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A Novel Transmission-Line Type High Frequeny Transformer using A Fine-Grain Mn-Zn Ferrite

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Abstract — **A novel transmission-line type high-frequency transformer has been developed by using a fine-grain Mn-Zn ferrite. The device consists of a fine-grain Mn-Zn ferrite core, polyimide insulator, copper planar winding and copper ground-plane, which operates as a distributed constant circuit. A quarter-wavelength transmission-line transformer with a large voltage-gain under high impedance termination has been investigated, and has been applied for high frequency power conversion.**

index terms **; Fine-grain Mn-Zn ferrite, Transmission-line, Transformer, High voltage gain, Discharge lamp**

I . INTRODUCTION

Recently, Ohguchi et al. [1] reported a novel scheme for an electronic-ballast for High Intensity Discharge lamp using a distributed constant line. They used a quarter-wavelength distributed constant line for a step-up transformer, because it had large voltage-gain assuming a high impedance load, for example, a discharge lamp. However, since the operating frequency of the ballast circuit was 1MHz, a coaxial-cable used as a transformer had a length of 50m. The long cable length is due to the small effect of the wavelength shortening.

On the other hand, the authors have proposed a novel magnetic device with a transmission-line structure [2][3]. This device consists of magnetic layers, dielectric layers, conductor lines and ground-plane, which operates as a distributed constant line. By using the large effect of the wavelength shortening due to the magnetic and dielectric layers, a small size quarter-wavelength transformer can be operated at a frequency of 1MHz.

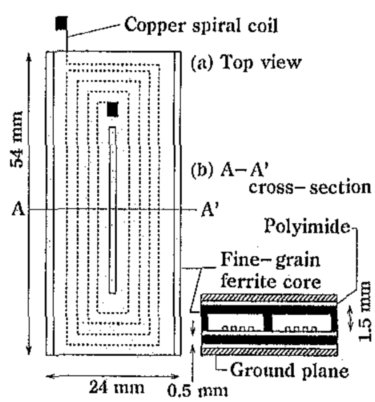

Fig.1 Transmission-line transformer using Mn-Zn ferrite core.

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II . TRANSMISSION-LINE TRANSFORMER

A. Transformer Structure

Fig.1 shows a schematic view of the structure of the transmission-line transformer using a fine-grain Mn-Zn ferrite core.The fine-grain Mn-Zn ferrite has grains with a diameter of a few μ m, and a high frequency iron loss is much smaller than that of the conventional Mn-Zn ferrite [4]. As shown in Fig.1, the device has a multilayered sandwich structure which consists of an inner planar spiral winding, ground-plane, dielectric layer, and fine-grain Mn-Zn ferrite core. This device functions as a distributed constant line. A distributed inductance Lo can be enhanced by ferrite core with a high permeability, and a distributed capacitance Co between conductor line and ground-plane is caused by the composite layer with ferrite and dielectric layers. Hence the wavelength of the standing wave becomes much shorter than that of free space.

B. Analysis of the Transmission-Characteristics

The in-plane magnetic flux $\phi(x)$ in the magnetic core is given by using the Jones' model [5] for a structure with a straight conductor line sandwiched between the top and bottom magnetic cores. The Jones' equation is;

$$\frac{d^2\phi(x)}{dx^2} - \frac{1}{\lambda^2}\phi(x) = -\frac{\alpha}{\lambda^2} I \qquad (1),$$

$$\lambda = \sqrt{\frac{\mu_s \cdot g \cdot t_m}{2}} \qquad (2),$$

$$\alpha = \frac{\mu_0 \cdot \mu_s \cdot t_m}{2w} \qquad (3),$$

I is the current flowing in the conductor line, μ_s is the static relative permeability of the magnetic core, g is the distance between upper and lower magnetic cores, t_m is the thickness of the magnetic core, and w is the conductor line width. Jones investigated the inductance and efficiency of the thin film recording heads on the basis of the static magnetic field analysis.

In order to estimate the dynamic behavior of the transmission-line transformer, the authors have replaced the static relative permeability by the complex relative permeability. Therefore, in the Jones' model;

$$\mu_s = \mu_s' - j\mu_s'' \qquad (4).$$

Consequently, λ , α and $\phi(x)$ become;

$$\lambda = \lambda' - j\lambda'' \qquad (5),$$

$$\alpha = \alpha' - j\alpha'' \qquad (6),$$

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$$\phi(x) = \phi(x)' - j\phi(x)'' \qquad (7).$$

$\phi(x)'$ and $\phi(x)''$ can be calculated using the same boundary condition as the Jones' method. Real and imaginary inductances in the single conductor line can be derived. The actual transformer has some conductor lines, hence for getting the distributed inductance $Lo(i)$ in the 'i' th conductor line, all of the interactions between adjacent conductor lines should be taken into account. Since these calculations were complicated, the numerical calculations were performed using the software package "Mathematica" [6].

In addition, the distributed conductor line resistance $Rco(i)$ has been estimated by using the method for a sandwich type planar inductor [7]. In this method, the eddy current due to the perpendicular flux passing through the conductor line was taken into account. The distributed constants $Ro(i)$ and $Lo(i)$ of the 'i' th conductor line are used for calculating the transmission characteristics;

$$Ro(i) = Rco(i) + \omega\, Lo(i)'' \qquad (8),$$
$$Lo(i) = Lo(i)' \qquad (9),$$

where $Lo(i)'$ and $Lo(i)''$ are the real and imaginary inductances of the 'i' th conductor line, and ω is the angular frequency.

As shown in Fig.2, the composite layer with a ferrite layer and two insulating dielectric layers contributes to the distributed capacitance. The dielectric constant and conductivity in each layer are shown in Table 1. The effective constants of the composite dielectric layer can be expressed by the following equations [2];

$$\varepsilon_{eff.} = K_1 \cdot d / (A^2 + B^2) \qquad (10),$$

$$\sigma_{eff.} = K_2 \cdot d / (A^2 + B^2) \qquad (11),$$

where d is the total thickness of the composite dielectric layer, and K_1, K_2, A, and B are as follows;

$$K_1 = A(\varepsilon_1 \cdot \sigma_2 + \varepsilon_2 \cdot \sigma_1) + B(\omega^2 \varepsilon_1 \cdot \varepsilon_2 - \sigma_1 \cdot \sigma_2)/\omega \qquad (12),$$

$$K_2 = \omega B(\varepsilon_1 \cdot \sigma_2 + \varepsilon_2 \cdot \sigma_1) - A(\omega^2 \varepsilon_1 \cdot \varepsilon_2 - \sigma_1 \cdot \sigma_2) \qquad (13),$$

$$A = 2 t_1 \cdot \sigma_2 + t_2 \cdot \sigma_1 \qquad (14),$$

$$B = 2 t_1 \cdot \omega \varepsilon_2 + t_2 \cdot \omega \varepsilon_1 \qquad (15).$$

The distributed capacitance Co and conductance Go can be derived on the basis of the parallel plate model using $\varepsilon_{eff.}$ and $\sigma_{eff.}$, and are as follows;

$$Co = \frac{\varepsilon_{eff.} \cdot w}{d} \qquad (18).$$

$$Go = \frac{\sigma_{eff.} \cdot w}{d} \qquad (19).$$

The characteristics of the transmission-line transformer can be estimated on the basis of the distributed constant circuit theory by using Ro, Lo, Go and Co, and the characteristic impedance Zc is expressed as follows;

$$Zc = \sqrt{(Ro + j\omega Lo)/(Go + j\omega Co)} \qquad (20).$$

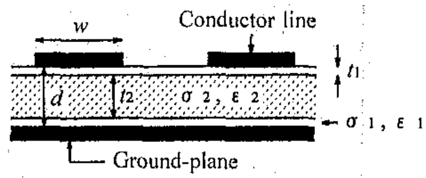

Fig.2 Composite dielectric layer consisting of a ferrite and insulators (polyimide + adhesion resin).

Table 1 Parameters for composite dielectric layer.

	Thickness	Conductivity	Dielectric constant
Insulator	t_1	σ_1	ε_1
Ferrite	t_2	σ_2	ε_2

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Fabrication of the Transmission-Line Transformer

A transmission-line transformer was fabricated by using 500 μm thick fine-grain Mn-Zn ferrite plates, a 35 μm thick copper planar spiral winding (line/space ; 250/260 μm, turns ;16.5), 50 μm thick polyimide sheet and adhesion resin. The air-gap between upper ferrite legs and lower ferrite plate was about 50 μm. The size of the fabricated transformer was 24mm wide, 54mm long and about 2.0mm high. The total conductor line length lc was about 1.8m.

B. Electrical and Magnetic Properties of the Ferrite

Fig.3 shows the frequency dependences of the relative dielectric constant ε_{2s} and conductivity σ_2 in the fine-grain Mn-Zn ferrite. ε_{2s} was very large. However, since σ_2 was relatively high, the conduction loss was not negligible. On the other hand, the frequency dependences of the real and imaginary parts (μ_s', μ_s'') of the complex permeability are shown in Fig.4. μ_s' and μ_s'' were about 1500 and 40 at 1MHz.

C. Electrical Properties of the Insulating Layer

To estimate the properties of the insulating layer with a polyimide sheet and adhesion resin, a parallel plate capacitor with the insulator was used for an admittance measurement. The measured results are shown in Fig.5. In spite of using the organic materials for the insulating layer, conductivity σ_1 and relative dielectric constant ε_{1s} were relatively high. A reason for high σ_1 at high

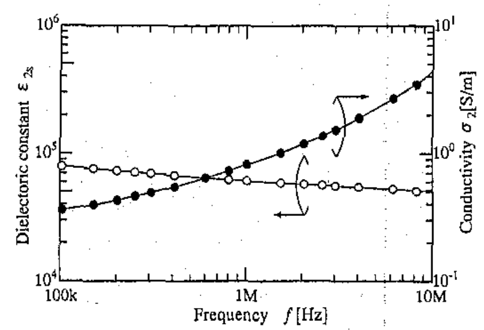

Fig.3 Frequency dependences of the relative dielectric constant ε_{2s} and conductivity σ_2 in the fine-grain ferrite plate.

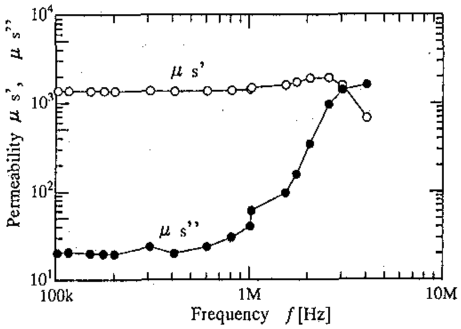

Fig.4. Frequency dependences of the real and imaginary permeabilities μ_s', μ_s'' in the ferrite toroidal core.

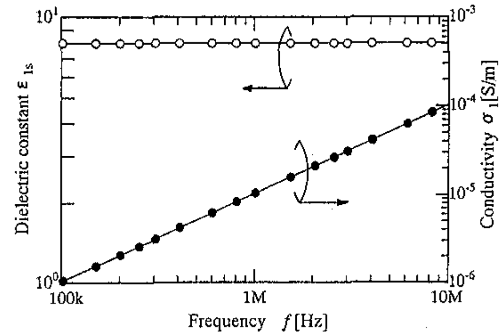

Fig.5. Frequency dependences of the relative dielectric constant ε_{1s} and conductivity σ_1 obtained by admittance measurement for insulating layer with polyimide and adhesion resin.

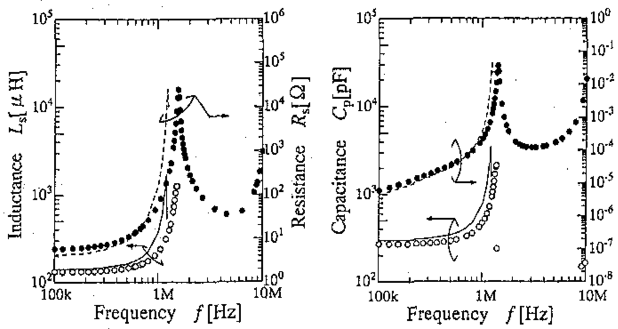

Fig.6. Frequency dependences of input impedance (*Rs*, *Ls*) and admittance (*Cp*, *Gp*) under short and open circuit conditions for the fabricated transformer.

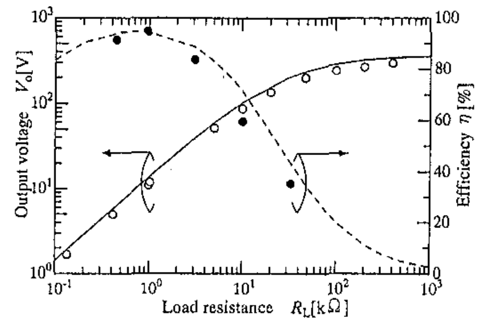

Fig.7. Output voltage *Vo* and transformer efficiency η versus termination resistance R_L measured at 1.3MHz.

frequencies (in other words ; relatively large dielectric loss) may be due to the moisture absorption. For example, polyimide has the typical moisture absorption of 1 %.

D. Transmission Characteristics of the Transformer

Fig.6 shows the frequency dependences of the equivalent inductance *Ls* and resistance *Rs* under short circuit condition, the equivalent capacitance *Cp* and conductance *Gp* under open circuit condition. The frequency at quarter-wavelength condition was about 1.3MHz. Solid and dashed lines represent the calculated values. Black and white circles represent the experimental values. The calculated and experimental results were in good agreement well each other.

Fig.7 shows the output voltage *Vo* and the efficiency η versus termination resistance R_L in the fabricated transformer. Since these data were measured under the conditions for the frequency of 1.3MHz and input voltage *Vi* of 10V, this device functioned as a quarter-wavelength transmission-line transformer. The output voltage *Vo* was increasing with increasing R_L, e.g., *Vo* reached 250V for R_L = 100k Ω . However, for large R_L, *Vo* saturated even as R_L was increasing. This was due to the various losses in the materials used. On the other hand, the efficiency had a maximum value of 95% when the termination resistance R_L was nearly equal to the characteristic impedance *Zc*, where *Zc* was about 0.8k Ω . In the large R_L region, however, the transformer efficiency η was decreasing with increasing R_L, e.g., η was about 60% for an R_L value of 10k Ω . In this figure, the calculated values are shown as the solid and dashed lines. The calculated *Vo* and η were comparable to the measured ones.

IV . CONCLUSION

The transmission-line transformer for high frequency power conversion was fabricated by using a fine-grain ferrite. Although the transformer under 100k Ω load condition had a voltage gain of 25, the power efficiency was very low. In order to obtain higher voltage gain and higher efficiency under high impedance load condition, all of the losses including iron loss, copper loss and dielectric loss should be as small as possible.

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