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FIBER-OPTIC CRACK SENSING IN STEEL STRUTURES AND BUILDINGS

إستخدام الألياف البصرية كحساس للتشرخات في المبانى والمنشآت المعدنية

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ملخص البحث:

في الأونة الأخيرة ظهر بشدة إستخدام تكنولوجيا الألياف البصرية كحساس بصري وذلك بسبب مميزات وخصائص الألياف البصرية المفيدة في هذا الغرض وهي قدرتها علي نقل المعلومة بالإضافة إلى عملها كحساس. ومن أهم أهداف هذا البحث هو بناء منظومة بصرية لها القدرة على قياس الإضمحلال في الألياف البصرية نتيجة للانحناءات التي تحدث فيها عند أقطار مختلفة لهذه الانحناءات وعند ترددات مختلفة للإشارات المستخدمة الداخلة في الليفة البصرية وعندما يتم لف الليفة عدة لفات متتابعة وبأقطار مختلفة. وقد تم إستخدام هذه المنظومة البصرية عمليا كحساس بصري لقياس التشرخات التي تحدث في المباني والمنشآت المعدنية كما تم مقارنة نتائج هذه القياسات بأخري أستخدم فيها أنظمة مختلفة وكانت نتائج المقارنة متوافقة مع بساطة ورخص تكلفة هذه المنظومة المقترحة .

Abstract

Fiber-optic sensing techniques have received a considerable interest in recent years. Optical fibers have several desired and advantageous attributes useful for sensor applications, including their ability to act as both sensing and information-transmitting media. One of the specific aims of this paper is to build an optical system having the capability to measure the attenuation in optical fibers due to its macrobending, and compare (or calibrate) our results with other who used different systems in order to ensure that our system is suitable to use.

The attenuation due to bending loss in optical-fiber at different bending radii of fiber, at different multiple circular loops bending of fiber, and at different optical frequencies transmitted through fiber, are measured experimentally by our optical system. The results for these measurements show that the attenuation (or bending loss) increases with decreasing the bending radius, with increasing number of fiber turns and with increasing transmitted signal frequencies through the bended fiber. This optical system can be used as a sensitive sensor to measure the cracks in steel structures and buildings.

Key words: Crack sensing, Optical fiber bending losses, Macrobending losses.

1-INTRODUCTION

Bending loss is classified according to the bend radius of curvature, microbend loss or macrobend loss. Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled. Macrobends are bends having a large radius of curvature relative to the fiber diameter as shown in Fig.(1). Fiber loss caused by microbending can still occur even if the fiber is cabled correctly. If fibers are bent too sharply , specially in corners and narrow places, macrobend losses will occur. Light propagation at the inner side of the bend travels a short distance than that on the outer side. To maintain the phase of the light wave, the mode phase velocity must increase. When the fiber bend is less than some critical radius, the mode phase velocity must increase to a speed greater than the speed of light. However, it is impossible to exceed the speed of light. This condition causes some of the light within the fiber to be converted to high – order modes. These high – order modes are then lost or radiated out of the fiber [1]. Fiber sensitivity to

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bending losses can be reduced by increasing the refractive index of the core. Sensitivity also decreases as the diameter of the overall fiber increases. However, the increase in the fiber core diameter increases fiber sensitivity. Fibers with large core size propagate more modes. These additional modes tend to be more lossy. The difference between propagation constants of adjacent modes is a function of the core diameter NA and affects the bending loss [2]. Macrobending loss depends also on the used light wavelength [3,4]. A660nm wavelength is used in the present work.

2- MEASURING ATTENUATION DUE TO MACROBENDING IN OPTICAL FIBER

Attenuation is the loss of optical power as light travels along the fiber. Signal attenuation is defined as the ratio of optical output power (Po) to the optical input power (Pi). Optical input power is the power injected into the fiber from an optical source. Optical output power is the power received at the fiber end or optical detector. The following equation defines signal attenuation per unit length[4].

$$\text{Attenuation} = -10\log(P_o/P_i) \quad (1)$$

In this paper the attenuation (bending loss) due to macrobending in optical fiber is measured at different bending radii of fiber, at different multiple turn loops bending of fiber, and at different signal frequencies.

An optical transmitter designed here to amplify the input electrical signal and convert it to its equivalent optical signal using a versatile link transmitter incorporating 660 nm LED in a horizontal housing [type HFBR-1524] which can be easily coupled to the optical fiber [5]. The equivalent optical signal is transmitted through a 5 meter cheap simplex fiber optic cable constructed of single step-index plastic fiber sheathed in a plastic jacket with characteristics reported in Ref.[5]. A blue plastic HFBR-2524 optical receiver module with high sensitivity is used and coupled with the previous optical fiber cable, [5]. It features an integrated photodetector and dc amplifier with high EMI immunity. It converts the optical signal transmitted through the optical fiber which suffers a bending to the equivalent electrical one which amplified by simple amplifier circuit to be easily monitored on digital oscilloscope and computer as shown in Fig.(2).

The transmitted signal through the bended optical fiber is a 1KHZ square wave (where very small bending loss) generated by GFG-8015G function generator.

Results are obtained at digital oscilloscope connected to the receiver and registered at computer.

2-1-LOSSES DUE TO CHANGING BENDING RADIUS

The following equation defines signal attenuation α_b (or bending loss)with the fiber bending radius[4,6]

$$\alpha_b = C_1 \exp(-C_2 R) \quad (2),$$

where R is the fiber bending radius in (cm) and C_1 & C_2 are constants which are independent of R and dependent on the dimensions of fiber and on the shape of the optical mode, C_1 in (dB/m) and C_2 in (1/cm).

This relation indicates that the bending losses increasing exponentially with the decreasing in fiber bending radius. The bending losses are measured experimentally at wavelength 660 nm with different fiber bending radii (R=0.25, 0.4, 1, 1.2, 1.75 cm), we notice the results on a digital oscilloscope where variations in the received signal due to variations in fiber bending radius are shown in Fig.3. As the bending radius decreases, the transmitted signal will extremely attenuate and disturb. The experimental results plotted in a curve shown in Fig.(4). This curve verify the equation (2) where the attenuation (bending loss) increasing exponentially with the decreasing of fiber bending radius. These experimental results (Fig.4) have agreement with that of Ref.[2]which is shown in Fig.(5). The ratio Po/Pi is commonly used in many researches as a measuring value for the power losses in fiber, so we calculate this value from equation (1) to easy compare with other research results. The experimental results of Po/Pi ratio at different fiber bending radii are shown in Fig. (6), which shows that the larger bending radius the larger output power.

2-2-LOSSES DUE TO MULTIPLE CIRULAR LOOPS BENDING

The fiber bending radius range for minimum and maximum loss depending on the fiber normalized frequency (V number) [7]. If the bending radius is less than a certain value (minimum range) all light in the inner core will leak out; whereas if the bending radius is more than a certain value (maximum range or critical bending radius), no inner core light will leak out. In some applications for fiber sensor it is used to measure the force or the load, the force sensing area is much larger than the fiber bending radius for desirable light leakage. Therefore, the multiple bends must be provided on the fiber under the force sensing area for proper light leakage from the inner core. For this reason, in this paper we have measured the bending loss due to multiple circular loops bending.

The light intensity loss due to multiple bends can be explained using the general definition of the ratio of the output power (Po) to the input power (pi). The ratio Po/Pi can be expressed for N bends as follows[7,8];

$$Po/Pi = (Po/Pi)_1 x (Po/Pi)_2 x (Po/Pi)_3 x \ldots\ldots x(Po/Pi)_{N-1} x (Po/Pi)_N \quad (3),$$

where, N =number of bends, Pi=input power , Po=output power,
$Pi = (Pi)_1$, $(Po)_1 = (Pi)_2$, $(Po)_2 = (Pi)_3$, $(Po)_{N-1} = (Pi)_N$, and $(Po)_N = Po$
Po/Pi for one bend can be expressed as follows

$$(Po/Pi)_{1,2,3,\ldots,N} = \exp(-2\,\alpha_b\,L_b)_{1,2,3,\ldots,N} \quad (4),$$

where L_b is the length of bend. Therefore, using Eq.(4) in Eq.(3), we can obtain

$$Po/Pi = \exp(-2\,\alpha_b\,L_b)_1 x \exp(-2\,\alpha_b\,L_b)_2 x \exp(-2\,\alpha_b\,L_b)_3 x \ldots\ldots\ldots\ldots x \exp(-2\alpha_b L_b)N-1 x \exp(-2\alpha_b L_b)_N \quad (5)$$

For identical bends, if every bend has the equal bend length, L_b, and equal bending loss coefficient , α_b , Eq.(5) is rewritten as

$$Po/Pi = \exp(-2\,\alpha_b\,L_b\,N) \quad (6)$$

This equation indicates that the larger number of bends the smaller output power.

Measurements of losses in an optical fiber cable due to multiple circular loops bending are measured. Multiple circular loops bending were made to optical fiber with a constant radii (R1=1.25cm,R2=0.96cm, R3=0.59cm). The experimental results of attenuation (bending loss) and Po/Pi due to multiple circular loops bending at different bending radii are shown in Fig.(7) and Fig (8) respectively. Slightly increasing number of loops would extremely increasing the attenuation(decreasing Po/Pi),while the attenuation and Po/Pi are constants at a certain value of circular loops especially for small bending radius. At smaller bending radius the attenuation increases sharply (Po/Pi decreases sharply) rather than at the greater bending radius. So the larger the radius of bends, more the number of bends is required to have the same amount of light loss from the fiber. By comparing these experimental results with other of Ref.[7] which shown in Fig.(9), we notice that there are a good agreement between the two results, the small difference between the two results owing to the bending radii are not exactly the same and the two fiber characteristics are different, but the important notes here that the two results have exactly the same shape and phenomena.

2-3 LOSSES DUE TO DIFFERENT PROPAGATING SIGNALS THROUGH BENDING FIBER

Studying the relation between the bending losses and the transmitted signal frequency is very important in order to determine the transmitted signal frequency at which minimum losses obtained with the fiber bending. Here losses are measured through bending fiber with different radii (R=1.25, 0.96, 0.59cm) for different optical frequencies transmitted signal through the bended fiber. The experimental results lead that as the signal frequency increases the attenuation increases and Po/Pi decreases as shown in Fig(10) and Fig. (11) respectively. These experimental results, for our knowledge, are a new results because we did not found a direct relation between the optical fiber bending losses and the frequency of the input signal transmitted through the bended fiber, but we can interpret these results from the following discussion :

According to Ref.[8] after a certain frequency (3-dB bandwidth) the modulation frequency is further attenuated. Also ref.[9] points out that the minimum required power level for the fiber system (called receiver sensitivity P_{min}) is given by the following equation;

$$P_{min} = (2\, e\, F\, K^2\, B) / r = C\, B \qquad (7),$$

where C is a constant depending on e, F, K and r, where e is the charge of an electron, F is the noise factor (1 for PIN photodiode, 0.4 for Si avalanche photodiode, 0.1 for Ge& GaAs avalanche photodiode), the value k is based on the signal –to-noise ratio , B is the required bandwidth (or bit rate), and r is the responsivity of the photodetector. The important note from the above equation is that the signal frequency is related directly to the minimum required power where, as the frequency increases the minimum required power level for the fiber system increases, in another word the output power in the receiver decreases (i.e. Po/Pi decreases) or the optical fiber bending losses (attenuation) increases. This interpretation have a good agreement with our experimental results as shown in Figs. (10,11)where as the signal frequency increases the bending loss increases after a certain frequency. From above discussion and experimental results, we note that there are a good relation between the signal frequency and the attenuation. The fiber bending will add losses to this attenuation which occurs from increasing input frequency. From this point of view, we propose to add a new term which is a function in frequency into Equ. (2) to become as follow;

$$\alpha_b = C1 \exp(-C2R) \qquad \text{for } f < fth \qquad (8\text{-i})$$

$$= C1[\exp(-C2\,R) + \exp(C3\,f)] \qquad \text{for } f > fth \qquad (8\text{-ii})$$

Where, C_1&C_2 are defined before, C_3 is a constant in (1/KHZ) and f_{th} is the threshold frequency at which the attenuation becomes increasing in (KHZ)

3-APPLICATION DEMONSTRATION

Application of the above proposed optical sensor was demonstrated by measuring the crack opening in steel structures and buildings where this sensor was successed to detect the attenuation due to optical fiber macrobending.

3-i- The importance of structure crack sensing by optical fiber sensor

The optical fiber provides high sensitivity accuracy, and security compared with electrical cable and wires. The crack opening which happens in steel structures and buildings could be detected using bending losses phenomena which formulated by Eq.2. For concert structures, crack opening beyond 0.2-0.4 mm may leads to durability problems associated with steel reinforcement. Large opening beyond 1-2 mm, which may be caused by over load during earthquakes and catastrophes naturally are a sign of severe damage and requires immediate closing of a facility [10]. The ability to detect these cracks at early stage will enable the execution of timely repair and avoid catastrophic failure. If we use the conventional sensor, the exact location of cracks can not be accurately predicted, so optical fiber techniques are used to predict the crack.

3-ii- EXPERIMENTAL SETUP AND RESULTS

The proposed optical fiber sensor system consists of optical transmitter, optical fiber, optical receiver, and indicators (digital Oscilloscope and Computer).

A steel prototype bridge was built from two ports very close to each other and mounted on a mechanical movable micrometer, a fiber-optic cable was bended with its critical radius of bending (which determined by 1.8 cm in paragraph "2-1")and then fixed on the surface of the steel prototype bridge as shown in Fig.(12). We simulate the crack opening in the steel structure by the space (displacement) between the two ports of the prototype bridge.

A square wave signal with a frequency of 1 KHZ is inserted to the optical transmitter($\lambda = 660$ nm) and detected by the optical receiver passing through the bended optical fiber. We notice that there is no attenuation on the input signal at critical radius of bending. We move the two ports of the prototype by moving the mechanical movable micrometer, the radius of bending will decrease from the tension force and this will produce an attenuation in the transmitted signal. As the space between the two ports (crack opening) increases, the attenuation increases and Po/Pi decreases as shown in Figs.(13,14) respectively. These experimental results indicate that the proposed optical fiber sensor is a good one to sense the millimeter crack in steel structures and buildings where larger crack, the more optical fiber bending losses.

By comparing the proposed system with others in Refs.[10,11], it is found that this system is simpler, very sensitive and very cheap where we use a simple designed optical transmitter and receiver, also we use a fiber bended at its critical radius of bending but the fiber in other methods is fixed on the steel structure without bending and when the crack occurs the fiber will be bend and gives signal attenuation (bending loss). The comparison between our experimental results shown in Fig.(13) and those of ref.[10] shown in Figs.(15,16). predict that there are a good agreement between them; it is not necessary to get the same results because the types of fiber ,transmitter, receiver, signal frequency and other mechanical tools are differs. The important point of comparison here is the shape of results not the values of results and the shapes are identical to each others.

4-CONCLUTION

The experiment carried out in this work confirmed that the macrobends become a great source of loss when the radius of curvature is less than centimeter, such that for bending radii (R=0.4 and R=0.25cm), that would extremely attenuate and disturb the transmitted signal. Also the experiment confirmed that slightly increasing number of circular loops would extremely increase the attenuation, at lower bending radius the attenuation would decrease rabidly and sharply rather than at greater bending radius.

Finally we deduce experimentally that increasing transmitted signal frequency would increase the bending losses. So a frequency dependent term has been added to the bending losses equation to account for this effect. These experimental results lead us to propose a simple and effective optical-fiber system sensor to measure the cracks of any structure and building. Larger cracks yields more optical fiber bending losses, this is because the increasing in crack thickness would decrease the radius of bending loop which increase the attenuation of the transmitted signal at the receiver. So it is considered as an effective method in determining the (health) of any structure by detecting and monitoring cracks.

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Fig.(1) Bending at Optical Fiber Cable

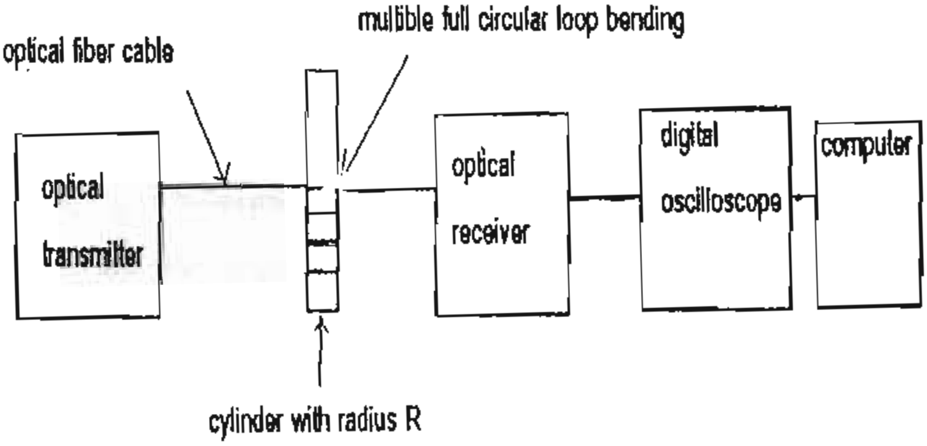
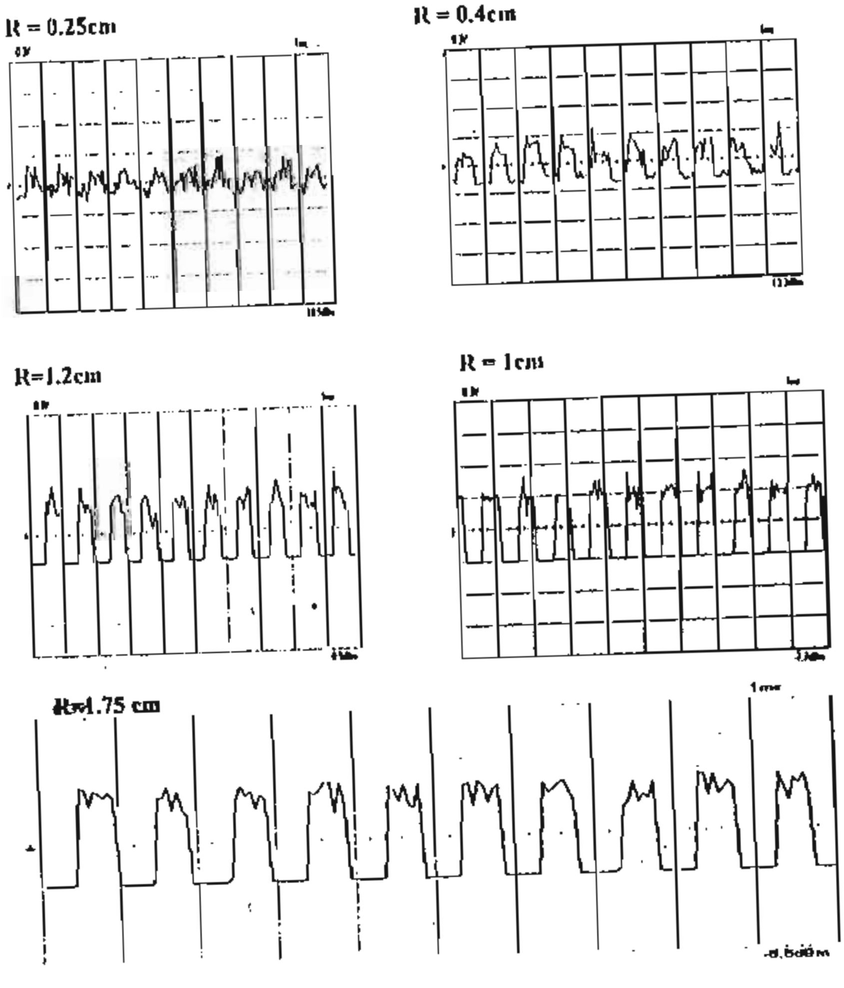


Fig.(2) Block diagram for the instrument used for measuring macrobending losses



R = 0.25cm

R = 0.4cm

R=1.2cm

R = 1cm

R=1.75 cm

Fig.(3) Experimental output signals at different bending radii

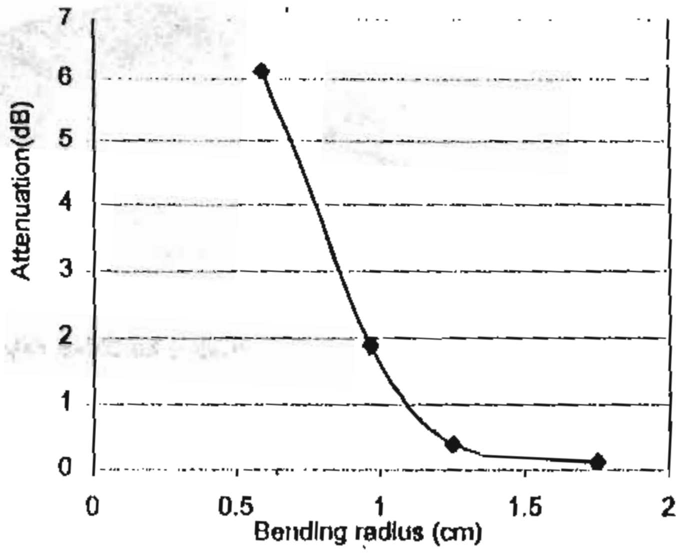


Fig.(4) Experimental results for attenuation (bending loss) of 5 meters fiber with different radii

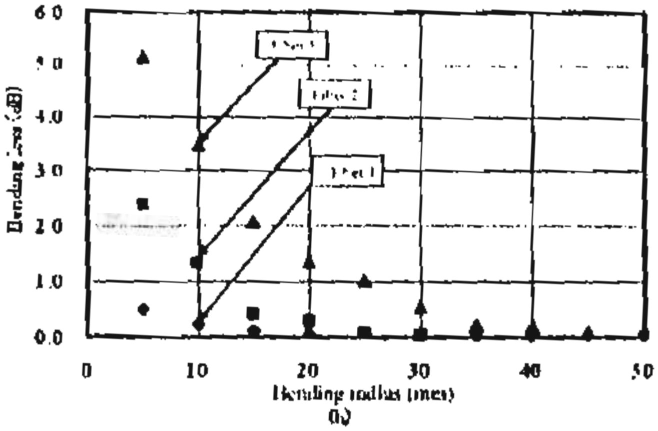


Fig.(5) Bending losses VS bending radius for different types of fibers[2]

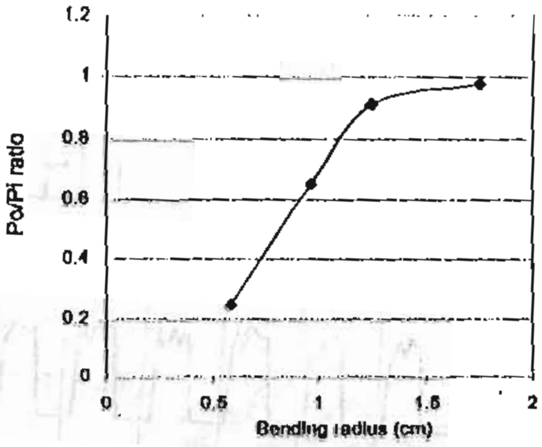


Fig.(6) Experimental results for Po/Pi ratio of 5 meters fiber with different radii

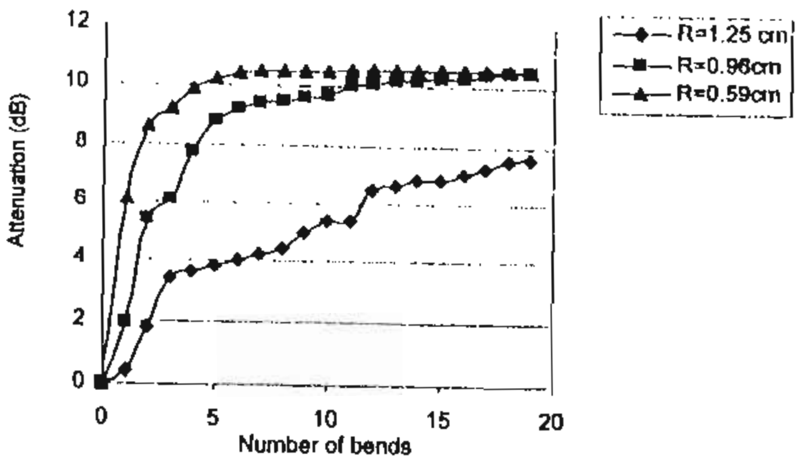


Fig.(7)Experimental results for attenuation(bending loss) of 5M fiber with number of bends at different radii

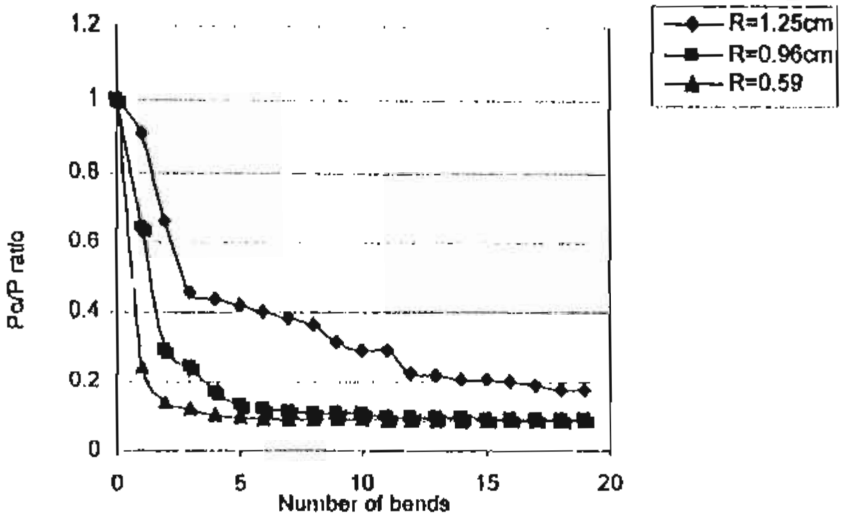


Fig.(8) Experimental results for Po/Pi ratio of 5M fiber with number of bends at different radii

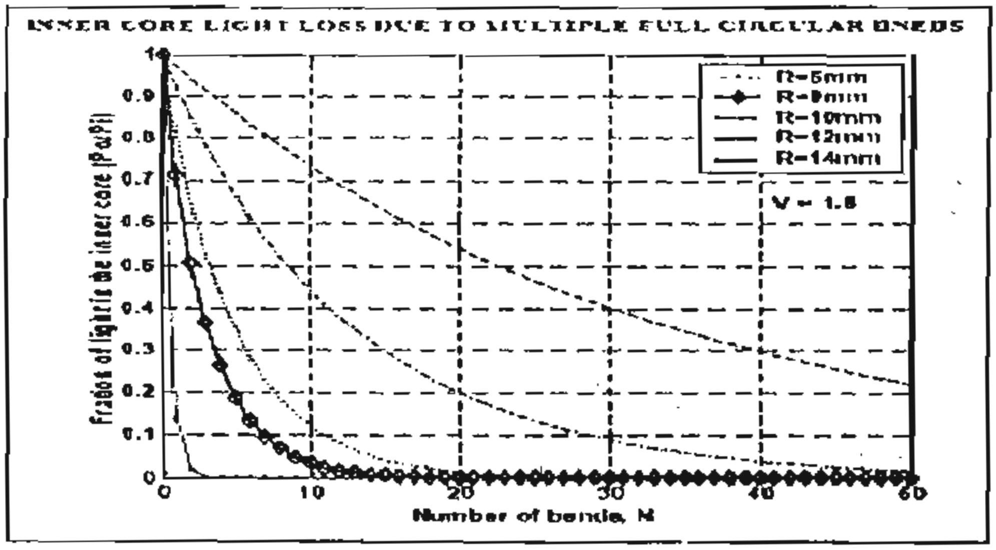


Fig.(9) Light loss from the inner core due to multiple full circular loops [7]

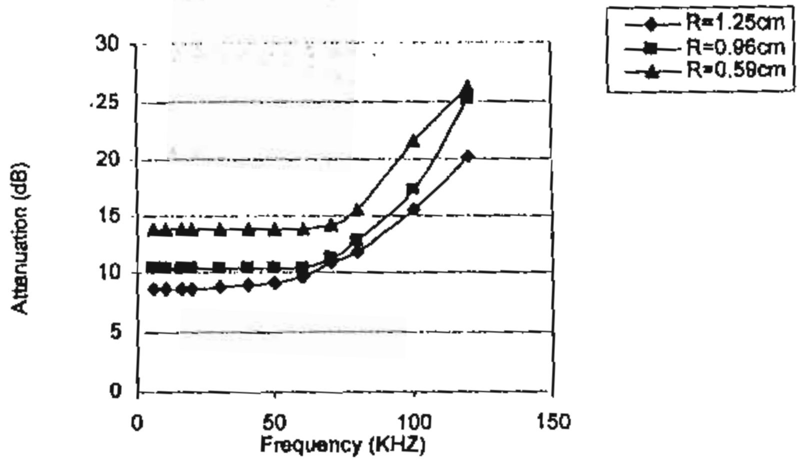


Fig.(10) Experimental results for attenuation (bending loss)of 5M fiber with different frequencies at different radii

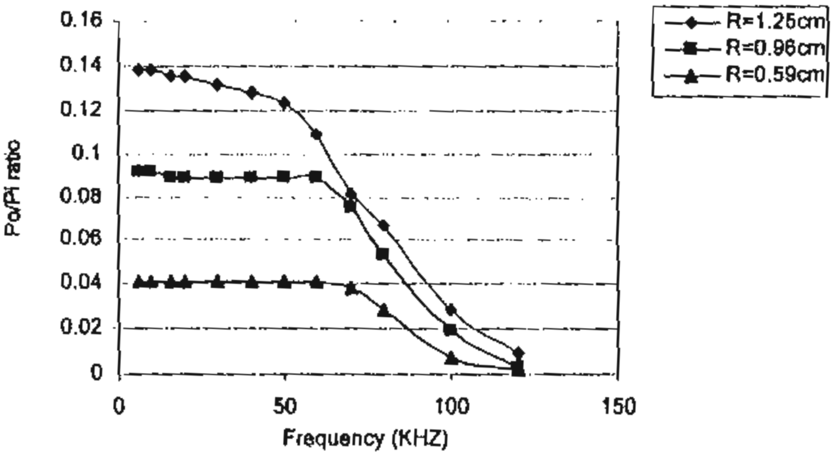


Fig.(11) Experimental results for Po/Pi ratio of 5M fiber with different frequencies at different radii

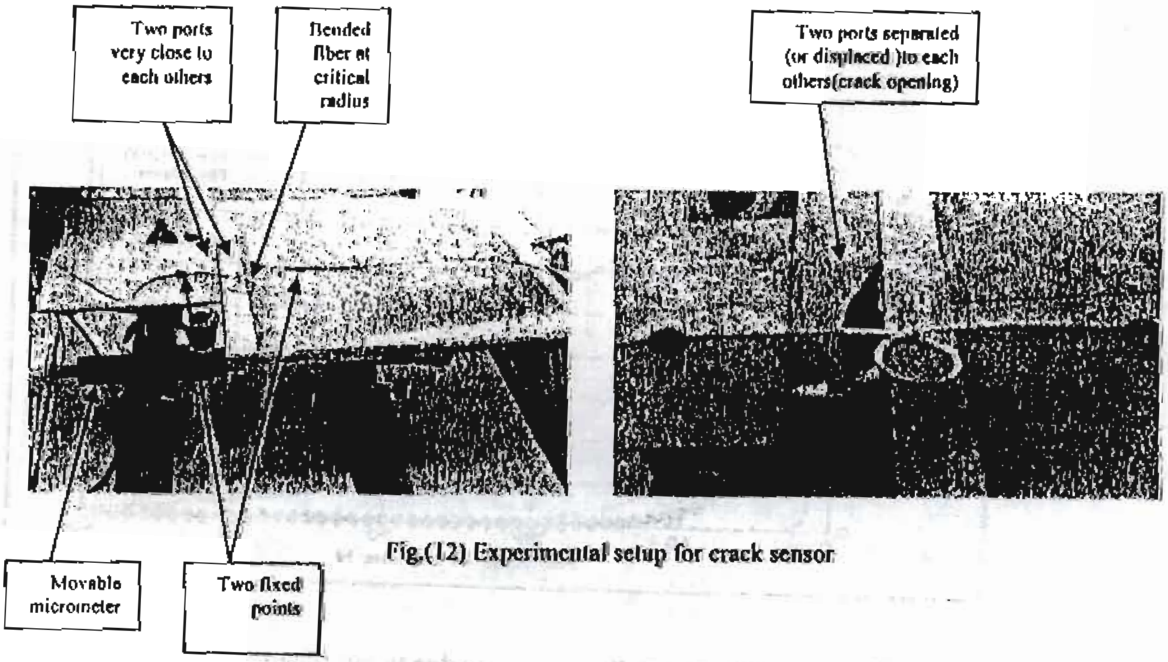
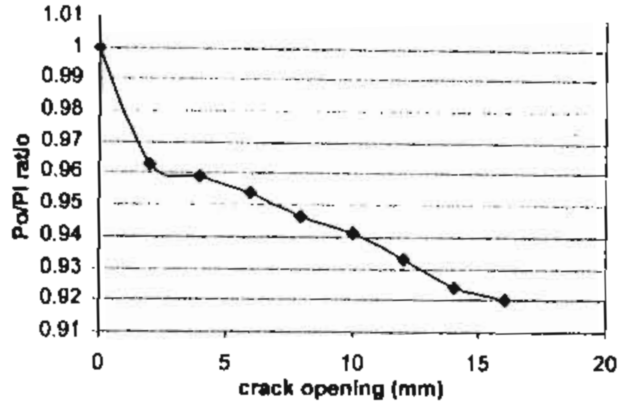


Fig.(12) Experimental setup for crack sensor



Fig(13) Experimental results for Po/Pi ratio with crack opening

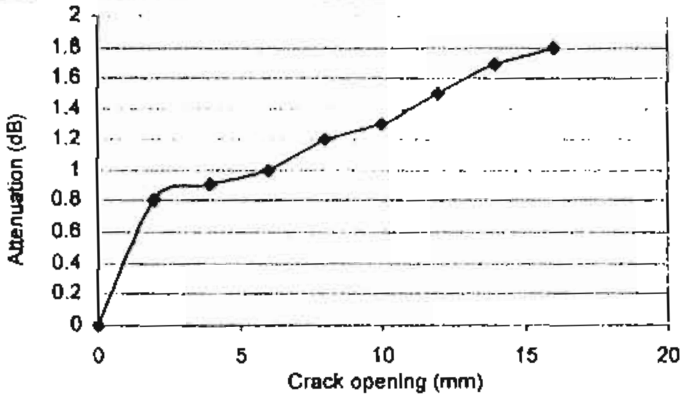


Fig.(14)Experimental results for attenuation (bending loss) of 5M fiber with crack opening

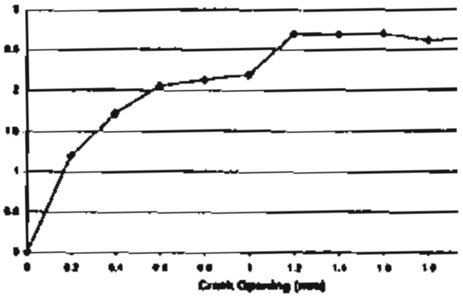


Fig. 15. Theoretical Results for Bending loss of 3M Fiber 10]

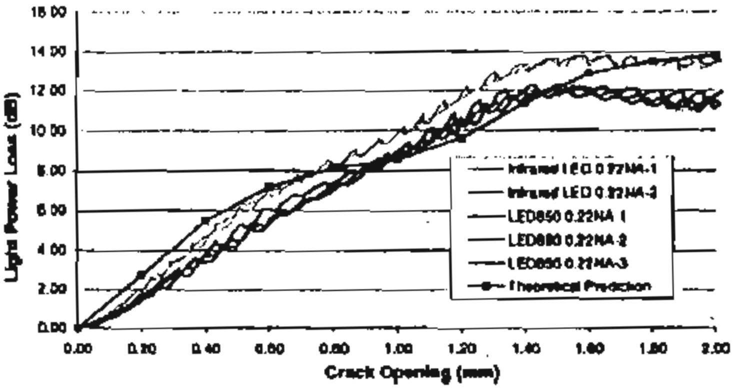


Fig.16. Comparison between theoretical prediction and test resukts for the Beljing fiber [10]