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On Impact of Dynamic Pressure and Thermal Loading on Refractive Index and Microbending Loss in Two-Layer Optical Fibers

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Abstract This paper analyzes the impact of dynamic pressure on refractive index in two-layer optical fibers exerted on each layers, and then calculate the microbending losses developed in the fiber. In our analysis, we determine the tangential, radial, and axial stresses and refractive index changes of different layers. In the presence of axial strain and thermal reduction, if an external dynamic pressure is applied on a fiber, with the elapse of time, the resulting lateral pressure exerted on the fiber causes its structure to experience expansion and contraction under parametric changes of coating layers in response to dynamic changes. When the pressure has a tensile form, the microbending loss of the fiber attains negative value, which practically indicates no loss in fiber transmissions. At different time intervals, when the nature of lateral pressure changes, the effect of layers' thickness, Young's modulus, and Poisson's ratio on microbending loss, normal stress components, and the refractive index would vary. At higher angular frequency of exerting dynamic pressure on fiber, the periodicity of the microbending loss changes would be lower.

Keywords Dynamic pressure, Microbending loss, Two-Layer optical fibers

1. Introduction

Mechanical pressures and thermal loading are two main factors that can leave undesired effects on optical fibers, resulting in increase of transmission losses. To avoid such adverse conditions, communication fibers during production process, are usually coated with two to three layers of polymeric materials, in which the inner layer is of a soft material to prevent the microbending of the fiber structure and the outer one is of hard enough material to protect the fiber against severe environmental factors [1]. Both the layers have common roles of minimizing transmission losses of fibers, which mostly comprises of macro- and microbending losses [2-5]. Another major role of the fiber outer layer is to increase the mechanical strength of the produced fiber for which extensive work have earlier been reported (see e.g., [6-9]).

In published works, the microbending loss and the radial, axial, and tangential stresses due to hydrostatic pressure and thermal loading have been dealt with to determine single [10] and two-layers [11-13] polymer coated optical fibers. Similar works have been reported for calculating microbending loss by considering a third tight layer jacketed over two-layer coated fibers [14, 15]. In another report [14] it is concluded that for minimizing the microbending loss due to lateral pressure, the Poisson's ratio of primary and secondary coating, and the Young's modulus of the jacket material should be increased and that of the primary coating should be decreased. A similar conclusion is drawn in case of two-layer coated optical fibers [11]. Yet, in another work, the combined optical effects of axial strain, thermal loading on double-coated optical fibers was analyzed [16].

In our previous work, we have presented an analysis of the effect of temperature rise and hydrostatic pressure on microbending loss, refractive index change, and stress components of a double-coated optical fiber by considering coating material parameters such as Young's modulus and the Poisson ratio [17].

In this paper, we consider the dynamic nature of an exerting pressure along with a constant thermal loading applied on the fiber. For our model, we consider a two layer coated fiber, having first and second layers of soft and hard materials, respectively.

In our analysis, we determine the pressure exerted on each layers and then calculate the microbending losses developed in fiber due to dynamic pressure and thermal variations. In our next attempt, we determine the tangential, radial, and axial stresses and refractive index changes of different layers.

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2. Lateral Pressure and Layer Displacement at Boundary Interface

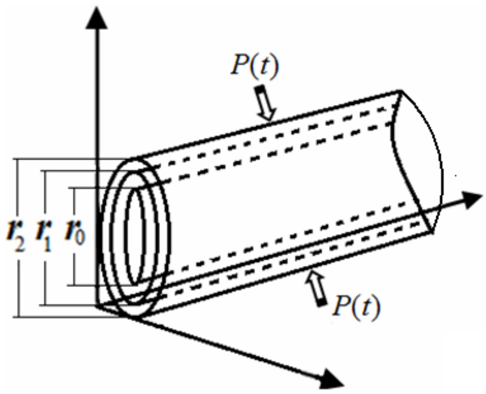


Figure 1. The fiber under dynamic pressure

Let us consider a long optical fiber of radius r_0 with primary and secondary coatings of r_1 and r_2, respectively, as shown in Fig. 1 [18-20]. Let the fiber be exposed to a dynamic pressure of $P(t)$ and an axial strain of ε_z along z-axis under a temperature reduction of ΔT. For simplicity, we further assume that the fiber and its coatings are axially symmetric in a cylindrical coordinate. The shear stress and strain are taken zero in three orthogonal directions. By ignoring theory of viscoelasticity and by considering the theory of elasticity, we can write the following expressions [20, 21]:

$$\varepsilon_r + \alpha\,\Delta T = \frac{1}{E}[\sigma_r - \nu(\sigma_\theta + \sigma_z)] \quad (1)$$

$$\varepsilon_\theta + \alpha\,\Delta T = \frac{1}{E}[\sigma_\theta - \nu(\sigma_r + \sigma_z)] \quad (2)$$

$$\varepsilon_z + \alpha\,\Delta T = \frac{1}{E}[\sigma_z - \nu(\sigma_r + \sigma_\theta)] \quad (3)$$

where σ_r, σ_θ, and σ_z are radial, tangential, and axial stresses, respectively, and ε_r, ε_θ, and ε_z represent the respective strains.

Using (2) and (3), we can write:

$$\varepsilon_\theta = \frac{u}{r} = -\alpha\,\Delta T(1+\nu) + \frac{(1-\nu^2)}{E}\left(\sigma_\theta - \frac{\nu}{(1-\nu)}\sigma_r\right) - \nu r\,\varepsilon_z \quad (4)$$

where u is the fiber or given coating displacement at radius r. The ratio u/r (or ε_θ) indicates the tangential strain.

Throughout our analysis, the values of Young's modulus (E), thermal expansion coefficient (α), and Poisson ratio (ν) are considered constant in each layer.

By using Lamé formula, σ_r and σ_θ in a cylindrical structure with inner and outer diameters of a and b, respectively, under external (P_e) and internal (P_i) pressures, are given as [22]:

$$\sigma_r = \frac{P_i a^2 - P_e b^2}{b^2 - a^2} + \frac{a^2 b^2 (P_e - P_i)}{(b^2 - a^2) r^2} \quad (5)$$

$$\sigma_\theta = \frac{P_i a^2 - P_e b^2}{b^2 - a^2} - \frac{a^2 b^2 (P_e - P_i)}{(b^2 - a^2) r^2} \quad (6)$$

By replacing (5) and (6) in (4), we obtain:

$$u = -\alpha\Delta T(1+\nu)r + \frac{(1+\nu)}{E(1-\xi^2)}[(1-2\nu)(P_i\xi^2 - P_e)r - a^2(P_e - P_i)/r] - \nu r\varepsilon_z \quad (7)$$

where $\xi(=a/b)$ is the ratio of a to b of the coating layer.

Let the displacement of fiber with respect to primary coating be denoted by u_{01} and the displacement of primary coating with respect to the fiber be shown by u_{10}. Therefore, by help of (7), we can write:

$$u_{01} = -\alpha_0\,\Delta T(1+\nu_0)r_0 - \frac{P_1(t)r_0}{E_0}(1+\nu_0)(1-2\nu_0) - \nu_0 r_0\varepsilon_z \quad (8)$$

$$u_{10} = -\alpha_1\,\Delta T\left(1+\nu_1\right)r_0 + \frac{\left(1+\nu_1\right)r_0}{E_1\left(1-\xi_1^2\right)} \times \left[\left(1-2\nu_1\right)\left(P_1(t)\xi_1^2 - P_2(t)\right) - \left(P_2(t) - P_1(t)\right)\right] - \nu_1 r_0\,\varepsilon_z \quad (9)$$

In (8) and (9), $P_1(t)$ is the lateral dynamic pressure exerted on the primary coating layer and $P_2(t)$ is the lateral pressure between the primary and the secondary coating layers, and $\xi_1 = r_0/r_1$.

The radial displacement of the primary coating layer at the interface with the secondary coating layer u_{12} and the corresponding parameter for the secondary coating layer with respect to the primary coating layer u_{21} are given, respectively, as:

$$u_{12} = -\alpha_1 \Delta T(1+v_1)r_1 + \frac{(1+v_1)r_1}{E_1(1-\xi_1^2)} \times \left[(1-2v_1)\left(P_1(t)\xi_1^2 - P_2(t)\right) - \xi_1^2\left(P_2(t)-P_1(t)\right)\right] - v_1 r_1 \varepsilon_z \quad (10)$$

$$u_{21} = -\alpha_2 \Delta T(1+v_2)r_1 + \frac{(1+v_2)r_1}{E_2(1-\xi_2^2)} \times \left[(1-2v_2)\left(P_2(t)\xi_2^2 - P(t)\right) - \left(P(t)-P_2(t)\right)\right] - v_2 r_1 \varepsilon_z \quad (11)$$

At the boundary interfaces, the coating layers displacements are equal, therefore, by equating u_{01} and u_{10} at $r = r_0$, and u_{12} and u_{21} at $r_1 = r_2$, the lateral pressure exerted on the fiber can be obtained in terms of temperature variations, dynamic pressure, and axial strain as [18]:

$$P_1 = \frac{1}{N_1}[\lambda_1 P - M_1 \Delta T - Q_1 \varepsilon_Z] \quad (12)$$

The quantities in (12) are defined and listed in Table 1. Similarly, the pressure exerted on the primary coating layer at the interface with the secondary coating layer is obtained as:

$$P_2 = \frac{1}{\lambda_0}[A_0 \Delta T + B_0 P_1 - G_0 \varepsilon_z] \quad (13)$$

The expressions (12) and (13) show that the lateral pressure is proportional to temperature variation, dynamic pressure, and radial strain and through their coefficients, related to the time, layer thickness, Young's modulus, thermal expansion coefficient, and Poisson's ratio.

Table 1. Definition of parameters in expressions (12) and (13)

$N_1 = \frac{B_0 B_1}{\lambda_0} - C_1$ | $M_1 = A_1 + \frac{B_1}{\lambda_0} A_0$	$C_1 = 2\frac{(1-v_1^2)r_1\xi_1^2}{E_1(1-\xi_1^2)}$
$A_0 = \alpha_0(1+v_0)r_0 - \alpha_1(1+v_1)r_0$	$G_0 = v_1 - v_0$; $G_1 = v_2 - v_1$
$B_0 = \frac{r_0}{E_0}(1+v_0)(1-2v_0) + \frac{(1+v_1)(1-2v_1)r_0\xi_1^2}{E_1(1-\xi_1^2)} + \frac{(1+v_1)r_0}{E_1(1-\xi_1^2)}$	$\lambda_0 = \frac{2(1-v_1^2)}{E_1(1-\xi_1^2)} r_0$
$A_1 = \alpha_1(1+v_1)r_1 - \alpha_2(1+v_2)r_1$	$\lambda_1 = \frac{2(1-v_2^2)}{E_2(1-\xi_2^2)} r_1$
$B_1 = \frac{[(1+v_1)(1-2v_1)+(1+v_1)\xi_1^2]r_1}{E_1(1-\xi_1^2)} + \frac{[(1+v_2)(1-2v_2)\xi_2^2+(1+v_2)]r_1}{E_2(1-\xi_2^2)}$	

3. Periodic Dynamic Pressure

To examine the dynamic pressure, thermal loading, and the axial strain on the fiber attenuation, let us consider a pressure having a sinusoidal variation exerted on the fiber given as [18]:

$$P(t) = A_0 \sin(\omega t) \quad (14)$$

where A_0 and ω are the pressure amplitude and the angular frequency, respectively, and t represents the time factor.

Table 2. Geometrical and physical specifications of the fiber and coating materials

Fiber/layers	Parameters			
	Radius (μm)	Young's modulus (MPa)	Thermal expansion coeff. (α), (J/°C)	Poisson ratio
Fiber	125	72,500	5.6×10^{-7}	0.35
1st layer	200	1	0.25×10^{-3}	0.36
2nd layer	250	1,200	1.7×10^{-4}	0.37

4. Microbending Losses

Experimentally, it was shown that the microbending losses and the exerting pressure are related as [18, 23-26]:

$$\Gamma = kP_1(t) \tag{15}$$

where k is a constant equal to 0.0029 (dB/km)/MPa.

5. Stress Components

The lateral pressures exerted on the coating boundaries, create orthogonal stresses within the coating layers. The radial and tangential stresses are obtained by (5) and (6) and the axial stress is given as:

$$\sigma_Z = E\alpha\Delta T + v(\sigma_r + \sigma_\theta) \tag{16}$$

With reference to the definitions of orthogonal stresses, we may calculate the stresses within the coating layers as follows:

$$\sigma_r = \sigma_\theta = -P_1 \qquad r \le r_0 \tag{17}$$

$$\sigma_Z = E_0\alpha_0\Delta T - 2v_0P_1 \qquad r \le r_0 \tag{18}$$

$$\sigma_r = \frac{P_1 r_0^2 - P_2 r_1^2}{r_1^2 - r_0^2} + \frac{r_0^2 r_1^2 (P_2 - P_1)}{(r_1^2 - r_0^2) r^2} \qquad r_0 \le r \le r_1 \tag{19}$$

$$\sigma_\theta = \frac{P_1 r_0^2 - P_2 r_1^2}{r_1^2 - r_0^2} - \frac{r_0^2 r_1^2 (P_2 - P_1)}{(r_1^2 - r_0^2) r^2} \qquad r_0 \le r \le r_1 \tag{20}$$

$$\sigma_z = E_1\alpha_1\Delta T + \frac{2v_1(P_1r_0^2 - P_2r_1^2)}{r_1^2 - r_0^2} \qquad r_0 \le r \le r_1 \tag{21}$$

$$\sigma_r = \frac{P_2 r_1^2 - P r_2^2}{r_2^2 - r_1^2} + \frac{r_2^2 r_1^2 (P - P_2)}{(r_2^2 - r_1^2) r^2} \qquad r_1 \le r \le r_2 \tag{22}$$

$$\sigma_\theta = \frac{P_2 r_1^2 - P r_2^2}{r_2^2 - r_1^2} - \frac{r_2^2 r_1^2 (P - P_2)}{(r_2^2 - r_1^2) r^2} \qquad r_1 \le r \le r_2 \tag{23}$$

$$\sigma_z = E_2\alpha_2\Delta T + \frac{2v_2(P_2r_1^2 - \mathrm{P}r_2^2)}{r_2^2 - r_1^2} \qquad r_1 \le r \le r_2 \tag{24}$$

6. Refractive Index Variations

The lateral pressure exerted on the interface of the fiber and the first coating layer causes a change of fiber geometry and thus results in incremental orthogonal variations of refractive index of the cross section along the fiber. The refractive index variations dependence on the axial, tangential, and radial stresses are, respectively, given as follows [19-21]:

$$\Delta n_r = n_r - n = -B_2\sigma_r - B_1(\sigma_\theta + \sigma_Z) \tag{25}$$

$$\Delta n_\theta = n_\theta - n = -B_2\sigma_\theta - B_1(\sigma_r + \sigma_Z) \tag{26}$$

$$\Delta n_Z = n_Z - n = -B_2\sigma_Z - B_1(\sigma_r + \sigma_\theta) \tag{27}$$

where n is the refractive index of fiber before any pressure and thermal loading are applied, and n_r, n_θ, and n_Z are the corresponding indices changes along orthogonal directions. $B_1(= 4.2\times10^{-6}\,/\,\text{MPa})$ and $B_2(= 6.5\times10^{-7}\,/\,\text{MPa})$ are the stress-optical constants for ordinary and extraordinary rays, respectively.

7. Numerical Calculations

The effects of the sinusoidal variations of the exerting pressure on two-layer fiber was examined by using the specifications given in Table 2 with dynamic pressure amplitude of 2×10^6 Pa and axial strain of 1×10^{-4}. In Fig. 2, the microbending loss is plotted with respect to time for the angular frequency changes of 2, 20, 200, and 2000 rad/s.

For the given dynamic pressure, when the applied angular frequency increases, the loss variations are detected at smaller time intervals. At the negative swing of the applied pressures, the corresponding loss becomes negative, which indicates that the applied pressure on fiber attains tensile nature and thus effectively no loss is developed to cause propagation attenuations.

To investigate the effects of coating layer thickness on the microbending loss, we have considered a periodic dynamic pressure with an angular frequency of 2 rad/s, taking time as the parameter. In Fig. 3 the loss variations are plotted with respect to the layers thickness r_1 and r_2. The pressure amplitude is taken as 2×10^6 Pa and the radial strain as 1×10^{-4}.

In different times, it is expected that the microbending loss would follow the pressure variations with a periodic changes. At $t = 0$ s, when the dynamic pressure is non-existent, one order of magnitude decrease is observed in fiber loss. The losses decrease with increase of first layer thickness at calculated times except at $t = 2$ s, at which the loss increases towards more positive value. At this time, the pressure amplitude is within its negative excursion, causing a tensile lateral pressure on fiber, as shown in Fig 2.

In Fig. 3, the effect of second layer thickness on the loss is plotted under the same condition as that of Fig. 2. In the case of no-pressure condition, i.e., at $t = 0$ s, an increase in second layer thickness causes loss increase, opposite to the case in Fig. 2. At other times, qualitatively, the nature of loss variation is the same as in Fig. 2. In both the cases in Figs 2 and 3, the first and second layers can not act effectively to reduce the compressive dynamic pressure being exerted on fiber.

Based on expression (15), in Fig. 4, the fiber loss is plotted versus Young modulus variations of first layer at different times with the same values of dynamic pressure and axial strain. This set of curves show that an increase of Young's modulus of soft layer up to $t = 1.5$ s, the fiber loss increases. Even when no dynamic pressure is exerted on fiber, the loss increase is observed. At $t = 2$ s, the loss attains negative values and decreases with increase of Young's modulus of the first layer.

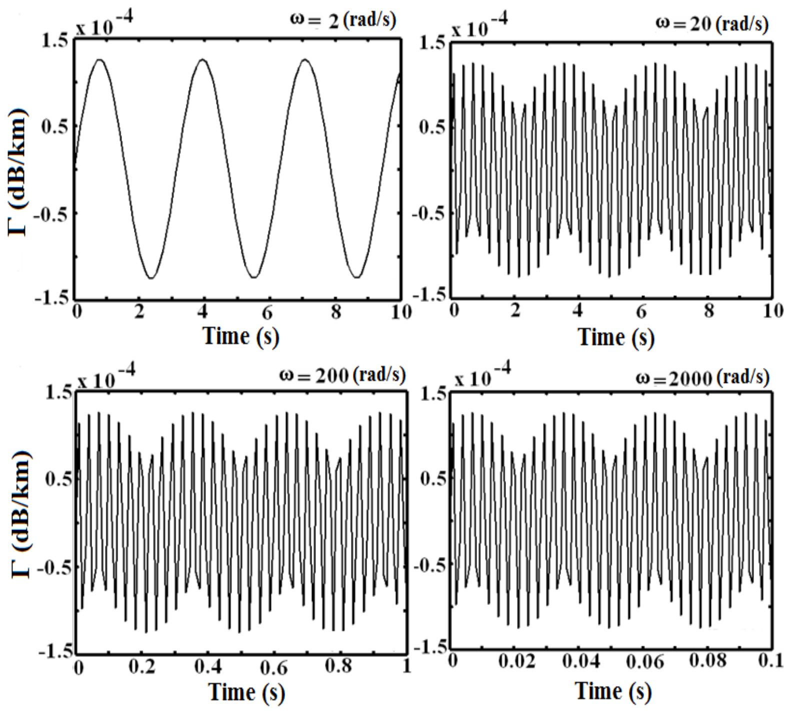
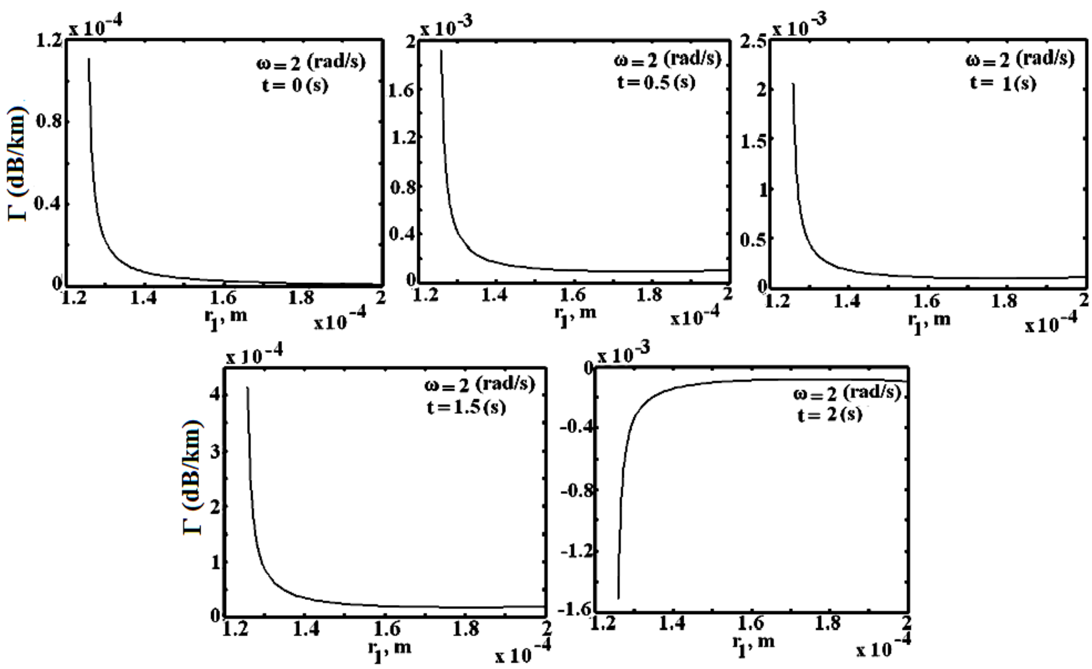


Figure 2. Effects of dynamic pressure on the microbending loss vs. time at different angular frequencies



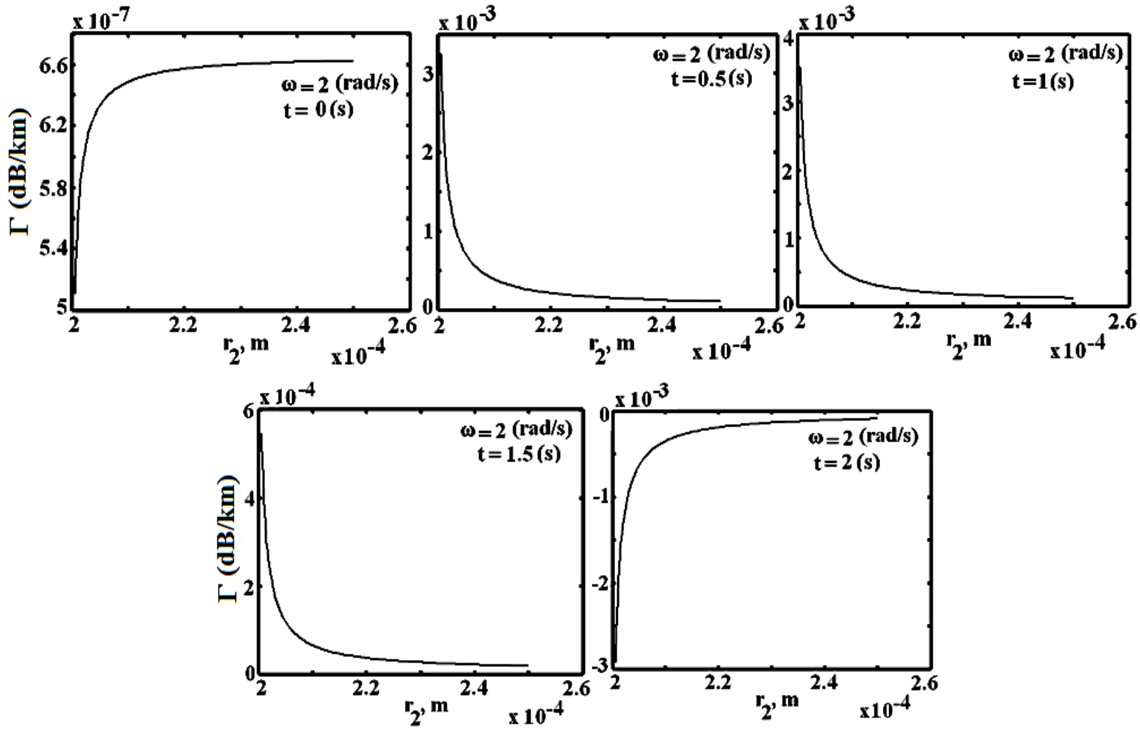


Figure 3. Effects of primary r_1 and secondary r_2 layers thickness on the microbending loss

The Young's modulus variations of the second layer have different effects on fiber loss under the same dynamic pressure and axial strain conditions as compared with the first layer, as shown in Fig. 4. At different times of 0.5 s, 1.0 s, and 1.5 s, the loss reduces against an increase of the Young's modulus. At $t=0$ s, when the dynamic pressure is not applied, a loss increase develops in fiber which is due to axial strain and temperature drops. The positive loss at this time is the result of a net compressive pressure on the fiber. At $t=2$ s, the tensile pressure on the fiber increases, resulting in negative loss increase.

With relation to expression (15), in Fig. 5, the effects of Poisson ratios of the first and second layers on fiber loss are, respectively, shown with dynamic pressure amplitude of 2×10^6 Pa at angular frequency of 2 rad/s and strain: of 1×10^{-4}. At $t=0$ and 2 s, an increase of Poisson ratio of the first layer causes reduction in the fiber loss whereas that of the second layer makes the fiber loss to decrease. At other calculation times, the loss variations reverse as compared with first two time intervals.

In the presence of dynamic pressure, how the layers thicknesses affect on normal stress components are depicted in Fig. 6 at different times. At times other than $t=0$ s, the normal stress components are negative within the two layers. Within these time intervals, the radial stress increases and tangential stress decreases with increase of layer thickness. On the contrary, at $t=2$ s, the variations of the radial and tangential stresses reverse. The axial stress within the layers remains constant in all the calculation time intervals.

With a close examination of the curves in Fig. 7, we find that by increasing the layers thicknesses for $t<2$ s, the refractive index changes attain decreasing positive values in both the layers, whereas at $t=2$ s, the values become increasingly negative along three directions. In the both cases, the fiber gets compressed and expanded, respectively, under influence of external factors.

In Figs. 8 and 9, the effects of the Young's modulus and Poisson ratios of the layers on refractive index components are depicted for different times in presence of dynamic pressure and axial strain of the same values. At time 0.5 s, 1 s, and 1.5 s, increase of the Young's modulus and Poisson ratios of the first layer, cause to increase the normal components of refractive indices. The amount of refractive index change at zero time for every increase in the Young's modulus of the first layer, in comparison with other time conditions, is negligible. At $t=0$ s, the refractive indices changes reduce with negative values with respect to the parametric changes in the first layer, resulting in a stretch of the fiber. In the second layer, the condition reverses.

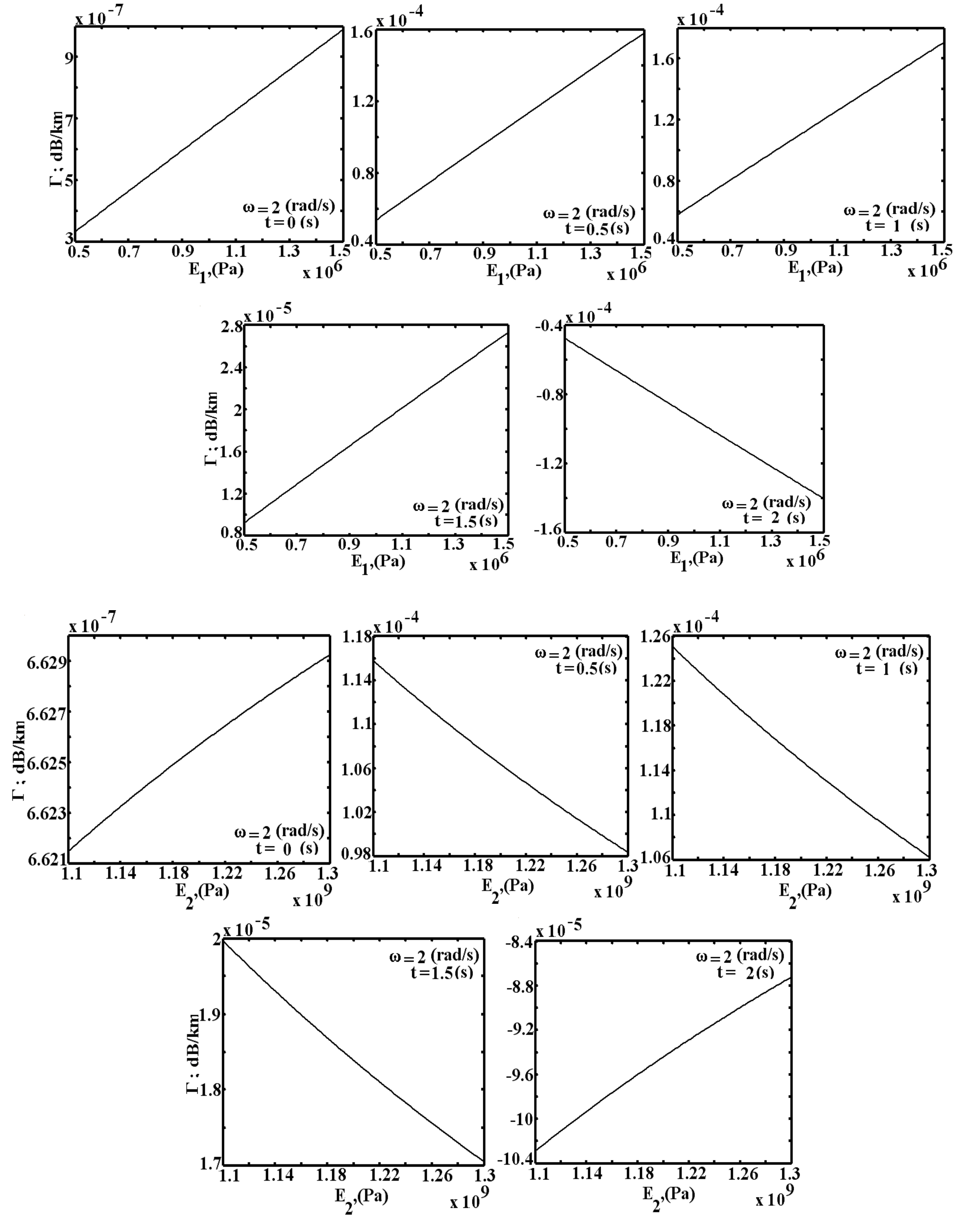


Figure 4. The effects of Young's modulus of layers on microbending loss

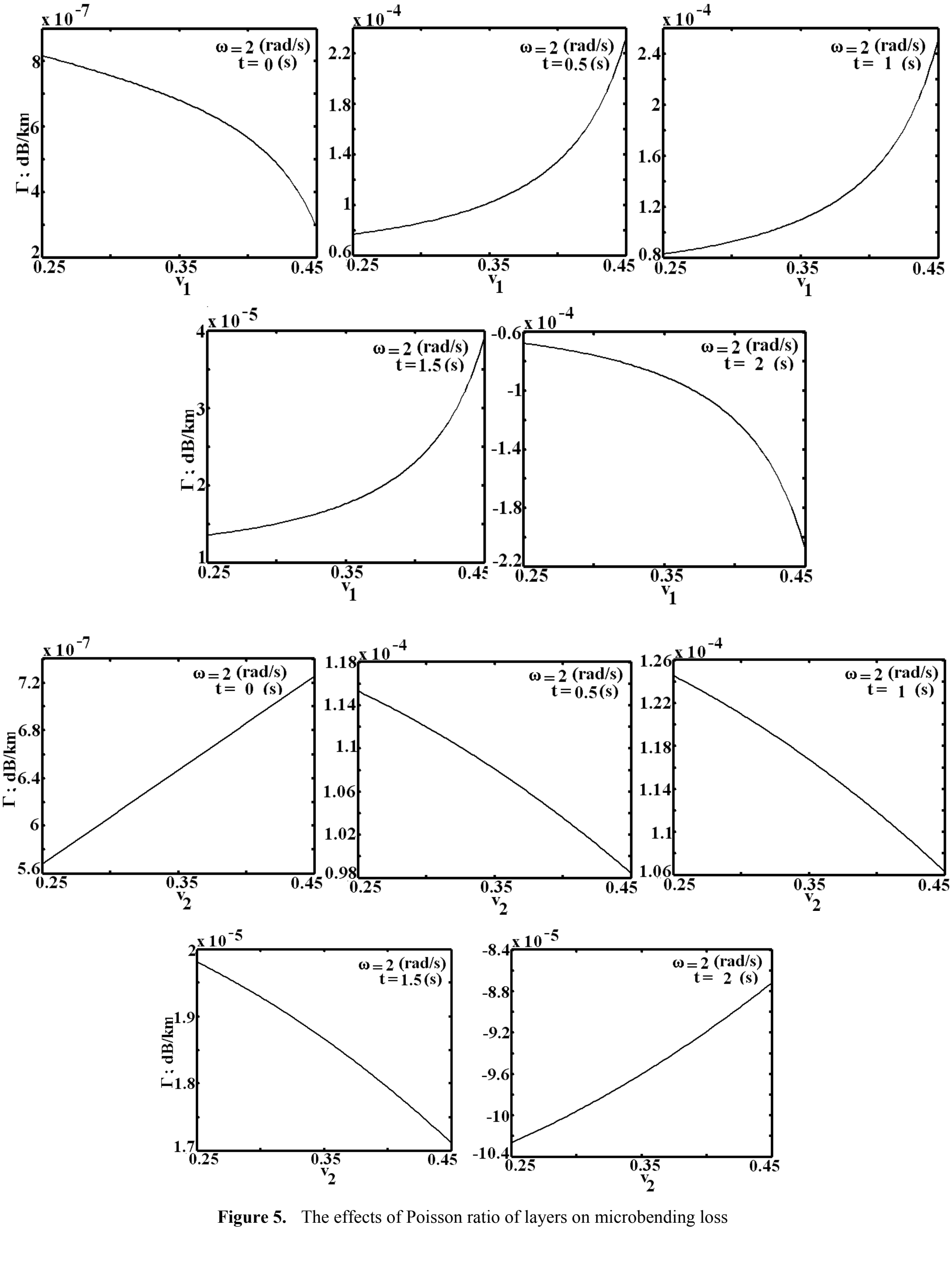


Figure 5. The effects of Poisson ratio of layers on microbending loss

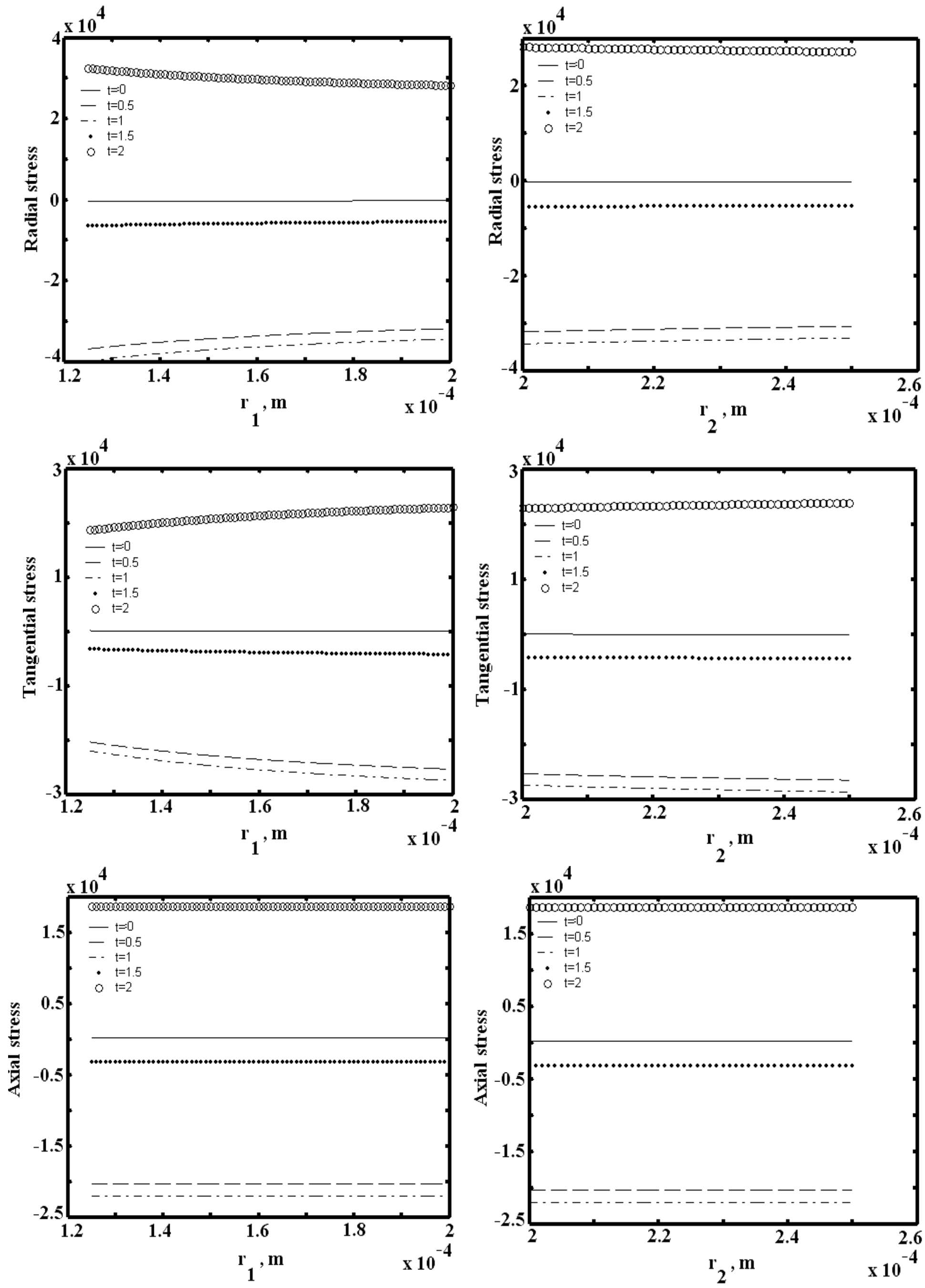


Figure 6. The effects of layers thicknesses on normal stresses at different times

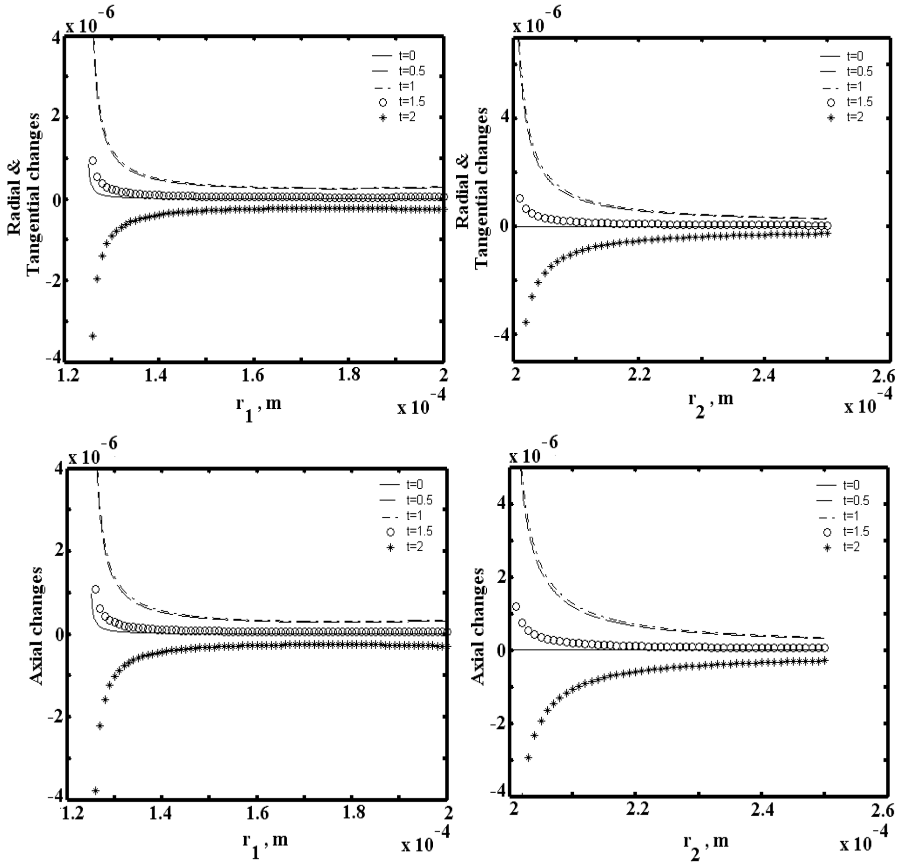


Figure 7. The effects of layers thicknesses on refractive index changes at different times

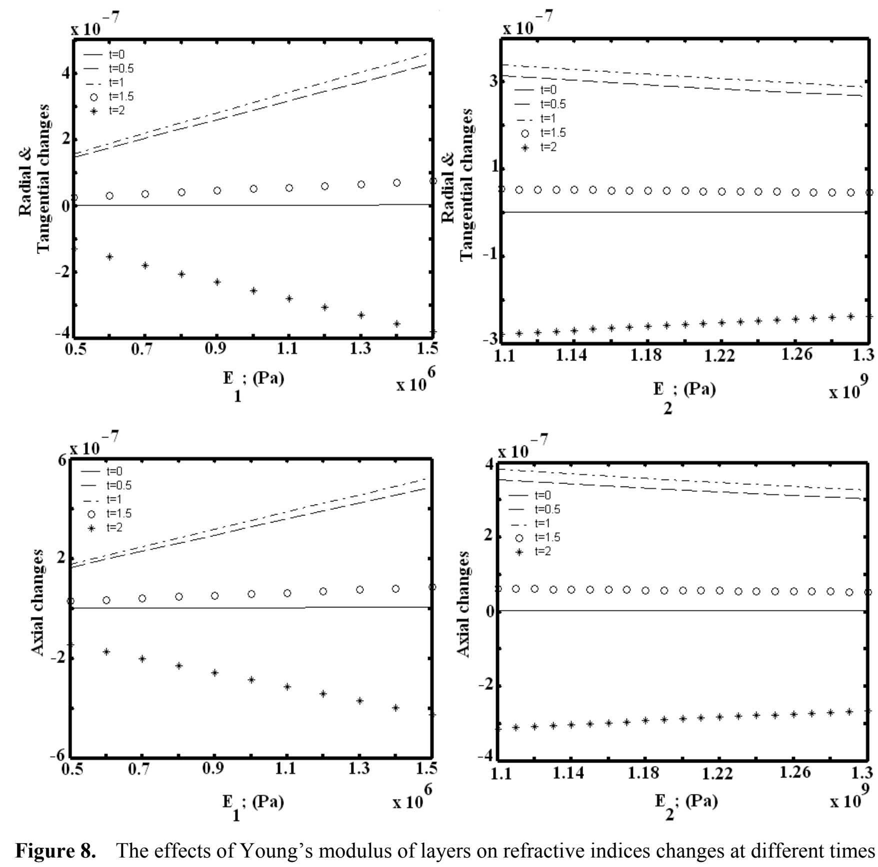


Figure 8. The effects of Young's modulus of layers on refractive indices changes at different times

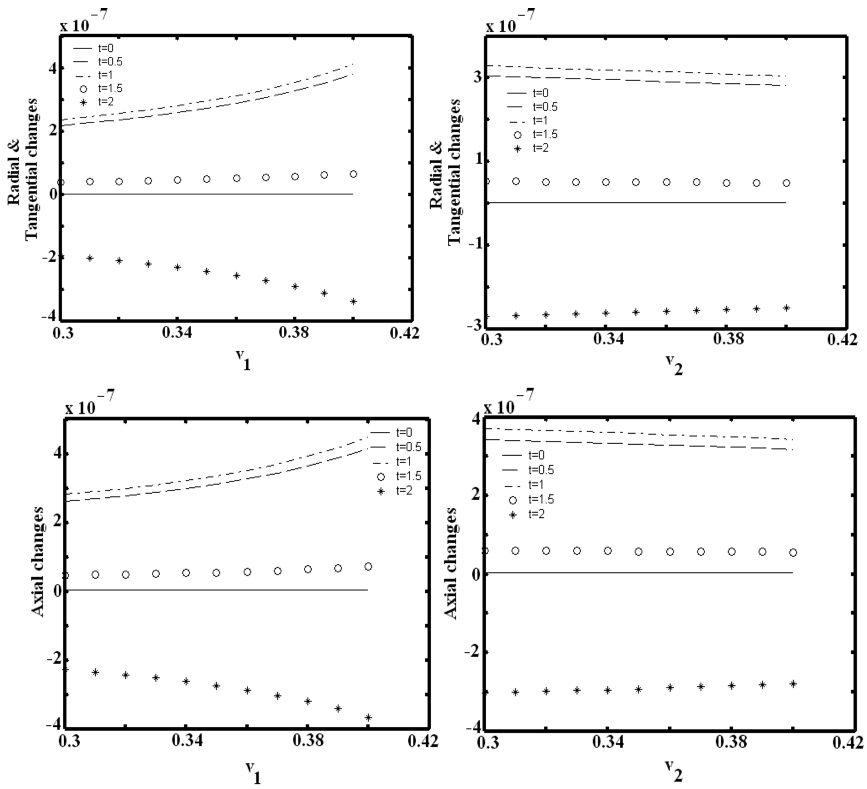


Figure 9. The effects of Poisson ratio of layers on refractive indices changes at different times

8. Conclusions

We have analyzed the effects of dynamic pressure, temperature reduction, and axial strain on index variations of two-layer optical fibers and microbending loss.

In the presence of axial strain and thermal reduction, if an external dynamic pressure is applied on a fiber, with the elapse of time, the resulting lateral pressure exerted on the fiber causes its structure to experience expansion and contraction under parametric changes of coating layers in response to dynamic changes. When the pressure has a tensile form, the microbending loss of the fiber attains negative value, which practically indicates no loss in fiber transmissions.

The effects of parameters such as Young's modulus, Poisson's ratio, and thickness of the layers on microbending loss, normal stress components, and the refractive index are functions of time. At different time intervals, when the nature of lateral pressure changes, the effect of thickness, Young's modulus, and Poisson's ratio on microbending loss, normal stress components, and the refractive index would vary, accordingly, unlike in case of hydrostatic pressure, where the effects of the parameters remain constant. The more the angular frequency of exerting dynamic pressure on fiber, lesser the changing periodicity of the microbending loss.

The results obtained in this analysis may be utilized in under-sea optical fiber transmission links, where dynamic pressures due to presence of water waves may exist.

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