Optical Data Synchronization Using Tunable Transmitters and Nonzero Dispersion Links

Peter Blixt, John E. Bowers, *Fellow, IEEE,* Erik Bødtker, O. Sahlén, and Roy S. Smith, *Member, IEEE*

***Abstract*—A new digital feedback loop for synchronizing optical data with a clock at an arbitrary point in a fiber-optic link has been experimentally demonstrated and its physical limitations have been analyzed. The feedback loop consists of a tunable transmitter, a nonzero dispersion link, and standard microwave and digital electronics. The feedback loop was able to suppress thermal fluctuations with an accuracy better than 1 ps using either a temperature tuned DFB laser diode or a current tuned DBR laser diode. No bit-error rate penalty was measured during closed loop operation compared to back-to-back transmission. The physical limitations of the loop stem from noise in the receiver and the actuator increment. Thermally induced phase fluctuations in the fiber at frequencies above the loop bandwidth were found negligible. The maximum experimental delay time for stable operation was 0.86 s, indicating the possibility of closed loop operation for very long fiber links. The feasibility of packet synchronization is discussed. Moreover, a new scheme is proposed to circumvent wavelength reset when the system approaches the operating boundaries.**

I. Introduction

SYNCHRONIZATION is a critical issue for all time-division multiplexed (TDM) systems. The standard deviation of the timing jitter should be less than 0.1 of the bit period for a negligible power penalty, assuming a gaussian timing-error probability density function [1]. All TDM systems require synchronization before multiplexing, switching, demultiplexing, etc. (Fig. 1). All-optical TDM systems require *optical* synchronization, while electrically switched, multiplexed, and demultiplexed systems may very likely benefit from performing the synchronization in the optical domain instead of the electrical domain at high speeds.

In this paper, we have investigated a new scheme using commercially available components to align and to synchronize *data* to a clock signal in a high-speed single TDM-channel.

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P. Blixt is with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106-9560 USA. He is on leave from the Institute of Optical Research, S-100 44 Stockholm, Sweden.

J. E. Bowers and R. S. Smith are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106-9560 USA.

E. Bødtker is with Tele Danmark Research, DK-2970 Hørsholm, Denmark.

O. Sahlén is with the Ericsson Components AB, Fiber Optics Research Center, S-164 81 Stockholm, Sweden.

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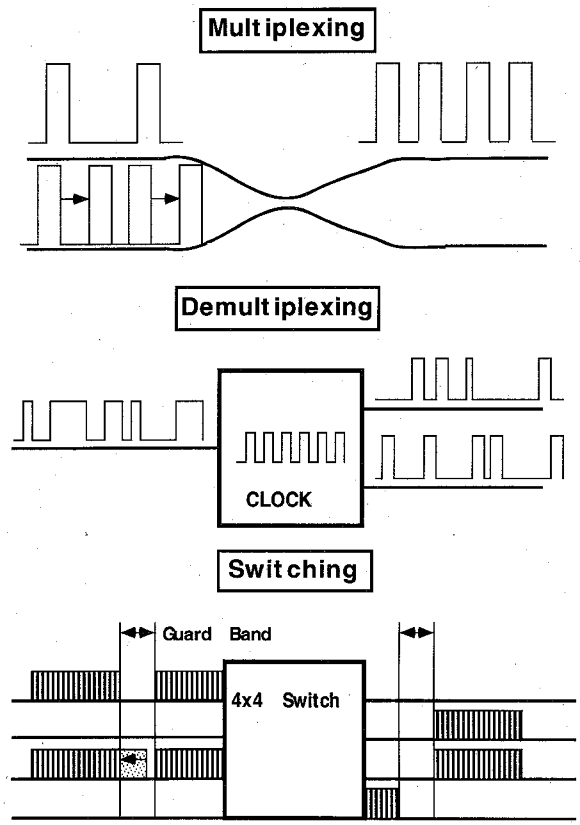

Fig. 1. Synchronization is required in TDM systems for multiplexing, demultiplexing, and switching. Bit synchronization is shown in the case of multiplexing and demultiplexing, while packet synchronization is shown in the case of switching.

We utilize tunable sources in combination with the dispersion of the link. There is no need for extra hardware, since the wavelength (or at least the temperature) of the source is typically controlled anyhow. Also, there are many high-speed systems designed for dispersive links, e.g., soliton systems [2], pre-chirping systems [3], and dispersion supported systems [4]. The basic principles of our new optical synchronization technique have been described and evaluated in the case of a temperature tuned and gain-switched distributed feedback (DFB) laser diode [5]. Optical synchronization has been theoretically studied in a few recent papers [6]–[8]. The proposed principle for optical synchronization common for these papers, i.e., the optical time delay switch, has been experimentally demonstrated recently, where Adda *et al.* [9] showed a 6 bit resolution unit with increments of 44 ps in the range of 0–2.772 ns. There are several advantages of using the optical time

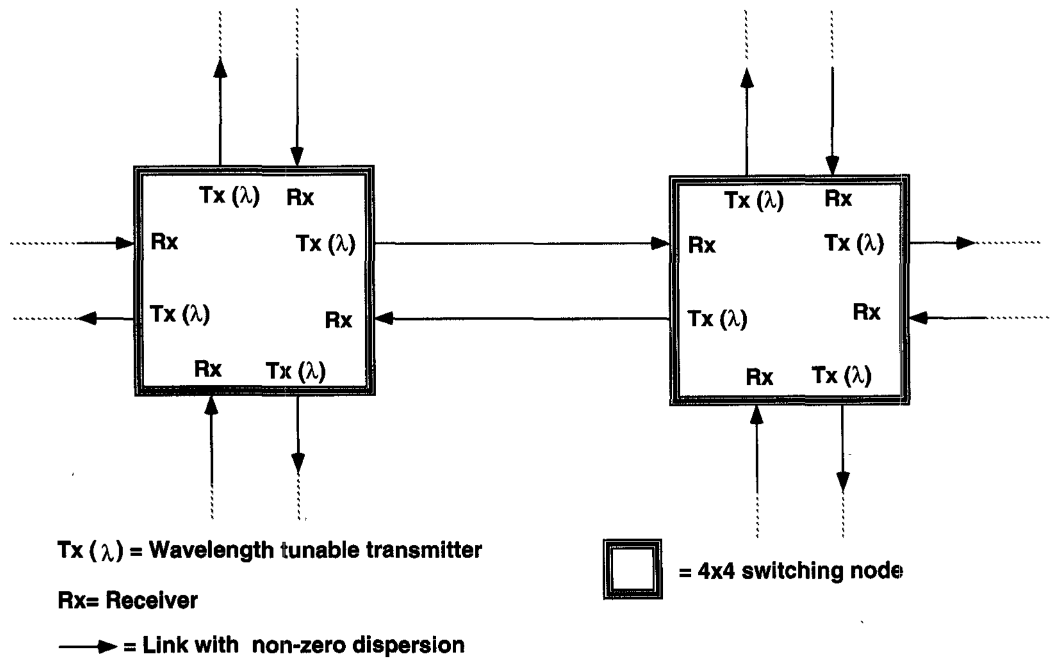

Fig. 2. A schematic of an optical network with 4 × 4 switching nodes utilizing optical synchronization by tunable transmitters and nonzero dispersion links.

delay switch, such as it is easy to obtain large delays, it is compatible with wavelength division multiplexing, and it is cascadable. However, it suffers from a few limitations, such as it is not continuously adjustable (reconfiguration time of a few ns), is quite lossy (~ -16 dB average), it is polarization dependent, the bias drift causes a varying extinction ratio with time, and sub-mm precision of the delay lines are required for an accuracy better than 5 ps.

Recently, different all-optical clock recovery techniques have been demonstrated for high-speed TDM systems [10]–[15]. These techniques are restricted to synchronizing a local clock to incoming data. There has, so far, only been demonstrated two techniques to synchronize the *data*-stream [5], [9], as mentioned above. In this paper we evaluate our recently demonstrated synchronization technique [5] using long Pseudo Random Bit Sequences (PRBS) and a digital feedback-loop for accurate alignment. We compare thermal tuning to electrical tuning. The sources of jitter are analyzed and the physical limitations of an optimized control loop are discussed.

II. Principle of Operation

The use of a tunable source for synchronization in an optical fiber network is illustrated in Fig. 2. The synchronization error is continuously measured at the synchronization point by a standard phase detector, e.g., a microwave mixer, a Gilbert cell or a digital phase detector. The error signal is digitized and processed by a micro-processor to generate a correction signal. The correction signal is transmitted back to the transmitter, whose wavelength is adjusted to compensate for the synchronization error. A protocol with a maximum packet rate for the synchronization correction of about 1 kHz has to be developed for this purpose. If the transmitter is approaching its wavelength tuning limits, a small adjustment ($\sim$1 Hz) of the local clock or the transmitter clock is performed. This is managed by a micro-processor. Fig. 2 shows an example of a system utilizing our principle of optical synchronization where two 4×4 switches having transmitters with tunable wavelengths to compensate for the timing drift are connected by links with nonzero dispersion. The switching can be performed electrically or optically. However, if optical switching is performed, a wavelength converter is required. The synchronization of individual links between the different switching nodes is maintained irrespective of the data path. Hence, data-path reconfiguration does not cause any problems.

The number of bits that can be shifted, N, is simply equal to $BDL\Delta\lambda$, where B is the bit rate, D is the dispersion parameter of the fiber, L its length, and $\Delta\lambda$ is the maximum wavelength shift of the transmitter. This relation is plotted in Fig. 3, for two different cases of link dispersion and for two different wavelength tuning cases. A continuous tuning range of about 5 nm is feasible by using, e.g., a temperature-tuned DFB laser diode [5] or a current tuned distributed Bragg reflector (DBR) laser diode [16], while a continuous tuning range of about 40 nm can be generated using a mode-locked erbium-doped fiber laser that generates a broad-band continuum [17], that can be filtered by continuously tunable optical band-pass filters. The dispersion imposes a limit on our synchronization scheme when using a standard linear transmission. This limitation can be overcome by using solitons [2], pre-chirping [3] or dispersion-supported transmission [4]. The standard linear transmission system has the following limitation [5]:

$$\Delta\lambda_{\text{bit}} < \alpha \cdot \Delta\lambda / N \tag{1}$$

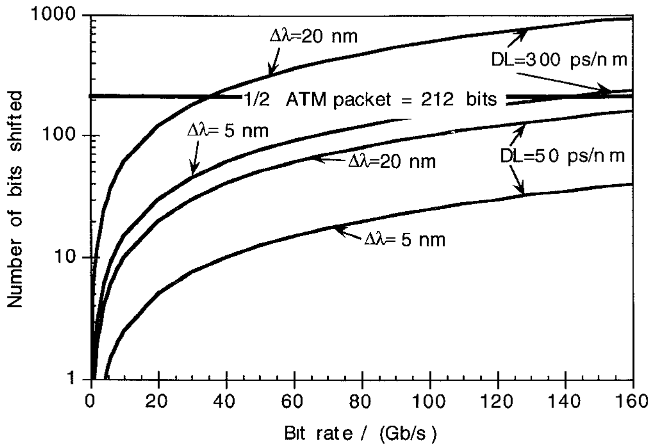

Fig. 3. The maximum number of bits shifted for sources with different tuning range (5 and 20 nm) and for two fiber links with different total dispersion. Bit synchronization is possible from 1 Gb/s to above 100 Gb/s in this case. ATM packet synchronization can be achieved above 40 Gb/s in this example.

where $\Delta\lambda_{\text{bit}}$ is the spectral width of the pulses and α is some factor <1, which expresses the allowable pulse spreading. Assuming Gaussian transform-limited pulses, $\Delta\lambda = 20$ nm, $\alpha = 0.5$, and a lasing wavelength of 1.55 μm, the maximum bit rate is >1 Tb/s for $N = 1$ and 13 Gb/s for $N = 212 = 1/2$ Asynchronous Transfer Mode (ATM) packet. Thus, for ATM-packet synchronization the standard dispersion limit has to be eliminated by using, e.g., nonlinear, pre-distortion or dispersion-supported transmission.

III. Alignment by Temperature Tuning of a DFB Laser Diode

A DFB laser diode can be tuned simply by varying its temperature. Fig. 4 shows the setup used for evaluating a system using a temperature tuned DFB laser diode as the tunable source. The DFB laser diode has a standard bias current controller keeping the average output power on a constant level, regardless of the temperature. PRBS data is imposed on the laser diode from a Bit-Error Rate Test-set (BERT) at 1 Gb/s. The data is then transmitted by a 6.5-km-long fiber with $D = -21.4$ ps/km/nm. The received data is mixed with the clock from the BERT. The low-pass filtered mixing signal is proportional to the synchronization error for small deviations ($\ll$bit period). This signal is digitized by a volt meter and converted to a temperature shift by a micro-processor. The calculated temperature shift is fed into a temperature controller actuating the Peltier element in the laser diode package. Digital interfaces in the set-up are GPIB. The bit-error rate is measured by the bit-error rate test set and the micro-processor stores the measured synchronization error signals.

The dc signal from the mixer had a maximum slope of 0.88 mV/°C for a PRBS word of length $2^{31} - 1$ at 1 Gb/s. The dc voltage as a function of temperature followed a sinusoidal function, as expected. A linear relation ($\Delta T = \Delta V \cdot 1140°\text{C/V}$) was then programmed into a computer, controlling the synchronization. Fig. 5 shows the synchronization error during closed loop and open loop operation for a period of more than 2 hours. The closed loop data was plotted as a

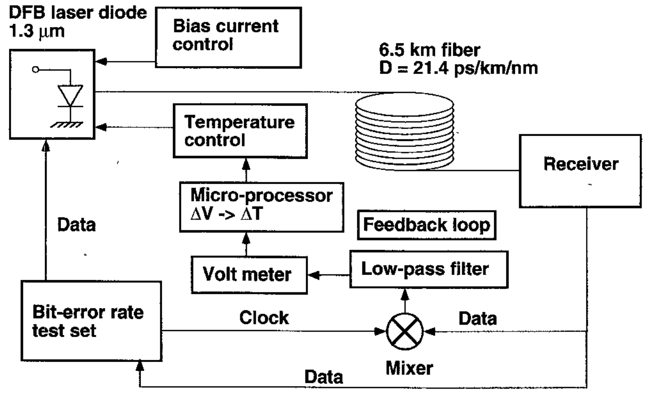

Fig. 4. Setup using a temperature-tuned DFB laser diode and a digital feedback loop for optical synchronization.

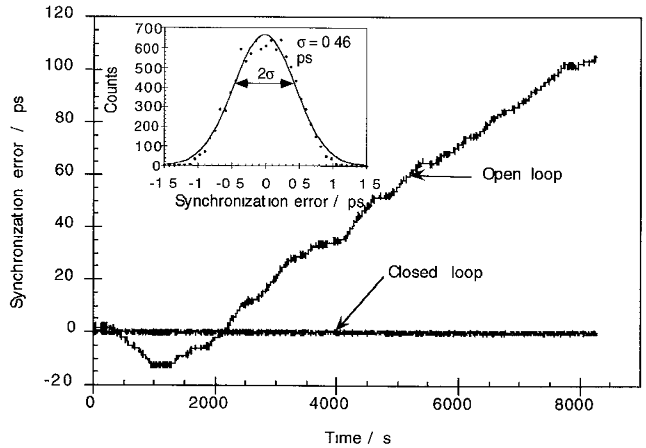

Fig. 5. Closed and open loop operation of the temperature tuned DFB system. Closed loop operation is obtained for several hours. The synchronization error is recorded each iteration of the loop, and its occurrence within a certain time slot has been plotted as a histogram.

histogram in the inset of Fig. 5. The interval from -1.5 to $+1.5$ ps is divided into an adequate number of intervals to resolve the measured synchronization-error density function. The data is fitted to a normal distribution function. The fitted normal distribution function had a standard deviation of 0.46 ps, which is sufficient for utilizing in systems up to 100 Gb/s. The pulse-to-pulse timing jitter was not measured, but it is not expected to be larger than the jitter of the source, which can be extremely small [18].

The bit error-rate penalty was negligible during closed loop operation. No errors were measured during 1 hour operation of the closed loop for a PRBS of $2^{23} - 1$. The bit error-rate was 2.2×10^{-10} for a PRBS of $2^{31} - 1$ during both closed loop operation and back-to-back. The errors were due to parasitics of the laser diode mount.

The resolution of the feedback loop is limited by the temperature control resolution of 0.1°C, which translates to an increment of 1.1 ps for a dispersion of 139 ps/nm. The bias current stability of the laser diode ($<10\,\mu$A), the receiver noise (0.34 μV), and the volt meter resolution (0.1 μV) all translates to an increment of only a few femtoseconds. A temperature controller with 0.01°C resolution, would yield a timing increment of about 110 fs.

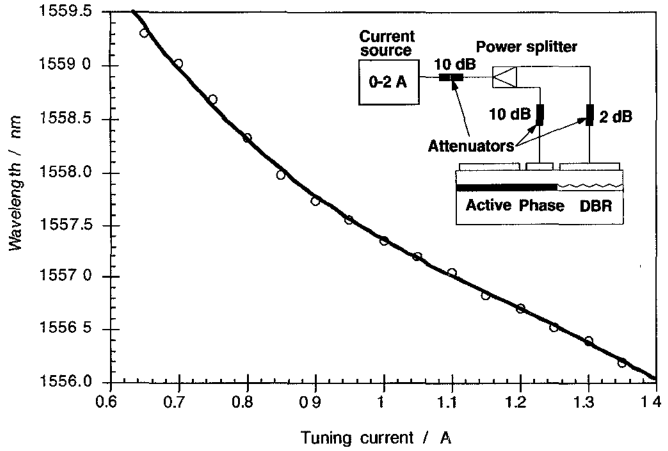

Fig. 6. The lasing wavelength versus the tuning current. The network for single current continuous tuning is shown in the inset.

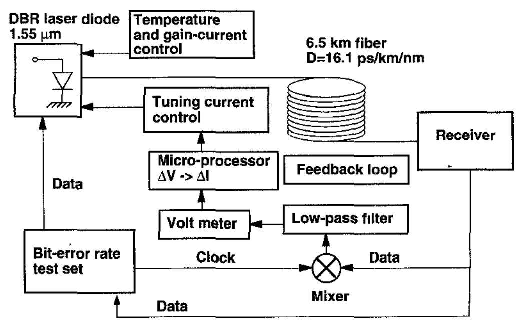

Fig. 7. The synchronization loop utilizing a current tuned DBR laser is similar to the DFB one (Fig. 4), except that the computer controlled temperature controller is replaced by a tuning current source.

IV. Alignment by Electrical Tuning of a DBR Laser Diode

Electrical tuning of a DBR laser diode is faster and more accurate than the more simple temperature tuning of the DFB laser diode. A continuous electrical tuning of a DBR laser diode has been achieved using a passive network [16]. The continuous tuning range was 3.8 nm, retaining a high side-mode suppression ratio. The tuning characteristics of our DBR laser diode (made by Ericsson Components) as well as its passive network is shown in Fig. 6. This laser diode was incorporated in a similar feedback loop for optical synchronization as the DFB laser diode. The setup is shown in Fig. 7.

The dc signal from the mixer follows a sinusoidal function with respect to the data delay, as expected. The data is fitted to a sinusoidal function and linearized around the operation point.

Open and closed loop operation is shown in Fig. 8. The loop was activated for more than 2 hours while transmitting data at 2.488 Gb/s with word lengths of $2^{31}-1$, PRBS. The synchronization error during closed loop operation is plotted in the inset of Fig. 8 as a histogram. The data was fitted to a normal distribution function, having a standard deviation of 99 fs. As expected, the accuracy is much better using a DBR laser diode than using a DFB laser diode.

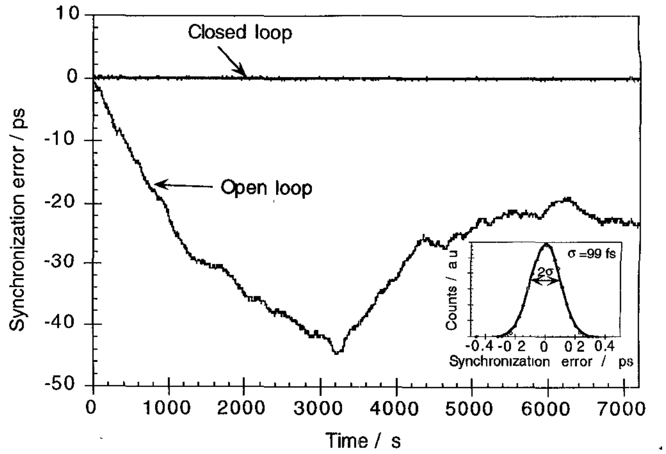

Fig. 8. Open- and closed-loop operation using the DBR laser diode during more than 2 hours. The synchronization error is recorded each iteration of the loop, and its occurrence within a certain time slot has been plotted as a histogram.

An ideal NRZ data format does not have a frequency component at the clock frequency. However, there is normally some clock component in most existing data generators. We used a Hewlett-Packard 3-Gb/s BERT (model HP 70841B/HP 70842B) in our experiment. The radio frequency spectrum fed to the mixer has a spike at 2.488 GHz of -11.6 dBm. The data power at 2.488 GHz is approximately 25 dB below the clock component. An ideal NRZ data stream would need some device to recreate the clock components by a nonlinear circuit, such as 1) a differentiating and rectifying circuit, 2) a delaying and multiplying circuit or 3) a digital phase detector [19]. These circuits have existed for more than a decade and are well understood.

The fundamental resolution of the loop is limited by both the current source resolution and the temperature stabilizer accuracy. The main contributing components to the overall loop resolution are the tuning current source resolution (0.5 mA), and the temperature stability ($<0.01°$C), which translates to a temporal increment of 150 and <130 fs, respectively, for a dispersion of 101 ps/nm. The receiver noise for an averaging time of 0.167 s is 0.34 μV, which translates to about 1 fs. The current source had a range of 4,000 points. With a more precise current source, the resolution would be limited by temperature fluctuations above the loop bandwidth.

V. Physical Limitations

Based on standard theory for digital feedback loops [20] and our experimental results, we will investigate the physical limitations of our system. A schematic of the digital control loop is shown in Fig. 9. $\theta_{\rm in}$ is the input phase of the clock at the receiver. A voltage, ν_d, proportional to the phase difference between the clock phase and the received data phase, θ_f, is filtered in an analog filter, where L is the inductance of the filter, R_L is the series resistance of the inductor, C is the shunt capacitance of the filter, and R is the shunt resistance of the filter. A digital voltmeter performs averaging of the signal and analog to digital conversion. The computer translates the

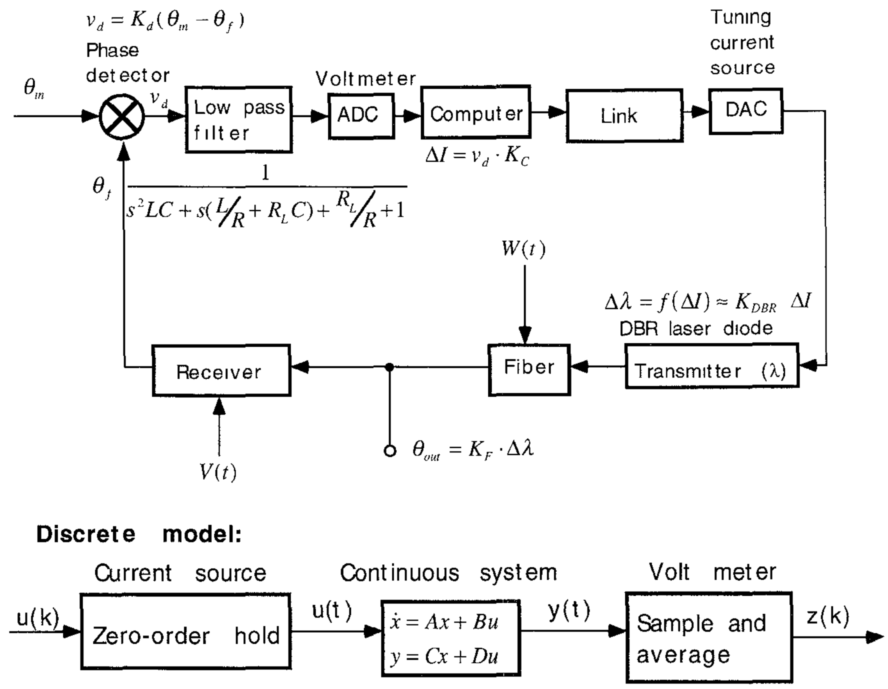

Fig. 9. A schematic of the digital control loop with the corresponding Laplace transfer functions adjacent to the different loop components.

voltage to a tuning current shift while introducing a delay. The tuning current shift is forwarded to the transmitter over the link. The current source acts as a digital to analog converter. The current shift is then transformed into a wavelength shift by the DBR laser diode that subsequently introduces the desired phase shift due to the dispersion of the fiber. The fiber length itself contributes with a delay. The receiver converts the optical phase to an electrical one. $W(t)$ is the thermally induced noise in the fiber which we intend to control by the closed loop. $V(t)$ is the noise of the receiver. The iteration time constant of the whole loop is T. The Laplace transforms of the different components are shown in Fig. 9. (See Table I for experimental values of the loop parameters.) Below the loop in Fig. 9 is a schematic of the part of the loop including the zero-order hold circuit (the current source), the state space representation of the continuous part of the system (transmitter, fiber, receiver, phase detector, and low pass filter), and the volt meter. $u(t)$ is the output of the current source, and $y(t)$ is the input to the volt meter. For details on the exact modeling of the averaging volt meter, see [21]. To benefit from existing CAD programs like the Matlab® μ-Tools, we write the continuous part of the system in the standard state-space form [20]

$$\dot{x} = Ax(t) + Bu(t) \tag{2}$$

$$y(t) = Cx(t) + Du(t) \tag{3}$$

which has the solution

$$y(t) = C \cdot e^{A \cdot t} \cdot x(0) + C \int_0^t e^{A(t-\tau)} Bu(\tau)\, d\tau + Du(t) \tag{4}$$

TABLE I
LOOP PARAMETERS AND THEIR EXPERIMENTAL VALUES

Loop parameters	**Experimental value**
τ_V	0.167 s
T	0.86 s
K_d	22 mV / rad
K_C	10 A / V
K_{DBR}	4.3 nm / A
K_F	1.58 rad / nm
$K = K_d \cdot K_C \cdot K_{DBR} \cdot K_F$	1.49
L	200 H
R	7 kΩ
C	10 nF
R_L	830 Ω

where $x(0)$ is the initial state. The volt meter averages the input from kT to $kT + \tau_V$, where k is an integer, T is the loop iteration period and τ_V is the averaging time constant of the volt meter. The output from the volt meter, z, (at the time $kT + T$) is then

$$z(k+1) = \frac{1}{\tau_V} \int_0^{\tau_V} y(kT + t)\, dt. \tag{5}$$

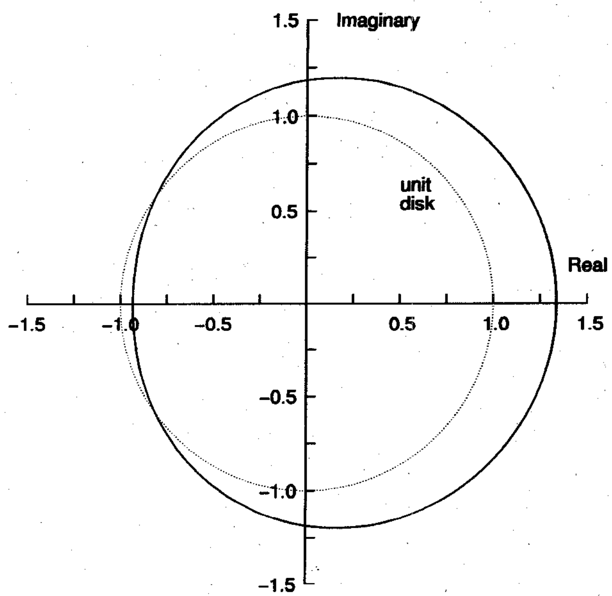

Fig. 10. A Nyquist plot analysing the experimental system using parameters given in Table I. The gain margin is 1.1 and the phase margin is 40°.

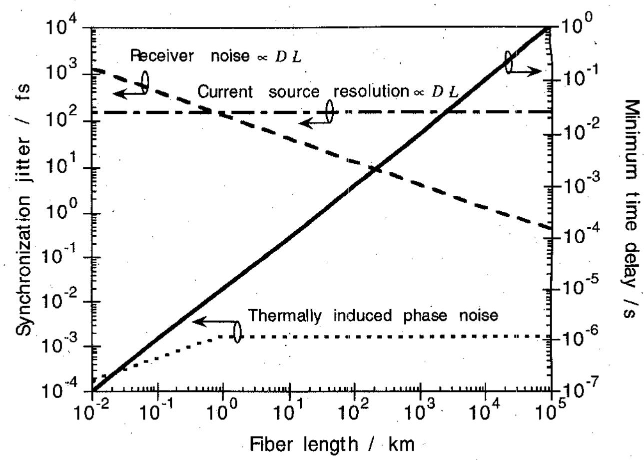

Fig. 11. Fundamental noise sources of the synchronization loop versus fiber length.

A discrete time model, from $u(k)$ to $z(k)$, can be derived from (4) and (5). This is then studied by closing the loop.

$$u(k) = K_C z(k) \tag{6}$$

where K_C is the computer gain. Equations (2)–(6) are solved using Matlab® μ-Tools. The system is stable. However, the gain margin is only 1.1 and the phase margin is about 40°. By approximating the volt meter by a first-order low-pass filter would yield an unstable system with a gain margin of 0.77. Experimentally, the feedback loop is stable and always recovered when transients where introduced in the system by, e.g., an electrical surge via the grounding. A Nyquist plot of the experimental system is shown in Fig. 10.

A 100-km link would require a minimum time delay of about 1 ms if the processing time is negligible. One ms accounts for sending data back and forth over the link. By using the exact model as above and adjusting the filter constants appropriately so that the bandwidth is around 100 Hz, we can predict the behavior of the feedback loop. By using an $L = 20$ H, $T = 1$ ms, and $\tau_V = 1$ ms, we obtained a stable system with a gain margin of 4.3 and a phase margin of 120°. The acquisition time in this case was determined by the volt meter to be 1 ms.

Let us now consider the different noise sources, $V(t)$ and $W(t)$. The receiver used in the experiment had a noise current of about 20 pA/$\sqrt{\mathrm{Hz}}$. The averaging time constant of the volt meter determines the bandwidth, and hence the noise current. The thermal noise from the fiber has been theoretically described [22] and recently measured [23]. The maximum rms phase fluctuations are about 1 μrad/$\sqrt{\mathrm{Hz}\cdot\mathrm{km}}$ [23], and the typical bandwidth is about 10^5 Hz [22]. We assume the worst case, i.e., the phase fluctuations are given by: 1 μrad $\times$ $\sqrt{(\text{bandwidth}) \times (\text{fiber length})}$. The receiver noise and thermally induced fiber noises are shown in Fig. 11 as a function of the fiber length for a dispersion of 101 ps/nm. A maximum averaging time permitted by back and forth transmission over the fiber length is assumed. The timing error of data due to noise in the receiver is proportional to the total dispersion of the link. For example, with a fiber length of 100 km, the dispersion has to be increased a factor of about 100 before the receiver noise is of the order of 1 ps.The current source introduces a timing error independent of fiber length but proportional to its dispersion. The thermally induced noise in the fiber only depends on the fiber length and is negligible in this case. A total dispersion of 300 ps/nm would yield a practical overall timing error below 1 ps. The jitter originating from erbium-doped fiber amplifiers should also be considered as a fundamental limit, and can be easily calculated with standard theories [24].

VI. Oscillator Adjustment

When the transmitter wavelength approaches its limits, we propose to slightly adjust the oscillator frequency to bring the operating wavelength further away from its maximum deviation point The micro-processor at the receiver controls now both the wavelength of the transmitter and a small adjustments of the transmitter clock. The local clock should be a high quality, fixed frequency oscillator. The frequency increment of the synthesizer at the transmitter has to be less than the loop bandwidth, i.e., less than 55 Hz in the example of a 100 km link, which is feasible. The jitter of the two independent oscillators will add incoherently. Their individual jitter is obtained by integrating the side-bands at frequencies above the loop bandwidth [25].

VII. Conclusion

We have investigated experimentally and theoretically a recently proposed scheme to align and to synchronize data with a reference phase at an arbitrary point in a fiber optic system. We utilize a tunable transmitter in combination with a link having a nonzero dispersion. The timing error is minimized by a digital feedback loop that adjusts the wavelength of the transmitter to compensate for the timing error. We have verified the principle by performing experiments with a temperature-tuned DFB laser diode and a current tuned DBR laser diode. The current tuned DBR laser diode system yielded a closed loop error of about 100 fs for a total dispersion of 101 ps/nm. The temperature tuned DFB laser diode system yielded a closed loop error of less than 500 fs for a total dispersion of 139 ps/nm. Based on those experiments, we estimate that this principle could be used for fiber lengths of about 100 km and a dispersion of about 300 ps/nm and still have a closed loop timing error of less than 1 ps. Continuous bit-synchronization is possible in the range from 1 Gb/s to 100 Gb/s. Full ATM packet-synchronization is feasible at bit rates above 40 Gb/s.

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Peter Blixt was born in Stockholm, Sweden in 1961. He received the M.S. and Ph.D. degrees in engineering physics at the Royal Institute of Technology, Stockholm, in 1986 and 1990, respectively. His Ph.D. thesis dealt with picosecond dynamics of semiconductor laser diodes.

Since 1990, he has been employed at the Institute of Optical Research, Stockholm working on concentration dependent effects in erbium-doped fiber amplifiers (EDFA's) and on combining tunable DBR lasers with EDFA's for generating high energy subpicosecond pulses. Since February 1994, he has been a Visiting Researcher in Professor John E. Bowers' group at the University of California, Santa Barbara, working in the project Thunder and Lightning on high speed fiber-optic systems.

Dr. Blixt is a member of the Optical Society of America and the European Optical Society.

John E. Bowers (S'78–M'81–SM'85–F'93) received the M.S. and Ph.D. degrees in applied physics from Stanford University with a dissertation on Sezawa wave signal processing devices.

He is a Professor in the Department of Electrical Engineering at the University of California, Santa Barbara, and a member of the Optoelectronics Technology Center and the NSF Science and Technology Center on Quantized Electronic Structures. His research interests are primarily concerned with high frequency optoelectronic devices and physics. He has worked for AT&T Bell Laboratories and Honeywell and is currently an optoelectronics consultant. He has published over 180 papers and has received 12 patents.

Dr. Bowers was elected as a Fellow of the IEEE "for contributions to the understanding and demonstration of novel ultrafast semiconductor lasers, photodetectors, and transmission systems." He is a recipient of the Thomas F. Andrew prize and the NSF Presidential Young Investigator Award.

Erik Bødtker was born in Fredriksberg, Denmark, on December 13, 1949. He received the B.Sc. degree from The Danish Engineering Academy in 1975 and M.Sc. degree in electronic engineering from The Technical University of Denmark in 1977.

From 1977–1978 he was engaged in development of consumer electronics for the entertainment industry. He was employed at Tele Danmark Research (formerly TFL, Telecommunication Research Laboratory) beginning in 1978. In 1987 he was appointed a Senior Researcher and in 1988 a Project Manager. He is now responsible for the experimental activities on high capacity optical communication systems at Tele Danmark Research. Until 1985, he was working on optical time domain reflectometry systems based on photon counting and real-time parallel digital signal processing. Since 1985 his main interest has been high capacity optical communication systems. From 1985–1990 his focus was on systems with coherent detection, but afterwards the scope has been widened to cover other families of advanced optical communication systems. He has specialized in high frequency and microwave optoelectronics and is an active experimentalist when time allows. From 1988–1991 he participated as a Project Manager in a large-scale field trial experiment with coherent communication. The aim was to transfer the coherent technology to an operating environment. A complete 565 Mb/s transmission system was developed and tested with live telephone traffic over a 157 km submarine cable for a period of three months. From May to September 1989, he worked at BELLCORE (Bell Communications Research), New Jersey, as a Visiting Researcher, and from May to September 1994 he was at the University of California, Santa Barbara. He has authored or co-authored more than 50 publications in the open literature.

O. Sahlén, photograph and biography not available at the time of publication.

Roy Smith (S'79–M'81–S'85–M'89) received the B.E. (Hons.) and M.E. degrees from the University of Canterbury, New Zealand, and the M.S.E.E. and Ph.D. degrees from the California Institute of Technology.

He has worked in industry and government laboratories on control and instrumentation problems in the areas of: boiler systems; linear accelerators and mass spectrometers; automotive emissions and fuel systems; and flexible structures. Since 1990 he has been with the University of California, Santa Barbara, as an Assistant Professor in the Electrical and Computer Engineering Department. His research interests include robust control, identification with uncertain models, and control applications in automotive systems, semiconductor manufacturing and flexible structures.

Dr. Smith is a member of SIAM, AIAA, and NZAC.