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ABSTRACT

When optical fibers are stressed, the deformations at the core-cladding interface induce signal attenuation. Because of their durable physical properties (high melting point) optical fibers can be embedded into certain composite materials at the manufacturing stage. Stresses on the composite induces stresses on the embedded fiber. The amount of stress on the fiber, and thus the stress on the composite, can be determined by measuring the attenuation of a signal passing through the fiber. Force was applied to a single mode and a multimode fiber in a microbend inducing plate, and the attenuation this stress created was measured.

INTRODUCTION

Smart structures are systems which detect environmental stresses and then take steps to report or compensate for those stresses. The first step in developing smart structures is the development of stress sensors. Due to their physical properties (such as high melting point), optical fibers can be embedded in certain composite materials. Optical fiber are currently being embedded in composite materials which are used in the manufacture of such products as the skins of airplanes [1]. The fibers are being used as sensors to detect strain and damage to the wings. Optical fiber is the ideal material for this type of project because they do not significantly effect the tensile and compressive strength of the composite material [2].

When stress is applied to optical fiber, the ability of the fiber to conduct light is compromised. This is due to deformations which form at the interface of the core and the cladding. Another source of loss is due to bending. Bending of the fiber causes the light propagating down the waveguide to be "incompletely reflected off one surface, resulting in loss to the cladding region"[†] [3].

This paper studies the suitability of fiber optic microdeformation sensors in determining the force exerted on a composite. The grating of Figure 1 was used to apply microbending stress on the fiber. Weights were placed on the grating and the attenuation of the signal passing through the fiber was measured.

[†]Udd, p. 29

BACKGROUND

Microdeformation losses are losses due to microbends and microscopic deformations of the fiber diameter. Whereas these losses are undesirable to companies in the communications industry, they can be utilized to develop stress sensors. When placed under stress, optical fibers develop greater microdeformations. Under non-stressed conditions the statistics of the fiber deformation is not accurately known [4]. This is even more so the case under stressed conditions. Thus microdeformation sensors are by nature qualitative and relative.

A laser signal travelling down a fiber optic wave guide loses intensity as it travels due to leakage of signal from the core to the cladding. The instantaneous decrease in intensity per length travelled is proportional to the intensity:

$$\frac{dI}{dl} = -\lambda_l I \qquad (1)$$

where λ_l is the constant of proportionality. λ_l should not vary with length in the stressed region. Thus (1) becomes

$$\frac{I}{I_0} = e^{-\lambda_l l} \qquad (2)$$

λ_l is a measure of what fraction of intensity is leaving the core per unit length. Microdeformations increase λ_l. As the fiber is stressed, the extent of the microdeformations increases. Thus λ_l is a function of the force, F, acting on the fiber. Since the length of the fiber is constant, let

$$\lambda(F) = L\lambda_l(F) \qquad (3)$$

where L is the length of the fiber in the region subjected to microdeformation stress. The transmission through the fiber is defined as

$$T \triangleq \frac{I}{I_0} \qquad (4)$$

Combining (2), (3), and (4) yields

$$T = e^{-\lambda(F)} \qquad (5)$$

If λ and F are linearly related, then the transmission through the fiber should decrease exponentially as the stress on the fiber increases linearly. The extent of microdeformations due to a stress is dependent on a number of complex material properties of the fiber. Thus it is unlikely that λ and F are linearly related. However, as F increases, the extent of microdeformations will increase. Thus λ increases and decreases with F. There is probably a range over which λ and F can be approximated as being linearly related. The attenuation in deciBels is defined as

$$A_{dB} \triangleq 10\log_{10}T \qquad (6)$$

Substituting (5) into this definition yields

$$A_{dB} = 10(\log_{10}e)\lambda(F) \tag{7}$$

Thus if λ and F are linearly related, a plot of A_{dB} versus F should be a straight line.

EXPERIMENTAL PROCEDURE AND RESULTS

The fiber was stressed with a microbend inducing plate as shown in Figure 1. For the single mode fiber FC type connectors were used to connect the fiber to a 1300 nm, 2 mW, laser diode at one end and a ImGaAs photo diode at the other end. For the multimode fiber, a 1 mW He-Ne laser signal was coupled using a microscopic objective lens and a photo detector. The same stress plate was used for both fibers. The signal and detection were not as strong for the multimode fiber, probably do to losses at the glass-air interfaces. The FC connectors provided an optical contact between the laser diode and the fiber and between the fiber and the photo diode.

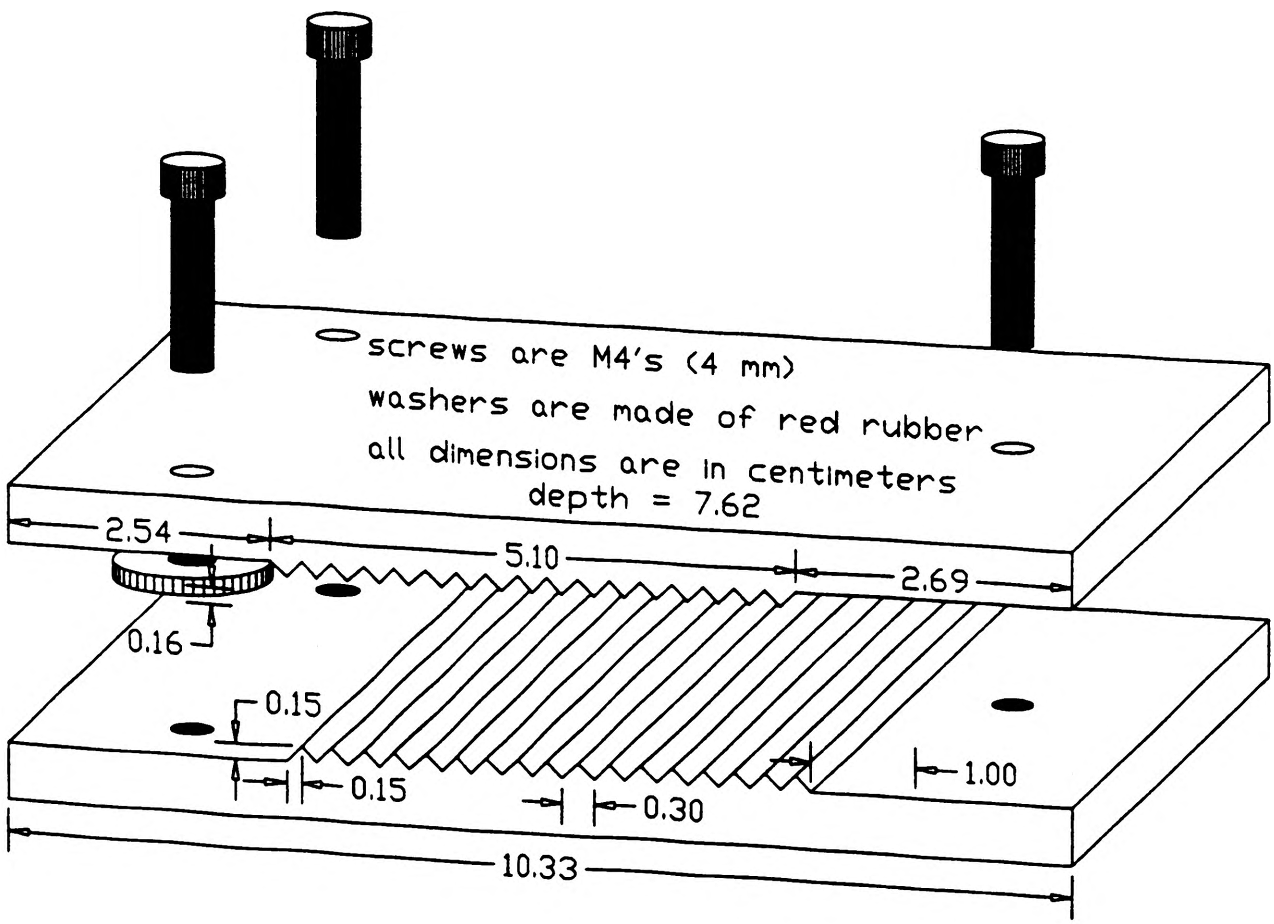

Figure 1. Microbend Grating

The single mode fiber was obtained from SpecTran Corporation of Sturbridge, MA. The fiber ID# was L0-108-0528-22-100C 02/28-91. The signal from the ImGaAs photo diode was read as a voltage on a Tektronic oscilloscope. The weights used were two-pan beam balance weights obtained from Lab 210 in the Chemistry building. The set contained 2000g, 1000g, 200g, two 100g, and 50g weights. The 500g weight was missing. All the weight was stacked squarely on the plate. Voltage readings were recorded and the weight was decreased in steps of 50g with 500g jumps. The voltage readings were divided by the no-load reading and then squared to obtain the transmission. This data was plotted with *QuattroPro* and is displayed in Figure 2. A_{dB} was computed using (5) and the data is plotted in Figure 3. The spacing of the microbend grating was 3 mm. A trial was also done with the fiber placed through the grating at an angle of 48° to yield an effective spacing of 4.5 mm.

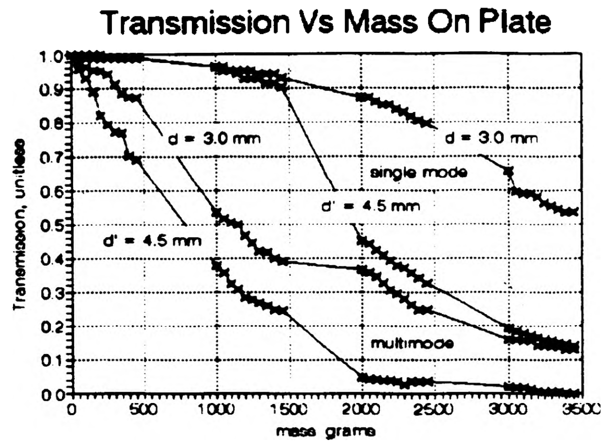

Figure 2. Transmission versus Mass on Grating

The detector used for the multimode fiber trials came with a microWatt meter. The data was generated and plotted as in the single mode fiber trials, except the data was read off the microWatt meter and not the oscilloscope. The attenuation is plotted in Figure 4. The fiber was purchased from Newport Corporation, Fountain Valley, CA. The model number was F-MLD-10.

ANALYSIS

Let $\lambda(F) = \lambda_F F + \lambda_H$, where λ_F is the coefficient which multiplies the first order of F and λ_H contains the higher order terms but is nearly constant for the region of concern. Then

$$A_{dB} = 10(\log_{10}e)(\lambda_F F+\lambda_H) \qquad (8)$$

Thus in a linear regression of A_{dB} vs. F data points, λ_F will be equal to the slope divided by $10(\log_{10}e)$ and λ_H will be equal to the y-intercept divided by $10(\log_{10}e)$.

The regression lines through the attenuation plots for the single mode fiber data have very good fits through the last two sets of data. The correlation coefficients of these lines were $R^2 = 0.987$ and $R^2 = 0.996$ for the $d = 3.0$ mm and $d' = 4.5$ mm sets respectively. The fit through all four data sets were not nearly as good. For the single mode fiber, A_{dB} approximates a linear function of F only for higher force values.

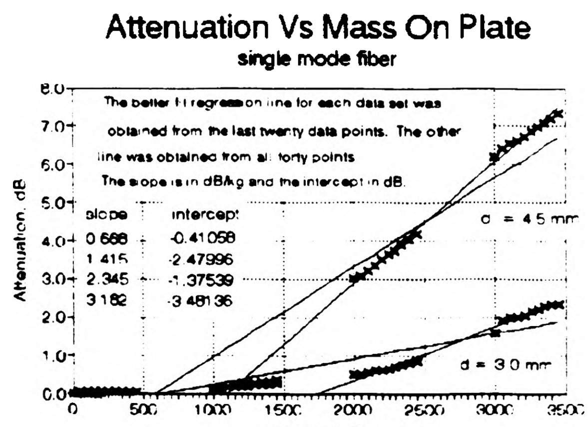

Figure 3. <u>Attenuation vs. Force</u>

As can be seen in Figure 4, A_{dB} approximates a linear function of F only for low values of F for the multimode fiber with the grating spaced at 4.5 mm. As was the case with the single mode fiber, for the multimode fiber with the grating spaced at 3 mm, A_{dB} approximates a linear function of F for a larger range of F.

Equation (8) was solved backwards to yield

$$T = Ae^{\lambda_F F} \qquad (9)$$

where A approximates a constant. Equation (9) was used to generate the curves in Figure 5 and Figure 6. The curves are not very good approximations of the data. One reason for this is that small errors in λ_F and λ_H are magnified when the exponential is taken.

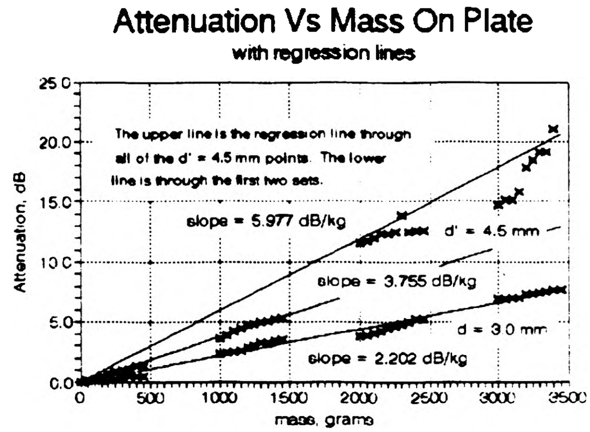

Figure 4. Attenuation versus Force

CONCLUSION

The results were not very quantitative. This is a draw back of microdeformation sensors. However, if a threshold is sought rather than a measurement, the sensors work very well.

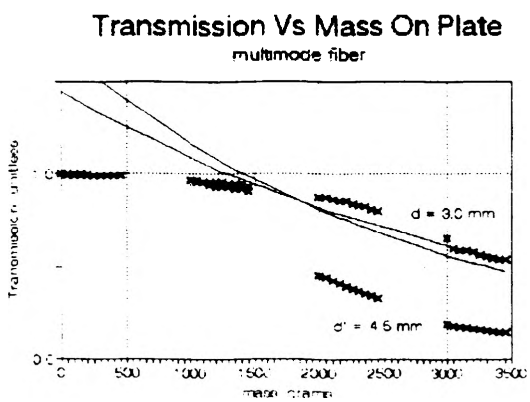

Figure 5. Transmission vs. Force

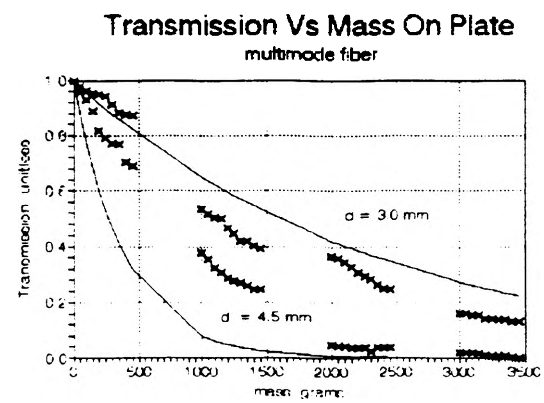

Figure 6. Transmission vs. Force

In studies with multimode fibers having specifications similar to the fiber used in this study, it was found that microbending sensors are most sensitive on a grading with periodicity 4 mm [5]. Another study [6] found the maximum periodicity to be related by the equation

$$\Lambda_c = \frac{2\pi}{k_c} = \frac{2\pi a n_0}{NA} \qquad (10)$$

where a is the core radius, n_0 is the refractive index on the fiber axis, and NA is the numerical aperture. In the data presented in this paper, a significant increase in sensitivity does occur between a grating spacing of 3 mm and one of 4.5 mm.

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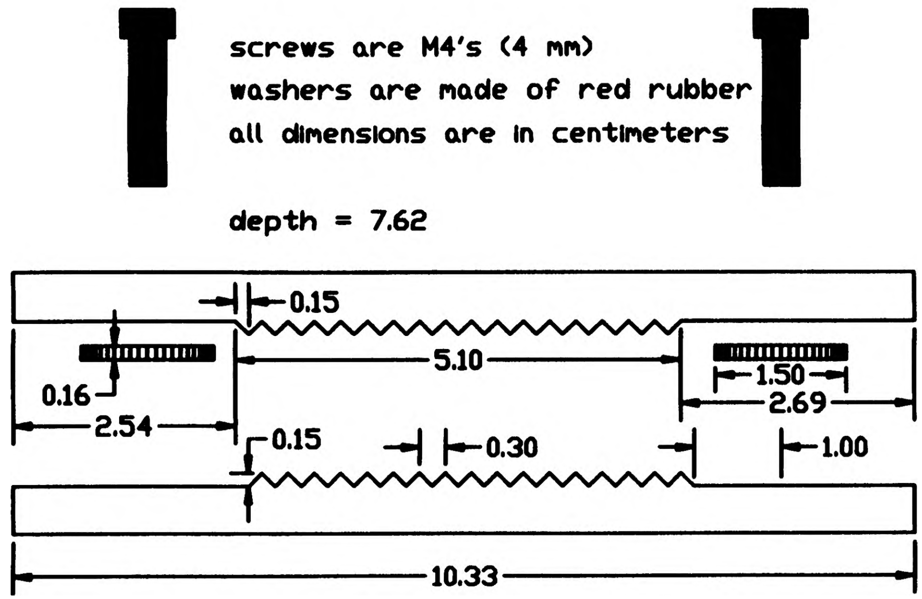
screws are M4's (4 mm)
washers are made of red rubber
all dimensions are in centimeters
depth = 7.62
0.15
5.10
0.16
1.50
2.69
2.54
0.15
0.30
1.00
10.33