = p_u \left[ \left( M_u^2 A^4 \right) / \mu_0 K^4 D^4 \right] \] (13)

\[ H_e = p_x \left[ \left( K^4 D^4 \right) / M_u^2 A^2 \right] \] (14)

\[ \mu_c = p_p p_c \left[ M_s \left/ (\mu_0 H_m) \right. \right] = p_x p_c \left[ A \left/ (\mu_0 H_m^{m} + H_p^m + H_c^m) \right. \right] \] (15)

where \( D \) is the grain size, \( p_u \) and \( p_c \) are constants.

## 2 The Loss and Parallel Inductance of Thin Film Transformer

The equal circuit of the thin film transformer is shown in Fig.2. \( U_i \) is primary inductance, \( R_1 \) and \( R_2 \) are the resistance of primary and secondly, \( R_b \) is the lose resistance; \( R_p \) is the parallel core resistance. According to the changes of based electronic circuit, the parallel inductance is described as

\[ L_p = \frac{\mu_0 H_e A N^2}{l_e} \] (16)

\[ L_p = \frac{2E_i (\mu_0 H_c)}{aoB^2 A l_e} \] (17)

\[ \text{Fig.2 The equal circuit} \]

with \( A_j = A_j^c / 8 \), \( l_j = A_j^c + B_j^c / 2 \), and \( B_j = B_j^c / 3 \), where \( A_j^c \), \( B_j^c \) and \( C_j^c \) are the length, width and thickness of the transformer, respectively. \( E \) is the inductance voltage, and \( \omega = 2\pi f \). The total loss of the transformer includes core loss (Iron \( P_e \)) and coil loss (copper \( P_o \)).

\[ P_e = P_e + P_o \] (18)

\[ P_e = \left( 3\mu_0 \alpha d \lambda H \right) V f + \pi B^2 A f (4r) \quad V_e = A l_e \] (19)

\[ P_o = P_e + P_o + P_2 \] (20)

In Eq.(20), \( P_e, P_o, \) and \( P_2 \) describe the DC current loss. Loss of surface eddy current and near loss of eddy current could be expressed as
\[
\begin{align*}
P_d &= I_d^2 R_d = 4I_d^2 \rho N \left( \frac{A'}{B'} l_c \right) \left( \frac{2 A'}{B'} + 1 \right) \pi d^2 \\
P_a &= i^2 R_a = i^2 \left( \mu_0 \mu_r \rho \frac{f}{\pi} \right)^{1/2} / d \\
P_p &= \pi \omega^2 B_{c}^2 l_{w} (B' - A'/4) F_{d} d^4 / (128 \rho)
\end{align*}
\]  

(21) \quad (22) \quad (23)

with

\[
l_{w} = \frac{A'}{B'} l_{c} \left( 2 \frac{A'}{B'} + 1 \right)
\]

where \( B_0 \) is the saturation inductance flux, \( F_{\omega} \) is the stiffness of surface effect, \( I_0 \) is the DC current, \( \alpha \) is the amplitude of exchange current, \( R_d \) and \( R_a \) are the equal resistance of DC loss and surface loss, respectively, \( \rho \) is the resistivity, \( d \) is the radius of coil, and \( N \) is the number of coil.

Minimizing the total energy, we can get the formula as follows

\[
\frac{dp_0}{dN} = 0 \quad \frac{dp_0}{dB_0} = 0
\]

(24)

For the high efficiency thin film transformer (\( \eta \geq 0.9 \)), we obtained

\[
P_{L} \approx R_{0}
\]

(25)

The parameters of thin film transformer can be decided by the Eq.(25).

3 The Efficiency and Output Power of Thin Film Transformer

Supposing the rate of heating exchange is constant \( R_{0} \) (about \( 300 \mu W \cdot mm^{-2} \)), then

\[
P_{i} = R_{0} A_{c}
\]

(26)

Here, \( A_{c} \) is the area of core and coil surface, that is

\[
A_{c} = 8 \frac{A'}{B'} l_{c} \left( 2 \frac{A'}{B'} + 1 \right)^2
\]

(27)

We have

\[
P_{i} = 8 R_{0} \frac{A'}{B'} l_{c} \left( 2 \frac{A'}{B'} + 1 \right)^2 = t_{i} l_{c}^2
\]

(28)

\[
P_{L} = t_{L} V_{c} + t_{F} A_{e} = t_{L} A_{c} + t_{F} A_{e}
\]

(29)

Here

\[
t_{i} = 8 R_{0} \frac{A'}{B'} \left( 2 \frac{A'}{B'} + 1 \right)^2
\]

(30)

\[
t_{L} = W_{d} f = \left( \frac{B_{0} d H}{\pi} \right) f
\]

(31)

\[
t_{F} = \pi B_{e}^2 f^2 / (4 \rho)
\]

(32)

For high efficiency thin film transformer

\[
P_{i} \approx R_{0}
\]

So the efficiency and output power of the transformer:

\[
P_{o} = P_{i} - P_{L}
\]

(33)

Here \( P_{i} \) and \( P_{o} \) are the input power and output power, respectively. \( P_{L} \) is the total loss of the transformer.

4 Design and Simulation of Thin Film Transformer

In order to design thin film transformer, the software named as MTDF1.0 based on the Windows9.X platform is developed. The main menu is not shown here. Two types of transformer based on Co and Fe are design with various turn ratios \( N_{1}/N_{2} \). For Co based transformer, the basic size parameters are: \( length=4 \text{ mm}, width=3 \text{ mm}, and thickness=3 \text{ \mu m} \). The height and width of the wind is \( 3 \text{ \mu m} \) and \( 3 \text{ mm}, \) respectively. The turn ratio \( N_{1}/N_{2} \) is set as \( 1:2, 2:2, 2:5 \), and \( 3:4 \). For Fe based transformer, the length, width and thickness are \( 12 \text{ mm}, 6 \text{ mm}, \) and \( 3 \text{ \mu m}, \) respectively. The height and width of the wind is \( 3 \text{ \mu m} \) and \( 6 \text{ mm} \). The turn ratio \( N_{1}/N_{2} \) is set as \( 1:2, 2:3, 1:4, \) and \( 3:4 \), respectively. The calculated properties of thin film transformer are shown in Fig.3.

The results in Fig.3 show that the \( Q \) value of Co base transformer is small at \( 1~500 \text{ KHz} \) but soars to over \( 18 \) at the high frequency. However, for Fe base thin film transformer, the maximum \( Q \) value of 15 is obtained in low frequency of \( 1~500 \text{ KHz} \) rather than high frequency. So we can design and manufacture the thin film transformer with Co based core at high frequency, while with Fe based core at low frequency.

<table>
<thead>
<tr>
<th>( f ) (MHz)</th>
<th>DC resistance (Ohm)</th>
<th>Parallel inductance (( \times \text{nH} ))</th>
<th>AC resistance (Ohm)</th>
<th>Q factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1~500 KHz</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>0.5~20 MHz</td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

(a) Co-based transformer
5 Summary

The size parameters of thin film transformer calculated by our theoretical formulae have been given with the size of 4×3 mm for the Co core film and 12×6 mm for the Fe core film. The theoretical calculation for the characteristic parameters of thin film transformer shows that the $Q$ value of Co base transformer is small at 1~500 KHz, the DC resistance between 1.5Ω and 3.6Ω, AC resistance between 0.38Ω and 0.95Ω, and parallel inductance between 205 nH and 315 nH. However, the maximum $Q$ value of Fe base thin film transformer is about 15 at frequency of 1~500 KHz, the DC resistance between 3.29Ω and 10.09Ω, AC resistance between 0.82Ω and 2.78Ω, parallel inductance between 235 nm and 285 nm.

We conclude that to achieve better characteristics of thin film transformer, the Co based core can be used at high frequency, while the Fe based core can be used at low frequency.

References


Brief Introduction to Author(s)

LIU Bao-yuan (刘保元) is now pursuing his Ph.D. degree in UESTC. His research interest includes thin film transformer.

SHI Yu (石玉) is an associate professor of UESTC. His is engaged in the application field of magnetic thin film including sensor, read-out head and transformers.

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