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Embedded Optical Fiber

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Abstract
The power attenuation of the optical fiber due to bends is investigated for the feasibility of the integration optical fiber into PCBs.

Introduction

When optical fiber is embedded in PCB, its optical attenuation is the primary concern. It is mainly due to the material, geometry, and layout. However, if the fiber is selected, the first two, the material properties and cross-section, are determined.

Of course, there are many other considerations that affect the attenuation of the embedded optical fiber. They are the choice of single mode vs. multimode, laser, numerical aperture, bits per second, modulation, etc. Usually, those are decided as systematic requirements before the fiber is to be laid out for PCB.

This work focuses on the integration of the optical fiber into PCB and the relation between the attenuation and layout from the viewpoint of the PCB designer. Other optimizations and improvements are separately accomplished.

Unlike the layout of the electrical interconnection, that of the optical wave-guide is largely sensitive to both the horizontal and vertical curvatures. Of course, the former is also affected in microwave frequencies.

The following discusses the attenuation of the optical fiber due to both the horizontal and vertical bends, which is the key concern for the integration of the optical fiber into PCB. In other words, the contribution of the embedded optical fiber to the overall attenuation of PCB optical network is presented as follows.

Linear Optical Fiber Attenuation

The optical attenuation of the optical fiber is expressed in terms of dB (decibels) per meter and abbreviated as dB/m. However, when the attenuation measurement is performed, the theory of the optical attenuation in the fiber ought to be reviewed in order to know what measurement and conversion must be made for obtaining the attenuation in decibels. Also, for the layout design, the implication of the attenuation in dB/m needs to be correctly understood.

The starting point is the experimental observation for the consistent ratio of the optical power loss to the same incremental length of the fiber. This means that the same percentage of the power loss is observed per unit length of the fiber.

However, the raw relation between power loss and length is not convenient to use due to the fact that the loss ratios are not added. Suppose a cable loses power by 20% per 1 meter. The loss for two meters is not 40% but 36% (1– 0.8× 0.8 = 0.36).

In order to circumvent the problem, the logarithmic conversion is used for the attenuation that is 1 – loss:

$$\text{Attenuation (dB/m)} = -10 \log (\text{attenuation in ratio /m}) \quad (1)$$

Using this definition, the logarithmic attenuation for two meters becomes $-10 \log (0.8^2) = -10 (\log 0.8 + \log 0.8)$. This means that each attenuation dB/m is added twice to get the attenuation in dB for two meters. The conversion from the attenuation in dB to the attenuation in ratio is written as

$$\text{Attenuation in ratio} = 10^{\frac{-attenuation(dB)}{10}} \quad (2)$$

In the example, the attenuation is recovered as follows using Equation (2):

$$\text{Attenuation} = 10^{\frac{10[\log(0.8\times0.8)]}{10}} = 0.8\times0.8 = 0.64 \quad (3)$$

Since attenuation, δ, is the same per any incremental fiber length, $\Delta L = 1/n$ meters, the attenuation in dB per meter is expressed using δ:

$$\text{Attenuation dB/m} = -10 \log \delta^n = -10\, n \log \delta. \quad (4)$$

For any length L, the attenuation in dB becomes

$$-10 \log \delta^{L/\Delta L} = -10\, L/\Delta L \log \delta = -L\, 10\, n \log \delta = L \text{ dB/m} \quad (5)$$

Attenuation At Bends

Based on the method for calculating the optical fiber attenuation described above, the attenuation at fiber bends is measured and calculated.

As mentioned earlier, the most important optical attenuations for the embedded optical fiber are those of both horizontal and vertical bends. The attenuation for the straight portion is calculated by Equation (5), once the attenuation in dB per meter is known.

First, the attenuations of horizontal bends are evaluated. As shown in Figure 1, a loop is made of a fiber strip and the power measurement with the loop is compared to one without the loop.

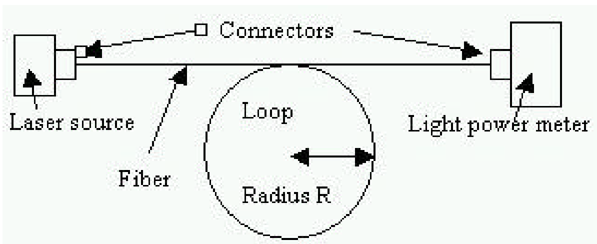

Figure 1 - Power Measurement for Fiber Bends

The ends of the optical fiber are connected with a laser source and a light power meter. Table 1 lists the ratios of the powers of the strip with loops to those without loops for different loop radii.

Figure 2 plots the power ratios versus the radii of the loops.

Table 1 - Ratios of Optical Powers of a Fiber Strip with Loops to Those without Loops

Loop radii (m)	Power ratio (dB)	Standard deviation (dB)
0.012 5	0.125 1	0.012 5
0.009	0.181 8	0.016 8
0.006 5	0.299 8	0.022 2
0.003 5	0.746 9	0.045 7

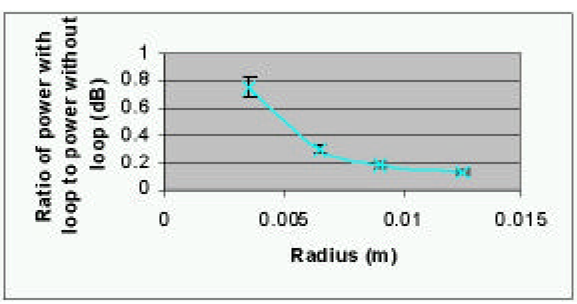

Figure 2 - Ratios of Optical Powers of a Fiber Strip with Loops of Various Radii to Those without Loops

The trend of the optical power attenuation due to the fiber curvature is investigated. However, the information that a CAD designer needs for the layout is specific to the power attenuation per unit length of a loop.

The additive nature of the attenuation in dB with length helps in analyzing the partial contribution of the attenuation. The difference in the attenuation in dB between the fiber with a loop and that without a loop is attributed to the difference in attenuation between the loop and a straight strip with the length of the circumference.

Therefore, the power ratio in dB in Table 1 is interpreted as the difference in dB between the attenuations for the loop and for the straight strip of the length of the circumference.

The values in Table 1 must be divided by the circumferences of the loops in order to have the attenuation difference per meter. Then the differences need to be added to the attenuation of a straight fiber to obtain the attenuation in dB per meter for the loop.

The attenuation in dB/m for the fiber is measured by comparing the power P_1 at the end of a cable of length L_1 with the power P_2 at the end of a cable length L_2 as follows:

$$\text{Attenuation in (dB/m)} = -\frac{1}{L_2 - L_1} 10\log\frac{P_2}{P_1} \quad (6)$$

Substitution of L_1 = 0.2 m, L_2 = 9.144 m, P_1 = 32.8 μW, and P_2 = 14.85 μW into Equation (6) yields 0.385 dB/m. This attenuation is to be added to the difference in attenuation between the loop and the straight strip of the equivalent length to obtain the attenuation of the loop.

The second column in Table 2 is obtained by dividing the values in second and third columns in Table 1 by the corresponding radii in the first column. The last column in Table 2 is obtained by adding 0.385 dB/m to the values in the second column.

Table 2 Power Attenuation for Loops

Loop radii (m)	Attenuation difference between loop and straight strip (dB/m)	Attenuation (dB/m)
0.012 5	1.593 ± 0.159	1.978 ± 0.159
0.009	3.215 ± 0.297	3.600 ± 0.297
0.006 5	7.341 ± 0.544	7.726 ± 0.544
0.003 5	33.965 ± 2.078	34.350 ± 2.078

Figure 3 plots the radii versus the power attenuation of loops in dB/m.

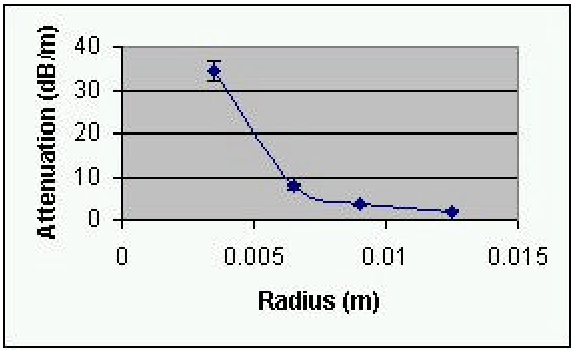

Figure 3 - Attenuation of Optical Fiber Loops

Next, the vertical bends are considered. As shown in Figure 4, a fiber strip of 0.2 m suspends a circuit board that embeds a part of the fiber, which is 0.1 m long.

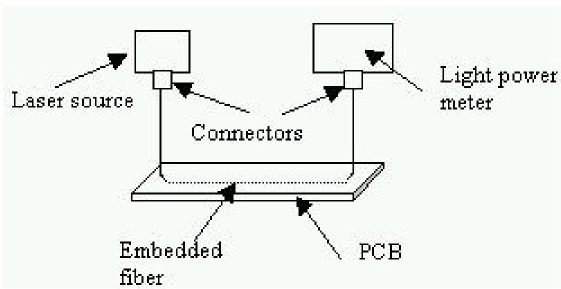

Figure 4 - Embedded Fiber

The thickness of the board is 0.001 6 m. The ratio of the power measured at the end of the fiber to that of the straight fiber is 0.146 2 ± 0.033 7 dB. This ratio is about twice of that for the loop of radius 0.003 5 m as listed in Table I.

Curvature and Critical Angle

A qualitative 2D (two-dimensional) analysis is performed using a ray tracing on a cross-section of the fiber as shown in Figure 5.

The two arcs indicate external and internal walls of the fiber. The radius of the external wall is R and the radius of the fiber is r.

Suppose the light enters along the axis of the fiber as indicated by an arrow. From Snell's law, the total reflection takes place on the tangential surface as long as the incident angle, 90° - θ, exceeds the critical angle:

$$90^{o} - \theta > \sin^{-1}(n_2/n_1) \quad (7)$$

The constants, n_1 and n_2, are refractive indices of the core and cladding materials respectively. Equation (7) requires $n_1 > n_2$.

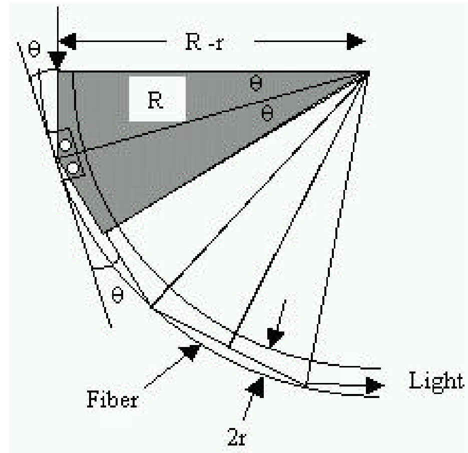

Figure 5 - Cross-Section of a Fiber Loop

The angle θ is that between the light and the tangential line and is complement to the dotted angle between the radius R and the incident light. Hence the apical angle of the shaded triangle is also θ. Hence the ratio of R – r to R is expressed by

$$\cos\theta = \frac{R-r}{R} = 1 - \frac{r}{R} \quad (8)$$

Combination of both Equations (7) and (8) results in

$$1 - r/R > n_2/n_1 \quad (9)$$

If the fiber radius keeps increasing relative to the external radius (reciprocal of the curvature), the equality cannot hold and the total reflection will not occur. Or, if the fiber curvature increases relative to the fiber radius, the total reflection ceases.

Otherwise, the total reflection is guaranteed along the outer fiber wall. Since the two shaded triangles share a hypotenuse and each corresponding angle is equal, they are identical. Therefore, the bottom, i.e., the ray, never touches the inner wall, because the height, R – r, is always less than R. The identical triangles fan out axially.

The same thing is true for any incident light that is perpendicular to the entrance plane.

If the condition expressed by Equation (9) is met or the light does not leak out of the fiber at the first reflection, the total reflection on the outer fiber wall is guaranteed for the light propagation through the fiber.

A similar phenomenon is the radio wave propagation around the earth. Although the radio wave is also reflected on the earth's surface with some attenuation, short wave broadcast is heard globally.

Oblique Incidence

If the light is not normal to the interface of the fiber, three refractive indices, n_0 (refractive index of the air), n_1, and n_2. As shown in Figure 6, the light is incident to the air to fiber interface with angle α.

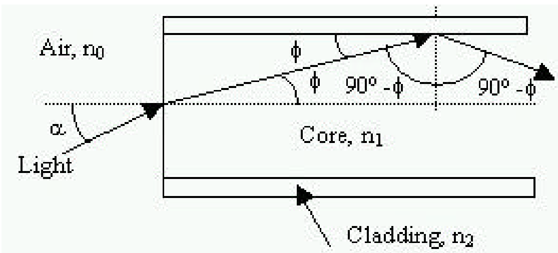

Figure 6 - Numerical Aperture

The refraction of the incoming light at the entrance of the fiber is expressed by:

$$n_0 \sin \alpha = n_1 \sin \phi \qquad (10)$$

The refractive angle inside the fiber core is denoted by φ. Since the refractive index of air is close to unity, Equation (10) can be rewritten as

$$\sin \alpha = n_1 \sin \phi \qquad (11)$$

On the other hand, at the side of the fiber, the condition of the total reflection is written as

$$\sin(90^o - \phi) = \cos \phi > \frac{n_2}{n_1} \qquad (12)$$

Combination of Equations (11) and (12) yields

$$\sin \alpha = n_1 \sin \phi = n_1 \sqrt{1 - \cos \phi^2} \le n_1 \sqrt{1 - \frac{n_2^2}{n_1^2}}$$
$$= \sqrt{n_1^2 - n_2^2} \qquad (13)$$

If the incident angle α is small enough, Equation (13) is rewritten as

$$\sin \alpha \cong \alpha \le \sqrt{n_1^2 - n_2^2} \qquad (14)$$

The angle α is expressed in radian:

$$\alpha \text{ (in radian)} = \alpha \text{ (in degree)} \times \pi / 180^o \qquad (15)$$

The quantity expressed by the right hand side of Equation (14), $\sqrt{n_1^2 - n_2^2}$, is called the numerical aperture which determines the maximum incident angle at the fiber entrance.

The core of the fiber used for this work is PMMA (polymethyl methacrylate) and the cladding is the fluorinated polymer. The refractive indices for PMMA and the fluorinated polymer are 1.492 and 1.405 respectively. Substitution of the values above into Equation (13) yields the numerical aperture = 0.502 and the maximum incident angle = 30.1^o.

Substitution of the refractive indices above into Equation (9) results in

$$\frac{r}{R} < 1 - \frac{n_2}{n_1} = 0.058\ 3 \qquad (16)$$

Since the radius r of the fiber used in this experiment is 0.000 5 m, Equation (16) gives the safe range for the radius, R, of the loop:

$$R > 0.000\ 5/0.058\ 3 = 0.008\ 58 \text{ m} \qquad (17)$$

The safe range of the loop, which is larger than 8.58 mm, is in good agreement with the result shown in Figures 2 and 3.

In the case of the embedded fiber as shown in Figure 7, the angle θ between the tangential line of the fiber and the normal incident light indicated by an arrow is important to determine the criteria for total reflection.

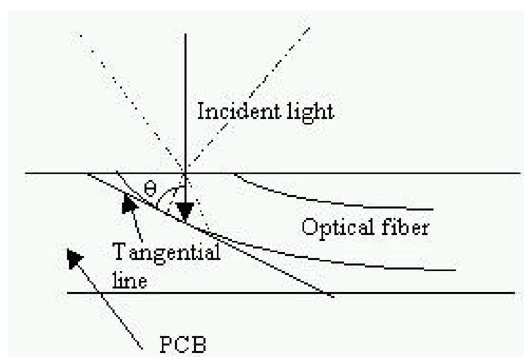

Figure 7 - Embedded Optical Fiber

Using Equation (7), the complementary angle of θ, i.e., 90° - θ, must be larger than $\sin^{-1} \frac{1.405}{1.492} = 70.3°$, which does not appear to happen in Figure 7. The focused light, which is shown in the dotted line, is no better than the normal incidence; it will also leak out of the fiber due to the large incident angle.

Conclusion

With a simple set of measurement devices, the relation between the optical fiber attenuation and the fiber curvature is investigated for the embedded optical fiber in PCBs.

Although the attenuation for the horizontal loops is acceptable, the loss at the vertical bends is not desirable in order to couple the light source with the entrance of the fiber. The vertical coupling geometry needs to be improved.

An optical analysis on the fiber bend geometry is performed to predict the critical curvature of the loop and is in good agreement with the experiment.

It is revealed that the light profile of the source much affects the attenuation on the fiber bend especially for vertical light coupling.

Therefore, a development is required for obtaining a focused light source in order to apply a realistic light source to the optical wave-guide in PCBs. Also, this approach may eliminate connectors thus accomplishing a direct measurement rather than the relative measurement currently used.