Measurement of Elasto-optic coefficient of SMF Using the Method of Periodic Circular birefringence

Abstract

Two mechanically induced long period fiber gratings are formed over a single mode fiber both under a constant pressure. The effect of twisting the fiber on one of the gratings is investigated. The spectra recorded at untwisted condition or at low twist rates contain two notches at $\lambda_1$ and $\lambda_2$ corresponding to the coupling of $LP_{11}$ and $LP_{12}$ cladding modes with core mode $LP_{01}$. When twist rate is increased, two new resonance notches appear at shorter wavelength side at $\lambda_1'$ and $\lambda_2'$, in addition to the original notches formed earlier. The observed shift in resonant wavelength towards shorter wavelength can be attributed to the induced circular birefringence in the cladding of the fiber due to the twist introduced. With in the limit of experimental errors this method allows to evaluate the elasto-optic constant ($g$ parameter) for various telecommunication fibers. Thus a novel, simple and direct method for determination of the elasto-optic constant for fibers is proposed.

5.1 Introduction

A perfectly circular optical fiber with a rotationally symmetric index profile will be non-birefringent, if it is free from mechanical and electrical perturbations. The presence of external perturbations such as stress, bend and twist in the fiber may induce linear, elliptical and circular birefringence in it [1]. Therefore the polarization
properties of single mode optical fibers used for telecommunication and sensor applications [2] become sensitive to any of these mechanical perturbations. In long distance high bit rate optical communication, polarization mode dispersion (PMD) in fiber is one of the parameters that degrade the system performance. External unwanted twist in the fiber may lead to circular birefringence and change in PMD. Therefore the dependence of the circular birefringence on wavelength is detrimental to system performance [3] and quantification and characterization of circular birefringence is of great importance in the development of more efficient high bit rate communication systems. The experimental measurement of elasto-optic coefficient $g$ of SM fibers is carried out by Smith [4] by measuring optical activity using output polarization rotation. The value obtained for $g$ in this method is less than the theoretically predicted value obtained by Ulrich [1]. Bertholds and Dandliker [5] have measured the individual strain optic coefficients interferometrically, utilizing the phase change of light induced by static longitudinal strain. Recently, Chartier et.al [6] has designed a method for measuring $g$ of SM fibers using magneto optic techniques. However all these methods involve experimental and mathematical complexity. In this chapter, a novel and simple method is proposed to analyze directly the evolution of circular birefringence with the externally applied twist, using periodic micro bends induced over a twisted fiber. From the observed results the elasto-optic coefficient of the fiber, the threshold twist rate required to change the effective core mode indices in mode coupling and the cut off twist rate at which the LP_{11} mode disappears are deduced.
5.2 Theory.

When a fiber is twisted, birefringence will be induced in it and consequently its polarization properties change [2], leading to elliptical and circular polarization states. For very small twist rates, a linearly birefringent fiber will become elliptically birefringent and at higher twist rates, the circular birefringence dominates over the other birefringences [1]. The resonant wavelength \( \lambda_{\text{res}}^m \) corresponding to the \( m^{\text{th}} \) cladding mode of a mechanically induced long period fiber grating is given by the following equation.

\[
\lambda_{\text{res}}^m = (n_{\text{co(\text{eff})}} - n_{\text{cl(\text{eff})}}^m) \Lambda
\]

(5.1)

where \( n_{\text{co(\text{eff})}} \) and \( n_{\text{cl(\text{eff})}}^m \) are the effective refractive indices of the core and \( m^{\text{th}} \) cladding mode and \( \Lambda \) the periodicity of the grating. When the fiber is twisted, the induced circular birefringence will modify the phase matching condition of resonance. Therefore the equation (5.1) can be modified as

\[
\frac{d \lambda_{\text{res}}^m}{d \phi} = \Lambda \left( \frac{dn_{\text{eff core}}}{d \phi} - \frac{dn_{\text{eff cl ad}}(m)}{d \phi} \right)
\]

(5.2)

The effective index changes in both core and cladding modes resulting from the photo-elasticity of a single mode fiber are sensitive to the applied shearing stress. The shearing stress under torsion is proportional to the radius of the fiber and to the applied twist rate. For a twisted single mode fiber, the shearing stress will be much
larger in its cladding compared to that in the core [7, 8]. The twist induced change in
effective core index and its contribution to the wavelength shift in cladding mode
resonances of an in-fiber grating is very small when the twist rate is not very high.
This result is found to be true even in photo-induced long period gratings [9]. Thus,
by neglecting the change in effective core index when compared to that of the
cladding, equation (5.2) can be approximated as,
\[ \frac{d\lambda_{\text{res}}}{d\phi} = -\Lambda \left( \frac{dn_{\text{c}(\text{eff})}^{m}}{d\phi} \right) \]  \hspace{1cm} (5.3)
This indicates that, the birefringence effect will be mainly in the cladding. The
studies of resonant behavior of microbend LPFG over a twisted fiber (Chapter 4)
show that the induced birefringence is equal and uniform for the coupled modes [8].
Therefore the effective index change [1] \( \delta n \) with respect to the twist rates can be
approximated as
\[ dn \approx dn_{\text{c}(\text{eff})}^{m} \approx (g\phi) \frac{\lambda_{0}}{2\pi} \]  \hspace{1cm} (5.4)
where \( \phi \) is the twist rate in radians/meter, \( \lambda_{0} \) is the resonant wavelength
corresponding to a twist-free fiber and \( g \) the elasto-optic coefficient. The elasto-optic
coefficient is defined as optical activity per unit twist rate and is given by
\[ g = \left( \frac{n^2}{2} \right) (P_{11} - P_{12}) = -n^2 P_{44} \]  \hspace{1cm} (5.5)
where \( n \) is the refractive index of the region under consideration, \( P_{11} \) and \( P_{12} \) are
the strain optic coefficients. For silica, the standard values of \( P_{11} \) and \( P_{12} \) are
0.121 and 0.27 respectively. The slope ‘m’ of the cladding index change Vs twist rate curve is a direct measure of ‘g’ parameter as

\[ g = \frac{d(\delta n)}{d\phi} \times \frac{1}{\lambda_0} \]

(5.6)

**5.3 Experimental**

The experimental setup for the measurement of the elasto-optic coefficient of SM fiber is as given in figure 4.2. Grooves of depth 200 μm and periodicity 0.7 mm are carved on aluminum plate of 5 cm long and 0.5 cm wide with an accuracy of ±5 μm. Two such plates are placed at a centre to centre distance of 60 cm and a standard single mode fiber (G652) having 9 μm core and 125 μm cladding, with the protective coating is positioned above these grooved plates. Two un-grooved plates (deformer plates) of same dimension are placed over the grooved plates such that the fiber is pressed between the plates. Mechanically induced long period fiber gratings (MLPFG) are thus formed by pressing plates by using indigenously developed well-guided loading systems. The twist is applied in the fiber at the first MLPFG section (G₁ section) using a rotator with a marker, to read the number of turns whereas the fiber in the second MLPFG section (G₂ section) is kept without any twist by fixing the fiber between the grating as shown in the figure1. The system is designed in such a way that any twist rate (turns/cm) could be applied by lifting the deformer plate up,
twisting the fiber, bringing the plate down and suitably applying a constant pressure (11 N/cm) over the deformer plate. MLPFG is thus formed for different twists and the resonance spectra due to the coupling of core and co-propagating cladding modes are recorded at constant pressure on both $G_1$ and $G_2$ sections. An unpolarized optical broadband source is used for launching the optical signals along the fiber and the transmission spectra are measured in the range from 600 nm to 1750 nm using an
Optical Spectrum Analyzer (OSA) (Anritsu-MS9710C). The experiment is repeated for different twist rates. The effect of twisting the fiber in clockwise and anticlockwise direction is also investigated.

5.4 Results and Discussion:

The transmission spectra recorded for different twist rates on first MLPFG by keeping equal pressures (11 N/cm) on both the gratings are shown in figure 5.3. This is same as the one given in figure 4.8. The spectra recorded at zero twist condition or at low twist rates contain two notches at \( \lambda_1 \) and \( \lambda_2 \) corresponding to the coupling of LP_{11} and LP_{12} cladding modes with core mode LP_{01}. When twist rate is increased, two new resonance notches \( \lambda'_1 \) and \( \lambda'_2 \) appear at shorter wavelength side of \( \lambda_1 \) and \( \lambda_2 \) respectively. Application and release of pressures alternatively in both gratings, G_1 and G_2 confirm that the new resonances \( \lambda'_1 \) and \( \lambda'_2 \) are due to the induced polarization birefringence at the twisted fiber section [8]. As stated earlier, shearing stress and photo elasticity cause the fiber to be circularly birefringent in the twisted region G_1. This causes the changes in \( n_{eff\text{core}} \) and \( n_{eff\text{clad}(m)} \). As the changes in cladding mode indices are more than that in core mode indices [7, 8], the observed shift in resonant wavelength can be attributed to the induced circular birefringence in the cladding of the fiber due to the twist introduced.
Fig 5.1 The variation of cladding mode index change Vs Twist rate (for Fiber #1)

As stated in chapter 4, two new notches at $\lambda_1'$ and $\lambda_2'$ shift to the shorter wavelength side with the increase of applied twist while those at $\lambda_1$ and $\lambda_2$ remains
at the original position. It is also observed that the introduction of a twist before or after the grating fiber sections will not result in noticeable shift in resonances. The shift in resonances is observed only when the grating is formed in the twisted fiber section. The resonant amplitude is found to decrease linearly with the applied twists. The coupling between the core mode and the cladding modes decreases resulting in the decrease of resonant peak amplitudes with the applied twist. Increase in width of resonances with twist rate is similar to that observed in photo induced LPFGs [9]. Twist rates applied in clockwise and anti-clock wise directions do not show any difference in the transmission spectra.

To determine the elasto-optic constant $g$, cladding index change $\delta n$ is calculated from the resonant wavelength shift $\delta \lambda_{res}^m$ for different twist rates using equation (5.3),

$$\delta n_{cl(m)} = \frac{\delta \lambda_{res}^m}{\Lambda}$$

$\Lambda$ being the periodicity of the micro-bend. The calculated value of $\delta n$ is tabulated in Table 5.1. A graph is plotted between the cladding index change $\delta n$ and twist rate $\phi$ for the modes LP$_{11}$ and LP$_{12}$ of the two G652 fibers as in figures 5.2 and 5.3. Since the induced circular birefringence $\delta n$ is linear as per equation (4), the slope $\frac{d(\delta n)}{d\phi}$ is the direct measure of the elasto-optic coefficient $g$ of the fiber. This is evaluated by fitting the plot linearly as given in figures 5.2 and 5.3. Beyond the linear portion of the graph the effective index of the core begins to modify the mode coupling for higher twist rates (Section 5.2). Therefore the slope is calculated only up to 0.38 turns/cm for the LP$_{12}$ mode and up to 0.5 turns/cm for LP$_{11}$ mode. At longer
wavelength, corresponding to the LP$_{12}$ mode the core mode profiles are distributed away from the core[10] and are easily affected by relatively low values of twist rates and therefore the resonant shift of LP$_{12}$ mode (that couples to the co-propagating core mode LP$_{01}$ at longer wavelength) is affected much earlier than that of the LP$_{11}$ mode. From the observed results, it can be inferred that the maximum twist rates required to get effective coupling of core mode indices to the cladding mode indices LP$_{11}$ and LP$_{12}$ lie in the range of 0.34 to 0.56 turns/cm for different types of G652 fibers. Also, there is a cut off twist rate for the LP$_{11}$ mode and it is found to be around 0.6 turns/cm at which the resonant notch $\lambda'_r$ disappears. From the experimental data of two different G652 fibers the elasto-optic constant is evaluated and is given in Table 5.2.

The elasto-optic coefficient $g$ is found to be 0.165 and 0.176 for LP$_{11}$ and LP$_{12}$ modes in the case of Fiber I and 0.170 and 0.173 respectively for the Fiber II. The obtained values of $g$ are comparable with the theoretically suggested value of 0.16 by Ulrich [1]. The experimental values of $g$ for silica SM fibers reported by Ulrich, Smith and Barlow are 0.13 [1], 0.138 [4] and 0.146 [11] respectively. These measurements are taken for $\lambda = 633$ nm. It is interesting to see that the value of $g$ for fibers are 7-18 percent lower than the expected value for bulk silica [12] which is between 0.16 and 0.17. These differences can be explained by the presence of dopants (Ge, B) in the core and in the cladding of the fiber which modify the photoelastic properties of the fiber material. This is pointed out to be the reason for getting lower values for $g$ [12]. Furthermore the effective value of $g$ may also depend on the refractive index profile of the fiber which, for a given wavelength, determines the
The wavelength dependence of $p_{44}$ has been investigated by Bertholds et al. [5]. They evaluated the optical activity per unit twist $g = -n^2 p_{44}$ for different wavelengths. The wavelength dependence $\frac{dg}{d\lambda}$ for silica fiber at 633 nm is thus obtained as 0.013 $\mu m^{-1}$. Thus, the value of elasto-optic coefficient $g$ increases by 0.013 for every micrometer. The range of optical wavelength used in the present study is in the range of 1480 nm $\sim$ 1650 nm and therefore the values for $g$ is obtained to be nearly 0.16. The comparable values of $g$ determined in the present study for the fiber from the resonant shift of the two cladding modes LP$_{11}$ and LP$_{12}$ confirm that the circular birefringence induced by the twist is equal and uniform for the modes.

<table>
<thead>
<tr>
<th>Results</th>
<th>Fiber1</th>
<th>Fiber2</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Slope of $\Delta n - \phi$ graph (Linear Fitting)</td>
<td>2.611</td>
<td>2.88</td>
</tr>
<tr>
<td>Elasto-optic coefficient</td>
<td>0.165</td>
<td>0.176</td>
</tr>
<tr>
<td>Cut off-twist rate (turns/cm)</td>
<td>0.62</td>
<td>-</td>
</tr>
<tr>
<td>Twist rate at which the core index change affects the mode coupling (turns/cm)</td>
<td>0.50</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Table 5.2. The elasto-optic coefficients determined from $\Delta n - \phi$ graph.

5.5 Conclusion.

The spectra recorded at untwisted condition or at low twist rates contain two notches at $\lambda_1$ and $\lambda_2$ corresponding to the coupling of LP$_{11}$ and LP$_{12}$ cladding.
modes with core mode LP$_{01}$. When twist rate is increased, two new resonance notches appear at shorter wavelength side at $\lambda'_1$ and $\lambda'_2$, in addition to the original notches formed earlier. The observed shift in resonant wavelength towards shorter wavelength can be attributed to the induced circular birefringence in the cladding of the fiber due to the twist introduced. Using these results a novel method is proposed for measuring elasto-optic coefficient of SM fibers using a mechanically induced long period grating, over a twisted fiber. This method is simple and direct compared to other techniques. The slope of the cladding index change vs. twist rate graph is a measure of the elasto-optic coefficient by assuming that the cladding index change is due to the circular birefringence. The mode coupling is also affected by the twist-induced changes in core mode indices for larger twist rates. The value of $g$ is consistent for clockwise and anti clockwise twist directions. The values of $g$ for LP$_{11}$ and LP$_{12}$ modes are comparable to the values reported earlier by taking into account the fact that the present studies are for $\lambda$ in 1480 - 1650 nm range.
Fig. 5.3. Comparison of spectral response of the two MLPFG sections
References


