Optical Fibers with Depressed Claddings for Suppression of Coupling into Cladding Modes in Fiber Bragg Gratings

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Abstract—A new method for suppression of coupling from guided optical modes into cladding modes in an optical fiber Bragg grating using a fiber with a strongly depressed cladding is proposed. Strong suppression of the coupling has been demonstrated both theoretically and experimentally.

Index Terms—Optical fiber gratings.

I. INTRODUCTION

OPTICAL fiber Bragg gratings have attracted much attention in recent years due to their numerous applications such as reflectors for fiber lasers, filters, and sensors. In a fiber grating with a photosensitive core, the guided LP01 mode, however, does not only reflect into the LP01 mode itself but also into cladding modes and radiation modes which are eventually absorbed by the high refractive index polymer coating. This coupling causes a series of loss bands at the short wavelength side of the main Bragg band. This loss can be quite severe in strong gratings and restricts the use of these gratings in a WDM system. One proposed method to counter this problem is based on suppression of the normalized refractive index modulation for this coupling by having a uniform photosensitive region across the cross section plane of the optical fiber [1]. From the orthogonality principle of the modes, the overlap of the modal fields and the grating index modulation would be zero in this case. The LP01 mode will therefore not couple into any of the cladding modes. Since the LP01 mode only has significant field distribution over the core and the part of the cladding immediately next to the core, it is usually sufficient to have only this part of the optical fiber photosensitive. Although it is possible to introduce a photosensitive cladding around a photosensitive core, it is, however, very difficult to obtain the same photosensitivity over both cladding and core. The second proposed method is to use a high NA fiber [2]. The use of a high NA fiber increases the gap between the main grating band and the next cladding mode coupling band, so it leaves a useful operation band. However, such a band is only ~7 nm wide in a high-NA fiber (0.25) and this is much less than what is desired in most applications.

In our proposed method, a depressed cladding is added between the photosensitive core and the normal cladding. Such a depressed cladding is very effective in reducing the cladding mode field strength over the core region of the optical fiber and therefore reduces the coupling strength between the guided mode to the cladding modes. This is also noted by authors of [3] for lower order cladding modes. By introducing a depressed cladding with appropriate index and thickness, substantial suppression of the coupling into the cladding modes can be achieved. This method can also be combined with the photosensitive cladding method to achieve a further suppression of the coupling. Most of the state of the art technology for silica optical fiber manufacture is based on a chemical vapor deposition process which allows a depressed cladding to be easily introduced by doping silica with fluorine or boron.

The effective index modulation for coupling between the guided LP01 and LP_{mn} modes is proportional to the coupling strength,

\[
\Delta n_{\text{eff}} = \int_0^{2\pi} \int_0^\infty \Delta n(r, \varphi) \psi_{01}(r, \varphi) \psi_{mn}(r, \varphi) r \, dr \, d\varphi
\]

(1)

where \(\Delta n(r, \varphi)\) is the refractive index modulation of the grating, and \(\psi_{01}(r, \varphi)\) and \(\psi_{mn}(r, \varphi)\) are the normalized optical field distributions of the LP01 mode and LP_{mn} mode respectively. Transmission at the resonant wavelength (\(\lambda_{\text{Bragg}}\)) of a uniform grating is given by \(1 - \tan^2(\pi \Delta n_{\text{eff}} L / \lambda_{\text{Bragg}})\), where \(L\) is the grating length.

We studied a 125-\(\mu\)m fiber that has a step index profile and a core with uniform photosensitivity for simplicity. In practice, an optical fiber does not have a step index profile and \(\Delta n(r, \varphi)\) is not constant over the core. This, however, will only introduce a quantitative error in the analysis and does not affect the general conclusion. Since \(\Delta n(r, \varphi)\) is uniform over the fiber core, i.e., \(\Delta n(r, \varphi) = \Delta n\) when \(r < \rho\), \(\Delta n(r, \varphi) = 0\) elsewhere, where \(\rho\) is the core radius, it can thus be taken out of the integral in (1). We are comparing coupling strength between modes with the same grating strength, i.e., the same \(\Delta n\). We can therefore drop \(\Delta n\) out of (1) and just use the remaining integration part in our analysis, which becomes

\[
\text{NOI} = \int_0^{2\pi} \int_0^\rho \psi_{01}(r, \varphi) \psi_{mn}(r, \varphi) r \, dr \, d\varphi.
\]
This is the normalized overlap integral of the two modes over the core region. Two sets of modes, LP\textsubscript{0n} and LP\textsubscript{1n} modes, are studied in our analysis. \(\psi_{0n}(r, \varphi)\) has a radial symmetry and does not depend on \(\varphi\), i.e., \(\psi(r, \varphi) = \psi(r)\), however \(\psi_{1n}(r, \varphi)\) is radially asymmetric and changes sign when \(\varphi\) changes by 180°, i.e., \(\psi(r, \varphi) = -\psi(r, \varphi + \pi)\). Therefore, for the LP\textsubscript{1n} modes, NOI in (2) equals to zero.

There is, therefore, no coupling between the LP\textsubscript{01} mode and the LP\textsubscript{1n} modes in a grating with a uniform index modulation over the core. If a grating is blazed or has a nonuniform refractive index change over the core, coupling between the LP\textsubscript{01} mode and the LP\textsubscript{1n} modes can occur. We consider the worst case in our analysis where \(\Delta n(r, \varphi) = -\Delta n(r, \varphi + \pi)\), hence the product \(\Delta n(r, \varphi) \psi(r, \varphi)\) in (1) will not change sign as \(\varphi\) changes. This is equivalent to replacing \(\psi_{1n}(r, \varphi)\) with only the positive part of \(\psi_{1n}(r, \varphi)\) in (2). In the analysis, we used the following parameters for the fiber core: a core radius of 2.8 \(\mu m\), and a core refractive index of 0.01 above that of the silica cladding. We have also assumed that air with a refractive index of 1 surrounds the optical fiber.

Fig. 1 shows the NOI of the LP\textsubscript{01} mode and the first nine modes of the LP\textsubscript{0n} modes over the core region at different depressed index depths of the depressed cladding. The thickness of the depressed cladding used is 13.4 \(\mu m\). As a depressed cladding with increasing depressed index depth is introduced, the guided LP\textsubscript{01} mode is more confined to the core and the increase of the field strength of the LP\textsubscript{01} mode over the core leads to an increase in the NOI between the LP\textsubscript{01} mode and the LP\textsubscript{01} mode over the core. As expected from the reduction of the field strength of all the other LP\textsubscript{0n} modes over the core, the NOI of the LP\textsubscript{01} mode with all the other LP\textsubscript{0n} modes over the core decreases with an increase in the depressed index depth. For the higher order LP\textsubscript{0n} modes, e.g., the LP\textsubscript{08} and LP\textsubscript{09} modes, the decrease is only significant if a depressed index depth of more than 0.003 is used. In general, a suppression of more than 20 dB can be achieved for the LP\textsubscript{0m} cladding modes in Fig. 1 if a depressed depth of more than 0.01 is used.

Fig. 2 shows the NOI of the LP\textsubscript{01} mode and the first nine modes of the LP\textsubscript{1n} modes over the core at different depressed index depths of the depressed cladding. For the lower order LP\textsubscript{1n} modes, the NOI over the core decreases as a depressed cladding with an increasing depressed depth is introduced. For the higher order LP\textsubscript{1n} modes, e.g., the LP\textsubscript{17}, LP\textsubscript{18}, and LP\textsubscript{19} modes, an increase of NOI over the core is seen with an increase in the depressed index depth when the depressed index depth is small [3]. However, a reduction of NOI over the core for all the LP\textsubscript{1n} modes in Fig. 2 can be obtained when a depressed index depth of more than 0.008 is used. A near 20-dB suppression for all the modes in Fig. 2 can be achieved with a depressed index depth of more than 0.012. In general, the coupling into the LP\textsubscript{1n} modes can be suppressed by reducing the blaze angle of the grating and having a uniform refractive index modulation over the core. These methods, however, do not suppress the coupling from the LP\textsubscript{01} mode into the LP\textsubscript{0m} modes.

Fig. 3 shows the NOI over the core between the LP\textsubscript{01} mode and the first nine modes of the LP\textsubscript{0n} modes at different thickness of the depressed cladding. A depressed index depth of 0.01 is used for this analysis. The NOI's between the LP\textsubscript{01} mode and all the other LP\textsubscript{0n} modes in Fig. 3 decrease with an increase in the thickness of the depressed cladding.

Fig. 4 shows the NOI of the LP\textsubscript{01} mode and the first nine modes of the LP\textsubscript{1n} modes over the core at different thickness of the depressed cladding. For the lower order LP\textsubscript{1n} modes, the NOI over the core decreases with an increase in the thickness of the cladding. For the higher order LP\textsubscript{1n} modes, e.g., LP\textsubscript{18} and LP\textsubscript{19} modes, an increase of NOI over the core is seen with an increase in the thickness of the cladding when the thickness is large. This shows the existence of an optimum cladding thickness for the suppression of these LP\textsubscript{1n} modes. In this case, the optimum thickness is \(\sim 12 \mu m\) where a suppression
Fig. 3. The effect of the thickness of the depressed cladding on NOF for the first nine modes of LP_{0n} mode.

Fig. 4. The effect of the thickness of the primary cladding on NOF for the first nine modes of LP_{1n} mode.

of more than 10 dB is obtained for the LP_{19} mode. We have fabricated an optical fiber with a depressed cladding to demonstrate the suppression of the coupling from the guided modes into cladding modes. The fiber has a core radius of 2.8 \mu m, an effective index difference of 0.01 between the core index and the index of the silica cladding, a depressed index depth of 0.009 and a depressed cladding thickness of 13.4 \mu m. The depressed cladding was achieved by boron-doping and the core was doped with germanium. The fiber has a LP_{11} mode cutoff of 1.4 \mu m.

Fig. 5 shows the transmission spectrum of a 15-mm-long grating with a \Delta n_{eff} of 0.001 in (a) a step index fiber with a photosensitive core with a NA of 0.15 and radius of 3.98 \mu m, and (b) the fiber fabricated with a depressed cladding. The strong suppression of the coupling of the guided LP_{01} mode into cladding modes in the fiber with a depressed cladding can be seen in Fig. 5(b). The coupling into cladding modes have been suppressed to \sim 10% in this case (\Delta n_{eff} = \sim 1 \times 10^{-5}), a suppression of 20 dB is achieved, close to what is predicted by the theory assuming some blaze in the grating. We cannot analyze the field for LP_{0n} and LP_{1n} modes for \nu > 10, limited by the software that we used. From [3], the largest overlap happens around \nu = 17 for LP_{0n} modes and \nu = 13 for LP_{1n} modes, and is less than 2 dB larger than that of LP_{011} and LP_{19} modes. It, therefore, will only cause a small error in our estimate of maximum suppression by using modes up to \nu = 9.

To conclude, we have demonstrated an effective method for suppression of coupling from a guided mode to cladding modes in a fiber grating. Although the fiber used in this study has a small modal field diameter, the principle can be used to design fibers with larger modal field diameters matched to standard single-mode fibers.

REFERENCES

