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# Mode Coupling within Inner Cladding Fibers

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We report the formation of inner cladding modes in the optical fiber having an inner cladding structure. The inner cladding layer located between the core- and the cladding- layers of a conventional fiber might have, so called, inner cladding mode(s). The brief history of the inner cladding fiber and the spectral properties of the inner cladding mode are presented. By utilizing fiber gratings, the spectral properties of the inner cladding mode formed in Dispersion Compensating Fiber (DCF) are discussed. It was observed that one resonant peak of a long-period fiber grating was not sensitive to the variation on the cladding surface. With a fiber Bragg grating, a small group of unusual resonant peaks was observed between the main Bragg peak and the series of usual peaks resulted from the mode coupling to counter-propagating cladding modes. Within the DCF by using fiber gratings, it is noted, at least one mode can be coupled to the inner cladding mode and a few outer cladding modes are severely affected by the inner cladding of the fiber.

*OCIS codes : 050.2270, 060.2270, 060.2280, 060.2300, 060.2330.*

## I. INTRODUCTION

A fiber grating has been widely studied as the device that couples the fundamental core mode of a fiber to another core mode or/and to the cladding modes of the fiber. [1] By tailoring the structure of the fiber grating, the spectral properties of the mode coupling can be adjusted. [2] In a single mode fiber, the coupled core mode beam is well guided through the fiber and can be retrieved by using a fiber coupler because it is merely the counter-propagating core mode of the fiber which is well guided in general. However, the coupled cladding modes disappear in general due to the scattering or absorption at the cladding's outer surface. [3] Thus the coupled cladding mode gives a loss peak only in the transmission spectrum of the mode-coupled fiber.

Recently, the coupled cladding modes are utilized for realizing fiber interferometers or chromatic dispersion compensators. If the cladding surface is well maintained to have a good optical quality, the coupled cladding mode can propagate through the cladding part of the fiber without appreciable loss. The fiber interferometer can be composed by making interference between the core mode and the cladding modes whose modal indices are lower than that of the fundamental core mode. [4,5] Similarly, the different modal index, and hence the different dispersion of the cladding mode can be used to implement a chromatic dispersion compensator. [6,7]

However, since the cladding mode is bounded by the TIR (Total internal reflection) at the cladding surface, the outer surface of the cladding layer should be kept to have lower refractive index than that of the cladding material. At the TIR, depending on the refractive index difference between the cladding and the surrounding materials and the propagation angle of a guided cladding mode, there exists a non-zero field, called an evanescent field, outside the cladding region. Theoretically, the evanescent field decays very rapidly but extends infinitely; therefore, the cladding mode is affected by the surface condition of the fiber cladding. [3,8] Even with a core mode, the evanescent field extends beyond the cladding surface. However, when the cladding has enough thickness, the evanescent field outside the cladding becomes negligibly small.

It is desirable to have mode coupling to a mode bounded inside the conventional cladding of a fiber.

This can be realized by introducing an additional layer, called an inner cladding layer, between the core and the conventional cladding layers of a fiber, which provides the so called inner cladding mode. The inner cladding mode is not sensitive to the variation on the outer cladding surface if there exists enough distance between the inner and outer claddings. Further, the mode coupling strength between the core mode and the inner cladding mode is greater than with the conventional cladding mode. Generally, the coupling strength is proportional to the overlap integral between two modes. The inner cladding mode is localized around the inner cladding layer; however, the conventional cladding mode extends across the whole cladding region of the fiber. Several types of fibers have been reported to have the inner cladding modes. In this paper, the brief history of the inner cladding fibers is presented, and the spectral properties of the inner cladding modes are discussed.

## II. INNER CLADDING FIBERS

The first trial for the inner cladding mode coupling was made by using the DSC (Dual shape core) type DSF (Dispersion Shifted fiber) fiber of Japan. [3,9] A long-period fiber grating (LPG) fabricated in the DSC-DSF had an unusual resonant peak in the transmission spectrum. The first resonant peak located in the shortest wavelength was much larger than the second peak. In general, the coupling constant becomes larger as the mode order increased with a conventional single mode fiber. The abnormally big peak in the location of the first order cladding mode was very peculiar and needed verification. To verify the abnormal peak, several experiments had been done and we reported that the peak was originated from the coupling to the inner cladding of the fiber. [3,10]

As shown with Fig. 1, the index profile of the DSC-DSF has a pedestal structure between the conventional core and cladding layers of a matched-cladding fiber. [9] Depending on the height and width of the pedestal layer, a mode coupling might be possible to the mode that is bounded by the TIR at the interface between the pedestal layer and the outer cladding layer. For this kind of mode coupling, the coupled mode does not interact with the cladding surface or boundary, thus, the coupled mode can be named as the inner cladding mode. And the pedestal layer of Fig. 1 can be regarded as an inner cladding of the fiber.

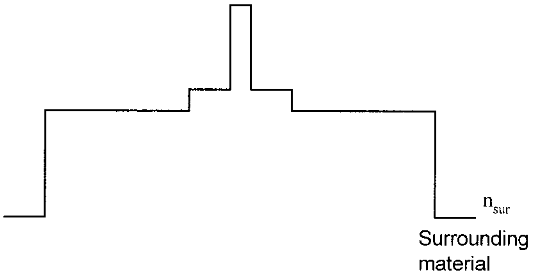

FIG. 1. The refractive index profile of DSC-DSF fiber. It has a pedestal layer.

As was mentioned above, the inner cladding mode is unaffected by the changes at the surface condition of the outer cladding. It was verified by inducing mechanical scratching and applying index matching-oil on the cladding surface of the LPG made in the fiber, and showing that only the first mode was not affected by the variations. [3] It was also verified by making an LPG pair in the fiber. [5,10] In the LPG pair, the cladding mode coupled by the first grating is re-coupled to the core mode by the second grating and makes interference with the core mode uncoupled by both gratings, which gives interference fringes in the series of resonant peaks of a conventional LPG spectrum. Therefore, with a conventional cladding mode, if the cladding surface between the gratings of the LPG pair is immersed in an index matching oil, then the resonant peak of the grating is affected; generally reduced and shifted. [1,3] However, the interference fringes formed in the first resonant peak of the LPG pair made in the DSC-DSF were not affected by the index matching oil applied on the cladding surface. [3]

Recently, in the name of few mode fibers or high order mode fibers, the inner cladding fibers were studied to make chromatic dispersion compensators. [6,7,11] Since the coupled cladding mode has different dispersion from that of the core mode, the dispersion accumulated during the propagation through the core of a fiber might be compensated by making it propagate through the properly designed cladding part of the fiber. For that case, tailoring the dispersion of the cladding mode is important, which can be done by adjusting the index profile of the middle (or inner cladding) layer of the fiber. Fig. 2 shows the index profile of the fiber that is specially designed to have the inner cladding mode that gives precise dispersion compensation. [7] The structure has a raised ring layer instead of the pedestal layer of Fig. 1. By adjusting the ring structure, the dispersion of the mode coupled into the ring layer could be adjusted to have proper dispersion compensation.

## III. INNER CLADDING MODES

In a conventional step-index single- or multi- mode fiber, the mode nomenclature is clear. If a mode is bounded by the TIR at the core-cladding boundary,

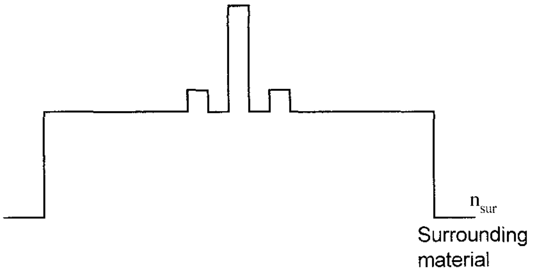

FIG. 2. The refractive index profile of few mode fiber. It has a raised ring layer.

it is a core mode. And if bounded by the TIR at the cladding-surrounding boundary, it becomes a cladding mode. In terms of effective index, the classification becomes simpler. If the effective index of a mode is higher than the refractive index of the cladding material, it is a core mode. Otherwise, it becomes a cladding mode.

However, with the fibers having middle layer structures as in Figs. 1 and 2, the classification in fiber and fiber modes becomes complicated. For the case of Fig. 1, if a mode has the effective index between the (outer) cladding and the middle pedestal layers, then the mode can be called an inner cladding mode or a higher order core mode at the same time. The fiber of Fig. 1 was designed as a single mode fiber but named as Dual Shape Core fiber; however, it can be regarded as a Dual Shape Cladding single mode fiber. Originally, the inner pedestal layer was simply inserted in order to adjust the dispersion of the fundamental core mode. Therefore, the pedestal layer might be regarded as the inner cladding layer, and if there exists a mode bounded by the interface between the pedestal and outer cladding layers then it can be called as an inner cladding mode. The existence of the inner cladding mode depends on the height and width of the pedestal layer.

The fiber of Fig. 2 is called a few mode fiber, which means there exists several core modes. If we regard the inner ring layer as a part of the core structure, then the fiber becomes a multi mode fiber having multiple core modes. However, the fiber was designed to have the first order core mode well confined within the central core structure and a few additional modes having appreciable field distributions in the ring layer region. Therefore, from the viewpoint of fiber gratings, it is more reasonable to regard it as the fiber having an inner cladding and carrying a single core mode and a few inner cladding modes. Without great effort, the beam launched through the fiber is guided through the single core mode and then can be coupled to the inner cladding modes by fiber gratings.

In general, the inner cladding part of a single mode fiber is tailored to adjust the dispersion properties or to enlarge the modal field diameter of the core mode. The fiber of Fig. 1 happened to have an inner cladding mode, while the fiber of Fig. 2 was intentionally designed to have a few inner cladding modes even though they were called higher order core modes. Software packages are available that can calculate the field profiles of the modes formed in the fiber having arbitrary index profile. However, the quantitative analysis is not helpful in understanding the formation of the inner cladding modes, further it is beyond the scope of this paper. We hope to report the mathematical analysis of the inner cladding modes in near future.

The similar inner-cladding mode was recently discovered with the DCF (Dispersion Compensating Fiber) made by KT Corp., Korea. The spectral properties of long- and short- period fiber gratings fabricated in the DCF are discussed in the following section. The verification of the inner cladding mode with the fiber gratings is presented.

## IV. FIBER GRATINGS IN DISPERSION COMPENSATING FIBER

The transmission spectrum of the LPG fabricated in the DCF of KT Corp., Korea is depicted in Fig. 3. Compared with the typical LPG spectrum of Fig. 4, we can see that the resonant peaks in the shorter wavelengths are not normal. Fig. 4 was obtained by fabricating an LPG in AT&T's single mode fiber having a slightly depressed inner cladding layer. The grating had a 400 $\mu$m periodicity. The resonant peaks in the shorter wavelengths are smaller than the ones in the longer wavelengths. According to the coupled mode theory, in a matched cladding fiber, the mode coupling coefficient increases with the mode order up to the first ten modes. [12] However, with the DCF the resonant peak of the lower order mode was not severely smaller than that of the other higher order modes as shown in Fig. 3. The grating was made by illuminating the fiber with an UV laser beam through

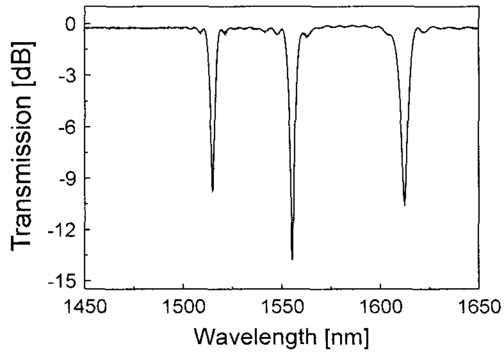

FIG. 3. The transmission spectrum of the LPG fabricated in the DCF of KT Corp., Korea.

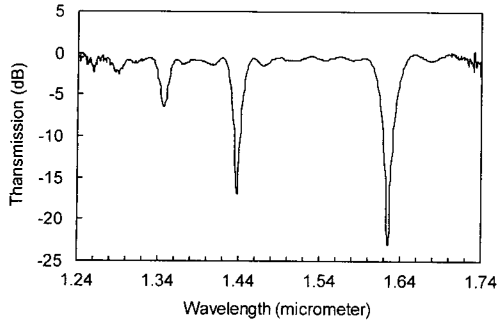

FIG. 4. The transmission spectrum of the LPG fabricated in the single mode fiber of AT&T.

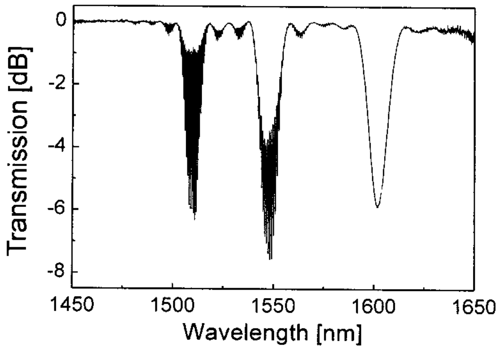

FIG. 6. The transmission spectrum of the LPG pair fabricated in the DCF. The acrylate coating between gratings was not removed.

an amplitude mask of a 700 $\mu$m periodicity. Even though the spectral ranges of Figs. 3 and 4 are not the same, there were no appreciable resonant peaks out of the ranges. Further, it was checked that the resonant peaks of Fig. 3 were not over-coupled.

The refractive index profile of the DCF is schematically depicted in Fig. 5. The diameter of the center core was about 3.1 $\mu$m, smaller than a conventional single mode fiber. The refractive index of the center core was about 2.5 % higher than that of the outermost cladding of the fiber. It had one raised-ring and one reduced-ring layers as the inner cladding structure, which had about ±0.5 % index variations, respectively. We can think of a mode or modes having the effective index between the indices of the outer cladding and the raised-ring layers. To verify the possibility, a pair of LPGs was made along the DCF. The separation between the gratings was 250 mm. The original acrylate coating on the surface of the cladding between the gratings was not removed. The transmission spectrum of the LPG pair is shown with Fig. 6. Among the three resonant peaks, the first peak at the shortest wavelength preserves the interferences fringe and the peak at the longest wavelength does not show any interference effect. The middle one has deteriorated fringes. Considering that the conventional cladding mode is absorbed by the acrylate coating on the cladding surface, the first peak can be considered as the peak resulted from the coupling to the inner cladding of the DCF. After removing the acrylate coating on the cladding surface, various index matching oils were applied on the cladding surface and the interference fringes in the first peak of Fig. 6 were monitored. As shown with Fig. 7, no appreciable oil-induced spectral change was observed.

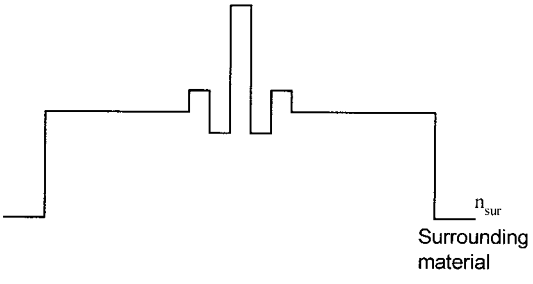

FIG. 5. The refractive index profile of DCF fiber. It has a raised and a reduced ring layers.

The near field images of the first two coupled modes were captured and shown in Fig. 8. A tunable laser beam tuned to the corresponding resonant wavelength of the mode was launched into the fiber, and the light intensity at the other fiber end was measured by a CCD camera. From Fig. 8(a), we can see that the first mode is well confined around the inner cladding and far from the outer cladding boundary having a radius of 62.5 $\mu$m. However, the second mode shown in Fig. 8(b) is not easily classified. We can consider it as the second order inner cladding mode or as the first order outer cladding mode. Further systematic analysis is required. Even though it was not depicted, the near field image of the core mode did not have interes-

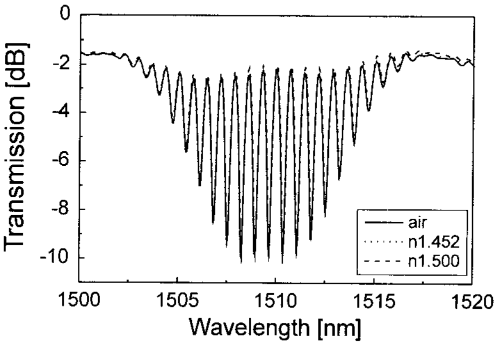

FIG. 7. The transmission spectrum of the LPG pair fabricated in the DCF. The interference fringes were not affected by the index matching oil applied on the cladding surface.

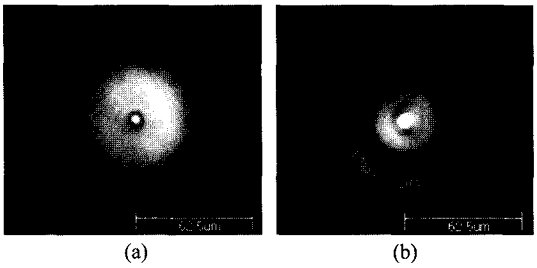

FIG. 8. The near field images of the first mode (a) and the second (b) mode coupled by an LPG fabricated in DCF fiber.

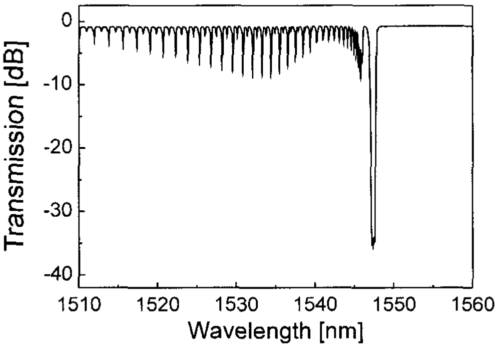

FIG. 9. The transmission spectrum of the FBG fabricated in the DCF of KT Corp., Korea.

ting feature. It had a single peak around the center core region, similar to the bright spots of Figs. 8(a) and(b).

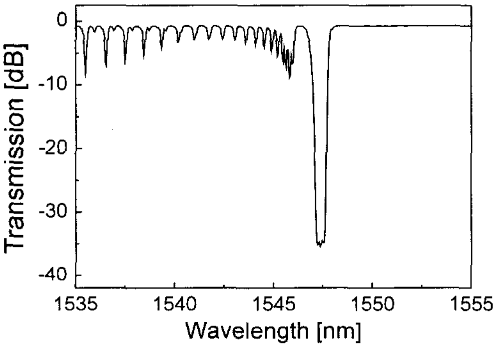

FIG. 10. The detailed spectrum of Fig. 9.

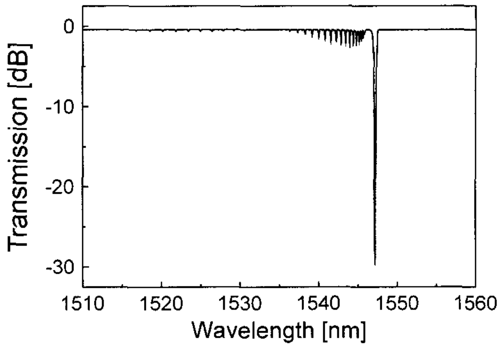

FIG. 11. The transmission spectrum of the FBG fabricated in photosensitive single mode fiber of FiberCore.

In the same DCF fiber, an FBG (Fiber Bragg Grating) was fabricated and the transmission spectrum was measured and shown in Fig. 9. The interesting thing is that the series of resonant peaks in the shorter wavelength region of the main peak has two groups. Fig. 10 shows the details of Fig. 9. In order to compare, the same FBG was fabricated into FiberCore's photosensitive single mode fiber. As Fig. 11 shows, we can observe only one group of resonant peaks varying smoothly, which is similar to the reported one with a weak LPG. [12] Considering that the resonant peaks in the shorter wavelength region of an FBG is resulted from the coupling to the counter propagating cladding modes [1,12], we can say that the small group of the peaks in Figs. 9 and 10 might have originated from, or at least be affected by, the inner cladding of the DCF. Due to the depressed layer of the DCF, the definition and interpretation of the inner cladding mode(s) become a little more complicated. However, we can clearly conclude that the DCF has at least one inner cladding mode that is not affected by the change in the outer cladding surface. Even though, the coupling mechanisms of the LPG and the FBG are a little bit different, the behaviors of the resonant peaks of the FBG originated from the coupling to the counter-propagating cladding are very similar. The location of the resonant peak is determined by the effective index of the cladding mode, and the resonant depth is proportional to the overlap integral between the core and the corresponding cladding mode.

The transmission spectrum of an LPG fabricated in DSC-DSF of Fig. 1 is redrawn in Fig. 12 from ref. [3] We can clearly see that the first peak is abnormally

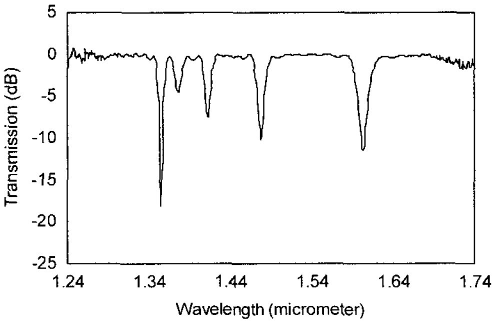

FIG. 12. The transmission spectrum of the LPG fabricated in DSC-DSF fiber.

strong against the other higher order modes. The grating had a 400 $\mu$m periodicity. However, when the grating periodicity was increased to have the first mode coupling around the 1.55 $\mu$m communication band, the relative strength of the first mode was severely reduced, which indicates that the mode was weakly coupled to the inner cladding of the fiber. As mentioned, the fiber was designed to adjust the dispersion of the core mode. If the inner pedestal layer of DSC-DSF (see Fig. 1) had a slightly higher refractive index, we would have a strong inner cladding mode in the 1.55 $\mu$m communication band. Active approaches to design and fabricate fibers having various inner cladding layers are required for advanced applications.

## V. CONCLUSION

We have presented the brief history of inner cladding fibers and the spectral properties of inner cladding modes. The inner cladding fiber has an intermediate layer between the core and cladding layers of a conventional single mode fiber. From the viewpoint of fiber gratings, the intermediate layer can be regarded as an inner cladding when it can handle at least one mode. Since the inner cladding mode is bounded at the interface between the inner and outer cladding layers, it is not affected by the changes at the outer cladding surface. Further, by adjusting the structure of the inner cladding layer, it is possible to have an inner cladding mode that can compensate the chromatic dispersion accumulated during the core mode propagation.

Properties of the fiber gratings fabricated in the DCF fiber of KT, Korea, have been reported. The transmission spectrum of an LPG had the resonant peak that was not affected by the index matching oil on the outer cladding surface. The FBG fabricated in the same fiber had two groups of side peaks at the shorter wavelength side of the main Bragg peak. One group is surely accounted for the mode coupling from the fundamental core mode to the counter-propagating cladding modes that are bounded by the outer cladding surface of the fiber. The other small group resulted from, or at least is affected by, the inner cladding layer of the fiber. Further systematic analysis is required to have better understanding of the inner cladding modes.

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