Variable Attenuation in Bent Single-Mode Fibers and its Utilization

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ABSTRACT

A new single-mode fiber-optic attenuator based on fiber bending is described. Methods of overcoming oscillations of loss with bending radius and wavelength and concerns about the reliability of bent fibers are discussed.

INTRODUCTION

In fiber-optic communication systems, it is often necessary to adjust the optical power level present in a given link to compensate for differing losses in each optical circuit. This is accomplished with the use of optical attenuators, either fixed or variable.

Removing light from an optical fiber might seem at first to be a relatively easy task, given the difficulties usually associated with efforts to keep it in. However, variable attenuators are required to have a low minimum loss and to be well-behaved over a range of different environmental conditions. Variable optical attenuators have traditionally been constructed using bulk optical techniques, i.e., light is transmitted out of one optical fiber, attenuated using some filtration technique, and focused into a second fiber for transmission through the rest of the system. This process presents problems when used with single-mode fibers, which have core diameters on the order of 10 microns. Optical components must be aligned with respect to each other to tolerances on the order of one micron, a process which is very labor-intensive. In addition, widespread use of epoxies to maintain those tolerances causes the alignment stations to be occupied for a relatively long time, limiting throughput. These difficulties result in high prices and undependable performance for most commercially available single-mode variable attenuators.

Light can be removed from optical fibers by bending them, a process that does not require difficult alignment processes or lengthy epoxy cure cycles. Because there is only one propagation mode in a single-mode fiber, no modal dependence exists in the attenuation induced by bending. Also, since the fiber is relatively weakly guiding, much less severe bends are required to induce losses than would be required with a multimode fiber.

Losses in a bent fiber are known to exhibit oscillatory behavior with bend radius and wavelength. This phenomenon has been shown to result from coherent interference among “whispering gallery” modes reflecting from the cladding/buffer and buffer/external medium boundaries and the core propagation mode.[1] Varying the fiber geometry and the bending scheme can result in a device in which interference does not cause significant untoward effects.

A major consideration affecting the use of bending to attenuate an optical signal is the reliability of the bent fiber. Bending a fiber creates tensile stresses in a portion of the glass which can cause propagation of subcritical cracks to failure. This is known as static fatigue and is associated with the action of water at areas of high tensile stress in a glass. The susceptibility of a given fiber configuration to this effect is quantified by the static fatigue constant for that fiber and is related to the expected lifetime of the fiber under stress. The use of hermetically coated fibers, which are known to have very high static fatigue constants, makes fiber bending a viable technique for attenuating an optical signal.

Loss Mechanisms in Bent Fibers

Figure 1 shows a bent single-mode fiber. In order for a wavefront to propagate along the core in the bent region, the part farthest away from the center of curvature of the bend must travel faster than the rest of the wave. Neglecting the refractive index variations caused by strain in the medium as the fiber is bent, the effect can be simu-

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lated by representing the bent fiber as a straight one with a distorted refractive index distribution:

$$n_{eff} = n(r) \cdot \left[1 + \left(\frac{r}{R}\right) \cdot \cos(f)\right], \qquad (1)$$

where

n_{eff} = the effective index distribution of the straight fiber,
r = radial coordinate in a plane normal to the fiber axis and with origin at the fiber center,
n(r) = the refractive index distribution of the undistorted fiber,
f = the polar angle in the fiber,
R = the bending radius.[2]

The larger optical path length experienced by the mode on the outside of the waveguide is simulated by a higher effective refractive index.

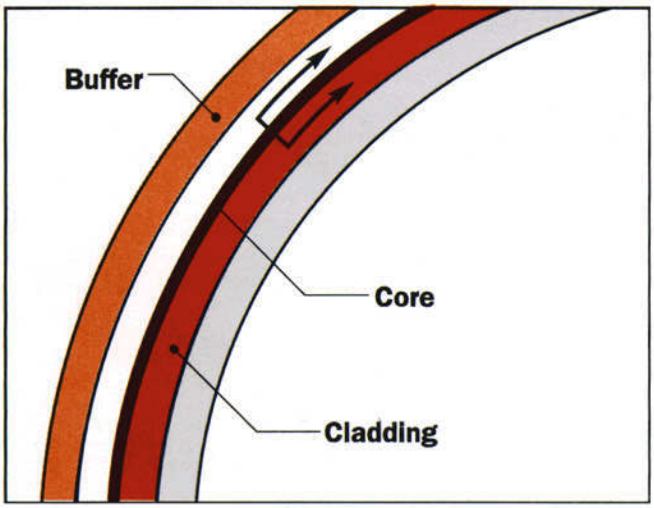

Figure 1. Light propagation in a bent single-mode fiber. The outer region of a mode must travel faster than its inner region.

According to Nagano *et al.*[3] the refractive index variations induced by strain in an optical fiber by bending are moderated by the strain in the glass, and it is suggested that the radius of curvature be adjusted by a factor of 1.25. Accordingly, the effective index distribution given by equation 1 is modified to

$$n_{eff} = n(r) \cdot \left[1 + \left(\frac{r}{1.25 \cdot R}\right) \cdot \cos(f)\right]. \qquad (2)$$

A corresponding index distribution is shown in Figure 2. The sloping line represents the modified refractive index of the fiber in the plane of the bend. Since the mode field in this equivalent fiber is different from that in the straight fiber, there is a loss encountered at the onset of the bend known as transition loss. This loss occurs only at the point where the curvature changes and is not affected by the length of the bend. It may be thought of as a loss caused by an impedance change at the junction of two dissimilar waveguides.

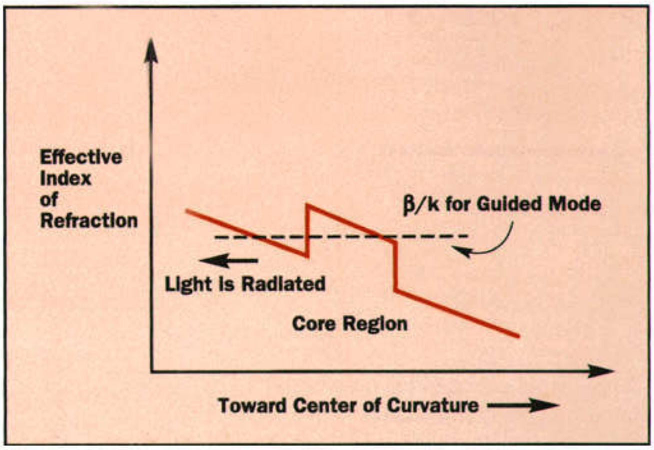

Figure 2. Effective index of refraction used to model the effect of fiber bending while assuming a geometrically straight fiber.

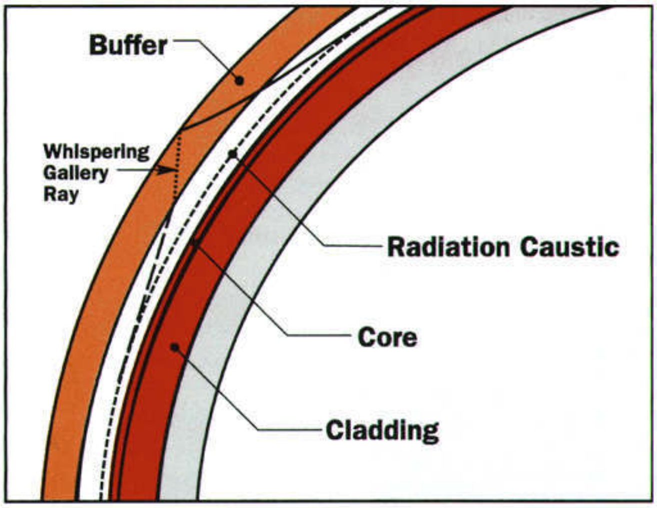

Figure 3. Illustration of origin of interference effects caused by light radiated from the core being reflected back into the core.

Because of the distortion of the bent fiber, the latter loses its ability to guide the wave without disturbance. This leads to the introduction of the concept termed "pure bending loss." In Figure 2, the side of the fiber with higher refractive index provides a larger optical path length. The dashed line corresponds to the effective refractive index β/k for the "guided" mode. The plane where the index β/k equals the effective local refractive index of the cladding is the *radiation caustic.* It marks the transition from guided mode to radiated wave. The light in the "guided" mode is evanescently coupled into this radiative region. The smaller the bending radius of the fiber, the more closely the radiation caustic approaches the core, and the more light is lost per unit length of the bent fiber.

INTERFERENCE EFFECTS

On its way out of the fiber, light radiating away from the core can be reflected at each of two interfaces: The boundary between core and cladding and the boundary between the buffer and the external medium. Since these boundaries are cylindrical, much of the reflected light is returned to the core, where it can interfere with the light already propagating there. This reflected light forms a set of whispering gallery modes,[4] the properties of which depend on the geometry and composition of the fiber, the radius of the bend, and the optical wavelength.

Figure 4 shows the wavelength dependence of attenuation for a single-fiber loop of 10 mm diameter without index matching of the buffer. The general trend toward increasing loss with increasing wavelength is due to the fact that the fiber is more weakly guiding for longer wavelengths. Without index matching the loss varies periodically ("oscillates") with wavelength, suggesting an interference effect. Index matching the buffer to its external environment causes the oscillations to disappear (see Figure 5). This indicates that the light being reflected at the outer buffer surface is the major contributing factor.

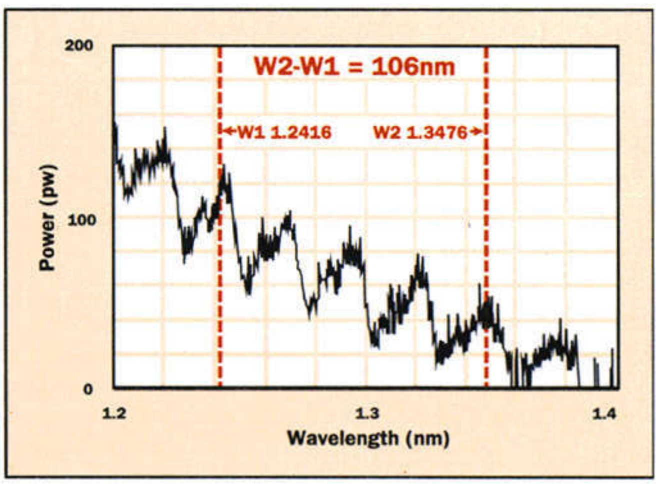

Figure 4. Oscillations superimposed on the monotone decreasing loss vs. wavelength function. This plot was obtained from one 0.375-inch loop of a Corning Titan single-mode fiber.

RELIABILITY CONSIDERATIONS

Bending optical fibers to a degree that causes measurable losses generates locally high levels of tensile stress in the

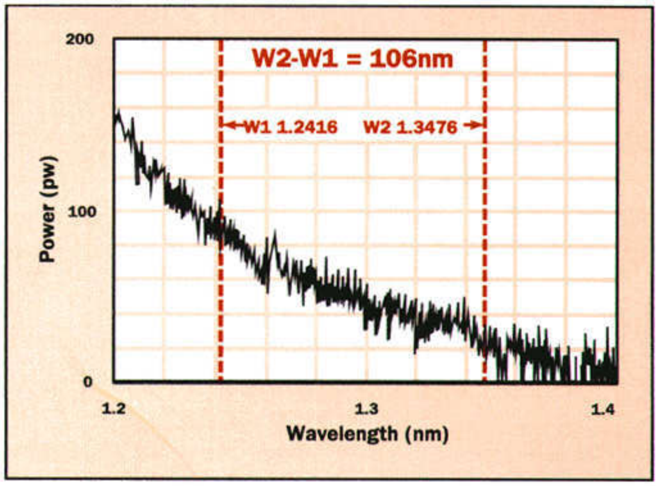

Figure 5. Index matching the outer surface of the buffer eliminates the oscillations shown in Figure 4.

fiber. Such levels can reduce fiber life significantly because of "static fatigue" of the glass. This phenomenon is strongly associated with the presence of water at the fiber surface. Taking it into consideration, the standard method for predicting the lifetime of fiber uses the power law

$$\frac{t}{t'} = \left[\frac{s'}{s}\right]^n, \qquad (3)$$

where

s = the stress encountered by the fiber,
s' = the stress applied during screening,
t = the estimated lifetime of the fiber,
t' = the length of time the screening stress was applied,
n = the static fatigue constant.

The exponent n is characteristic for the particular fiber under consideration.[5] Typical fatigue constants for most commercially available fibers are between 20 and 30, values which are quite high for most applications. These values are known to drop significantly[6] in humid environments; consequently, in such environments rapid failure of the fiber must be expected.

Preventing water from reaching the surface of the fiber may be accomplished in two ways. One approach is to seal hermetically the attenuator enclosure; the other approach is to use hermetically sealed fibers. Of these two methods, the use of hermetically sealed fibers is preferred for design, manufacturing, and cost reasons. Hermetically sealed fibers have static fatigue constants n well in excess of 100, sometimes approaching 200. This increases the reliability noticeably. An additional benefit of using hermetically sealed fibers is the coating's ability to absorb some of the light present in the undesirable "whispering gallery" modes in the bent fiber.

For the purpose of this study, the stress experienced by a fiber during bending can be approximated by

$$s = \left(\frac{r}{R}\right) \cdot E, \tag{4}$$

where

s = stress,
r = the fiber radius,
R = the bend radius,
E = effective Young's modulus of the system core/cladding, approximately 10.2×10^6 psi.

The effective Young's modulus increases at high strains, and the stress according to Gulati *et al.*[5] is approximated by

$$s = \left(\frac{r}{R}\right) \cdot E \cdot \left[1 + 3 \cdot \left(\frac{r}{R}\right)\right]. \tag{5}$$

In the present attenuator design, the fiber experiences a tensile force of about 1/2 lb, which when added to the stress caused by bending the fiber to a .087 inch radius, yields a tensile stress of 300 kpsi.

If, before the device is assembled, a 125-mm fiber is screened at 450 kpsi for a period of 1 second, and a fatigue constant of n = 100 is assumed, the lifetime of the fiber when bent to a 0.087 inch radius would be estimated, according to equation 3 to be

$$t = 7 \cdot 10^8 \text{ years.}$$

DEVICE CONFIGURATION

The above considerations indicate that placing the buffer in an index-matching environment would be the best way to eliminate interference effects in an attenuator design. However, there are practical difficulties with most approaches designed to use this observation. Some of them are addressed here.

Filling the housing of the device with a liquid or gel increases its mechanical complexity. One aspect is that the housing must be sealed to retain the fluid under changing external conditions. In addition, as the device is actuated, the interior volume is not generally conserved, which would create difficulties if for incompressible liquids or gels no special compensating device is incorporated in the design.

Coating the fiber with an absorptive or index-matching organic polymer can cause the attenuation to drift over time. In fact, the use of acrylate or silicone buffer coatings on the fiber was found to cause the attenuation to drift unacceptably. This drift was only overcome after switching to a 10 μm polyimide buffer coating.

These and similar considerations entered the design process for the attenuator shown in Figure 6. The fiber is wrapped around a horseshoe-shaped spring so that too tight a bending radius is avoided. A plunger with a rounded end engages the fiber in the unsupported central section. As the fiber is deflected by the plunger, critical bending occurs at the three points, identified in Figure 6 as a, b, and c. When the plunger is actuated, the length of fiber subjected to bending in any of these three locations increases, bringing about an increase of the total attenuation. If the radius of any of these bends were to vary significantly over its length, and if the environment is not index-matched to the outer buffer surface, the interference effect described above would vary as more fiber was wrapped. Since it is difficult to maintain a tight tolerance on the radius of a bent arc spring, mandrels were turned on a lathe and attached to the spring at points a and c.

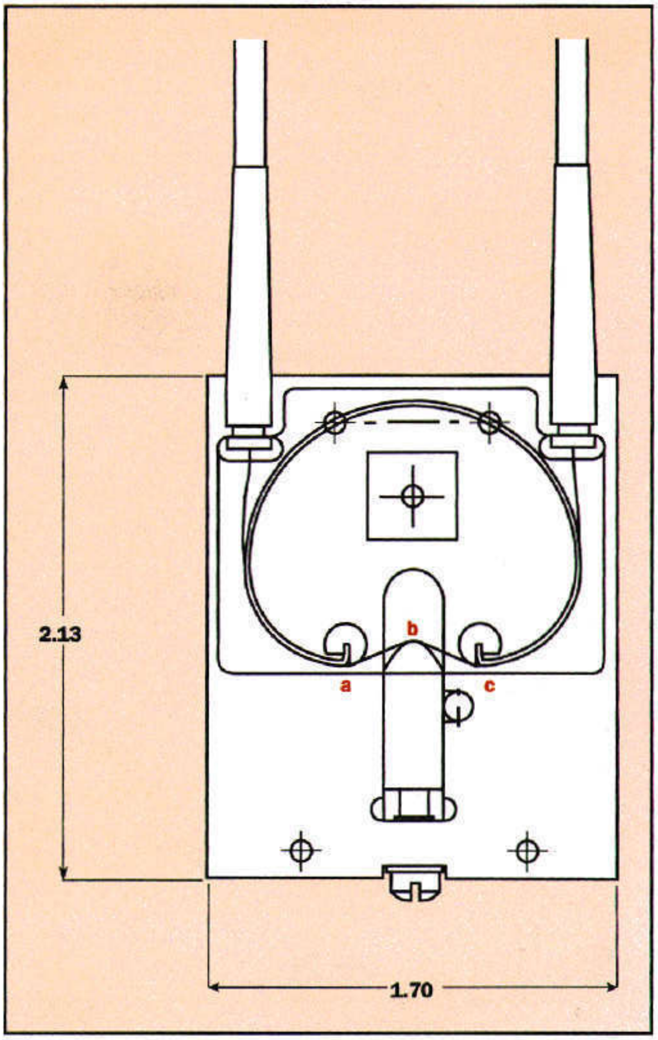

Figure 6. Schematic of attenuator design. Details in the text.

The use of fiber with a thin buffer has the advantage of decreasing the optical path difference between the whispering gallery modes and the core mode, which increases the distance between the maxima in the resulting interference pattern. This reduces the likelihood that this interference will result in attenuation that is nonmonotonic either with actuation or wavelength.

Figure 7 shows a typical plot of attenuation with respect to actuation of the lead screw. The attenuation is monotone with actuation because the length of the fiber subjected to the bend changes but not the radii of the bends.

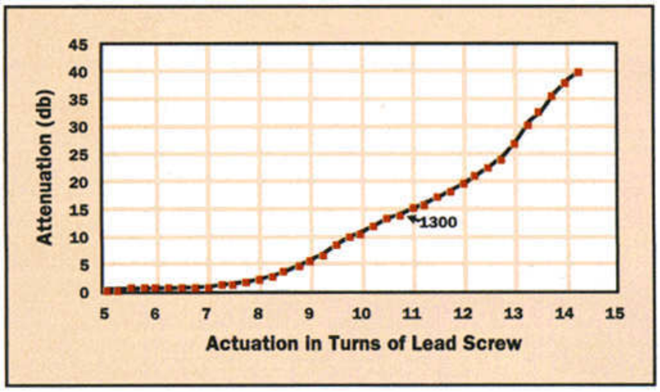

Figure 7. Plot of attenuation vs. actuation representing a monotone increasing function.

Figure 8 shows a plot of the wavelength dependence of the attenuation over the range 1.52 to 1.62 µm. Up to a wavelength of approximately 1.59 µm the transmission decreases monotone with wavelength. The erratic response recorded above 1.59 µm is not related to the interference mentioned above but is most likely due to instrument noise.

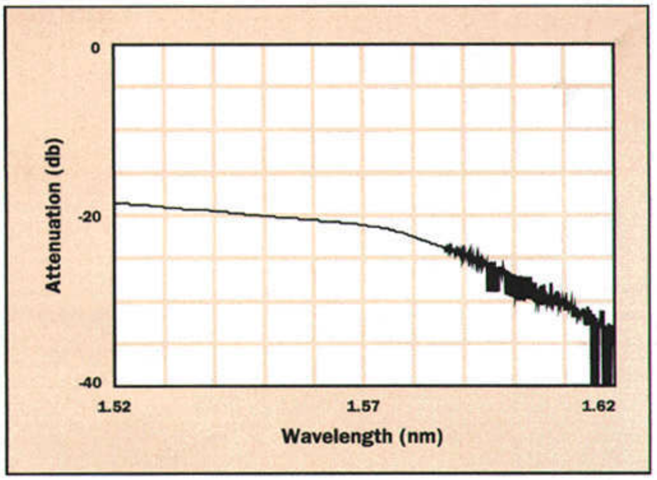

Figure 8. Plot of attenuation vs. wavelength representing a monotone decreasing function. The irregular behavior above 1.595 µm is not related to interference of primary mode and reflected components but is most likely due to instrument noise.

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