

Chirped in-fiber Bragg gratings for compensation of optical-fiber dispersion

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A linearly chirped in-fiber Bragg grating is reported that can compensate at 1549 nm for the dispersion [≈ -19 ps/(nm km)] of standard telecommunications optical fiber optimized for 1300-nm operation.

It is well known that chirped (aperiodic) refractive-index Bragg gratings can be used for compensating for the dispersion of optical fiber waveguides.¹ When used in reflection mode (in contrast to transmission mode), such Bragg gratings exhibit large dispersion. As well, the sign of the dispersion in reflection mode is easily controlled. Together these two characteristics suggest the use of chirped Bragg gratings for dispersion compensation in optical-fiber systems. Theoretical calculations show that a relatively short Bragg grating device can compensate, over a useful bandwidth, for the dispersion of an optical fiber that is tens of kilometers long.

In this Letter we discuss the optical characteristics of low-excess-loss (0.1-dB) linearly chirped Bragg gratings photoimprinted in the core of standard telecommunications fiber that has been H₂ loaded² to enhance its photosensitive response.³ The gratings are chirped in the sense that the optical pitch (i.e., effective refractive index $n_{\text{eff}} \times$ grating pitch Λ) varies linearly along the length of the structure. Our Bragg grating devices were designed to compensate, within an optical bandwidth approximately 0.4 nm wide, for the dispersion exhibited at 1549 nm [≈ -19 ps/(nm km)] by a 20-km length of standard telecommunication optical fiber optimized for use at 1300 nm (zero-dispersion wavelength).

Further development of the technique should easily permit compensation of dispersion over narrower bandwidths (matched to 10-Gbit/s channels, for example) and significantly longer fiber strands.

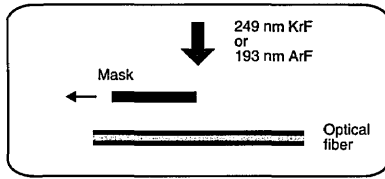
To make the devices, we use a novel double-exposure photoimprinting method for precisely controlling the chirp. A schematic of the technique is shown in Fig. 1. In the first exposure, actinic radiation from either a KrF (249-nm) or an ArF (193-nm) excimer laser beam irradiates a segment of an optical fiber screened by a mask that is translated along the length of the fiber at constant velocity (see Fig. 1, top). The motion of the mask increases the fraction of the fiber segment that is exposed to excimer light, thereby varying linearly along the fiber length the

total irradiation dose that is received by the fiber segment. Since the photoinduced refractive-index change is a function of the received dose, the first exposure photoinduces an effective refractive index, n_{eff} , that increases linearly along the length of the fiber segment. In the second exposure, we photoimprint a Bragg grating in the same segment of optical fiber by passing the actinic radiation through a zero-order nulled phase mask⁴ (see Fig. 1, bottom). The second exposure patterns a uniform (spatially periodic) refractive-index Bragg grating into the core of the waveguide. Although the grating is spatially periodic, its effective optical pitch is chirped because of the photoinduced index change produced in the first exposure.

Using the double-exposure photoimprinting technique, we fabricated a 1.5-cm-long Bragg grating with a center resonant wavelength λ_0 of 1549 nm and linear chirp of 0.03%. The chirped Bragg grating was fabricated in Corning SMF-28 optical fiber that had been photosensitized by H₂ loading before irradiation. The measured reflectivity of the chirped grating as a function of offset from the center frequency is shown in Fig. 2.

Using coupled-mode equations, we have calculated theoretically the reflection response of a grating with a linear chirp; the results are also plotted in Fig. 2. We fitted the theoretical curve to the experimental curve, using $\kappa L = 2$, where κ is the grating coupling coefficient and L is the grating length. The close agreement between the theoretical and the experimental curves suggests that the double-exposure chirping technique provides good control of the Bragg grating chirp. As an aid in the design of linearly chirped gratings for dispersion compensation, we note the following relationship between the percent chirp and the other parameters of the Bragg grating. For weak band-stop reflectivity ($R < 50\%$) the full width at quarter-maximum of the spectral response curve of a linearly chirped Bragg grating is given by the percent chirp multiplied by the center Bragg resonant wavelength (λ_0) of the device. An alterna-

● Velocity Modulated Exposure Control for Chirping Bragg Grating Resonance



● Zero-Order Nulled Phase Mask Photoimprinting

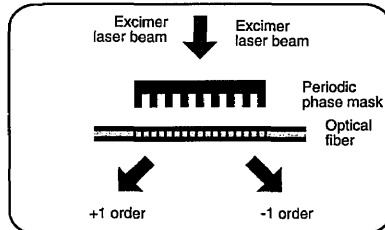


Fig. 1. Schematic diagram showing the double-exposure technique for fabricating the chirped gratings.

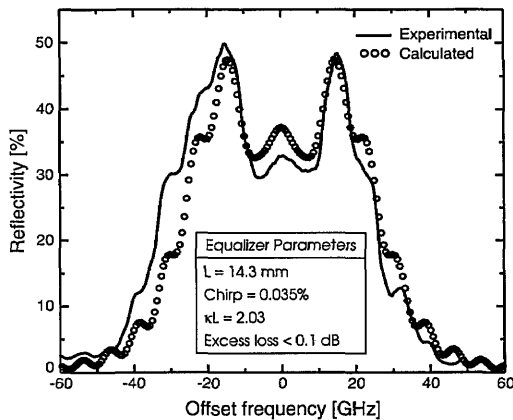


Fig. 2. Theoretical and experimental reflectivity of an optical-fiber dispersion compensator.

tive approximate analytic expression for the percent chirp is

$$\frac{50\lambda_0|\kappa|^2L}{n_{\text{eff}}\ln[(1-R)^{-1}]}$$

The experimental and the theoretical dispersion-delay spectral response characteristics of the same chirped Bragg grating are shown in Fig. 3. The dispersion measurements were made by the method described in Ref. 5. The measured dispersion-delay response is seen to be in good agreement with the response obtained by numerical solution of the coupled-mode equations that we use to model Bragg grating devices.

As Fig. 3 shows, the dispersion-delay characteristic is not linear but has a ripple that will result in a power penalty in the fiber-optic system design. One can reduce this power penalty by designing chirped Bragg gratings with a smoother dispersion-delay characteristic. One approach to reducing the ripple is to apodize the Bragg grating.^{1,6,7} In an apodized chirped Bragg grating the amplitude of the

photoinduced refractive-index modulation is varied along the length of the grating to have a bell-like function shape. Apodization has the effect of reducing the sidelobes in the spectral reflection response of a Bragg grating. It also reduces the ripple in the dispersion-delay characteristic to provide a more linear dispersion-delay response. This is shown in Fig. 4, which illustrates the calculated reflection response and dispersion-delay response of a linearly chirped Bragg grating that has been apodized. In this case, $\lambda_0 = 1550$ nm, $L = 3.0$ cm, $\kappa L = 7.0$, reflectivity at $\lambda_0 = 99.6\%$, and the chirp is 0.015%.

The application of chirped Bragg gratings to dispersion compensation is carried out preferably for each individual wavelength-division-multiplexing (WDM) channel taken one at a time rather than by attempting to use the technique to compensate over the entire useful bandwidth of the fiber at once. For example, as is shown in Fig. 5, several WDM channels can be dispersion compensated simultaneously by use of either a Michelson⁸ interferometer or a circulator-based device geometry to invert the response of chirped Bragg gratings matched to the WDM channels. We also note that, in WDM networks, nonlinearities such as four-photon mixing⁹ often limit the network performance. Improved network performance is possible if fiber with a higher dispersion is used to reduce the phase-matching dis-

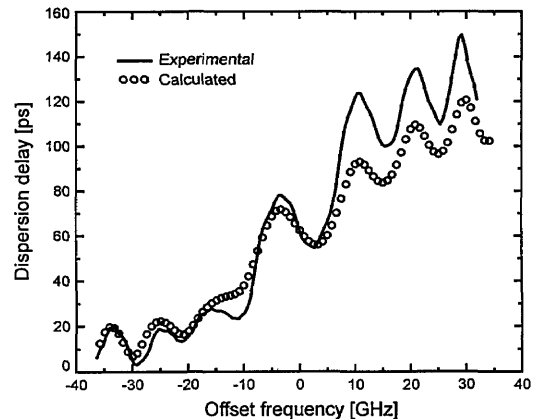


Fig. 3. Theoretical and experimental delay of an optical-fiber dispersion compensator.

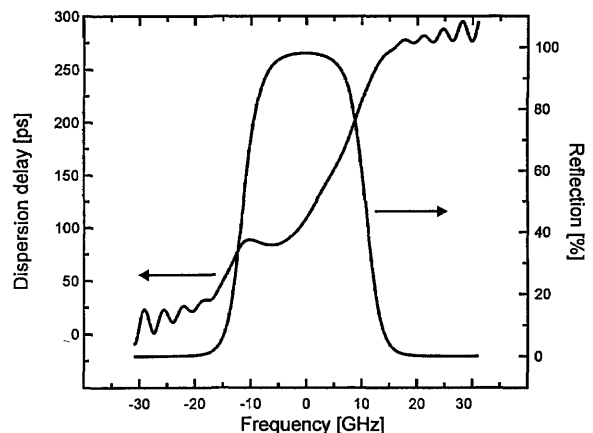


Fig. 4. Calculated reflectivity spectrum and dispersion-delay characteristic for an apodized chirped grating.

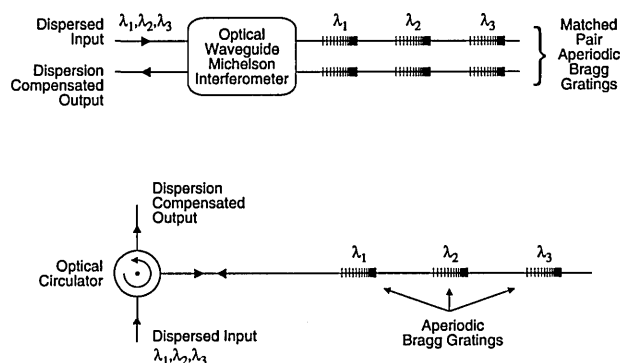


Fig. 5. Device geometry for WDM multichannel optical waveguide dispersion compensation.

tances for the nonlinear processes and the increased dispersion is compensated for by use of chirped gratings in the network.

In summary, using a novel double-exposure method, we have fabricated high-quality in-fiber chirped Bragg gratings that have application as dispersion compensators in fiber-optic networks.

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