

# Crack extension research of FR4 substrate embedded 90° bend optical fiber under the random vibration

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**Keywords:** OPCB; J integral; Crack expand; Random vibration

**Abstract.** For the reliability problem of the 90 ° bend optical fiber embedded FR4 substrate in the bad service environment especially for military, the easily failure area of this modal under environments of random vibration and characteristics of interface cracks extending are researched. Firstly, modal analysis is conducted by ANSYS, to confirm the factors affecting the natural frequency of the base board, and to find the natural frequency in the status of the minimum bending loss. Combined with Military standard electronic products environmental stress screening method (GJB1032-90), the random vibration tests are conducted. Then, the stress distribution is treated as boundary conditions to calculate J integral. Ultimately, the results of calculating shows that under frequency between 440.45 and 440.45Hz, the minimum bending loss model prone to resonance; when the crack length is greater than 0.094mm, crack began to expand, and lead to low stress brittle fracture; crack growth and the J integral are linear positive correlation, so was the crack growth rate and the  $K_{I1}$ .

## 1. Introduction

Interconnection between chips are basically using traditional wire interconnection, due to the physical nature of limited transfer speed, it has been unable to meet the requirements of new situation in many fields. Consequently, changing signal transmission medium is a necessary means to solve the bottleneck of the development of the electronics industry. As such, a new board-level interconnect carrier optical printed circuit board is on the rise.

In 2010, Dong Min Im of the Korean academy researched the, 90° bend on both ends optical fiber are cured by using thermosetting epoxy resin, and then embedded into the FR - 4 plate to make OPCB. The fabrication process of the 90°-bent fiber connector U-grooves having 250 μm pitch formed by a grooving technique is illustrated [1]. In 2014, Evert designed a buckling cavity in which the SMF (single-mode fiber) can buckle in a controlled way to ensure good optical performance as well as mechanical stability. Finite element analysis suggests that mechanically a minimal buckling cavity length of 20mm is necessary to keep the excess optical loss from bending below 0.1dB [2].

## 2. Model analysis and simplifying

Analysis sample of board level optical interconnects principle as shown in figure 1, this article only take 90 ° bend optical fiber embedded part (OPCB connector) model as the analysis objects. OPCB connection part of engineering application is multiplexed connections, to reduce the computational complexity, only a single path is analyzed. Simplified model shown in figure 2, considering the 90 ° bend optical fiber's optical loss, thermal properties, processing technology, optimize the structure parameters of the geometric and material: Substrate size is 6mm \* 6mm, and the thickness is 1mm, and the curvature radius of the fiber is 3mm; to adhere fiber the thermosetting resin's modulus of elasticity is 18GPa, and the thermal expansion coefficient is  $30 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ . Fiber structure including fiber layer and coating layer, fiber layer including core and cladding, diameter of core and cladding respectively is 50 microns and 80 microns, the diameter of coating layer is 250

microns; in this condition, the largest bending loss is 0.2 dB[3].

Considering the low bending sensitivity and the gradient refractive index, the standard optical fiber SMF28 is chosen. After the optical fiber are embedded into FR4 substrate, formed a different areas called resin enrichment region around the fiber, the resin enrichment region is usually regarded as similar to the shape of a wedge, the size of this area is usually adopt the form of  $R = 3r$ ,  $R$  is radius of the resin area section curvature,  $r$  is the radius of the optical fiber [4], as shown in figure 2.

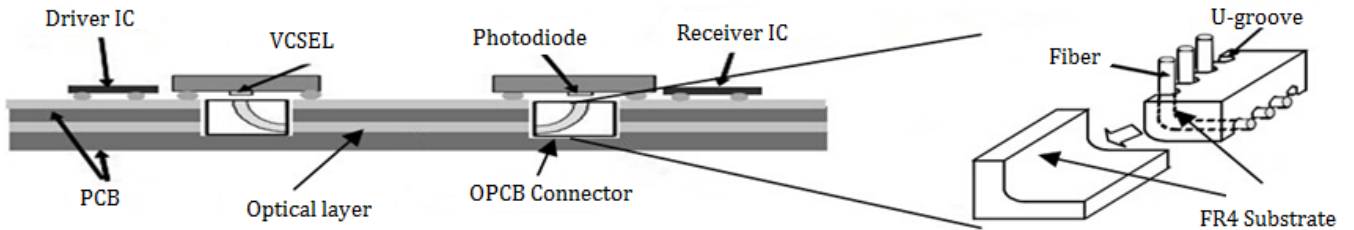


Fig.1 Board level optical interconnects principle

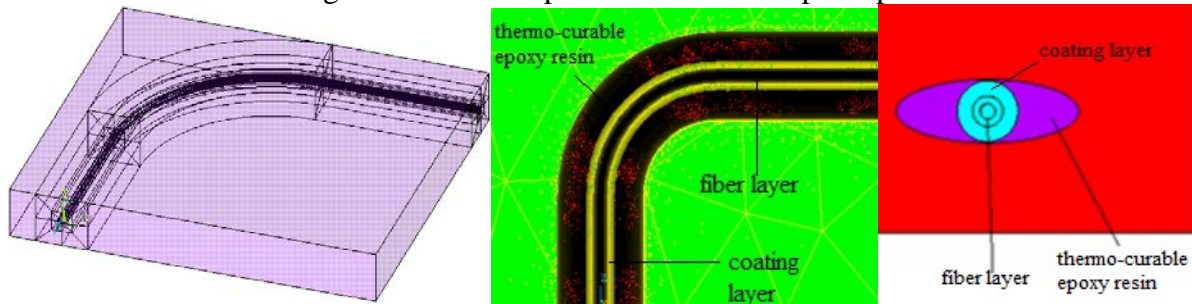


Fig.2 Simplified modal

### 3. Analysis methods

The interface of two different materials' crack propagation is analyzed, by calculating the crack tip J integral value. In 1968, Rice has pointed out: J integral indicate the strain energy release rate [5].

According to the green formula, the J integral value and its integral path are independent. Therefore, the choice of calculation path are depended on the calculation path whether convenient. The significance of application of J integral is: J integral is not only suitable for linear elastic deformation, but also applies to elastic-plastic deformation problems, and to avoid direct calculating complex stress field of crack tip.

According to the test the critical fracture toughness is  $107 \text{ MPa} \cdot \sqrt{\text{mm}}$ , and the  $K_I$  can be calculated by the relationship between  $K_I$  and between crack length for the critical crack size [6]. According to the above formula, defined by use of ANSYS software, the crack tip node components, the propagation of the crack and the crack propagation direction, thus it is concluded that the calculated value of J integral.

### 4. Simulation analysis

#### 4.1 Modal analysis

The main purpose of the modal analysis is to solve the natural frequencies and corresponding vibration mode. Due to the restrictions significantly impact on the modal analysis, so considering actual installation condition of the OPCB connection part, to determine the constraints. The modal's area in contact with the PCB is applied Y direction constraints, the model's two end face are applied X direction constraints. Considering the bending radius value of the optical fiber as 1~5, will be able to meet the low fiber bending loss, five radius value are selected, to study the relationship between fiber bending radius and the model's surface pressure and the first-order natural frequency. As shown in figure 3(a), Abscissa H for preloading force, ordinate  $\omega_1$  for the first order natural

frequency. When bending radius is 1mm and preloading force is  $10^6\text{N}$ , first-order natural frequency up to 1500Hz. With the increasing of preloading force, the value of first-order natural frequency show “bell” type change. The first-order natural frequency is significantly influenced by preloading force in the scope of  $10^5\text{N}$  to  $10^5\text{N}$ . With the increase of fiber bending radius, first-order natural frequency values decrease rapidly. For the bending radius is larger than 3mm, first-order natural frequency probably stay at around 450Hz, i.e. the bending radius is larger than 3mm, its impact on the first order natural frequency is very small.

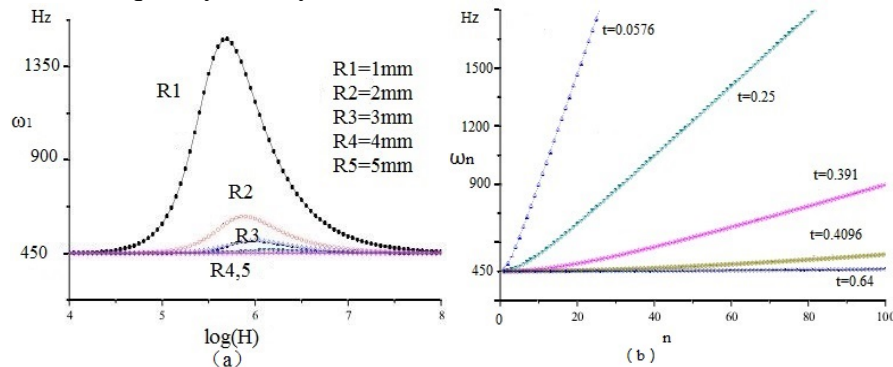


Fig.3 (a) The relationships between H and natural frequencies

Fig. (b) The relationships between t and natural frequency

Figure 3 (b) shows that in a certain pressure ( $10^6\text{N}$ ) and the bending radius of 3 mm, the ratio of core layer and fiber layer section area affect the  $n$  order natural frequency,  $n$  means order of frequency,  $\omega_n$  means order natural frequency. It has chosen five common set of the diameter of the core layer and fiber layer:  $30\ \mu\text{m}/125\ \mu\text{m}$ ,  $62.5\ \mu\text{m}/125\ \mu\text{m}$ ,  $50\ \mu\text{m}/80\ \mu\text{m}$ ,  $80\ \mu\text{m}/125\ \mu\text{m}$ ,  $100\ \mu\text{m}/125\ \mu\text{m}$ , the corresponding ratio of core layer and layer fiber cross section area is 0.0576, 0.25, 0.391, 0.4096, 0.64. The higher modal order, the larger influence of the ratio of core layer and optical layer section area affect the natural frequency. With the increasing of  $n$ , natural frequency is linearly increasing. And with the increase of  $t$ , the frequency-order linear slope is gradually decreasing.

According to optimized structure parameters of the geometric and material, when pre-compress on both ends is  $10^6\text{N}$ , the first order natural frequency is 440.45Hz, the second order natural frequency is 452.22Hz, the third order natural frequency is 479.35Hz, the discrepancy frequency between the first order and the second order is 11.77Hz, the discrepancy frequency between the second order and the third order is 27.13Hz. Due to discrepancy is small, the modal prone to multiply order resonance.

#### 4.2 PSD Base excitation

According to the national military standard Electronic products environmental stress screening methods (GJB1032-90), the modal is imposed based incentives. To simulating the electronic products in the actual environment by vibration [7], the left and right side of the modal is applied the X direction constraints.

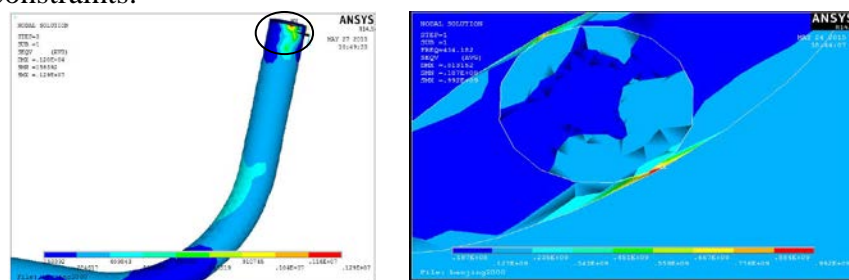


Fig.4 Optical fiber part stress nephogram

The extracted part stress nephogram is shown in figure 4: maximum stress located in the fiber and rubber filling contact angle position, the value is  $990\text{e}+6\text{ Pa}$ , and here is also the biggest stress gradient; stress and stress gradient in the direction of optical fiber core layer is becoming more and more small. Due to the adhesion strength of the interface between different materials is weaker, and

the scratches during processing FR4 substrate, and the bonding technology the micro cracks is likely to be generated at the interface. When the stress exceeds interface material can withstand the maximum stripping stress, interface layer began destroyed, the separation of interface cracks are formed at this time.

#### 4.3 Calculation of J integral and stress intensity factor K

Based on the ANSYS to carry on the secondary development, the maximum stress under PSD based incentives is treated as boundary conditions, to compile the calculation APDL program of stress intensity factor K and J integral. Crack tip point is a singular point, therefore around the crack tip the first line of the units are adopt singular elements. Because of the singular element have their own stress and strain singularities, adopted less grid can reach a certain precision. This article selects six node isoparametric elements. Isoparametric element mid-edge nodes around the crack tip are moved to near the crack tip in a quarter points, can make the crack Angle point of stress and strain of singularity. From the crack's down surface to up surface, an integral path in a closed loop is chosen. Due to the type of the load stress are perpendicular to the crack, stress intensity factor is the type I.

Change crack size  $a$ , to solve the crack tip stress intensity factor, as shown in figure 5(a).The data points in the diagram using polynomial fitting, satisfy:

$$K_I = 5E+8a+6E7 \quad (1)$$

Among them, the linear correlation coefficient  $R$  is 0.98993. When  $K_I$  is equal to  $K_{IC}$ , crack length is 0.094 mm. Threshold crack length is small, not easy to be found by crack flaw detector. And it is prone to low stress brittle fractures, and needs pay more attention to this phenomenon. Also, the relationship between the J integral and the crack length are given as:

$$J = 2E+7a-488064 \quad (2)$$

Among them, the linear correlation coefficient  $R$  is 0.92446. Obviously, the J integral values with the increase of crack length linear growth trends.

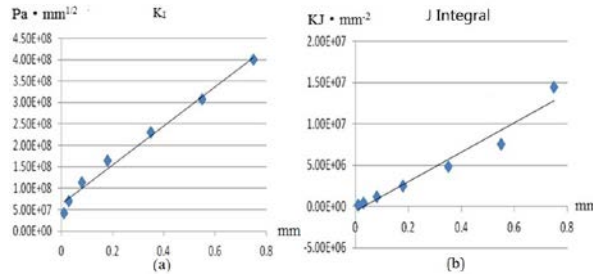


Fig.5(a) The relationship between crack length and  $K_I$

Fig.5(b) The relationship between crack length and J integral

#### 5. Summary

(1) Under the random vibration environment, the substrate embedded  $90^\circ$  optical fiber is apt to form a larger stress interface near the edge of the substrate material. There are the crack extension points between two layers. When the frequency is between 440.45 and 440.45 Hz, model prone to resonance, and crack initiation and propagation are apt to happen.

(2) The value of the first-order natural frequency shows "bell" type trend, with the increasing of preloading force in certain bending radius. With the increase of fiber bending radius, first-order natural frequency values decrease rapidly. When bending radius greater than 3 mm, its impact on the first order natural frequency is very small. The higher modal order, core layer and optical layer section area ratio of the impact on the natural frequency is larger.

(3) Near the edge of the substrate, the crack on is relatively easy to expand, to the depths stress reduced and bonding strength is bigger so crack is difficult to extend to the depths. When the crack length is more than 0.094 mm, the crack begins to expand, prone to low stress brittle fracture, J integral value shows linear growth trends with the increasing of crack length.

#### Acknowledgements

This work was supported by "The photoelectric \*\*\* technology research projects".

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