Tunable dispersion slope compensator using novel tailored Gires-Tournois etalons

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Abstract: We present a novel concept of tailored Gires-Tournoise etalon structure and show that such devices are very useful for the realization of dispersion slope compensator with almost arbitrary dispersion profile and also with tunability in dispersion slope.

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1. Introduction

Wavelength-division-multiplexing (WDM) is a key technology for expanding the capacity of optical fiber transmission systems. With increasing bit rate, chromatic dispersion compensation is more and more critical for such systems. However, mismatch between the dispersion slopes of the transmission and dispersion compensating fiber (DCF) results in only one wavelength that is perfectly compensated and different amounts of residual dispersion on all of the other channels. The impact of dispersion slope on system performance increases as the operating bandwidth increases and also as the transmission distance and bit rate increases. Moreover, the dispersion slope itself may also change due to optical path reconfiguration in network and environmental temperature variation. Thus, dispersion compensators with dispersion slope tunability are desirable for dispersion managed high-speed WDM system. Although there have been some reports of dispersion slope compensators (DSCs) [1-3], most of them can only compensate dispersion slope with fixed value [1] or can compensate variable slope but only for a single channel [2]. Only few schemes have shown performance for both multi-channel compensation capability and tunability [3].

Recently, we introduced all-in-fiber distributed Gires-Tournois etalons (DGTEs) for dispersion slope compensation [4]. This approach has promising features such as low loss, low group delay ripple and low cost. Although the reported DGTE-based DSC can compensate for fixed dispersion slope and also has addition tunability in dispersion [4], the dispersion slope cannot be adjusted after fabrication. In this paper, we extend the GTE concept to demonstrate a tailored GTE structure and show that such devices are very useful for the realization of DSC with almost arbitrary dispersion slope profiles and also tunability in dispersion slope.

2. Concept and characteristics of tailored Gires-Tournois etalons

A GT interferometer is a special configuration of a Fabry-Perot etalon, which consists of a partially reflective mirror (first mirror) and a 100% reflective mirror (second). Recently, distributed GTEs have been developed that replace traditional mirrors with directly UV-written Bragg grating in optical fiber [5]. Both traditional GTEs and distributed GTEs have similar properties such as periodical oscillation structure in group delay and dispersion, which make them suitable for identical multi-channel dispersion control. In a GTE, the reflectivity of the first mirror/grating mainly determines the dispersion properties (such as group delay amplitude, dispersion amplitude) of the structure. The concept proposed here involves a tailored GTE that is used to produce arbitrary group delay profiles by tailoring the reflectivity profile of the first mirror/grating - the reflectivity of the second mirror/grating is still kept close to 100% to achieve all-pass function. For bulk optical mirrors, it is difficult to tailor their reflection spectra and thus such structures would be difficult to achieve. However, by using fiber Bragg gratings in the GTE structure makes the realization of tailored GTE much easier since the reflection spectra of fiber Bragg gratings can be readily tailored during fabrication to have an almost arbitrary profiles.

To obtain a target group delay profile, $\Delta\tau(\lambda)$, (i.e. envelop of the group delay amplitude), we derived that the reflection spectrum of the first mirror/grating of the GTE, $R_1(\lambda)$, should be tailored to the following profile,

$$R_1(\lambda) = \left[\sqrt{\left[\frac{2T_0}{\Delta\tau(\lambda)}\right]^2 + 1} - \frac{2T_0}{\Delta\tau(\lambda)}\right]^2 \tag{1}$$

Where $T_0 = 2nd/c$ is the round trip time in the cavity, n is the mode effective index, d is the cavity length, c is the light speed in vacuum.

We have fabricated both linearly and nonlinearly tailored DGTEs in the experiments. As examples, three of them are shown in Fig.1. The measured group delay spectra, the envelopes of group delay amplitudes and their corresponding reflection spectra of the first grating recorded in fabrication are plotted in Fig 1a, 1b and 1c, respectively. DGTE (I) and (III) that have FSR of about 50GHz are formed by two chirped fiber gratings (CFGs) with overlapped structure and DGTE (II) that has FSR of about 25GHz is formed by two CFGs with separated structure [5]. It is clearly seen from Fig. 1a and 1b that DGTE (I) has linearly increased amplitude in group delay, while the DGTE (II) and (III) have positive quadratic and negative quadratic varied amplitude in group delay, respectively. Though the oscillation amplitudes of group delay vary channel by channel, for each channel, the group delay is quadratic and result in linear variation in dispersion.

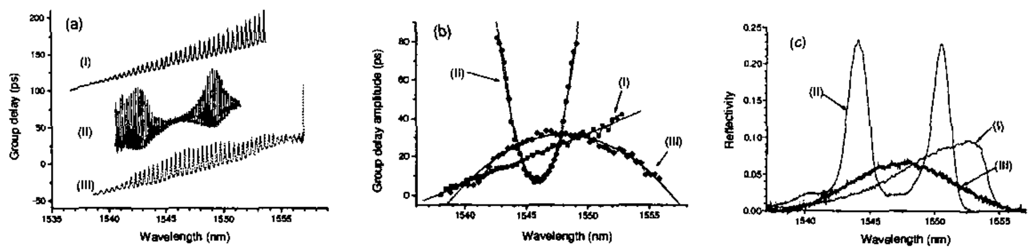

Fig.1. Experimental examples of tailored DGTEs. (a) Measured group delay spectra, (b) the envelopes of group delay amplitudes, (c) reflection spectra of the first grating recorded in fabrication.

3. Tunable dispersion slope compensators based on tailored DGTEs

We first demonstrate a simple tunable DSC realized with a single linearly tailored DGTE. The principle is schematically shown in Fig.2a. The linearly tailored DGTE has the oscillation amplitude of the group delay increasing channel by channel, and thus resulting in the dispersion slope increasing channel by channel. Before tuning, each channel has been set at zero dispersion, therefor the dispersion slope over these channels is zero.

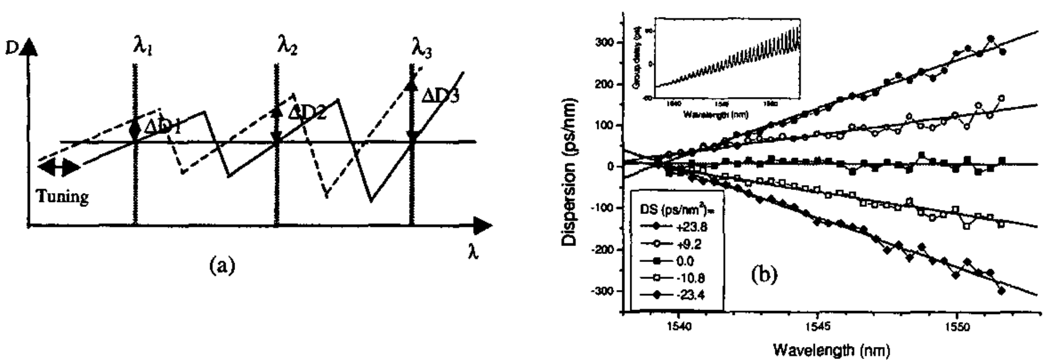

Fig.2. Tunable DSC with a single linearly tailored DGTE. (a) The principle, (b) measured dispersion values at different dispersion settings. Inset: measured group delay spectrum of the tailored DGTE.

When tuning, different channels will suffer different dispersion changes (ΔD1<ΔD2<ΔD3), therefor dispersion slope over these channels will be generated. The dispersion slope increases as the tuning increases. A negative dispersion slope can be readily realized by tuning the DGTE in the contrary direction shown in Fig.2a. The measured group delay spectrum of the linearly tailored DGTE used in the experiment is shown in the inset of Fig. 2b. The different dispersion slope settings are realized by simply applying different strain to the DGTE. The measured dispersion values for dispersion slope settings of +23.8, +9.2, 0.0, -10.8 and $-23.4 ps/nm^2$ over about 30 channels are shown in Fig.2b, which clearly indicates the slope tunability with such a tailored GTE. The drawback of this scheme is that the slope for each channel (internal) is not compensated, therefore such a DSC can only be suitable for the case of small signal bandwidth. This shortcoming can be overcome by using a pair of tailored DGTEs as described below.

The principle of combining using two tailored DGTEs as a tunable DSC is schematically shown in Fig.3a. The two DGTEs both have linear envelopes of group delay amplitude over a certain number of channels. The envelopes are properly designed so that for each channel, the dispersion slopes of two DGTEs have same magnitude but different signs in a certain region. Therefor, for each channel, there is a region where dispersion

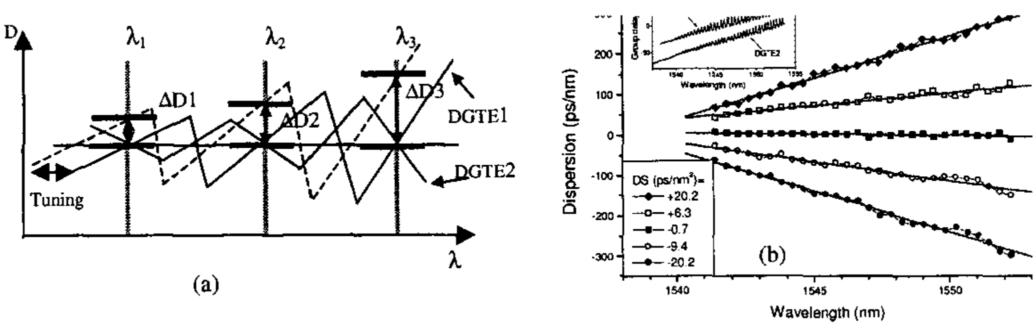

Fig.3 Tunable DSC with two linearly tailored DGTEs. (a) The principle, (b) measured dispersion values at different dispersion settings. Inset: measured group delay spectra of the two tailored DGTEs.

is constant when the two DGTEs are combined. The dispersion value for each channel is determined by the relative spectral shift between two DGTEs, which can be controlled either thermally or by strain. When the dispersion for each channel is set at zero dispersion, as shown in Fig.3a, the dispersion slope over these channels is also zero. When tuning the DGTE1 towards shorter wavelength, the dispersions for all channels increase but the amounts of dispersion changes are different, as shown in Fig.3a, thus a dispersion slope is generated over these channels. The dispersion slope increases as the DGTE1 is shifted further. The group delay spectra of the two linearly tailored DGTEs selected for the experiment are shown in the inset of the Fig.3b. The two DGTEs were combined using a four-port optical circulator. In the experiment, we simply controlled the relative spectral shift between them by applying strain. The measured results for dispersion slope settings of +20.2, +6.3, -0.7, -9.4, and -20.2ps/nm^2 for near 30 channels were plotted in Fig.3b, which clearly indicate the slope tunability. The slope tuning range of this DSC is from –22 to +22ps/nm^2 and the usable bandwidth for each channel is about 45% of the FSR (50GHz).

To demonstrate even higher order dispersion compensation capability, we designed a DSC using two quadratically tailored DGTEs. The simulated group delay spectra for the two nonlinearly tailored DGTEs are shown in the inset of Fig.4. The principle of tuning is similar to Fig.3a. When there is a relative spectral shift between each other, the higher order slope (i.e. quadratic coefficients of the dispersion profile) will change. For the plotted dispersion curves in Fig.4, the quadratic coefficients vary between +6.3 and -7.1 and one clearly sees the change of dispersion profile over these channels. This example strongly indicates that tunable control of arbitrary dispersion profile may be realized by properly designed tailored DGTEs.

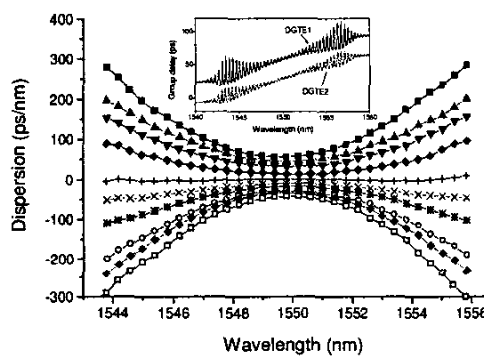

Fig.4. Design of tunable high-order DSC with two quadratically tailored DGTEs. Inset: calculated group delay spectra of the two tailored DGTEs.

4. Conclusion

We have introduced a novel concept of a tailored Gires-Tournois etalon, which is an all-pass filter with specially designed group delay profile achieved by tailoring the reflectivity of the first mirror/grating. Linearly and nonlinearly tailored DGTEs have been fabricated with UV-written fiber Bragg gratings. We have successfully demonstrated the use of such devices as tunable dispersion slope compensators that can compensate for complex dispersion profiles with tunability. Due to the compact all-in-fiber design, such a DSC is an attractive solution for tunable dispersion slope compensation, having advantages such as low loss, low cost and low group delay ripples.

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