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Dispersion Compensator in Transmission using Tilted Chirped Fiber Bragg Grating Pair

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Introduction

Chromatic dispersion is an intrinsic property of optical fibers that allows an optical pulse to spread as it propagates along the fiber and spread more severely as the propagation distance and the data rate increase. With the increasing demand for high-bit-rate optical communication system, chromatic dispersion compensation in optical fibers has become a crucial issue. Thus, various methods to compensate for chromatic dispersion in high-speed optical systems have already been reported, including dispersion-compensated fibers (DCFs), a compensator using a pair of mode converters, dispersion-compensating technique based on a holey fiber and DCFs, and fiber gratings, such as fiber Bragg grating (FBG) and long-period fiber grating (LPFG) [1–4]. A dispersion compensator using a DCF has a nonlinear effect and needs to be spliced with an existing installed optical fiber network, thereby increasing the installation costs due to additional equipment. However, the use of chirped fiber gratings as a dispersion compensator has received considerable recent attention due to their low-insertion loss, fiber compatibility, simple fabrication, and passive operation. LPFGs fabricated with a relatively high delta value as an efficient dispersion compensator have also been proposed for dispersion compensation [5]. Based on choosing the length of the grating and refractive index modulation, a significant dispersion compensation can be achieved over a reasonable bandwidth using a high negative dispersion. However, this device requires coupling to a very high order cladding mode, which is highly prone to bend losses.

Plus, a large power loss occurs when it is connected to a single mode fiber. When using unchirped gratings in a transmission mode for dispersion compensation, it has been shown that only a small amount of dispersion compensation can be achieved, due to the small bandwidth of the high dispersion region and thereby strongly limiting the bandwidth-distance product [6-8].

As a dispersion compensator based on a chirped FBG is generally used as a reflective device, additional optical components, like an optical circulator are required, which increase the cost. Therefore, extensive research has been conducted on dispersion compensators operating in a transmission mode. Oullette et al proposed a dispersive FBG filter for efficient dispersion compensation in a transmission mode based on coupling between two co-propagating waveguide modes with different group velocities [4].

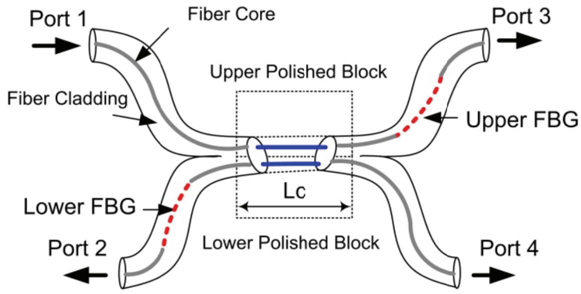
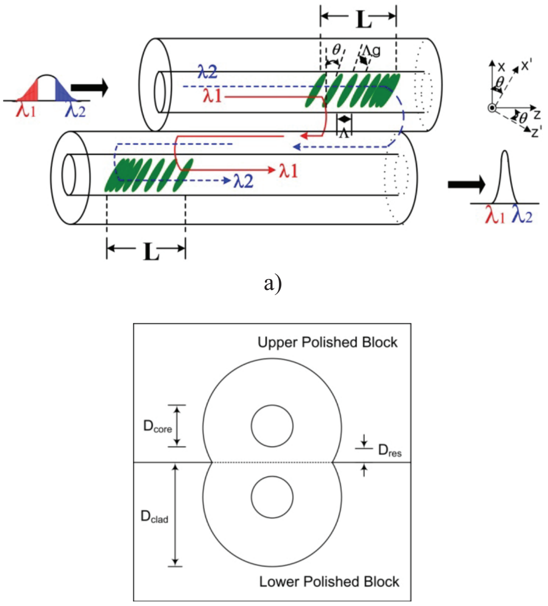


Fig. 1. The structure of the proposed FBG pair

The filter uses this intermodal dispersion, which is quite large and can be tailored by changing the waveguide parameters to compensate for chromatic dispersion. Yet the transmission is very low, as part of the power is reflected. In this case, the performance can be improved by utilizing a tilted chirped FBG pair placed alongside each other in close proximity, which has many advantages, including a good degree of freedom in a dispersion compensator design and large dispersion performance compared to single chirped grating and chirped FBGs. For the upper tilted chirped FBG, a forward-propagating core mode is coupled to the backward-propagating hybrid cladding mode using any azimuthal order number *l*. Then, for the lower tilted chirped FBG, the coupled backward-propagating cladding mode is coupled to the forward-propagating core mode. Accordingly, this paper presents a novel dispersion compensator in a transmission mode, as a result of double reflection and double mode coupling, using a tilted chirped fiber grating pair.

Principle of the transmissive-type dispersion compensator based on a tilted chiped grating paris

The Fig. 1 shows the structure of the proposed FBG pair. The proposed tilted chirped FBG pair consists of a pair of polished FBG blocks with a long effective coupling length. Both of upper and lower side-polished FBG blocks contain tilted chirped fiber Bragg gratings with high reflectivity, which are seperated with a coupling length (Lc) for complete coupling. In the upper polished block, propagating core mode is reflected at the upper FBG and coupled to counter-propagating cladding modes. The counter-propagating cladding modes are guided in the upper fiber cladding up to the upper polished block. When the upper and lower polished blocks are deeply polished to closely place the upper and lower fiber cores alongside each other, the counter-propagating cladding modes in the upper fiber cladding are completely coupled to the lower fiber cladding within the coupling length. And the coupled counter-propagating cladding modes are coupled to core mode at the lower FBG.



a)

b)

Fig. 2. Dispersion compensator in transmission based on tilted chirped fiber Bragg grating pair, where L and θ are length and tilt angle in titled fiber grating, respectively, and Λg and Λ are actual period and period in axial direction in tilted fiber grating, respectively(a); Cross-section of dispersion compensator (b)

Fig. 2(a) shows a conceptual view of the proposed dispersion compensator, which consists of two tilted chirped gratings in a fiber, and (b) shows the cross-section of the proposed grating pair with the following parameter: diameter of fiber core (Dcore)=5um, cladding radius=62.5um, distance of polished residual (Dres)=2.5um, and coupling length (Lc)=2.5mm. While the two gratings have the same tilt angle, their periodicities are in a reverse order from each other. Optical pulses in an optical fiber are broadened due to chromatic dispersion. Thus, when these dispersed pulses enter the first tilted chirped grating, the long wavelength components are reflected in front of the grating, while the short wavelength components are reflected at the end side of the grating, yielding to mode coupling from a fiber core mode to fiber cladding modes, simultaneously. Thereafter, the reflected optical pulses are backward-propagated as the cladding modes re-enter the second tilted grating, where the long wavelength components are re-reflected at the rear of the second grating, while the short wavelength components are reflected in front of the second grating.

As a result, due to the double reflection and mode coupling between a fiber core mode and fiber cladding modes, the proposed dispersion compensator operates in a transmission mode. Whereas an untilted fiber grating couples from the forward-propagating LP_{01} core mode to a backward-propagating hybrid cladding mode with azimuthal order number l=1, a tilted grating couples from LP_{01} core mode to a hybrid cladding mode with any azimuthal order number l [9]. Here, the tilted grating in the proposed dispersion compensator is used to increase the degree of freedom in the dispersion compensator design, as the mode coupling between fiber core mode and fiber cladding modes is very limited with an untilted grating.

Coupled-mode theory in a linearly chirped tilted grating

The mode coupling between fiber mode ν and fiber mode μ is well described by the coupling coefficients. Thus, for a tilted chirped fiber grating, the tangential coupling coefficient $K_{\nu\mu}$ including a dielectric perturbation Δε is given by

$$k_{\nu\mu} = (\omega/4)\int_0^{2\pi} d\phi \int_0^{\infty} r dr \Delta\varepsilon(r,\phi,z,\theta) E_\nu(r,\phi) E^*_\mu(r,\phi), \qquad (1)$$

where E_ν and E_μ are the transverse and longitudinal electric field of fiber mode ν and fiber mode μ, respectively. Equation (1) indicates that the energy exchange between the two fiber modes depends strongly on the electric field overlap integral. To design a dispersion compensator in a transmission mode based on a tilted chirped fiber grating pair, the optimum tilt angle must be known. From reference [9], the grating tilt angle θ_{opt} for maximum coupling between a fundamental core mode and hybrid lm(l≠1) cladding modes can be expressed by $\theta_{opt}=\tan^{-1}[(n^2_1- n^2_{01,eff})^{1/2}/(n_{01,eff} + n_{cl,eff})]$, where n_1 is the core index and $n_{01,eff}$ and $n_{cl,eff}$ are the effective index of the LP_{01} core mode and hybrid lm(l≠1) cladding modes, respectively.

Fig. 3 shows the grating tilt angles for the maximum LP_{01} core-to-hybrid 2m cladding mode coupling in a linearly chirped fiber grating at a wavelength of 1300nm to 1700nm. A tilted chirped fiber grating is formed in a single mode fiber with the following parameters: core radius a_1=2.5μm, cladding radius a_2=62.5μm, cladding index of n_2=1.45, relative index difference of Δ=0.005, and index of the surrounding medium of n_3=1.0. Here, the straight line and dots represent the LP_{01} core mode-to-HE_{2m} cladding mode coupling and the LP_{01} core mode-to-EH_{2m} cladding mode coupling, respectively. Fig. 2 indicates that the mode coupling between the LP_{01} core mode and the hybrid lm cladding mode was strong in the tilted chirped grating slanted by an angle of approximately 2 ~ 3 degrees. The maximum tilt angles for fiber mode coupling vary with the mode number m.

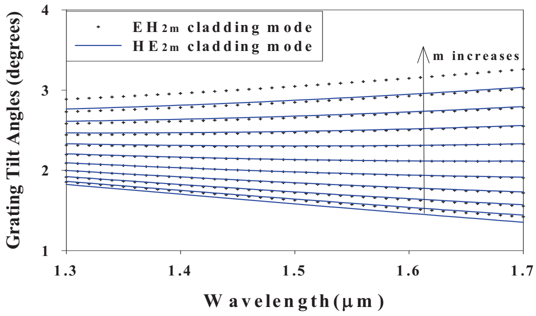
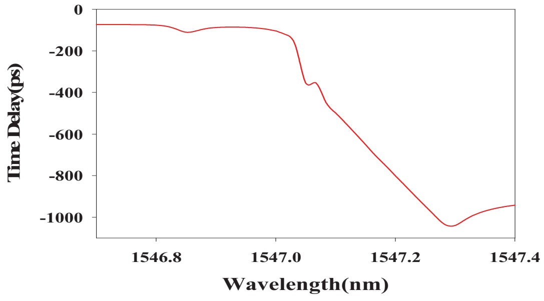


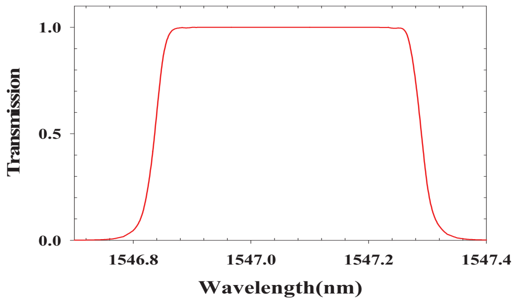
Fig. 3. Optimum tilt angles for maximizing mode coupling between core mode and hybrid 2m cladding mode in tilted chirped fiber grating

For a simple performance evaluation of the proposed dispersion compensator, an analytic expression was derived based on ray-optics approach. Based on the assumption that the optical pulse broadening is essentially the maximum relative delay between the shortest and the longest wavelengths, the dispersion D of the proposed dispersion compensator can be roughly written as $D=2L(n_{01,eff} + n_{cl,eff})/c\Delta\lambda$, while a conventional chirped fiber grating has a dispersion of $2Ln_{01,eff}/c\Delta\lambda$. Here, L is the length of the grating and $\Delta\lambda$ and c are the optical bandwidth and light velocity, respectively. Meanwhile, the phase-matching condition allowing different resonant wavelengths along the length of the grating in the proposed dispersion compensator can be expressed by $\beta^{co}_{01} + \beta^{cl}_{lm} = 2\pi/\Lambda(z)$, where β^{co}_{01} and β^{cl}_{lm} are the propagation constant of the LP_{01} core mode and hybrid lm cladding mode, respectively. Plus, $\Lambda(z)$ is the grating period along the fiber axis, and different resonant wavelengths are reflected at different positions of the grating, equivalent to $\Lambda_0 + Cz$, where Λ_0 is the grating period along the fiber axis in a grating that meets the phase-matching condition for a specific resonant wavelength λ_0 and C is the chirp rate of the fiber grating.

Fig. 4 shows time delay and spectrum in the proposed dispersion compensator based on a 50mm-long, 3 degree-tilted grating pairs. The tilted angle is apodized by tanh apodization function with α=4 and β=3.



a)



b)

Fig. 4. Time delay (a) and transmission spectrum (b) with proposed dispersion compensator

Table 1 and Table 2 summarize the dispersion characteristics of the proposed compensator according to two different lengths and chirp rates, respectively. A chirp rate C of 0.19nm and length of 200mm were fixed in tables 1 and 2, respectively, while the remaining simulation parameters were as the follows: fiber tilt angle of 2 degree, refractive index modulation Δn of 2×10^{-4} .

Table 1. Comparison of dispersion characteristics when using simple analytic equation and coupled-mode equation for proposed dispersion compensator with two different lengths

2L (mm)	Bandwidth (nm)	Dispersion(ps/nm) using coupled-mode equation	Dispersion(ps/nm) using simple analytic equation
100	0.5	-1,898	-1,946
200	0.5	-3,931	-3,891

Table 2. Comparisons of dispersion characteristics when using simple analytic equation and coupled-mode equation for proposed dispersion compensator with two different chirp rates

C (nm)	Bandwidth (nm)	Dispersion(ps/nm) using coupled-mode equation	Dispersion(ps/nm) using simple analytic equation
0.4	1.0	-1,746	-1,965
0.6	1.4	-1,167	-1,351

These parameters met the condition for mode coupling between the LP_{01} core mode and the HE_{24} cladding mode. Fig. 3 shows the transmission and time delay spectra within the proposed dispersion compensator based on 50mm-long, 2-degree tilted grating pairs. The tilted grating was apodized using tanh apodization function with α=4 and β=3.

Conclusions

In conclusion, this paper proposed a dispersion compensator in transmission based on a tilted chirped FBG pair. The proposed dispersion compensator operates in a transmission mode as a result of double reflection and double mode coupling between a forward-propagating core mode and a backward-propagating hybrid cladding mode with any azimuthal order number l in two tilted fiber gratings. Plus, the optimum tilt angle to maximize the mode coupling between a guided core mode and a hybrid cladding mode with an arbitrary azimuthal order number is investigated along with the phase matching condition for a resonant wavelength along the fiber grating. To evaluate the performance, the transmission spectrum and dispersion characteristics of the proposed dispersion compensator are simulated using the coupled mode equations, while a simple analytical equation for the dispersion characteristics is also derived using a ray–optics approach. A comparison of the dispersion results when using the simple analytic equation and coupled-mode equation showed a good agreement.

Acknowledgements

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References

1. **Stegall D. B., Erdogan T.** Dispersion control with use of longperiod fiber gratings // J. Opt. Soc. Am. A., 2000. – No. 17. – P. 304–312.
2. **Oh K., Choi S., Jung Y., Lee J.** Novel Hollow Optical Fibers and their Applications in photonic devices for optical communincations // J. Lightw. Technol., 2005. – No. 23**. –** P. 524–527.
3. **Painchaud Y., Poulin M., Morin M.** Grating superposition encoded into a phase mask for efficient fabrication of dispersion slope compensators // Proceedings of ECOC'2005, 2005. – No. 3. – P. 419–420.
4. **Eggleton B. J., Stephens T., Krug P.A., Dhosi G., Brodzeli Z., Oullete F.** Dispersion compensation using a fiber grating in transmission // Elect. Lett., 1996. – No. 15 – P. 1610–1611.
5. **Das M., Thyagarajan K.** Dispersion compensation in transmission using uniform long period fiber gratings // Opt. Comm., 2001. – No. 19. – P 159–163.
6. **Hinton K.** Ramped unchirped fiber gratings for dispersion compensation // Lightw. Technol., 1997. – No. 15. – P. 1411–1418.
7. **Litchinitser N. M., Patterson D. B.** Analysis of fiber Bragg gratings for dispersion compensation in reflective and transmissive geometries // J. Lightw. Technol., 1997. – No. 15. – P. 1323–1328.
8. **Litchinitser N. M., Eggleton B. J., Patterson D. B.** Fiber Bragg gratings for dispersion compensation in transmission: Theoretical Model and design criteria for nearly ideal pulse recompression // J. Lightw. Technol., 1997. – No. 15. – P. 1303–1313.
9. **Lee K. S., Erdogan T.** Fiber mode coupling in transmissive and reflective tilted gratings //Appl. Opt., 2000. – No. 39. – P. 1394–1404.

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Jonghun Lee, Cherl-Hee Lee. Dispersion Compensator in Transmission using Tilted Chirped Fiber Bragg Grating Pair // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 6(122). – P. 125–128.

A novel transmission-type dispersion compensator based on a tilted chirped fiber grating pair is proposed. Using the mode coupling between two tilted chirped fiber Bragg grating cores, the proposed dispersion compensator provides a good degree of design freedom, as well as the merits of transmission-type fiber gratings. The dispersion characteristics of the proposed compensator are investigated using a coupled-mode equation and ray-optic equation. The tilt angle to maximize the mode coupling and phase matching condition for a resonant wavelength along the fiber grating are also analyzed. A simple analytical expression for the dispersion in the proposed dispersion compensator is derived using a ray–optics approach. A comparison of the dispersion results when using the simple analytic equation and coupled-mode equation shows a good agreement. Ill. 4, bibl. 9, tabl. 2 (in English; abstracts in English and Lithuanian).

Jonghun Lee, Cherl-Hee Lee. Dispersijos kompensatorius perdavimo linijoje naudojant pasuktą Brego gardelių porą // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 6(122). – P. 125–128.

Pasiūlytas naujas transmisijos tipo dispersijos kompensatorius, kurio veikimas pagrįstas pasuktos Brego gardelių poros panaudojimu. Poruojant dvi pasuktas Brego gardelių šerdžių modas, pasiūlytasis dispersijos kompensatorius užtikrina didelį projektavimo laisvės laipsnį. Kompensatoriaus dispersijos charakteristikos ištirtos naudojant sudvejintų modų lygtį ir optinio spindulio lygtį. Analizuotas pasukimo kampas, siekiant maksimizuoti modų poravimo ir fazių sutapimo sąlygas rezonansiniam bangos ilgiui. Pasiūlyta paprasta analitinė išraiška dispersijai skaičiuoti optinio spindulio metodu. Il. 4, bibl. 9, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).