160-Gb/s Tunable Dispersion Slope Compensator Using a Chirped Fiber Bragg Grating and a Quadratic Heater

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Abstract—**We demonstrate a tunable dispersion slope compensator using a linearly chirped fiber Bragg grating and a thin-film heater that provides a variable quadratic temperature gradient along the grating. We achieved 2–10-ps/nm^2 compensation over 3 nm suitable for 160-Gb/s return-to-zero signals.**

Index Terms—**Dispersion compensation, fiber gratings, optical fiber devices.**

I. Introduction

In OPTICAL systems with bit rates of 40 Gb/s and higher, tunable dispersion compensation is necessary [1] in addition to fixed dispersion compensation [2]–[4] in order to guarantee system performance. However, at bit rates of 160 Gb/s and above, the dispersion slope within a single channel may pose limitations to transmission as well [5]. At higher bit rates, the system tolerance to dispersion slope becomes tighter, thus, tunable dispersion slope compensation (TDSC) would be necessary. TDSC has previously been demonstrated with mechanical tuning of chirped fiber Bragg gratings [6]–[9] and application of nonlinear chirp in fiber gratings [10]–[12]. Most recently, a temperature-controlled TDSC using a divided thin-film heater has been demonstrated [13].

In this letter, we demonstrate a TDSC using a linearly chirped fiber Bragg grating, where the tunability of the dispersion slope is controlled by thermal gradients similar to the method of [1] but with a nonlinear temperature profile. Unlike [13], where substantial control over the grating phase response was gained by using multiple heaters, our nonlinear temperature profile is controlled by a single nonuniform thin-film heater. Thus, dispersion slope is controlled with a single drive voltage, simplifying dispersion compensation control algorithms and eliminating dependence on calibration of multiple heaters.

We show that our TDSC can achieve slope compensation from 2 to 10 ps/nm^2 over a bandwidth of 3 nm with a bias dispersion of approximately ~260 ps/nm.

II. System Effects of Dispersion Slope

As bit rates increase, the signal requires greater bandwidth, and at some bit rate B, this bandwidth is large enough that dispersion slope compensation becomes necessary. The dispersion slope limit of a system may be derived according to arguments in [2]. If we require at least 95% of the pulse energy to remain within the bit slot of a system with bit rate B (assuming Gaussian pulses of root-mean-square pulsewidth σ), then the criterion $4B\sigma \leq 1$ should hold. From the pulsewidth–bandwidth product criterion, it follows that the upper limit of transmission distance (L) for cubic dispersion (dispersion slope) assuming pure dispersion slope ($D = 0$; $S = dD/d\lambda$) is $SL \sim \alpha\ \mathrm{B}^{-3}$. This shows that there is an inverse cubic dependence of transmission distance limit on bit rate, unlike the linear dispersion length limit, which is proportional to the inverse square of the bit rate. To verify this simple argument, we computed eye opening penalties (EOPs) for 40- and 160-Gb/s 50% return-to-zero (RZ) data pulse trains subjected to a purely cubic phase (pure dispersion slope). Fig. 1 shows the cubic decrease of the maximum tolerable dispersion slope (for a given EOP) as the bit rate increases. These plots also allow a rough estimate of the dispersion slope limited distance for transmission fibers, i.e., the maximum transmission distance when linear dispersion is completely compensated and only dispersion slope predominates. For 160 Gb/s, the EOP rises to 0.5 dB at about $S = 0.04$ ps/nm^{2}km, and a transmission distance of 50 km. Typical transmission fibers have dispersion slopes in the range from 0.04 to 0.1 ps/nm^{2}km, giving 160-Gb/s slope limited distances of between 50 and 20 km.

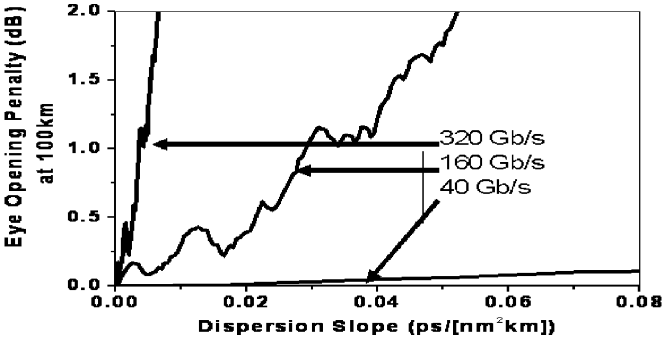

Fig. 1. EOP at 100 km versus dispersion slope.

III. Device Principle and Results

Our device consists of a linearly chirped fiber Bragg grating with 3-nm bandwidth combined with a voltage controlled thin-film heater. To achieve the desired TDSC, a roughly quadratic temperature variation along the length of the chirped grating is required, as discussed in [13]. Fig. 2(a) shows a schematic of the device. The thin gold film used to achieve

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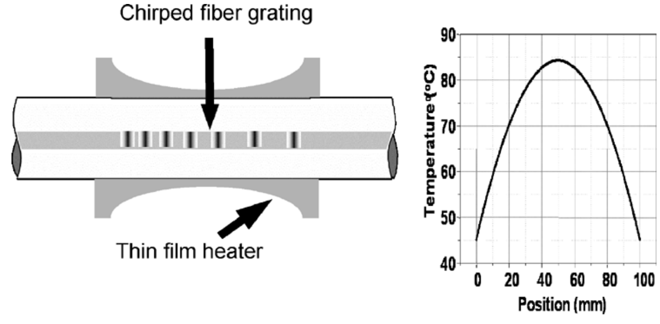

(a) (b)

Fig. 2. (a) Schematic of the TDSC which consists of a chirped fiber grating and a thin gold film capillary heater shown schematically in gray, and (b) temperature profile imposed on grating to tune the dispersion slope.

quadratic temperature variation along the length of the grating was grown onto a glass capillary surrounding the fiber, and is shown schematically as the gray area at the surface of the fiber. The corresponding quadratic temperature profile we employed to achieve slope compensation is shown in Fig. 2(b). The tunability of the dispersion slope is achieved by applying variable dc voltage to the thin film.

The grating was written with a bias chirp giving roughly 260 ps/nm of dispersion in the cold grating. By changing the temperature of the grating quadratically along its profile, we change the effective dc index profile of the grating, introducing a dispersion slope change. Since the grating has a tendency to shift to longer wavelengths when it is heated, a stability heater is placed on the device to provide a bias temperature. The bias temperature is changed depending on the temperature of the quadratic heater on the grating to keep the center wavelength from shifting. Fig. 3(a) shows the reflection spectra of the grating for various voltage settings of the nonlinear heater. Fig. 3(b) shows the plots of group delay versus wavelength of the grating at various voltages on the quadratic heater. Fig. 3(c) shows the group delay ripple versus wavelength after subtraction of a linear fit. Several voltage settings of the thin-film heater are shown. Small offsets were added in the y values of the reflection spectrum, group delay, and dispersion slope graphs for each voltage setting to simplify the comparison. Fig. 3(d) shows the dispersion and dispersion slope of the grating as a function of drive voltage. These values were derived from quadratic fits of the group delay curves

$$\tau(\lambda) = \tau_0 + D(\lambda - \lambda_0) + \frac{S(\lambda - \lambda_0)^2}{2} \tag{1}$$

where D is the dispersion and S is the dispersion slope plotted in the right and left graphs, respectively, of Fig. 3(d). The device can achieve a dispersion slope of up to 10 ps/nm^2 over a bandwidth of 375 GHz. Given the typical slope values previously stated, this corresponds to compensation of between 100 and 250 km of fiber. The linear dispersion value of the grating changes by <10 ps/nm as the dispersion slope is being tuned. The small change in dispersion is most likely due to asymmetry of the heating profile and can be brought close to zero.

We then performed system simulations using our measured data. The data format was 160-Gb/s RZ with 50% duty cycle. We considered a fiber link in which all chromatic dispersion was compensated, i.e., $D = 0$ and only dispersion slope was present. To simulate the system response, we subtracted the best fit linear (setting $D = 0$) and quadratic (simulating slope compensation) responses from our measured group delay curves at each voltage. These were the values of dispersion and slope plotted in Fig. 3(d). The residual group delay ripple after subtraction then gave EOP on the compensated signal. For a more comprehensive analysis, we also considered several values of the 160-Gb/s carrier frequency. The plot in Fig. 3(e) shows the EOP as a function of carrier frequency for a signal compensated by the grating. Over much of the range of frequency offsets, the EOP is substantially less than 1 dB. Beyond $S = 10\ \text{ps/nm}^2$, the device has substantial penalty. This could be caused by imperfect heater profile and can be improved with an optimized thin-film heater. Moreover, a grating with improved group delay ripple would also have better performance as a dispersion slope compensator.

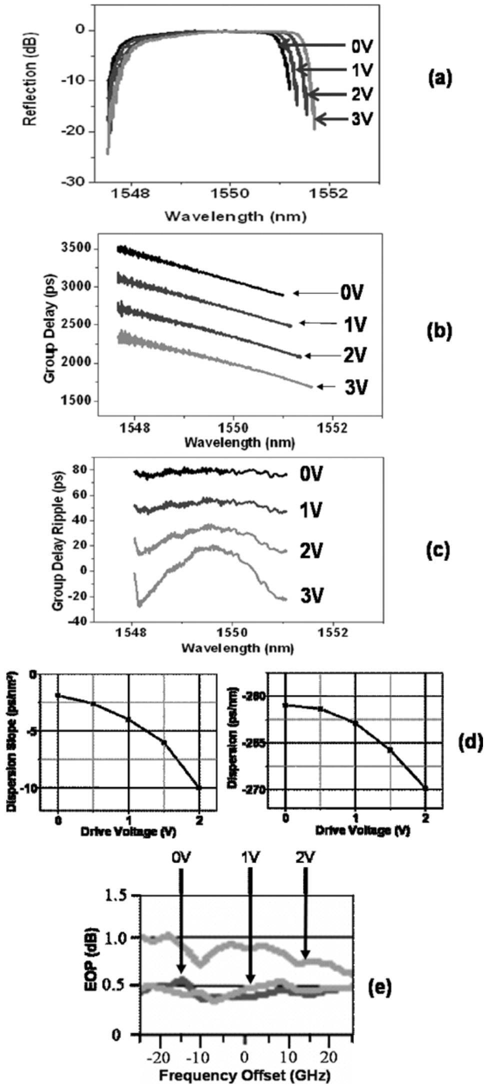

Fig. 3. (a) Reflection spectra, (b) group delay, and (c) dispersion slope characteristic with linear fit subtracted for various voltage settings. (d) Left: Dispersion slope versus heater drive voltage; right dispersion derived from linear fit for grating bandwidth within 1549–1552 nm. (e) EOP versus carrier frequency for the curves in (c). Small offsets were added in the y values of the reflection, group delay, and dispersion slope graphs for each voltage setting to simplify comparison.

IV. CONCLUSION

We have demonstrated a tunable dispersion slope compensator using a linearly chirped fiber Bragg grating with a variable quadratic temperature gradient to control the dispersion slope. Our device achieved up to 10 $\mathrm{ps/nm^2}$ of dispersion slope compensation over a bandwidth of 3 nm. Such a device would be significant for compensating 160-Gb/s signals, since the maximum transmission distance drops with the cube of the bit rate and varies inversely with dispersion slope. Our analysis shows that dispersion slope could be a limiting factor for any 160-Gb/s transmission system on standard transmission fibers.

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