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A Study on Coplanar Structures for High Speed Transmission

Isao Kaneda, Yukitaka Shirakura, Hirosi Iinaga and Hideo Takakusagi
Oki Printed Circuits Co., Ltd.
Joetsu-City, Niigata, Japan

Abstract
Demand for higher speed digital signal processing is notable today in the electronics industry. To meet this demand, circuit designs that employ coplanar structure, either for both single-end and differential transmission, are increasing. The purpose of coplanar structure is mostly cross-talk (noise) reduction. It is mostly the case that guard-earth lines are added to microstrip line or strip line structure to make coplanar structure. However, electro-magnetic field tends to be very complicated for such structures, and so how the structure is related to characteristic impedance or cross-talk is not well understood yet. For example, there are some cases where characteristic impedance would be 30% or more different by adding coplanar lines to simple micro-strip line structure. In these cases, conventional methods will not work well to predict characteristic impedance with sufficient accuracy. What is making it so difficult is the complicating relation between the signal line references to the ground layer and to the coplanar lines, and so understanding the electro-magnetic reference mechanism with coplanar structure is essential to achieve good enough control of characteristic impedance, noise, and cross-talks. We made a detailed analysis on a coplanar structure and worked out an explanation as to the mechanism with a simple, practical coplanar structure. In this paper, details of our study on coplanar structures shall be reported, with some proposals as to the design of coplanar pattern in terms of cross-talk reduction.

Introduction
In the field of high-speed digital signal processing, the use of printed wiring board (PWB) designs that employ a coplanar structure is increasing. The probable reason is cross-talk noise: circuit designers must pay attention to cross-talk noise when they design a high-frequency circuit. Today, signal speed is getting much higher, while the operating voltage of electronic devices continues to drop.

In general, there are several ways to solve cross-talk noise problems, such as maintaining adequate separation between adjacent signal conductors, abbreviating the length of parallel signal conductors (modifying signal traces), adding a ground trace to a parallel signal conductor (coplanar structure), and so on. However, in practice it is difficult to keep enough space between parallel signal conductors and/or to modify traces within most PWB designs. This is the case because at present, most PWBs do not contain enough space for signal traces. The situation is the same with a coplanar structure, which requires one or two signal conductors to be provided with parallel ground traces, resulting in a circuit that would need more space than a simple microstrip-line or strip-line structure. These methods employ structures that all take up space. Why then do PWB designers employ coplanar structures? Probably, the reason is that such structures are the most effective solution to cross-talk noise in PWB designs.

A coplanar structure with characteristic impedance control can be employed in order to avoid noise problems. However, characteristic impedance control on a coplanar structure circuit is not an easy task. With such a circuit, characteristic impedance would be more of a factor than for the case of a simpler structure, such as a strip or microstrip. Interaction between the signal conductor and the ground trace makes the electric and magnetic fields much more complicated. The situation is the same with the cross-talk noise mechanism. Thus, conventional simulation methods may not work.

This paper shall report the details of the analysis, a proposed formula for characteristic impedance control, and some remarks as to the parameters with respect to cross-talk noise.

Cross-Talk Noise
Solutions to PWB cross-talk noise must address a two-fold problem: near end cross-talk and far end cross-talk. A typical cross-talk noise model is shown in Figure 1. Cross-Talk noise is induced by mutual capacitance and mutual inductance between a signal conductor and a parallel signal conductor.[1, 2, 3]

The near end voltage is given by

$$V_n = (i_{cn} + i_l) \cdot Z_0 \cdot k_n \tag{1}$$

$$t_r \le 2l/l$$

The far end voltage is given by

$$V_f = (i_{cf} - i_l) \cdot Z_0 \cdot l \cdot dv/dt \cdot k_f \tag{2}$$

$t_r \le l/l$ t_r: Input signal rise time, l: signal conductor length, l : transmission speed.

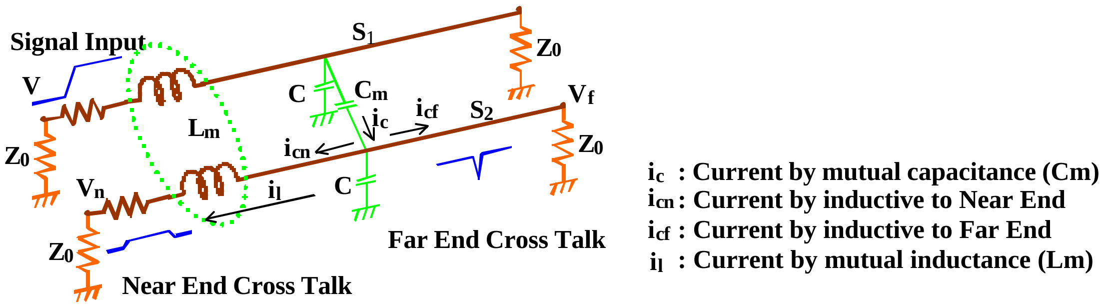

Figure 1 - Typical Cross-Talk Noise Model

If cross-talk voltage exceeds thresholds, it will result in malfunctioning of the circuit. A successful PWB design requires an understanding of which type of cross talk (near end or far end) most affects the circuit performance. Near end cross-talk is not influenced by signal conductor length and input signal rise time, while far end cross-talk is influenced by these factors.

Measurement

Measurements of characteristic impedance and cross-talk noise on a coplanar structure were made on a number of experimental boards with different layer structures, conductor widths, space between signal layer and ground layer, and space between parallel conductors (See Figures 2 and 3).

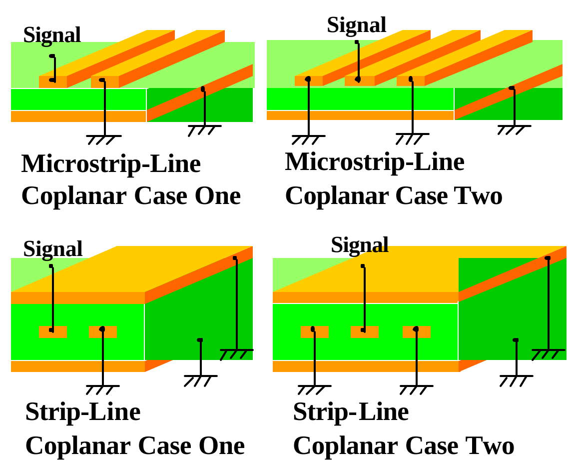

Figure 2 - Measurement of Characteristic Impedance Structure

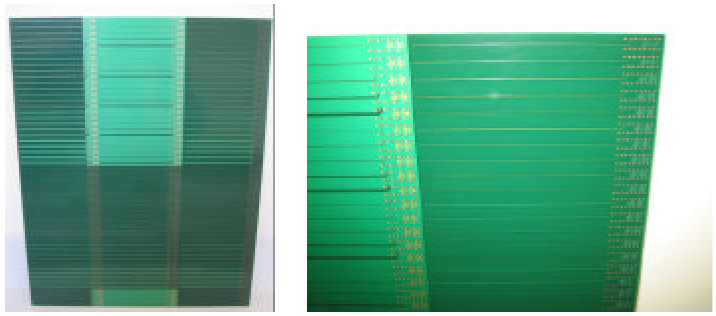

Figure 3 - Schematic of Experimental Board for Characteristic Impedance

Figure 4-7 show the relationship between characteristic impedance and conductor width for both microstrip-line and strip-line structures. The material used in the experimental boards was FR-4; the microstrip-line (with solder resist) and strip-line conductor thickness (t) was about 0.040mm (microstrip) and 0.032mm (strip), respectively; the dielectric thickness (h or h1 and h2) was in the 0.100-0.500 mm range; and the space between parallel conductors (s) was approximately in the 0.100-1.000 mm range.

Figure 4 and 5 show the microstrip-line coplanar case one and case two. Case one has one signal conductor, one parallel ground conductor in coplanar, and ground layer. Case two has additional parallel ground conductors.

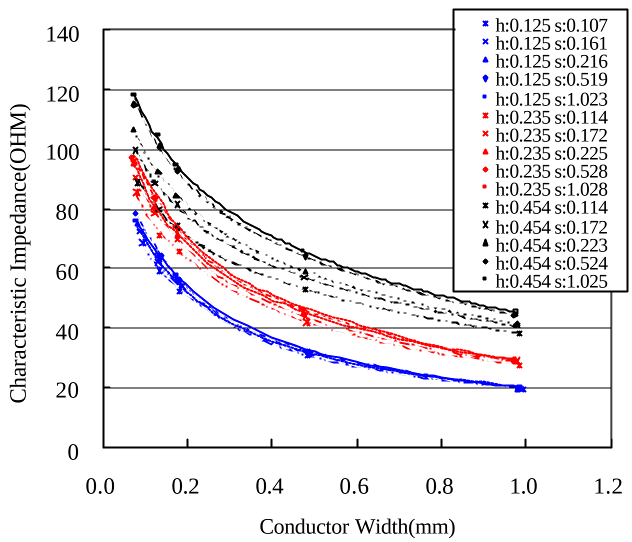

Figure 4 - Characteristic Impedance vs. Conductor Width for Microstrip-Line Coplanar Case One

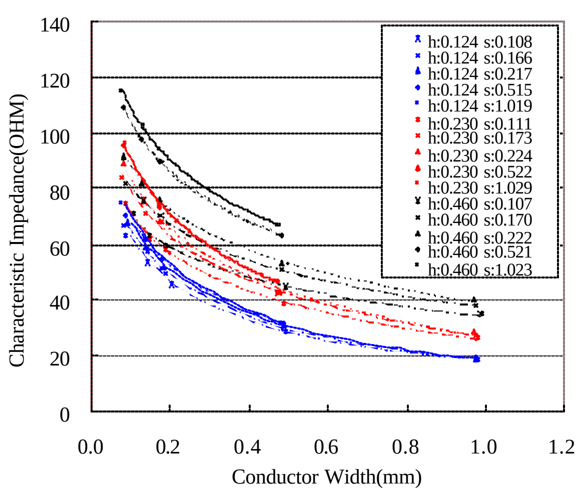

Figure 5 - Characteristic Impedance vs. Conductor Width for Microstrip-Line Coplanar Case Two

Figure 6 and 7 show the strip-line coplanar cases one and two.

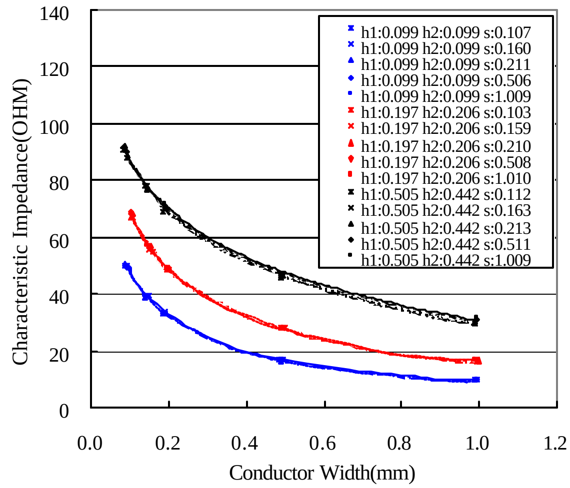

Figure 6 - Characteristic Impedance vs. Conductor Width for Strip-Line Coplanar Case One

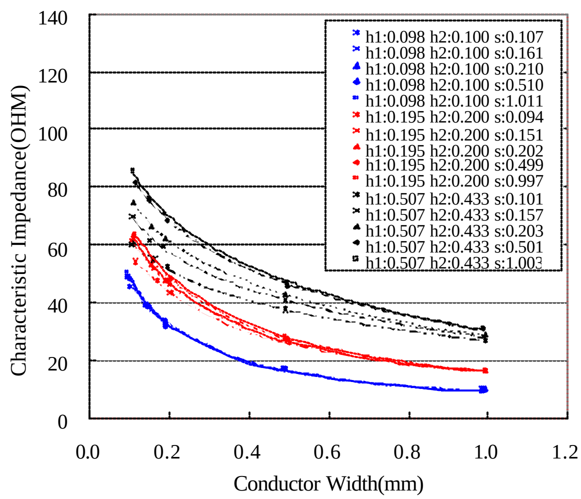

Figure 7 - Characteristic Impedance vs. Conductor Width for Strip-Line Coplanar Case Two

Figures 8 and 9 show the characteristic impedance of a microstrip-line coplanar without a ground layer. The material forming the experimental boards was Fr-4, t is about 0.040 mm, h was about 0.760 and 2.400 mm, and s in the range 0.100-1.000 mm.

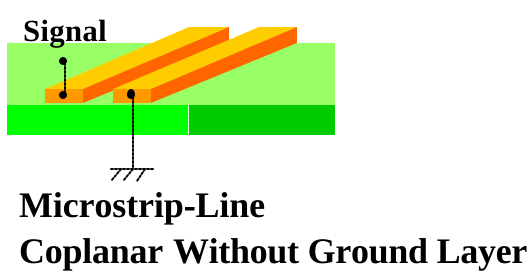

Figure 8 - Measurement of Characteristic Impedance Structure

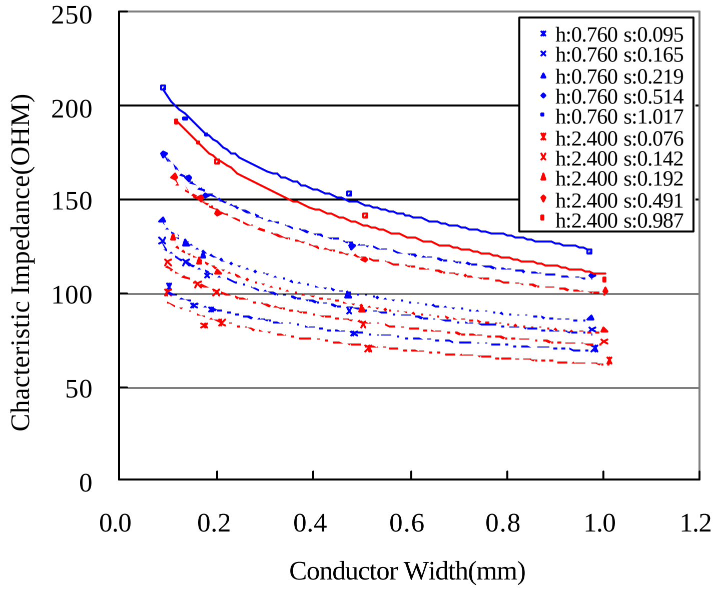

Figure 9 - Characteristic Impedance vs. Conductor Width for a Microstrip-Line Coplanar Structure without a Ground Layer

Measurement of Cross-Talk Noise

Figure 10 shows the measurement of cross-talk noise structure and Figure 11 shows a schematic of experimental board for cross talk noise. Figures 12-15 show the relationship between near end and far end cross-talk for simple and coplanar structures. The experimental board material was FR-4, the microstrip-line (with solder resist) and strip-line conductor thickness (t) was about 0.040mm (microstrip) and 0.032mm (strip), respectively, and the dielectric thickness (h or h1 and h2) was in the 0.100 - 0.500mm range. This yields a space between the parallel conductors (s) in the 0.100 - 1.000mm range. The length (l) of the parallel signal conductors was 315mm. The input step signal was a square wave with 35ps rise time at 200mV and 500kHz.

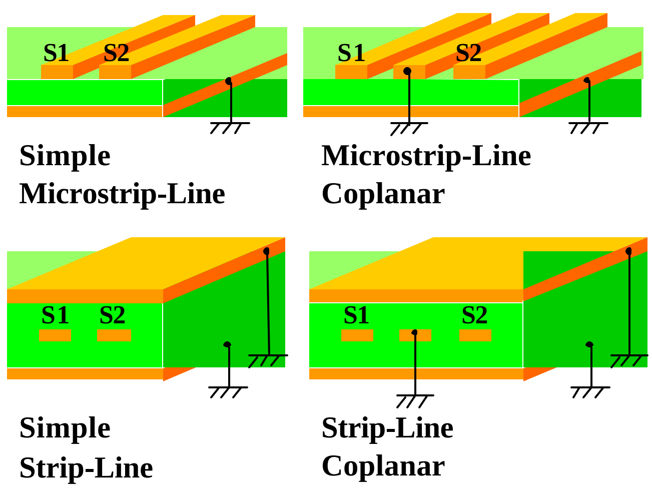

Figure 10 - Measurement of Cross-Talk Noise Structure

Figure 11 - Schematic of Experimental Board for Cross Talk Noise

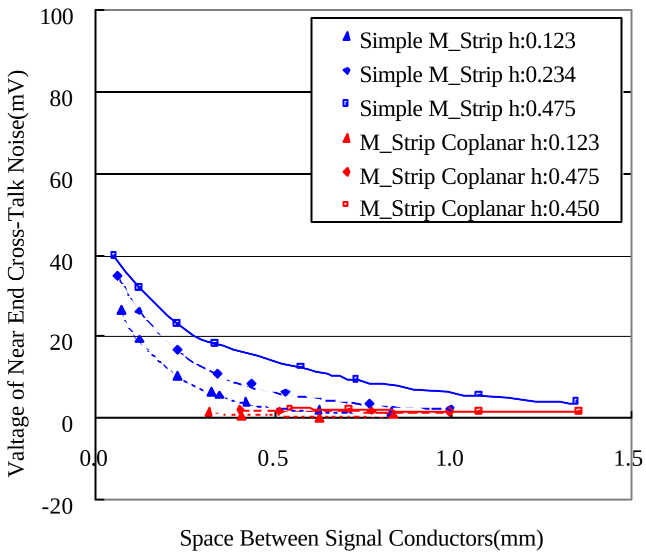

Figure 12 - Near End Cross-Talk vs. Space between Signal Conductors for the Microstrip-Line Structure

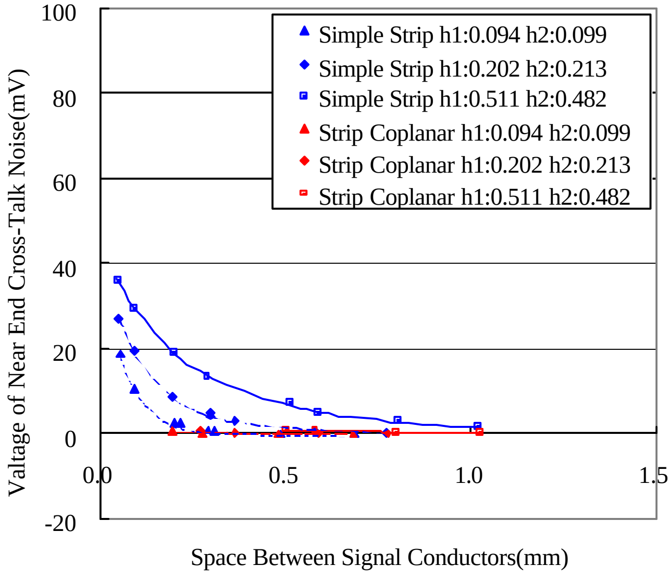

Figure 13 - Near End Cross-Talk vs. Space between Signal Conductors for the Strip-Line Structure

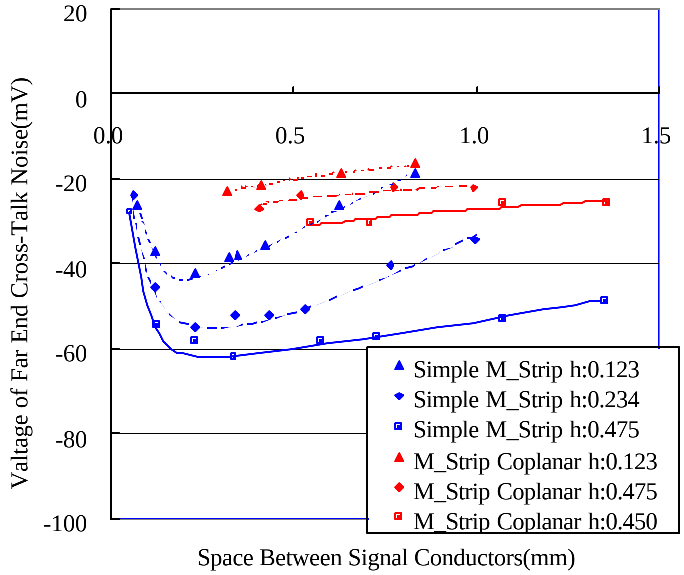

Figure 14 - Far End Cross-Talk vs. Space between Signal Conductors for the Microstrip-Line Structure

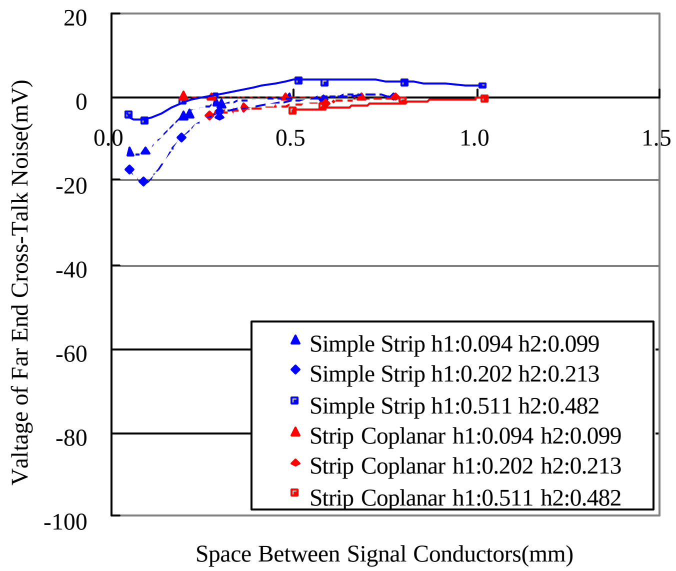

Figure 15 - Far End Cross-Talk vs. Space between Signal Conductors for the Strip-Line Structure

Results and Discussion

Based on the measurements, we studied the characteristic impedance of a microstrip-line coplanar structure. The parameters that determine the characteristic impedance of this structure are conductor width, conductor thickness, dielectric constant of the substrate, and layer-to-layer thickness, particularly the space between the signal conductor and the coplanar ground conductor. The space between parallel conductors is greater for a microstrip-line with a coplanar structure than that without such a structure (Figure 16). Initially, we examined the characteristic impedance relationship between the signal conductor and the coplanar ground conductor.

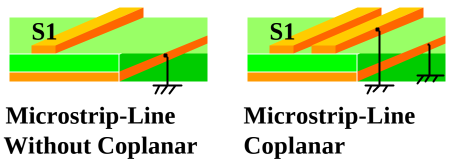

Figure 16 - Simple Microstrip-Line and Microstrip-Line with Coplanar Structure

Figure 17 shows the relation between the characteristic impedance of a microstrip-line coplanar without a ground layer (Z0cmn) and the ratio of signal conductor diameter to space (rd/s). In this case, we note that the characteristic impedance (Z0cmn) is almost independent of dielectric thickness (h), and is proportional to the ratio of the signal conductor diameter to the space between conductors (rd/s).

The rd/s would be given by:

$$rd/s = d/(s+d/2) \quad (3)$$

where d is the signal conductor diameter. However, the signal conductor does not have a circular cross section. The above discussion is based on an assumption of a signal conductor on the PWB that is circular in form. This paper focuses on very high signal speeds, so signals should propagate only along the conductor surface due to the skin effect.

We propose that d would be given by:

$$d = k_d \cdot w \cdot t/p$$

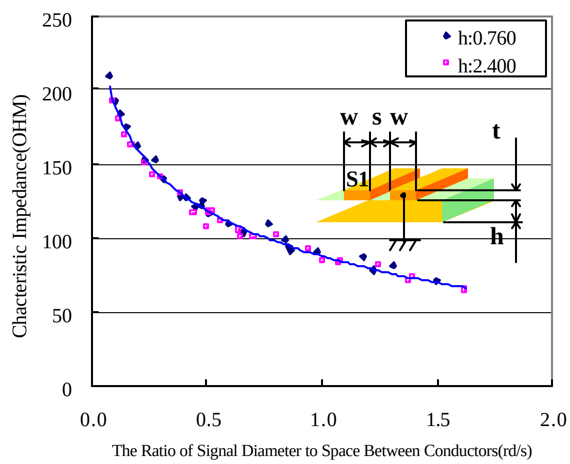

Figure 17 - Z0cmn vs. the Ratio of Signal Diameter to Space between Conductors for a Microstrip-Line Coplanar Structure without a Ground Layer

In the figure, the blue curve represents an approximation of the relation between Z0cmn and rd/s.
This curve is of the form of a natural logarithm, so Z0cmn is given by:

$$Z_{0cmn} = k_0 / \sqrt{e_{re}} \cdot \ln(d/(s+d/2)) + k'_0 \quad (4)$$

Figures 18 and 19 show the relationship between the ratio of characteristic impedance (Z0mf) to characteristic impedance (Z0cm) and the ratio of space between parallel conductors to the layer-layer thickness (rs/h). Z0mf is defined as the characteristic impedance of a simple microstrip-line by formula[4),5)] while Z0cm is the measured characteristic impedance of a microstrip-line with a coplanar structure. The material for these experimental boards was Fr-4, t was about 0.040mm and 0.055, h was 0.100mm to 2.400mm range, and s ranged from 0.100mm to 1.000mm. The data indicates that the ratio of Z0mf to Z0cm is almost proportional to the ratio of s to h (rs/h), while the ratio of Z0mf to Z0cm approaches zero % when the ratio of s to h (rs/h) is two and over.

Ratio of Z0mf to Z0cm: $\left(Z_{0mf}-Z_{0cm}\right)\cdot 100/Z_{0mf}$

Ratio of s to h: $\left(s+d/2\right)/\left(h+d/2\right)$

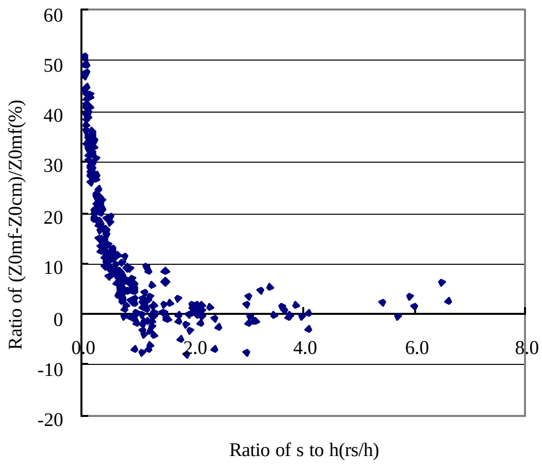

Figure 18 - Ratio of Z0mf to Z0cm vs. rs/h for Microstrip Line with a Ground Coplanar Structure: Case One

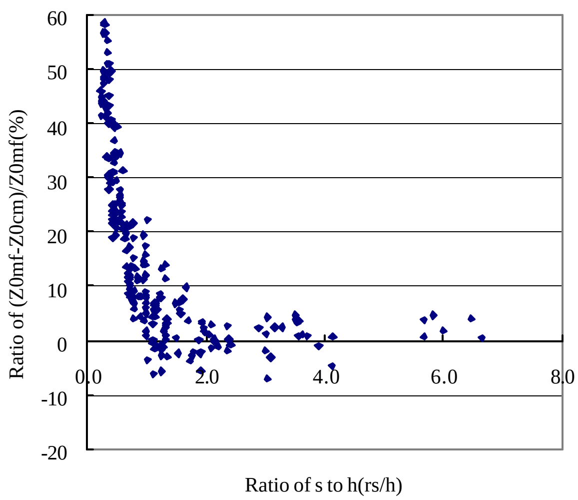

Figure 19 - Ratio of Z0mf to Z0cm vs. rs/h for Microstrip Line with a Ground Coplanar Structure: Case Two

In reality, the ratio of Z0mf to Z0cm is not zero, and appears to have been under-predicted based on the considering the characteristic impedance mutual influence in the microstrip-line and the microstrip-line coplanar structure. Although the graph shows the ratio of Z0mf to Z0cm to be zero and under, these values are probably due to measurement deviation and formula accident error.

Near end cross-talk noise model of simple microstrip-line structure is shown in Figure 20 and cross-talk noise model for a coplanar structure is shown in Figure 21.

We note that the near end cross-talk noise is almost proportional to rs/h. Therefore, the near end cross-talk noise was determined from the ratio of space between the signal conductors (s) to that between the signal layer and the ground layer (h). The result is that the values in Figure 20 are very similar to those in Figure 18. Therefore, the near end cross-talk noise is proportional to the ratio (Z0mf -Z0cm)/Z0mf.

The near end cross-talk noise of a simple microstrip-line would be given by:

$$V_n(\%) = a\cdot\left(\left(s+d/2\right)/\left(h+d/2\right)\right)^b \tag{5}$$

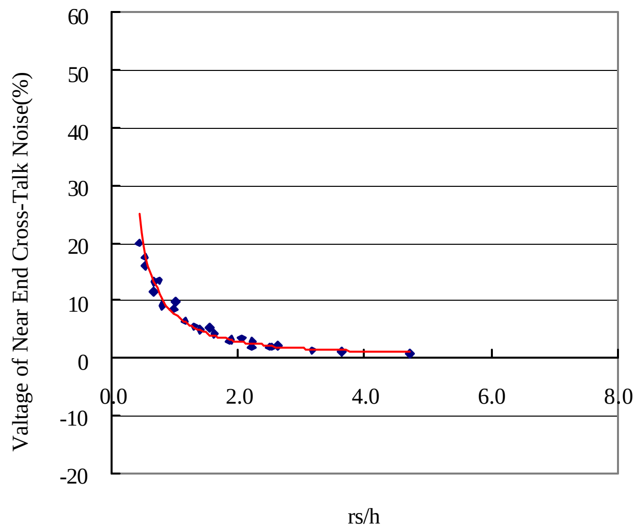

Figure 20 - Near End Cross-Talk Noise vs. rs/h for a Simple Microstrip-Line

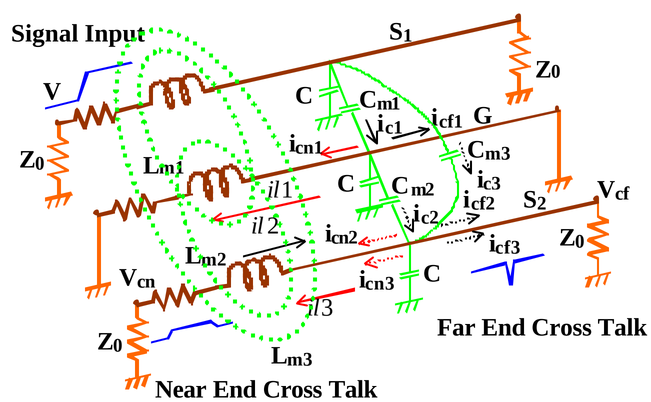

Figure21 - Cross-Talk Noise Model for a Coplanar Structure

The near end voltage with a ground coplanar structure is given by this formula:

$$V_{cn}(v) = \left(i_{cn2} + i_{cn3} - i_{l2} + i_{l3}\right) \cdot Z_0 \cdot k_{nc} \qquad (6)$$
$$t_r \leq 2l/l$$

The near end voltage (Vcn) value can be derived from this formula, albeit with some difficulty. There are more factors of Vcn then is the case with the simple cross-talk model. From a different viewpoint, we examined the cross-talk noise model using a coplanar structure. Figure 22 shows the relation between Vn(%)–Vcn(%) and rs/h. Vn(%) is the near end voltage between the ground conductor and signal conductor from formula(5), Vcn(%) is the near end voltage measured for the coplanar conductor structure, and rs/h is the ratio of space between the coplanar ground conductor and the parallel signal conductor (the layer-layer thickness). The values of Figure 22 are very similar to those in Figure19.

The value of Vn(formula G-s)-Vcn(measurement) of the microstrip-line for a ground coplanar is given by:

$$V_n - V_{cn}(\%) = a_c \cdot \left(\left(s_c + d_c/2\right)/\left(h_c + d_c/2\right)\right)^{b_c} \qquad (7)$$

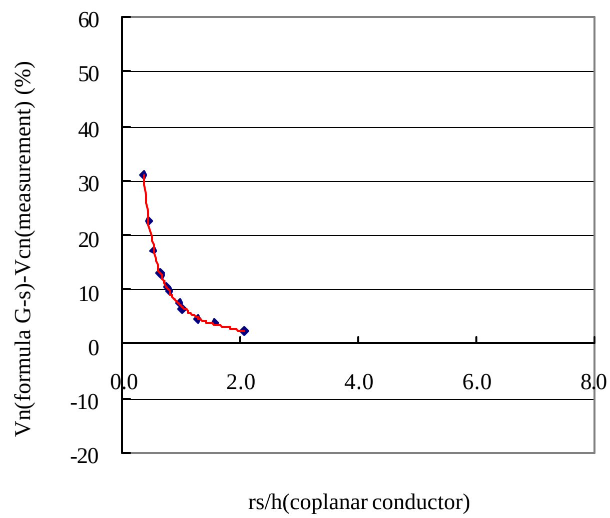

Figure 22 - Vn(formula G-s)-Vcn(measurement) vs. rs/h of Microstrip-Line for a Coplanar Structure. Line Coplanar Structure

In view of formulas (5) and (7), Vcn of the microstrip-line with ground coplanar is given by:

$$V_{cn}(\%) = a \cdot \left((s_c + d_c/2)/(h_c + d_c/2)\right)^b - a_c \cdot \left((s_c + d_c/2)/(h_c + d_c/2)\right)^{b_c} \quad (8)$$

s_c : Space between the signal conductor and coplanar ground conductor, d_c : the ground conductor diameter, h_c : the layer-layer thickness, a and b : the modulus from formula (5), a_c and b_c : the modulus from formula (7).

The measured value of Vcn is very similar to the values of Vcn from formula (8), as shown in Figure 23.

The foregoing discussion has focused on a microstrip-line coplanar structure in near end mode, but it is possible to make the same analysis of other structures such as the strip-line. However, the analysis should be applied to the strip-line case carefully, since it is more complicated than the case of microstrip-line structure.

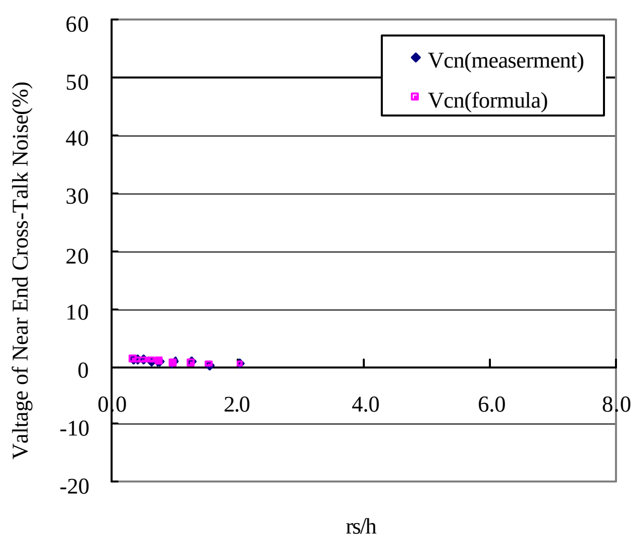

Figure 23 - Measured Vcn Values vs. Vcn Value from Formula 8 for a

Conclusion

By using the formula of characteristic impedance presented here, and by maintaining precise control of manufacturing tolerances for each parameter, we believe it is possible to control a coplanar structure with good accuracy. Moreover, by understanding the mechanism of near end cross-talk noise and by setting the parameters appropriately, one can design a quality printed circuit in terms of minimizing the near end cross-talk noise problem. However, the issue of far end cross-talk noise mechanisms remains to be studied, and warrants future work. Nonetheless, it is evident that far end cross-talk noise is dependent on parallel conductor length, input signal rise time, and the parameters that determine characteristic impedance.

Recommendations on parameter setting are:

1. The coplanar structure is more advantageous than a simple structure for both the microstrip-line and strip-line cases;
2. The s/h ratio should be made as large as possible to minimize the near end cross-talk. This presumably also applies to far end cross-talk.

When designing a PWB for high-speed transmission, as in the case where the coplanar structure is employed, it is necessary to consider the parameters totally. One must consider not only the characteristic impedance and cross-talk noise, which I have discussed in this paper, but also other parameters such as dielectric constant and tangent loss of base material.

Having both simple and coplanar structure on one circuit would make the design more complicated. Various parameters have to be considered in the design of a high-speed transmission circuit, and the overall capability of the PWB designer and manufacturer will become important.

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