Sub-picosecond skew in multimode fiber ribbon for synchronous data transmission

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ABSTRACT

For the first time we demonstrate skew of less than $0.25 ps/m$ across a 10-wide graded index multimode fiber ribbon. This sub-picosecond skew extends practical applications of multimode fiber ribbon to include synchronous parallel transmission with an aggregate data-rate distance product of greater than $10 Gb/s \cdot km$.

Advanced laser-based parallel optoelectronic transceivers which make use of fiber ribbons are being promoted as high-density, high-throughput solutions to interconnect bottlenecks in future switching and computing systems [1-3]. Low-cost fiber-optic links use multimode (MM) fiber with a $50mm$ or $62.5mm$ diameter graded index core as this results in relaxed optical alignment tolerances as well as more robust fiber splices and connector components. However, an important factor determining the maximum rate of synchronous parallel data transmission is difference in signal propagation time between fiber channels. Skew of approximately $10\,ps/m$ has limited applications of parallel links based on fiber ribbons.

Recently we reported that interchannel skew in a fiber ribbon could be reduced to $1.25ps/m$ by forming each channel from fiber sequentially cut from the same pull [4]. In this letter we demonstrate a more than five-fold improvement in skew by selection of fiber with low modal dispersion and by controlling edge stress in the fiber ribbonization process. We have achieved a sub-picosecond skew of less than $0.25ps/m$ in $62.5mm$ diameter 10-wide graded index MM fiber ribbon.

The MM fiber used in our experiments is manufactured by Corning, ribbonized by Siecor and terminated using MT connectors supplied by USConec. In Fig. 1 we show measured optical delay after transmission of $l = 1.3mm$ wavelength radiation through a $300m$ and $30m$ length of 12-fiber ribbon. It is clear from these results that optical delay is significantly shorter for fiber 1 and fiber 12 than for the inner 10 fibers. This is due to stress at the edge of the ribbon. Our lowest skew data is obtained using fiber 1 and fiber 12 as supporting outer members to minimize stress across the fiber array due to the ribbonization process.

The measured propagation delay after transmission through 461m of such 10-wide ribbon fiber is shown in Fig. 2. The variation in optical pulse delay across the central 10 fibers is 110ps or $0.24ps/m$. This value is more than 5 times lower than our previously reported results [4]. The low skew is due to correlation between the properties of the high quality fibers making up the ribbon. The pair correlation function r_d for optical delay is shown as an insert to Fig. 2. The -3dB frequency bandwidth of the fiber is limited by modal dispersion and is measured by detecting the small signal response of the fiber using an rf modulated Fabry Perot laser diode operating at wavelength $l = 1.3mm$. We obtain a bandwidth of $917Mz \cdot km$. With this high bandwidth it is possible to transmit data at a rate in excess of $1Gb/s$ over distance of at least 1km. However, to send synchronous data 1km over 10 parallel fibers at a rate of $1Gb/s$ per fiber a decision time window of at least 240ps is needed to accommodate interchannel skew.

Bit Error Rate (BER) experiments were performed using a $1Gb/s$ $2^{10}-1$ non-return-to-zero (NRZ) pseudo random bit stream (PRBS). Fig. 3 shows BER as a function of time delay relative to the clock edge. The decision time window closes mainly due to the finite fiber bandwidth as well as signal attenuation due to the fiber ($-0.5dB/km$) and 4 connectors for a total attenuation of -1.3dB. After transmitting data at $1Gb/s$ through 922m of MM fiber the extrapolated width of the eye at a BER of 10^{-10} is 700ps. This large phase margin can easily accommodate the 240ps/km of skew developed in the fiber ribbon. Hence, it is possible to send synchronous data at a rate greater than $1Gb/s$ per fiber in parallel via MM fiber ribbon if the clock is also transmitted through one of the fibers.

If both MM fiber ribbon skew and bandwidth of the fiber scale linearly with length of the fiber, the maximum rate, $R_{\max}$, at which data can be transmitted in parallel through a n-wide fiber ribbon will be inversely related to the length, L. The aggregate data-rate distance product is $nR_{\max} \times L = const$ and for our 10 wide fiber ribbon this value is greater than $10Gb/s \cdot km$.

Skew and bandwidth limits of fiber arise due to variations in refractive index profile during manufacture. The change in the refractive index as a function of radius r, is given by

$$n(r) = n_o\left[1 - 2\Delta\left(\frac{r}{a}\right)^{a}\right]^{1/2} \qquad \text{for } r<a$$

and

$$\mathrm{n(r) = n_o}\left[1 - 2\Delta\right]^{1/2} \qquad \text{for } r>a,$$

where n_o is the refractive index of the core layer, a is the radius of the core region, Δ is a measure of the radial change in refractive index between the core and the cladding layer and $1 \le \alpha \le \infty$. For the fibers used in the experiments $\Delta = 0.02$. The value of a which maximizes bandwidth is $a_0 = 2 - 2\Delta$. If $a = a_0 + da_r$ the impulse response width is [4-5],

$$t_{width} = \frac{1}{8}\left(\Delta + \frac{|da_r|}{2}\right)^2 \frac{n_o L}{c}$$

where da_r is the average variation of radial refractive index profile within each fiber channel. $n_0 L/c$ is approximately equal to the average pulse propagation time through the fiber. The measured average impulse response width for the 461m long ribbon fiber is 258ps giving $da_r = 0.0197$.

The normalized propagation time t, for different propagating modes ignoring delay common to all modes is [4]

$$t = \frac{c\,t}{n_o L} - 1 = \frac{a-2}{a+2}\,d + \frac{3a-2}{a+2}\,\frac{d^2}{2}\,.$$

where t is the total propagation time for the mode of interest, a is the refractive index profile and d can take values from 0 to Δ.

Assuming $a = 2 - b$ where $b << 1$ then t may be approximated as,

$$t \approx \frac{-b}{4}\,d + \frac{d^2}{2}\,.$$

For each d, there is a t which is the normalized arrival time for the corresponding mode. The range of values that t takes as d varies gives the width of the impulse response. For $0 \le b \le 4\Delta$ the range of values t can take has a minimum. Hence, the constraint $0 \le b \le 4\Delta$ minimizes the width of the impulse response or, equivalently, maximizes the bandwidth of the fiber. In this situation, the normalized arrival time of the impulse response is $t_{ar} = -b^2/32$. If the refractive index profile of two fibers being compared is $b_1 = 2\Delta + da_1$ and $b_2 = 2\Delta + da_2$ respectively, then the normalized skew, $\Delta(t_{ar})$ is,

$$\Delta t_{ar} = \frac{1}{16}\left(2\Delta + \frac{da_1 + da_2}{2}\right)\left(da_1 - da_2\right).$$

$da_1 - da_2 = da_{skew}$, where da_{skew} is the difference in longitudinal refractive index profile between fibers in the two channels being compared. Usually $da_{skew} << (da_1 + da_2)/2$ so we may assume $(da_1 + da_2)/2 = da_r$ where da_r is the average variation of the radial refractive index from its optimal value. We can now derive a new expression for interchannel skew,

$$\Delta(t_{ar}) = \frac{1}{16}(2\Delta + da_r)da_{skew}\frac{n_o L}{c}\,.$$

The radial variation da_r and longitudinal variation da_{skew} in refractive index both contribute to skew. By forming ribbon using fibers sequentially cut from the same pull we increase the correlation r_d and minimize da_{skew}. In our experiment $da_{skew} = 0.0126$ for the ribbon ($d\alpha_{skew} = 0.0035$ per fiber on average).

In summary, we have demonstrated skew of less than $0.25\,ps/m$ across a 10-wide ribbon of MM graded index fibers. The ribbon is created using fiber of high modal bandwidth (corresponding to small da_r), a characteristically low da_{skew} and by controlling stress in the ribbonization process. Our experimental results extend the practical applications of multimode fiber ribbon to include synchronous parallel transmission with an aggregate data-rate distance product of greater than $10\,Gb/s \cdot km$.

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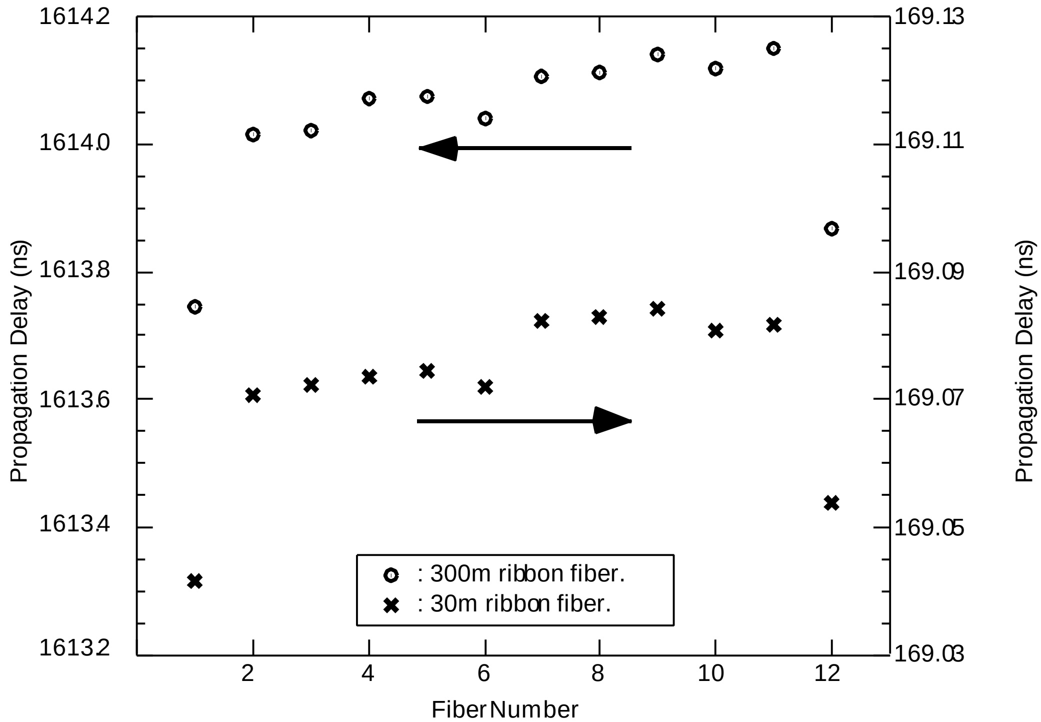
FIGURE CAPTIONS

Fig.1: Measured optical delay for $l = 1.3mm$ light after transmission through 300m and 30m of MM fiber. Total interchannel skew for the 12-wide ribbon is 400ps and 44ps for the 300m and 30m long sections respectively. Skew drops to 130ps and 14ps if only the inner 10 fibers are considered. The additional stress on the outer fiber channels reduces propagation time, thus increasing interchannel skew.

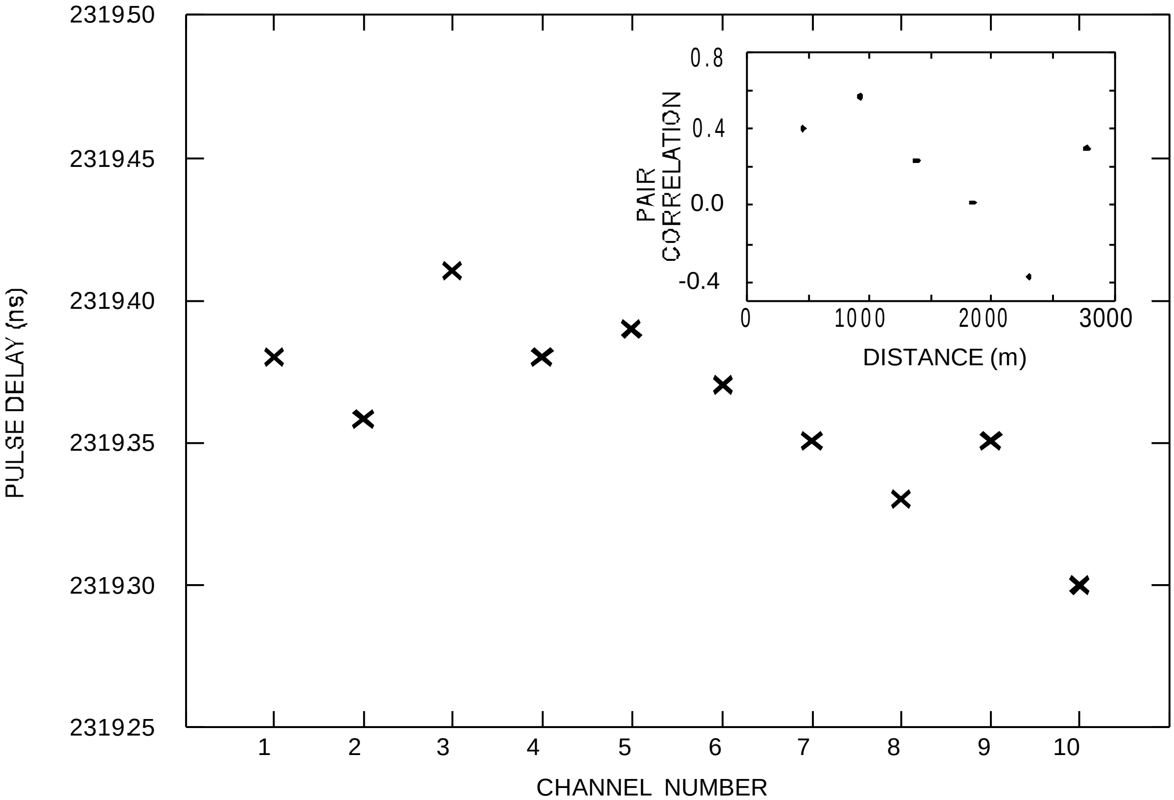
Fig.2: Measured optical delay for $l = 1.3mm$ light after transmission through 461m of ribbon fiber manufactured from high bandwidth graded index MM fibers cut sequentially from the same pull. Maximum inter channel skew is 110ps or 0.24ps/m. Average delay is 2319.36ns and $n_{eff} = 1.51$, maximum delay is 2319.41ns, minimum delay is 2319.3ns, and the standard deviation is 0.032ns or 0.068ps/m. The insert shows the pair correlation function r_d as a function of distance.

Fig.3: BER at input to ribbon fiber, after 461m and 922m measured relative to the clock edge for data transmitted at the rate 1Gb/s using a 2^{10} NRZ PRBS. $l = 1.3mm$ and the received signal power is 67µW. The time window at an extrapolated BER of 10^{-10} is 870ps, 820ps and 700ps at the input, after 461m and after 966m respectively. The insert shows the eye diagram at the input to the ribbon fiber and after 966m of ribbon fiber.



1614.2
1614.0
1613.8
1613.6
1613.4
1613.2
Propagation Delay (ns)
169.13
169.11
169.09
169.07
169.05
169.03
Propagation Delay (ns)
2
4
6
8
10
12
Fiber Number
: 300m ribbon fiber.
: 30m ribbon fiber.

Figure 1.



231950
231945
231940
231935
231930
231925
PULSE DELAY (ns)
1
2
3
4
5
6
7
8
9
10
CHANNEL NUMBER
0.8
0.4
0.0
-0.4
PAIR CORRELATION
0
1000
2000
3000
DISTANCE (m)

Figure 2.

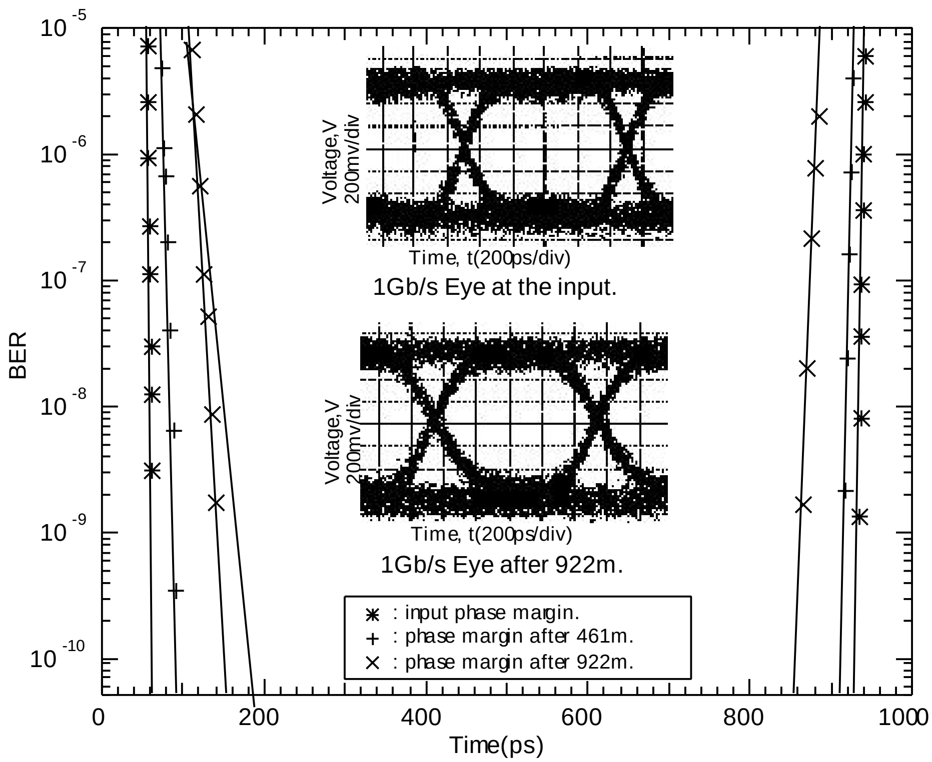

BER
Time(ps)
1Gb/s Eye at the input.
1Gb/s Eye after 922m.
Voltage,V 200mv/div
Time, t(200ps/div)
: input phase margin.
: phase margin after 461m.
: phase margin after 922m.

Figure 3.