Dispersion compensation in transmission using uniform long period fiber gratings

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Abstract

It is proposed that the high dispersion at the transmission band edges of uniform long period gratings (LPG) fabricated on relatively high $\Delta$ fibers can be used for efficient dispersion compensation. Since the transmission of LPG varies with length of the grating or refractive index modulation, we show that it is possible to tailor the transmission spectrum to obtain high transmission with constant dispersion and negligible delay ripple over a reasonable bandwidth. Since the proposed structure works in transmission it should be suitable for fiber optic communication links.

Keywords: Long period fiber gratings; Dispersion compensation; Transmission

1. Introduction

With the coincidence of low loss window and the gain bandwidth of erbium-doped fiber amplifiers at 1550 nm, the major concern of optical fiber communication link has shifted from optical compensation of loss to optical compensation of dispersion. With increasing demand for high bit rate optical communication system, the chromatic dispersion in the optical signal is becoming a crucial issue. There are many techniques for compensating dispersion in fiber optic systems. These include use of dispersion compensating fibers [1] and fiber grating [2]. Dispersion compensator working in reflection mode utilizing chirped fiber Bragg grating was proposed by Oullette [2] and has been demonstrated experimentally [3]. This is considered as one of the efficient methods for dispersion compensation. But the use of such fiber Bragg gratings requires the use of expensive circulators besides the complexity of chirping the grating. Hence there has been great interest among researchers to device all-fiber dispersion compensators working in transmission mode. These efforts include chirped gratings enabling coupling between two co-propagating modes having different group velocities [4]. Apart from being chirped, the inherent disadvantage of this system is that after dispersion compensation the power has to be coupled back into the fundamental core mode for further transmission. This would affect the compensated dispersion as well as increases loss in transmission. Oullette [5] has discussed the
limitations of using short period fiber Bragg gratings in transmission mode for dispersion compensation. It was shown that only a small amount of dispersion compensation could be achieved, due to the small bandwidth of the high dispersion region and also there is a considerably low transmission due to part of power being reflected. Its performance can be improved by apodizing the grating but this too has its inherent limitations. This has also been experimentally demonstrated [6]. Recently the use of concatenated chirped long period gratings (LPG) has been proposed for dispersion compensation [7]. This device requires coupling to a very high order cladding mode making it highly prone to bend losses.

In this paper we propose the use of a uniform LPG, fabricated on fiber with relatively high $A$ value, as an efficient dispersion compensator. We show that by appropriately choosing the length of the grating and the refractive index modulation one can achieve a large dispersion over a reasonable bandwidth with very low transmission loss. We show that weak and relatively long LPGs act as efficient dispersion compensators with negligible delay ripples.

2. Theory

LPGs have perturbation period typically above 100 μm and couple power from the fundamental core mode to the cladding modes. We consider a uniform LPG with a perturbation period $A$ that is capable of coupling power from core mode to one of the cladding modes. The complex transmission amplitude of the LPG is given by [8]

$$T(z) = \cos(\gamma z) + i \frac{\delta \sin(\gamma z)}{\gamma}$$

(1)

where $\delta$ is the detuning experienced by different wavelengths and is given by $2\delta = \beta_{sc} - \beta_{cl} - (2\pi)/A$, where $\beta_{sc}$ and $\beta_{cl}$ are the propagation constants of the core mode and the coupled cladding mode respectively and $\gamma^2 = \kappa^2 + \delta^2$, where $\kappa$ is the coupling coefficient. From the complex transmission amplitude the phase response $\phi(\omega)$ can be obtained as

$$\phi(\omega) = \tan^{-1}\left(\frac{\delta \tan(\gamma z)}{\gamma}\right)$$

(2)

Now, the delay experienced by the frequency component $\omega$ is given by $\tau = d\phi/d\omega$. Differentiating Eq. (2) with respect to $\omega$ we get

$$\tau = \frac{2\delta \sec^2(\gamma z) \frac{dz}{d\omega} + \tan(\gamma z) \frac{d\delta}{d\omega}}{\left(1 + \frac{\delta^2}{\gamma^2} \tan^2(\gamma z)\right)}$$

(3)

The rate of change of delay with frequency gives the dispersion experienced by the frequency components on traversal through the grating. Thus the group velocity dispersion $D$ is given by [9]

$$D = -(2\pi c/\lambda^2) \frac{d^2\phi}{d\omega^2}$$

(4)

The wavelength component having minimum detuning would be the central wavelength $\lambda_c$ of the transmission spectrum. On either side of $\lambda_c$, detuning increases in magnitude with positive or negative sign. With increasing magnitude of detuning the frequency components suffer lesser coupling to cladding region with maximum power flow confined to the core region. Since the group velocity in the core region is lesser than in cladding, these sideband wavelengths would suffer larger delay in propagation compared to the central wavelength, with increasing delay on both sides. This results in a positive dispersion corresponding to one band edge and negative dispersion corresponding to the other band edge. Magnitude of dispersion would depend upon the slope of the delay variation with frequency. Hence steeper the delay variation, larger would be the dispersion.

3. Results and discussion

To show the dispersion compensation capability of LPGs, we consider an LPG of length ($L_e$) 2 m with a uniform periodicity of 147.7 μm (corresponding to coupling from fundamental core mode to LP_{01} cladding mode) formed on a fiber with a core radius of 4.0 μm, cladding radius 62.5 μm and $A = 0.01$ (cladding is assumed to be made of pure silica). Fig. 1 shows the transmission spectra and the corresponding dispersion curves.
for different values of $\kappa L_g$ (with $\kappa$ the central wavelength coupling coefficient). Our calculations show that for $\kappa L_g$ value of 2.55, dispersion is constant over a reasonably large bandwidth. For larger values of $\kappa L_g$, higher dispersion can be obtained but over a lower bandwidth. Dispersion of about 1300 ps$^2$ is obtained over a bandwidth of about 0.07 nm for $\kappa L_g = 2.55$.

One of the main concerns in dispersion compensators based on chirped Bragg gratings is the ripple in the delay spectrum leading to nonuniformity in the dispersion compensated. In order to check the ripple in the delay variation for the proposed dispersion compensator, in Fig. 2 we have plotted the wavelength variation of delay with a resolution of 0.0012 nm. It can be seen that in the present case the delay ripple is negligible which is a desirable character for a dispersion compensator. The delay plot for $\kappa L_g = 2.55$ is almost linear (implying constant dispersion) about the center wavelength. The reflective chirped Bragg grating dispersion compensators show considerable delay ripples due to multiple reflections occurring within the grating. This problem can be reduced by apodization but it decreases the bandwidth $[10]$. The proposed device with prominent co-directional coupling and negligible reflection effects shows (see Fig. 2) very smooth delay curves as expected. Since the proposed device uses very long and weak gratings (peak refractive index change $\sim 10^{-5}$) the Fabry-Perot like reflection effects due to the grating edges would also be negligible.

Since the transmission of LPG is dependent on the length and refractive index modulation of the grating, by judiciously varying the refractive index modulation or grating length, constant dispersion can be achieved over a larger bandwidth. The bandwidth of the filter can be increased by decreasing the device length, but at the expense of a lower magnitude of dispersion being compensated. Thus with $L_g = 1.5$ m, for $\kappa L_g = 2.55$ at the central wavelength, an almost constant dispersion of about 730 ps$^2$ is obtained for $\Delta \lambda = 0.092$ nm. Fig. 3 shows the dispersion and the transmission plots for this case. Only the region of positive dispersion ($d^2 \phi / d \omega^2$ positive) which is of interest is shown. Transmission loss is $<1.5$ dB for both the cases. A dispersion compensation bandwidth of 0.092 nm corresponds to 11.5 GHz and can be used for compensation of dispersion accumulated in 2.5 and 10 Gbit/s systems.

In order to compare different grating dispersion compensating structures, a figure of Merit, $M$ was introduced by Priest and Giallorenzi $[9]$

$$M = \delta \omega^2 \frac{d^2 \phi}{d \omega^2}$$

(5)

where $\delta \omega$ is the bandwidth of the pulse or maximum bandwidth over which the dispersion of the filter is constant with high transmission. The compression ratio of the Gaussian pulse propagating in the grating is given by $[4]$.
\[ \frac{\tau_1}{\tau_2} = \sqrt{1 + (M')^2} \]

where \( M' = M/4\ln 2 \); \( \tau_1 \) is the FWHM of the pulse entering the dispersion compensating filter (DCF) after propagating through the fiber and \( \tau_2 \) is the FWHM of the recompressed pulse at the end of the DCF. For the grating parameters corresponding to Fig. 1 with \( \kappa L_2 = 2.55 \) the compression ratio is 1.66. For the grating corresponding to Fig. 3 the compression ratio is 1.7. These results show that LPGs can act as efficient dispersion compensators. By choosing suitable parameters better compression ratios can be achieved. Thus a properly designed LPG can provide an almost flat dispersion over a reasonably high transmission band. With low insertion loss and negligible delay ripple, this simple structure working in transmission mode seems suitable for being used in the optical communication links.

Since the cladding modes have a greater sensitivity to the surroundings, care has to be taken in packaging the LPG based devices. The fiber can be recoated with a material that has a refractive index lower than the cladding. Also fiber geometries that inherently shield the cladding mode from the surrounding can be used [11]. Since the proposed device uses coupling to the lower order cladding modes bend loss would not be as significant as with the proposal of Ref. [7] where coupling to very higher order cladding mode is considered. Since LPGs have a period at least two orders of magnitude larger than the signal wavelength, they are expected to be less sensitive to waveguide inhomogeneities compared to the short period gratings. The issues of packaging LPG based devices are discussed in detail in Ref. [7]. The present result shows that the proposed device could compensate only over a bandwidth which are too narrow for use in the >10 Gbit/s communication systems. But by suitably choosing the grating profile the bandwidth could be improved. The concatenated chirped LPG proposed [7] although offers relatively larger bandwidth for similar dispersion values, requires more components like two concatenated oppositely chirped gratings with a core mode block or a Bragg grating in between with possible problems of bend loss. Since the proposed system working in transmission is simple and less sensitive to bend loss an improvement in the bandwidth could make it suitable for even >10 Gbit/s systems.

4. Conclusions

In conclusion we have proposed the use of uniform LPG fabricated on relatively high \( A \) fibers as efficient dispersion compensators. We have shown that such compensators have high disper-
sion values with reasonable pulse compression ratio with negligible delay ripple. The proposed filter works in the transmission mode and avoids expensive circulators and the complexity of chirping the grating. This proposed device with a very simple structure, low insertion loss and negligible delay ripple should be suitable for optical communication links.

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