J. Magn. Soc. Jpn., **30**, 523–527 (2006) 〈Paper〉

Transmission Loss Analysis and Design of Transmission Lines for High-Data-Rate HDDs

N. Nishiyama and T. Ikeda*
Hitachi Global Storage Technologies Japan, Ltd., *Kirihara 1, Fujisawa, Kanagawa 252-8588, Japan*
*Hitachi Advanced Digital, Inc., *Yoshida 292, Totsuka-ku, Yokohama 244-0817, Japan*

The suspension used in a hard disk drive (HDD) mainly supports the magnetic head, which flies at a height of several nanometers over a recording medium. Micro-strip transmission lines for the read and write data signals are installed on the stainless steel of the suspension. The conventional transmission line system uses stainless steel as the base metal, which determines the suspension's mechanical characteristics. This stainless steel base metal is the dominant contributor to high-frequency signal losses. The base metal signal loss contributions are revealed by electromagnetic field simulation. At high frequencies, a significant amount of power is consumed in the base metal by induced currents and the base metal's resistance. To reduce the base metal power, we calculated the power consumption, using a copper base metal. Electromagnetic simulation results support our findings on the contributions of the base metal to the signal losses. The results indicate that the thickness of the copper base metal should be more than 2 micrometers. We suggest a new layer structure for the suspension with reduced transmission loss. To confirm that the new layer structure of the transmission line system reduces the transmission loss, measurements were made on sample coupons using copper base metal and coupons using stainless steel base metal. The results clearly show the benefits of using a copper base metal suspension to reduce the transmission loss for suspension interconnects.

Key words: magnetic recording, HDD, transmission line, transmission loss, high data rate, write current waveform, copper base metal, stainless steel base metal

1. Introduction

Today's maximum data transfer rate for conventional HDDs is close to or may already exceed 1.2 Gbps. In the near future, higher-data-rate drives will be required.

An HDD consists of a magnetic head, which reads and writes magnetic information, a suspension, which supports the magnetic head, a preamp, which drives the read-write system, and a recording medium. The HDD uses an actuator as a basic element to fix the magnetic head's position on one side of the recording medium. The magnetic head consists of a write head and a read head.

Magnetic data are recorded on a recording medium by treating a "1" bit of write data as a magnetization reversal. Therefore, the write current input into a write head is transmitted as a fixed current by means of a reversal current and "0" and "1" bit of write data. Thus, a write current waveform becomes a rectangular wave with an overshoot current. Furthermore, when a reversal current is used, in order to record a magnetization reversal, the current reversal time has to be shortened. That is, the transmission system is required to reduce the loss not only in the write current frequency but also in the harmonic frequency. A write current waveform is shaped by the preamp, and a reproduction signal from the read head is amplified by it. High-data-rate transmission technology has come to be required for the transmission line between the magnetic head and preamp. A flat design for the characteristic impedance of the transmission line is especially strongly required. Thus, a suspension and a combined "integrated lead suspension " and transmission line have come to be used.

The main purpose of a suspension is to support a magnetic head, to stabilize it, and to enable it to fly over a recording medium. It is necessary to use a thin spring made of stainless steel as a suspension. Therefore, the transmission line will be installed on stainless steel [1]. Furthermore, the transmission line structure is required to be such that the spring characteristic of a suspension is not affected.

Griffith and Dahandeh [2] state that an interconnect with reduced transmission loss would be required to improve the overshoot amplitude of the write current. We know that the insertion loss consists of (a) dielectric loss, (b) power loss due to the induced current, and (c) transmission loss due to roughness on the trace surface. Items (a) and (c) occur at frequencies over 8 GHz. We therefore focused on the power consumption of the trace and ground plane of the transmission line, and analyzed the phenomenon of the transmission loss with a 2.5 D transmission line model by EM simulation [3], in order to understand where the dominant loss occurs in the transmission line. We made some transmission line samples and measured their transmission properties.

2. Transmission loss analysis by EM simulation

We assumed that the transmission loss is due to power consumption. To obtain the power consumption of the trace and ground plane of the transmission line, we adapt the following calculation procedure:

I. Calculation of the current distribution map for the transmission line at 1 GHz, using EM simulation.

II. Calculation of the power consumption, using Eq. (1):

$$P = \int i_c^2 \times \rho(v) dv, \qquad (1)$$

where P is the power consumption, i_c is the current in the trace and metal back, and ρ is the resistivity of the trace and metal back.

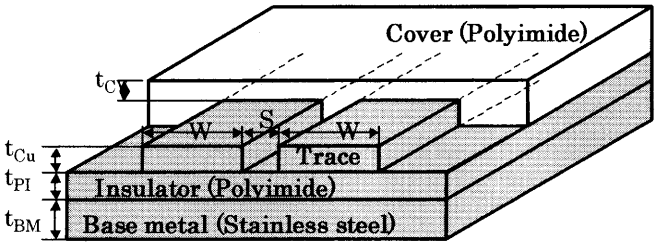
In this equation, the resistivity is constant. Thus, Eq. (1) can be transformed into Eq. (2):

$$P = \rho(v) \int i_c^2 dv, \qquad (2)$$

This equation is applied to (a) the trace and (b) the metal back. We can thus obtain the power consumption in the trace and in the metal back.

2.1 Conditions and Parameters

A conventional transmission line is shaped as a micro-strip line. The structure is shown in Fig. 1. The transmission line consists of a trace pair, an insulator, a base metal, and a cover. The trace pair is made of copper. The insulator and the cover are made of polyimide. The base metal is stainless steel.



t_{CV}: cover thickness
t_{Cu}: trace thickness
t_{PI}: insulator thickness
t_{BM}: base metal thickness
W: trace width
S: space between traces

Fig. 1 transmission line structure on the suspension.

The parameters for this simulation are the conductivity and thickness of the base metal, and the insulator thickness.

A current flows in the opposite direction (differential) as a signal in the trace pair. The other conditions for the simulation are shown in Table 1. They were calculated by using a 2D-EM simulator [3].

2.2 Results of the simulation and discussion

Table 1 Simulation conditions

Trace	
W : Width	50 μm
S : Space	15 μm
t_{cu} : Thickness	10 μm
σ : Conductivity (=1/ρ)	5.8×10^7 S/m
μ_s : Permeability	0.999991
Insulator	
t_{PI} : Thickness	From 5 μm to 10 μm
ε s : Permittivity	3.4
Base metal	
t_{BM} : Thickness	W : Width
σ : Conductivity (=1/ρ)	From 1.1×10^7 S/m to 5.8×10^7 S/m
μ_s : Permeability	From 1.0 to 0.999991
Signal current	1A/trace, differential

We can consider a reduction of the power consumption as a either decrease in the current or as an increase in the conductivity. We calculated the current distribution map on a cross-section of traces and base metal, and obtained the power consumption of each part in the transmission line. The results are shown in Table 2. In case B (the structure of today's transmission lines), the base metal consumes much more power than the trace. Case A in Table 2 shows the case where the thickness of the insulator is smaller. The base metal consumes twice as much power as the traces. In the traces, the power consumption in case A and case B is the same. In the base metal, however, the power consumption in case A is much higher than in case B.

Table 2 Power consumption of each part

	Case A	Case B (today's)	Case C
Power consumption			
Trace	60 W/m	60 W/m	60 W/m
Base metal	110 W/m	80 W/m	20 W/m
Condition			
Conductivity			
Trace	5.8×10^7	5.8×10^7	5.8×10^7
Base metal	1.1×10^6	1.1×10^6	5.8×10^7
Trace width	50 μm	50 μm	50 μm
Space	15 μm	15 μm	15 μm
Thickness			
Trace	10 μm	10 μm	10 μm
Insulator	5 μm	10 μm	10 μm
Base metal	20 μm	20 μm	20 μm

Conductivity :

5.8×10^7 S/m $\longrightarrow$ Copper

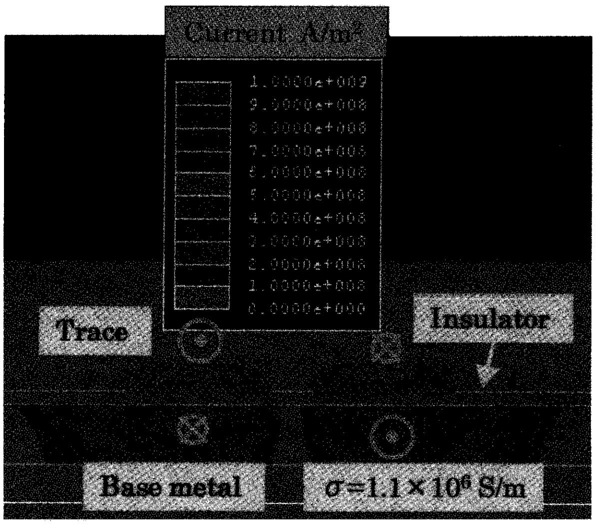
1.1×10^6 S/m $\longrightarrow$ Stainless Steel

Case C in Table 2 shows the situation when different materials are used as the base metal. In the traces, both case B and case C result in the same power consumption, but in the base metal, case C involves much less power consumption than case B. In case C, the base metal consumes only a third of the power consumed by the traces. To understand the reason for these phenomena, we show a map of the current distribution map on a cross-section of the transmission line in Fig. 2. Figure 2(a) shows the current distribution map for case A in Table 2. Figure 2(b) shows the current distribution map for the case where copper is used as the base metal in the framework of case A in Table 2. In both cases, the current in the base metal flows underneath the respective traces in the trace pair in opposite directions. The current is induced by the magnetic flux of the signal current in the trace pair. In particular, the induced current distribution in the base metal is different in (a) the case where stainless steel is used as the base metal and (b) the case where copper is used as the base metal. In the first case, the induced current flows almost throughout the entire thickness of base metal in the area below the traces, as shown in Fig. 2(a). In the second case, the current flows in the skin-depth and on the trace side of the base metal below the traces, as shown in Fig. 2(b). When copper is used as the base metal, there is a secondary induced current flowing below the first induced current in the thick base metal. Thus, case C in Table 2 shows an improvement in the power consumption of the transmission line. In other words, it is very important to reduce the power consumption by using a highly conductive material as the base metal.

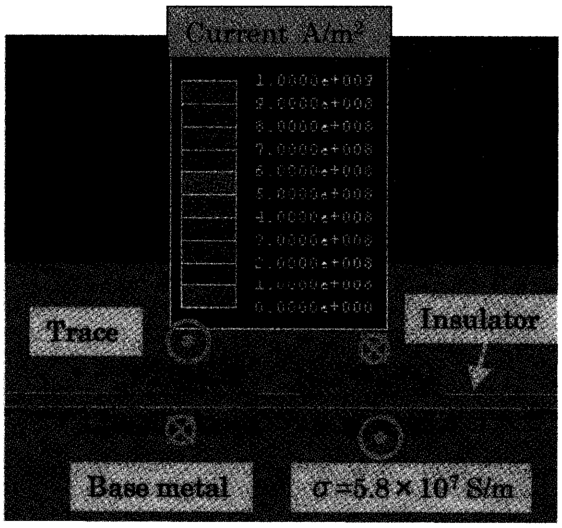
The suspension has to support the magnetic head as a mechanical part. The suspension therefore needs low stiffness, but it needs a stainless steel plate as a spring. In other words, the transmission line should have a structure with low stiffness, a minimum total thickness, and a stainless steel base metal.

Let us change the viewpoint. Figure 3 shows the power consumption as a function of the base metal thickness with the parameter of conductivity.

We will first focus our discussion on the power consumption of a base metal with a thickness of over 5 micrometers. The power consumption of a base metal with high conductivity is much lower than that of one with the low conductivity. Moreover, in the case of low conductivity (1.1 x 10^6), the power consumption increases with decreasing thickness of the base metal. On the other hand, in the case of high conductivity (5.8 x 10^7), the power consumption remains more or less the same with decreasing thickness. The cause of this phenomenon is as follows. In the case of the low-conductivity base metal (stainless steel), if the thickness of the base metal is reduced, the flow of the induced current will be influenced by the thickness, as



(a) Stainless steel base metal



(b) Copper base metal

⊗ and ⊙ means current flowing direction.

Fig. 2 Current distribution map of stainless steel base metal case and copper base metal case.

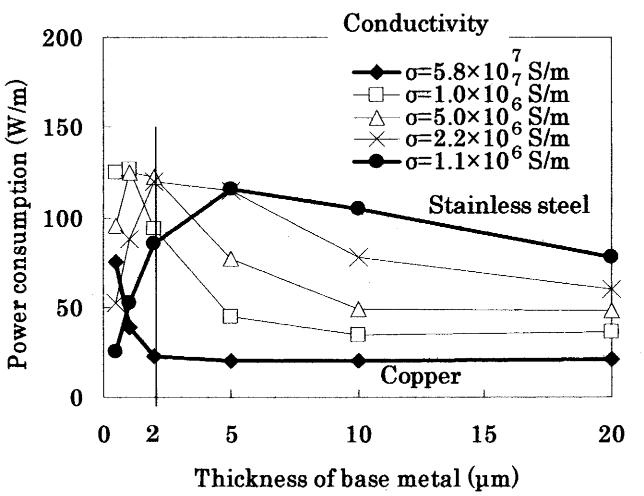
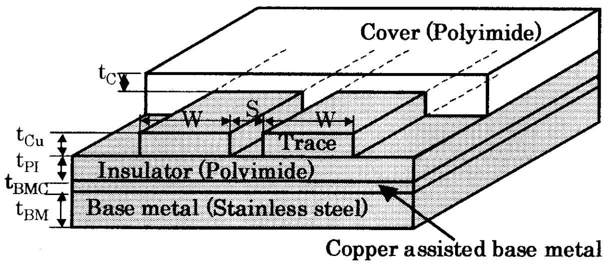


Fig. 3 Power consumption depend on the thickness of base metal with parameter of conductivity.

shown in Fig. 2(a). However, in the case of the high-conductivity base metal (copper), the flow of the current will not be influenced by the thickness, as shown in Fig. 2(b).

Next, we will turn our attention to the power consumption of the base metal with a thickness of less than 5 micrometers. In this regime, for the case of low conductivity (1.1×10^6), the power consumption keeps on decreasing with decreasing thickness. For the case of high conductivity (5.8×10^7), on the other hand, the power consumption keeps on increasing with decreasing thickness. For the case of medium conductivity (5×10^6), the power consumption first increases and then decreases with decreasing thickness. For each conductivity condition, there is a different thickness at which the power consumption reaches a peak. The area to the left of the peak power consumption in each conductivity condition has an extraordinary property. In this area, the base metal layer is not able to assist the trace pair. In particular, when copper is used as the base metal, if the thickness of the base metal is less than 2 micrometers, the transmission loss will increase, because an insufficient induced current flows in the base metal.

Therefore, we will propose a new structure for the suspension transmission line, which gives it good characteristics both as a mechanical part and as an electrical part. Our proposed structure is shown in Fig. 4. Our proposal is to add a copper-assisted base metal between the insulator layer and the stainless steel base metal layer. The thickness of the copper-assisted base metal layer is from 2 μm to 5 μm.



t_{CV}: cover thickness
t_{Cu}: trace thickness
t_{PI}: insulator thickness (10 μm)
t_{BMC}: copper assisted base metal thickness (from 2 μm to 5 μm)
t_{BM}: base metal thickness (around 20 μm)
W: trace width
S: space between traces

Fig. 4 The proposal of the new transmission line structure with good characteristics both mechanical part and electrical part.

3. Evaluation of the transmission line samples

Ideally, we would like to fabricate and evaluate transmission line samples with our proposed structure. However, since the process of copper plating stainless steel is very difficult, we are unable to create transmission line with our proposed structure. Instead, therefore we made simple structured samples of a transmission line with a copper base metal of 5 μm thickness, and measured their transmission properties, in order to determine the difference in the transmission loss when a different material is used as the base metal.

3.1 Layer structure and measurement

We made simple structured transmission line samples with a 5 μm copper base metal. One has an insulator thickness of 12.5 μm, and the other has an insulator thickness of 25 μm. These samples are structured by using a double metal flex, covered on one side with solder resist. Their detailed layer structure is shown in Table 3, with the conventional structure as a reference.

Table 3 The layer structure of the transmission line samples.

Structure	Material & Thickness		
	Type-1	Type-2	Conventional (Ref.)
Layer			
Cover : t_{CV}	Solder resist 12 μm	12 μm	Polyimide 3 μm
Trace : t_{Cu}	Copper 15 μm	15 μm	Copper 12 μm
Insulator : t_{PI}	Polyimide 25 μm	12.5 μm	Polyimide 10 μm
Copper assisted base metal : t_{BMC}	Copper 5 μm	5 μm	
Base metal : t_{BM}	(---------) ------	------	Stainless steel 24 μm
Trace design (common design both Type-1 and Type-2)			
Width : W	From 40 μm to 150 μm		
Space : S	From 25 μm to 120 μm		

The thickness of the insulator is 25 micrometers in Type-1 and 12.5 micrometers in Type-2. We measured their S-parameters and TDR waveforms, and obtained their transmission loss and characteristic impedance.

3.2 Results and discussion

The measurement results are shown in Fig. 5 as the transmission loss in relation to the differential characteristic impedance of the transmission line samples.

The transmission loss of the Type-1 samples reduces the transmission loss of the conventional type by 17 dB at the same characteristic impedance. However, the insulator thicknesses of the conventional transmission line and Type-1 samples are very different.

Consequently, the transmission loss of the sample transmission lines in Type-2 is 13 dB less than that of the conventional transmission line, with a 13 Ω characteristic impedance difference, because the insulator thicknesses of the conventional transmission line and the sample transmission lines in Type-2 are close. We confirmed that the 5-μm-thick copper base metal helps to reduce transmission loss.

Therefore, our proposed structure for the transmission line will reduce the transmission loss while preserving the mechanical characteristics.

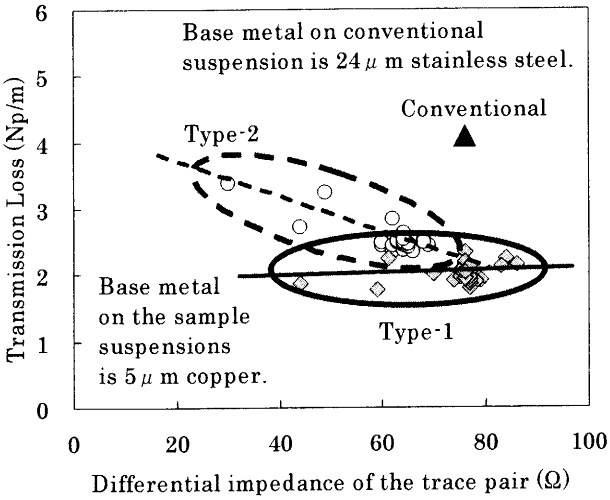


Fig. 5 The relationship between transmission loss and differential impedance of the transmission lines. The benefit of the transmission loss reduction from conventional suspension case to the sample suspension case.

4. Conclusion

In the simulation analysis section, we showed that the transmission loss was able to be defined as the power consumption of the transmission line. In the case of a low-conductivity base metal, stainless steel, the base metal generates about two times as much power consumption as the trace pair. The high-conductivity base metal, copper, generates much lower power consumption than the low-conductivity base metal, stainless steel. Moreover, in the case of the high-conductivity base metal, the induced current flows in the skin depth and on the trace side of the base metal, below the traces. We can therefore design a thinner base metal, but it needs to be at least 2 μm. It seems that the features of metals disappear from the base metal at peak power consumption if it is a thin film with a lower thickness.

We proposed a new layer structure for the transmission line, including a copper-assisted base metal inserted between the insulator and the stainless steel base metal.

In the measurement section, we described how we fabricated simple layered transmission line samples, and showed that the transmission loss is reduced 13 dB by the change in conductivity resulting from changing the base metal from stainless steel to copper, with a 13 Ω characteristic impedance difference. The transmission loss increases with decreasing insulator thickness.

We conclude that the front-end should use a transmission line with a copper-assisted base metal 2 to 5 μm in thickness between the insulator and stainless steel base metal, to reduce the transmission loss. This suspension has good characteristics from both a mechanical and an electrical viewpoint.

Acknowledgements We owe our sincere gratitude to Mr. Ohwaki and Mr. Ookawa in Nitto Denko and Mr. Arai and Mr. Kawatake in NHK Spring for fabrication of the samples, help with calculations, and enlightening discussions.

References

1) K. B. Klaassen, J. C. van Peppen, and Xinzhi Xing: *IEEE Trans. Magn.*, **37**, 619 (2001)
2) J. M. Griffith, Shafa N. Dahandeh; *IEEE Trans. Magn.*, **38**, 1821 (2002)
3) Maxwell 2D, Ansoft Corporation

Received Jun. 27, 2006; Revised Aug. 23, 2006; Accepted Sep. 04, 2006