Fiber Bragg grating based dispersion compensator slope-matched for LEAF fiber

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Abstract: A dispersion compensator matching the spectrally-varying dispersion of LEAF fiber is presented, based on a multi-channel fiber Bragg grating that operates over the full C-band.

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1. Introduction

Chromatic dispersion in the transport fiber of a telecommunication system causes impairments that must be addressed at data rates of 10 Gb/s and higher. Optical dispersion compensating devices are most often used to alleviate this problem. Dispersion compensating fiber (DCF) is widely used, but devices based on fiber Bragg gratings (FBGs) are attractive due to their reduced cost, size and insertion loss. In a wavelength division multiplexing (WDM) system operating at 10 Gb/s, optical dispersion compensation is performed simultaneously over all channels. In this case, for an optimal result, the channel-to-channel variation of the dispersion must be taken into account. The dispersion compensator must cancel not only the dispersion but also the dispersion slope of the transmission link to which it is applied . For example, the chromatic dispersion of a standard single-mode fiber such as SMF-28 is 15.6 ps/nm/km at 1530 nm and 17.7 ps/nm/km at 1565 nm. Such small dispersion slope is relatively easy to manage with both DCF and FBG technologies. However, NZ-DSF fibers such as LEAF, with a low dispersion but a significantly higher relative dispersion slope, are now being deployed and raise new challenges for dispersion compensators. The chromatic dispersion of LEAF fiber is 2.5 ps/nm/km at 1530 nm, 4.2 ps/nm/km at 1550 nm, and 5.5 ps/nm/km at 1565 nm. Albeit lower, the dispersion of such fibers still requires compensation. Perfect matching of the dispersion and dispersion slope of LEAF fiber with DCF still represents a challenge [1]. Fiber Bragg grating technology can provide an excellent slope matching through grating superposition [2]. However, this approach suffers from a poor manufacturability for the high channel counts required to cover the full C-band. Phase sampling has been proposed as an efficient way to produce multi-channel gratings covering a wide spectral range [3]. Dispersion slope-matching of SMF-28 fiber was so demonstrated [4], but this approach leads to a passband bandwidth times dispersion product that is equal over all channels. This limits its applicability to fibers with a weak dispersion slope. Other FBG techniques were recently proposed to eliminate this problem by providing a multi-channel grating with all channels having the same passband but different dispersions [5-6]. In a similar approach, all the FBG complexity was included into its phase profile [7]. As demonstrated over a limited number of channels, this allows encoding most of the grating complexity into a phase mask for an efficient manufacturing.

This paper demonstrates the slope-matched compensation of the chromatic dispersion accumulated over 160 km of LEAF fiber using a multi-channel FBG operating over 51 channels covering the full C-band. The FBG was written in an efficient and practical manner using a complex phase mask.

2. Design approach

The design approach is based on FBG superposition. Each single channel grating is designed individually, which allows a full flexibility in the optical characteristics. Instead of being performed at the writing stage [2], the superposition is carried out mathematically at the design stage. The resulting complex FBG is encoded into a phase mask for manufacturing efficiency [7]. The grating superposition produces a complex FBG with highly structured apodisation and phase profiles. Using standard lithography, only a phase profile can be encoded into the phase mask. However, a phase modulation along the FBG can act as a equivalent apodisation [8]. The FBG complex structures is thus transferred to its phase profile while keeping a uniform or smoothly varying apodisation profile. The resulting FBG phase profile is encoded into a phase mask, taking into account diffraction effects [9]. The proposed design approach thus contains three key steps: 1. Grating superposition, 2. Phase apodisation and 3. Phase mask encoding.

Grating Superposition: The FBG components (one for each channel) are first designed and their associated apodisation and phase profiles $\Delta n_k(z)$ and $q_k(z)$ are obtained. The overall complex grating is obtained by summing the FBG components according to:

$$\Delta n(z) = \Delta n_{offset} + \sum_k \Delta n_k(z) \cdot \exp\left(i\left(q_k(z) + f_k\right)\right) = \Delta n_{offset} + \Delta n_a(z) \cdot \exp\left(iq(z)\right), \qquad (1)$$

where $\Delta n_a(z)$ and $q(z)$ are the overall apodisation and phase profiles and f_k are the relative phases between the grating components, which can be chosen to minimize the peak index change of the overall grating. An index offset Δn_{offset} is also required to make the total index change strictly positive.

Phase Apodisation: Since only phase information can be encoded into the phase mask, it is preferable to include most of the complexity into the phase profile of the overall grating while keeping the apodisation profile as simple as possible. After summation of the grating components, both $\Delta n_a(z)$ and $q(z)$ are found to be finely structured. The fine apodisation structures are replaced by phase structures that act as an apodisation by locally decreasing the FBG efficiency [8]. Accordingly, the modified complex grating given by:

$$\Delta n_m(z) \;=\; \Delta n_{offset} \;+\; \Delta\tilde{n}_a(z)\cdot\exp\left(i\left(q(z)+f_a(z)\sin\left(\frac{2pz}{p_a}\right)\right)\right), \tag{2}$$

has virtually the same optical characteristics within the spectral region of interest as the original grating. The finely structured apodisation profile $\Delta n_a(z)$ in Equation (1) is replaced by a smooth apodisation profile $\Delta\tilde{n}_a(z)$ in Equation (2). The two structures provide the same optical characteristics provided that the apodisation period p_a is small enough to produce side bands outside of the spectral region of interest and provided that the spatially varying phase modulation amplitude $f_a(z)$ is given by:

$$f_a(z) \;=\; J_0^{-1}\left(\frac{\Delta n_a(z)}{\Delta\tilde{n}_a(z)}\right). \tag{3}$$

In Equation (2), the modified apodisation profile $\Delta\tilde{n}_a(z)$ can be chosen to be uniform or to vary smoothly as a function of z like the envelope of the finely structured profile $\Delta n_a(z)$ for example.

Phase mask encoding: Since the phase profile to be encoded into the phase mask contains fine structures, diffraction effects occurring from the mask surface to the fiber core must be taken into account. One must consider that the light pattern creating the grating is produced by the interference of two UV beams diffracted by the phase mask at two different points. For a typical separation of 10 µm between the mask surface and the fiber cladding surface, the separation Δz_{UV} between these two points is about 24 µm. Phase mask structures having short spatial periodicities (100 µm or smaller) are not transferred into the fiber with the same efficiency. They are rather transferred with an efficiency, or transfer function, given by [9]:

$$T(f_p) \;=\; \cos\left(p\cdot\Delta z_{UV}\cdot f_p\right), \tag{4}$$

where f_p is the spatial frequency of the phase structure. This transfer function must be considered when designing the phase mask. The Fourier spectrum of the phase profile encoded in the phase mask must equal half of the Fourier spectrum of the desired FBG phase profile divided by T.

3. Experimental Results

This approach was used to design a complex phase mask for writing FBGs capable of compensating the chromatic dispersion over 160 km of LEAF fiber. The spectral response of the FBG thus obtained are shown in Fig. 1. It covers the full C-band, comprising 51 channels spaced by 100 GHz. The optical performances are good and comparable to those of a non dispersion sloped FBG designed with a phase sampling approach. The maximum deviation from the dispersion target is 4.4%.

4. Conclusion

A new method for designing and fabricating complex multi-channel FBG is presented. It provides full flexibility in the optical characteristics, since each single channel grating is designed individually. It allows the production of multi-channel dispersion compensators with an equal passband but a different dispersion in each channel. Slope-matching of LEAF fiber over the whole C-band has been demonstrated. Efficient and cost-effective manufacturing is allowed by the use of a complex phase mask.

5. References

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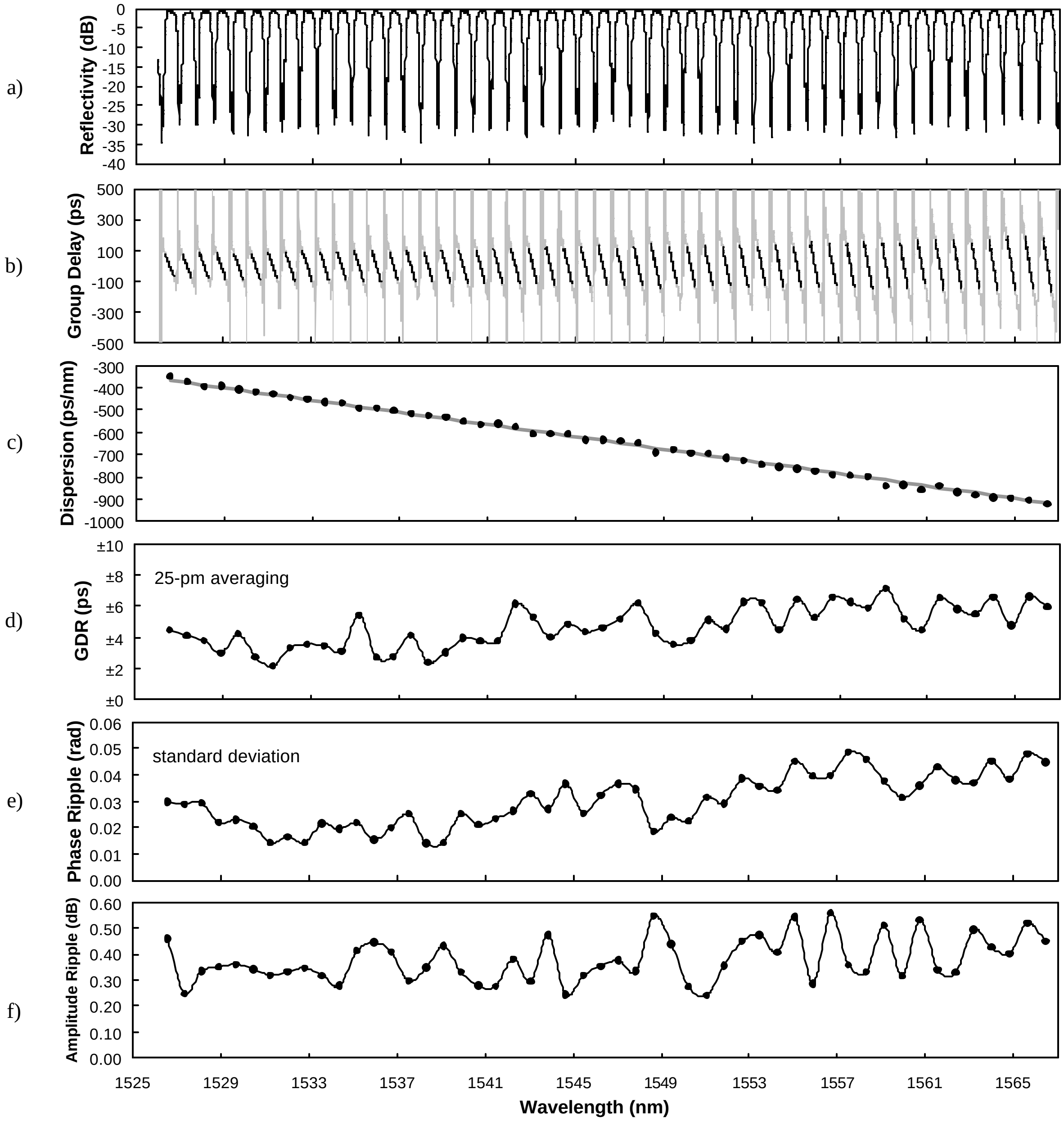

Fig. 1. Optical response of a 51-channel LEAF slope-matched dispersion compensation grating: a) reflectivity spectrum; b) group delay spectrum; c) dispersion (dots) compared to the target (line); d) 25-pm averaged group delay ripple amplitude; e) phase ripple standard deviation; f) reflectivity ripple amplitude.