Sinc-Sampled Fiber Bragg Gratings for Identical Multiple Wavelength Operation

Morten Ibsen, Michael K. Durkin, Martin J. Cole, and Richard I. Laming

***Abstract*—Through a periodic sinc modulation of the refractive index-profile in fiber Bragg gratings (FBG's), we demonstrate gratings with multiple equally spaced and identical wavelength channels. We show 10-cm-long gratings with 4, 8, and 16 identical uniform wavelength channels separated by the ITU spacing of 100 GHz and a 22.5-cm-long grating with four identical dispersion compensating channels with a 200-GHz separation designed to dispersion compensate 80-km data transmission through standard fiber at 1.55 µm.**

***Index Terms*—Dispersion compensation, Fiber gratings, WDM technology.**

I. INTRODUCTION

Fiber Bragg grating (FBG) fabrication technology is now well established and grating devices are finding many applications in optical communications networks and sensors. Of particular interest in optical communication is the correction of chromatic dispersion in existing fiber links by chirped FBG's [1], allowing an increase in the transmission data rate and distance. Wavelength-division multiplexing (WDM) is being employed to further increase the bandwidth.

A powerful fiber grating approach to the WDM solution is to use chirped Moiré fiber gratings as we recently demonstrated [2]. In order to generate even more channels, the use of sampled FBG's as multichannel dispersion compensators has been proposed [3]. A sampled grating is generated by a periodic modulation of the refractive index amplitude and/or phase in the fiber. The resultant reflection spectrum and channel separation is a function of the shape and period of this modulation. Previously reported sampled FBG's have utilized simple binary sampling functions with regions of dead-space that create channels of unequal strength and bandwidth [3]–[5]. Identical channel sampled gratings have been demonstrated in semiconductor lasers using a linear change in the grating pitch in each sampling section [6], [7]. In this letter, we propose and demonstrate, in contrast, a sinc-shaped sampling function that also causes the overall envelope to be square. Furthermore, the individual sections are concatenated thereby ensuring a continuously alternating refractive index amplitude and phase profile. This technique is more attractive than over-writing many gratings at different wavelengths [8] in the same length of fiber since exact wavelength matching of the channels is automatically achieved from the sampling process and the time taken to write these devices minimized.

In this letter, we demonstrate sampled FBG's with identical wavelength characteristic in a predictable and finite number of channels. As examples, we show short 10-cm gratings with up to 16 identical wavelength channels separated by 100 GHz. To demonstrate the potential of these gratings as multi-channel dispersion compensators we show a 22.5-cm-long chirped grating with four wavelength channels separated by 200 GHz and with channel bandwidths of 200 GHz each channel exhibiting dispersion characteristics to compensate 80-km transmission through standard fiber at 1.55 m.

II. THEORETICAL BACKGROUND

Fourier theory is applicable to grating responses when weak gratings are investigated. A sinc-shaped refractive index profile has been shown to generate a at-top or square-filter shape when the strength of the grating (R < 50%) is low [9]. As these gratings consist of many identical or nearly identical (if chirped) short grating sections the reflection from each section will at all times experience a full sinc-profile, hence the square overall envelope. The concatenation of identical sinc structures will create channels within this square envelope and the channel separations will be determined by the period between the maxima of this modulation.

As is the case for sampled gratings generated with a digital sampling function the channel separations are given by

$$\Delta\lambda = \frac{\lambda_B^2}{2 \cdot \eta_{eff} \cdot P}$$

with η_{eff} being the effective refractive index in the grating and P the period between the maxima of the modulation. Another way of visualizing the effect of this refractive index profile is by the adding up of the spectral components from each of the wavelengths. Using the Fourier theory, the entire gratings refractive index profile can be expressed in a single sampling function Σ:

$$\Sigma(z) = \frac{\sin\left(N \cdot \frac{L_{gr}}{P} \cdot \pi \cdot z + \left(\frac{P}{2 \cdot L_{gr}}\right)\right)}{N \cdot \sin\left(\frac{L_{gr}}{P} \cdot \pi \cdot \left(z + \frac{P}{2 \cdot L_{gr}}\right)\right)}, \quad 0 \le z \le 1$$

where N is the number of channels, L_{gr} is the length of the entire grating, and P is the period of the inde modulation maxima.

Fig. 1 shows the complex refractive index profile and

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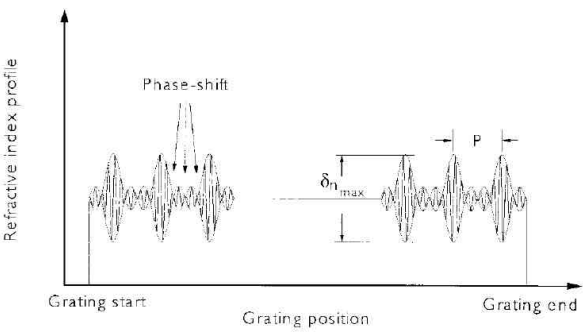


Fig. 1. Refractive index and phase profile of equal strength sampled fiber gratings.

the regions of phase shift in the gratings, the exact profile shown gives rise to a 4-channel device. An 8-channel device has six side loops between the maxima of the index modulation and a 16-channel device has 14. The sinc-shape of the refractive index modulation is generated using apodization along the length of the grating. In order to create the sign change in the refractive index profile between the side loops a discrete - π phase shift (half a local grating period) is inserted.

III. FABRICATION TECHNIQUE

The gratings were written using a recently developed continuous grating fabrication technique [10]. This technique effectively writes grating plane by grating plane and apodization is obtained by dephasing one grating period with respect to the next one [11], or in other words by filling up the gaps between the grating planes to effectively reduce the index depth δn, but keeping the average refractive index n_{ave} constant. Providing that the index change is in the linear regime with fluence, full control of the apodization is obtained. An interferometer is used to monitor the position of the fiber during writing to ensure that the individual grating planes are written with a position accuracy of ~1 nm.

Each sampled grating was written in a 0.2-*NA* Deuterium loaded germanosilicate fiber with a 100-mW 244-nm CW UV-source.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 2 (a)–(c) shows examples of 10-cm-long sinc-sampled gratings with Bragg wavelengths of 1560.5 nm comprising 4-, 8-, and 16 wavelength channels respectively, all with complete out-of-band wavelength-channel suppression. All channels exhibit identical characteristics, being uniform with a 16-pm bandwidth and ~10 dB of transmission loss. The channel separation is 100 GHz giving a finesse of 50. The time taken to write the sampled grating with 16 identical channels was just 15 min and the requisite refractive index change for such a structure is $\sim 1.8 \bullet 10^{-4}$. Additional apodization of the entire structure would result in identical channels with characteristics determined by the apodization profile, such as channel sidelobe suppression.

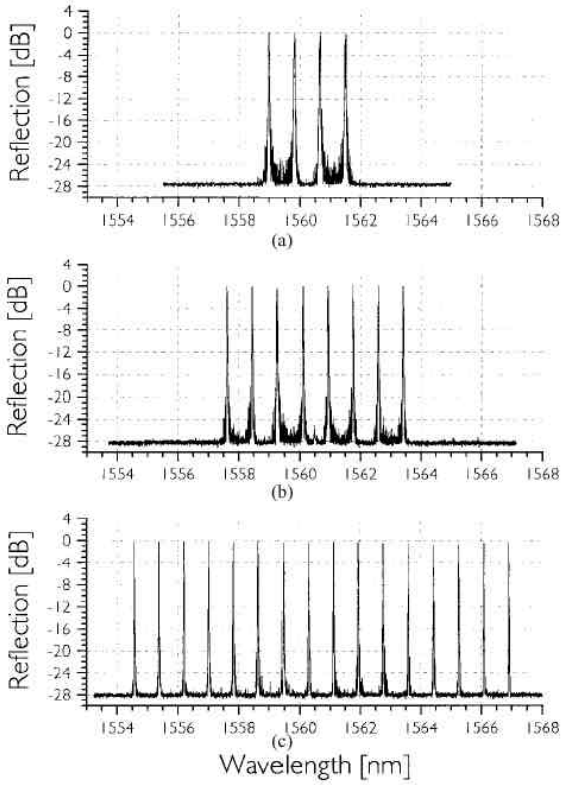


Fig. 2. Measured reflection characteristics of 10-cm-long sampled FBG's with channel separations of 100 GHz. (a) 4 channel. (b) 8 channel. (c) 16

Fig. 3(a) shows a chirped sinc-sampled fiber grating with a Bragg wavelength of 1554 nm and length of 22.5 cm. The grating has four wavelength channels separated by 200 GHz, each with a bandwidth of ~200 GHz. In order to generate this channel separation, a sampling period of 521 μm is used, see (1). The resultant average dispersions of the four channels are D_I = -1410 ps/nm, D_{II} = -1406 ps/nm, D_{III} = -1392 ps/nm and D_{IV} = -1392 ps/nm. To reduce the ripple in the dispersion characteristics the grating is apodized over 10% of the total grating length at either end using cosine apodization. The resultant deviations from linear time delay is 30-ps peak-to-peak [see Fig. 3(b)]. Each channel exhibits a transmission loss of ~8 dB, indicating a reflectivity of approximately 84%. The gratings were tested for reflectivity with a wavelength resolution of 1 pm using a tunable laser and a wavemeter. The chirped grating was tested for time delay by amplitude modulating the signal from a tunable laser and measure the group delay between successive wavelength steps on a network analyzer. The modulation frequency used is 500 MHz.

For these devices to be able to compete with other approaches to WDM gratings [8] they must be easier to fabricate to specification, cheaper to manufacture and more stable when packaged. Benefits of these devices and for sampled gratings in general are that they simplify the manufacturing of multiple matched gratings where very accurate wavelength separations are re-

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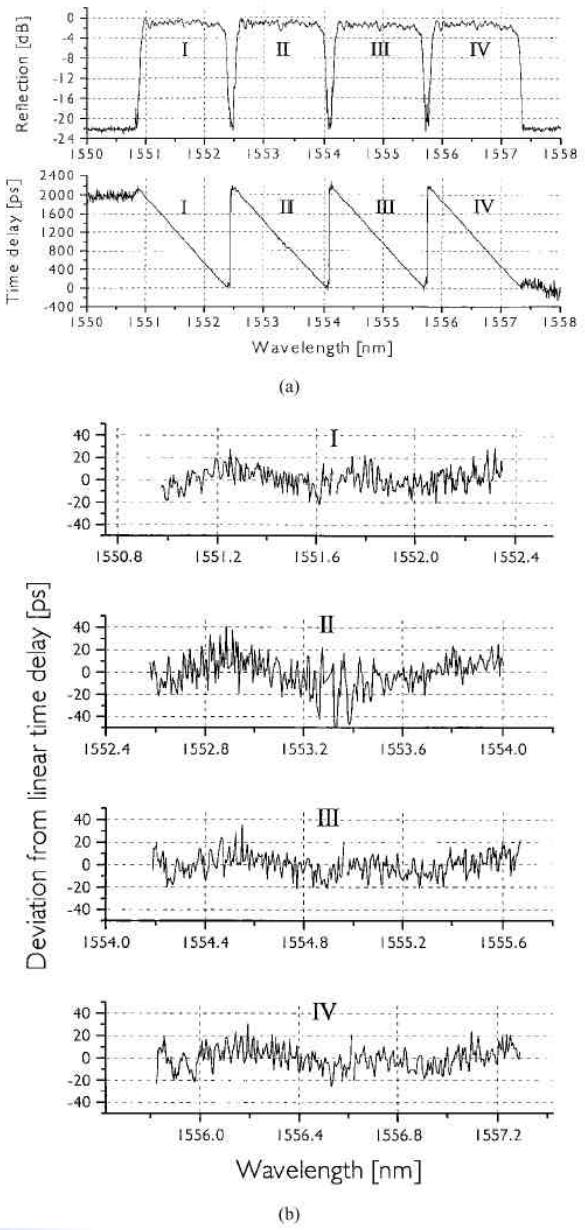


Fig. 3. (a) Measured reflection and time-delay characteristics of a 22.5-cm-long continuously chirped fiber grating with four wavelength channels separated by 1.6 nm (200 GHz) and channel bandwidths of 1.6 nm. The dispersion in the channels are D_{I} = -1410 ps/nm, D_{II} = -1406 ps/nm, D_{III} = -1392 ps/nm, and D_{IV} = -1392 ps/nm channel. (b) Measured deviations from linear time delay for channels I, II, III, and IV.

quired. Packaging and temperature stabilization demands are also reduced because these gratings are all effectively contained within the same length of fiber. Furthermore, by chirping the Bragg wavelength they can offer practical, multi-channel WDM dispersion compensation exhibiting finite and controllable numbers of wavelength channels with a spectral response devoid of out-of-band wavelength-channels as demonstrated in Fig 3.

V. CONCLUSION

We have demonstrated sampled FBG's with identical characteristics in all wavelength channels and with complete suppression of out-of-band spectral features. The gratings are generated through a controlled sinc-shaped modulation of the refractive index amplitude and phase profile in the fiber. Examples of 4-, 8-, and 16-channel gratings with channel separations of 100 GHz and uniform characteristics in all channels are shown. Furthermore, we demonstrate the application of these structures to multichannel dispersion compensators through a 4-channel device with 200-GHz channel separation designed to compensate transmission through 80 km of standard fiber at 1554 nm.

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