Group Velocity Dispersion Cancellation and Additive Group Delays by Cascaded Fiber Bragg Gratings in Transmission

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***Abstract*— We have demonstrated that cascaded fiber Bragg gratings can provide delays of propagating pulses with minimal pulse reshaping. The grating pair used exhibited an overlap transmission region centered at 1551.05 nm, where both gratings contribute to the group delay and the group velocity dispersion (GVD) was canceled. Using wavelength tunable pulses spectrally sliced from a mode-locked fiber laser, the measurement was performed in the time domain with single picosecond resolution. Both gratings were 3 mm long and a maximum group delay of 15 ps was measured for the cascaded sequence. This compound grating configuration can be implemented as encoders and decoders in spread spectrum CDMA systems.**

***Index Terms*— CDMA, dispersion compensation, fiber Bragg grating, group delay, wavelength slicing.**

I. Introduction

UNIFORM fiber Bragg gratings, essentially one-dimensional photonic crystals, exhibit low group velocity and large dispersion near their stop bands. Therefore, delays can be achieved in transmission at band edge frequencies of uniform gratings, eliminating the need for circulators or couplers in conventional reflection schemes [1]. These delays are also coupled with dispersion, which severely limits their application to communication systems. In this letter we demonstrate that this dispersion can be effectively compensated for by transmission through opposite sides of grating pair stop bands, while both gratings contribute to the additive delay. Simulations have demonstrated the advantages afforded by gratings in long-haul fiber dispersion compensation [2], [3]. So far experimental investigations in this arena have been performed in the frequency domain [4] or in the time domain using a 50-GHz sampling oscilloscope [5]. Previously we reported single picosecond resolution time-domain measurements of group delay incurred by optical pulses propagating through a uniform grating [6]. We also demonstrated that the group delay was additive for nearly identical cascaded gratings; however, the transmitted pulse was severely distorted [7].

In this letter we explore a fiber Bragg grating pair that provided a 15-ps group delay with compensated GVD in transmission. The gratings were 3 mm long each and spatially separated to avoid any coupling effect. The measured transmission spectrum is shown in Fig. 1. The grating pair exhibited bandgap centers at 1550.25 and 1552.10 nm with 3-dB bandwidths of 1.40 and 1.82 nm, respectively. The overlap transmission region had a 1551.05-nm central wavelength, a 0.5-nm 3-dB bandwidth, and −3-dB peak intensity transmission. A commercial simulation program was used to model the gratings with parameters chosen to match the measured transmission spectrum. The simulated group velocities are shown in Fig. 2. The constant effective group velocity from 1550.99 to 1551.10 nm in the overlap transmission region resulted from GVD and higher order dispersion compensation. This was confirmed experimentally in the time domain by the minimal pulse distortion.

II. Experimental Setup

The output from a 1.55-μm mode-locked erbium-doped fiber laser exhibiting a 56-nm bandwidth was spectrally sliced [8] by an HP optical spectrum analyzer. The resulting 0.5-nm bandwidth pulses produced a ∼16-ps full-width at half-maximum (FWHM) auto-correlation. Using a 3-dB coupler the pulse train was divided into the grating pair and into a reference fiber, subsequently recombined, and fed to an auto-correlator. The pulse train timing difference was then measured from the separation between the cross-correlation and auto-correlation traces, and the grating pair induced pulse distortion from the cross-correlation trace, by varying the center frequency of the 0.5-nm optical pulses. This experimental arrangement was detailed in [6] and [7].

III. Results

The wavelengths at which the measurements were performed are labeled on the transmission spectrum. Point A was situated at 1545.00 nm where we expected no grating pair effect. E was at the center of the overlap transmission region. B and F were on opposite sides of the spectrum and had the same transmission as E. D produced the same delay as that of E. C was the spectral midpoint of B and D.

For some of these wavelengths the correlation traces are plotted in Fig. 3(a). The 52-ps separation between the cross-

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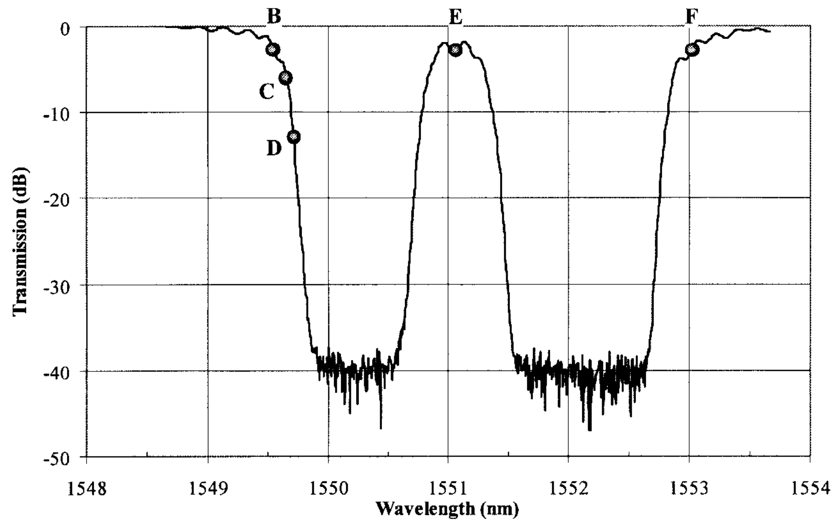

Fig. 1. Transmission spectrum of the grating pair, with bandgap centers at 1550.25 and 1552.10 nm, and 3-dB bandwidths 1.40 and 1.82 nm, respectively. The overlap transmission region had a 1551.05-nm central wavelength, a 0.5-nm 3-dB bandwidth, and −3-dB peak intensity transmission. Operating wavelengths of interest are B: 1549.55 nm, C: 1549.63 nm, D: 1549.70 nm, E: 1551.05 nm, and F: 1553.01 nm.

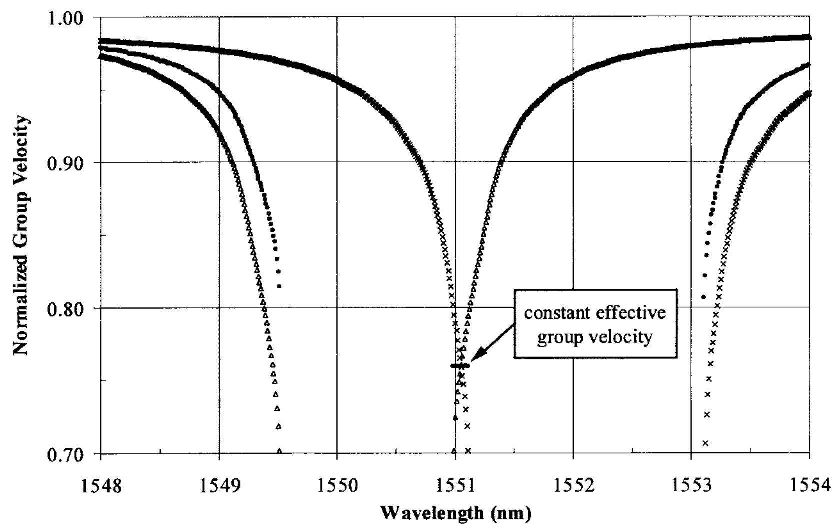

Fig. 2. IFO_Gratings simulation results. (△) normalized group velocity of the grating centered at 1550.25 nm, (×) normalized group velocity of the grating centered at 1552.10 nm, and (•) normalized effective group velocity of the gratings cascaded. The group velocities are normalized to the speed of light in bare fiber. Note the almost flat effective group velocity from 1550.99 to 1551.10 nm.

correlation and auto-correlation traces for point A was intentionally introduced by choosing the grating pair arm ∼1 cm longer. Group delays of 11, 13, 15, 15, and 7 ps for points B, C, D, E, and F, respectively, were measured as the additional displacement of the cross-correlation trace relative to the auto-correlation trace. The maximum 15-ps delay corresponds to a group velocity 66% of the speed of light in bare fiber. Assuming a symmetric bandgap for each of the gratings the delay at E was expected to equal that at B plus F, 18 ps. At points E, B, and F the transmission loss amounted to 3 dB. In comparison, point D provided the same delay as E with a 13-dB transmission loss.

A zoom-in view of the cross-correlation traces for several wavelengths is shown in Fig. 3(b). From these we deduced the extent of pulse reshaping. The traces were purposefully superimposed and normalized to their respective peak values for ease of comparison. The structure that appeared at ∼90 ps was caused by the leading edge of the auto-correlation trace. The cross-correlation at A exhibited a FWHM of 19.0 ps and it was taken as the reference pulse shape. Operation at E produced a cross-correlation trace with a FWHM of 21.5 ps, 13% larger than that at A. There were three reasons for the slight pulse reshaping at E. First, for a uniform grating, there were oscillations in the transmission and group velocity characteristics [4]. Second, although the GVD was canceled, cubic and higher order dispersion were not [2]. Third, the 0.5-nm pulse bandwidth was larger than the 0.11-nm zero dispersion region. At C and D the cross-correlation FWHM were 28.3 and 29.3 ps, respectively. The pulses widened as expected since at these points there was no dispersion compensation.

IV. Conclusion

We have experimentally demonstrated a grating pair sequence with wavelength dependent group delay exhibiting

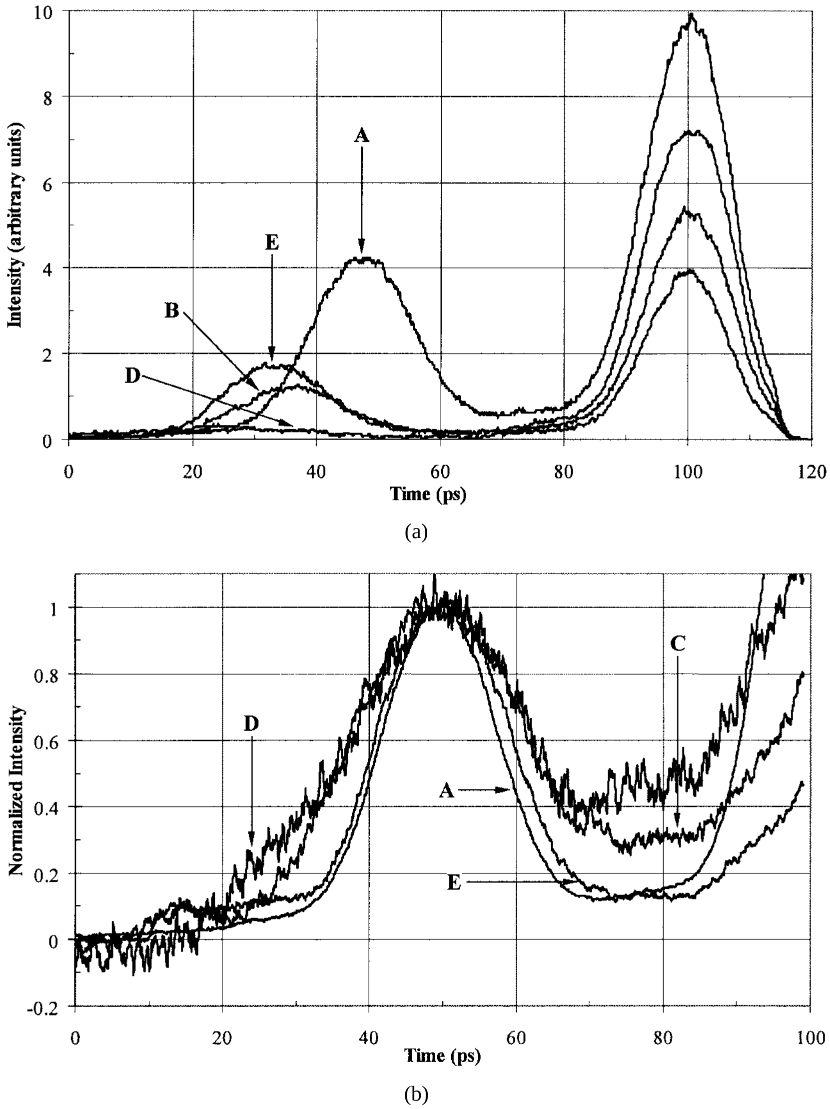

Fig. 3. (a) Correlation traces for the various operating wavelengths. The auto-correlation traces are located at 100 ps. (b) Zoom-in view of normalized cross-correlation traces for various operating wavelengths defined in Fig. 1.

compensated GVD over a 0.5-nm band. Over this range both gratings contributed to the optical pulse propagation characteristics enabling a 15-ps group delay with 3-dB transmission loss. One possible application of this is in matched filtering schemes, where for a fixed center wavelength one grating in the transmitter stretches the pulse in time while a conjugate grating in the receiver is used for pulse reconstruction. Both gratings can be further expanded as specially designed grating sequences to meet orthogonal code requirements among different channels for CDMA systems.

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