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Bend induced loss in single mode fiber for designing simple interferometric temperature sensor

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Optical loss in a bend induced over moded fiber has been measured as a function of temperature was observed. These observations are explained on the basis of interference between the core-guided mode and whispering Gallery (WG) modes by reflection at the buffer air interface. The experimental results are consistent with the optothermal properties of the fiber and buffer.

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1. Introduction

Losses of single mode optical fibers are caused by a) Material absorption b) Material scattering which mainly consists of Rayleigh scattering and c) radiation losses due to curvature [1]. In single mode fibers the transmission loss arises from the fundamental mode to leaky core modes whenever there is a change in curvature of the fiber axis, e.g. from straight to curved or vice versa [2,3]. The pure bend loss results from the continual loss of guidance at the outer portion of the evanescent field of the fundamental mode [2,3]. This loss of guidance is due to the phase velocity of the outer part of the evanescent field becoming equal to the speed of light in the cladding. The smaller the radius of the bend the greater the fraction of evanescent field affected and hence greater the percentage of light lost at the bend [14]. However, not all the light leaving the fundamental mode by the above methods is permanently lost, as some can reenter by coupling from the leaky core modes and cladding modes to the fundamental [4,5].

Most theories assume an infinite cladding and thus predict a monotonic dependence loss on bend radius and length [6]. Oscillations in bend loss with bend radius [7], length [5] and wavelength [8] were observed. These observations are explained using an interference model. The fiber cladding [or buffer coating] to form a whispering Gallery (WG) mode [8] guides light ejected from the core by the bend. The requirement is that refractive Index of the buffer is slightly higher than that of the cladding. Light, which is ejected from the core of an optical fiber by a bend and enters the cladding [5-7] or buffer [9] of the fiber, may be coupled back into the core guided to modify the bend loss. The whispering gallery mode recouples with core-guided mode with a relative phase, which is dependent on the fiber geometry, bend radius and illuminating wavelength. The buffer properties must therefore be taken into account when predicting bend loss or designing fiber optical components such as local light detectors [8] in which bend is deliberately introduced to the fiber and to do this, optical properties of the buffer must be known.

Majority of the buffer material of the monomode optical fibers is a type of UV-cured acryl ate [12], the optical properties of which may change because of the coating process during which a monomer bulk material is polymerized, to form a mixture of monomer and polymer components whose refractive index will depend on the degree of polymerization. In addition, the buffer coating may be formed with residual stresses, which will also modify the buffer refractive index practical techniques were explained for the measurement of the diameter and refractive index of the buffer coating of a monomode optical fiber [13]. Bending loss in optical fibers has been studied extensively, chiefly because of its adverse effect on power budget in telecommunications [15]. However, bend loss has been exploited to sample light guided by a fiber without interrupting the fiber, to form local light detectors. Bend loss is also used as transduction mechanism in some type of fiber optic sensors, for example where the measurand produces a displacement that causes a change in fiber bend radius and hence modulates the optical attenuation.

Most of the oscillations in the bend loss could formed the basis of a number of applications, which include: (a) using the rapid rise in the loss to sense changes in the radius of an object to which, the fiber is attenuated and (b) minimizing the bend loss in single mode optical communication links by designing fibers to give synchronized coupling from the whispering gallery mode to the fundamental mode at the operating wavelength and bend radius to be used. Recent experimental and theoretical work shows that bend loss is a strong function of wavelength. The strong wavelength dependence of loss is also a complicating factor in the design of intensity modulated fiber optic sensor. The general form is an increase of loss with wavelength 1.2 to 1.6 μm [10] with higher loss at smaller bend radii.

In this present work, the experimental study made on oscillations of bend loss with temperature, which arises from the temperature dependence of the phases of the core mode and whispering gallery mode coupling for He-Ne of wavelength in the visible region. Our observations of the temperature dependence of bend loss suggest the possibility of designing high temperature sensitivity communication interferometric fiber optic sensor.

2. Theory

Whenever fiber forms a bend, whispering gallery (WG) modes created [8], propagated in the cladding or buffer, which can interfere with the guided core mode to produce oscillations in bend loss depending on bend geometry or light wavelength. The formation of such whispering gallery modes creates an interferometer within the fiber one arm (length L_1), being within the core and other L_2 primarily within buffer. The thermal sensitivity of an optical path may be expressed as [10]

$$\frac{1}{l}\frac{\partial\phi}{\partial T}=\frac{2\pi}{\lambda}(n\alpha+\beta)$$

where α is the thermal expansion coefficient, β is the thermo-optic coefficient, l is the length and $\frac{\partial\phi}{\partial T}$ is the temperature coefficient of optical phase. The path length $L_1$and L_2 will have temperature induced phase shifts of $\Delta\phi_1$ and $\Delta\phi_2$ respectively, and the relative phase change $\Delta\phi$ will be given by

$$\Delta\phi=\frac{2\pi\Delta T}{\lambda}\left[L_2(n_2\alpha_2+\beta_2)-L_1(n_1\alpha_1+\beta_1)\right]$$

This phase shift will lead to observed oscillations of bend loss as the relative phase of the whispering gallery and core modes change with temperature.

3. Experiment

The fiber bend induced by making mandrels of different radii, bent portion dipped in the Paraffin oil bath (for controlling temperature). A polarized He-Ne source used for launching of wavelength 632.8 nm, output power- 5 mw and beam diameter 0.75 + or - 0.05 nm. Readings of power transmitted through the fiber were made using photo detector (818 - SL Newport model, range 400-1100 nm). The detector was a power meter (1815 - C, Newport model, operating environment < 70% relative humidity non condensing 18 ^{o}C – 28 ^{o}C). Temperature induced bend loss were observed. For bend loss measurement, a zero-bend reference power level (i.e. with the fiber straight) was measured. The bend arc and length were increased to desired value and dipped into paraffin oil bath, which was heated from ambient temperature to higher values (not greater than 85 ^{o}C above, which buffer coating would suffer degradation). The power levels were noted with respect to temperature. The process was repeated for different bend radii. The calculated losses are in dB-m.

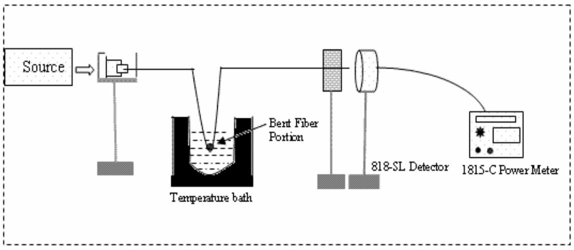

Fig. 1. Experimental arrangement.

Table 1. Fiber properties.

	Core	Cladding	Buffer
Refractive index (n)	1.448	1.444	1.53
Radius	9 µm	125 µm	400 µm
Thermal Expansivity (α)	5× 10^{-7} K^{-1}	5 × 10^{-7} K^{-1}	20 × 10^{-5} K^{-1}
Thermo-optic Coefficient (β)	1.9 × 10^{-5} K^{-1}	—	-23 × 10^{-5}

Table 2. Calculations of ΔT spacing.

Bent Radius	180^0 angle		360^0 angle	
	Calculated	observed	calculated	observed
0.5 cm	8.95 K	6.8661 K	4.48 K	6.8754 K
1.0 cm	17.90 K	7.4100 K	8.95 K	7.6400 K

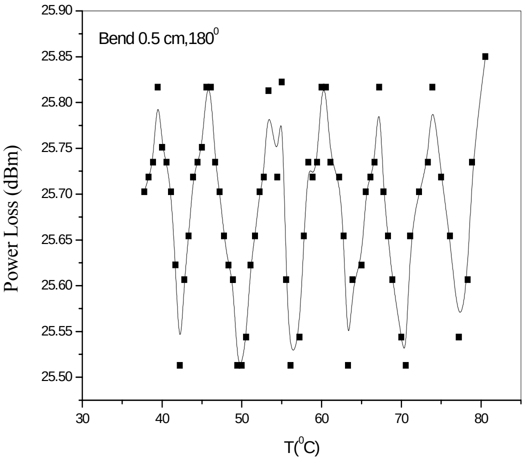

Fig. 2. Temperature dependent bend loss for 0.5 cm, 360^0 bend optical fiber.

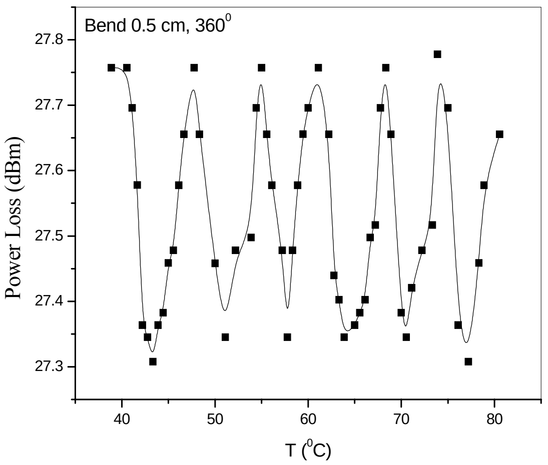

Fig. 3. Temperature dependent bend loss for 0.5cm, 360^0 bend optical fiber.

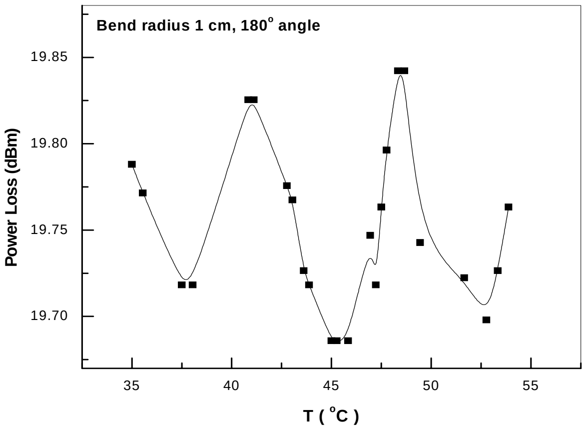

Fig. 4. Temperature dependent bend loss for 1cm, 180^0 bend optical fiber.

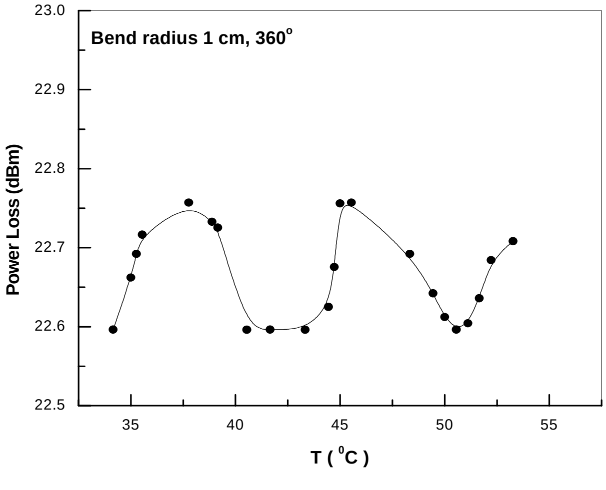

Fig. 5. Temperature dependent bend loss for 1 cm, 360^0 bend optical fiber.

4. Results and discussion

Bend loss as a function of temperature for the fiber of table 1 are presented in figs 2 to 5**.** Optical transmission through a bend of radii 0.5cm and one cm and arc of length of 180^0 and 360^0 are studied. Temperature dependence bend loss characteristics for bend angle 180 and 360 degrees for a bent of 0.5cm are shown in Fig. 2 and 3 respectively. It is observed that loss oscillations are consistent with rise of temperature and loss is higher at larger bend angle i.e. at 360^0 with a difference of 1-dBm power. The same is true for other bent radius 1 cm. Using fiber properties given in table 1, calculations are made for determining the spacing ΔT of the transmission peaks by equating the phase change of $\Delta\Phi$ to 2π. It therefore predicts that generation of whispering gallery modes at cladding modes at cladding / buffer increases as the bend radius decreases in agreement with theoretical model.

It is seen that, the calculated spacing for 0.5 cm bend radius, 360^0 is $\Delta T = 8.95$ K, while average peaks in figure 2 is 6.8661 K. Experiment and theory thus agree within the experimental error and uncertainties associated within the data of Table 1. It is also observed that ΔT spacing is increases with increase in bent radius due to attenuating or damping of whispering gallery modes are in good agreement with theoretical model. Hence the general form is an increasing loss with temperature on which is superimposed an oscillations whose spacing increases with bent radius. It is seen from all graphs, the temperature sensitivity raises to approximately 0.1 dB/K with a total variation of 1dB increase between maximum and minimum values.

5. Conclusions

The results of temperature dependence of the bend loss for single mode fiber of different bend radii and angles have been analysed. It has been found that peaks appear in the bending losses due to the interference between the guided modes in the cladding and whispering gallery mode is guided by reflection at buffer/air interface. Measured values are in good agreement with theoretical values. The bend loss in buffered single mode fiber shows oscillations with very low power loss and inconsistent for He-Ne laser of 632.8 nm.

It has been shown that whispering gallery modes propagating in the buffer coating of a monomode optical fiber, can lead to oscillations in the bending loss as a function of temperature. The period of oscillations varies as a function of the bend geometry and of the optical and physical properties of the buffer coating. The oscillations interns of the coupling of light from whispering gallery mode in the cladding to the fundamental mode in the core under weak coupling conditions. The cladding mode is formed from the light leaving the fundamental mode due to the pure bend loss. The minima or troughs in the oscillations result from synchronized i.e., in phase coupling of light from the whispering gallery mode to the fundamental mode and the peaks of oscillations corresponding to asynchronous, i.e. out of phase coupling.

The bend radii in which synchronized coupling takes place are in good agreement with experiment. This temperature effects are clearly relevant to the design and operating of devices such as local detectors in which a bend is deliberately introduced into a fiber. The temperature sensitivity in Figs. 2 to 5 is approximately 0.1 dB/K with total variation of 1 dB-m in intensity between maximum and minimum values. This high temperature sensing of interference induced by bending gives rise to possibility of designing of a simple rugged interferometric sensor.

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