Multi Gbit/s Bit Parallel WDM Transmission Using Dispersion Managed Fibers


Abstract—This paper demonstrates the feasibility of a bit parallel WDM (BP-WDM) system using dispersion managed fibers. An expression for the total bit skew as a function of the fiber dispersion and system bandwidth is derived and compared with experimental results. A 4 bit \(\times 10\) Gbit/s-per bit BP-WDM transmission experiment over 30 km DMF is used and an aggregate bit rate \(\times\) distance product of 1.2 Tbit/s-km is obtained. The total bit skew of the system is reduced to one half of the bit period. We believe that systems using BPWDM will be useful for computer interconnects in high-speed parallel systems and ring networks.

Index Terms—Bit skew compensation, optical parallel transmission, wavelength division multiplexing systems.

I. INTRODUCTION

THE GREAT majority of the optical systems operating nowadays are serial and demand expensive parallel-to-serial and serial-to-parallel conversions. These conversions can be the ultimate limitation in such optical systems. An alternative to the serial system is the parallel system where all bits are sent through the transmission media at the same time. The first idea of an optical parallel system was simply to use an optical fiber per each bit, the so-called ribbon fiber. Several projects and consortia have been working in this technology [1]–[4] and some commercial products are already available. At high bit-rates, temporal alignment is difficult to maintain since each bit has a different optical path. The lack of alignment is the main restriction of this system, and its application is limited to very short distances and low bit-rates [5].

A second option for the parallel system is the use of WDM technology. In such systems, each bit of the digital word is used to modulate one different optical wavelength. These wavelengths are then launched into the same fiber. Loeb and Stilwell [6] proposed the first bit parallel WDM (BP-WDM) system in 1988. In that work, they showed that it is possible to transmit up to 1 Gbit/s per channel for a few kilometers using standard single-mode (SM) fiber. Ten years later, Bergman et al. [7] proposed a new system working at 1 Gbit/s, 2 bit, and a 32-km long dispersion shifted (DS) fiber.

In this letter, we propose a new BP-WDM system using dispersion managed fibers (DMF). A 4 bit \(\times 10\) Gbit/s-per bit BP-WDM transmission experiment over 30 km of dispersion managed fiber (DMF) is used to show that with this fiber, it is possible to greatly improve the aggregate bit rate \(\times\) distance product while maintaining a low clock rate.

II. BIT PARALLEL WDM SYSTEM

The BP-WDM system uses WDM technology to transmit information. Each bit is used to modulate a laser diode at a different wavelength; the wavelengths are then multiplexed and launched into a single fiber. After transmission, the wavelengths are separated and the digital word is recovered. Fiber attenuation, dispersion, and nonlinearities are the performance impairments for both serial and parallel transmission systems. The main difference between parallel and conventional WDM is that in parallel systems, all channels are used to transmit information of the same binary word and the bits must arrive at the receiver end at the same time. Bit skew due to fiber dispersion is the most important restriction for this system.

The fiber plays an important role in the BP-WDM system. It is responsible for most of the bit skew and can be used to cancel it. Bergman and Yeh [7] have shown that simply by changing the single-mode fiber for a DS fiber, it is possible to improve the bit rate-distance (B-L) product of the system. In the DS fiber system, the dispersion is near zero but bit skew still exists due to the dispersion slope; in order to minimize and increase the BL product, the dispersion slope also must be compensated.

Recently, a new kind of fiber has been reported [8]. Alternating sections of positive and negative dispersion and slope are pulled in a single continuous fiber without splices, forming a dispersion managed fiber (DMF). Fig. 1 shows the fiber. The first section is a single-mode fiber with positive dispersion, positive slope, and length \(L_1\), and the second section has negative dispersion and slope, and length \(L_2\). The dispersion, slope, and length of each section are chosen in such a way that the total dispersion and the slope are virtually zero and a flat dispersion fiber is obtained. As the fiber is formed by sections of single-mode
fibers with high positive and negative dispersion, nonlinear effects such as four-wave mixing and cross-phase modulation are reduced [8].

The bit skew in the fiber can be written as a function of the dispersion as follows: The total dispersion in a single-mode fiber, expressed as a function of the dispersion slope $S_0$, the zero-dispersion wavelength $\lambda_0$, and wavelength $\lambda$, is given by [9]

$$D = \frac{\lambda S_0}{4} \left[ 1 - \left( \frac{\lambda_0}{\lambda} \right)^4 \right].$$  

(1)

The difference in the group delay between the fastest and the slowest wavelengths determines the maximum bit skew. For the sake of simplicity, we assume that all wavelengths are on the same side of the zero-dispersion wavelength. In this case, the delay between the first wavelength and the last wavelength gives the maximum bit skew. If we define a system with $n$ wavelengths (i.e., a digital word with $n$ bits) equally spaced and total bandwidth $\Delta \lambda$, the wavelength of the first and the last wavelengths can be expressed as a function of the central wavelength $\lambda_c$. The maximum bit skew per unit of length is given by

$$\frac{\Delta \tau_2}{L}_{\text{MAX}} = \int_{\lambda_1}^{\lambda_n} D(\lambda') d\lambda'.$$

(2)

Substituting (1) in (2) and assuming that $\lambda_c \gg \Delta \lambda$, then

$$\frac{\Delta \tau_2}{L}_{\text{MAX}} = \frac{\lambda_c S_0}{4} \left[ 1 - \left( \frac{\lambda_0}{\lambda_c} \right)^4 \right] = \Delta \lambda D(\lambda_c).$$

(3)

Equation (3) shows that the maximum bit skew is a function of the total bandwidth and of the dispersion of the fiber at the central wavelength and it is still valid even if different expressions are used for the dispersion in (1) [10]. The only assumptions made here are that the central wavelength must be much greater than the total bandwidth and all wavelengths are on the same side of the dispersion zero wavelength.

For the DMF, the total bit skew can be computed by adding the contribution of each section of the fiber. It is easy to prove that if [10] $L_1 S_0 = -L_2 S_0$, and $\lambda_0 = \lambda_{Q2}$, where $L_i$, $S_0$, and $\lambda_0(i = 1, 2)$ are, respectively, the lengths, dispersion slope, and zero-dispersion wavelength of each section of the fiber (see Fig. 1), the bit skew is nulled in the DMF.

### III. EXPERIMENTAL DEMONSTRATION OF A 4-BIT, BP-WDM SYSTEM AT 10 GBIT/S

In this section, a 4 bit $\times$ 10 Gbit/s BP-WDM transmission experiment over 30 km of DMF is presented. Fig. 2 shows the experimental setup. The transmitter had 4 DFB lasers diodes (LD) with wavelengths 1557.03 nm (bit 1), 1558.74 nm (bit 2), 1560.87 nm (bit 3), and 1561.77 nm (bit 4). For simplicity, the outputs were multiplexed (using a 4 $\times$ 1 coupler) and simultaneously modulated by a LiNbO$_3$ Mach–Zehnder modulator with 10 Gbit/s $2^{31}-1$ PRBS, although in a field transmission system each bit would be modulated separately and then multiplexed. In order to simulate a truly independent pseudo-random bit stream for each of the wavelengths, a simple scheme using a 4.8–km-long SM fiber was implemented. The high dispersion of the SM fiber creates a different delay for each wavelength and at the end of the fiber, each bit stream is separated by at least one bit period.

After the SM fiber, the four optical signals were transmitted over the DMF with optical power of 0 dBm per wavelength. The nominal section lengths ($L_1$ and $L_2$) of the DMF were between 1.7 and 2.0 km, the zero-dispersion wavelength for both sections was 1370 nm, and the dispersion slope about 0.03-0.035 ps/nm km. The differences in the section lengths cause one small amount of dispersion, and the dispersion is not fully managed in the fiber. The residual dispersion slope was 0.03 ps/nm$^2$ km, the zero-dispersion wavelength was 1535.8 nm, and the loss was 0.4 dB/km. An arrayed-waveguide grating (AWG) [11] with interchannel crosstalk of 25 dB and insertion loss of 10 dB was used as a demultiplexer. Optical amplifiers were used to compensate for the losses in the coupler, fibers, and AWG. In the future, the 4 $\times$ 1 coupler will be substituted by an AWG with the same characteristics of that used as demultiplexer.

Fig. 3 shows a picture of the four received pulses. A long sequence of zeros followed by a single “one” was generated in the pulse pattern generator (PPG) and used to modulate the optical signal. A computer was used to dump the traces for each channel from the oscilloscope as shown in Fig. 2. The maximum delay generated by the fiber was 500 ps. After the DMF [Fig. 3], the
The measured maximum bit skew as a function of the total bandwidth ($\Delta \lambda$) for the DMF and a DS fiber with $S_0 = 0.08$ ps/nm$^2$-km and $\lambda_0 = 1537$ nm. The straight lines were obtained by (3).

The same experimental setup was used to measure the bit skew as a function of the total bandwidth ($\Delta \lambda$) for the DMF and for a DS fiber ($S_0 = 0.08$ ps/nm$^2$-km and $\lambda_0 = 1537$ nm). In this experiment, one fixed wavelength laser and one variable laser are used. As the wavelength changes, $\Delta \lambda$ and $\lambda_c$ also change. The results for both fibers, shown in Fig. 4, show a good agreement with those obtained theoretically with (3) [continuous lines in Fig. 4].

A 100 ps maximum bit skew represents a system bit skew of 50 ps, i.e., one half of the bit period. Those values can be easily compensated by the receiver circuits or optically. The inset in Fig. 2 shows an optical bit skew compensator (OBSC) using a three-port circulator and fiber gratings [12]. Experiments were done with two gratings (i.e., two wavelengths only). The separation between the two gratings was chosen in such way that the bit skew was totally compensated. A full description of OBSC with fiber gratings will be given in a future paper.

Finally, Fig. 5 shows demultiplexed 10 Gbit/s waveforms for back-to-back and after DMF and the last bits. The eye closure after the fiber is mainly due to noise in the optical amplifiers used in the system. The power penalty due to the AWG crosstalk also was measured to be a maximum of 2 dB in the worst case.

IV. CONCLUSION

We have proposed the use of dispersion managed fibers in parallel WDM systems. The characteristics of these fibers have been briefly presented, and expressions for the minimum bit skew have been given. The advantage of the DMF over DS fibers for this kind of application also has been shown.

A 4 bit×10 Gbit/s-per bit BP-WDM transmission experiment over 30 km DMF has been used, and an aggregate BL product of 1.2 Tbit/s-km was obtained. The system bit skew was ±50 ps, which represents one half of the bit period. This bit skew can be easily compensated optical or electronically. An OBSC using fiber gratings was presented and is currently being implemented. A higher BL product can be achieved if a denser WDM system is employed.

We believe that systems using BP-WDM will be useful for computer interconnects in high-speed parallel systems and ring networks.

REFERENCES