Inter-Channel Residual Dispersion Compensator for 40 Gbit/s WDM Optical Systems

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Abstract: We present a tunable dispersion compensator which allows the equalization of residual inter-channel dispersion profiles. We discuss the complex FBG design, present the spectral response and demonstrate the reconfigurable capability of the device.

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1. Introduction

It is well known that optical communication systems suffer from Chromatic Dispersion (CD) impairments that grow as the square of the bit rate, which consequently increases the dispersion management complexity of high-bit-rate WDM systems. Even in long haul optical links that use dispersion compensating fiber to periodically offset the chromatic dispersion, slight mismatch of CD slopes can cause the accumulation of significant residual CD for some of the channels after propagation over several hundred kilometers. Furthermore, network reconfiguration or environmental perturbations can modify the CD level of each channel. For WDM systems operating at 40 Gbit/s it thus becomes essential to have a device that can be tuned to compensate the CD of several channels simultaneously and that can achieve reconfigurable inter-channel CD slope profiles.

Various optical components were developed and commercialized in the last decade for WDM dispersion compensation but only a few of these solutions are tunable. Among these technologies, bulk Gires-Tournois etalon (GTE) [1] and fiber optics Distributed GTE (DGTE) [2] are attractive devices because of their intrinsic multi-channel response. A tunable compensator is made by cascading two GTE or DGTE, one that presents a spectral response characterized by a Group Delay (GD) with a positive curvature while the second one has a negative curvature within each Free Spectral Range (FSR). By shifting the relative position of the spectral response of the two filters, it is possible to tune the total GD and therefore to adjust the resulting CD. By introducing a mismatch between the FSR of the two GTE or DGTE elements, it is also possible to achieve residual inter-channel CD slope compensation [1,3]. However, this technique does not allow independent tuning of the CD level and of the inter-channel CD slope. This means that the compensator is constrained to a specific CD profile across the wavelength range of interest and therefore is not fully reconfigurable. We previously demonstrated the possibility to use Quasi Periodic Chirped Fiber Bragg Grating (QPCFBG) [5] to make flexible CD compensators. Like DGTE, QPCFBG are filters with resonating cavities that show a periodic GD spectral response. The QPCFBG however differ from previous implementation of DGTE by the use of a low chirp (long grating length), high number of cavities (highly structured index profiles) and reflectivity slightly lower than one (for inverse scattering design). It is the low chirp combined to a segmented heater that gives flexibility in the CD profiles of the compensator.

In resonating devices like DGTE or QPCFBG, the dispersion compensating range varies as 1/FSR². GTE compensators with 100 GHz FSR were demonstrated by using bulk multi-cavity etalons [6], but fiber based devices have so far been limited to FSR of 50 GHz. A similar limitation applies to channel bandwidth (CBW) and results are often reported for 20 GHz CBW or 40% of the FSR. To access 40 Gbit/s applications, it is essential to increase the FSR and to enlarge the CBW. In this paper, we present new grating designs for the two elements of the cascade (QPCFBG A and B) which have a 100 GHz FSR. This grating pair is use to make a 32-channels compensator with a CD range of ±400 ps/nm over a CBW of 60 GHz. Because of the distribution of the cavities along the fiber length and with the use of a 16-element chromium heating electrodes, we demonstrate a tunable compensator that can be reconfigured to match various inter-channel dispersion slope profiles.

2. Quasi Periodic Complex Fiber Bragg Grating: design and experimental results

The QPCFBG design starts by modeling the desired spectrum over one FSR by using z-transform [7]. The use of a z-transform equivalent discrete filter ensures the causality of the filter response and consequently the existence of a physical solution. That preliminary design results in an all-pass optical filter. Afterward, this one-FSR characteristic is replicated to cover the whole spectral range and is limited by a windowing function. To ensure that the spectrum will lead to a distributed Bragg structure, a monotonous GD slope is added to the GD replica. Subsequently, an inverse scattering algorithm [8] is used to identify the complex Bragg grating structure parameters corresponding to the target spectrum. It would be possible to choose the target spectrum without using the z model but an arbitrary choice cannot ensure causality and the use of the z-model is also useful to...
limit the structure complexity by using low order $z$ polynomials. The spectral response of the resulting QPCFBG filter is then calculated from the determined index modulation. Fig. 1 shows the grating profile of QPCFBG$_B$. Because this grating structure is obtained from a $z$ design with more than eight coupled cavities, the grating profile is highly structured in terms of index modulation apodization and local period. To facilitate its fabrication, the index modulation apodization is converted in a phase apodized form [9] and thus the entire design properties are included in a binary phase mask. However, phase apodized masks are limited by the transfer function which relates the mask phase and the grating phase [10]. Due to this phenomenon, some amplitude apodization details can not be exactly reproduced in the phase apodized form but the responses of the fabricated gratings still closely match the desired spectrum. Fig. 2 illustrates the GD difference between a simulation of the GD grating response and experimental measurement for gratings QPCFBG$_A$ and QPCFBG$_B$.

Fabrication of 100 GHz FSR coupled cavity structures is highly challenging because of the phase accuracy needed to keep the phase matching between each cavity. In the case of distributed coupled cavities that are the basis of the QPCFBG filters, the response of the resonating structure is affected by average index non-uniformities. To ensure a good phase matching for all channels, a post-fabrication correction technique was developed to identify and correct the average index non-uniformity. This technique is based on identification of the average index non-uniformities by using an iterative algorithm which determines the average refractive index variations that provides the best fit to the spectral measurements. Afterwards, UV scanning is performed, without phase mask and at various speeds, to level the average refractive index along the grating. This procedure improved the average PR standard deviation from 0.19 to 0.13 rad and average peak-to-peak variations from 0.85 to 0.6 rad. The PR characteristics demonstrate that improvements could still be made to increase the in-channel phase quality characteristics. The inset of the Fig. 2 b shows that the remaining GD imperfections are mainly distributed at the top zone of the parabolic shape. This spectral region has a major impact on the PR because it is always present in the CBW zone.

3. Reconfigurable dispersion compensator: experimental results and discussion

The tunable compensator is made by using the previously described gratings in an optical cascade. Fig. 3 shows the schematic representation of the compensator where each grating is placed on holders with 16 discrete heating elements made by depositing chromium thin film electrodes on a glass substrate. That produces a series of electrical resistors which are used to apply a temperature profile along each grating.

Fig. 2 shows that each QPCFBG has a GD response with a monotonous slope indicating that the optical fields of the various channels resonate in different portions of the Bragg structure. By using the temperature control system, it is possible to apply different temperature profiles and thus to modify differently the spectral shift along the grating. This allows tuning of the CD profile and consequently leads to increase flexibility in the inter-channel CD compensation setting. Fig. 4 shows two specific temperature settings (circles and squares) applied on each grating (A,B). The resulting CD for the 32 channels is represented in Fig. 5a), where each channel are analysed over a 60 GHz CBW. Each marker indicates the CD when a linear GD fitting is performed over the 60 GHz bandwidth. The error bars indicate the maximum and minimum CD values obtained when we consider a sub-bandwidth of 40 GHz into the 60 GHz CBW. Fig. 5 b and c illustrate the Phase Ripple (PR) characteristics in term of worst case of peak-to-peak phase ripple and standard deviation over a 40 GHz sub-bandwidth respectively. Even though only two CD settings are illustrated in this example, various inter-channels
CD profiles are easily attainable by properly adjusting the temperature profiles along each gratings. Different CD slopes and average values are achievable in the range of ±400 ps/nm.

Fig. 3. Schematic of the tunable dispersion compensator

Fig. 4. Temperature profiles, a) QPCFBGA (T_A) and b) QPCFBGB (T_B)

5. Conclusion

We discussed the first demonstration of a CD compensator based on a high number of distributed coupled cavities with a FSR of 100 GHz. We obtained a chromatic dispersion range of ±400 ps/nm for 32 channels with a bandwidth of 60 GHz. We also show that the proposed structure allows tuning of inter-channels CD compensation by profiling the temperature along each grating. Further improvements in the design and fabrication procedures should lead to better PR performances. This research opens the door for new type of flexible multi-channels CD compensator applicable to 40 Gbit/s WDM systems.

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7. References