Demonstration of Timing Skew Compensation for Bit-Parallel WDM Data Transmission with Picosecond Precision

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***Abstract*— We demonstrate transmission of seven wavelength-division-multiplexed (WDM) bit-parallel channels with a total of 15-nm spectral span over a 2.5-km standard single-mode fiber/dispersion-compensating fiber link with less than 3-ps timing skew. The synchronized WDM channels are generated by spectrally slicing pulses from a single femtosecond fiber laser using a femtosecond pulse shaper. The small residual timing skew arises from the residual dispersion slope of the link. We measure a dispersion slope of $D' = 0.017$ ps/km/nm^2, which is roughly four times less than for an equivalent length of dispersion-shifted fiber. Our work shows that the dispersion-compensating fiber technique could significantly reduce the timing skew for WDM bit-parallel transmission over a several-kilometer fiber link.**

***Index Terms*— Dispersion compensation, femtosecond pulse shaping, fiber transmission, timing-skew compensation, wavelength-division multiplexing.**

I. Introduction

THE DEMAND for higher data rate communications has grown substantially in parallel processing computer networks [1]. Difficulties in producing electronic circuits (serializer/deserializer, etc.) with required speeds at a reasonable cost limit interconnections based on the conventional serial data transmission format. Bit-parallel wavelength-division-multiplexed (WDM) data transmission has been proposed as an alternative strategy for computer communications [1], [2]. In this technique, each bit of a byte (or word) of data is transmitted at a separate wavelength, and WDM is used to transmit the data bytes over a single fiber. Since the transmission of data in parallel form (serial-by-byte, parallel-by-bit) is compatible with computer architecture, electronic bottlenecks are reduced. The attractive feature of WDM bit-parallel transmission versus fiber ribbons [3] is that the timing misalignment imposed by multiple path lengths and complex connectors is eliminated. However, the timing skew between different bits due to the group velocity dispersion (GVD) of the fiber link is still a major problem. Several techniques have been proposed to deal with this timing skew. These techniques include the use of dispersion-shifted fiber [1], electronic bit realignment in the receiver [2], and a shepherd pulse technique [4] based on nonlinear optics. Drawbacks of these techniques include high pulse energy to induce fiber nonlinearity [4] or lack of high resynchronization accuracy (~100 ps) [2]. In addition, the shepherd pulse technique requires that the passive component skew be within the capture range of the shepherd pulse (~5 ps), which complicates the design of optical couplers [5]. It is desirable to develop a linear timing-skew compensation technique to improve the timing alignment accuracy for future ultrahigh capacity WDM data transmission. In this letter, we demonstrate the timing skew compensation using a combination of standard single-mode fiber (SMF) and dispersion-compensating fiber (DCF). Highlights of this work include: 1) generation of seven synchronized WDM channels over a 15-nm wavelength span from a single femtosecond pulse; 2) demonstration of less than 3-ps timing skew over a 2.5-km dispersion compensated fiber link, limited by the third-order dispersion; and 3) first direct measurement of small residual dispersion slope [~4 times less than dispersion-shifted fiber (DSF)] in a several-kilometer fiber link dispersion compensated with picosecond accuracy. To our knowledge, this is the first report of linear timing skew compensation for bit-parallel WDM transmission with picosecond precision over kilometer fiber links.

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II. Experiment and Results

When synchronized WDM wavelengths are launched into a standard SMF, they will arrive at the receiver end at different times due to the GVD of the fiber link. The dispersion effect can be expressed in terms of the variation in the group delay per unit length $T(\omega)$ with respect to deviations in wavelength as follows:

$$\begin{aligned} D(\lambda) &= \frac{dT(\omega)}{d\lambda} = \frac{d}{d\lambda}\left(\frac{d\beta}{d\omega}\right) \\ &= D(\lambda_c) + D'(\lambda_c)(\lambda - \lambda_c) + \cdots . \end{aligned} \tag{1}$$

Here, $'$ means derivative with respect to wavelength λ. β is the frequency dependent propagation constant. $D(\lambda_c)$ and $D'(\lambda_c)$ are the dispersion and dispersion slope. They are related to β_2 and β_3, where $\beta_m = ((d^m\beta)/(d\omega^m))_{\omega=\omega_c}$ [6]. This GVD induced timing skew can be substantial (>200 ps) when the length of a SMF transmission link is over several kilometers for a sufficiently wide WDM spectral range (over 10 nm). To minimize the timing skew, we adopt the dispersion compensating fiber technique previously developed both for dispersion compensation for systems operating in the tens of gigabits per second [7], [8] as well as in femtosecond pulse

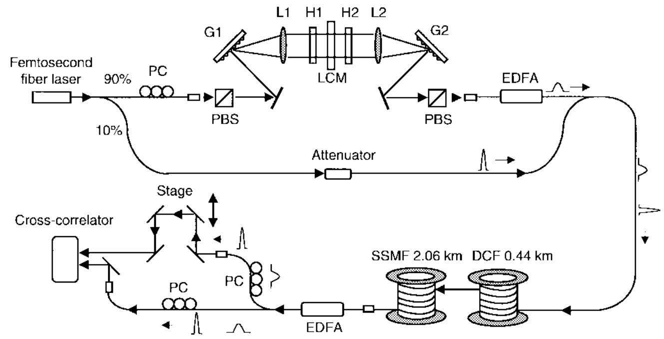


Fig. 1. Experiment setup for the generation of WDM multiple wavelength channels and for timing skew measurement. LCM: Liquid crystal modulator array. H1, H2: Half-wave plate. L1, L2: Lens. G1, G2: Grating. PBS: Polarization beam splitter. PC: Polarization controller.

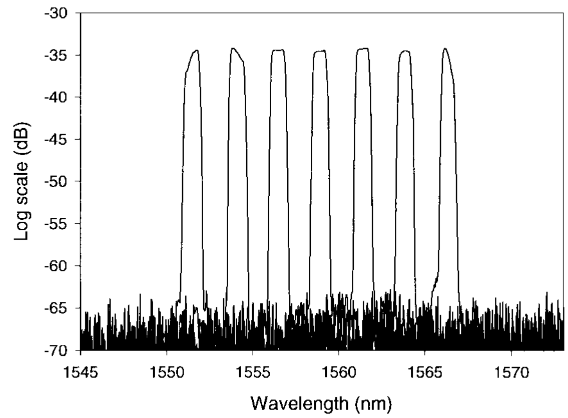


Fig. 2. Spectra of seven WDM wavelength channels after the amplitude equalization (log scale).

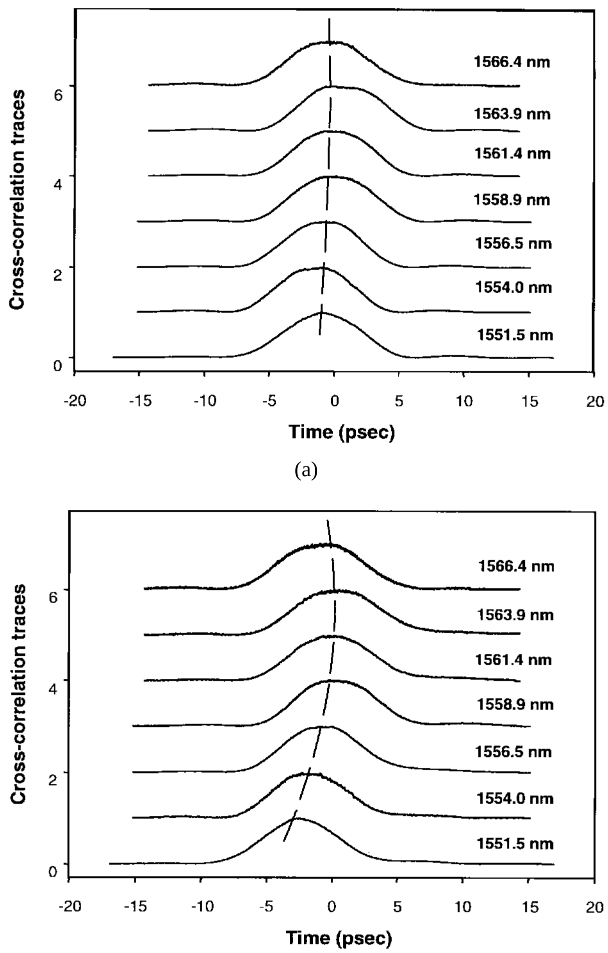
transmission applications [6]. We constructed a dispersion compensated fiber link by concatenating a standard SMF and a carefully chosen DCF. The overall dispersion of the compensated link is given by

$$D = \frac{D_{\rm smf} \times L_{\rm smf} + D_{\rm dcf} \times L_{\rm dcf}}{L_{\rm smf} + L_{\rm dcf}} \tag{2}$$

where $D_{\rm smf}$ and $D_{\rm dcf}$ are the 2nd order dispersion of SMF and DCF, respectively. $L_{\rm smf}$ and $L_{\rm dcf}$ represent the lengths of the corresponding fibers. The SMF and DCF have the opposite sign of second-order dispersion and dispersion slope. With an optimal length ratio between them, DCF will cancel out all the second-order dispersion of SMF and partially compensate the third-order dispersion. In our current work, we demonstrate that this SMF/DCF fiber link can reduce the timing skew for WDM bit-parallel data transmission to a picosecond range. The remaining timing skew is limited by the residual third-order dispersion and is less than 3 ps over our 2.5-km link.

The experimental setup for generating synchronized multiple-wavelength channels and for timing skew measurement is shown in Fig. 1. A stretched-pulse passively mode-locked fiber ring laser [9] generating 150 fs [full-width at half-maximum (FWHM)] pulses at 35-MHz-repetition rate serves as a broad-band source. The synchronized multiple-wavelength channels were derived from the femtosecond laser pulses using a modified pulse shaper, which is equipped with a 128-pixel liquid crystal modulator array (LCM) [10]. We used the pulse shaper-LCM combination as a voltage programmable amplitude modulator with independent control over different wavelength components. A total of seven wavelength channels (~0.83-nm FWHM per channel) with channel separation ~2.5 nm were generated over a 15-nm span from the initial femtosecond pulse. The on–off contrast ratio of each channel reaches 30 dB. By applying appropriate voltages on the LCM, we were also able to equalize the amplitudes of each individual wavelength channel, which vary by ~3 dB before equalization. Fig. 2 shows the equalized spectra of seven channels generated from the pulse shaper. The timing skew compensation was accomplished by concatenating a 2.06-km standard SMF (AT&T 5D) ($D = 17$ ps/km/nm, $D' = 0.06$ ps/km/nm^2 at 1550 nm) and a 0.44-km length of DCF [6], [7]. The DCF ($D = -76$ ps/km/nm, $D' = -0.2$ ps/km/nm^2) compensates the second-order dispersion and much of the third-order dispersion of SMF. Our previous work showed that 250-fs pulses could be transmitted over this link with only ~ two times pulse broadening as limited by the residual dispersion slope [6]. Our current work shows the reduction of timing skew for WDM bit-parallel transmission over this link and provides a more accurate measurement of the residual third-order dispersion. The timing-skew of the 2.5-km dispersion compensated link was measured by comparing the relative timing position of each individual wavelength channel before and after the link. This was accomplished through intensity cross correlation using second-harmonic generation (SHG) with a short reference pulse derived from the fiber laser. The experiment was performed with one wavelength channel turned on at a time. To suppress laser jitter effects and environmentally induced timing changes, we launched both the signal pulse (~6.5 ps FWHM for one channel) and the reference pulse (~0.5 ps FWHM) into the 2.5-km link with ~900 ps delay in between and separated them at the end of the link for the cross correlation measurement. The power levels were kept low enough to avoid any fiber nonlinearity in the link.

Fig. 3(a) shows seven well-aligned signal pulses (bits) at different wavelengths before the transmission link. The timing misalignment (~525 ps estimated) incurred in the 2.06-km SMF is compensated by DCF. Fig. 3(b) shows measurements of different wavelengths (bits) after the SMF/DCF link. The cross-correlation traces of seven signal pulses show similar pulsewidth (~6.5 ps) and pulse shape before and after the link. The timing skew of the dispersion compensated link [i.e., the difference between Figs. 3(b) and 3(a)] is shown in Fig. 4. A maximum of only 2.4-ps timing skew was observed over the 15-nm spectral span. Based on the timing variations of several independent measurements, we estimate the timing accuracy of our measurement reaches ±0.2 ps. The quadratic nature of the wavelength dependent time delay shown in Fig. 4 indicates the timing skew over the link is limited by the residual 3rd order dispersion of the compensated link. From our data, we calculate a zero net dispersion at 1562 nm with a dispersion slope $D' = 0.017$ ps/km/nm^2 ($\beta_3 = 0.027$ ps^3/km). The accuracy of the β_3 measurement for the 2.5-km fiber link is estimated to be ±0.003 ps^3/km. This result is consistent with



(a)

(b)

Fig. 3(a). Seven signal pulses (bits) at different wavelengths (a) before and (b) after the transmission link. Dashed line: Peaks position fitting.

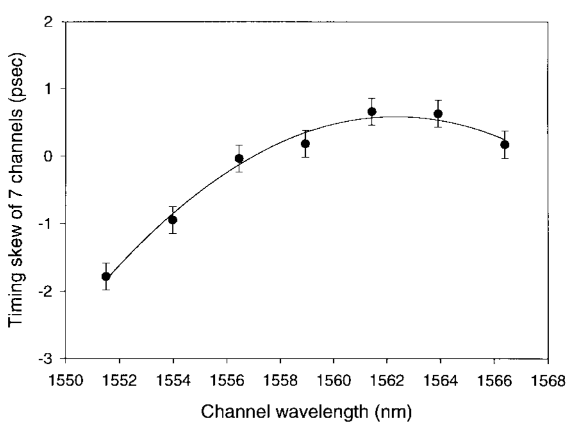


Fig. 4. Measured timing skew of the 2.5-km dispersion compensated link. Solid line: Fitting curve.

our previous estimation of the dispersion slope ($\beta_3 \approx 0.026$ ps^3/km), which was based on matching the measured and simulated pulse shapes in a femtosecond pulse transmission experiment [6]. We note that our previous experiments were designed to yield an approximate but not exact measurement of the residual dispersion. Our current experiment provides a direct measurement of residual dispersion slope and therefore gives a more reliable result. The measured dispersion slope is $\sim$4 times less that of DSF ($D' \approx 0.06$ ps/km/nm^2). It indicates the timing skew over a dispersion compensated fiber link is significantly smaller than that over a DSF link with equivalent length. We note that with $<$3 ps timing-skew as demonstrated in our experiment, the aggregate data throughput in a timing-skew limited WDM bit-parallel transmission link could reach over 100 Gbytes/s for future ultrahigh capacity computer networks.

III. Conclusion

We have demonstrated timing-skew compensation for seven WDM bit-parallel transmission channels over $\sim$15 nm spectral span with a resynchronization error of $<$3 ps in a 2.5-km dispersion compensated link. Our work shows that the DCF technique can significantly reduce the dispersion induced timing-skew and increase the throughput for ultrahigh capacity WDM data transmission.

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