Broadband fiber Bragg grating with channelized dispersion

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Abstract: We present here a new class of multi-channel Fiber Bragg grating (FBG), which provides the characteristics of channelized dispersion but does so with only a single reflection band. An FBG of this type can provide pure phase control of the spectral waveform of optical pulses without introducing any deleterious insertion-loss-variation. We anticipate that this new class of FBG will find some applications in wavelength-division-multiplexing systems.

OCIS codes: (060.2340) Fiber optics components; (060.4510) Optical communications

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1. Introduction

Fiber Bragg grating (FBG) technology provides a unique in-fiber platform for optical signal control, processing and manipulation with many significant advantages such as compact size, low insertion loss, low cost and robust and reliable performance [1, 2]. A large variety of FBG-based devices have been fabricated for short pulse compression [3], repetition-rate multiplication [2], slowing down the speed of light [4], and second- and third-order dispersion compensation in optical communication systems [5, 6]. An FBG with multiple channel manipulation capability is highly desirable due to its important applications in wavelength-division-multiplexing (WDM) systems. To date, the design and fabrication of multi-channel FBGs has been based primarily on sampling methods [7-10]. Sampled fiber Bragg gratings (SFBGs) can provide a series of wavelength channels with accurate inter-channel separations and customized, e.g., identical, in-band specifications. A typical SFBG has both a channelized reflection band (i.e. multiple reflection bands) and channelized dispersion spectrum: although channelized reflection bands can add a filtering function, in some cases their presence also reduces the efficiency of the usage of the spectrum. Moreover, the dispersion may exhibit sharp changes near the band edges which, when combined with the inevitable insertion loss variation, serves to limit the device performance in some applications such as tunable dispersion compensators [7], 2R regeneration (pulse reamplification and reshaping) [11], and collision-induced timing jittering reduction [12]. We present here a new class of multi-channel FBGs, which provides the characteristics of channelized dispersion but does so with only a single reflection band. An FBG of this type can provide pure phase control of the spectral waveform of optical pulses without introducing any deleterious insertion-loss-variation. Such FBGs may find applications in WDM systems and may also open up some new applications.

2. Concept and properties

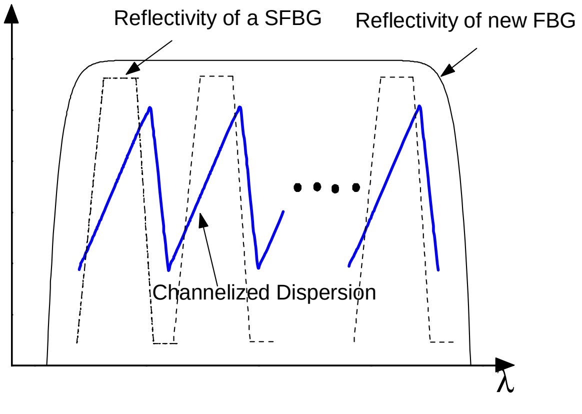

Fig. 1. Schematic of the properties of the proposed new class FBG. The reflection bands of a SFBG are also shown in dashed line for comparison.

The proposed new class of FBG with general properties as shown schematically in Fig. 1. In marked contrast with the multi-reflection bands of SFBGs (dotted curve), the new FBG demonstrates a single wide and flat reflection band (solid curve). The dispersion in each channel can be individually designed to have any shape, including linear and nonlinear variations. When such an FBG is used to manipulate optical pulses, it does so without influencing the power spectrum and provides pure phase control. This characteristic is particularly desirable for some applications such as tunable dispersion compensation since it does not introduce any insertion loss variation. It should be noted that a distributed GT etalon (DGTE) [13] can also realize similar spectra, i.e. a wide band with channelized dispersion. As

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compared with the new structure described herein, however, the DGTE has some drawbacks: the dispersion profiles in each channel cannot be freely defined to arbitrary shapes, and the DGTE must incorporate a very high reflectivity grating to reduce the variation of the reflectivity. For example, the new grating described herein with reflectivity of 95% may be designed to have almost no reflectivity variation (<0.03dB), whilst the DGTE with the same reflectivity has 0.5dB power variation in reflection spectrum (taking its weaker grating reflectivity to be 15%). Once a target dispersion and reflectivity profile is defined, we can use a layer-peeling, inverse-scattering method [14] to derive the corresponding coupling strength and grating period profile. Several interesting examples of such FBGs are demonstrated below.

3. Design and experimental examples

We first designed a broadband FBG with multi-channel V-shaped dispersion profile. The V-shaped FBGs have been shown to have superior properties for optical signal manipulation and chirp control compared to conventional FBGs with constant dispersion or with constant dispersion slope [15]. For example, they can produce larger signal chirp with less pulse broadening compared to a corresponding conventional FBG with constant dispersion. Also, they may be used to create a signal with the phase having different (controllable) behaviors at the center and at the pulse tails, which represents a potentially interesting feature for application to advanced modulation formats using differential phase shift keying. For an 8-channel V-shaped FBG with channel spacing of 50GHz reconstructed by layer-peeling, the resulted coupling strength (κ) and period variation ($\Delta\Lambda$) profile along the grating position are plotted in Figs. 2(a) and 2(b). It is interesting to note that the grating has a length of just

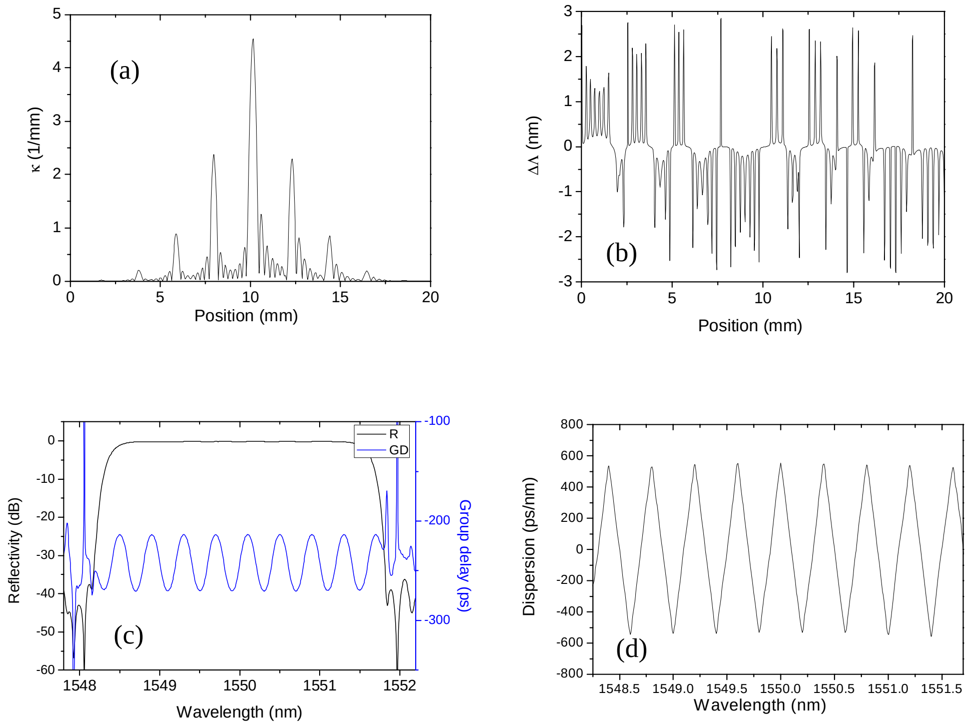

Fig. 2. The designed 8-channel V-shaped grating. (a) Coupling coefficient (b) Period variation profile. (c) Calculated reflectivity and group delay response. (d) Calculated dispersion spectrum.

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20mm, and both the coupling coefficient and period variation have many complex oscillation peaks. Detailed analysis shows that the separation of the main peaks in the coupling strength profile is about 2.1mm and the locations of the period peaks correspond to the minimum (or zero) points in the coupling strength profile. The 2.1mm separation of the main peaks in κ corresponds to a channel spacing of 50GHz, indicating that light is actually resonant between these peaks when propagating within the grating. We use the transfer matrix method [16] to verify the designed profile and the calculated reflectivity, group delay and dispersion spectra are shown in Figs. 2(c) and 2(d). As expected, it is clearly seen in Figs. 2(c) and 2(d) that the grating has only a single flat and wide band in reflection, a continuously varying curve in group delay, and multiple V-shapes in dispersion. The reflectivity of the designed grating is ~95% with only 0.025dB variation on the top.

We then designed a 4-channel V-shaped FBG with a relatively simple structure for an experimental test. The reconstructed coupling strength and period variation profiles are shown in Fig. 3(a); the grating length is still 20mm, but the structure is not as complex as that depicted in Fig. 2. The fabrication system used was a continuous-writing system: this system allows for FBG inscription plane-by-plane and for control of the apodization and period of the FBG continuously along the grating length. The UV writing beam (244nm) was generated from a frequency-doubled Argon ion laser. The beam size was reduced to tens of micrometers and a small portion of a uniform phase mask was used to generate interference fringes in the experiment. The hydrogen-loaded photosensitive fiber was mounted on an air-bearing translation stage moving at constant speed with good stability and accuracy, and the apodization profile and the varied period were realized by appropriately controlling the ON/OFF of an acousto-optic modulator and synchronously translating the fiber Following

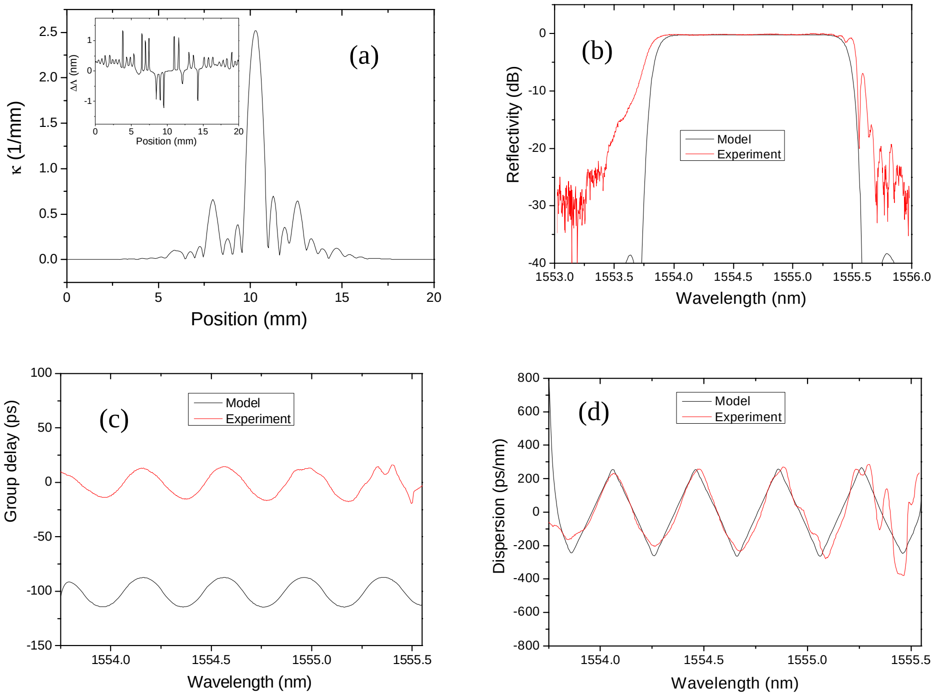

Fig. 3. The design and experimental results of a 4-channel V-shaped grating. (a) Coupling coefficient and period variation profile (inset). (b) Measured and simulated reflection spectra. (c) Measured and simulated group delay response. (d) Measured (with 100pm average window) and simulated dispersion spectrum.

inscription, the grating was characterized using an Agilent Chromatics Dispersion Test Set (86073C) with the wavelength resolution and the modulation frequency in the measurement set at 2.5pm and 250MHz, respectively. Figures 3(b)-3(d) show the reflection profile, the time delay response and the dispersion of the fabricated and modelled gratings showing, in each case, good agreement. The reflectivity of the grating is about 97% with ripple of less than 0.3dB on the top, which is worse than the corresponding theoretical result of 0.013dB.

We finally demonstrated a broadband FBG with multi-channel linear dispersion. Figure 4(a) shows the designed coupling strength and period variation profile. Figures 4(b)-4(d) show the reflection profile (b), the time delay response (c) and the dispersion (d) of the fabricated and modelled gratings. This grating has four channels with a separation between them of 100GHz. For each channel, the grating has a quadratic group delay and a linear dispersion with average slope of about -1450ps/nm^2. Though the ripples in the experiment for both the reflectivity and dispersion are worse than the theoretical model, the agreement between them is still reasonably good. We believe that better results can be produced by improvements to the mechanics of our continuous-writing fabrication system or, alternatively, by considering encoding the profile in a phase mask [7]. Gratings of the type we have demonstrated have many important applications including pure third-order dispersion compensation [12], tunable dispersion compensator (TDC) implementation [7, 17], 2R regeneration [11], and collision-induced timing jittering reduction [12]. For example, to make a tunable dispersion compensator we use two gratings with equal dispersion slopes but opposite signs, and adjust the dispersion by shifting the relative wavelength positions of the two FBGs. The FBG shown

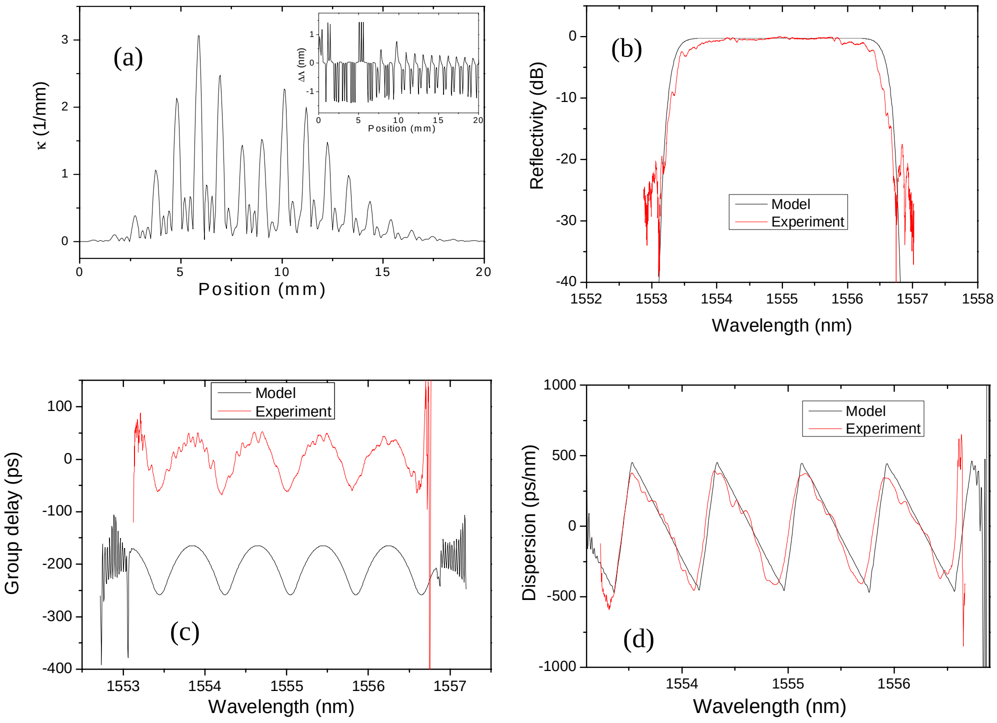

Fig. 4. The design and experimental results of a 4-channel linear dispersion grating. (a). Coupling coefficient and period variation profile (inset). (b). Measured and simulated reflection spectra. (c). Measured and simulated group delay response. (d). Measured (with 200pm average window) and simulated dispersion spectrum.

in Fig. 4 has a negative slope: to obtain a positive slope, we simply launch the light from the opposite side of the structure, and the TDC comprises two identical cascaded FBGs used in opposing orientations. For a TDC so formed, Figure 5 shows the simulated group delay response when the device is tuned to dispersion levels of -200, 0 and +200ps/nm. The dispersion can be continuously adjusted from -200 to +200ps/nm and for all levels, the group delay responses exhibit very good linearity and are almost ripple-free. Also, it is important to recognise that the tuning process is accompanied by almost no insertion loss variation. The usable bandwidth for each channel in this case is about 70GHz, which is good enough for 40Gb/s system applications. Although the demonstrated examples have only 4 or 8 channels, more channels with wider bandwidth are possible provided that we can achieve stronger photosensitivity or combine using appropriate period chirp.

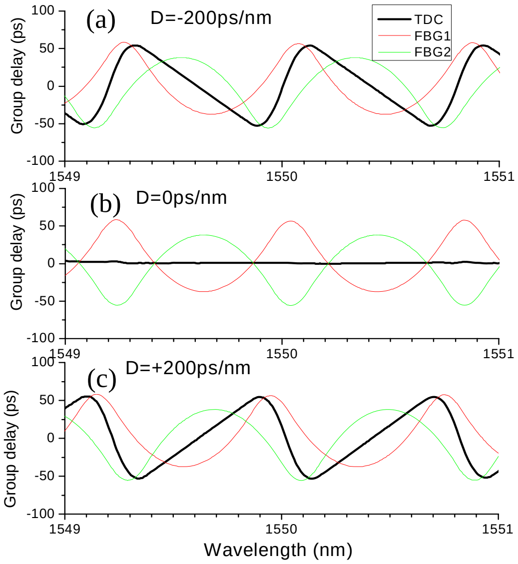

Fig. 5. Simulated group delay response of the TDC with different dispersion settings. (a)D=-200ps/nm, (b)D=0ps/nm, (c)D=+200ps/nm. The TDC constructed from two FBGs, whose group delay responses are also shown.

4. Conclusion

In summary, we have presented a novel class of broadband fiber Bragg gratings with channelized dispersion but a single reflection band. These gratings have been designed using a layer-peeling inverse-scattering algorithm. As examples of the class, we designed and fabricated a multi-channel V-shaped dispersion grating and a multi-channel linear dispersion profile grating. The experimental results agree very well with the simulations. Such gratings provide pure phase control of optical signals and have many important applications including short pulse manipulation and dispersion compensation. Although we have restricted the demonstrated examples to structures having identical dispersion profile for all channels, in fact each channel can be individually designed, which may find some new applications.

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