Polarization-dependent loss and birefringence in long-period fiber gratings

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Widely used descriptions and relationships for birefringence and polarization-dependent loss (PDL), developed primarily for ultraviolet-induced long-period fiber gratings (LPFGs) written in optical fiber, can be invalid for other types of LPFG. The understanding of PDL is expanded to include LPFGs with birefringence in the core only, in the cladding only, and in both the core and the cladding. Equations that link resonant wavelength separation, one factor that determines PDL, and birefringence for the three categories are presented, along with relevant approximations. Measurement results for two LPFGs fabricated by different techniques are presented that illustrate the effect of birefringence on PDL.

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1. Introduction

Polarization effects play a key role in the operation of many important optical devices. For example, arrayed-waveguide-grating routers fabricated in silica, which are used as multiplexers and demultiplexers in optical communication networks, exhibit polarization-dependent performance that requires compensation to ensure correct wavelength separation.[1,2] Polarization-state evolution in interferometric fiber-optic gyroscopes can generate nonreciprocal errors that affect instrument stability and accuracy.[3] Chirped fiber Bragg gratings used as chromatic dispersion compensating devices can introduce detrimental polarization-mode dispersion when they are inserted into optical networks.[4] Stress-induced birefringence has been used to create single-polarization, single-frequency distributed-feedback fiber lasers[5] for use in optical communication networks. The devices enumerated above are examples of ways in which polarization effects can significantly influence the performance of optical devices. Because of such effects it is essential to understand the source(s) of polarization-dependent behavior.

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Polarization effects, especially polarization-dependent loss (PDL), are also important in long-period fiber grating devices. Long-period fiber gratings (LPFGs), which consist of a periodic change in the refractive index along the longitudinal axis of an optical fiber, couple light from a core-guided mode into forward-propagating cladding-guided modes at or near resonant wavelengths.[6,7] Light coupled into the cladding modes eventually radiates out of the optical fiber, thus creating a broadband, wavelength-selective filter with low backreflection. These gratings exhibit polarization-dependent behavior including PDL, and such behavior can negatively affect optical-device performance. For example, PDL that occurs in optical network components, such as LPFGs that are used as gain-flattening filters in erbium-doped fiber amplifiers, contributes to fluctuations in signal-to-noise ratio and increased bit-error rates.[8,9] Conversely, PDL can be used productively to create polarization-based devices such as in-line fiber polarizers.[10]

Because PDL can affect device performance, it is important to understand the factors that generate it in LPFGs. At a fundamental level, an optical fiber with a general azimuthal index profile in its core, cladding, or both will exhibit birefringence; if birefringence is present within a grating structure, then that grating will exhibit PDL. Birefringence in LPFGs manifests as a change in grating resonant wavelength and attenuation in the transmission spectrum with changing polarization of incident light. Both of these alterations lead to wavelength-dependent PDL. The role of birefringence in generating PDL has been examined primarily in relation to LPFGs fabricated by exposure to ultraviolet light. The form of the induced birefringence and its effect on grating coupling characteristics have been measured and modeled for ultraviolet-induced (UV-induced) LPFGs,[11–14] and a theory that relates birefringence and PDL in this type of grating has been reported.[15] These efforts have necessarily focused on birefringence limited to the optical fiber core because of the mechanisms involved in creating an index change. Related to this focus, an approximation that neglects birefringence outside the core is typically made when PDL in UV-induced LPFGs is examined.[15]

Gratings other than those induced by ultraviolet light can possess birefringence that is not restricted to the optical fiber core; an example is LPFGs written in optical fiber with highly birefringent core and cladding. The presence of birefringence outside, or in addition to, the core region of a fiber can affect PDL in a LPFG.[16] The approximation made for UV-induced LPFGs that neglects birefringence outside the core can be invalid for other types of LPFG. This is particularly true when one is equating birefringence to resonant wavelength separation, which is one factor that determines PDL in a grating.[15] With such existing issues, consideration of the relationship between birefringence and PDL for other types of LPFG is needed.

In this paper, PDL and birefringence in LPFGs are discussed in general terms, and the explanation of PDL in UV-induced LPFGs is extended to include other types of LPFG. A review of the origins of PDL in LPFGs is presented to highlight the role of birefringence in generating grating PDL. Three categories of LPFG are identified, based on the location(s) of birefringence over the optical fiber cross section: core-only birefringence, cladding-only birefringence, and both core and cladding birefringence. Each of these forms contributes to PDL in LPFGs, but the relationship between birefringence and the factors that determine PDL vary among them. This variation is discussed in terms of modal birefringence, resonant wavelength separation, and the grating phase-matching condition. Approximations that are valid in the equations that relate resonant wavelength separation to modal birefringence are identified for each category of LPFG. One can draw several conclusions regarding decreasing and increasing grating PDL and measuring birefringence in these gratings by examining the expressions for each category. Additionally, PDL-related measurement results are presented for two LPFGs fabricated by different techniques but that possess similar transmission spectra for randomly linearly polarized light. The PDL and resonant wavelength separation measured for the two gratings highlight the significant differences that can exist among various types of LPFG.

This paper is organized as follows: In Section 2 we review the origins of PDL in LPFGs. In Section 3 we identify and describe three categories of birefringent LPFG. Examples of types of LPFG that belong to each category are given. The equations that describe resonant wavelength separation for the three categories of birefringent LPFG are presented in Section 4, along with related approximations and their effects. The results of PDL-related measurements of two types of LPFG are presented in Section 5, and the differences in PDL and resonant wavelength separation discussed.

Although only LPFGs are treated here, the same approach could be applied to short-period fiber Bragg gratings[12,17] (core-only birefringence) and to thin-film gratings used in optical fibers[18–20] (both core and cladding birefringence).

2. Origins of Polarization-Dependent Loss in Long-Period Fiber Gratings

PDL in a LPFG originates from the birefringence that is present in the grating structure. Birefringence, in most cases, arises from a general variation in the azimuthal index profile in an optical fiber. Because of the birefringence, the grating properties (resonant wavelength, coupling strength, etc.) depend on the state of polarization (SOP) of light incident upon the grating, and it is this dependence on polarization that generates PDL in LPFGs.

Birefringence alters the grating transmission characteristics in two distinct ways. First, the resonant wavelength of the grating, defined by the phase-matching condition, depends on the SOP of light incident upon the grating. Second, the peak refractive-index modulation is different for each SOP. The variation in index modulation with polarization implies that for each SOP the amount of light coupled to the relevant cladding mode changes. These changes lead to a variation in attenuation in the grating transmission spectra with polarization. As a result of these two phenomena, each incident SOP possesses a particular resonant wavelength and transmission spectrum (with associated bandwidth and wavelength-dependent attenuation). At any wavelength, it is the absolute difference between maximum and minimum transmitted power over all SOPs that defines the PDL. The change in PDL with wavelength is referred to as wavelength-dependent PDL.

The variation of the resonant wavelength and attenuation over all SOPs determines the PDL of a LPFG. For all possible incident SOPs about a particular coupling resonance, there exists a maximum and a minimum resonant wavelength. The difference between maximum and minimum resonant wavelengths is defined as the resonant wavelength separation. Associated with the maximum and minimum resonant wavelengths are transmission spectra, each with a peak attenuation, established by the coupling characteristics for that SOP (peak index modulation, number of periods, envelope profile).[6] For low to moderate levels of birefringence, the transmission spectra of the resonant wavelengths still overlap. The absolute difference between the associated transmission spectra then yields the wavelength-dependent PDL of a grating. Taking the absolute difference produces a distinctive peak–

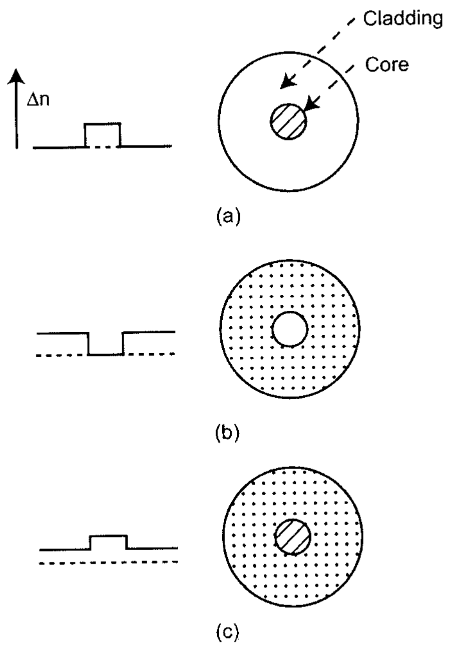

Fig. 1. Illustration of the three categories of long-period fiber grating (LPFG) based on the location(s) of birefringence over the optical fiber cross section: (a) core-only birefringence, (b) cladding-only birefringence, (c) core and cladding birefringence. Hatched areas indicate the presence of birefringence in the cross sections (right-hand side). The raised portions of the line profiles (left-hand side) indicate the same. Δn is representative of birefringence.

trough–peak appearance resulting from the intersection of the spectra, in the grating wavelength-dependent PDL.[15]

The sources of birefringence that generate PDL can be either intrinsic to the optical fiber into which a LPFG is written or induced by the mechanism that creates the refractive-index change. Intrinsic birefringence is a fundamental property of an optical fiber and can be either low (e.g., in standard telecommunications fiber) or high (e.g., in polarization-maintaining fiber), depending on the fiber type. The location and the type of birefringence induced in a LPFG during writing depend on the fabrication technique employed.

3. Categories of Birefringent Long-Period Fiber Grating

Independently of the fabrication technique used to write a LPFG and of the sources of birefringence, three categories of LPFG can be delineated based on the location(s) of the birefringence over the optical fiber cross section: core-only birefringence, cladding-only birefringence, and both core and cladding birefringence. As the designations suggest, the first category consists of LPFGs that have birefringence only in the core of an optical fiber; LPFGs in the second category have birefringence only in the fiber cladding and LPFGs the third category have birefringence in both core and cladding.

Figure 1 illustrates the location of birefringence for each of the three categories. The third category represents the most general situation in LPFGs, but in several practical cases the restrictions of the first two categories are valid. The three categories encompass existing LPFGs fabricated in optical fiber. Which category an LPFG belongs in can be established by measurement of the transverse refractive-index profile over the grating region by use, for example, of computed tomography methods.[21,22] In some cases the location of birefringence is evident from the fiber geometry alone. The significance of categorizing LPFGs in this way will be evident when the equations that govern birefringence and resonant wavelength separation are considered in Section 4 below.

UV-induced LPFGs fabricated in low-intrinsic-birefringence photosensitive optical fiber are the primary example of LPFGs that belong in the core-only birefringence category. Because of the presence of photosensitive dopants only in the fiber core, the index change is limited to this region. This implies that the induced birefringence is confined to the core as well. As mentioned in Section 1, birefringence in this type of UV-induced LPFG has been studied extensively. Induced birefringence, for this type of grating, can be attributed to one-sided exposure, which creates a larger index change on the side of the core where the UV beam is incident,[11] to the polarization of the incident writing beam,[12] or to both. Other examples of gratings that belong to this category include LPFGs created by poling a liquid-crystal-filled hollow-core optical fiber[23] along with UV-induced LPFGs written in elliptical core polarization-maintaining fiber (PMF).[10] In the latter type of grating, any induced birefringence is dominated by the intrinsic birefringence of the elliptically shaped core.

LPFGs written in low-intrinsic-birefringence optical fiber in which an index change is induced over the entire optical fiber cross section tend to belong in the cladding-only birefringence category. When the index change is over the entire fiber cross section, both the core and the cladding may be birefringent. However, for an azimuthally asymmetric refractive index that is not rapidly varying over the cross section, the index change in the core region can be considered azimuthally symmetric because the core covers only a small portion of the overall fiber cross section. The birefringence in the core is much smaller than that in the cladding; therefore the core birefringence can be neglected and the cladding is the only portion of the fiber cross section that is birefringent. This condition is the opposite of core-only birefringence. Examples of LPFGs that belong to this category include CO_2-laser-induced LPFGs, as indicated by recent measurements,[21] and LPFGs fabricated in standard telecommunications optical fiber by ion implantation.[24] Electric-arc-induced LPFGs[25] belong, potentially, in this category, but a measurement of the transverse refractive-index profile has not been reported.

As was mentioned above, the third category represents the general case in which birefringence is present in both the core and the cladding. Birefringence in both regions of a fiber can be due to the intrinsic properties of the fiber (such as in certain PMFs), to the induced index change, or to both. For example, UV-induced LPFGs fabricated in stress-induced PMF possess birefringence in both the core and the cladding because of the intrinsic properties of PMF (not because of UV exposure). The stress members that are present in the cladding introduce birefringence into both the PMF core and cladding. LPFGs fabricated in etched optical fibers by ion implantation[24] belong in this category as well because, for certain ion energy levels, the induced refractive-index change covers the core and a portion of the cladding. Another type of LPFG, created by application of pressure with a grooved plate,[26] potentially belongs in this category, but a transverse refractive-index profile has not been measured.

4. Resonant Wavelength Separation and Phase-Matching Condition

The three different categories of birefringent LPFG all introduce PDL into the grating transmission spectra. However, the relationship between birefringence and one of the factors that determine PDL, resonant wavelength separation, differs for each category. The different forms of the relationship are due to approximations that can be made for core-only and cladding-only birefringence. In this section we discuss the approximations that are valid for each category of LPFG and how the approximations affect the relationship between resonant wavelength separation and birefringence. Consequences of these approximations in regard to altering grating PDL and measuring modal birefringence are also given. The discussion begins with a consideration of the general grating phase-matching condition for LPFGs before we examine each category individually.

For an ideal LPFG with no birefringence, the phase-matching condition that describes the center wavelength of the transmission resonance in a LPFG may be expressed as

$$\lambda_{\mathrm{res}} = \Lambda(n_{01} - n_{mn}) = \Lambda(\Delta n), \qquad (1)$$

where λ_{res} is the resonant wavelength, Λ is the grating period, n_{01} is the effective guided-mode index of the LP_{01} core-guided mode, and n_{mn} is the effective guided-mode index of the LP_{mn} cladding-guided mode.[6]

The condition given by Eq. (1) is true for nonbirefringent gratings only; if a grating is birefringent, then the resonant wavelength will depend on the SOP of the light incident upon the LPFG. For each SOP there exists a specific resonant wavelength defined by the effective indices of the core-guided and the cladding-guided modes for that polarization state. Again, the variation in indices with SOP is due to birefringence. The actual refractive index that each SOP experiences is related to the effective index[27,28]; therefore the variation in refractive index (birefringence) with polarization is related to the variation in the effective guided-mode index.

For all possible input SOPs, a minimum and a maximum wavelength ($\lambda_{\mathrm{res}}^{\min}$ and $\lambda_{\mathrm{res}}^{\max}$) exist that correspond to a minimum and a maximum effective guided-mode index difference ($\Delta n^{\min}$ and $\Delta n^{\max}$):

$$\lambda_{\mathrm{res}}^{\min} = \Lambda(\Delta n^{\min}), \qquad (2)$$

$$\lambda_{\mathrm{res}}^{\max} = \Lambda(\Delta n^{\max}). \qquad (3)$$

The wavelength separation between the minimum and the maximum resonant wavelengths is then given by

$$\Delta\lambda_{\mathrm{res}} = \lambda_{\mathrm{res}}^{\max} - \lambda_{\mathrm{res}}^{\min} = \Lambda(\Delta n^{\max} - \Delta n^{\min}), \qquad (4)$$

where $\Delta\lambda_{\mathrm{res}}$ is the largest resonant wavelength separation for a particular cladding-mode resonance.

From Eq. (4) it is apparent that the resonant wavelength separation is related to the change in effective indices (which is due to birefringence) with polarization through the $\Delta n^{\min}$ and $\Delta n^{\max}$ terms, but it is not immediately clear how the birefringence in the core and the cladding individually relates to the resonant wavelength separation because the Δn terms represent an index difference. However, approximations can be made in Eq. (4), depending on the type of grating and on what category it belongs in, that can simplify the relationship between the resonant wavelength separation and birefringence. The approximations that are valid for each category are examined below.

For LPFGs in the first category, the birefringence is limited to the fiber core. The assumption can then be made that the cladding mode's effective index (n_{mn}) is independent of the incident polarization state (i.e., is constant).[15] Then the minimum and maximum Δn terms involve only the variation in the LP_{01} effective indices, and Eq. (4) reduces to

$$\Delta\lambda_{\mathrm{res}} \approx \Lambda(n_{01}^{\max} - n_{01}^{\min}), \qquad (5)$$

where $n_{01}^{\max}$ and $n_{01}^{\min}$ are the maximum and minimum effective indices, respectively, for the LP_{01} core-guided mode over all polarization states. The approximation and the equation for this category have the same form as those commonly cited for UV-induced LPFGs written in low-intrinsic-birefringence optical fiber.[15] The $n_{01}^{\max} - n_{01}^{\min}$ term in relation (5) represents the modal birefringence[28,29] in the fiber core.

The first category contained gratings with birefringence in the core only. By contrast, LPFGs in the second category have a birefringent cladding and a nonbirefringent core. If the induced index change is over the entire cross section and is mostly azimuthally symmetric (not rapidly varying) in the core region, the effective indices of the core-guided mode (n_{01}) can be considered constant (not birefringent). Equation (4) then reduces to

$$\Delta\lambda_{\mathrm{res}} \approx \Lambda(n_{\mathrm{mn}}^{\max} - n_{\mathrm{mn}}^{\min}), \qquad (6)$$

where n_{mn}^{max} and n_{mn}^{min}, respectively, are the maximum and minimum effective indices for the LP_{mn} cladding-guided mode over all polarization states. Relation (6) has a form similar to that of relation (5), but now the modal birefringence of the cladding-guided mode is represented by the $n_{mn}^{max} - n_{mn}^{min}$ term, and the core-guided mode is not birefringent. As the polarization state of the light incident onto this category of grating changes, it is the variation in the cladding-guided mode's effective indices that determines the degree of resonant wavelength separation.

The third category of birefringent LPFG, for which both the core and the cladding are affected, represents a more complex situation than the core-only and cladding-only birefringence categories. The relationship between resonant wavelength separation and the difference in effective index cannot be directly simplified by neglect of birefringence in a particular location over the optical fiber cross section. Therefore the relationship between birefringence and resonant wavelength separation as described by Eq. (4) applies; it is the *combination* of birefringence in the core and the cladding that determines the separation and not the individual birefringences, as in the situations of core-only and cladding-only birefringence. The quantity $\Delta n^{max} - \Delta n^{min}$ in Eq. (4) cannot be directly interpreted as modal birefringence because it is not merely the difference between two effective indices, as in relations (5) and (6), but is the difference between the largest effective guided-mode index difference (between core and cladding modes) and the smallest effective guided-mode index difference (between core and cladding modes) for all input SOPs. General comments about LPFGs that exhibit core and cladding birefringence, beyond the ones already given, are difficult to make, inasmuch as the form and the combination of birefringence are dependent on the type of optical fiber into which a grating is written and on the fabrication method; distinct combinations of core and cladding birefringence yield distinct resonant wavelength separation and PDL behavior.

Several conclusions can be drawn from resonant wavelength expressions (4)–(6) for each category. For LPFGs with core-only or cladding-only birefringence, if the approximate birefringence of the relevant region is known then the resonant wavelength separation can easily be calculated. Here, resonant wavelength separation serves as an indirect measure of PDL, with a larger wavelength separation indicating a larger peak PDL value and a larger wavelength range affected by PDL (resulting from a larger separation of the associated transmission spectra). Conversely, it is possible to measure modal birefringence from the resonant wavelength separation for LPFGs in the first two categories. Relations (5) and (6) also suggest that one can increase or decrease PDL by directly increasing or decreasing the relevant birefringence. For LPFGs in the second category, the core-guided modes are not birefringent. The situation is more complicated for LPFGs in the third category, but a certain flexibility exists inasmuch as a correct combination of core and cladding birefringence could be used for compensation to increase or decrease PDL. For example, it is theoretically possible to cancel the effect of core birefringence by introducing offsetting birefringence in the cladding. This might be difficult to do in practice because it would require the ability to establish individually the core and cladding birefringences, but it might be accomplished by combining an elliptical core PMF (core-only birefringence) with grating fabrication, using a CO_2 laser. Increasing PDL through a combination of core and cladding birefringence, however, has already been demonstrated in LPFGs written into stress-induced PMF.[10]

Resonant wavelength separation is only one factor that determines the PDL in a LPFG. The amount of light coupled (attenuation) and the bandwidth of the transmission curve associated with a particular SOP is the other factor that influences PDL. Whereas resonant wavelength separation is easily described through the phase-matching condition, establishing the actual wavelength-dependent PDL is more difficult in practice. Ishii *et al.* presented a model for calculating wavelength-dependent PDL by using an approximate loss formula, but this approach requires knowledge of the transmission bandwidth, among other factors.[15] As stated in Section 2, for low to moderate levels of birefringence (which include most LPFGs not fabricated in PMF) the wavelength-dependent PDL is well characterized by the difference between the transmission curves associated with minimum and maximum resonant wavelengths. If the refractive-index modulation associated with minimum and maximum cladding effective indices is known, then the transmission curves can be calculated by use of a variety of techniques, including coupled-mode theory. Once the transmission spectra are calculated, one calculates the wavelength-dependent PDL by taking the absolute value of the difference between the spectra. For LPFGs with

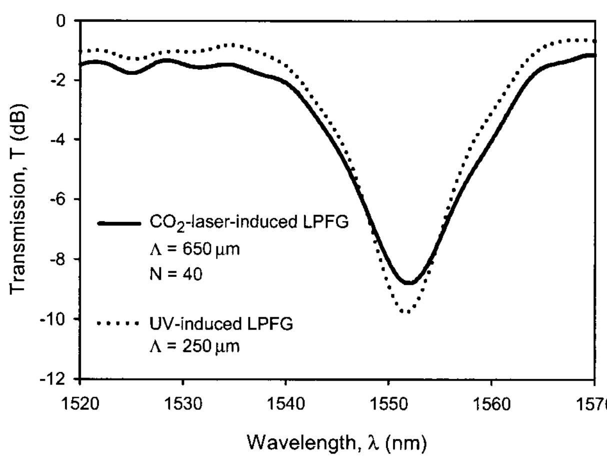

Fig. 2. Transmission spectra of a CO_2-laser-induced LPFG and a UV-induced LPFG near resonance for randomly linearly polarized light.

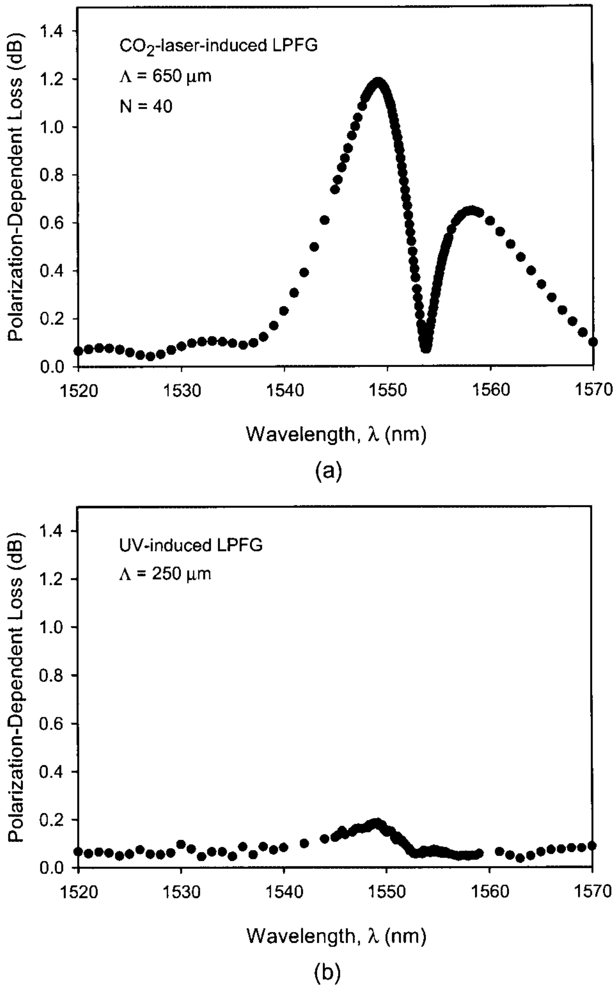

Fig. 3. Polarization-dependent loss of the CO_2-laser-induced LPFG and of the UV-induced LPFG.

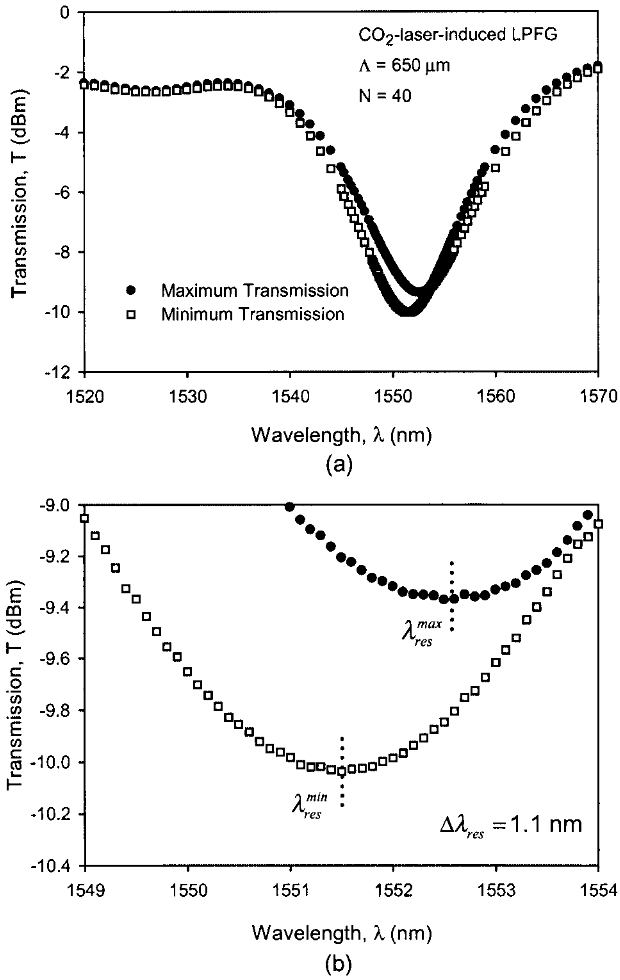

Fig. 4. (a) Minimum and maximum transmitted power of the CO_2-laser-induced LPFG. (b) Transmitted power near peak attenuation (resonance). The minimum and maximum resonant wavelengths are evident, with a separation of 1.1 nm between them.

higher levels of birefringence, the method given by Ishii *et al*. yields better results.

5. Comparison of Two Types of Long-Period Fiber Grating

As an illustration of some of the concepts discussed above and to highlight the significant differences that can exist among different types (categories) of LPFG, we measured the wavelength-dependent PDL, the resonant wavelength separation, and the modal birefringence of two LPFGs. The first LPFG was fabricated by exposure to CO_2-laser light[30] and belongs in the cladding-only birefringence category. The second LPFG was fabricated by exposure to ultraviolet light[31] and belongs to the core-only birefringence category. These two categories represent the important limiting cases, and the present experimental work is restricted to these two types. The gratings were fabricated to possess similar transmission spectra. The transmission spectrum of each LPFG for randomly linearly polarized light is shown in Fig. 2 (referenced to 0 dB). The two gratings have approximately the same resonant wavelength, though the UV-induced LPFG has 1-dB higher attenuation at resonance.

Figure 3(a) shows the PDL of the CO_2-laser-induced LPFG, and Fig. 3(b) shows the PDL for the UV-induced LPFG. The wavelength-dependent PDL was measured by the polarization-scanning technique.[32] Though the two LPFGs possess similar transmission spectra for randomly linearly polarized light, the peak PDL of the CO_2-laser-induced LPFG is 1.2 dB, compared with less than 0.2 dB for the UV-induced LPFG. Lower PDL is characteristic of commercially available LPFGs designed for use in optical networks. The higher PDL of the CO_2-laser-induced LPFG is a result of an induced azimuthally asymmetric refractive-index change in the fiber cladding by one-sided exposure. Again, the peak–trough–peak nature of the grating PDL over the wavelength range is due to crossover of the transmission spectra associated with the minimum and maximum resonant wavelengths.

The spectra associated with the minimum and

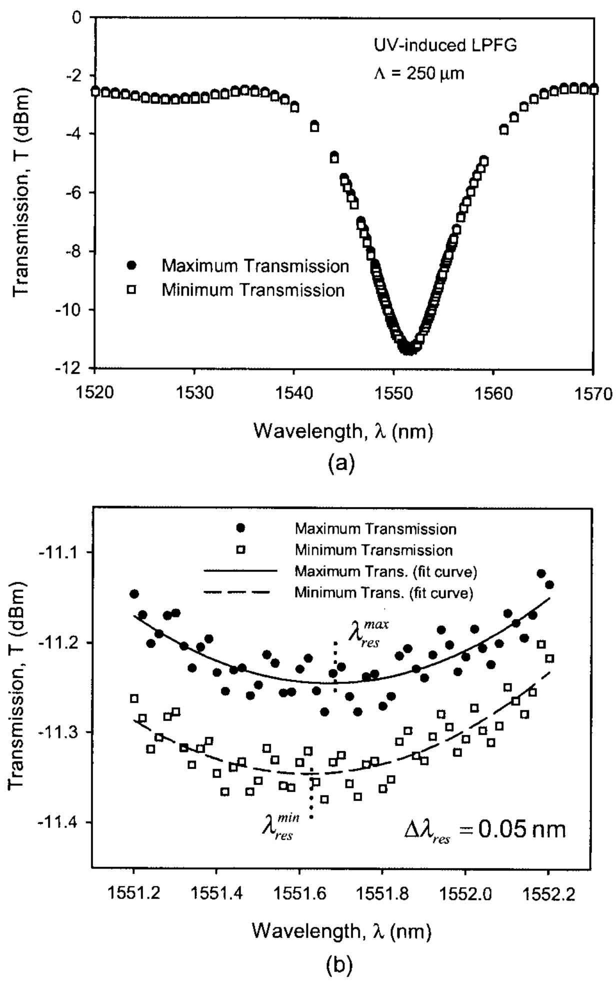

Fig. 5. (a) Minimum and maximum transmitted power of the UV-induced LPFG and (b) transmitted power near peak attenuation (resonance). The minimum and maximum resonant wavelengths were determined from the fitted curve, with a separation of 0.05 nm between them.

maximum transmitted power (also measured with the polarization-scanning technique) are shown in Figs. 4(a) and 5(a) for the CO_2-laser-induced LPFG and the UV-induced LPFG, respectively. A narrower range of the resonant wavelength regions is shown in Figs. 4(b) and 5(b), where the minimum transmission and the maximum transmission resonant wavelengths in each case are clearly shown. The reason for the larger peak PDL for the CO_2-laser-induced LPFG is evident from Fig. 4(b); the resonant wavelength separation ($\Delta\lambda_{res}$) is 1.1 nm, versus 0.05 nm for the UV-induced LPFG. This result indicates that the birefringence that is present in the cladding of the CO_2-laser-induced LPFG is larger than the birefringence that is present in the core of the UV-induced LPFG. Because these two gratings exhibit either core-only or cladding-only birefringence, the modal birefringence that is present in each can be estimated from the resonant wavelength separation [from relations (5) and (6)]. For the CO_2-laser-induced LPFG the estimated modal birefringence is 1.7×10^{-6}, whereas for the UV-induced LPFG it is 2×10^{-7}. Both values agree approximately with previously published measurements and calculations of modal birefringence despite differences in grating properties.[21,33]

6. Summary

Polarization-dependent loss affects the performance of long-period fiber grating devices. Birefringence in the refractive index leads to PDL in LPFGs. Previously, only birefringence in UV-induced LPFGs had been examined. We have extended previous work on birefringence and PDL to include other types of LPFG by identifying three general categories of birefringent LPFG, namely; those with core-only birefringence, with cladding-only birefringence, and with both core and cladding birefringence. Equations relating resonant wavelength separation, one factor that determines PDL, and modal birefringence have been presented for each category of LPFG. Approximations that neglect birefringence in certain areas of an optical fiber can be made for the core-only and cladding-only birefringence categories, and the approximations simplify the resonant wavelength expressions. Measurements of PDL for two types of LPFG, one fabricated by exposure to CO_2-laser light (cladding-only birefringence) and the other by exposure to ultraviolet light (core-only birefringence), illustrate the significant differences that can exist in PDL and birefringence.

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