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Dispersion Pre-Compensation for a Multi-wavelength Erbium Doped Fiber Laser Using Cascaded Fiber Bragg Gratings

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Abstract: A dispersion compensator for the output of a multi-wavelength erbium doped fiber laser (EDFL) is designed using the dispersion characteristics of cascaded fiber Bragg gratings (FBGs) through transmission at the light source. The proposed technique can be used to compensate the dispersion of any number of channels by changing the number of the cascaded FBGs.

Key words: Dispersion compensation, Fiber Bragg grating (FBG), Erbium doped fiber laser (EDFL).

INTRODUCTION

Dispersion of the light signal causes distortion for both digital and analog transmission along optical fibers. For digital modulation, the dispersion mechanisms within the fiber cause a pulse broadening for the transmitted light traveling within a channel. The broadened pulses overlap with neighbors causing intersymbol interference[1].

FBGs are emerging as one of the most important components for designing fiber-optic communication systems. They are likely to have applications in two main areas: dispersion compensation in long-haul fiber networks[2-4] and wavelength routing in wavelength division multiplexed (WDM) lightwave systems[3]. In both areas, grating dispersion will impact the system performance. FBGs exhibit dispersion both in reflection, especially when the grating is chirped[2], and in transmission at wavelengths close to the stop band[3,4]. At wavelengths close to the grating stop band, the group-velocity dispersion (GVD) of an FBG is many orders of magnitude larger than that occurring in standard optical fibers used for signal transmission. In a WDM network, many channels need to be compensated simultaneously, and therefore the impact of total dispersion possessed by numerous gratings need to be examined.

In this paper, a dispersion compensator for the output of a multi-wavelength EDFL is designed using the dispersion characteristics of cascaded FBGs through transmission at the light source.

2. Theory: Consider a cascade of two gratings with Bragg frequencies υ_1 and υ_2 such that the frequency separation, $|\upsilon_1 - \upsilon_2| = \upsilon$, is larger than the width of the stop band of each grating. Then, there is no spectral overlap and thus, one can ignore interference effects between the gratings. We assume for simplicity that the coupling strength, k, is the same for both gratings. Following the approach of[3-5], one finds the following analytical expressions for the second and third order GVD coefficients, β_2^g and β_3^g, for the first FBG, respectively as

$$\beta_2^g = -\left(\frac{n}{c}\right)^2 \left[\frac{k^2}{(\delta^2 - k^2)^{3/2}} sign(\delta)\right] \quad (1)$$

$$\beta_3^g = -3\left(\frac{n}{c}\right)^3 \left[\frac{k^2 \delta}{(\delta^2 - k^2)^{5/2}}\right] \quad (2)$$

where, $\delta = n(\omega - \omega_B)/c$ is the detuning of the channel carrier frequency, ω, from the resonant Bragg frequency, ω_B, c is the free space speed of light and n is the fiber core refractive index.

Similarly, β_2^g and β_3^g can be obtained for the second FBG in the region between the stop bands of the two fiber gratings as[5]

$$\beta_2^g = \left(\frac{n}{c}\right)^2 \left[\frac{k^2}{\left[(\delta+\Delta)^2 - k^2\right]^{3/2}} sign(\delta)\right], \quad (3)$$

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and

$$\beta_3^g = 3\left(\frac{n}{c}\right)^3\left[\frac{k^2(\delta+\Delta)}{\left[(\delta+\Delta)^2-k^2\right]^{5/2}}\right] \quad (4)$$

where $\Delta = 2\pi n\Delta\nu / c$.

Using Eq. (1) to Eq. (4), the total β_2^g and β_3^g for the two cascaded FBGs can be obtained in the region between the two stop bands, resulting in

$$\beta_2^g = \left(\frac{n}{c}\right)^2\left[\frac{k^2}{\left[(\delta+\Delta)^2-k^2\right]^{3/2}} - \frac{k^2}{(\delta^2-k^2)^{3/2}}\right] sign(\delta)\ , \quad (5)$$

and

$$\beta_3^g = 3\left(\frac{n}{c}\right)^3\left[\frac{-k^2\delta}{(\delta^2-k^2)^{5/2}} + \frac{k^2(\delta+\Delta)}{\left[(\delta+\Delta)^2-k^2\right]^{5/2}}\right] \quad (6)$$

Both expressions Eq. (5) and Eq. (6) diverge at the band edge of each grating, i.e., at $\delta = -k$ and $\delta = k -$.

The ratio between the second and third order dispersion terms is often used as a figure of merit (FOM) for characterizing the performance of a fiber grating. The grating FOM, F(d), is defined as[5]

$$F(\delta) = \left|\frac{\beta_2^g}{\beta_3^g}\sigma_o\sqrt{2}\right| , \quad (7)$$

where σ_o is the transform-limited rms pulse width (for a Gaussian pulse, rms pulse width σ_o is related to the (1/e) width, $T_{1/e}$, through $\sigma_o = T_{1/e}/\sqrt{2}$ [5]).

RESULTS AND DISCUSSION

We apply the results of the described model to design a dispersion compensator for a 16-channel dense wavelength division multiplexing (DWDM). We assume that the channels in the DWDM system are equally spaced by 0.8 nm (= 31.4 cm^{-1}). We assume that the channel spacing is large compared to the pulse bandwidth and that the grating stop bands satisfy 2k < . Then, to a good approximation, one can consider only the effect of two consecutive gratings on transmission of any particular channel and neglect the effect of all other gratings. This approximation is valid in practice because the dispersion of each grating reduces significantly far away from its own stop band[5].

First, one will verify the model of two cascaded FBGs and then design a system for dispersion compensation of the proposed 16-channel EDFL. Using Eqs. (1) and (2), the GVD and third order dispersion parameters, β_2^g and β_3^g for the two cascaded gratings, as well as those of individual gratings are shown in Figs. 1 and 2, respectively, as functions of the detuning parameter, δ, for a channel spacing of 100 GHz (= 31.4 cm^{-1}) after choosing k = 7 cm^{-1} (the reason of choosing this value for k will be mentioned later) and n = 1.48.

The solid curve in Fig. 1 shows that in the presence of another grating, the GVD becomes zero at |δ| = /2. Therefore, in contrast with the single grating case, there exists a zero- GVD wavelength. This zero-GVD wavelength can be easily shifted by varying the grating design parameters k and . It is noteworthy that the third-order dispersion is always positive for each grating and, since the two contributions are additive between the stop bands, the total dispersion does not vanish at any wavelength as shown in Fig. 2. This feature is similar to that of standard telecommunication fibers for which the third-order dispersion is always positive as well[5]. Therefore, the third order dispersion term cannot be eliminated. The effect of the third-order dispersion coefficient for standard optical fibers can be neglected when the magnitude of the second order GVD of standard optical fibers, exceeds 0.1 ps^2/km. Clearly, to minimize the FBG third-order dispersion effects, the FOM, Eq. (7), should be as large as possible for a given set of design parameters.

Clearly, for an ideal dispersion compensator that recompresses the dispersion-broadened pulse to its original width, one must satisfy

$$\beta_2^g L_g = -\beta_2^f L_f \quad (8)$$

where L_g is the grating length and L_f is the fiber length.

We use a graphical approach to find the optimum detuning parameter, δ_{opt}, from Eq. (8). In Fig. 3, the left hand side (solid line) and right hand side (dashed line) of Eq. (8) are plotted for k = 7 cm^{-1}, L_g = 10 cm, β_2^f = -20 ps^2/km (for standard optical fibers)[3] at L_f = 100 km. The intersection of two lines provides a solution for δ_{opt}. One must note that the stop band of one grating is centered at δ = 0 while the corresponding stop band of the other grating is centered at δ = - = -31.4 cm^{-1}.

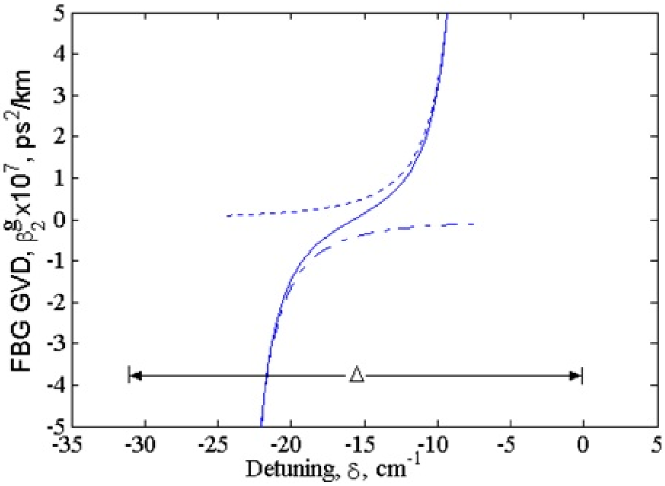

Fig. 1: GVD as a function of δ for a single grating centered at δ = 0 (dotted line) and δ = – (dot-dashed line), and for two cascaded gratings (solid line).

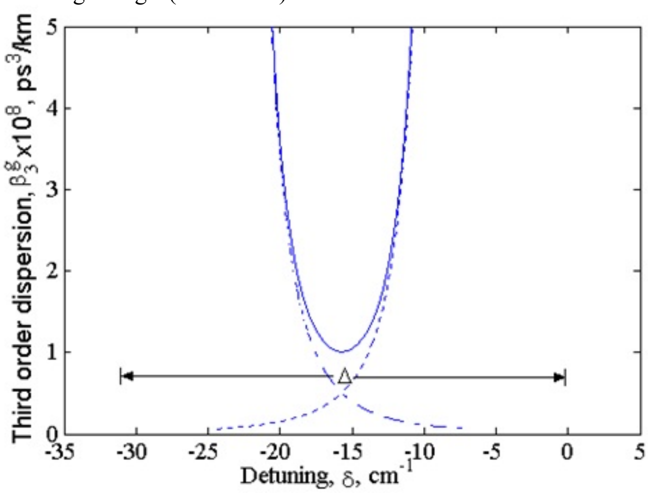

Fig. 2: Third order dispersion as a function of δ for a single grating centered at δ = 0 (dotted line) and δ = – (dot-dashed line), and for two cascaded gratings (solid line).

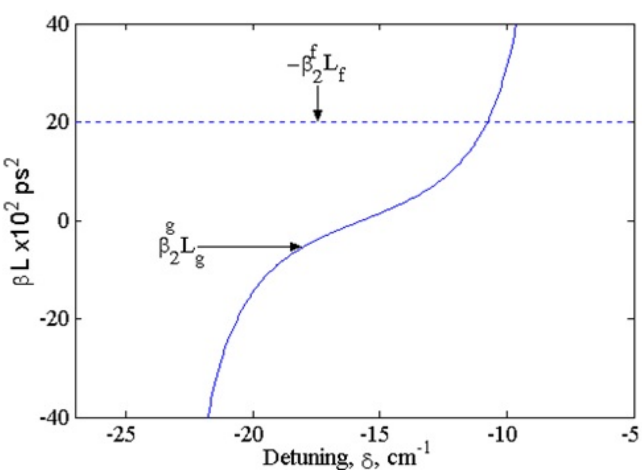

Fig. 3: Graphical solution of Eq. (8) for L_f = 100 km, β_2^f = - 20 ps^2/km, k = 7 cm^{-1}, L_g = 10 cm and υ = 100 GHz.

The reason for selecting k = 7 cm^{-1} is as follows: Figure 3 depends on the value of the coupling coefficient, k. As k changes, the optimum detuning value, δ_{opt}, also changes. The FOM depends on the value of δ_{opt}, Eq.(7). Hence, we have to select the value of k that gives an optimum detuning δ_{opt} for which, the FOM is maximum to reduce the effect of β_3^g, i.e, we select a value of k and then determine δ_{opt} to evaluate the FOM till finding the best value of k that satisfies that condition. This is illustrated in Figs 4 and 5, respectively.

Now, one will apply this model for dispersion compensation of the ITU 16 channels system propagating in an optical fiber with a fiber length L_f = 100 km and β_2^f = -20 ps^2/km. This technique can be used for any other systems with different specifications.

Using the graphical solution of Fig. 3, the optimum detuning value is found to be δ_{opt} = -10.78 cm^{-1}. Now, knowing the optimum detuning values and also, the wavelengths of the ITU 16 channels one can easily find the Bragg wavelengths for the two cascaded FBGs of each channel. Figures 6 and 7 give examples to the design of two ITU channels at wavelengths 1543.73 and 1544.53 nm, respectively.

One may take Fig. 6 as an example to explain how the dispersion compensation process takes place. The transmitted channel through the optical fiber has a wavelength of 1543.73 nm. This wavelength must be the optimum wavelength at which the dispersion is compensated. The optimum detuning $\delta_{opt} = n(\omega_{opt} - \omega_B)/c$ = -10.78 cm^{-1} is already known, Fig. 3. This optimum detuning gives the optimum wavelength shift between the transmitted wavelength, λ_{opt} = 1543.73 nm, and the Bragg wavelength of the first dispersion compensator FBG. So, easily one gets the first Bragg wavelength of the FBG used for dispersion compensation to be 1543.45 nm. The Bragg wavelength of the second dispersion compensator FBG (1544.25 nm) is obtained easily, because, the channel spacing is υ = 100 GHz (0.8 nm). At λ_{opt} = 1543.73 nm (the wavelength of the transmitted channel), $\beta_2^g L_g = -\beta_2^f L_f$ and the dispersion is compensated. The design for all remaining channels can be obtained by the same way.

Seventeen cascaded FBGs are used to compensate the dispersion in the ITU 16 channels such that each channel requires two cascaded FBGs for dispersion compensation. The Bragg wavelengths of these 17 cascaded FBGs used for dispersion compensation are 1543.45, 1544.25, 1545.05, ………, 1555.45 and 1556.25 nm with spacing of 0.8 nm.

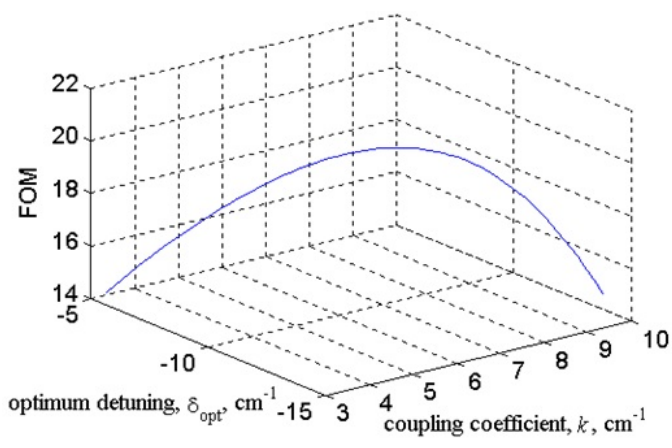

Fig. 4: Figure of merit for different values of the coupling coefficient and optimum detuning.

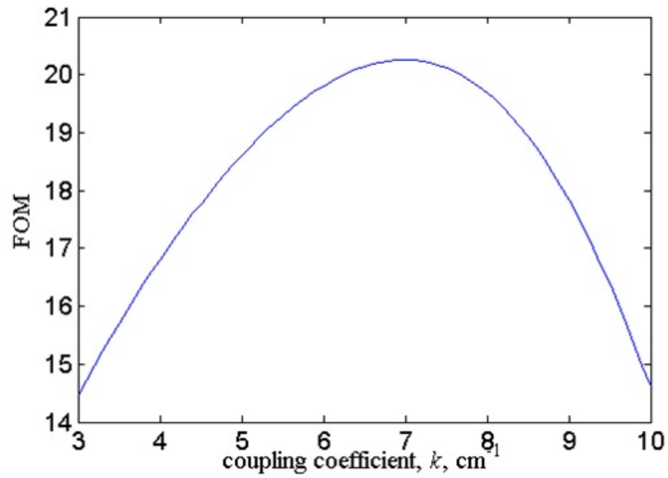

Fig. 5: Figure of merit versus coupling coefficient with optimized detuning for each k for υ = 100 Ghz.

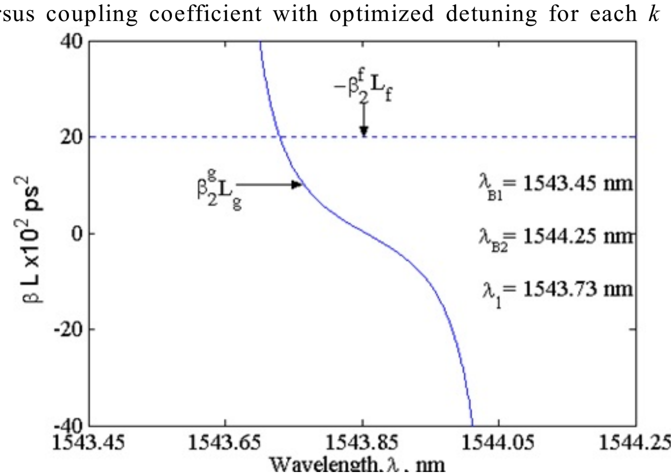

Fig. 6: Dispersion compensation design for a channel at 1543.73 nm.

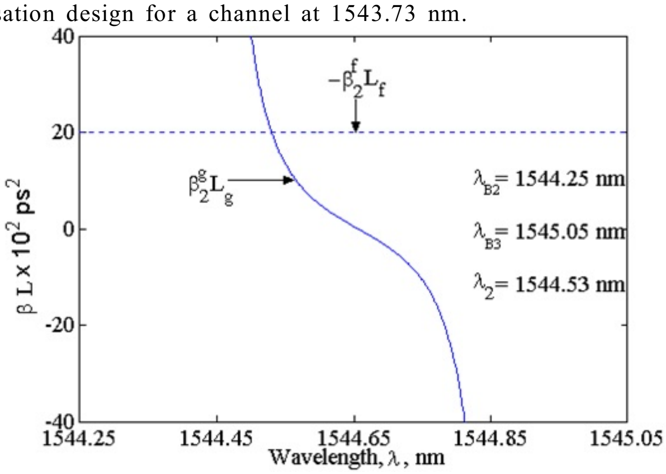

Fig. 7: Dispersion compensation design for a channel at 1544.53 nm.

Figure 8 gives the configuration of the designed laser source that produces 16 channels with wavelengths coinciding with the ITU industrial standard. These channels then pass through 17 cascaded FBGs with Bragg wavelengths mentioned before. These 17 cascaded FBGs are used to compensate the dispersion of the 16 laser channels transmitted through an optical fiber of 100 km length.

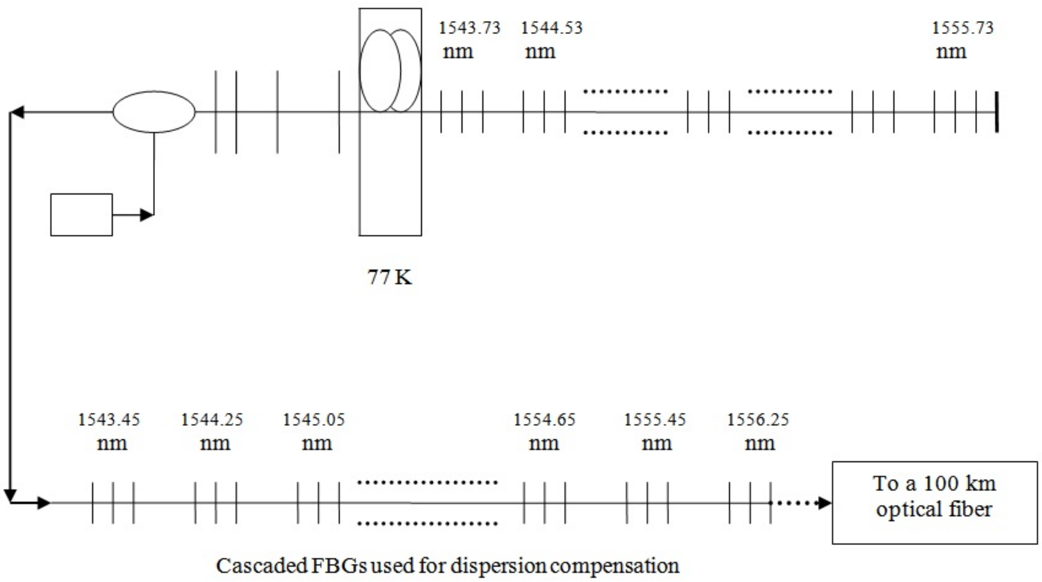

Fig. 8: The schematic of 16 channels EDFL followed by the dispersion compensation System.

4. Conclusion: In this work, a dispersion compensator for the output of a 16-wavelength EDFL is designed using the dispersion characteristics of cascaded FBGs through transmission at the light source. Seventeen cascaded FBGs are used to compensate the dispersion in the ITU 16 channels such that each channel requires two cascaded FBGs for dispersion compensation. The Bragg wavelengths of these 17 cascaded FBGs used for dispersion compensation starts at 1543.45 nm and ends at 1556.25 nm with spacing of 0.8 nm. The dispersion compensator is designed for the transmission through a 100 km optical fiber. In the same spirit, this technique can be used to compensate the dispersion occurring through any other optical fiber length.

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