Suppression of Cladding Mode Coupling Loss in Fiber Bragg Gratings

Liang Dong, Gang Qi, Marlene Marro, Vikram Bhatia, Lisa L. Hepburn, Martin Swan, Adam Collier, and David L. Weidman

***Abstract*—We have demonstrated, for the first time, the suppression of cladding mode coupling loss to ~0.1 dB in 30-dB fiber Bragg gratings for both nonhydrogenated and hydrogenated fibers. These fibers have also been optimized to give 0.04-dB average splice loss to SMF-28 fiber. The suppression of cladding mode coupling is achieved by accurately characterizing and controlling the photosensitive profile. This low level of cladding mode coupling loss has opened up a new range of broadband applications, previously restricted by the limited free spectral range of fiber Bragg gratings.**

***Index Terms*—Fiber Bragg grating, fiber photosensitivity.**

I. Introduction

FIBER Bragg gratings increasingly have become a critical technology for wavelength-division-multiplexing (WDM) systems. Very few other technologies can compete with fiber Bragg gratings for their high optical quality and large spectral slopes. Combined with relative ease of fabrication, and, therefore, potentially lower cost, fiber Bragg gratings have become an important technology platform for the implementation of a range of devices, including channel add-drop filters, multiplexer-demultiplexers, gain–flattening filters, band splitters and dispersion compensators.

In a fiber Bragg grating, there exists a glass-air or glass-polymer interface, depending on fiber coating. This structure supports a large number of cladding modes. They can be either guided modes or leaky modes, depending on the index of the external media. Power coupled from the guided mode to cladding modes by a Bragg grating creates a series of loss peaks on the shorter wavelength side of the Bragg wavelength $\lambda_{\rm Bragg}$. Most commercial WDM gratings are made in high Δ fibers to extend the onset of the cladding mode coupling loss to up to 10 nm away from $\lambda_{\rm Bragg}$ to allow a 10-nm free-spectral range on the short wavelength side. This severely restricts the application of fiber Bragg gratings in many WDM applications, where a much wider spectral range is desired. At the same time, high splice losses between SMF-28 fibers and the high Δ fibers also leads to higher insertion loss.

Several previous efforts have been directed at the fabrication of a specialty fiber for the suppression of cladding modes. A photosensitive cladding achieved with Ge- and F-doping has been used in a fiber in [1] to achieve a 0.5-dB cladding mode coupling loss in a 26-dB grating. A depressed cladding was used in [2] to achieve a 0.5 dB-cladding mode coupling loss in a ~40-dB grating. The depressed cladding method is further studied in [3] to achieve 0.4 in a 20-dB grating. Recently, a report on a photosensitive cladding fiber achieved with Ge- and B-doping achieved 1-dB cladding mode coupling loss in a 20-dB grating, without using hydrogen loading [4]. Splice loss to SMF-28 fiber is not addressed in any of the prior works. In practical applications, a higher level of cladding mode coupling loss suppression is required than what has been reported thus far. The higher level of suppression also requires new mean of accurately characterizing photosensitive profile and high precision control of the photosensitive profiles in fiber.

In this work, we report the effort for achieving cladding mode loss below 0.1 in 30-dB gratings and 0.12 in a 40-dB gratings, while keeping the splice loss to SMF-28 fiber to an average of 0.04 dB. This same method has been used to achieve 0.1-dB cladding mode coupling loss in 30-dB grating, in both hydrogenated and nonhydrogenated cases, by adjustment in the compositions used. It must be stressed that it is critical to have very good control over photosensitive profile to achieve this level of cladding mode loss. This differentiates this work from published works in the literature. The key to this low level of cladding mode coupling is a novel technique to characterize accurately transverse photosensitive profile and the ability to control the photosensitive profile to a very high accuracy. This low level of cladding mode coupling loss has opened up a new range of applications resulting from the much broader free spectral range (few hundreds of nm) available for WDM systems.

II. Theory

The strength of coupling between any two modes by a grating can be measured by a coupling coefficient, containing an overlap integral done over the cross section of the fiber (see [5] for example). As an example, the coupling coefficient of mode i and j can be expressed as:

$$\kappa_{ij} = \frac{\omega}{4} \iint_{A\infty} dx\, dy\, e_i(x,y) e_j(x,y) \Delta n_g(x,y)$$

where $A\infty, \omega, e_i(x,y)$ and $e_j(x,y)$ and $\Delta n_g(x,y)$ are fiber cross section, angular optical frequency, modal field for mode i, modal field for mode j and photosensitive profile, respectively. One aspect to note here is that the photosensitive profile referred to in the context of this paper is the profile of the amplitude of index modulation.

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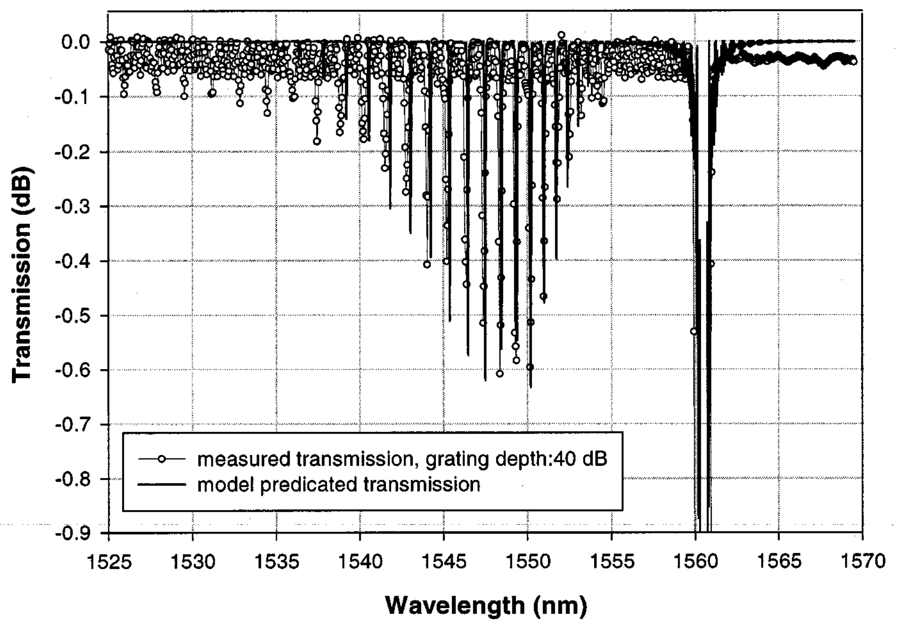

Fig. 2. Measured and predicated transmission for a not –yet-optimized fiber. Grating is 40 dB deep at peak. Fiber was hydrogenated.

This coupling coefficient, as well as grating length, determines the total coupling between two modes in a grating. It is important to note that all the modes involved are from the set of modes defined by the refractive index structure of the fiber, including the core, cladding and its surroundings. Consequently, the overlap integral will disappear for inter-modal coupling, due to modal orthogonality, if the grating is made constant over the fiber cross section, i.e. $\kappa_{ij} = 0$. In a practical sense, the fundamental mode LP_{01} only has nonzero power around the center of the fiber. It is, therefore, sufficient to make the grating profile constant over the center part of the fiber. This includes core and a small ring in the cladding next to the core. We refer to the photosensitive profile, when normalized to its peak, as normalized photosensitive profile.

As a design example to illustrate the requirements for the precision in photosensitive profile, a fiber is chosen with a Δ of 0.69%, radius of 3.3 μm, photosensitive cladding thickness of 3.3 μm and cut-off wavelength of 1460 nm. A small thickness for the photosensitive cladding is desirable to reduce the size of the doped region, and also to reduce the sensitivity to blaze angle in the grating. A perfect nonblazed grating (grating lines perpendicular to the fiber axis) will not couple the fundamental mode into asymmetrical cladding modes. This coupling is forbidden by the symmetry requirement. In a practical grating writing process, however, some amount of blaze always exists. This will couple the fundamental modes into asymmetrical modes, and this coupling is not suppressed by this photosensitive cladding approach. In fact, the sensitivity for this to happen increases with the diameter of the photosensitive region in the fiber. It is, therefore, essential that blaze be minimized. The normalized photosensitive profile is modeled, as consisting two uniform sections, one over the core and cladding, to reflect the different compositions used in a fiber to achieve the refractive index profile required for achieving guidance of the fiber.

To study quantitatively the extent of photosensitivity matching required for the core and cladding, the overlap integral for all the relevant modes are calculated and compared with what is required for achieving certain cladding mode suppression. Fig. 1 shows the resulting tolerance in photosensitive profile for achieving certain levels of cladding mode suppression for this fiber design. Three sets of lines define the maximum overlap integral for achieving less than 0.1-dB cladding mode coupling loss for a 30-dB, a 40-dB, and a 50-dB grating. As can be seen, for achieving 0.1-dB cladding mode coupling loss for a 30-dB grating, cladding photosensitivity must be matched to within $\pm 20\%$ of that of the core. The core and cladding photosensitivity needs to be very closely matched to achieve 0.1-dB cladding mode coupling loss in a 40-dB grating. It should be also noted that 0.1-dB cladding mode loss for 50-dB grating could not be achieved in this case. This is due to the fact that the photosensitive region is not large enough in this case. To achieve this, a larger photosensitive cladding is required. It should be noted that cladding photosensitivity of 80% (-20%) of that of core provides the same level of cladding mode suppression as that of cladding photosensitivity of 120% $(+20\%)$ of that of core.

III. Dopant Considerations

In a conventional optical fiber, germanium-doping in the core normally is used to raise the refractive index of the core. Either an undoped or a phosphorous- and fluorine-doped cladding is used. In such a fiber, only the core is photosensitive, as a result of the germanium-doping. The refractive index structure requires that the core and cladding be made of different compositions to give the core a larger refractive index. To first order, the photosensitive profile required for achieving cladding mode coupling suppression demands that the germanium level in the core and

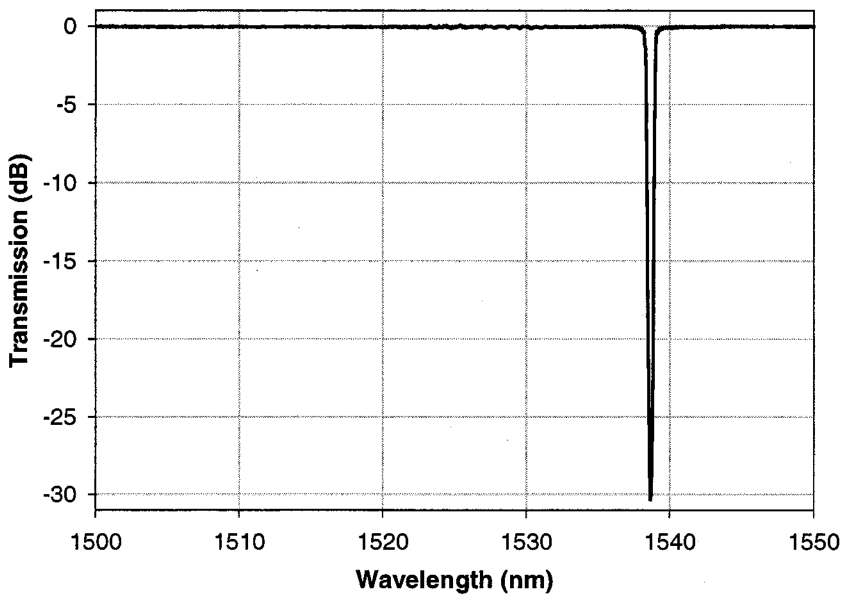

Fig. 3. Transmission of a 30-dB grating in a fiber optimized for nonhydrogenation. Fiber was not hydrogenated for this grating.

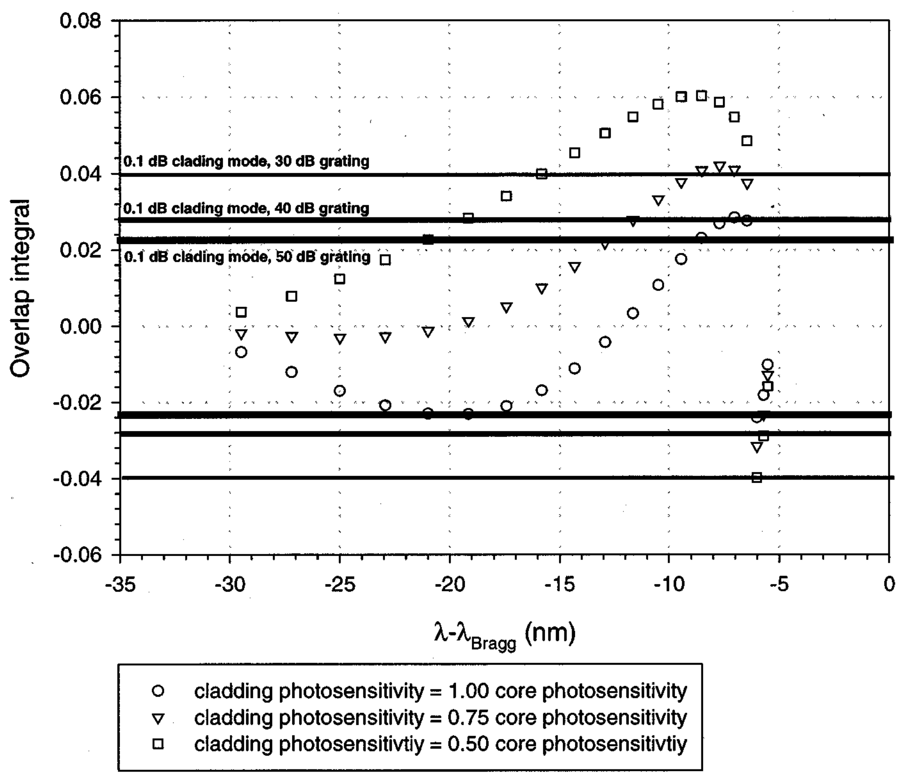

Fig. 1. Tolerance on the level of photosensitivity match between core and cladding to achieve cladding mode coupling suppression of 0.1 dB for 30 dB, 40 dB, and 50 dB gratings. $\Delta = 0.69\%$, core radius $= 3.3\ \mu$m, thickness of photosensitive cladding $= 3.3\ \mu$m.

cladding be similar, if other dopants do not have a large influence on photosensitivity. Fluorine- and germanium-doping in the cladding is used in ref [1]. Fluorine-doping reduces the refractive index and germanium raises it. Fluorine-doping in the cladding was used in this case to achieve a refractive index in the cladding similar to that of a undoped silica. Due to the limited refractive index reduction achievable by fluorine-doping, a much higher germanium level is always expected in the core with this choice of dopants. This is equivalent to saying that a photosensitivity matching between core and cladding is never

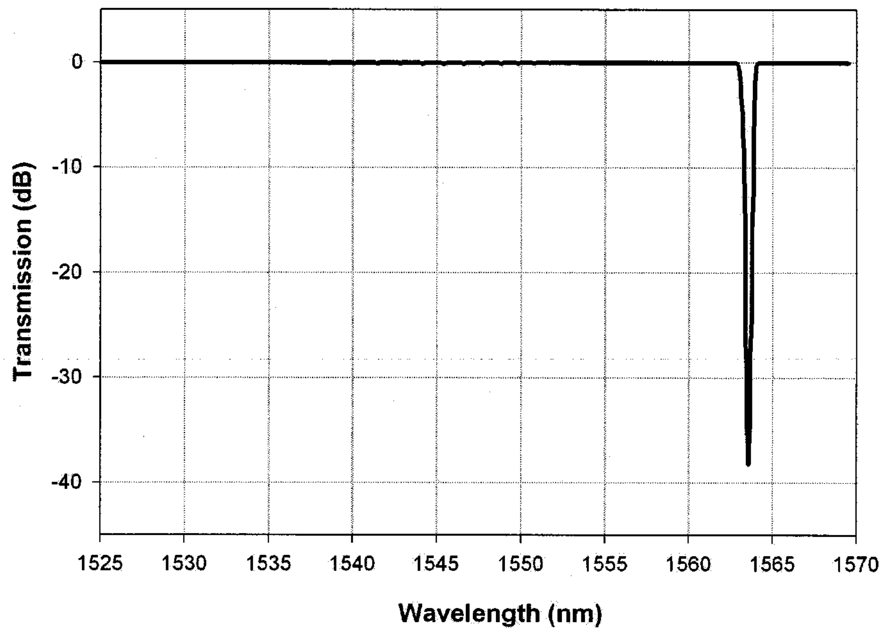

Fig. 4. Transmission of a 40 dB-grating in a fiber optimized for hydrogenation. The fiber was hydrogenated at room temperature at ~ 200 bars for ~ 2 weeks.

achievable in this case, and that the level of cladding mode coupling suppression is limited.

To achieve the photosensitive profile required for achieving cladding mode coupling suppression, as well the index profile, a third dopant that either reduces the photosensitivity in the core or increases the photosensitivity in the cladding is required. Phosphorous co-doping in a germanium-doped core has the effect of reducing core photosensitivity [6], [7], and also raises core refractive index to allow a lesser amount of germanium to be used in the core is one option. Another option is boron-co-doping in a germanium-doped cladding to enhance the photosensitivity of the cladding [8]. Boron-doping also reduces the refractive index of the cladding, and allows an overall refractive index profile similar to that of the undoped silica to be achieved. In this work, the second option was chosen, as it also gives a more photosensitive fiber.

Hydrogen-loading [9] is now commonly used for achieving a much improved fiber photosensitivity. It has to be noted that the mechanism for photosensitivity in a hydrogen-loaded fiber is substantially different from that of an unloaded fiber, and therefore the normalized photosensitive profiles for these two cases are different for the same fiber. This is to say that a fiber, which achieves good cladding mode coupling suppression in a hydrogen loaded fiber, is generally not expected to perform as well when the same fiber is not hydrogen loaded. It has been found in this study that cladding mode suppression can be achieved in the same fiber for both hydrogenated and nonhydrogenated cases, but not to the same extent.

IV. Characterization of Normalized Photosensitive Profile

The normalized photosensitive profile is the most important parameter to control in the optimization of fiber fabrication process. The ability to characterize the normalized photosensitive profile is critical to the success of highly accurate control of the normalized photosensitive profile for the level of cladding mode coupling loss suppression desired. The only method reported in the literature involves measuring the refractive index profile of an exposed fiber with a near-field scanning method [7]. This method measures the profile of the total index change, and is limited to very high index changes on the order of 0.001. As was discussed earlier in this paper, what must be characterized is the profile of index modulation, not the total index change. There is typically an index change, which does not vary along the fiber, and therefore does not contribute to index modulation. Most gratings of interest have an index modulation much less than 0.001, and are not measurable by this technique.

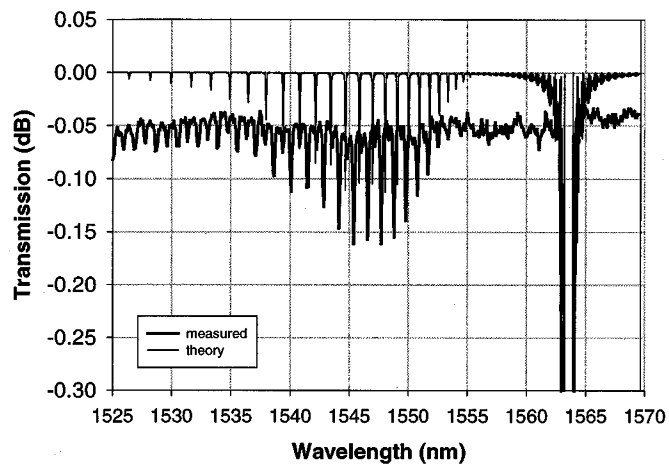

Fig. 5. Transmission of the grating in Fig. 4 on an expanded scale as well as the theoretical modeling results of the grating transmission.

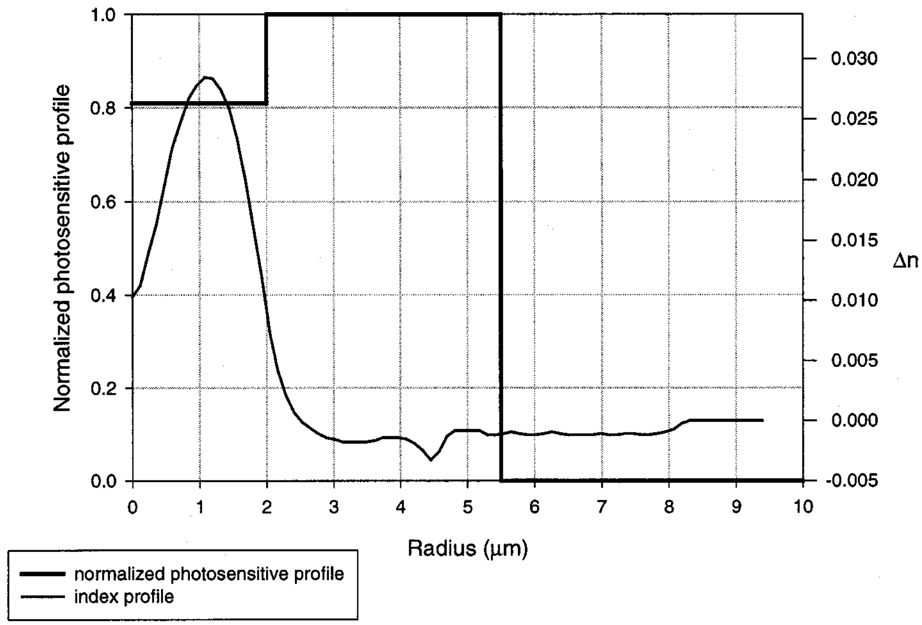

Fig. 6. Index profile and normalized photosensitive profile for the grating in Figs. 4 and 5. The core photosensitivity is 81% of that of the cladding.

A new technique was developed for the characterization of normalized photosensitive profile. This technique uses an iterative routine, in combination with a grating simulator, which is capable of simulating all the cladding modes of interests. First, a grating is written in a test fiber to a depth of around 30 dB. A transmission spectrum is taken, covering all the cladding modes. The grating simulator uses the measured fiber refractive index profile and an initial guess of the normalized photosensitive profile to calculate the cladding mode loss spectrum covering 100 cladding modes for the measured grating depth. The result then is compared with the measured cladding mode loss to generate the next normalized photosensitive profile. The procedure is repeated until a close match between the measured and modeled is obtained.

A two-step photosensitive profile was found to be adequate for most fibers. The ratio of photosensitivity of the two steps and the position of steps is adjusted in each iteration. This is equivalent to taking effective step photosensitivity in the core and cladding. Fig. 2 shows the modeled and measured transmission for a not-yet-optimized fiber, as an example demonstrating the level of accuracy of the established model. Grating strength in this case is 40 dB.

V. Optimization Procedure

A two-stage process has been adopted for the optimization of fiber fabrication process, since compositions are controlled during fiber fabrication, not the desired photosensitivity. A series of fibers, with systematic changes of composition in the core and cladding, are made at stage 1. Due to the complex nature of the photosensitivity where core and cladding photosensitivity are not entirely independent of each other, the accuracy of the data collected during the first stage is not sufficient to give a final optimized design. It only provides a good approximation.

In the second stage, the cladding composition is fixed, and the core composition is finely tuned by adjusting the level of boron in the core to achieve the desired photosensitive profile.

VI. Results and Discussions

As we have mentioned earlier, cladding mode coupling suppression needs to be optimized independently for use with non-hydrogen-loaded and hydrogen-loaded fiber. Two different optimized fiber fabrication process were developed. In both non-hydrogen-loaded and hydrogen-loaded cases, we have achieved suppression of cladding mode coupling to 0.1 dB for a 30-dB grating.

All the gratings were written with a phase-mask technique, using a KrF excimer laser. Typical grating length is ~12 mm. In a typical hydrogenated fiber, the grating depth would reach 40 dB between 0.5 and 2 minutes at 5-Hz repetition rate. The test gratings in this paper were written a long way from growth saturation. In fact, a lower repetition rate was used to slow down writing to enable accurate control of grating depth.

Fig. 3 gives the cladding mode measurement for a fiber optimized for nonhydrogenation, with a cladding mode coupling loss of 0.1 dB for a 30-dB Bragg grating. This fiber was not hydrogenated for this grating. Figs. 4 and 5 show the 0.12 dB-cladding mode coupling loss in a 40-dB grating for another fiber optimized for hydrogenation. The fiber was hydrogenated at room temperature at ~200 bars for ~2 weeks. Fig. 6 gives the index profile of the fiber and its photosensitive profile. The higher level of photosensitivity in the cladding is derived from previous systematic composition study. It cannot be

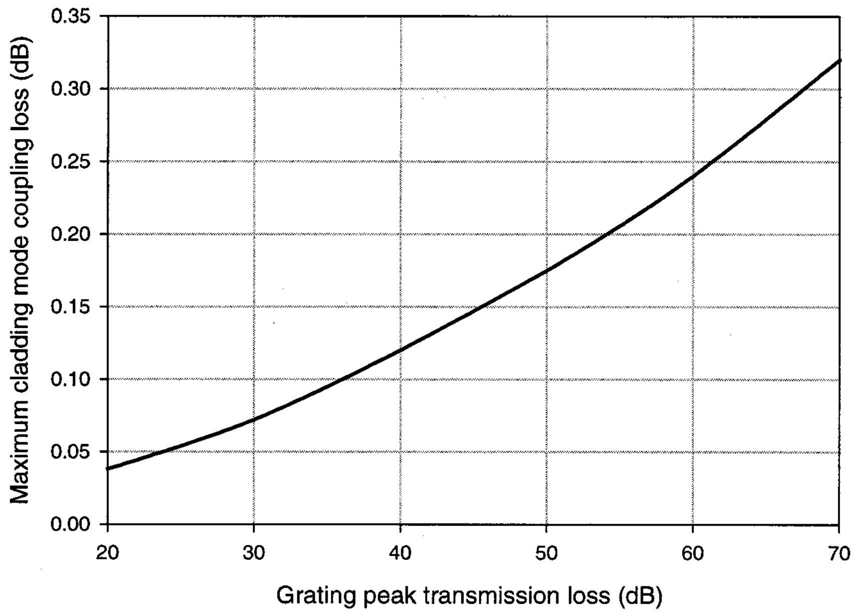

Fig. 7. Dependence of maximum cladding mode coupling loss on peak grating strength modeled for the hydrogenated fiber shown in Fig. 6.

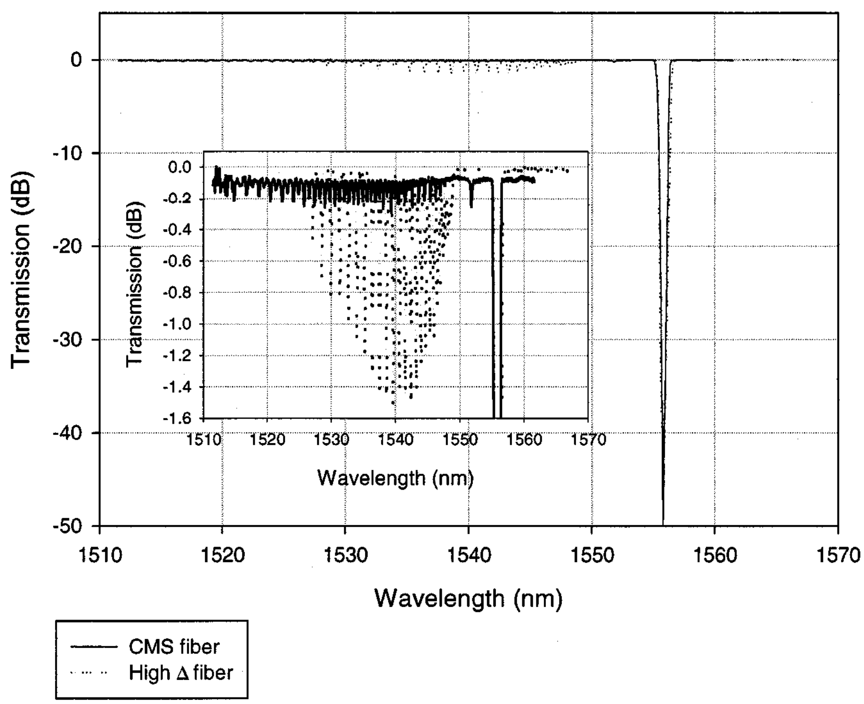

Fig. 8. Transmission of a 50-dB grating written in a hydrogenated fiber similar to that in Fig. 6 together with that of a 40-dB grating written in a fiber with a 2% Δ. It is shown that a maximum cladding mode coupling loss is ~ 0.2 dB for the cladding mode suppression (CMS) fiber while it is 1.5 dB for the 2% Δ fiber.

derived from a single grating measurement, as a lower cladding photosensitivity by the same amount would give the same cladding mode structure. It is shown clearly in Fig. 6 that the photosensitivity in the core and cladding is matched to within 20%. The results, presented in this paper, have been measured with an ASE source and a high resolution OSA. Measurements on selected gratings were also measured, with a tunable single frequency diode laser with a detector. No discernible difference was noted.

It needs to be noted that the growth characteristic of index modulation in core and cladding is expected to be different, due to the large difference in compositions in these two regions of

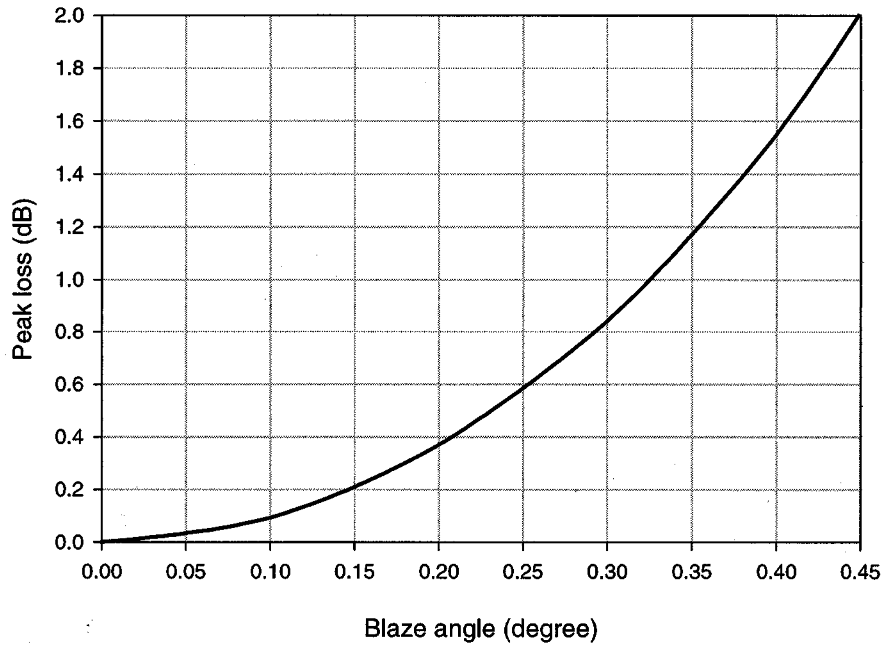

Fig. 9. Blazing sensitivity of coupling loss to LP_{11} mode calculated for a fiber similar to that in Fig. 6 using measured refractive index profile and photosensitive profile.

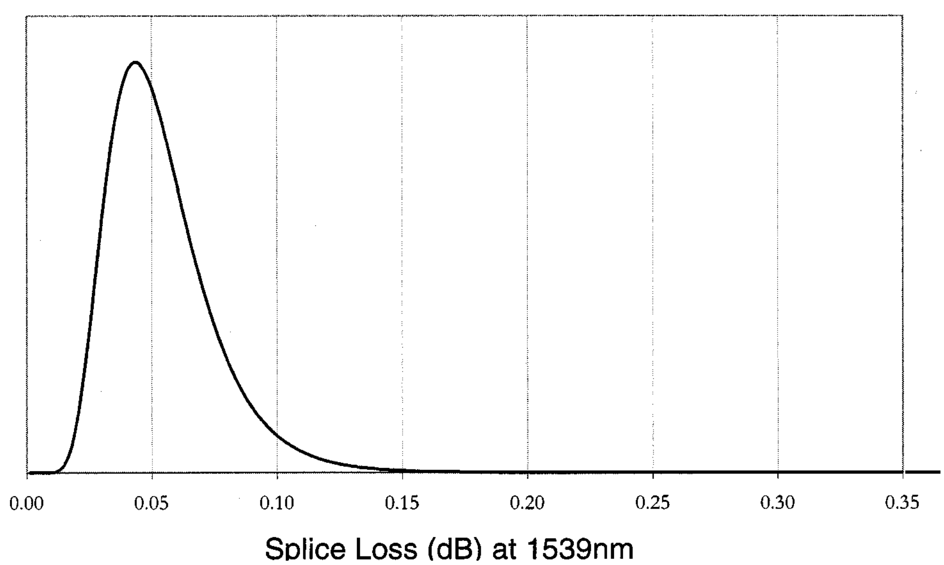

Fig. 10. Distribution of splice loss measured at 1539 nm for a finally optimized fiber.

the fiber. Consequently, the photosensitive profile is expected to vary slightly during grating growth. Indeed, we did observe a small change in cladding mode loss in gratings written to different depths from what is expected, if the photosensitive profile is constant. The projected maximum cladding mode loss at various grating depths for the fiber in Fig. 6, if the photosensitive profile is constant during growth, is given in Fig. 7. This fiber has a measured maximum cladding mode loss of 0.12-40 dB. The projected maximum cladding mode loss is 0.175 dB at 50 dB and 0.24 dB at 60 dB. In a similar fiber, the transmission of a 50-dB grating was measured (see Fig. 8). The maximum cladding mode loss is 0.2 dB, in this case. In the light of growth dependence of photosensitive profile, it needs to be noted that our fiber is optimized for gratings at test grating depth, i.e., 30 dB for nonhydrogenated fiber and 40 dB for hydrogenated fiber. Should a different grating depth is preferred, final fine optimization should be done at the desired grating depth to achieve a better result. The transmission of a 40-dB grating written in a

2% Δ-fiber is also shown in Fig. 8. The 40-grating in the 2% Δ-fiber gives a maximum cladding mode loss of 1.5 dB.

As mentioned earlier, minimizing the blaze angle in the grating writing process is very important in suppression of all cladding modes. Cladding mode coupling loss into asymmetrical cladding modes can become significant, if the grating is blazed. The coupling loss to the LP_{11} mode in a 30-dB grating is calculated for various blaze angles for a fiber similar to that in Fig. 6, using the measured refractive index profile and photosensitive profile, and is plotted in Fig. 9. To achieve a coupling loss less than 0.1 dB into LP_{11} mode in this case, blaze angle needs to be less than 0.13-degree. The LP_{11} mode loss peak is clearly seen in Fig. 8 between the Bragg grating peak and the symmetrical cladding mode peaks. In this case, the LP_{11} loss peak is comparable with that of the maximum symmetrical cladding mode loss peaks.

The final fiber has also been optimized for reduction of splice loss to SMF-28 fiber, by balancing the needs for ease of manufacturing, minimizing blaze sensitivity and modal field diameter matching to SMF-28. With the aid of the fast diffusion constant for the highly doped core and cladding, an average splice loss of 0.04 dB to SMF-28 fiber has been achieved on a conventional splicer, while maintaining the cladding mode coupling suppression performance. A optimization procedure based on a factorial process was used to develop the splice recipe. Fig. 10 gives the distribution of the splice loss with an optimized splice recipe.

To conclude, we have been able to design, model and fabricate fibers for cladding mode coupling suppression in fiber Bragg gratings. We have demonstrated cladding mode coupling loss less than 0.1 dB for 30-dB gratings in different fibers for both hydrogenated and nonhydrogenated cases. The fiber also has been optimized for splicing, with a low average splice loss, of 0.04 dB to SMF-28 fiber.

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