

## Investigation of bending loss in a single-mode optical fibre

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**Abstract.** Loss of optical power in a single-mode optical fibre due to bending has been investigated for a wavelength of 1550 nm. In this experiment, the effects of bending radius (4–15 mm, with steps of 1 mm), and wrapping turns (up to 40 turns) on loss have been studied. Twisting the optical fibre and its influence on power loss also have been investigated.

Variations of bending loss with these two parameters have been measured, loss with number of turns and radius of curvature have been measured, and with the help of computer curve fitting method, semi-empirical relationships between bending loss and these two parameters have been found, which show good agreement with the obtained experimental results.

**Keywords.** Single-mode optical fibre; bending loss; radius of curvature; turns in optical fibres.

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### 1. Introduction

It is obvious that bending of optical fibres causes loss of optical power, and reduces its performance. So the exact modelling of bending loss is very important for designing communication systems and optical instruments [1,2]. In recent years various fibre bending sensors have been proposed and the bending-type fibre-optic sensors could be used to measure different physical parameters such as voltage, pressure, strain, temperature, etc. [3]. Microbending (bending with small radius of curvature) has been studied by some researchers [4,5]. But irregular small cracks (macrocracks) occur during the manufacture of optical fibres and microbending and this sort of stress (like torsion) would make these cracks bigger and this render the fibre useless. Macrobending (where radius of the bend is much greater than the radius of the fibre) which does not cause this kind of problem, has been investigated

by many workers. Bending loss for various wavelengths, and bending parameters like radius of curvature and wrapping turns have been reported [6]. It is well-known that loss increases with bending, and especially for longer wavelengths, researches show that temperature and the presence of protection layers can also affect the bending loss [7,8].

Different models have been suggested, and used to calculate and fit the experimental results, but due to the fluctuation behaviour of bending loss with radius of curvature some disagreement between theoretical modelling and the real data of experimental results are obtained [9].

Simple models which treat the single-mode fibres consider fibre with a core and infinite cladding structure, and since fibres with protecting layers show different bending loss behaviour, and also since bending loss does not show a smooth exponential wavelength and radius of curvature dependency, this simple model is not very suitable to work with. Bend loss modulation is often observed, which can be due to coherent coupling between the core propagating field and fraction of radiation field reflected by cladding interface or from coating (protecting) layers [10]. In some experimental work, effects of bending radius, and also the number of wrapping turns have been investigated, but in most of them either the radius of curvature is very small or the number of turns is small and limited [11,12].

In this work we used different radii of curvature (up to a value in which the bending loss is very low or nearly zero), and also up to 40 wrapping turns have been employed, to investigate their effects on bending loss. A simple semi-empirical relationship between bending loss and radius of curvature, and also wrapping turns has been suggested, which shows good agreement with the experimental results. Influence of torsion stress on core and clad structure has also been investigated in this work. The work done on this subject is very limited.

## 2. Theory

For a single-mode fibre (SMF) with length  $l$ , bending loss ( $L$ ) is usually obtained by [10]

$$L = 10 \log_{10}(\exp(2\alpha l)) = 8.686\alpha l, \quad (1)$$

where  $\alpha$  is the bending loss coefficient, and it is a function of bending radius, wavelength of light used in the fibre, and also optical fibre structure and material of the fibre. Often when bending reaches a critical radius of curvature ( $R_c$ ), then loss due to bending can be neglected, and  $R_c$  is defined as [4]

$$R_c = \frac{3n_2 \cdot \lambda}{4\pi(NA)^3}, \quad (2)$$

where  $R_c$  is the critical radius of bending,  $n_2$  is the refractive index of the clad,  $NA$  is the numerical aperture of the fibre and  $\lambda$  is the wavelength.

In a very simple approach the bended fibre is modelled as a curved dielectric slab surrounded by an infinite cladding, then by this approach a closed form of solution might be obtained.

Although the simple torodial coordinate system is of relevance in realistic situation, unfortunately no exact solution of Maxwell's equations exists in this frame. So different approaches have been employed for evaluation of the bending loss.

Bending loss coefficient ( $2\alpha$ ) (dB/km) which has been proposed by Marcuse, according to the mode coupling theory is presented as eq. (3) [13]

$$2\alpha = \sqrt{\pi}\delta^2 L_c \left( \frac{2n_1 k a \Delta}{bW} \right) - \sum_s \exp \left\{ - \left[ (\beta_g - \beta_{1s}) \frac{L_c}{2} \right]^2 \right\} \frac{J_1^2 \left( j_{1s} \frac{a}{b} \right)}{J_0(j_{0s})} \exp \left( \frac{-2a^2}{W^2} \right) \quad (3)$$

which usually is considered in step index optical fibres, uses Bessel function of zero and first order ( $J_0, J_1$ ) and also the root of Bessel function ( $J_{0s}, J_{1s}$ ), with boundary conditions  $J_0(J_{0s}) = 0, J_1(J_{1s}) = 0$ . Tsao and Cheng have modified eq. (3) for  $2\alpha$ , and they considered other parameters like number of wrapping turns ( $N$ ), and curve fitting function ( $F$ ), and also  $V$  number, and the suggested formula is as follows:

$$2\alpha = 2FN \left[ 4\sqrt{\pi}\delta^2 \frac{1}{\Lambda_c} \left( \frac{n_1 k \Delta}{b} \right)^2 - \sum_s J_1^2 \left( j_{1s} \frac{b}{a} \right) V^{-2} \right], \quad (4)$$

where  $\Lambda_c$  is the spatial perturbation wavelength, and is defined as

$$\Lambda_c = 2R, \quad (5)$$

where  $R$  is the radius of curvature of the bend, and for loss they used the following equation:

$$L_R = \eta_{R1} \exp(-\eta_{R2} \cdot R), \quad (6)$$

where  $\eta_{R1}, \eta_{R2}$  are fitting parameters, and for  $\lambda = 1550$  nm, their values are given as 70 and 0.5 respectively. Although their results show good agreement with this model, in their work, fluctuation behaviour of loss against radius was not considered. Also they did not mention whether  $\eta_{R1}, \eta_{R2}$  are functions of bending radius or wavelength only. They also proposed a linear relationship between losses and number of turns as in (7).

$$L_N = \eta_N \cdot N, \quad (7)$$

where  $L_N$  is the loss due to the number of wrapping turns ( $N$ ). This sort of simple equation (linear) is good and valid only for larger radius of curvature, since usually for higher number of wrapping turns, saturation behaviour for bending loss against  $N$  happens when radius of the bend is low.

In most of these models one can see the effect of refractive index of the fibre (core and clad) and their differences ( $\Delta$ ), which are important physical parameters. Since guided mode in the fibre core can be transferred to radiation mode in the fibre cladding induced by bending, it is complicated by the explanation of simple electromagnetic effects.

It is claimed [9], that oscillation of bending loss appears for sufficiently strong curvature, i.e., when  $R$  is smaller than the threshold value of bending radius ( $R_{\text{th}}$ ) which is given by

$$R_{\text{th}} = 2k^2 n_2^2 \frac{b}{\gamma^2}, \quad (8)$$

where  $k = 2\pi/\lambda$ ,  $n_2$  is the refractive index of the clad,  $\gamma = [\beta_0^2 - k^2 n_2^2]^{1/2}$ , where  $\beta_0$  is the complex propagation constant and  $b = (x^2 + y^2)^{1/2}$ .

Oscillation of the bending loss with both the wavelength and bending radius have been observed by many workers, and Harris and Castle [14] have explained this behaviour by coupling the fundamental mode and the so-called whispering gallery modes using ray optics.

This bending loss in coated optical fibres has been investigated by means of numerical methods based on wave optics [15].

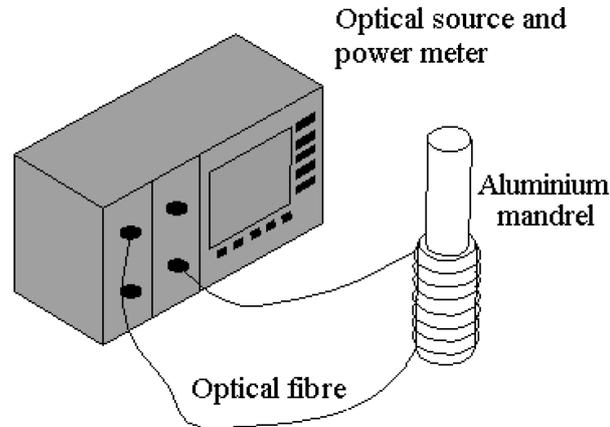
Faustini and Martini [10], studied the oscillation behaviour of bending loss against radius of the bend, for different wavelengths, and the model which they have used showed better agreement for lower wavelength (880, 920 nm), while for higher  $\lambda$  (1480, 1550 nm), fitting is not that good. The other problem with their results is that their model is satisfactory for bending radius ( $R$ ) greater than 13 mm. So for low  $R$  where amount of loss is more important and much higher, this model cannot be used.

Wang *et al* [7] have suggested another model for calculating bending loss in SMF for wavelengths of 1500, 1600 nm, with radii of curvature ( $R$ ) between 8 and 13 mm and their results demonstrated good fits, but it is not clear if this model can be employed for bigger values of  $R$ . Secondly, effect of wrapping turn is not considered. For these reasons, in this work, loss due to bending up to 40 turns has been investigated for 1550 nm wavelength which is used in communication systems.

### 3. Experimental details

In this work different sets of measurements were carried out using single-mode optical fibre (SAMIN-0sJ-001, G.652.c), which was manufactured by LG-Cable company. This standard fibre has a core diameter of  $9 \pm 0.5 \mu\text{m}$ , cladding diameter of  $125 \pm 1 \mu\text{m}$ , and buffer and its cover with diameters of 250, 400  $\mu\text{m}$  respectively. The length of the fibre used for these experiments was 2–5 m and its grade was SMF 28. Light source for the measurement was an InGaAsP laser (IE-60825) with 1525–1575 nm wavelength, which was used at  $\lambda = 1550 \text{ nm}$ .

Laser beam was sent to the fibre to be tested using another optical fibre with similar core diameter and a numerical aperture (NA) of 0.1. For connecting this standard fibre (Seicor, with 50 cm length) to the power meter and the laser, a D-4106.66/KP connector was used, and a welding device (Model X60Series 3000) and a multi-meter (8163A-Agilent) with two slits for light source and detection of light (81635-Agilent power meter) were employed. For bending the optical fibre, aluminum mandrels (cylindrical rods) of different diameters ( $D$ ) (with radius  $R = D/2$ ,  $4 \leq R \leq 15 \text{ mm}$ , with steps of 1 mm) were made and used. To study the effect of the number of turns ( $N$ ), up to 40 turns were investigated. Since



**Figure 1.** Schematic diagram of the optical set-up for measuring bending loss of the fibre.

exactness and reproducibility of the results were important, for every data each set of measurement was repeated to check the obtained results and many runs of tests and calculations for measured results were carried out. Schematic diagram of the set-up for measuring bending loss is shown in figure 1.

#### 4. Results and discussion

For investigating the bending loss and its variation, work was carried out in two parts. First the effect of bending radius ( $R$ ) was studied, and then the influence of wrapping turn number ( $N$ ) on loss was investigated. Before applying bending to the optical fibre, the transmitted optical power was measured exactly, and then after wrapping the fibre around aluminum (Al) mandrels, the output power as well as attenuation due to bending were measured.

##### 4.1 Effect of bending radius

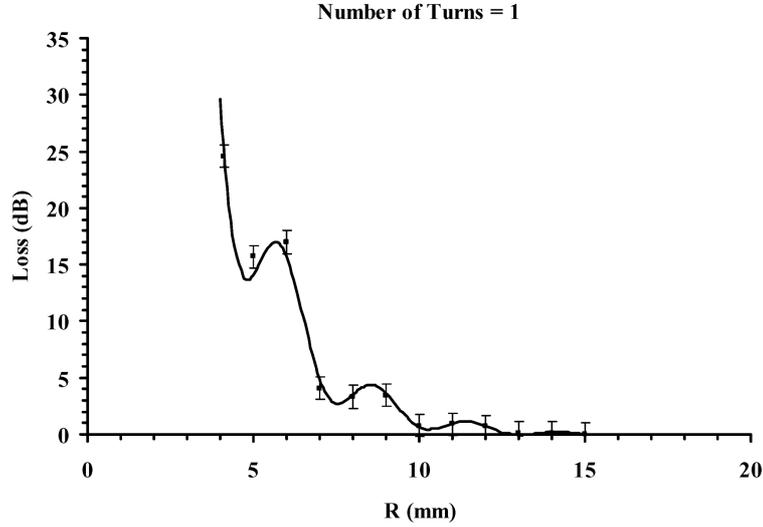
The optical fibre was wrapped around Al rods with different radii of curvature, and each time bending loss ( $L$ ) was calculated. Variation of loss against radius of bending ( $R$ ) is given in figure 2.

As can be seen in figure 2, as  $R$  increases, loss decreases, but at some point reduction does not happen, but rise of loss is obtained (oscillation behaviour of  $L$  with  $R$ ).

For these obtained results we suggest a semi-empirical formula between bending loss ( $L$ ) and radius of curvature ( $R$ ) as in eq. (9).

$$L = 5F_1(5F_2 + F_3), \quad (9)$$

where  $F_1, F_2, F_3$  are found to be



**Figure 2.** Variation of loss against radius of curvature ( $R$ ) (continuous line is for eq. (9)).

$$F_1 = c \exp\left(-\frac{R_{\text{eff}}}{3}\right), \tag{10}$$

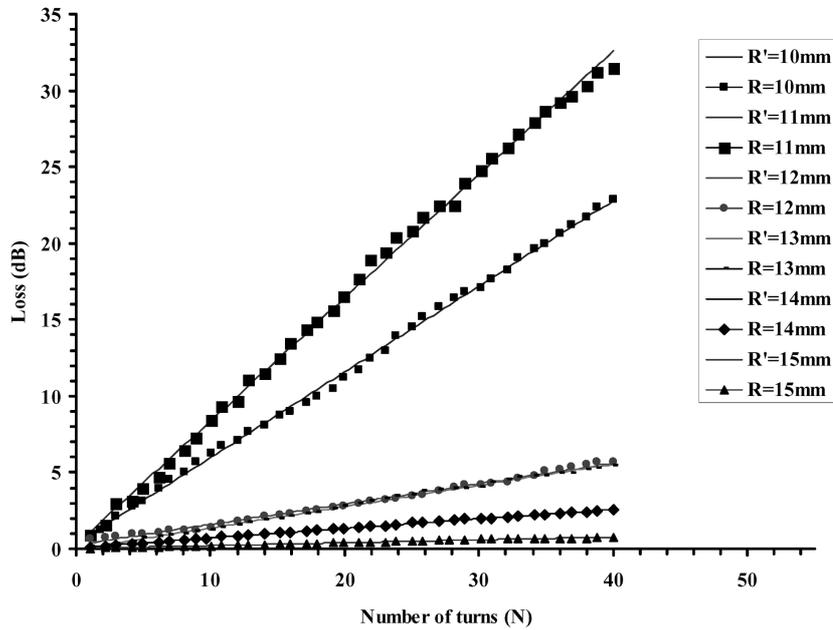
$$F_2 = aJ_1(2.25R_{\text{eff}}), \tag{11}$$

$$F_3 = b \exp\left(-\frac{R_{\text{eff}}}{5}\right), \tag{12}$$

where  $J_1$  is the Bessel function of first order,  $a, b, c$  have values  $-1.59, 12.05$  and  $2.79$  respectively and  $R_{\text{eff}} = R - 0.8$  ( $R_{\text{eff}}$  is the effective bending radius, which differs from actual (experimental) radius ( $R$ ), by a material-dependent elastic-optical correction factor [10]).

This model (equation) which is for one complete turn ( $360^\circ$ ) of bending satisfies the obtained results. In figure 2 the continuous line stands for eq. (9), which is in good agreement with the measured data. Variation of  $L$  with  $R$  might show exponential reduction, but the oscillation property of the loss against radius prevents using a simple exponential form equation or model. This behaviour obtained in many studies (as mentioned before), can be due to coupling between fundamental propagation field either by core and clad structure, or by the coating (protecting) layers, (which is the so-called whispering-gallery mode). This property is observed even for half-turns [10]. The interpretation of oscillation in bend loss curves in terms of a thin film effect on the lateral leaky mode radiation explains this behaviour.

So a simple model which allows fast calculations of bending loss cannot be employed when a wide range of bending radius especially low  $R$  is employed, and usually Bessel function (often first order) must be employed. These results show that smaller bending radius induces a greater bending loss.



**Figure 3.** Variation of bending loss vs. wrapping turns ( $N$ ), for  $10 \leq R \leq 15$  mm (fitted lines are for eq. (13)).

The reason which stops us to use  $R$  less than 4 mm was that in very low  $R$ , bending loss was very high, and secondly the presence of microcracks in optical fibres, especially in very low radius of bending, can cause problems and affect its performance. For radius more than 15 mm, the amount of attenuation due to bending was very small, and loss was very low. So the measurements would give wrong results (so the loss is neglected).

#### 4.2 The influence of wrapping turn

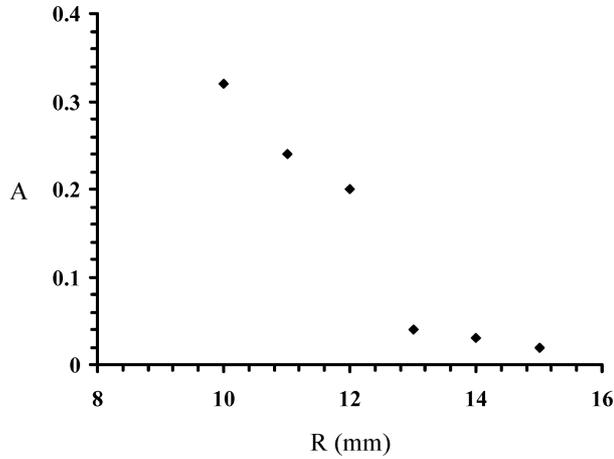
To study the effect of bending turn, optical fibre was wrapped around Al mandrels, up to 40 turns. The obtained results are of two types due to the different behaviour of bending loss against wrapping number of turns.

In figure 3 variation of loss ( $L$ ) vs.  $N$  is shown for radii of curvatures between 10 and 15 mm ( $10 \leq R \leq 15$  mm).

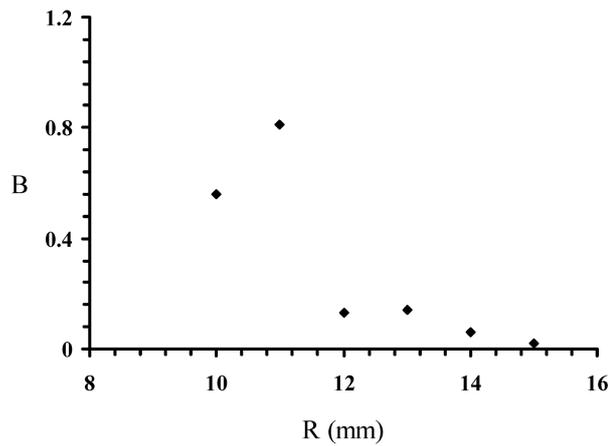
A linear behaviour between loss and bending number of turns is obtained, and the slope of these obtained lines depends on the radius of curvature. For these results a linear function such as (13), between  $L$  (loss) and  $N$  can be used, which satisfies the results.

$$L = A + BN. \tag{13}$$

Both  $A$  and  $B$  should show reduction with increasing  $R$ , but due to oscillatory behaviour between  $L$  and  $R$ , these two parameters ( $A$ , and specially  $B$ ) also show



**Figure 4.** Variation of fitting constant ( $A$ ) with radius of bending ( $R$ ), for  $10 \leq R \leq 15$  mm.



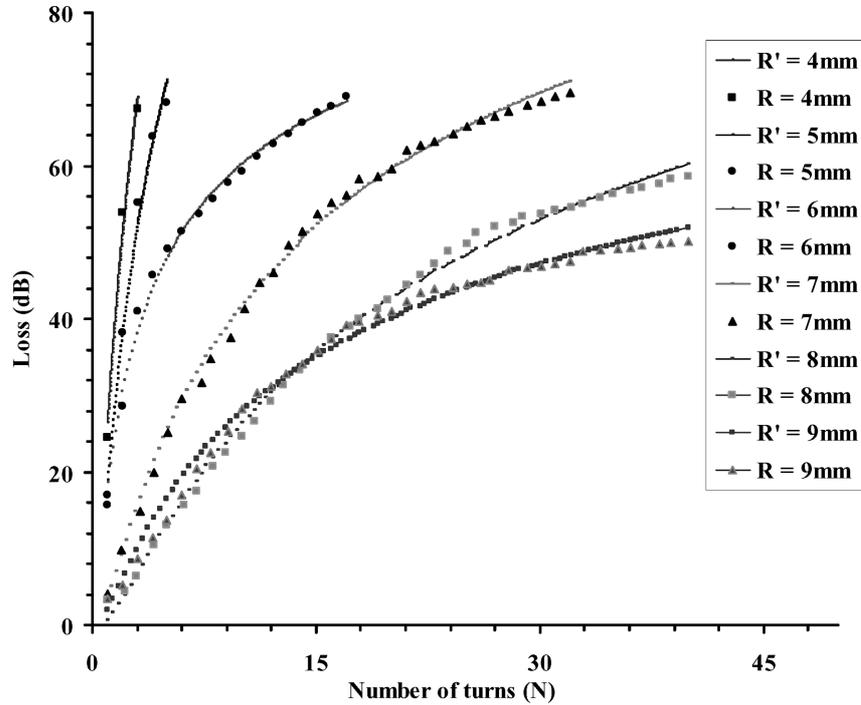
**Figure 5.** Variation of  $B$  against radius  $R$  for  $10 \leq R \leq 15$  mm.

this property as well. Figures 4 and 5 give variations of  $A$  and  $B$  respectively with radius of curvature.

As shown in figure 4,  $A$  decreases with  $R$ , but when  $R$  reaches a certain value,  $A$  tends to be near zero, and can be neglected.

When bending loss was measured for  $4 \leq R \leq 9$  mm, and variations of  $L$  against  $N$  were plotted, to begin with loss rises linearly with the number of turns, and then as wrapping number gets higher, loss starts to show a sort of saturation behaviour, and remains roughly constant. When  $R$  is low ( $R \approx 4, 5$  mm), loss increases very sharply, and this variation of  $L$  vs.  $N$  for  $4 \leq R \leq 8$  mm is shown in figure 6.

For the results obtained in this section, an empirical relationship between  $L$  and  $N$  which satisfies the results would be in the form of (14).



**Figure 6.** Variation of bending loss vs. number of wrapping turns ( $N$ ), for  $4 \leq R \leq 8$  mm (continuous lines are for eq. (14)).

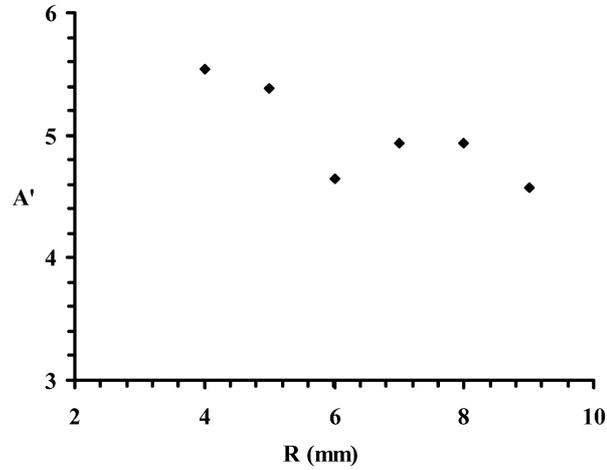
$$\ln(L) = A' + \frac{B'}{\sqrt{N}}, \quad (14)$$

where  $A'$  and  $B'$  are constants, and are functions of bending radius. Figures 7 and 8 respectively show variations of  $A'$  and  $B'$  with  $R$ . Once again one would expect  $A'$  and  $B'$  to reduce with increasing  $R$ , but due to fluctuation of  $L$  with  $R$ , this does not happen.

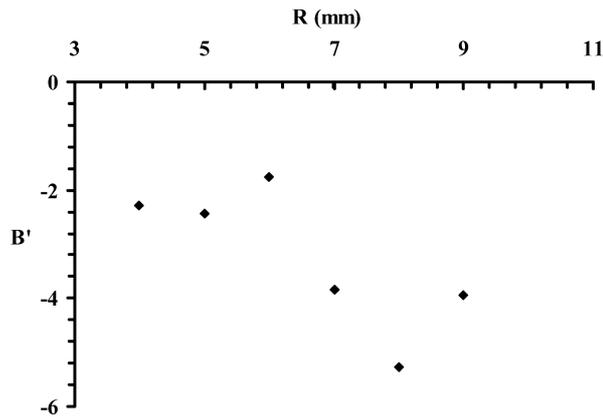
Bending fibres cause a reshaping of the guided field, which travels toward the outer part, resulting in an increase in radiation, and as a consequence calculation of the bend loss exactly needs a detailed knowledge of the propagating radiative field. Also important parameters such as refractive index, wavelength and their variations under various experimental conditions (temperature) can affect the results, but these sorts of empirical equations can help in the calculation of loss very much.

#### 4.3 Effect of torsion

Since twisting the optical fibre also affects optical power and produces loss, and reduces fibre performance, in this section, the effect of torsion and its influence on loss in fibre has been reported [16].



**Figure 7.** Variation of fitted parameter ( $A'$  in eq. (14)) against radius of curvature ( $R$ ).



**Figure 8.** Variation of fitted parameter ( $B'$  in eq. (14)) with radius of bending ( $R$ ).

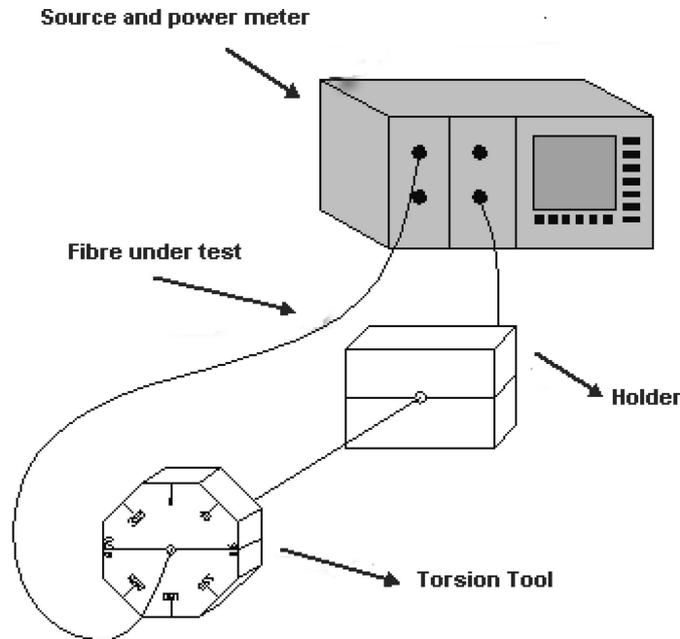
To measure the loss due to twisting of the optical fibre, an experimental set-up shown in figure 9 was arranged.

Variation of loss due to torsion stress on the core and the clad of the fibre was investigated, and torsion is defined as eq. (15), [17],

$$T = G\gamma, \tag{15}$$

$$\gamma = \frac{r\theta}{l}, \tag{16}$$

where  $T$  is the torsion,  $l$  is the length of the fibre which has been twisted,  $r$  is the radius (distance between a point on the clad or core and axis of torsion),  $\theta$  is



**Figure 9.** Experimental set-up for measuring torsional bend and its effect on optical loss in fibre.

the twisting angle (figure 9), and  $G$  is the torsion modulus, which for the material (glass) used for making optical fibres is about 26.211 Pa. Since radii of the core and cladding in the single-mode fibre used were 4.5 and 62.5  $\mu\text{m}$  respectively, by changing  $\theta/l$ , loss due to torsion stress on the core and the clad was investigated.

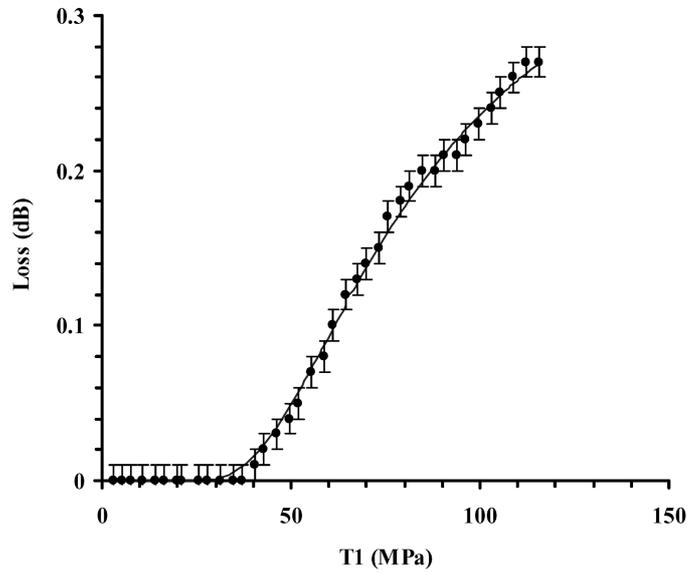
Variation of loss against torsion stress is given in figures 10 and 11 for the core and the clad respectively. As can be seen in figures 10 and 11, very similar behaviour has been obtained, and results of these measurements could be presented in eq. (17), and satisfactory fits are occurred (continuous lines in figures 10 and 11).

$$\ln L = C + \frac{D}{T^2}, \quad (17)$$

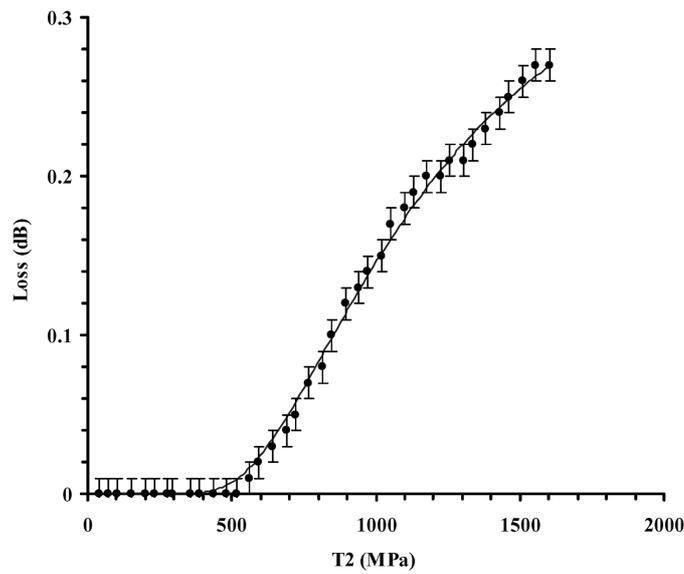
where  $C$  and  $D$  are constants, and for both cases  $C$  has the same value (0.88), while  $D$  is  $-0.6094$  for the core and  $-1150828$  for the clad. These results give the clue that value of  $D$  depends on radius of the core and the clad. So their ratio is given in eq. (18).

$$\frac{D_{\text{clad}}}{D_{\text{core}}} = \left( \frac{r_{\text{clad}}}{r_{\text{core}}} \right)^2 \approx 190. \quad (18)$$

By looking at these results, one can observe the difference of bending and twisting effects on optical loss in single-mode fibre.



**Figure 10.** Variation of optical loss against changes of torsion on the core of the fibre.



**Figure 11.** Variation of loss against torsion on the clad of the fibre.

## 5. Summary and conclusion

Variation of bending loss in a single-mode fibre (standard fibre for communication) against bending radius ( $4 \leq R \leq 15$  mm), up to 40 turns has been investigated. Loss

reduction with increase of curvature radius was obtained and oscillatory behaviour of  $L$  against  $R$  also was occurred. This property can be due to coupling of the fields from core and cladding, or from coating layer or due to coating-air interferences, which contribute to re-injection, so two systems peak the observed phenomena. Therefore, a simple model of exponential reduction of loss with bending radius does not satisfy these results. A semi-empirical relationship proposed for the obtained experimental results shows good agreement.

For variation of  $L$  against wrapping turn ( $N$ ), the results should be divided into two parts, for low  $R$  ( $R \leq 9$  mm), and for high  $R$  ( $R \geq 10$  mm), and this is due to different kinds of behaviour which were obtained. The suggested equations for these measurements show good and satisfactory fits.

Constants used in eqs (13), (14) ( $A, B, A'$  and  $B'$ ) should show reduction with rise of  $R$ , but due to fluctuation behaviour of  $L$  against  $R$  they also show this sort of behaviour (fall and rise behaviour). For loss due to the twisting of the optical fibre, an empirical relationship was suggested, which gives satisfactory agreement with the obtained results.  $C$  for torsion on the core and the clad has the same value, while the second parameter ( $D$ ) depends on the radius or diameter of the core and the clad.

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