OFFICE OF INDUSTRIAL RESEARCH

STUDY ON OPTICAL FIBER CABLING LOSSES

PHASE 1 - FINAL REPORT

Submitted to
DEPARTMENT OF SUPPLY AND SERVICES

Prepared by
Dr. K. C. Kao

March 31, 1977

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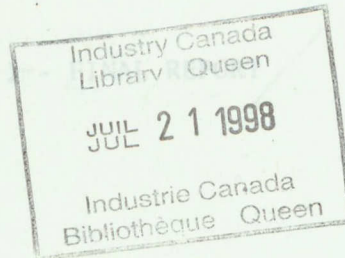The University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

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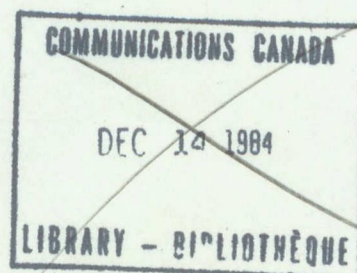March 31, 1977

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CONTENTS

ACKNOWLEDGEMENTS

ABSTRACT

Bending losses caused by circular bends, bump bends, microbends and mechanical vibrations have been systematically studied for step-index multi-mode optical fibers with a glass cladding or a silicone cladding, with and without protective coatings. The experimental results show clearly that bending losses are due mainly to mode coupling which transfers normal guided modes to higher order modes, and some high order mode to leaky modes. The studies of the effects of intentional perturbations also reveals the presence of unintentional mode coupling caused by unintentional perturbations in optical fibers, such as the non-uniformity of both the core size and the refractive index distribution along the fiber axis, the inhomogeneity of the core and cladding materials, the inherent microbends created by the protective coatings, and the imperfections in the interface between the core and the cladding. Excess losses due to unintentional perturbations may be of significant import-ance to design consideration in system applications of low-loss optical fiber cables. However, it should be noted that mode coupling is generally detrimen-tal to attenuation but beneficial to dispersion. Many systems in which optical waveguides are presently being contemplated may be bandwidth- rather than attenuation-limited. The bandwidth of a multimode waveguide is limited by arrival time differences among various modes, intramodel and intermodel. Thus, intentional mode coupling by means of intentional fluctuations of the core size or the refractive index along the fiber axis is worthy to be considered in the design of multimode optical fiber cables in order to optimize the trade-off between the attenuation and the bandwidth.

The effects of temperature and thermal cycling on attenuation in optical fibers have also been preliminarily studied, and some typical imper-fections in fibers observed under a scanning electron microscope. A brief review of the mechanisms responsible for optical fiber cabling losses and references related to them are also given.

I   INTRODUCTION

There are numerous advantages of optical fibers over the copper coaxial-cable systems, such as small size, large bandwidth capability, low attenuation, and freedom from electromagnetic interference. Furthermore, the raw materials that make up optical fibers are unlimited in resources, implying that the cost of optical fibers will be much less than that of copper wires. However, before these inherent advantages can be realized, suitable manufacturing processes must be found not only to produce optical fibers of highly uniform cross-section and highly homogeneous refractive index pattern along the fiber axis, and free of imperfections between the core and the cladding; but also to package them into cables to protect the fibers from environmental damage and to provide additional tensile strength without causing the formation of microbendings.

Although a glass fiber in the pure state is extremely strong in mechanical strength, any impurities that touch it before the protective coating is applied degrades its strength considerably. The material of such a protective coating may have different thermal expansion coefficient and other mechanical properties from those of the glass fiber due to different chemical structures. Thus, the jacketing of optical fibers and the forming of them into cables can introduce microbends and abrasion.

Many investigators [e.g., Black and Cook 1975, Murata et al 1975] have reported that the attenuation of fibers with a protective coating or inside a cable is larger than that of bare fibers of the same kind. The increase in attenuation may be due to microbends or abrasion caused by the cabling process. However, the true mechanisms as to the causes of microbends and abrasion and the additional losses due to the presence of them have not yet been fully understood and, therefore, an investigation into optical fiber cabling losses is of great importance not only to the manufacturers who are responsible for improving the characteristics of optical fiber cables, but also to the system engineers who are responsible for the design and the performance of the whole communication system.

In this report we shall confine ourselves to optical attenuation characteristics due to the bending of the fibers under various experimental conditions and to the discussion concerning the mechanisms responsible for the increase of the attenuation losses due to the bending and related perturbations. The causes of the bending and related perturbations in cables are also discussed.

The development of optical fiber cables is now in progress in Canada. The work being presented here was carried out at the University of Manitoba under a contract with the Department of Communications of Canada. It is hoped that the performance of optical fiber cables will improve rapidly through a joint effort of the Communication Research Centre, the manufacturers and the Universities in Canada.

II   BASIC CONCEPTS OF PROPAGATION LOSSES

Propagation losses can be grouped into the following three categories:

(A)   The losses are due to the dissipative and scattering losses of the core and cladding materials and the interface between the two. This category of losses depends mainly upon the absorption characteristics of the materials with a direct bearing upon the impurity contents and other imperfections in the materials.

(B)   The losses are due to the finite cladding width and the lossy jacket around the cladding. This category of losses depends mainly upon the design of the fiber configuration, and sometimes the lossy jacket is required to suppress unwanted cladding modes so as to avoid crosstalk between adjacent fibers in a cable [Marcuse 1971, 1974].

(C)   The losses are due to the radiation suffered by modes which are not fully guided (or fully confined with-in the fiber core) and which are sometimes referred to as radiation modes [Marcuse 1972]. This category of losses consists of the losses due to the presence of an infinite number of radiation modes and the losses due to coupling among the guided modes of a multimode wave-guide (multimode waveguide refers to the guided modes) caused by imperfections in the refractive index distribution or in the

geometry of the waveguide such as microbends, core distortion (non-uniform core cross-section in shape and in dimension) and imperfections in the interface between the core and the cladding.

All three categories of propagation losses have different effects for different modes. In general, coupling of modes as a result of perturbations along the fiber may be beneficial for reducing the delay distortion (or the dispersion) that results from uncoupled multimode operation [Personick 1971, Marcuse 1972]. However, the conversion of modes will cause additional losses in all modes.

In this report we are concerned mainly about the radiation losses in category (C). The losses and dispersion inherent in the materials used for fabricating the fibers (category (A) losses) and those caused by the finite cladding width and the lossy jacket (category (B) losses) will not be considered here, but it should be noted that categories (A) and (B) losses are indirectly associated with category (C) losses. For optimization of the performance of optical fibers all three categories should be considered when low-loss cables are designed.

On the basis of the profiles of the index distribution in the fiber, there are many types of fibers and they are (i) single - mode clad fibers, (ii) multimode clad (step-index) fibers, (iii) dielectric tube fibers, (iv) parabolic index or selfoc fibers, (v) graded index fibers (vi) w-types fibers (vii) single material fibers, etc. [Arnaud 1976]. In the present report we are concerned mainly about the step-index multimode fibers because our experiments being

reported here are referring to this type of fibers. However, it is hoped that in the future other types of fibers will also be studied in order to compare the results about the microbending losses and other kinds of radiation losses and their relation with the profile of the refractive index distribution.

For practical applications it may be desirable to use multi-mode fibers and an incoherent light source to carry the signals. In order to confine most guide modes to the core region of a step-index multimode fiber whose core of radius "a" has a refractive index n_1 and is surrounded by a cladding of thickness t and refractive index n_2, the necessary condition is that n_2 must be slightly lower than n_1. Thus, we can write

$$n_2 = n_1 (1-\Delta) \tag{1}$$

where

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{2}$$

Under this condition the guided wave field is mainly confined to the core region though some field does extend into the cladding, but it decays almost exponentially with radial distance from the core boundary and can be made negligibly small at the outer fiber surface of radius (a + t) from the core center. Such fibers are usually coated with a lossy jacket material whose function is to absorb radiation that is scattered from the core into the cladding, to avoid possible crosstalk between adjacent fibers in a multifiber cable, and also to protect the fiber from mechanical damage and environmental effects. In the following some basic concepts about waveguide modes and radiation losses are summarized.

2.1 Optical Fiber Waveguide Modes

In general, a step index fiber consists of many modes which propagate at different group velocities because of different path lengths. In practice, fibers that transmit only a limited number of modes are of interest from optical communications point of view because the larger the number of modes, the higher is the signal distortion over long distances. To reduce the number of modes the core radius "a" must be small and the difference between n_1 and n_2 must be small [Kao and Hockham 1966, Gloge 1971].

Within a fiber as shwon in Fig.2.1, the propagation constant β of a bound mode will lie within the range

$$n_1 k \geq \beta \geq n_2 k \tag{3}$$

where k is the wave number in free space given by

$$k = \frac{2\pi}{\lambda} \tag{4}$$

in which λ is the wave length of the light beam in free space.

On the basis of ray theory, for a meridional ray incident at one end of a fiber at an angle θ between the ray and the axis as shown in Fig. 2.1, the maximum angle θ_M which is accepted by the fiber is:

$$\sin \theta_M = (n_1^2 - n_2^2)^{\frac{1}{2}} \simeq n_1 (2\Delta)^{\frac{1}{2}} \tag{5}$$

if Δ is small and n_0 is equal to 1 in air. The value of $\sin \theta_M$ is also referred to as the numerical aperture (NA) given by

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} \simeq n_1 (2\Delta)^{\frac{1}{2}} \tag{6}$$

This means that the fiber can accept and propagate a cone of light incident on its end face provided that the conical semi-angle is less than θ_M. Rays with $\theta > \theta_M$ are leaky rays.

(A)

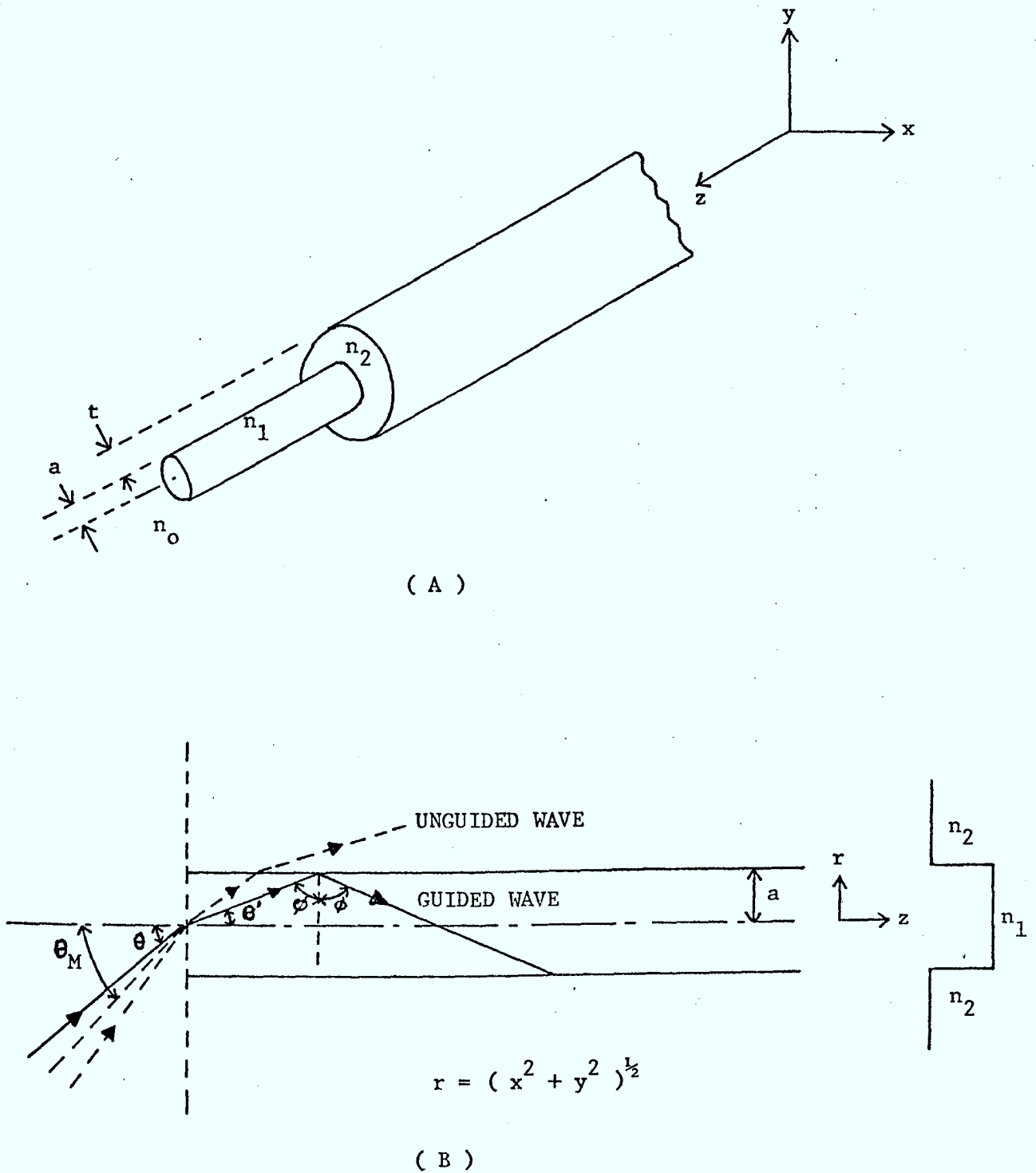$$r = (x^2 + y^2)^{\frac{1}{2}}$$

(B)

Fig. 2.1. (A) Illustrating core of index n_1 and diameter 2a and cladding of index n_2 and thickness t surrounded by a medium of index n_o , (B) Showing guided modes with $\theta \lessgtr \theta_M$ and leaky modes with $\theta > \theta_M$.

There are pairs of modes that are perpendicularly polarized with respect to each other and each pair occupies a cone of solid angle $\pi\delta^2$, where δ is given by

$$\delta = \frac{\lambda}{\pi a} \tag{7}$$

Thus, the total number of free space modes accepted by the fiber is [Gloge 1971]

$$N \simeq 2 \left(\frac{\theta_M}{\delta}\right)^2 = 2 \left(\frac{\pi a \theta_M}{\lambda}\right)^2 \tag{8}$$

which is also the number of modes transmitted by the fiber.

By defining the following parameters

$$u = a(n_1^2 k^2 - \beta^2)^{\frac{1}{2}} \tag{9}$$

$$w = a(\beta^2 - n_2^2 k^2)^{\frac{1}{2}} \tag{10}$$

the mode field can be expressed by Bessel function $J(ur/a)$ inside the core and modified Hankel function $K(wr/a)$ outside the core. The quadratic summation

$$v^2 = u^2 + w^2 \tag{11}$$

leads to a third parameter

$$v = ak (n_1^2 - n_2^2)^{\frac{1}{2}} = ak (NA) \tag{12}$$

Then Eq. (8) can be written as

$$N = 2 \left(\frac{\pi a \theta_M}{\lambda}\right)^2 \simeq 2 \left[\frac{\pi a (NA)}{\lambda}\right]^2 \tag{13}$$

$$= \frac{v^2}{2}$$

For linearly polarized modes $L_{\ell m}$, any particular mode order contains four sets of possible field distributions. Apart from the

lowest mode order, the number of modes up to the vth order is
approximately equal to $4v$ if v is large. At cut-off, $v = u_c$ which
corresponds to the fact that cut-off for the vth mode to occur is

$$u_c = (2v)^{\frac{1}{2}} \qquad (14)$$

On the basis of the assumption that the operation is far
from cut-off and that few modes appreciably close to cut-off are
ignored, Gloge [1971] has derived an expression for the power flow
in the cladding P_{clad} in terms of the total power flow in the
fiber P, and it is given by

$$\frac{P_{clad}}{P} = \frac{4}{3} N^{\frac{1}{2}} \qquad (15)$$

This implies that the power flow in the cladding decreases with
decreasing number of modes or, in other words, with decreasing
difference between n_1 and n_2.

2.2 Radiation Losses

We have mentioned that the radiation losses are due to
(a) the presence of an infinite number of radiation modes and
(b) the mode coupling caused by imperfections or perturbations.
Only part (b) will be discussed in this section because this part
is directly relevant to our experimental work in Chapter IV.

2.2.1 Bending Losses

Several investigators [Gloge 1972, 1975, Marcuse 1972,
1973, Olshansky 1975, 1976, Petermann 1976] have investigated the
theory of mode coupling in multimode fibers caused by bends.

Keck [1974], Gardner [1975], Gardner and Gloge [1975] have observed that increasing tension in a fiber wound on a drum generates mode coupling that, in turn, reduces temporal dispersion and increases attenuation losses. The curvature of a guide has two effects:

(i) The phase fronts in a bent fiber (broken lines) are not parallel as shown in Fig. 2.2. With increasing distance from the center of the curvature, the distance between two phase fronts and also the local phase velocity increase. When the phase velocity equals the local velocity of the light, the light is no longer guided and radiates from the fiber. This loss is significant only for radii of the curvature in the order of a few mm and decreases for increasing curvature radius R following the relation

$$\alpha_r = C \exp (- R/R_o) \qquad (16)$$

where C and R_o are constants.

(ii) The conversion of modes to high-order modes causes an additional loss. With increasing radius of the curvature, the loss decreases with $1/R^2$. Thus, in the case of microbending with large radii of the curvature, this loss always exceeds the loss described in (i).

(A) The Curvature Loss

The curvature loss aforementioned as curvature effect (i) has been studied by several investigators [Marcatili and Miller 1969, Marcatili 1969, Gloge 1972]. The attenuation loss is given by [Gloge 1972]
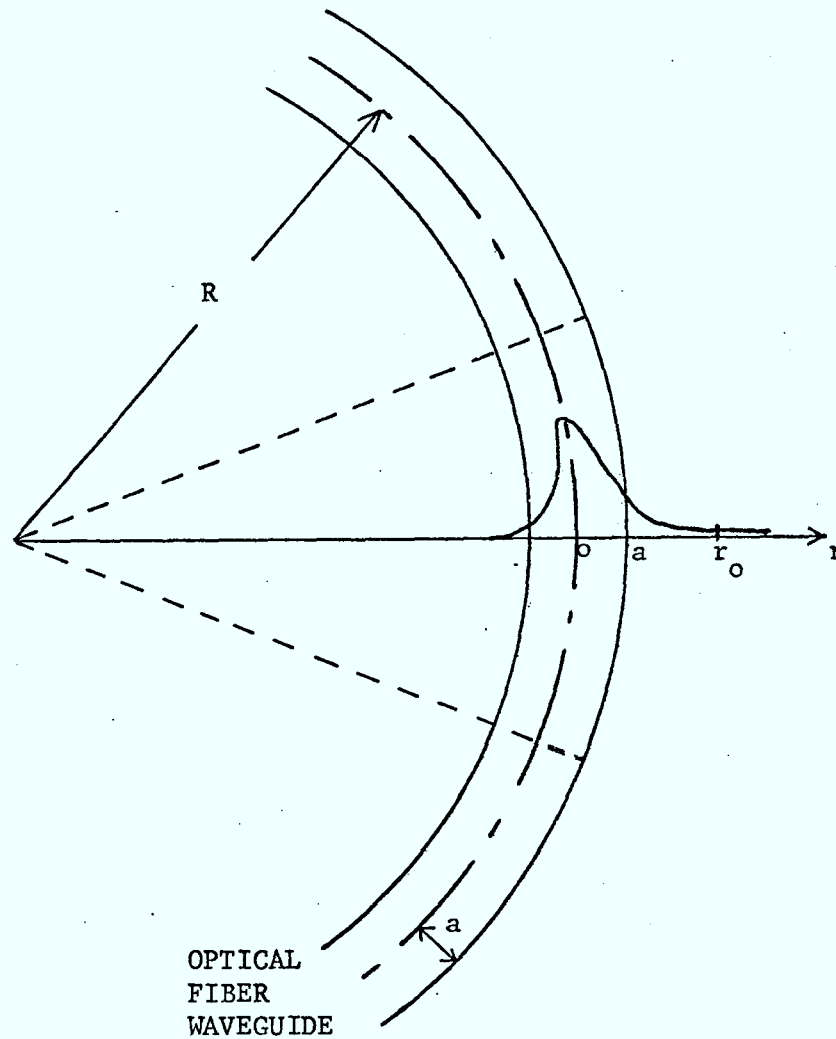
Fig. 2.2. Illustrating radiation caused by the curvature of an optical fiber waveguide.

$$\alpha_r = \frac{2\gamma^2(o)}{\beta} \exp\left[-2\int_a^{ro}\gamma(r)\,dr\right] \qquad (17)$$

where

$$\gamma^2(r) = \beta^2 R^2/(r+R)^2 - n_2^2 k^2 \qquad (18)$$

$$r_o = R\beta/n_2 k - R \qquad (19)$$

and R is the curvature radius (see Fig. 2.2.)

The physical concept of the above equations is described as follows. For a straight waveguide the mode field decreases as $\exp\left[-\gamma(o)(r-a)\right]$ in the cladding. A loss mechanism such as a scatter center or a lossy jacket at a distance r from the waveguide axis produces a loss for this mode, and this loss is proportional to $\exp\left[-2\gamma(o)(r-a)\right]$. However, for a curved waveguide the curvature stretches the waveguide at the outside of the bend resulting in an increase of the mode velocity in the outer wing of the mode and hence in an apparent decrease of the propagation constant there. As a result, β has to be replaced by $\beta R/(r+R)$ and the mode field by $\exp\left[-\int_a^r\gamma(r)\,dr\right]$. At $r = r_o$ the mode velocity reaches the velocity of light in the cladding material $[\gamma(r_o) = o]$, and the mode energy at $r \geq r_o$ will be lost by radiation.

For a step-index profile the curvature loss is given by [Gloge 1972]

$$\alpha_r = 2n_1 k(\theta_c^2 - \theta^2)\exp\left[-\frac{2}{3}n_1 kR(\theta_c^2 - \theta^2 - \frac{2a}{R})^{3/2}\right]$$

$$= C\exp(-R/R_o). \qquad (20)$$

where

$$\theta_c = \frac{\theta_M}{n_1} = \left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{\frac{1}{2}} \simeq (2\Delta)^{\frac{1}{2}} \qquad (21)$$

$$C = 2n_1 k(\theta_c^2 - \theta^2) \qquad (22)$$

$$R_o = [\frac{2}{3} n_1 k (\theta_c^2 - \theta^2 - 2a/R)^{3/2}]^{-1} \qquad (23)$$

Equation (20) is valid only for high order modes not too far from cut-off, and becomes invalid for $\theta << \theta_c$.

It should be noted that α_r can go from a negligibly small value to a prohibitively large value within a range of about 2:1 in R. For example, the case with λ = 630 nm and Δ = 0.001 gives r_o = 16 um, C = 10^4 dB/m, $R_o = 10^{-2}$ m^{-1} and the curvature loss $\alpha_r \simeq 8.68$ dB/m for R = 0.18 m but α_r becomes negligibly small for R = 2 x 0.18 m since α_r decreases exponentially with R [Miller, Marcatili and Li 1973]. The larger the value of Δ, the smaller is the value of α_r. Thus, in practice $\Delta > 0.001$, it is possible to reduce α_r to a negligbly small value for R as small as 1 cm.

The number of modes for step-index optical fibers is thus reduced by the bending of its axis due to this curvature loss mechanism. Equation (8) for the number of guided modes reduces to [Gloge 1972]

$$N(R) \simeq N \left(1 - \frac{a}{R\Delta}\right) \qquad (24)$$

(B) The Microbending Loss

By transforming the bent fiber into an equivalent straight fiber with a new refractive index distribution as shown in Fig.2.3, we can write the refractive index of the equivalent fiber n as

$$n^2 = n_s^2 (x, y, z) = n_b^2 (x, y) + n_p^2 (x, y, z) \qquad (25)$$

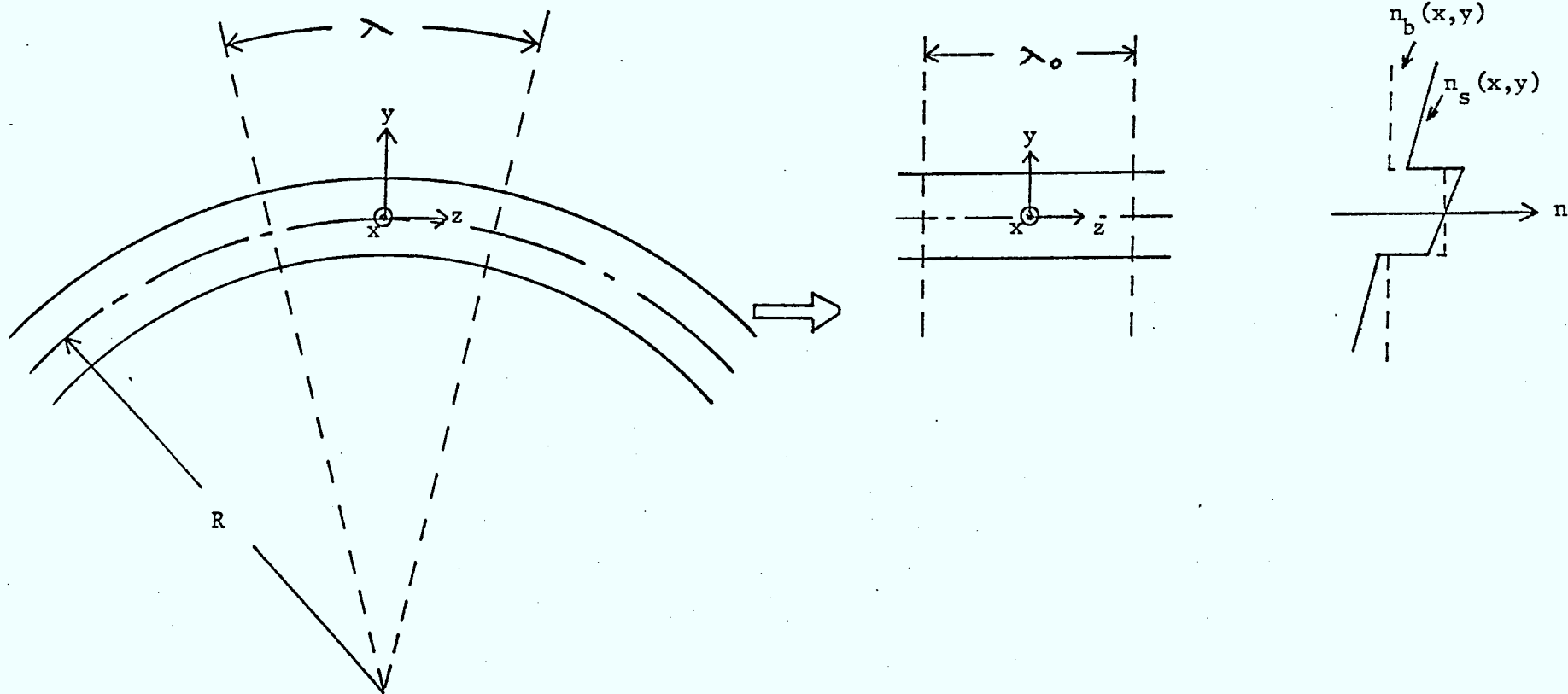where n_b (x, y) is the refractive index distribution of the bent

Fig. 2.3. Transformation of a bent optical fiber into an equivalent straight optical fiber
(n_b denotes the index distribution in the bent fiber and n_s in the equivalent straight fiber).

fiber, $n_p(x, y, z)$ represents the perturbation term due to the curvature and derives from the condition that the dependence of the transverse field on x and y in the bent fiber and in the equivalent straight fiber must be equal. On the assumptions that the curvature radius R is sufficiently large to satisfy the condition $R >> y$ for all relevant values of y and that the refractive-index difference between the core and cladding is sufficiently small that the propagation constant for a normal straight fiber $\beta \simeq n_1 k$, Petermann [1976] has derived an expression for the micro-bending loss in single-mode step-index fibers, and it is given by

$$\alpha_m = \frac{1}{2} <R^{-2}> (n_1 k\omega_0)^2 \int_0^\infty \phi(u) \cos(\Delta\beta u) \, du \qquad (26)$$

where $<R^{-2}>$ denotes the mean value of R^{-2}, ω_0 is the spot radius for a circularly symmetric or a Gausian field $E_b(x, y) = E_b(r)$ and is given by

$$\omega_0^2 = \frac{\int_0^\infty r^3 E_b^2 dr}{\int_0^\infty r E_b^2 dr} \qquad (27)$$

$\phi(u)$ is an autocorrelation function taking into account the statistical character of the curvature and it is introduced as

$$\phi(u) <R^{-2}> = \lim_{L \to \infty} \frac{1}{L} \int_0^L \frac{dz}{R(z) R(z+u)} \qquad (28)$$

$2\pi/\Delta\beta$ denotes the beat wavelength between the field distribution $E_p(x, y)$ and $E_b(x, y)$, and

$$\Delta\beta = (n_1 k\omega_0^2)^{-1} \qquad (29)$$

The integral in Eq. (26) denotes the Fourier transform of ϕ (u) at the spatial frequency $\Delta\beta$.

By using Olshansky's assumption for the power spectrum [Olshansky 1975]

$$\phi \ (\Delta\beta) \ <R^{-2}> \ = \ C/(\Delta\beta)^{2p} \qquad (30)$$

with p=1 for a step-index fiber, Petermann [1976] has obtained an expression for the steady state microbending loss in a multimode step-index fiber as

$$\alpha_{m \ (multimode)} \ = \ 0.16 \ C \ (a/\Delta)^2 \qquad (31)$$

and an expression for a single-mode step-index fiber as

$$\alpha_{m \ (single \ mode)} \ = \ 0.25 \ C \ (n_1 k\omega_o)^4 \ \omega_o^2 \qquad (32)$$

Thus, we obtain

$$\frac{\alpha_m \ (single-mode)}{\alpha_m \ (multimode)} \ = \ 1.56 \ (n_1 k\omega_o)^4 \ \left(\frac{\omega_o \Delta}{a}\right)^2 \qquad (33)$$

However, a transverse stress exerted by the coating material on the fiber in a cable may induce microbends as shown in Fig. 2.4. For multimode step-index fibers Olshansky [1975] has derived an expression for microbending loss γ_m (in dB) and it is given by

$$\gamma_m \ = \ 0.9M \ <h^2> \ \frac{a^4}{(a + t)^6 \Delta^3} \ \left(\frac{E_e}{E_f}\right)^{3/2} \qquad (34)$$

where M is the number of randomly spaced bumps, h is the height of the bump, E_f and E_e are, respectively, the elastic moduli of the fiber and the coating material.
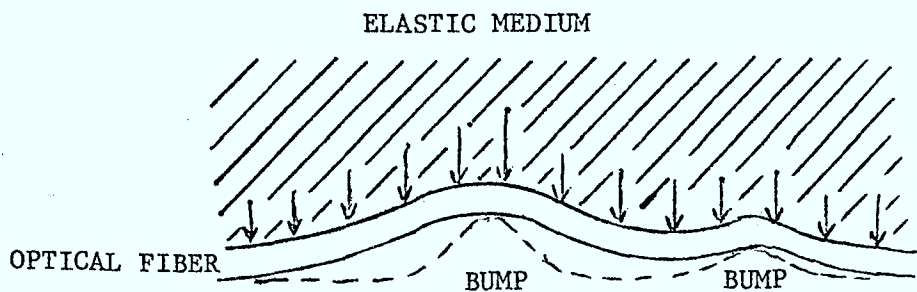
ELASTIC MEDIUM

OPTICAL FIBER

BUMP   BUMP

Fig. 2.4. The formation of microbends by the force (indicated
by arrows) exerted by the coating material.

Equations (31) and (34) indicate that excess microbending loss can be reduced considerably by decreasing the core diameter, and by increasing the thickness of the plastic coating, the numerical aperture and the curvature radius R (or increasing the bump height h).

It should be noted that pulse dispersion is proportional to the value of Δ in step index fiber waveguides. Hence the reduction of the microbending loss by increasing the value of Δ will also cause a reduction of the transmission bandwidth. The information about the trade-off between disadvantages and advantages of microbending may be of importance to the optimal design of optical fiber cables. However, such information is not available yet.

2.2.2 Other Perturbation Losses

So far, we have assumed that the core cross section and the index distribution of the fiber are perfectly uniform along the fiber axis. However, there are always unavoidable fluctuations in diameter and in shape of the fiber core along the axis as shown in Fig.2.5. Such fluctuations will cause the mode coupling and hence the conversion of guided modes to radiation modes.

Supposing that two guided modes have propagation constants β_p and β_q, a complete transfer of power from one mode to the other will occur provided that the diameter of the fiber core varies periodically along the fiber axis z according to
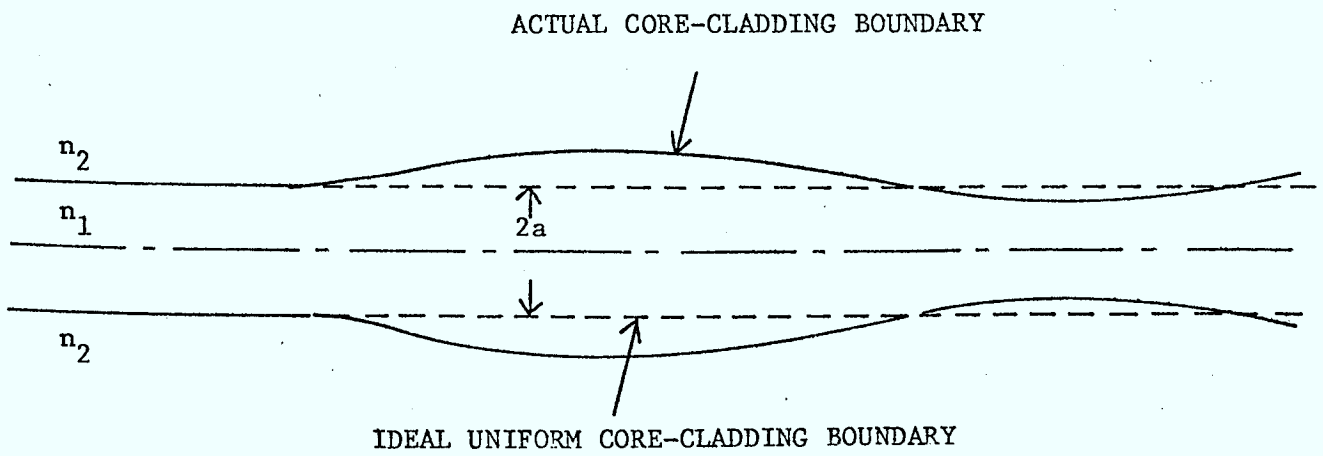
$$G(z) = A \sin \Omega_{pq} z \qquad (35)$$

ACTUAL CORE–CLADDING BOUNDARY

n_2

n_1

$2a$

n_2

IDEAL UNIFORM CORE–CLADDING BOUNDARY

Fig. 2.5. The perturbation in core cross-section of the optical fiber.

and if

$$\Omega_{pq} = \beta_p - \beta_q \tag{36}$$

Marcuse [1969, 1970, 1971, 1972, 1973] has studied the radiation loss due to such a periodic perturbation in fiber core size in two-dimentional slab waveguides and in round clad fibers. When the driven wave has a propagation constant β_p and

$$\beta_p - \beta_2 < \Omega_{pq} < \beta_p + \beta_2 \tag{37}$$

where $\beta_2 = 2\pi n_2/\lambda$ is the propagation constant in the cladding, then power is radiated into the cladding.

With the coupling written as

$$G_{\nu u} = K_{\nu u} f(z) \tag{38}$$

and the correlation function of $f(z)$ to be Gaussian

$$<f(z)f(z-u)> = \sigma^{-2} \exp[-(u^2/L_c^2)] \tag{39}$$

Marcuse [1972] has derived an expression for the radiation loss in multimode dielectric slab waveguides. The loss coefficient for the νth mode is given by

$$\alpha_{p\nu} = \frac{\left(\pi\right)^{7/2}}{4} \frac{(n_1^2 - n_2^2)}{n_1} \frac{(\nu+1)^2}{(1+1/\gamma_\nu t_c)} \frac{\sigma^{-2} L_c}{\lambda t_c^3} \tag{40}$$

where t_c = slab - core thickness

γ_ν = $\left(\beta_\nu^2 - n_2^2 k^2\right)^{1/2}$

β_ν = propagation constant of mode ν

n_1 = refractive index of the core

n_2 = refractive index of the cladding

L_c = correlation length

σ = $(n_1^2 k^2 - \beta^2)^{1/2}$

β = propagation constant for the radiation modes in the z direction

Equation (40) is restricted to the cases in which $L_c/\lambda \ll 1$. Marcuse [1972] has also derived expressions for $\alpha_{p\nu}$ for large L_c. It should be noted that Eq.(40) can be used to predict the radiation loss for round-clad fibers provided that the coupling magnitudes (perturbations) are small and $n_1 - n_2$ is small. To avoid or to minimize the radiation loss due to this perturbation the fiber manufacturing process should (a) maintain a uniform fiber cross-section, and (b) keep the unavoidable (or residual) core-size changes to occur with very long periods $\Omega_{pq} \ll \beta_p - \beta_q$ [Miller, Marcatili and Li 1973].

Since a fiber with a uniform distribution of core size and a non-uniform distribution of refractive index along the fiber axis can be transformed to an equivalent fiber with a non-uniform distribution of core size and a uniform distribution of refractive index along the fiber axis, the approach given above can be used for the cases with a perturbation in refractive index (a change of refractive index distribution pattern along the fiber axis).

The above is only a brief review of the work related to optical fiber cabling losses. For detailed information the reader is referred to the references given at the end of this report.

III   EXPERIMENTAL TECHNIQUES

In the initial phase the investigation was concentrated on the microbending loss characteristics and the radiation losses due to the presence of imperfections in the fiber samples, with the aim that some information about the origins of the cabling induced losses can be deduced from the results. To do this, several experiments have been performed using the techniques described below.

(A)   <u>Circular Bends</u> - The fiber was wound around a cylindrical former of various diameters as shown in Fig. 3.1. No tension was applied to the fiber to avoid the formation of microbends due to the micro-irregularities on the surface of the cylindrical former. The experiment was to study the excess loss due to such a bending as a function of the radius of the circular bend.

(B)   <u>Bump Bends</u> - The bend was formed by placing the fiber over cylindrical steel rods, and on the top of the fiber was placed a block elastomer and an aluminum plate, and then a weight was applied to force the fiber to conform to the shape of the steel rod as shown in Fig. 3.2. The experiment was to study the effects of the transverse stress applied to the fiber, the bending curvature radius, the number of bends, and the spacial separation between bends on the attenuation of the fiber. To ensure whether the excess loss caused by the bending is due to the mode coupling, measurements were also made for the fibers with and without a mode-coupling former placed at a distance of 1 meter from the first bend on the side close to the light source. The mode-coupling former was made by winding under a longitudinal tension about 50 turns of the fiber on a PVC rough-surface drum of diameter of 7.5cm. Such a
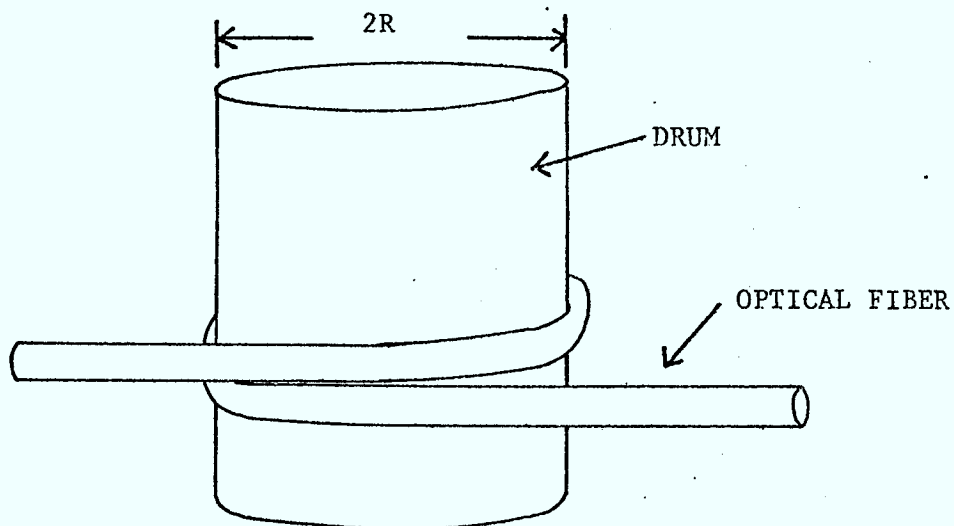
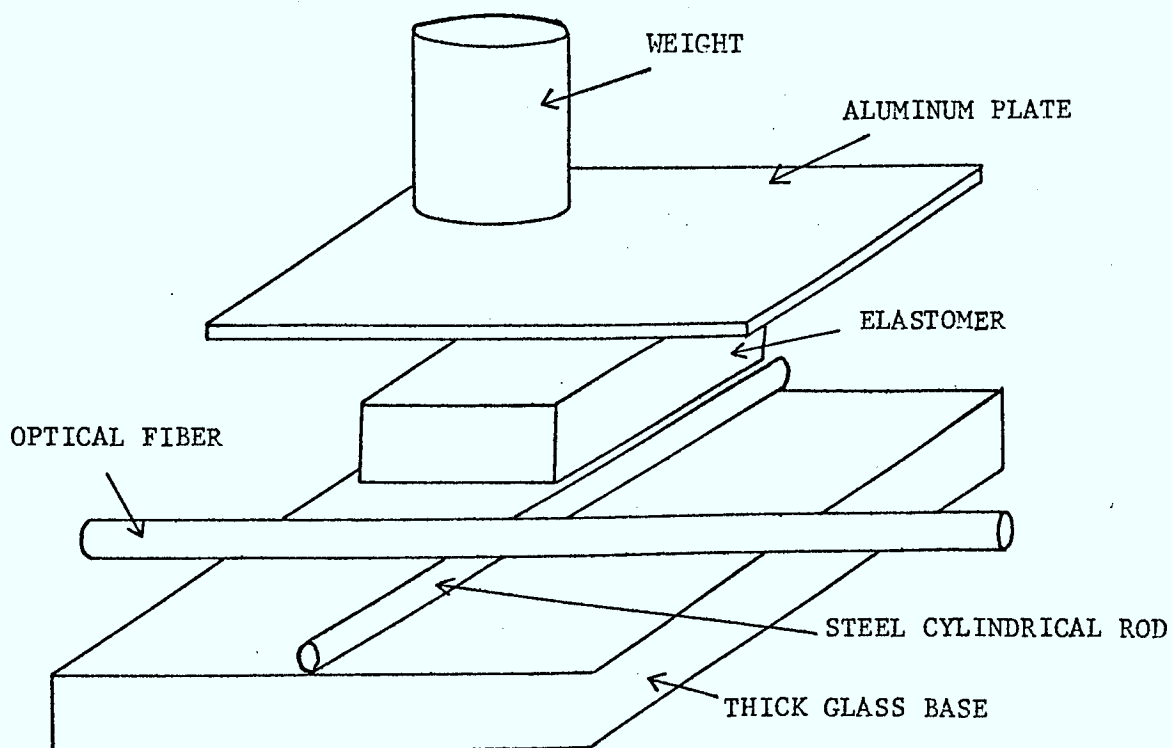Fig. 3.1. Illustrating the formation of a circular bend.

Fig. 3.2. Illustrating the formation of a bump bend.

former should produce many microbends which would suppress a number of high-order modes. If several bump bends were used, the last one was kept at a distance of 1 meter from the end of the fiber close to the detector.

(C) <u>Microbends</u> - Microbends were formed by winding under a longitudinal tension about 50 turns of the fiber on an acrylic drum of diameter of 10.5 cm. The thermal linear-expansion coefficient of the acrylic drum is $8 \times 10^{-5}/^{o}C$ which is larger than that of glass fiber, so that an increase in temperature will introduce elongation of the fiber, thus forcing the fiber to conform to the drum irregularities and to form tension-induced microbends.

(D) <u>Temperature Effect</u> - For the measurements of the temperature dependence of the loss characteristics, 50 turns of the fiber were wound loosely on a smooth glass drum of diameter of 12.5 cm with the same thermal linear expansion coefficient as the fiber so that no additional microbends would be produced in this case. For these measurements the fiber sample was placed inside a thermostatically controlled oven.

(E) <u>Thermal Cycling Effect</u> - The same technique as that described in (D) was used for this experiment but the temperature was adjusted to change following a temperature cycle of $20^{o}C \rightarrow 40^{o}C \rightarrow -40^{o}C \rightarrow 20^{o}C$ at a repetition rate of 1 cycle per hour. This experiment was designed to study whether the temperature cycling would produce any imperfections (such as microbends, microcracks, etc.) along the fiber due to dissimilarity in thermal expansion coefficient between the fiber and the coating material.

(F) Vibration Effect - Fibers in a cable cannot be considered to be always in static equilibrium even if it is installed underground for communications. Cars or trains on the ground surface may introduce micro-vibration to the fibers underground. In view of the fact that this effect may be of importance to the system engineers responsible for the performance of the cable, an experiment was designed to study whether a small vibration would cause an excess loss of the fiber.

(G) Microscopic Investigation - MINI SEM scanning electron micro-scope and optical microscope were also used to observe the imperfec-tions in fiber samples.

The excess loss was measured using the experimental set-up shown in Fig. 3.3. Both ends of the fiber to be evaluated were cleaved. One end was mounted on a movable fiber holder with micro-manipulator which was later adjusted to maximize the light input to the fiber. Between the light source and the end of the fiber a lens was used to focus the light to the end of the fiber. The other end of the fiber was also mounted on a movable fiber holder with micro-manipulator with the light output at the end focusing to the detector which was located in a light-tight chamber. The fiber holder at the input end was then adjusted to maximize the power out-put recorded at the detector end. The input light is a monochromatic light of wavelength of 630 nm. The excess loss is determined by the following equation.

$$\text{Excess loss} = 10 \log \frac{P_a}{P_b}$$

Where P_a and P_b are, respectively, the light output power measured at the detector end without and with applied perturbations (such
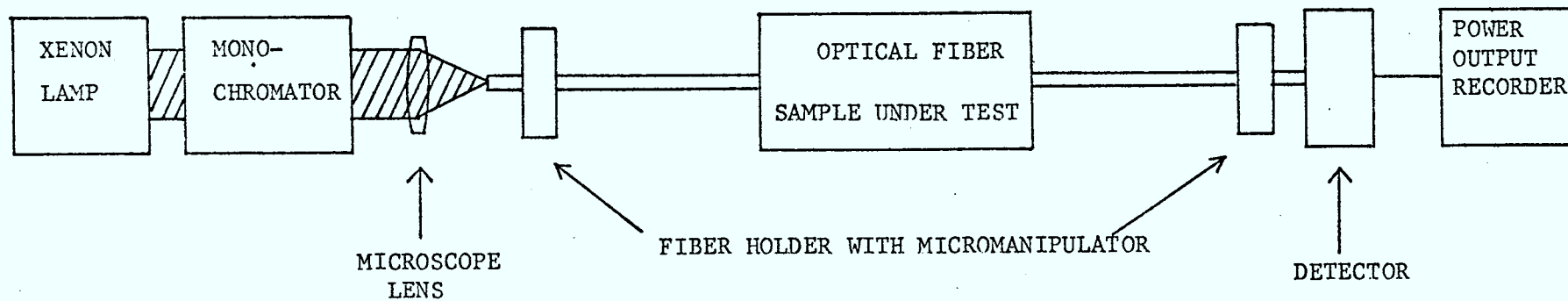
Fig. 3.3. The experimental set-up for measurements of the excess loss in optical fibers.

as microbending, etc.)

All experiments were repeated at least six times, and they are reproducible and consistent as far as the general trend is concerned. The results to be presented in Chapter IV are the typical results selected from each of different types of experiments.

IV   EXPERIMENTAL RESULTS AND DISCUSSION

Stress applied perpendicularly to the axis of a fiber inside a cable may introduce microbends if structural irregularities are present, and also induce axial tension which may, in turn, introduce microbends along the irregular structure, or elongate the fiber and open microcracks. The effects of these possibly-induced perturbations on the propagation losses must be taken into account in the design of cables and in the fabrication process of optical fibers for a particular application.

In general, a microbend with a curvature radius in the order of $\left[a \left(NA \right)^{-2} \right]$ will result in very high radiation losses, and such a curvature can easily be formed in optical fibers if no precaution is made to minimize their susceptibility to the micro-bend formation.

In this section we shall present some experimental results about the effects of these possibly-induced perturbations. Five fiber samples were used for the experiments and they were supplied by Canada Wire and Cable Company Limited. Some properties of these samples are listed in Table 4.1.

TABLE 4.1.   SOME PROPERTIES OF FIBER SAMPLES

Fiber Sample No.		#1	#2	#3	#4	#5
Glass core diameter (μm)		71±1.2	71±1.2	98	125	112
Cladding material		Glass	Glass	Silicone	Silicone	Silicone
Cladding thickness (μm)		18.7±1.3	18.7±1.3	25	18	20
Inner EVA coating (μm)		35.4 ± 11	35.4 ± 11	-	-	-
Outer PVC coating (mm)		-	1.016 ±0.05	-	1.016 ± 0.05	1.016 ± 0.05
Fiber diameter = core + cladding (μm)	measured by CWC	108.4	108.4	148 (core dia=98)	161 (core dia=125)	152 (core dia=112)
	measured by MRL *	106.7	109.4	158 (core dia=97.2)	160 (core dia=110)	143.3 (core dia=73.3)
Length (meters)		200	255	225	247	135
Numerical Aperture		0.19	0.19	0.29	0.29	0.31
Attenuation at 850 nm (dB/km)		19.7	18.8	14.7	20.5 (12.3 before buffer)	62.5 (21.4 before buffer)

CWC   refers to Canada Wire and Cable Company Limited
MRL   refers to Materials Research Laboratory of the University of Manitoba

*   measured by means of a microscope with a magnification of X 300

We have measured the size of each of the fiber samples received using a microscope. It can be seen from Table 4.1 that our measured values are in good agreement with those quoted by the supplier, except Fiber sample #5. For this fiber sample our measured core diameter is 73.3 μm which is much smaller than 112.0 μm quoted by the supplier. However, this particular sample has a high attenuation and is not sensitive to externally applied perturbations. This may be attributed to the fact that there are a great number of inherent imperfections in this sample, possibly produced during the fabricating process. These imperfections dominate the whole attenuation characteristics. For example, if a perturbation is applied to this fiber sample (e.g., a bump-bend) at a position near the location of an inherent imperfection (e.g., a microcrack in the cladding), this inherent imperfection which is more detrimental than an applied bump-bend will cause a large portion of transmitting light to leak away through the microcrack, thus making the bump-bend inefficient to generate leaky modes because the inherent microcrack has filtered out most of higher-order guided modes which may be converted to leaky modes by the bump-bend. For this reason this particular fiber sample has not been included in our studies on the effects of applied perturbations. When a light beam is applied to one end of this fiber sample which is in the drum received, many light spots can be observed, indicating that there are a great number of serious imperfections existing in this particular fiber sample. We shall present our observations and discussion of such imperfections in a later section. In the following we shall present first our experimental results and discussion for Fiber samples #1, #2, #3 and #4.

4.1   The Effects of Circular Bends:

Using the method shown in Fig. 3.1 to form a circular bend, we have measured the excess loss due to such a bend in the fiber as a function of radius of the bend. The results are shown in Fig.4.1. The excess loss is practically negligible for R > 5 cm. But it increases slowly first with decreasing R below 5 cm; and when R approaches 0.8 cm. the excess loss for Fiber samples #1 and #2 increases dramatically with decreasing R. On the basis of Eqs. (20) and (34), the smaller the core diameter and the numerical aperture, the higher is the bending loss. The values of a and NA of Fiber samples #1 and #2 are smaller than the corresponding values of these parameters of Fiber samples #3 and #4. This may explain why the excess loss in Fiber samples #1 and #2 is larger than that in Fiber samples #3 and #4. The PVC jacketing material does cause a higher excess loss in both types of glass fibers. It is possible that the longitudinal tensions T_1 and T_2 in the directions shown in Fig. 4.2 may induce a net transverse stress which produces additional micro-bends inside the circular bend. The curvature radius of such additional microbends decreases with decreasing radius of the circular bend (decreasing R) because both T_1 and T_2 increases with decreasing R. Thus, such microbends would filter out more high-order modes than the circular bend. However, it is most likely   that   additional microbends may be formed only when R reaches a certain critical value such that T_1 and T_2 become large enough to cause the formation.
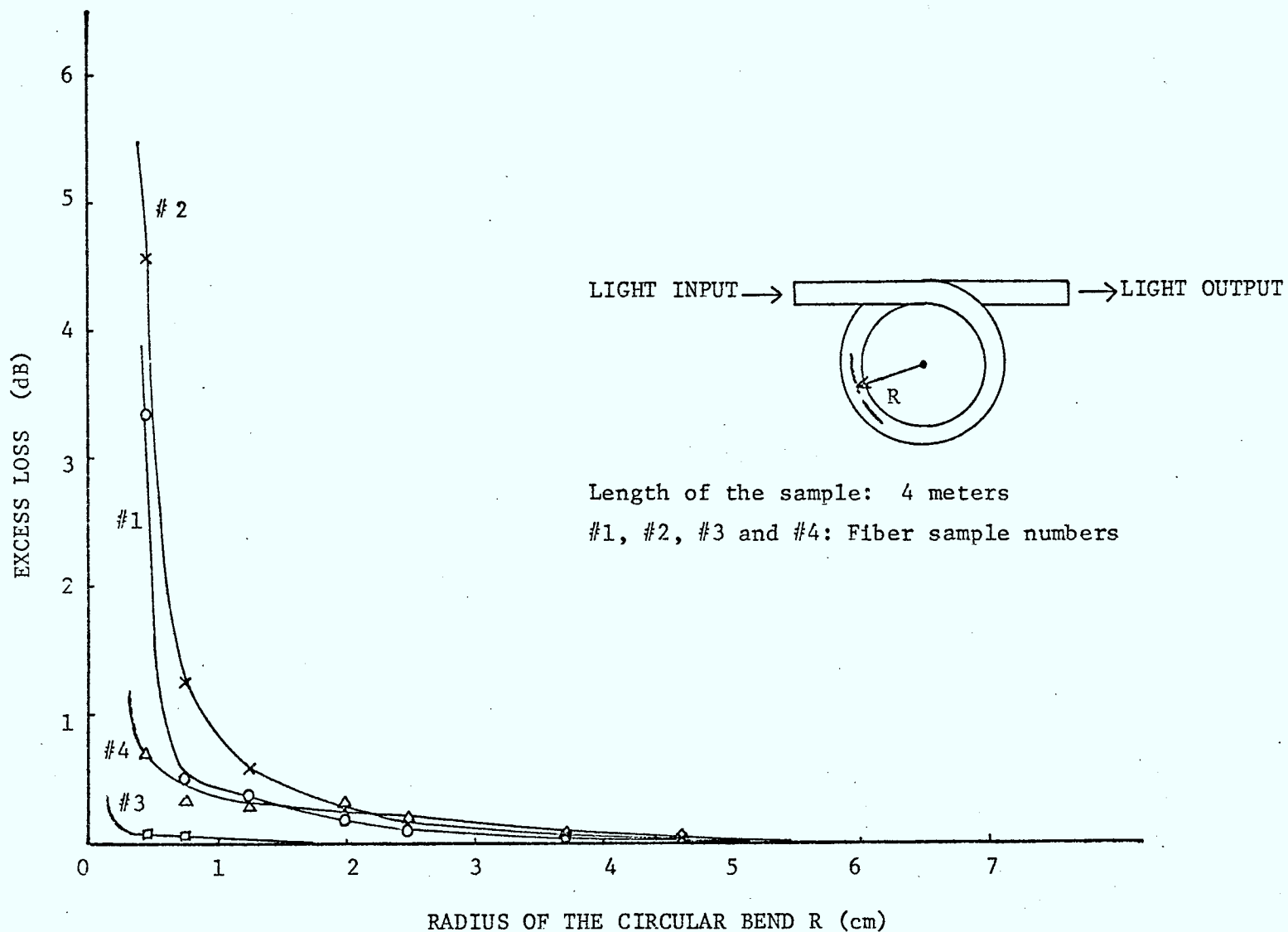
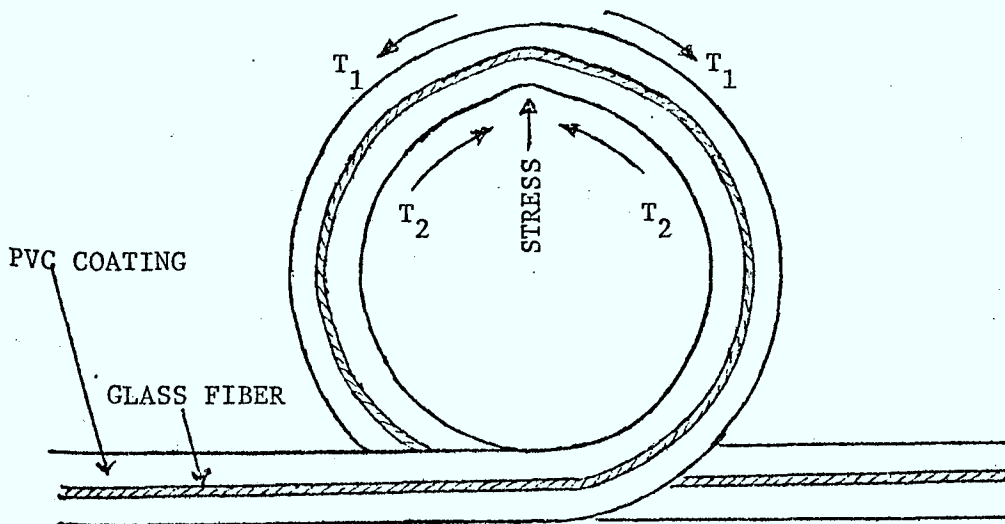Fig. 4.1. The excess loss due to a circular bend in the fiber as a function of radius of the circular bend.

Fig. 4.2. Illustrating additional microbends induced by transverse stress created by longitudinal tensions

When the value of R was reduced to about 0.4 cm, the light leaking out through the PVC coating could be seen by naked eye. Two typical photographs of this phenomenon are given in Fig. 4.3. When the circular bend was released and the fiber was made to return back to its original straight form, the excess loss reduced to zero for R > 0.5 cm. But with R < 0.4 cm the fiber usually suffered from mechanical damage, particularly for Fiber samples #1 and #2 with glass cladding which is more stiff and less elastic than silicone cladding for Fiber samples #3 and #4. For R < 0.4 cm the excess loss did not reduce to zero when the circular bend was released to allow the fiber to return to its straight form. We have also examined the bends with R < 0.5 cm and found that for the cases in which the excess loss did not reduce to zero after the bend was released and made to return back to its original straight form, the fiber sufferred with microcracks in the cladding and in severe cases the core was broken. We have also found that although the core was not broken, the interface between the core and the cladding was opened up due to such a bending. The minimum radius below which the fiber would suffer from mechanical damage is about 0.4 cm.

It should be noted that for R slightly higher than 0.5 cm, leaking light through the PVC coating could also be seen in the dark though it is very dim, indicating that some high-order modes have become leaking modes due to the bending even without mechanical damage.
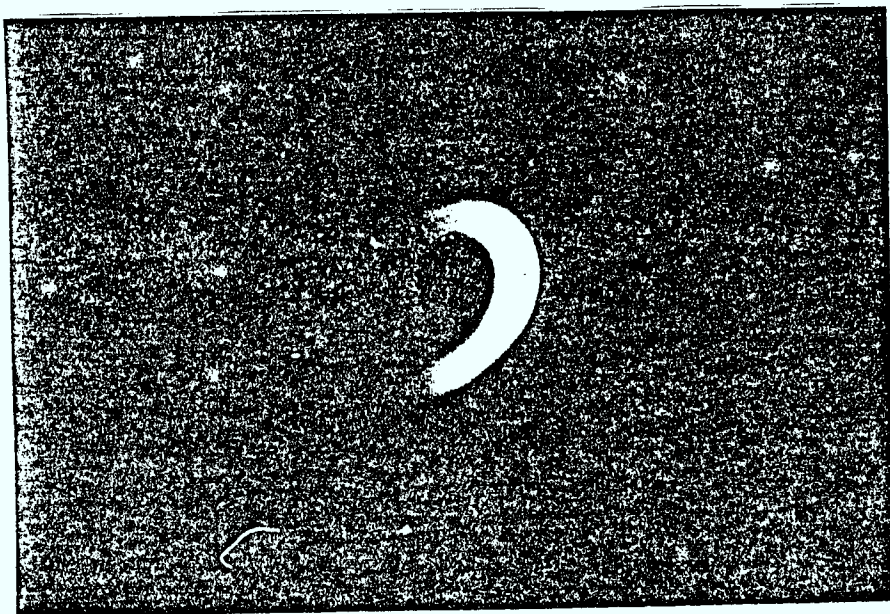
(A)
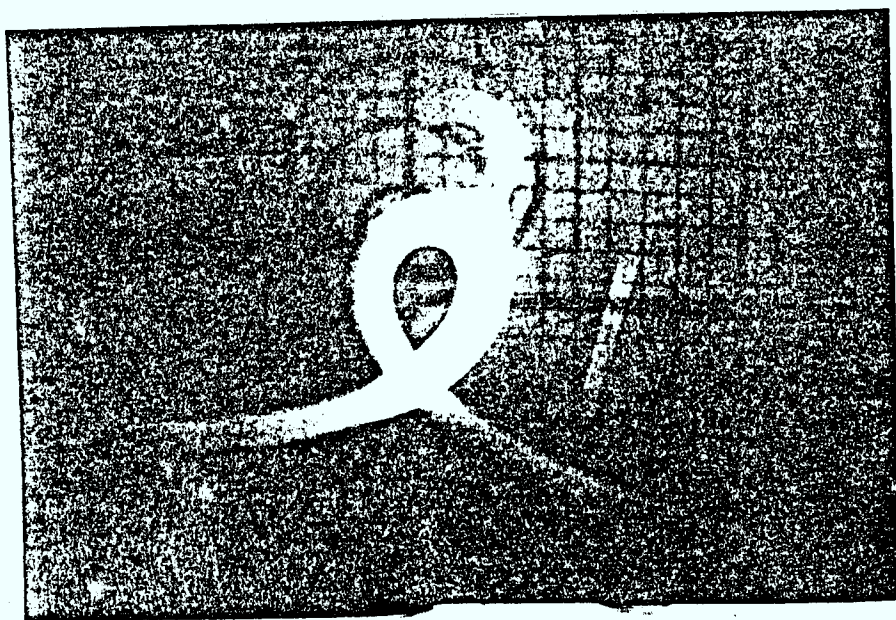
(B)

Fig. 4.3. Photographs showing the leaking light through the PVC
jacketing material in the bend of Fiber #2 obsered
in the dark (A) exposure time: 10 seconds, (B) exposure
time: 120 seconds; radii of the reference circles: 3 mm,
5 mm and 7 mm; the approximate radius of the circular
bend: 4 mm.

4.2   The Effects of Bump Bends

Using the method shown in Fig. 3.2 to form bump bends, we have measured the excess loss due to such bump bends in the fiber. Before presenting our results, it is interesting to note that the tension and twist applied to a suspended optical glass fiber (coated or uncoated) do not cause any change in losses and impulse response for tensile force up to near the breaking point [Private communication from the Furukawa Electric Co. Ltd. in Japan]. A similar result for a tensile force larger than 1 N has also been reported by Geckeler and Schicketanz [1975]. But the tension applied to a fiber wound on a drum causes a great increase in losses, indicating that the tension forces the fiber to conform to surface irregularities of the drum, resulting in the formation of random microbends [Gardner 1975, Gardner and Gloge 1975, Geckeler and Schicketanz 1975]. In this case the tensile force is only the indirect cause of this effect. The direct cause is the introduction of a transverse stress over bumps (irregularities on the drum surface) creating microbends in a way similar to that shown in Fig. 2.4. Such microbends induce bending losses as described in Section 2.1. In the experiments for the effects of bump bends, we used the weight in such a range that it would not cause mechanical damage to the fiber. For all experiments the excess loss returns back to zero when the weight is reduced to zero. All experiments are reproducible and consistent.

4.2.1   The Effects of the Transverse Stress Applied to the Fiber over the Bumps, and the Size of the Bumps

It is obvious that the increase of the applied weight means the increase of the applied stress to force the fiber to bend more

to conform to the shape of the cylindrical rod. The more the fiber
conforms to the shape of the cylindrical rod, the smaller is the
curvature radius of the bend, thus causing a higher excess loss as
shown in Figs. 4.4 - 4.8. Of course, when the fiber becomes more or
less conformable to the shape of the rod, further increase in weight
would not cause further change in excess loss, provided that the
weight does not cause mechanical damage. The critical weight for the
excess loss to reach a saturation value depends on the type of the
fiber as shown in Figs. 4.4 - 4.8. In Figs. 4.4 and 4.5 it can be
seen that the effect of the weight on Fiber sample #2 is much larger
than that on Fiber sample #4 (with PVC coating), and this effect on
Fiber sample #1 is larger than that on Fiber sample #3 (without
PVC coating). The trend of the excess loss for these four Fiber
samples is similar to that shown in Fig. 4.1, so that the same mechan-
ism responsible for the excess loss due to a circular bend can be
used to explain the trend in Figs. 4.4 and 4.5. The weight applied
to the fiber with a PVC coating not only forces the fiber to conform
to the shape of the cylindrical rod, but also induces microbends in a
similar manner to that shown in Fig. 4.2. Such an indirect effect
diminishes with decreasing diameter of the cylindrical rod as shown
in Figs. 4.7 and 4.8. The decrease in rod diameter reduces the
height of the bump (or in other words, increases the bending curvature
radius), which, in turn, results in a smaller excess loss as predicted
by Eq.(34). Furthermore, the decrease in rod diameter reduces the
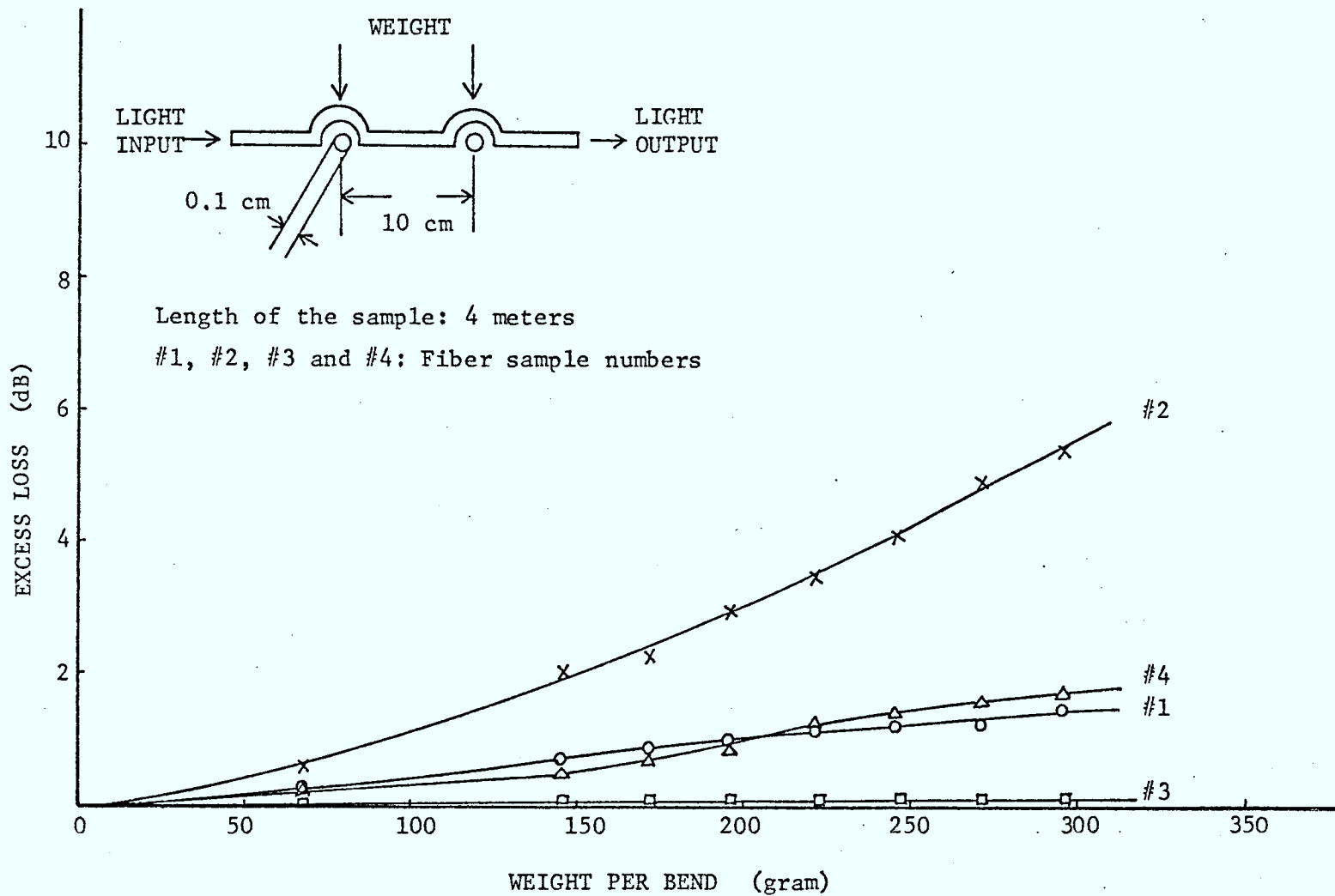contact area between the fiber and the rod, thus reducing the

Fig. 4.4. The excess loss due to two bump bends in the fiber as a function of
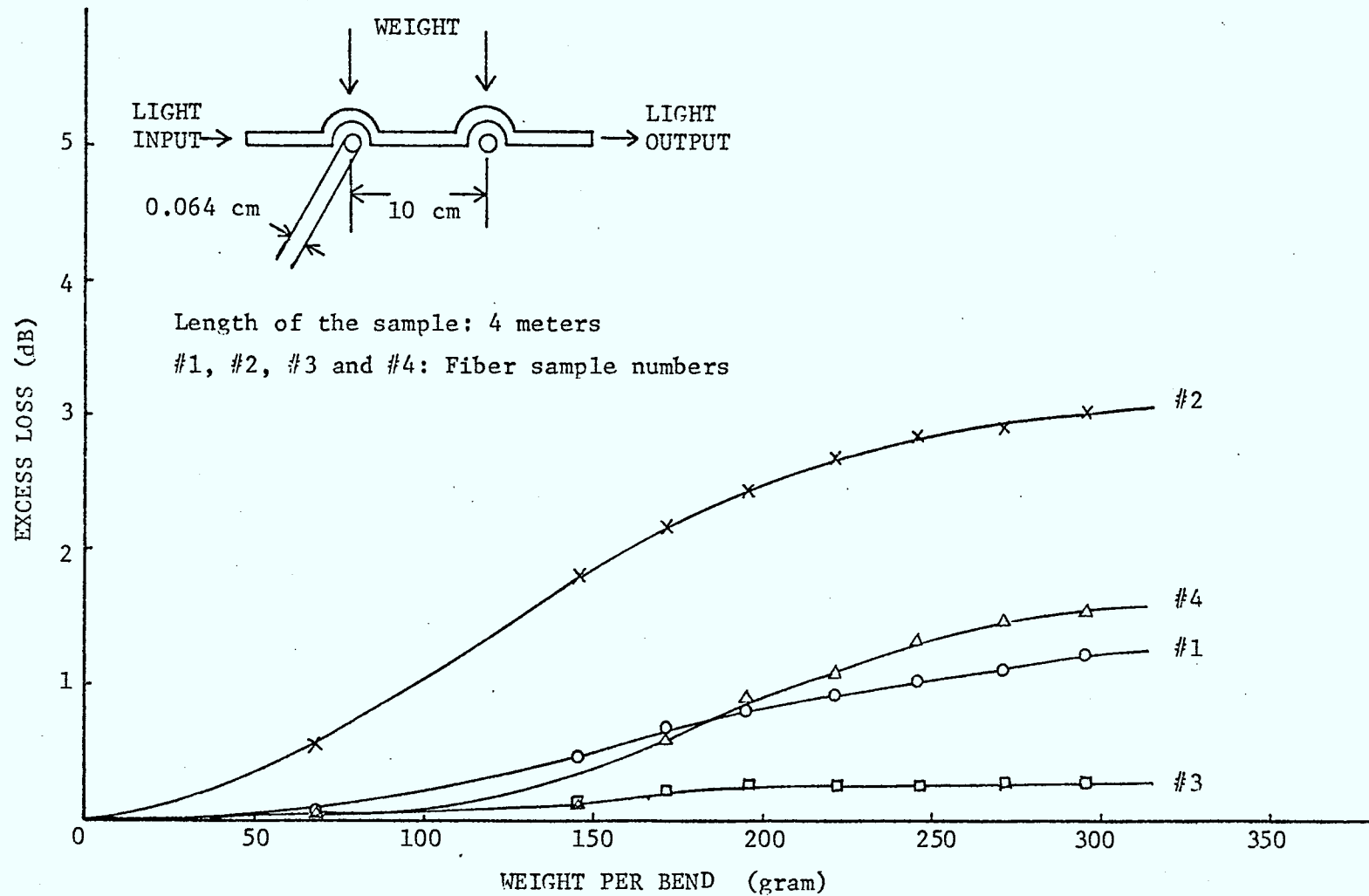weight for the rod of diameter of 0.1 cm.

Fig. 4.5. The excess loss due to two bump bends in the fiber as a function of weight for the rod of diameter of 0.064 cm.
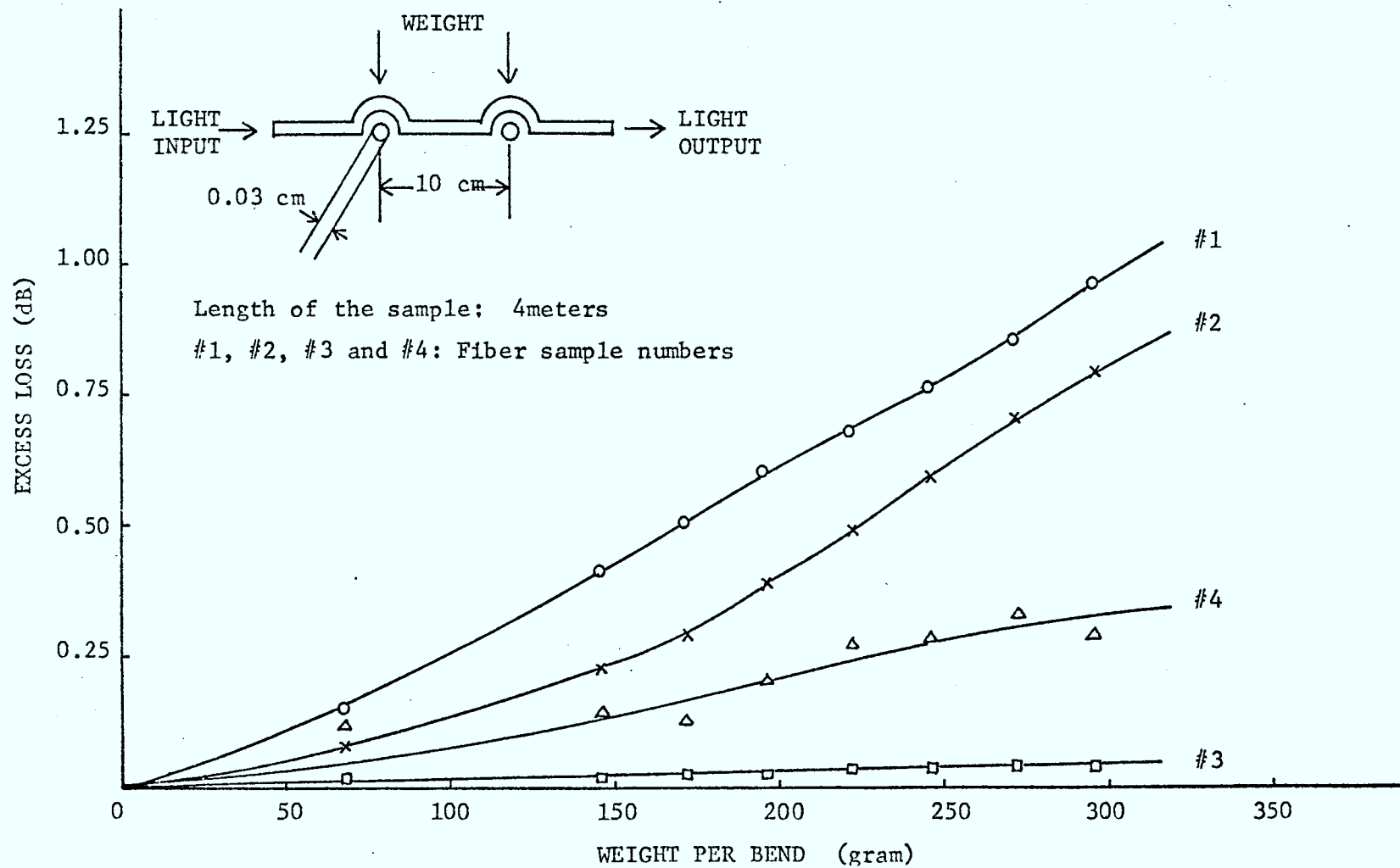
Fig. 4.6. The excess loss due to two bump bends in the fiber as a function of weight for the rod of diameter of 0.03 cm.
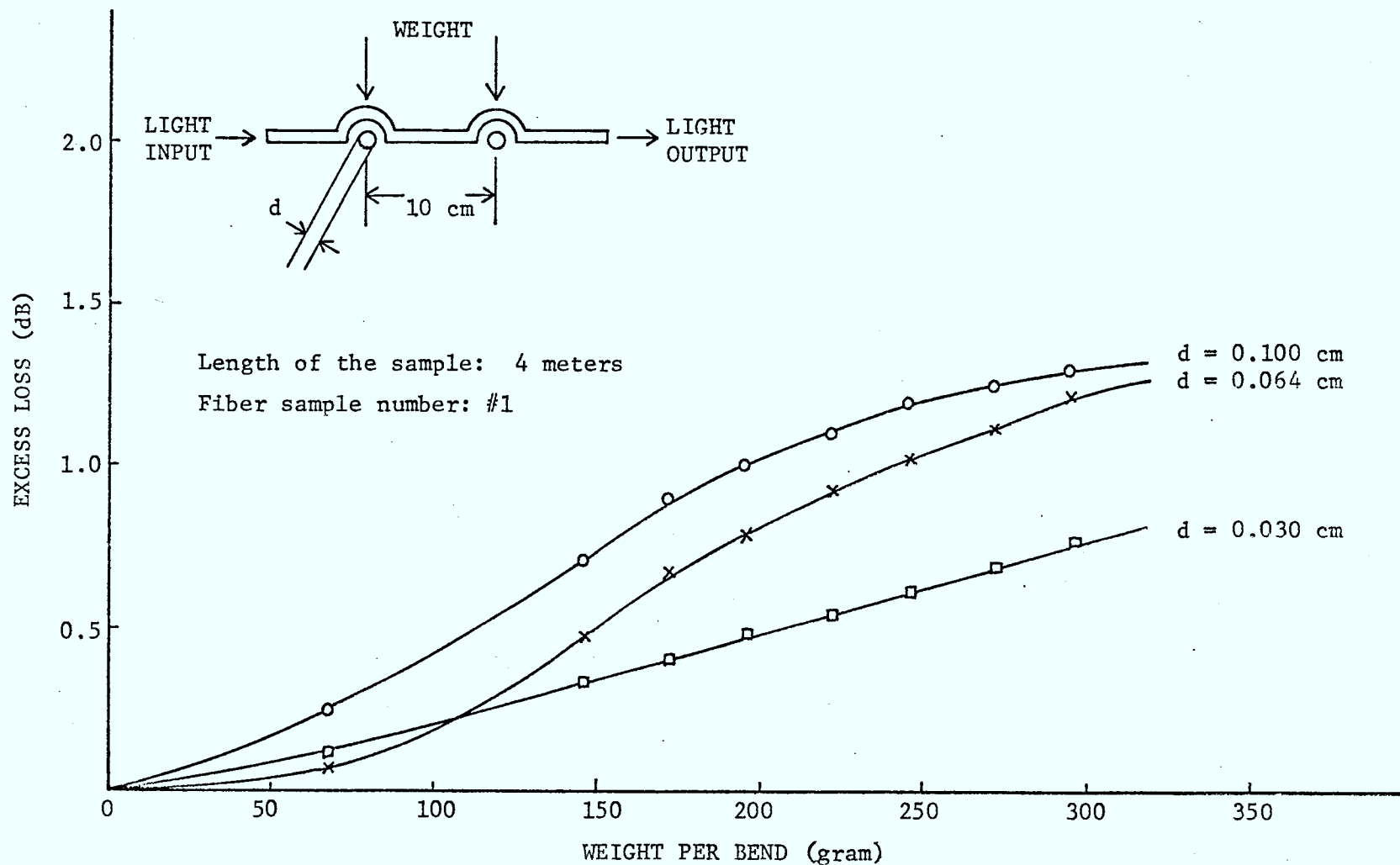
Fig. 4.7. The excess loss due to two bump bends in the fiber as a function of the diameter of the rod at various weights for fiber sample number #1.
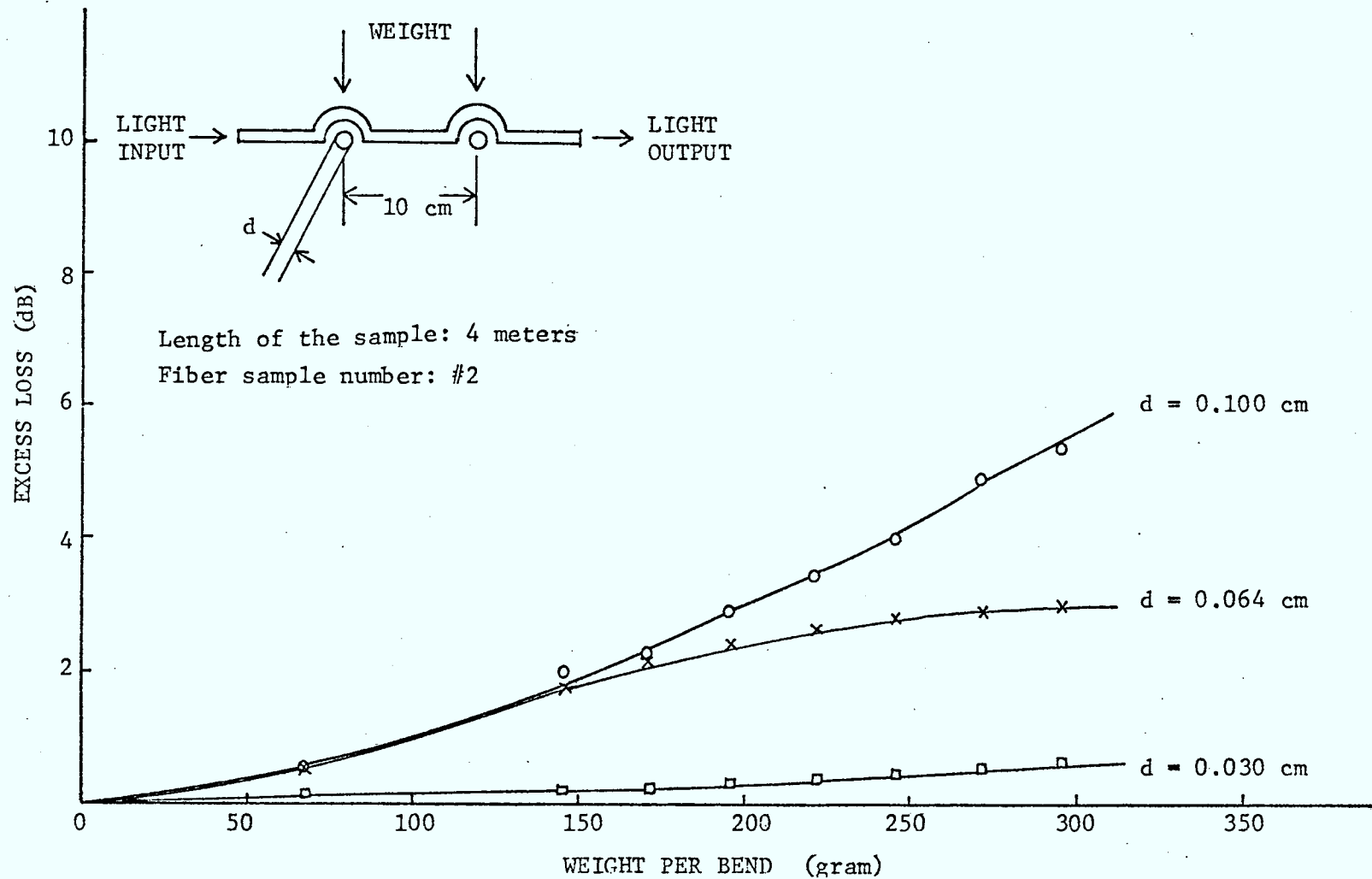
Fig. 4.8. The excess loss due to two bump bends in the fiber as a function of the diameter of the rod at various weights for fiber sample number #2.

probability for the formation of microbends around the bump. The fact that Fiber sample #3 with an elastic silicone cladding, but without PVC coating, has the smallest excess loss supports this hypothesis.

It is interesting to note that with the rod diameter of 0.03 cm the excess loss of Fiber sample #1 is higher than that of Fiber sample #2 (Fig. 4.6), just opposite to the trend for larger rod diameters (Figs. 4.4 and 4.5). This phenomenon may be attributed to the fact that it is easier to force a fiber with a stiff glass cladding but without coating (Fiber sample #1) to conform to the shape of the bump than to force the same with a PVC coating (Fiber sample #2) for small rod diameters (or small bump sizes).

To ensure that the excess loss for all the cases was caused by the bending and not by the weight, we placed the weight alone directly on the fiber with the absence of cylindrical rods so that no bump bends were formed, and found that under this condition the excess loss is practically negligible for all fiber samples. This implies that the excess loss is completely due to the bending losses as described in Section 2.2.1. For the bump bending of the range of curvature radii under investigation, the radiation losses are mainly due to the mode coupling. Fig. 4.9 shows the radiation field pattern taken at the light-output end. Without bump bends in the fiber, the output light spreads out to a farther distance from the center of the core, while with bump bends the output light is much confined and weaker, indicating that with bump bends a great number of high-order modes has been converted to leaky modes and filtered out.
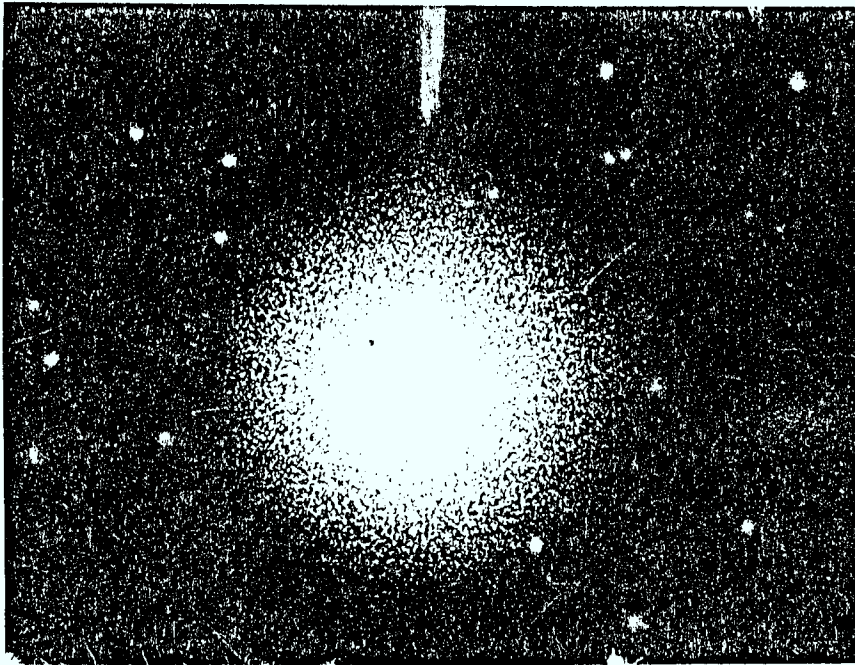
(A) WITHOUT BUMP BENDS IN THE FIBER
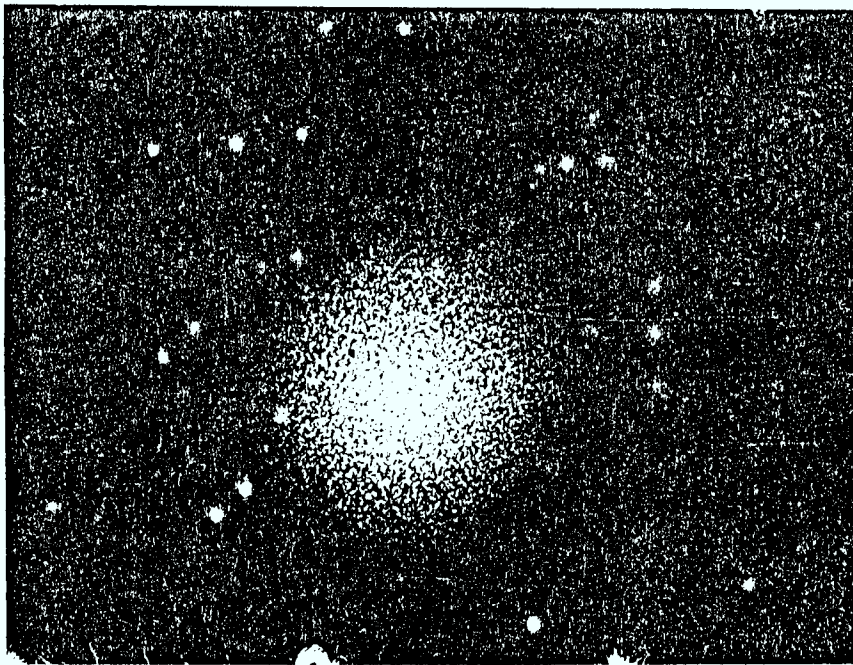
(B) WITH BUMP BENDS IN THE FIBER

Fig. 4.9. Photographs showing the light brightness distribution as a
function of r from the center of the fiber core corresponding
to the radiation field patterns for (A) without bump bends and
(B) with two bumpbends in fiber sample number #2 caused by two
cylindrical rods of diameter of 0.1 cm at a seperation of 10 cm
under a weight of 300 grams per bend.

4.2.2   The Effect of the Number of Bump Bends

We have also studied the effect of the number of bump bends. The results about this effect for Fiber samples #1 and #2 are given in Figs. 10 and 11. We have not measured the excess loss for these particular pieces of Fiber samples with two bends at the same separation of 5 cm. However, we replotted one of the curves from Fig. 4.12A on Fig. 4.10 (the dashed curve is for two bends at a separation of 5 cm measured on a different piece of Fiber sample #1). It can be seen that the rate of the increase in excess loss is large when the number of bends is increased from two bends to four bends, keeping the separation between bends unchanged. However, the rate of this increase in excess loss diminishes when the number of bends is increased from four bends to six bends. It can be predicted that the rate of the increase in excess loss will continue to diminish and finally the excess loss will approach to a saturation value if the number of bump bends is continued to increase. A bump bend can be thought of as a high-order-mode filter to convert guided modes to higher-order modes and to convert some high-order modes to leaky modes which are filtered out. If there are a series of bump bends, the first bend suppresses the efficiency of the second bend, and the second bend suppresses the efficiency of subsequent bends in the performance of their filtering function. This argument does explain the results in Figs. 4.10 and 4.11.

4.2.3   The Effect of the Separation Distance between Bump Bends

The excess loss due to two bump bends increases with increasing separation distance between the bends as shown in Figs. 4.12A, 4.12B and 4.13. This phenomenon indicates indirectly that the fiber

Fig. 4.10. The excess loss due to bump bends in the fiber as a function of number of bends for fiber sample number #1.

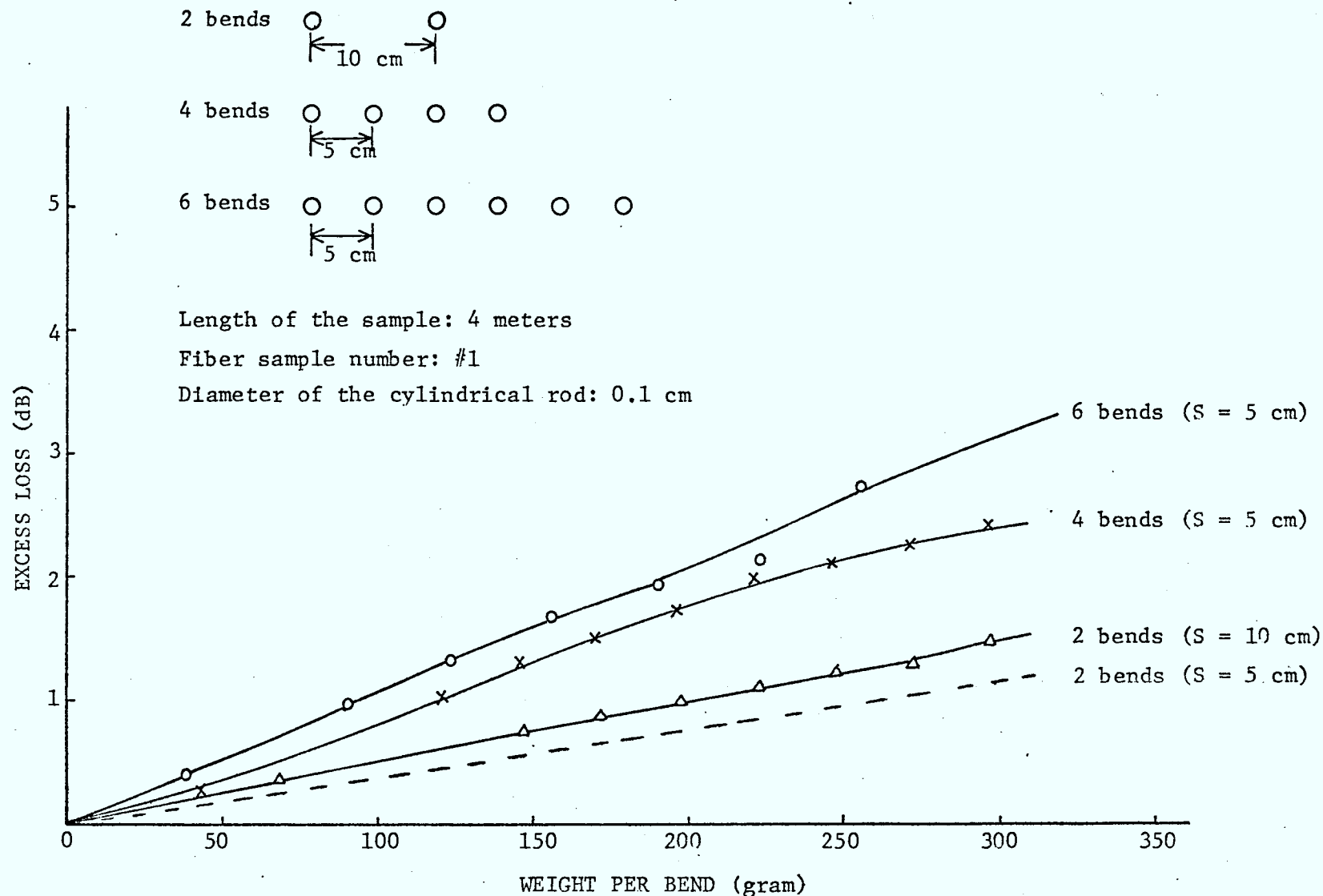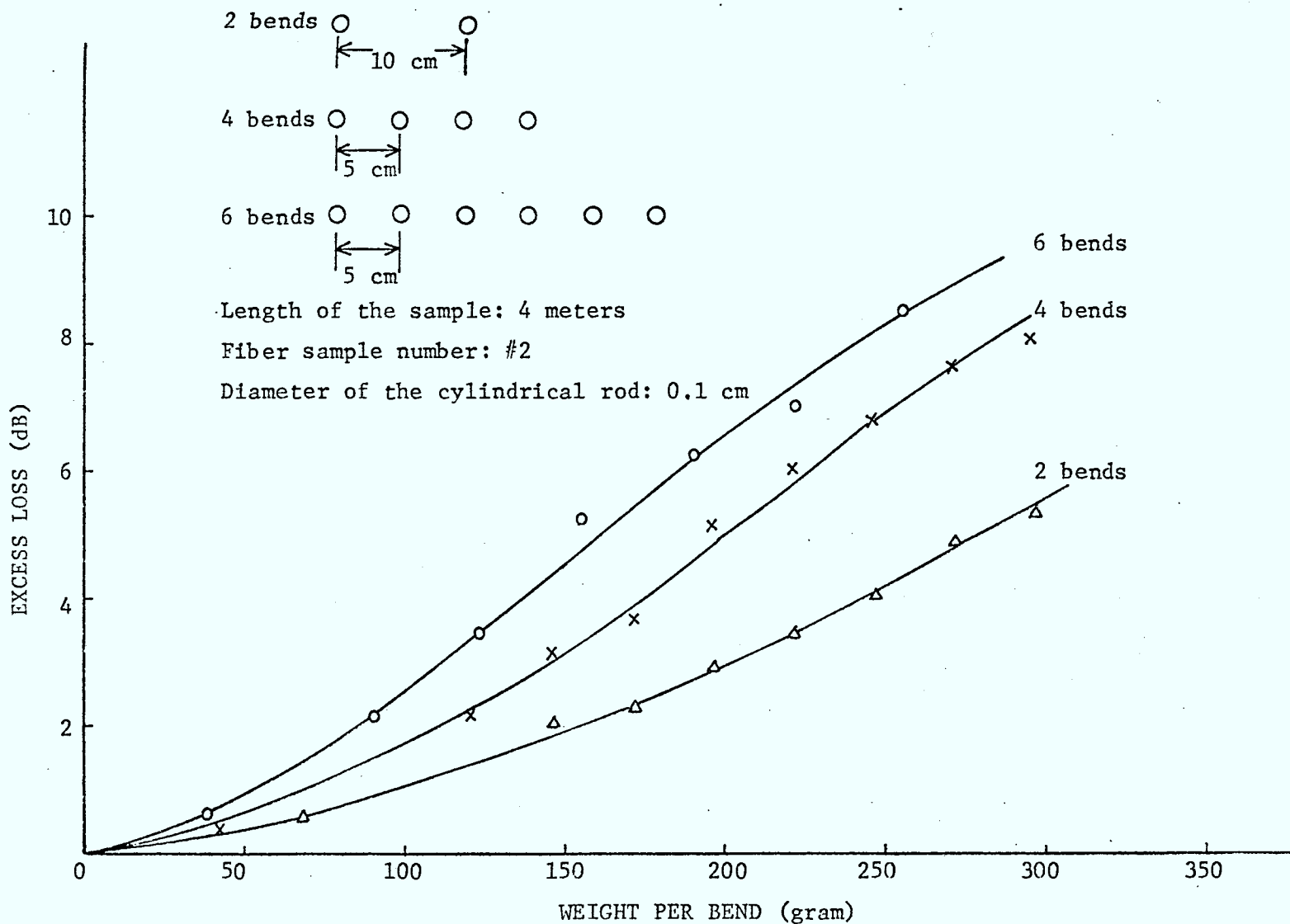Fig. 4.11. The excess loss due to bump bends in the fiber as a function of number of bends for fiber sample number #2.

Fig. 4.12A. The excess loss due to two bump bends in the fiber as a function of the separation of the two bends for the cylindrical rod diameter of 0.1 cm.

Fig. 4.12B. The excess loss due to two bump bends in the fiber as a function of the separation of the two bends for the sylindrical rod diameter of 0.1 cm.
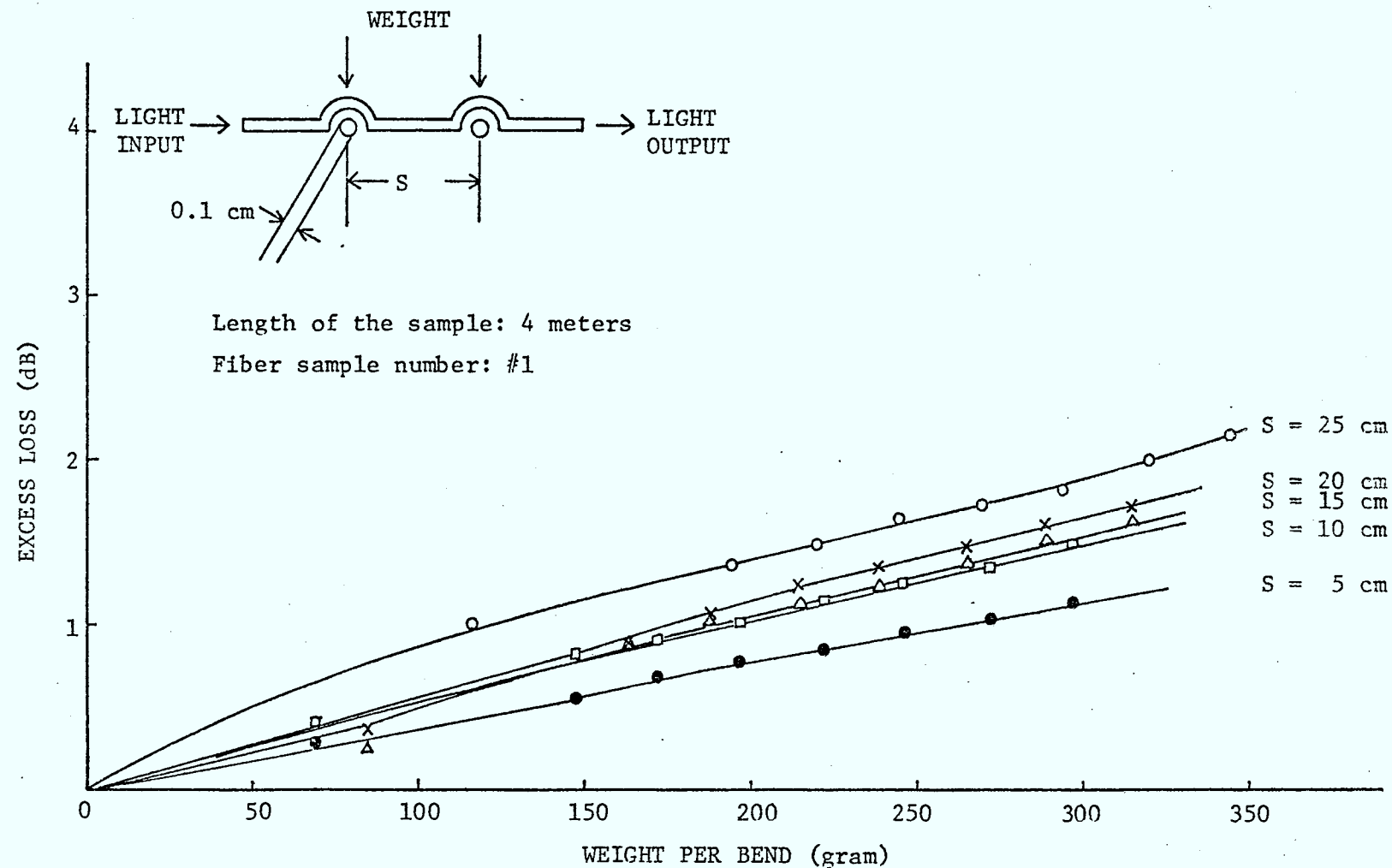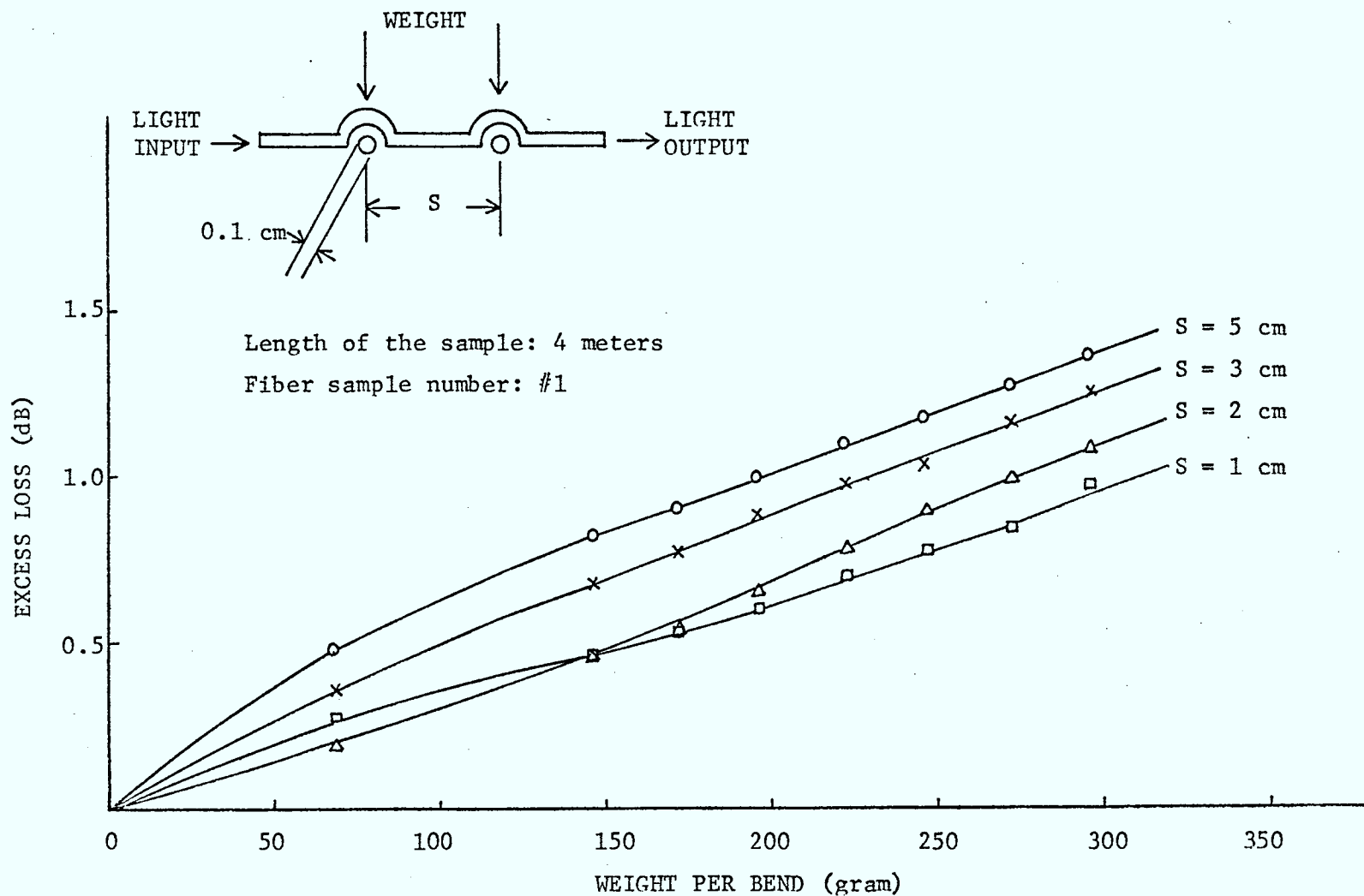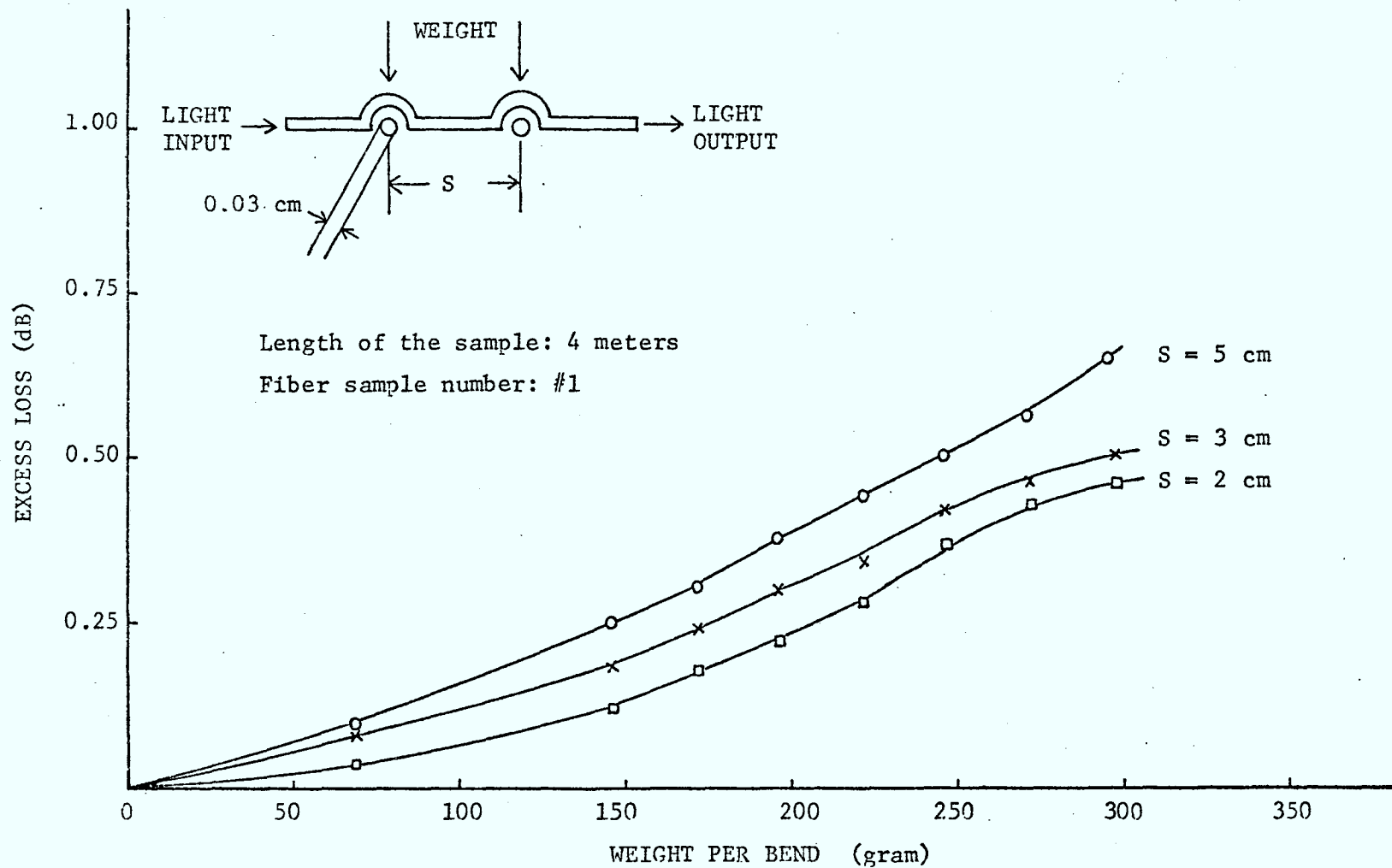
Fig. 4.13. The excess loss due to two bump bends in the fiber as a function of the separation of the two bends for the cylindrical rod diameter of 0.03 cm.

is not completely uniform and homogeneous in core cross-section and in refractive index distribution along the fiber axis. After the first bump bend filters out some high-order modes, the guided modes passing through this bend will be subjected to weak conversion to higher order modes due to the non-uniformity and non-homogeneity of the fiber before they reach the second bump-bend. The larger the separation distance between the bends, the more is higher order modes to be formed prior to the filtering action of the second bump bends. This explains the results in Figs. 4.12A, 4.12B and 4.13.

The measurements of the effect of the separation distance between two bump bends may be used as a method to assess the number of higher order modes created by a given length of the fiber, and hence to estimate the degree of non-uniformity and non-homogeneity of the fiber along the fiber axis.

4.2.4 The Effect of the Mode-Coupling Former

By placing a mode-coupling former between the light-input end and the first bump bend of the fiber, the excess loss for the case with such a mode-coupling former is less than that without such a mode-coupling former as shown in Fig. 4.14. The mode-coupling former suppresses some high order modes before the light beam is allowed to enter the bump bends. In this case the bump bends filter out less light power so that the excess loss is smaller. This experiment provides a further evidence that the function of the bump bends is to convert guide modes to higher order modes and then to convert some high order modes to leaky modes which are filtered out.
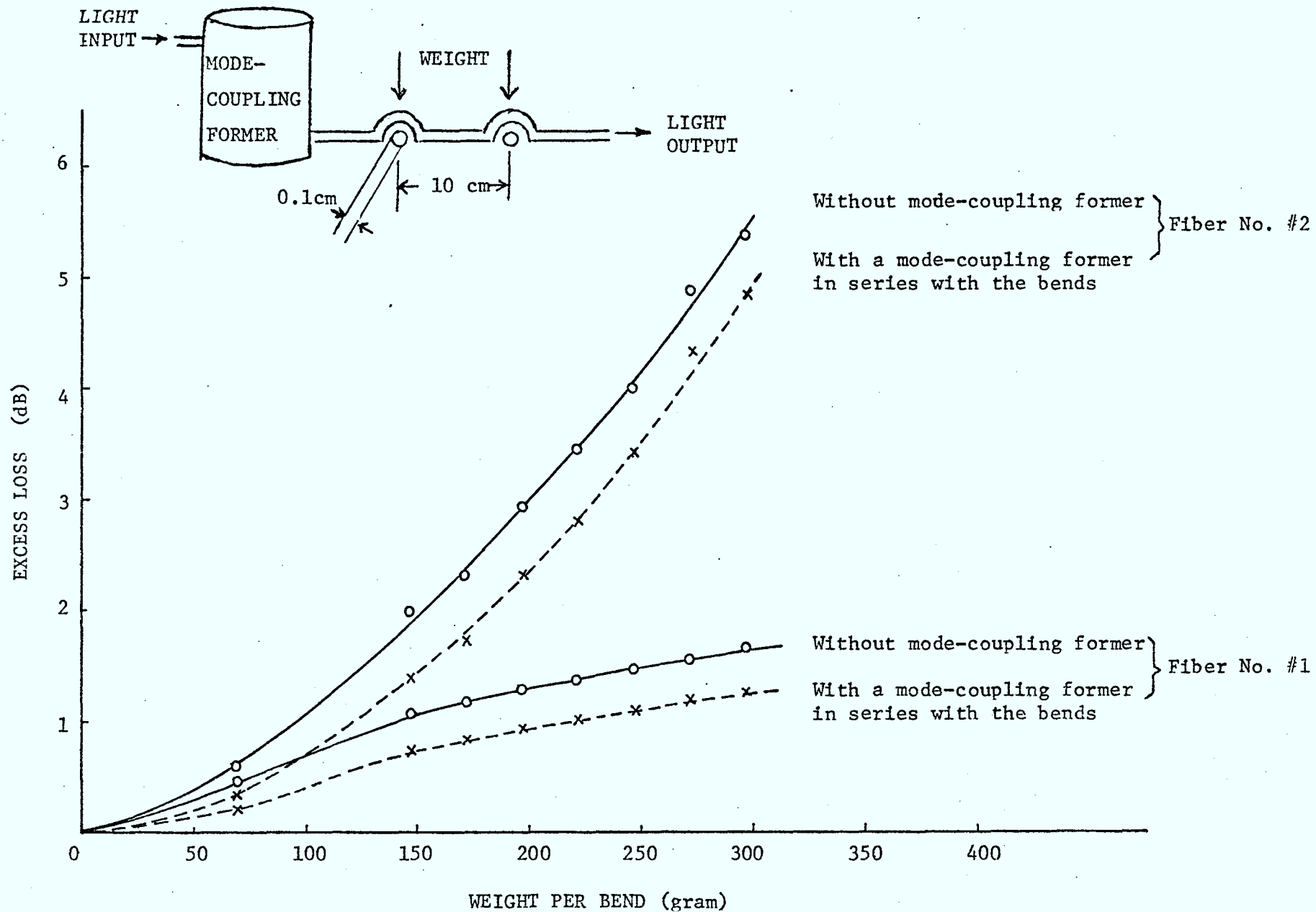
Fig. 4.14. The effect of a mode-coupling former on the excess loss due to two bump bends.

4.3   The Microbending Loss

Using the techniques described in Chapter III to form microbends by thermal-expansion-induced tension which forces the fiber to confrom to surface irregularities of the acrylic drum, we have measured the excess loss caused by such microbends by comparing the attenuation losses at higher temperatures with those at room temperature ($20^{o}C$). The results are shown in Fig. 4.15. In this experiment, Fiber sample #1 suffers the highest excess loss. This may be due to the stiff glass cladding coupled with the small core, which are more susceptible to being forced to conform to the shapes of irregularities. Fiber sample #3 has an elastic silicone cladding which may screen partially the core from suffering the microbending. Fiber samples #2 and #4 suffer much less excess loss because the PVC coating has a much more effective screening effect to protect the fiber from the microbending due to surface irregularities of the acrylic drum. Our results are not inconsistent with those reported by Goell [1976]. Thus, from the standpoint of excess loss due to inherent microbending, the use of elastic cladding and elastic coating is advantageous.

4.4   The Temperature Dependence of Attenuation Losses

Several investigators [e.g., Inao et al 1974, Black and Cook 1975] have reported that within a certain temperature range the attenuation of uncoated glass fibers is independent of temperature, while the attenuation of coated glass fibers is temperature-dependent. Using the techniques described in (D) of Chapter III, we have measured the excess loss of all fiber samples as a function of temperature with the temperature of $20^{o}C$ as the reference temperature. The results are shown in Fig. 4.16. Fiber samples #1 and #2 suffer negligibly small excess loss for the temperature

ACRYLIC DRUM

THERMOSTATICALLY CONTROLLED OVEN

LIGHT INPUT →

→ LIGHT OUTPUT

10.5 cm

Length of the sample:

Fiber sample #1:   52.40 meters
Fiber sample #2:   53.08 meters
Fiber sample #3:   63.97 meters
Fiber sample #4:   54.13 meters

#1

#3

#2

#4

EXCESS LOSS (dB/100 m)

TEMPERATURE (°C)

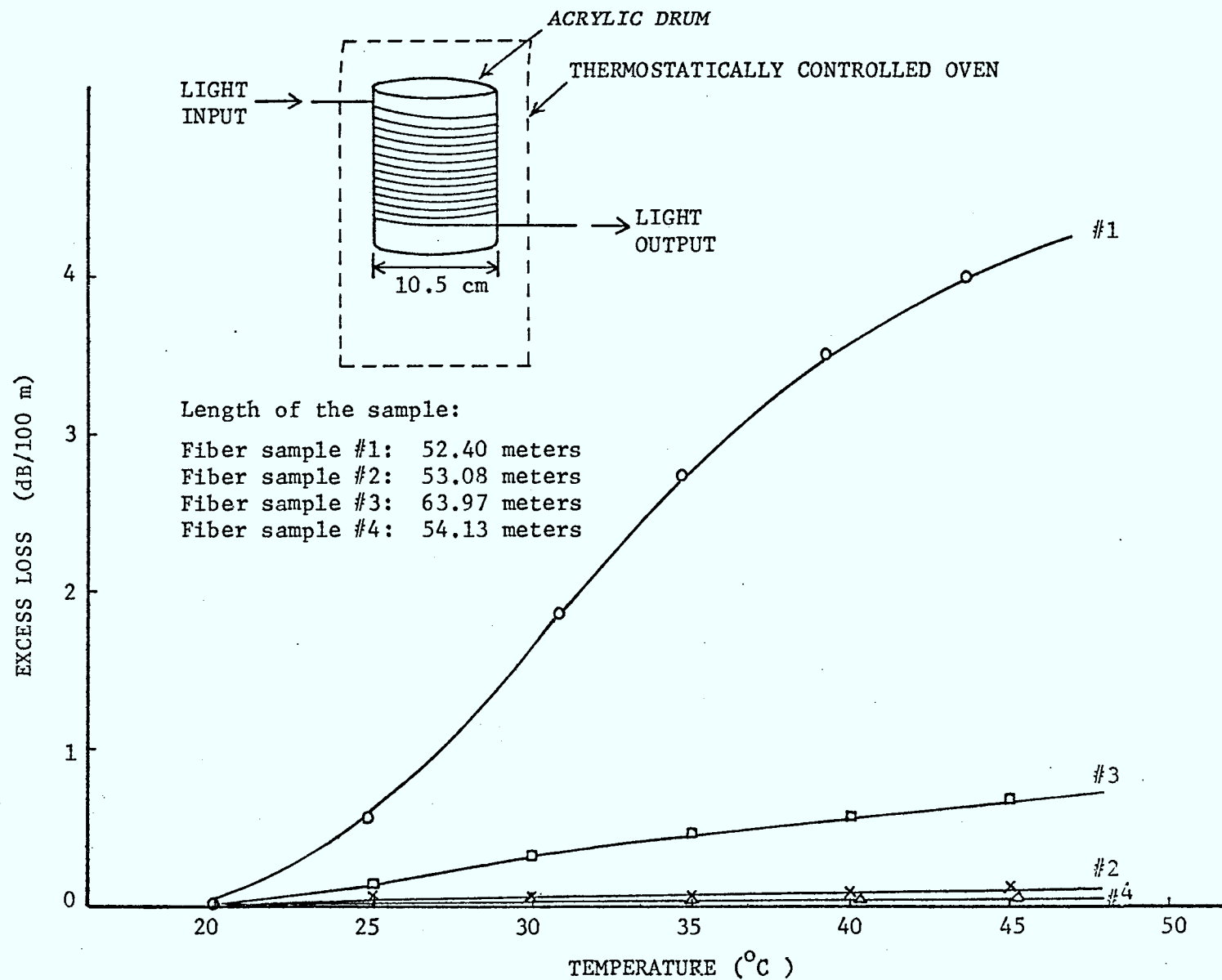Fig. 4.15. The excess loss due to microbends produced by thermal-expansion-induced tension forcing the fiber to conform to the drum surface irregularities.

CHANGE IN LOSS (dB/100 m)
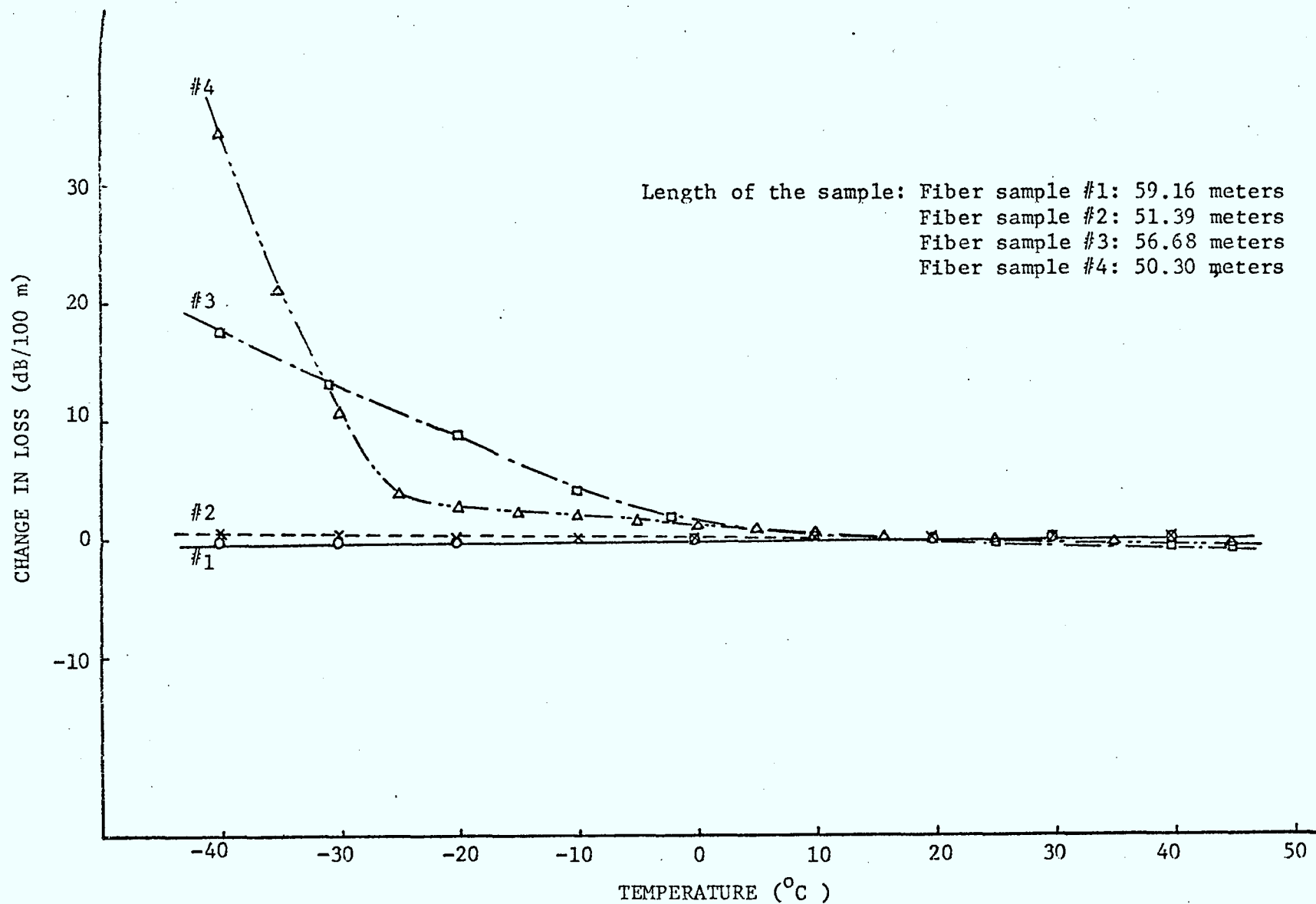
TEMPERATURE (°C)

#4

#3

#2

#1

Length of the sample: Fiber sample #1: 59.16 meters
Fiber sample #2: 51.39 meters
Fiber sample #3: 56.68 meters
Fiber sample #4: 50.30 meters

Fig. 4.16. The effect of temperature on the losses of the fiber.

range from -40°C to 40°C (practically insensitive to temperature change within this temperature range). This may be due to the fact that for these fibers both the core and the cladding are made of glass which are not sensitive to temperature in this temperature range. For Fiber samples #3 and #4 the excess loss increases with decreasing temperature for temperatures below 10°C. This may be due mainly to the fact that the cladding of these fibers is made of silicone. Silicone has a higher thermal expansion coefficient than the glass, and becomes less elastic at low temperatures. That the excess loss increases with decreasing temperature may be associated with microbends produced by the contraction of the silicone cladding which is faster than the contraction of the glass core when the temperature is decreased.

The comparison between Figs. 4.15 and 4.16 indicates that fibers with glass cladding and elastic coating such as Fiber sample #2 may be more suitable for the environment with an extreme climate such as in Manitoba where the temperature may change from -40°C or below in winter to about 40°C in summer. This experiment also suggests that the material chosen for the fiber core and that for the cladding should have approximately the same thermal expansion coefficient at least for the range of temperatures at which the fibers are in operation.

4.5   The Effects of Thermal Cycling

It is most likely that optical fiber cables installed in an underground conduit will probably be exposed to temperatures from -40°C to $+40^{\circ}$C, particularly in Canada. Different dimentional changes due to different linear thermal expansion coefficients of different materials for the core, the cladding and the protective jacket may result in creation of additional temporal or permanent microbends, breaking-up of either the junction between

the core and the cladding, or the junction between the cladding and the jacket, or even microcracks. If the materials are not chemically stable, the thermal cycling may cause the change of chemical structures, particularly for polymeric materials which are often used for the protective jacket because of their high elasticity. Some changes may be of a reversible nature and some of an irreversible nature. Thus, the measurement of temperature dependence of the optical transmission properties alone is not sufficient to determine such effects, because such effects depend on thermal history and not on temperature alone as time is required for them to occur. For this reason we have also studied the effects of thermal cycling. But unfortunately, we have performed this test for only six temperature cycles owing to lack of time. Some preliminary results are shown in Fig. 4.17. The change in loss during each temperature cycle is due to the change of temperature in the same way as that shown in Fig. 4.16. In this test no significant change has been found although the test was performed on Fiber sample #4 which consists of three different materials -- glass core, silicone cladding and PVC jacket, and is expected to be more susceptible to thermal cycling. It is possible that the number of temperature cycles used is too small to exhibit the effects. It should be noted that for this test we used manual control and it is therefore not easy to carry on this test for a large number of temperature cycles. We plan now to build an automatic controlled thermal cycling oven for the cycling temperatures of $-40^{\circ}C \rightarrow -20^{\circ}C \rightarrow 0^{\circ}C \rightarrow 20^{\circ}C \rightarrow 40^{\circ}C \rightarrow -40^{\circ}C$ at a frequency of one cycle per 30 minutes, and to carry out such a thermal cycling test for a few hundred thermal cycles. The thermal cycling test is a kind of life test which is usually performed at a temperature range slightly beyond the usual climate temperature range and also at a reduced duration for one thermal cycle [Lebduska 1974]. Several investigators [Buckler and Santana 1977, Nishida et al 1977] have performed thermal cycling
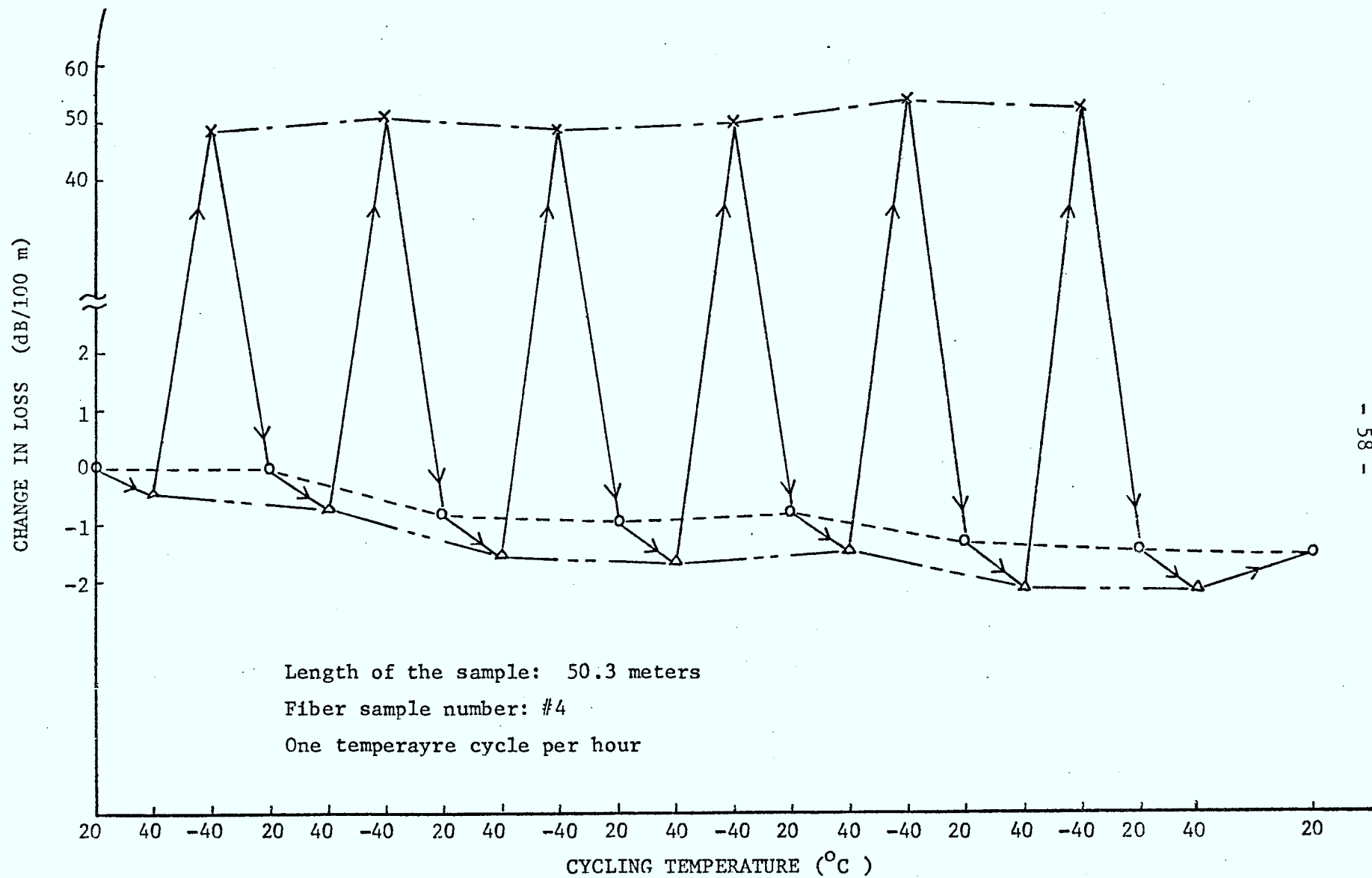
Fig. 4.17. The effect of temperature cycling on the
losses of the fiber

tests on optical fiber cables. The thermal cycling tests are essential in order to evaluate the long term stability of the optical fiber cables against the environmental conditions.

4.6   The Excess Loss Caused by Mechanical Vibrations

Several investigators [Nelson et al 1977, Nishida et al 1977] have attempted to study the vibration-induced loss in optical fibers. Nishida et al [1977] have reported that the wind-induced vibration on a cable of 1500 m in length aerially installed does not cause additional loss in the cable. This may be understood that in their experiment the vibrational spatial wavelength is very large and thus the vibration would not cause any bending loss. However, Nelson et al [1977] have observed vibration-induced intensity modulation of light transmitted in bent fiberguides, which results from vibrational amplitudes much less than the fiberguide diameter. They have attributed this effect to modulated bending loss. They have also suggested that modulated bending loss can be a potential source of inter-ference in fiberguide transmission,and that a combination of large radii of curvature and low amplitudes of vibration is needed to remove it.

We believe that if an optical fiber is subjected to mechanical vibrations of large vibrational frequencies but small vibrational amplitudes and spatial wavelengths, additional bending loss may arise. In fact, such mechanical vibrations may be easily induced in optical fiber cables installed underground, by longitudinal mechanical waves generated by cars, trains, or even jet aeroplanes and transmitted from the ground surface to the cables underground. By considering this possible effect, we have measured the excess loss due to mechanical vibrations as a function of vibrational frequency and spatial wavelength at a constant vibration amplitude. Some preliminary results are shown in Fig. 4.18. For this experiment a section of the fiber
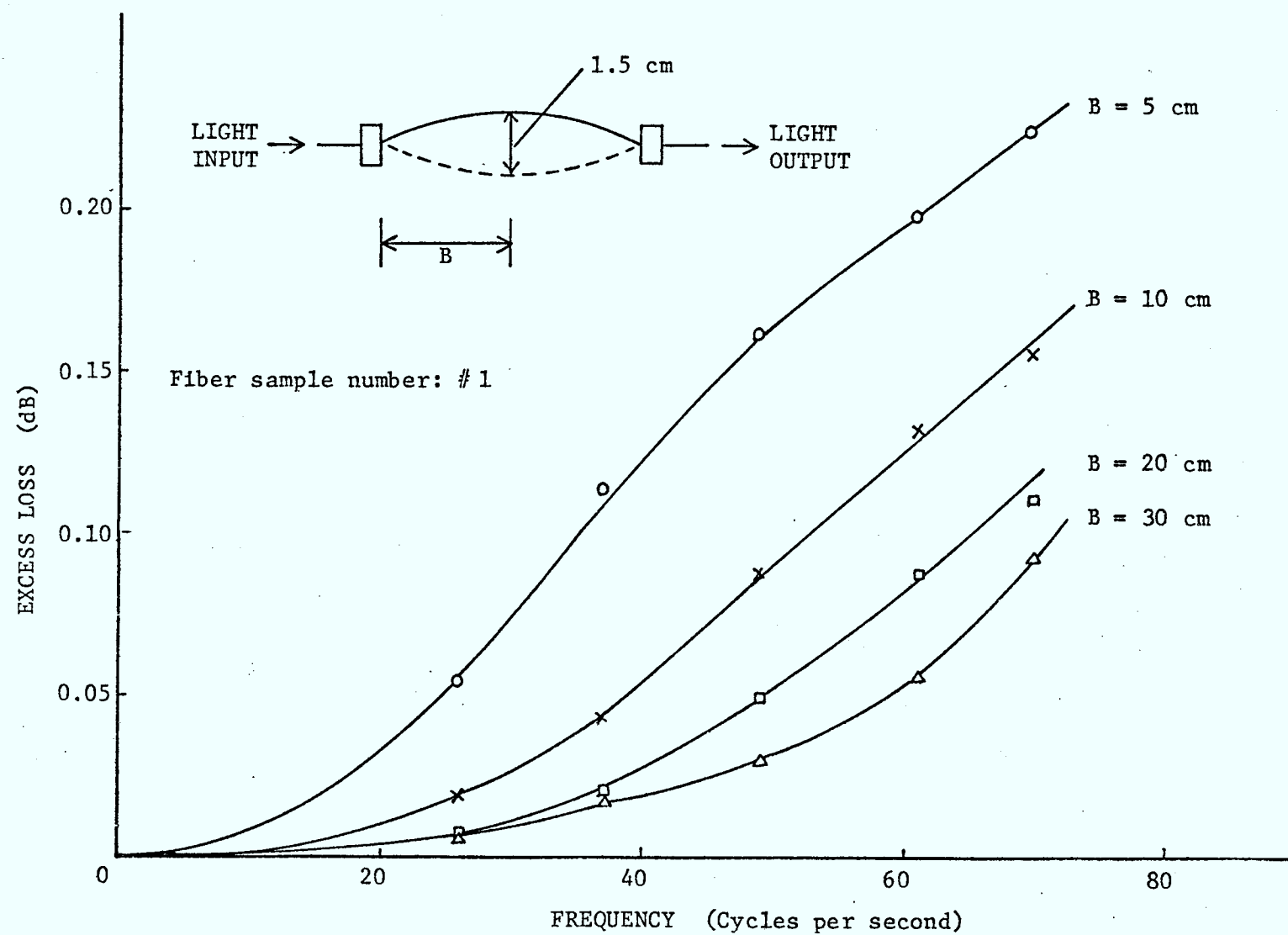
Fig. 4.18. The excess loss caused by mechanical vibration between two fixed points.

was epoxied to rigid mounts at each end and a point near its center was attached to a vibrator which could be electrically operated and adjusted for any frequencies, the length of the section being 2B as shown in Fig. 4.18. It can be seen that the excess loss increases with increasing vibrational frequency and decreasing value of B. This phenomenon can be well explained in terms of bending losses.

It should be noted that such a vibration-induced bending loss could be a source of interference to systems which use intensity modulation for signal communications. More work is being carried out to study systematically the effect of mechanical vibrations.

## 4.7   Microscopic Observation of Imperfections in Optical Fiber Samples

Except Fiber sample #2, light spots can be seen in the dark in the drums of Fiber samples #1, #3, #4 and #5 received, when a light beam of wavelength of 630 nm is focussed through a lens to one end of the fiber. Some typical photographs are shown in Fig. 4.19. The light spots indicate that there are many imperfections including microbends in these fiber samples. For Fiber sample #2 the outer PVC coating is thick so that the leaking-out light cannot be seen. The worst sample is Fiber sample #5 in which the number of light spots per unit length of the fiber is the highest among all samples though some light spots are dim. It should be noted that the light spots may be due to the microbending caused by the PVC coating.

The silicone cladding of Fiber sample #3 is sticky. Since there is no PVC coating to protect it, the fiber in the drum sometimes sticks to each other at some locations, and it is easy to cause damage to the cladding surface when the fiber is taken out from the drum. A typical damage is shown in Fig. 4.20.   In Fiber sample #3 and Fiber sample #4 with the PVC coating removed, we have observed the non-uniformity of the refractive index distribution at some points as indicated by arrows in Fig. 4.21. At those points

dark rings appear around the fiber and usually light spots also occur there, indicating that at those points the relative index difference Δ may be smaller as compared with that of the whole fiber.

In Fiber sample #4 we have also found that the light spot at a point may sometimes be made to disappear by removing the PVC coating around that point, indicating that the PVC coating may have caused the formation of a microbend at that point.

The PVC coating was removed by immersing the fiber in chloroform, and the EVA coating and the silicone cladding were removed by burning off them over a burner. After the removal of a layer the fiber was cleaned in a beaker containing either methyl alcohol or acetone. Using this technique, we can observe the surfaces of the core, the cladding and the coating using a scanning electron microscope. Fig. 4.22 shows two valleys on the glass cladding surface of Fiber sample #1, and Fig. 4.23 shows no imperfections on the glass cladding surface. In fact, there are only a few manufacturing imperfections in Fiber samples #1 and #2 as far as the glass fiber itself (the core and the cladding) is concerned. Fig. 4.24 shows some convex irregularities on the core surface and a large valley on the silicone cladding surface of Fiber sample #3. Figs. 4.25 and 4.26 show, respectively, the imperfections on the core and the cladding surfaces in Fiber samples $4 and $5. It should be noted that the imperfections like those shown in Fig. 4.26 appear more frequently along the fiber in Fiber sample #5, and this may explain why the attenuation is specially high in this fiber sample.
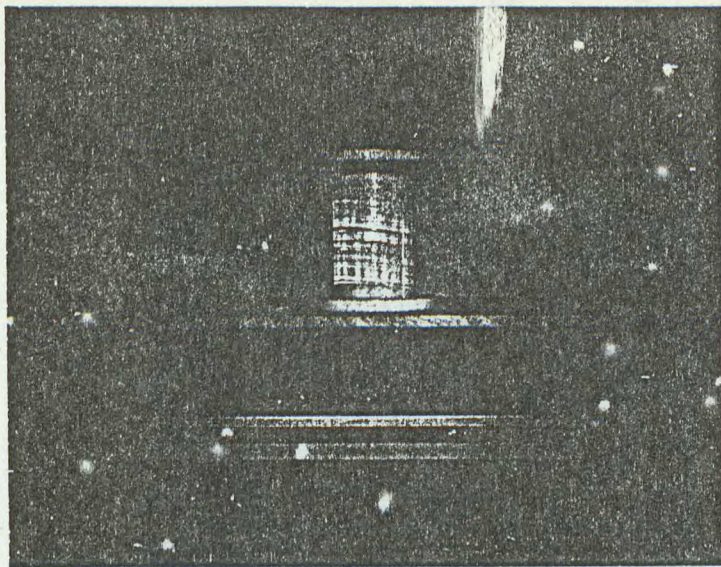
Fiber sample #1
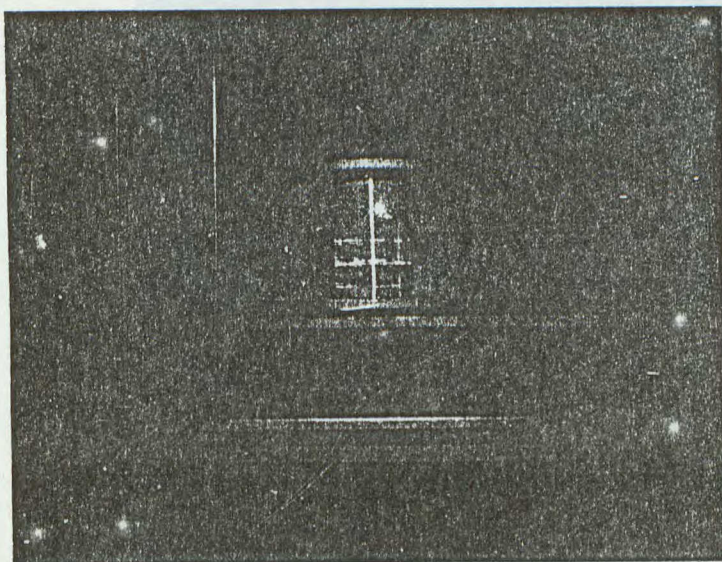Glass core, glass cladding
and thin EVA coating.
Light spots are quite bright
because the EVA coating is
thin.

Fiber sample #2
Glass core, glass cladding,
thin inner EVA coating, and
thick outer PVC coating.
No light spots can be seen
because the outer coating
is thick.
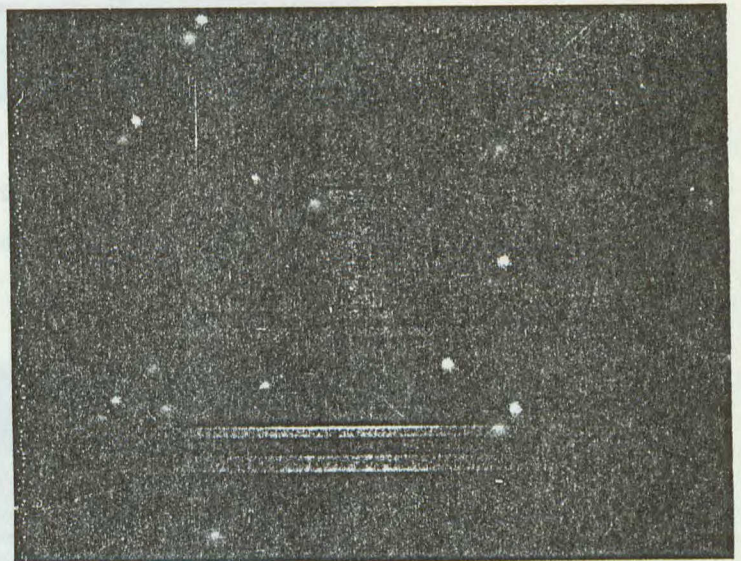
Fiber sample #3
Glass core, silicone cladding.
Light spots are bright because
there is no coating. The
number of light spots per
unit length is less in this
fiber sample.

Fig. 4.19. Photographs showing light spots in the optical fiber drums
received from CWC. The vertical light in each photograph
is due to the reflection of the flash light.
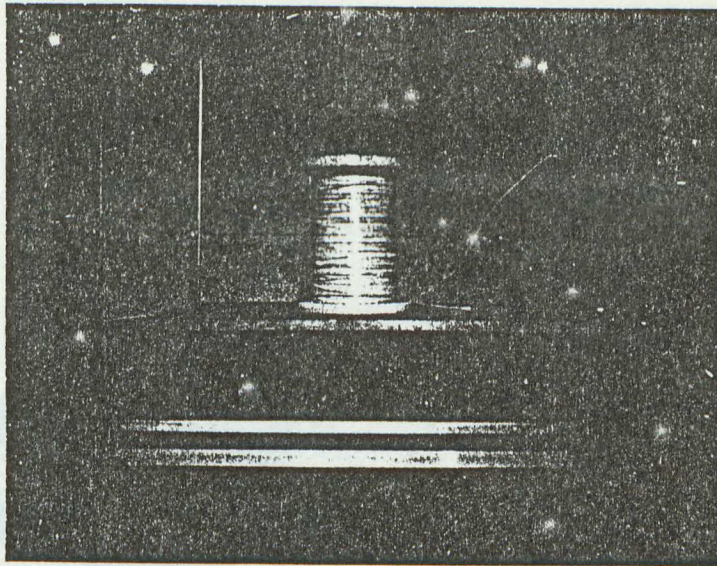
Fiber sample #4: Glass core, silicone cladding and PVC coating.
Only a few light spots can be seen because the PVC coating is thick.
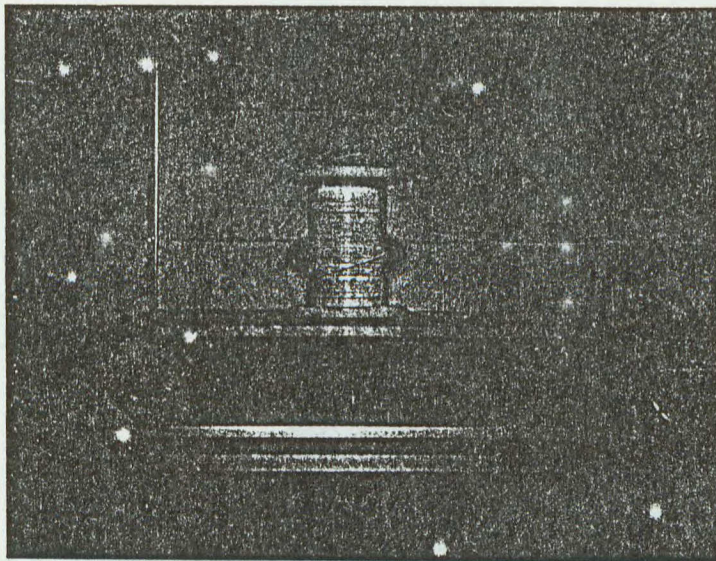
Fiber sample #5: Glass core, silicone cladding and PVC coating.
A great number of bright and dim light spots can be seen though
the PVC coating is thick.

Fig. 4.19. Photographs showing light spots in the optical fiber drums received
from CWC. The vertical light in each photograph is due to the
reflection of the flash light.
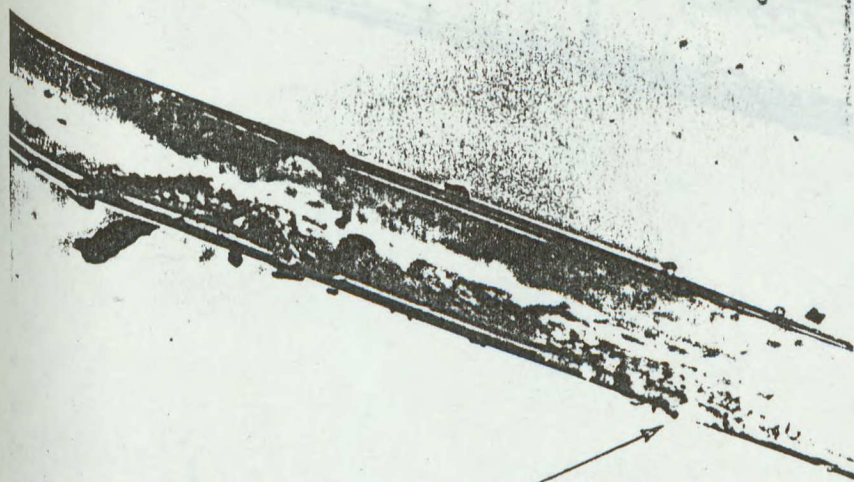
The microcrack in the silicone
cladding and the imperfections
in the vicinity of this
microcrack.

Some light leaking out
through these imperfections. →

Fig. 4.20.   Imperfections in the silicone cladding of Fiber sample #3.

Fig. 4.21. Photographs showing the change of refractive index in the
silicone cladding at points indicated by arrows along the
axis of Fiber sample #3.
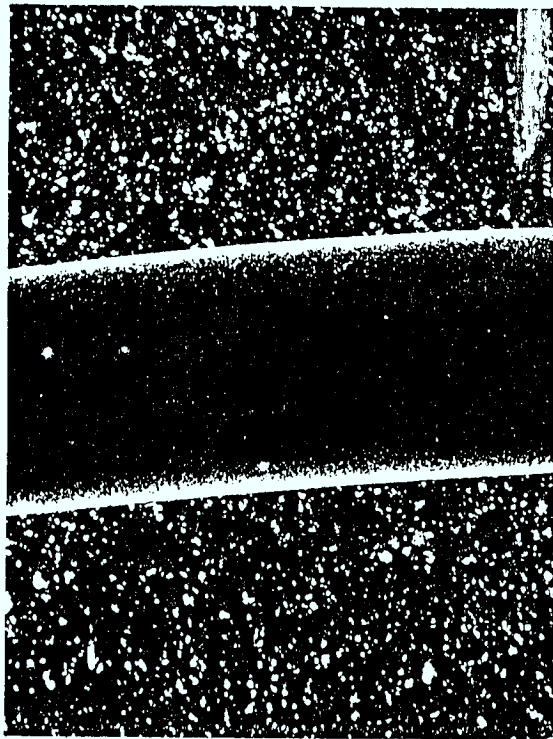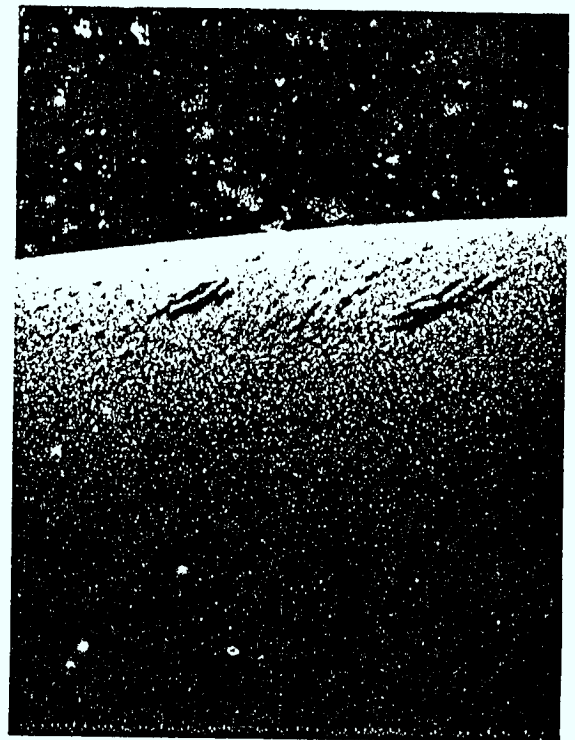
Magnification: X 300   Magnification: X 1200

(A) The outer surface of the cladding.
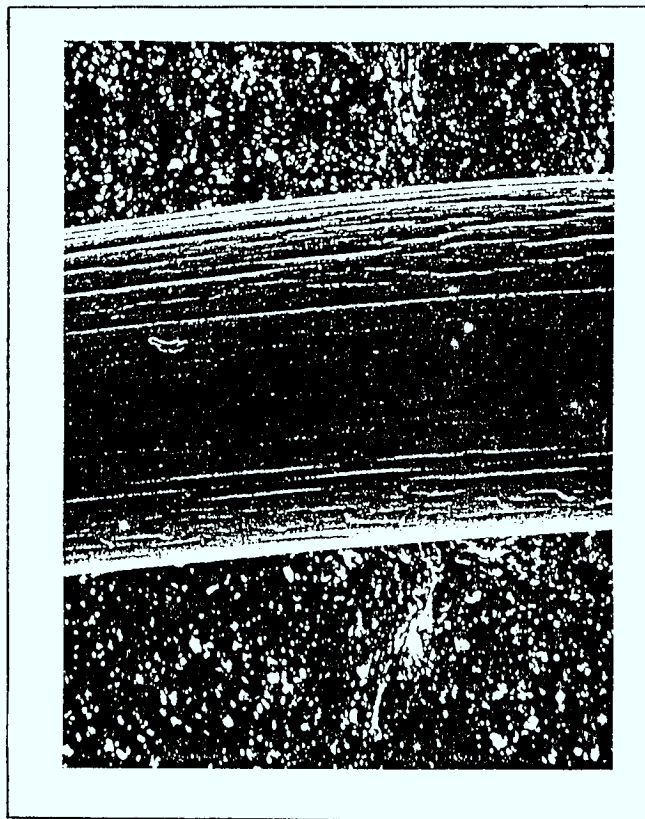
(B) The outer surface of the EVA coating.   Magnification: X 300

Fig. 4.22.   Scanning electron microscope pictures showing convex irregularities
on the outer surface of the glass cladding of Fiber sample #1.
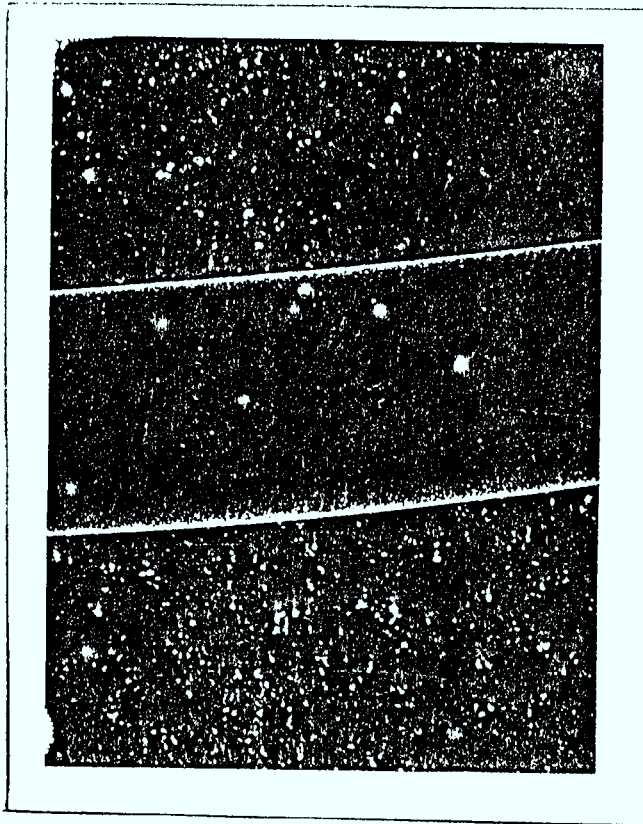
(A) The outer surface of the cladding.
Magnification: X 288
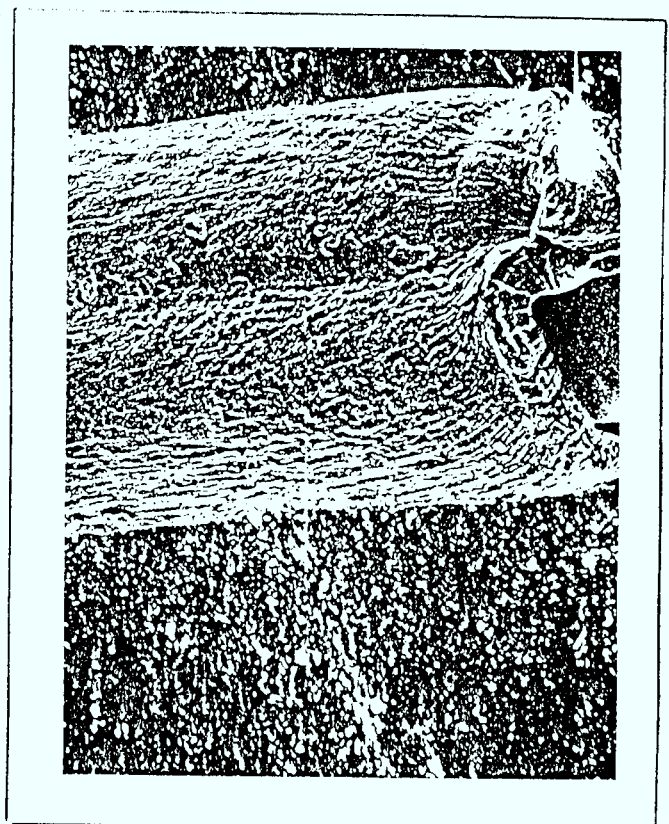
(B) The outer surface of the EVA coating after the removal of the PVC coating.
Magnification: X 288

Fig. 4.23.   Scanning electron microscope pictures showing no imperfections
on the outer surface of the glass cladding of a particular
piece of Fiber sample #2.
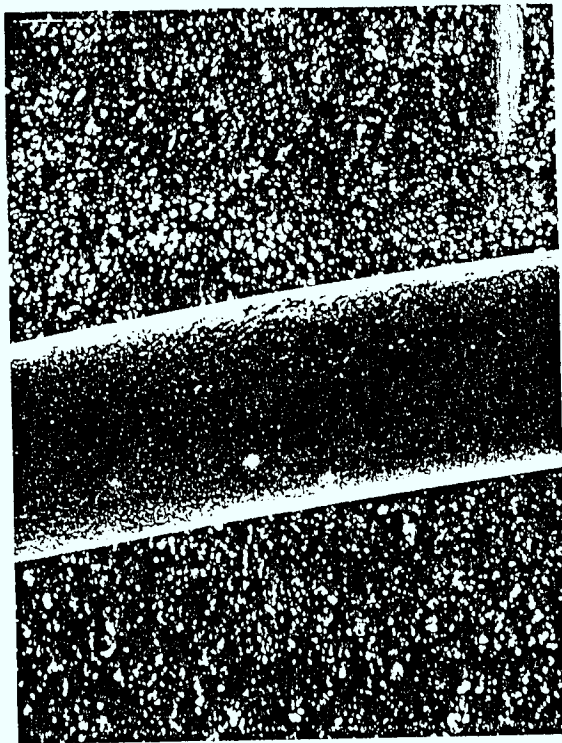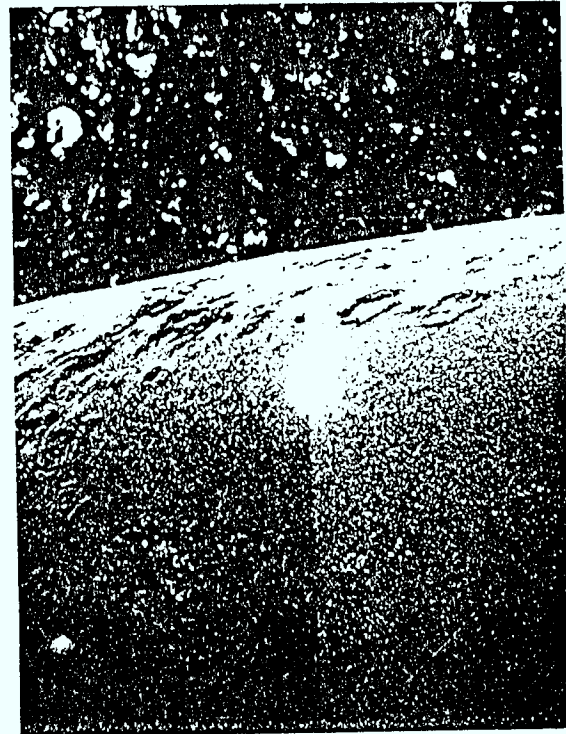
Magnification: X 288   Magnification: X 1152

(A) Concave and convex irregularities on the core surface.
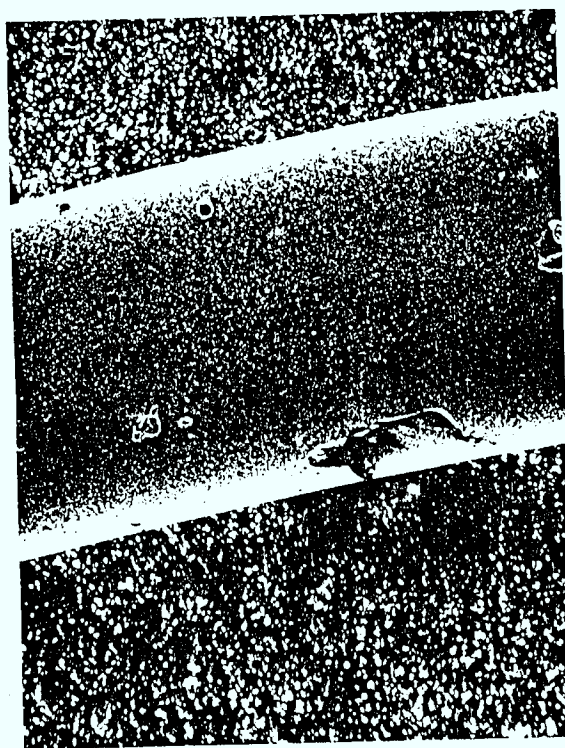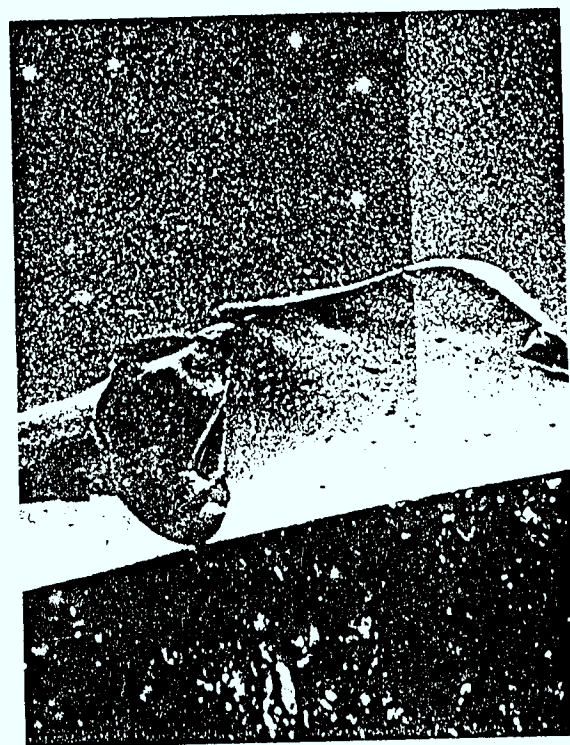
Magnification: X 288   Magnification: X 1152

(B) A large concave valley on the outer surface of the silicone cladding.

Fig. 4.24. Scanning electron microscope pictures showing various irregularities
on the glass core surface and on the outer surface of the silicone
cladding of Fiber sample #3.
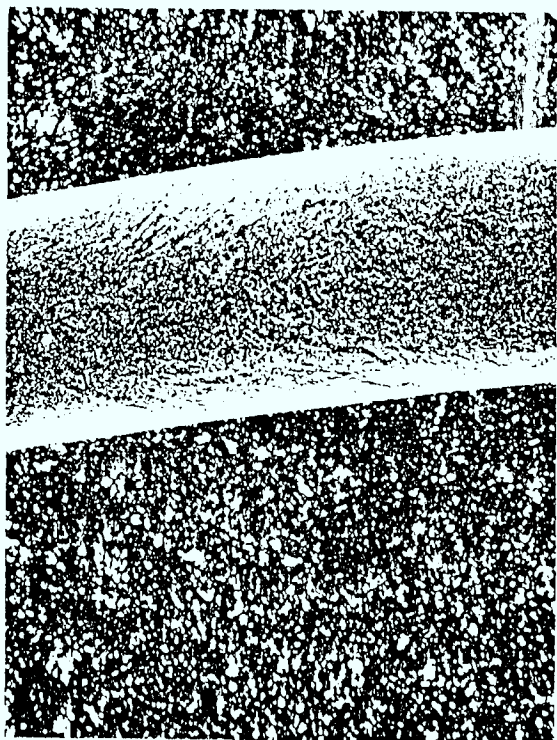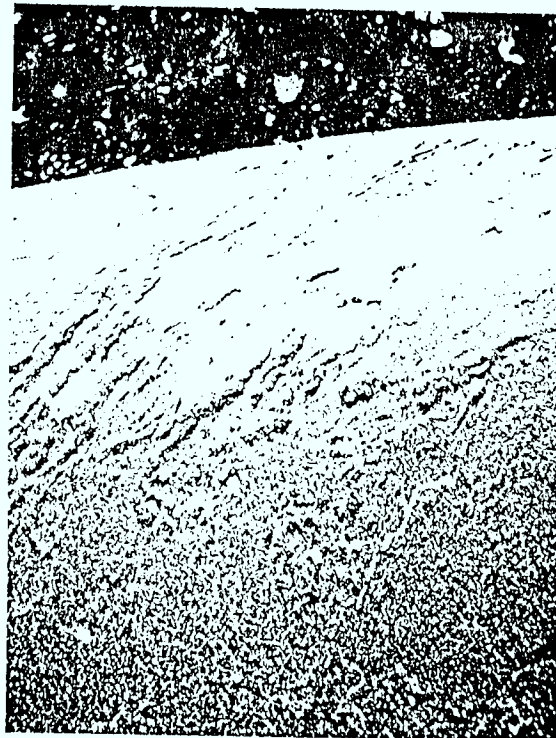
Magnification: X 300   Magnification: X 1200

(A) Concave and convex irregularities on the core surface.
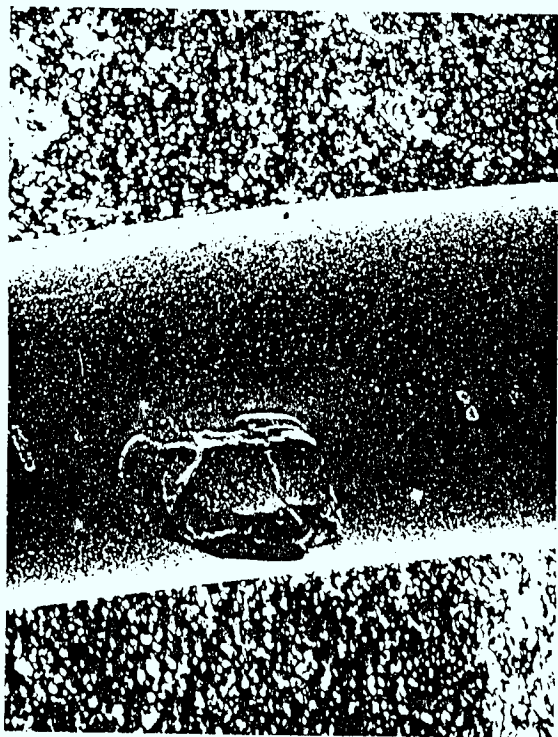
Magnification: X 300   Magnification: X 1200

(B) A very large concave valley on the outer surface of the silicone cladding

Fig. 4.25. Scanning electron microscope pictures showing various irregularities
on the glass core surface and on the outer surface of the silicone
cladding of Fiber sample #4.
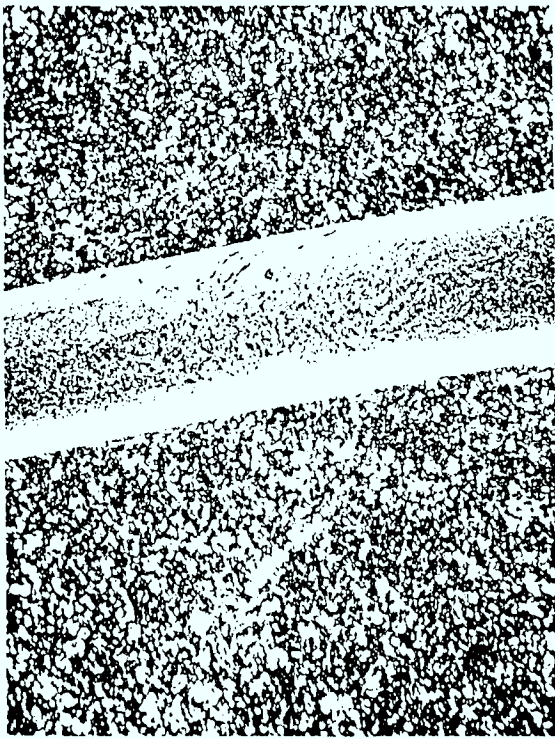
Glass core. Magnification: X 300

Glass core. Magnification: X 1200
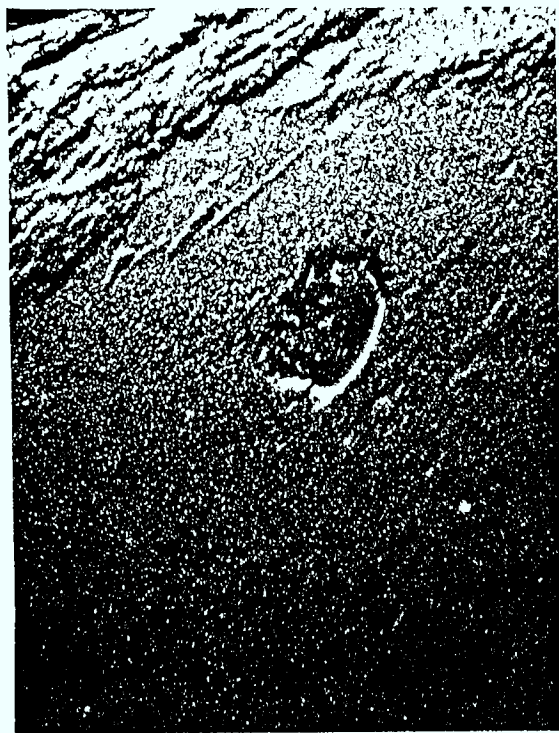
Glass core. Magnification: X 3000
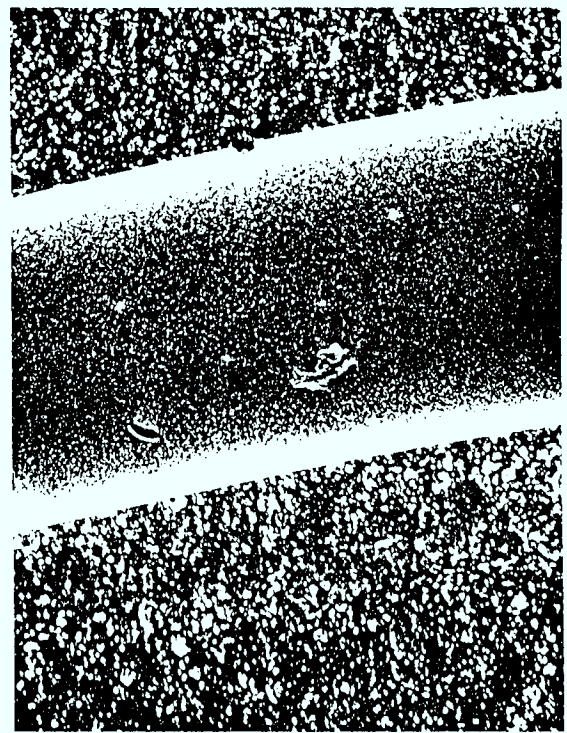
Silicone cladding. Magnification: X 300

Fig. 4.26. Scanning electron microscope pictures valleys and hills on the glass core surface and two concave valleys on the outer surface of the silicone cladding of Fiber sample #5.

V   CONCLUDING REMARKS

From the experimental results presented in the previous chapter we draw tentatively the following conclusions:

(i) The excess loss due to circular bends, bump bends and microbends is due mainly to mode coupling which converts normal guided modes to higher order modes, and some high modes to leaky modes. Such an excess loss decreases with increasing curvature radius R (or decreasing the bump height h), increasing core radius a, increasing relative index difference Δ , and increasing overall diameter of the fiber (or increasing thickness of the protective coating). The loss also decreases with decrease of the ratio of E_e/E_f, where E_f and E_e are, respectively, the Young's moduli of the fiber and the encapsulating material. This implies that if the core is made of glass, the encapsulating material must be very elastic (low Young's modulus) in order to reduce the microbending loss. On the basis of this concept, if two protective coatings are used, the inner coating should be more elastic than the outer one. It should be noted that in cables the bump sizes or the bump heights due to the rough surfaces of the supporting members are small (or the curvature radii are large), the microbending loss per bend is usually very small. However, the total mocrobending loss depends on the number of microbends. Therefore, the smoothness of the supporting member surfaces is also very important to the reduction of the microbending loss.

(ii) Materials chosen for the core, the clading and the protective coating should have approximately the same linear thermal expansion coefficient in order to avoid the formation of microbends due to the difference in contraction or expansion between the materials when the temperature is changed.

(iii) Before the fiber cables become broadly used for communication systems, the assessment of the life of the cables is of economical and technical

importance to system designers. The life is usually estimated roughly by acceleration tests which involve short-duration and extended-duration thermal cycling tests, humidity steady state and cycling tests, and other environmental tests. The most important component of the fiber is the protective elastic coating because it is in direct contact with the environmental atmosphere. Thus, the material for the protective coating should have the following properties:

(a) chemically stable in the surrounding environment including the change of temperature,

(b) elastic within the operational temperature range to reduce the possibility for the formation of microbends,

(c) highly adhesive to the cladding to prevent local stress concentration in the fiber,

(d) lossy to absorb unwanted cladding modes to avoid crosstalk between fibers in the cable, and

(e) with the thermal expansion coefficient similar to that of the fiber.

Although no intentional stress is exerted on the fiber inside a cable, the inherently induced stress due to the dissimilarity of the thermal expansion coefficients may be sufficient to produce microbends or other unintentional perturbations. Therefore, the thermal cycling tests are essential to the evaluation of the long-term stability of fiber cables.

(iv) Although mode coupling is detrimental to the attenuation and beneficial to the dispersion, mode coupling due to the random non-uniformity and non-homogeneity of the core size or the refractive index distribution along the fiber axis is not desirable. For reducing the dispersion, a controllable intentional mode coupling by means of periodic variation of core

size or refractive index distribution may be useful.

(v) The five fiber samples have many imperfections. By excluding the imperfections, their optical transmission properties may be much better than the average properties including the imperfections. However, apart from the aforementioned factors which should be considered in order to improve the optical transmission properties of the fibers, the uniformity of the core size and the index distribution and the homogeneity of the materials should be precisely controlled to avoid the formation of unintentional perturbations.

(vi) The effect of mechanical vibrations should be fully investigated to determine the tolerance of interference which may be produced by unexpected vibrations. Such unexpected vibrations may be caused by mechanical waves generated by cars, trains or even by jet aeroplanes moving on or above the ground, and transmitted from the ground surface to the fiber cables installed underground. An investigation into the effects of such vibrations and the method of suppressing the possible interference is of importance to the design of communication systems.

FUTURE PLAN

Our plan for phase II of the present project is outlined as follows:

(A) To repeat the experiments on the effects of circular bends, bump bends and microbends for the W-type fibers (from Japan) in order to compare with the results for the step-index fibers and to find the factors controlling the bending losses in terms of the index distribution pattern.

(B) To investigate which of the following factors plays the most important role in causing the high losses in the optical fibers:

(i)   the non-uniformity of core diameter resulting in the generation of high order modes.

(ii)   the inhomogeneity of cladding material resulting in the variation of refractive index along the fiber.

(iii) the non-uniformity of outer diameter of the cladding coupled with the coating material resulting in the formation of microbends.

(iv)   the core-cladding interface imperfections.

(v)   the cladding-jacket interface imperfections

(C) To study the effects of thermal cycling in order to investigate the following possible sources to cause additional losses:

(i)   localized stresses created due to the difference in thermal expansion coefficient between the fiber and the inner and outer coating materials, resulting in either microbending or micro-cracking.

(ii)   the effect of inner coating material on the attenuation losses at various temperatures.

(iii) the effect of stiffness of the inner and outer coating materials on the formation of unintentional perturbations.

(D) To study more systematically the effects of mechanical vibrations

(vibrational amplitude, vibrational frequency and spatial wavelength)

on the attenuation losses, the dispersion and the output light field

pattern (or the output light intensity as a function of radial distance

from the core center); and to perfrom the experiments for both the

step-index fibers and the W-type fibers in order to compare the results

from their response to mechanical vibrations.

(E) To study theoretically the factors governing the attenuation losses

and the dispersion based on the experimental results from (A), (B), (C)

and (D) given above for optical fiber cables.

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