Fiber Modal Index Measurements Based on Fiber Gratings

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A novel method based on fiber gratings for measuring the effective indices of fiber modes is proposed. The effective index difference between the core mode and a cladding mode was obtained by analyzing the interference fringe of a pair of cascaded long-period fiber gratings. In order to extract the core mode index from the measured index difference, an index matching oil immersion method is proposed. By analyzing the interaction between the cladding mode and the oil applied on the cladding surface, the mode order and the effective index of the involved cladding mode might be calculated. Experimental results about the interference fringe shifts induced by the oil index and the oil-applied length are also presented.

Keywords fiber gratings, long-period fiber gratings, cascaded fiber gratings, dispersion measurements, cladding mode, optical fiber, grating pair

The core mode dispersion of an optical fiber restricts the bandwidth of a long-haul fiber optic telecommunication systems. The dispersion of the fiber has been usually measured by measuring the time delay of an optical pulse travelling along the fiber as a function of optical wavelength [1]. Recently, several interferometric techniques using short fibers, have been proposed [2,3,4]. In this study, we propose a novel method for measuring the core mode dispersion of fiber by using the interference phenomenon of a pair of cascaded long-period fiber gratings (LPGs). It was reported that the core mode spectrum of a LPG pair had a series of interference fringes in each stop band of a single grating’s spectrum [5,6,7]. The formation of the interference fringe was explained as the interference between the core mode and the cladding mode that was coupled by the first grating and then recoupled to the core by the second grating. The fringe spacing was related with the center-to-center

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distance between the gratings and the difference between the effective indices of the core mode and the cladding mode. By analyzing the interference fringes, the differential effective index of the fiber was calculated and reported [7].

The effective index difference between the core and the cladding modes are important in determining the resonant wavelength of a LPG and for studying its behaviors [8,9]. However, in the field of fiber optic telecommunication, the dispersion of the core mode, not the difference, is widely required. As a promising method, the index-matching oil immersion method is proposed, which is expected to factor out the effect of the cladding mode from the differential effective index measured by the LPG pair experiment. Since the coupled cladding mode propagates along the cladding of the fiber, the effective index of the cladding mode is affected by the refractive index of the material surrounding the cladding [10,11]. When a part of the fiber region between the gratings of the LPG pair is immersed in an index-matching oil, the interference condition is affected by the oil index so that the interference fringe is shifted. The amount of the fringe shift is related with the refractive index of the oil and the length along which the fiber is immersed. Therefore, if we use the index-matching oil whose dispersion is well known, then we might calculate the dispersion of the core mode only. In this article, we describe in detail the relationship between the interference fringe of a LPG pair and the modal indices, and then present the possibility of measuring the core mode dispersion by using the proposed index-matching oil immersion method.

Effective Index Difference Between the Core Mode and a Cladding Mode

The core mode transmission spectrum $T_{\text{pair}}$ of a LPG pair is given as a function of the single grating’s core mode intensity $T_{\text{single}}$, the cladding mode intensity $R_{\text{single}}$, the intensity loss $\alpha$ in the cladding mode, and the phase difference between the core and cladding modes $\Psi$ [7,12]:

$$T_{\text{pair}} = T_{\text{single}}^2 + \alpha^2 R_{\text{single}}^2 - 2\alpha T_{\text{single}} R_{\text{single}} \cos \Psi,$$

$$\Psi = 2 \tan^{-1} \left( \frac{\Delta \beta}{2s} \tan sd \right) - \Delta \beta d + (\beta_{\text{core}} - \beta_{\text{clad}}) L,$$

$$\Delta \beta \equiv \beta_{\text{core}} - \beta_{\text{clad}} - K. \tag{3}$$

Where $\beta_{\text{core}}$ and $\beta_{\text{clad}}$ are the propagation constants of the core and the cladding modes, respectively, $K$ is the grating momentum, $d$ is the grating length, $L$ is the center-to-center distance between the gratings, and $s$ is defined by $s^2 \equiv k \kappa^2 + (\Delta \beta/2)^2$ with $\kappa$ being the coupling coefficient of the single grating. Due to the wavelength dependent phase difference $\Psi$, the core mode transmission spectrum $T_{\text{pair}}$ of eq. (1) has a fast varying sinusoidal fringe pattern whose amplitude is smoothly modulated (or enveloped) by the spectrum functions of the single grating, $T_{\text{single}}$ and $R_{\text{single}}$.

The core mode intensity of the LPG pair, from eq. (1), has the maximum denoted as $T_{up}$ and the minimum denoted as $T_{lo}$, when the phase term becomes $\cos \Psi = \mp 1$, respectively.

$$T_{up} = (T_{\text{single}} + \alpha R_{\text{single}})^2,$$ \tag{4}

$$T_{lo} = (T_{\text{single}} - \alpha R_{\text{single}})^2.$$
\[ T_{lo} = \left( T_{\text{single}} - \alpha R_{\text{single}} \right)^2. \] (5)

Since \( T_{\text{single}} \) and \( R_{\text{single}} \) are wavelength dependent, \( T_{up} \) and \( T_{lo} \) become functions of the wavelength also. From these relationships, the phase term of eq. (1) can be also expressed with the core mode transmission spectrum of the LPG pair and its envelope curves,

\[ \cos \Psi = \frac{T_{up} + T_{lo} - 2T_{\text{pair}}}{T_{up} - T_{lo}}. \] (6)

By taking the inverse of the cosine function, the phase difference between the core and cladding modes is obtained. However, because it is a cosine function, adding any integral multiple of \( 2\pi \) to the phase difference \( \Psi \) does not change the value; thus the phase difference is not uniquely determined without considering the phase matching condition of a single LPG, which is followed.

While, in eq. (2), the first two terms of the right side is the phase difference induced by both gratings, and the last term is induced by the propagation along the fiber. We define them as

\[ \Psi = \Psi_g + \Psi_f, \] (7)

\[ \Psi_g = 2 \tan^{-1} \left( \frac{\Delta \beta}{2s} \tan sd \right) - \Delta \beta d. \] (8)

\[ \Psi_f = (\beta_{\text{core}} - \beta_{\text{clad}})L. \] (9)

Then we obtain

\[ \beta_{\text{core}} - \beta_{\text{clad}} = \frac{1}{L} (\Psi - \Psi_g). \] (10)

Where the grating-induced phase difference \( \Psi_g \) is small enough to be neglected for weak gratings or can be approximately calculated from the parameters used to get the fitting envelope curves in eq. (2) [7]. Its effect to the interference fringe was reported to be less than 1\% when the grating separation was longer than 300 mm [7].

Further, as mentioned above the measured phase difference \( \Psi \) is not uniquely determined from eq. (6) only. However, it is uniquely determined from the phase matching condition of a single grating, which holds at the center wavelength \( \lambda_0 \) of the envelope curves [13],

\[ \beta_{\text{core}}(\lambda_0) - \beta_{\text{clad}}(\lambda_0) = K. \] (11)

At the resonant wavelength \( \lambda_0 \), \( \Delta \beta \) of eq. (3) vanishes, thus eq. (8) becomes \( \Psi_g(\lambda_0) = 0 \). Therefore, eq. (7) becomes

\[ \Psi(\lambda_0) = \Psi_f(\lambda_0) = [\beta_{\text{core}}(\lambda_0) - \beta_{\text{clad}}(\lambda_0)]L. \] (12)

Plugging in eq. (11) into eq. (12) gives

\[ \Psi(\lambda_0) = KL. \] (13)
The phase difference at a wavelength (in this case, at the resonant wavelength $\lambda_0$) is uniquely determined from the phase matching condition of eq. (11); thus the phase difference at other wavelengths can also be uniquely determined. By rewriting eq. (10) as

$$\beta_{\text{core}}(\lambda) - \beta_{\text{clad}}(\lambda) = \frac{1}{L} [\Psi(\lambda) - \Psi(\lambda_0) + \Psi(\lambda_0) - \Psi_g(\lambda)], \quad (14)$$

and by defining a relative phase $\Psi_{\text{rel}}$ as

$$\Psi_{\text{rel}}(\lambda) \equiv \Psi(\lambda) - \Psi(\lambda_0), \quad (15)$$

then we have

$$\beta_{\text{core}}(\lambda) - \beta_{\text{clad}}(\lambda) = \frac{1}{L} [\Psi_{\text{rel}}(\lambda) - \Psi_g(\lambda)] + K. \quad (16)$$

Where the relative phase difference $\Psi_{\text{rel}}$ is obtained by subtracting a constant from the phase difference $\Psi$ calculated from eq. (6) to make it be zero at the band center $\lambda_0$.

Finally, the effective index difference between the core and the cladding modes is given as [12],

$$\beta_{\text{core}} - \beta_{\text{clad}} = \frac{2\pi}{\lambda} \left( n_{\text{eff}}^{\text{core}} - n_{\text{eff}}^{\text{clad}} \right), \quad (17)$$

where $n_{\text{eff}}^{\text{core}}$ and $n_{\text{eff}}^{\text{clad}}$ are the effective indices of the core and the cladding modes, respectively. Plugging it in eq. (16) and using the periodicity of the grating $\Lambda$, $\Lambda = 2\pi/K$, we have

$$n_{\text{eff}}^{\text{core}}(\lambda) - n_{\text{eff}}^{\text{clad}}(\lambda) = \frac{\lambda}{2\pi L} [\Psi_{\text{rel}}(\lambda) - \Psi_g(\lambda)] + \frac{\lambda}{\Lambda}. \quad (18)$$

Therefore, it is concluded that the effective index difference between the core and the cladding modes can be uniquely calculated from the interference fringe spectrum of a LPG pair. In order to get the core mode effective index from eq. (18), the contribution of the effective cladding mode index should be factored out. It might be done by studying the interaction between the cladding mode and the refractive index of the material surrounding the cladding surface. Its discussion is followed.

**Interaction Between the Effective Cladding Mode Index and the Surrounding Media**

A fiber can hold a series of cladding modes when the cladding of the fiber is surrounded by a material whose refractive index is lower than that of the cladding material. The total internal reflection at the cladding-surrounding interface allows the cladding to hold the modes. In this case, the modal index of the cladding mode is determined by the cladding diameter and the refractive indices of the cladding and the surrounding materials. Even though the cladding mode is affected by the existence of the fiber core, due to the small core size compared with the cladding size, the effect is small enough to be neglected in the first order approximation. With the small core approximation, the cladding mode index is completely calculated by
using the standard waveguide equation of an optical fiber [14]. However, it was reported that the cladding mode equation could be simply obtained from the geometric-optics approximation that is [15,16]

\[
\frac{2\pi D_{cl}}{\lambda} \sqrt{(n_{el})^2 - (n_{0p}^{cl})^2} = 2\cos^{-1} \frac{(n_{el})^2 - (n_{0p}^{cl})^2}{(n_{el})^2 - (n_{amb})^2} \left( p - \frac{3}{4} \right) 2\pi.
\]

(19)

where \(D_{cl}\) is the diameter and \(n_{el}\) is the material refractive index of the fiber cladding, \(n_{amb}\) is the refractive index of the material surrounding the cladding, \(p\) is the order of the cladding mode, and \(n_{0p}^{cl}\) is the effective index of the \(LP_{0p}\) cladding mode. Though the equation is not absolutely correct, it gives a good physical meaning. That is the round-trip phase gain of the \(p\)th order cladding mode should be the sum of the phase shift at the cladding-surrounding boundary and the \(p\)-multiple of \(2\pi\). Thus, when the fiber is immersed in an index matching oil, the amount of the phase shift at the cladding-oil boundary (the first term of eq. (19)) is affected by the refractive index of the oil.

From the above analysis, we can calculate the effective index of the cladding mode, at least by using a graphical method [15,16]:

\[
n_{0p}^{cl} = f(n_{el}, n_{amb}, p).
\]

(20)

Where the material refractive index of the fiber cladding is well known for the fused silica case, and the index of the oil is also known if we use a well-known standard index matching oil. Therefore, if the cladding mode order \(p\) is obtained by any method, then the modal index of the cladding can be calculated. In the reverse order, if we know the effective indices of the cladding modes, or their difference at two different ambient indices, then the mode order \(p\) can be determined. For an example, when the difference of the effective indices of the \(p\)th order cladding mode measured with air \(n_{0p}^{cl,air}\) and oil surrounding \(n_{0p}^{cl,oil}\) is available, we have

\[
n_{0p}^{cl,oil} - n_{0p}^{cl,air} = f(n_{el}, n_{oil}, p) - f(n_{el}, n_{air}, p).
\]

(21)

While, in the previous chapter, it was presented that the difference between the effective indices of the core mode and the cladding mode could be obtained from the interference fringe of the LPG pair. It has also been experimentally observed that the interference fringe was shifted when a part of the fiber was immersed in an index matching oil. Therefore, if we measure the phase differences with two different ambient indices, for example, with air and an oil, then we can obtain from eq. (18) the effective index difference between the cladding modes

\[
n_{0p}^{cl,oil}(\lambda) - n_{0p}^{cl,air}(\lambda) = \frac{\lambda}{2\pi L} \left[ \Psi_{rel}^{air}(\lambda) - \Psi_{rel}^{oil}(\lambda) \right],
\]

(22)

where \(\Psi_{rel}^{air}(\lambda)\) and \(\Psi_{rel}^{oil}(\lambda)\) are the relative phases of the interference fringes measured with air and with oil, respectively. Thus the cladding mode order \(p\) is obtained by choosing the best \(p\) that matches eq. (21) with eq. (22).

In a summary, from the oil-induced interference fringe shift of a LPG pair, eq. (21) and (22), the cladding mode order is calculated. From the mode order, by using the relationship of eq. (20), the effective index of the cladding mode is calculated.
Finally, from eq. (18) the effective index of the core mode is calculated as a function of wavelength. The required measurements are two spectra of the LPG pair with air and oil surroundings. The refractive index of the oil should be known with other methods or a standard oil whose refractive index is well known should be used.

Experiments and Discussion

A LPG was made in a hydrogen-loaded DSC-type (dual shape core) dispersion-shifted fiber (DSF) of Mitsubishi by illuminating an KrF excimer laser beam (248 nm) through an amplitude mask. The periodicity and the length of the grating were 500 μm and 20 mm, respectively. In order to form a grating pair, an identical grating was made in the same fiber with the same condition but after shifting the fiber by 300 mm along the fiber. The coating between the gratings was removed. The core mode transmission spectra of the LPG pair were measured by using an optical spectrum analyzer (OSA) of a 0.1-nm spectral resolution. The light source used for the spectrum measurements was a broadband LED whose peak intensity was near 1.55 μm.

Figure 1 shows the measured core mode transmission spectrum of the LPG pair. It is noted that the spectrum consists of a sinusoidal pattern enveloped by slowly varying curves. The sinusoidal pattern is the interference fringe resulted from the phase difference between the core and the cladding modes, one has propagated along the core and the other along the cladding of the fiber between the gratings. The envelope curves are determined by a function of the single grating's spectrum. The best fitting envelope curves were depicted with the slowly varying lines of the figure. To get the best-fitting envelope curves, the loss factor $\alpha = 0.9$ and the coupling coefficient $\kappa = 0.249 \pi / d$ were used. From Figure 1, the cosine of the phase difference between the modes was calculated by using eq. (6) and depicted in Figure 2. In principle, the $\cos \Psi$ graph should reach $\pm 1$ alternatively as wavelength increases. However, due to the measurement noise and the finite resolution of the spectrum analyzer, the graph does not always reach $\pm 1$. The LED light source had about 0.2 dB noise level over the whole spectral range, while the spacing between adjacent

![Graph](image)

**Figure 1.** The measured core mode transmission spectrum of a pair of long-period fiber gratings. Each grating had a length of 20 mm and the center-to-center separation between gratings was 300 mm. The slowly varying top and bottom lines are the fitted envelope curves.
peaks of Figure 2 was measured not to be constant, which can be explained by the
dispersion of the fiber. In other words, from the measured fringe spacing variation,
the dispersion information of the fiber modes can be extracted also.

The phase difference $\Psi$ was obtained by taking the inverse cosine of Figure 2.
From the obtained phase difference, the differential effective index between the core
and the cladding modes was calculated by using the relationship of eq. (18), and then
depicted in Figure 3. In the first look, the index difference decreases as the wave-
length increases by a rate of $(−2.16 \pm 0.03) \times 10^{-3}$ $\mu$m. This decrement was reported
to govern the spectral width of the stop band of a single grating and the spacing
between the adjacent fringe peaks of the grating pair [7]. The graph fitting for the
differential effective index was not good enough with a linear curve. With high order
polynomials, the RMS (root mean square) deviation in the differential index from a
4th order polynomial fitting was calculated to be $2.2 \times 10^{-7}$ and $1.9 \times 10^{-7}$ with a 6th
order polynomial. It corresponds to about $0.1$ nm RMS deviation in the wavelength

![Figure 2](image1.png)

**Figure 2.** The cosine function of the phase difference, between the core mode and a cladding
mode, obtained from the LPG pair spectrum and its envelope curves of Figure 1.

![Figure 3](image2.png)

**Figure 3.** The difference of the effective indices of the core and the cladding modes calculated
from Figure 2 and the deviation from the best fitted 4th order polynomial. The root-mean-
square deviation from the 4th order polynomial is $2.2 \times 10^{-7}$ and $1.9 \times 10^{-7}$ with the 6th order
polynomial.
domain, which is limited by the resolution of the optical spectrum analyzer. From the fitted differential effective index, the interference fringe was reconstructed and compared with the measured spectrum in Figure 4. The solid line of the figure is the data curve and the dotted line is the reconstructed curve. We can see both curves are well matched with each other within the resolution of the OSA, 0.1 nm, while with a linearly fitted differential effective index the discrepancy between the data curve and the fitted curve could not be reduced below 0.3 nm. It leads us to conclude that the differential effective index can be obtained from the interference fringe of the grating pair and its envelope curves. It is noted that even though the polynomial fitting was good within the fitted wavelength range, it was not good to get the dispersion information out of the fitted range. Basically, the material indices of the core and the cladding of a fiber are given as Sellmier equations [15]. Therefore, after getting the core mode index by using the proposed oil method, we might fit the data with the Sellmeier equation so that the core mode index at other wavelength can be estimated. From the core mode index, by taking double derivative with respective to wavelength, the generally required second-order core mode dispersion of the fiber can be obtained.

As was mentioned with eq. (19), the effective cladding index is given as the function of the ambient index and the mode order. The numerically simulated results for the first three cladding modes are depicted in Figure 5 as the function of the ambient index. The simulation was done at a wavelength of 1.55μm and the material index of the cladding at that wavelength was used to be 1.450. As shown in the figure, the effective cladding index increases as the ambient index increases. The increment rate grows rapidly when the ambient index approaches the material index of the cladding. However, because the effective index of the core mode is not affected by the ambient index variation, the resonance peaks of the single LPG and the LPG pair are expected to be shifted to the shorter wavelength direction. From Figure 5, we know that the amount of ambient-index-induced fringe shift was related with the order of the cladding mode. In other words, by measuring the amount of the resonant wavelength shift, it is also possible to get the order of the related cladding mode.

As a basic experiment for getting the relationship between the effective index of the cladding mode and the ambient index, a LPG pair of 100 mm separation was prepared. Each grating was made with a 400μm periodicity and a 20 mm length. A series of index matching oils of Gargille was applied between the gratings. The oil-

![Figure 4](image)

**Figure 4.** The comparison between the measured spectrum of the LPG pair, solid line, and the fitted curve reconstructed with the index difference of Figure 3, dotted line.
applied length was about 25 mm. The wavelength of each interference fringe peak was tracked and plotted in Figure 6. The horizontal axis of the figure is the oil’s label index measured at 589.3 nm. Similar to the case of single LPG [10,11], as the oil index increased each fringe shifted toward the shorter wavelength first and then disappeared near oil index of 1.452, and finally reappeared with oils of greater than 1.50 index, while the amount of the fringe shift was measured to be proportional to the length of the oil-applied region of the grating pair. The oil used for this experiment had the index of 1.448 and the oil-applied length was varied from 0 to 25 mm. The result is plotted in Figure 7. The peak wavelength decreased by a rate of \((-3.0 \pm 0.1)\) nm/cm. It is understood that the index matching oil applied on the cladding surface changed the effective index of the cladding mode and the oil-induced phase shift was proportional to the product between the induced index variation and the oil-applied length. Therefore, it is concluded that the information

![Effective cladding mode index vs. Ambient index](image1)

**Figure 5.** The simulated effective indices of the first three cladding modes. The index increases with the increment of the ambient index. The higher order mode has the more rapid increment rate.

![Peak wavelength vs. Refractive index of oil](image2)

**Figure 6.** The plot of the peak wavelengths of an interference fringes formed in a stop band of a LPG. The measurements were done by applying index-matching oils on the cladding surface between the gratings of the LPG pair. The oil-applied length was 25 mm and both gratings were separated by 100 mm.
Figure 7. The peak wavelength shifts induced by the variation of the oil-applied length. An index matching oil of refractive index of 1.448 was applied between the gratings. The peak wavelength decreased by a rate of $(-3.0 \pm 0.1)$ nm/cm.

on the cladding mode index can be extracted by analyzing the interaction between the interference fringe of the LPG pair and the material surrounding the cladding of the fiber.

In order to get the core mode dispersion only, it is necessary to know the precise dispersion of the index matching oil in the interesting wavelength region, which was not available at the time of experiment but is available in principle. It is also necessary to know the effective index of the cladding mode as a function of the applied oil index. Unfortunately, the functional form of eq. (20) is not available at least in a closed form. An approximated expression is being investigated and a graphical solution is also being prepared. In our experiment, we got the differential dispersion only within the wavelength range of 25 nm, from 1535 to 1560 nm. Practically, the bandwidth was too narrow to get the dispersion information proper to telecommunications. However, it is possible to get the dispersion at other wavelength ranges by simply changing the periodicity of the gratings. Making a wide-band interference fringe is also possible by reducing the length of each grating of the LPG pair. Finally, the measurement noise is expected to be appreciably reduced by using a tunable laser as the source for the spectrum measurements.

**Conclusion**

A novel dispersion measuring method based on long-period fiber gratings was proposed. By analyzing the interference fringe spectrum of a grating pair, the effective index difference between the core mode and a cladding mode was obtained as a function of wavelength. In order to get the core mode index only, it was proposed to measure another spectrum after applying an index matching oil on the cladding surface between the gratings. The oil-induced interference fringe shift is related with the effective index of the cladding mode and the material index of the oil. Therefore, when the oil index is available, the effective index of the core mode can be calculated from the two spectra measured in air and in a well known index matching oil.

With a grating pair made in a DSF fiber of DSC type, the effective index difference between the core mode and a cladding mode was measured to decrease
as wavelength increased at a rate of \((-2.16 \pm 0.03) \times 10^{-3}/\mu\text{m}\) in the 1.55 \(\mu\text{m}\) wavelength region. The measured data was well fitted with a polynomial of an order greater than 4. The root mean square (RMS) deviation in the differential index from the 4th order polynomial fitting was calculated to be \(2.2 \times 10^{-7}\) and \(1.9 \times 10^{-7}\) with the 6th order polynomial. It corresponds to about 0.1 nm deviation in the wavelength domain. From the fitted differential effective index, the interference fringe was reconstructed and compared with the measured spectrum. The data curve and the fitted curve well matched each other within the spectral resolution of the optical spectrum analyzer, 0.1 nm. As a basic experiment for the cladding mode, the oil-induced spectrum variation of the grating pair of 100 mm separation was investigated. Each peak of the interference fringe was shifted toward the shorter wavelength direction as the oil index increased and the shifting amount was measured to be proportional to the oil-applied length at a rate of \((-3.0 \pm 0.1)\text{nm/cm}\).

If the resolution of the spectrum measurements is increased and an index matching oil with a well-known dispersion information is available, then it is expected that the core mode dispersion of a fiber can be calculated from the spectra of a pair of long-period fiber gratings.

References


**Biographies**

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