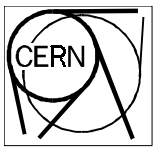

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GP-MIMD

T9000 Fiber Optic Link Extensions

Report on 850nm Fiber Optic Transceiver

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1. Overview

A fiber optic transceiver for 125MBaud using low cost 820nm optical components is presented. The transceiver is designed to be used to connect T9000 transputer links over optical fiber.

The main design issue for such a link is to achieve low error rates. For a 1000 node transputer machine with 250 fiber optic links, the individual link error rate has to be as small as 10^{-18} to achieve less than 1 failure per year due to link transmission errors.

The transceiver circuit has been breadboarded and extensive tests have been carried out. Finally a printed circuit board has been produced.

Section 2 gives an overview of the design parameters of a digital fiber optic transmission system and defines the characteristics for this particular application. A system specification is also included.

In section 3 the procedures and test setups used to measure the key parameters of the link are presented. This allows the measurements to be repeated under the same conditions.

The test results are presented in section 4 and section 5 formulates the conclusions from these results.

2. Fiber Optic System

The fiber optic system should conform to the following specifications :

- A bit rate of 125MBaud is required to provide sustained data rate for a 100MBaud DS-link, assuming a 4B6B encoding scheme.
- The maximum link length should be between 250 and 500 meters. This provides for connections between two transputer boxes or between a transputer machine and some I/O subsystem.
- The optical components for the fiber optic transmitter and receiver should be low cost, reliable and easy to use. Therefore a LED is preferred as optical source.
- Multimode fiber is preferred over monomode fiber, because of lower cost, less problems with connector alignment and the possibility to use an LED transmitter. Monomode fiber would only be required in long haul applications.

2.1. Optical Fiber

Graded index multimode fiber with 62.5µm core and 125µm cladding is used. This type of fiber has become quite popular through its use for FDDI. For fibers with smaller core diameter (e.g. 50/125µm fiber, widely used by PTT's) the optical power being launched into the fiber will decrease. Fiber types with bigger core diameter (e.g. 100µm) are not very common and will also show a reduced bandwidth-length product, due to higher modal dispersion (see 2.1.2).

The connector used for the prototype is ST, providing low loss (~0.6dB) and easy handling. For later implementations SC would be preferred (easier to use and higher packing density), but the optical components do not exist in an SC housing yet.

2.1.1. Attenuation

The attenuation of the selected fiber type is specified as 4dB/km. This results in 1dB fiber attenuation for the maximum target length of 500m (see also 2.4.2). Attenuation for connectors and splices has to be added, to get the total link loss (see 2.4.1).

2.1.2. Modal Dispersion

Modal dispersion is caused by different modes propagating along a multimode fiber. A simplified view is of different rays of light traveling on different path through the fiber, and therefore experiencing different delays. This effectively spreads out the transmitted light pulses.

The modal bandwidth of the fiber is given by the manufacturer as bandwidth-length product (BLP). It is measured using a narrow spectral width source (laser).

The BLP for the selected 62.5µm core multimode fiber is 160MHz*km. Modal bandwidth can then be calculated as :

$$B_M = \frac{BLP}{L}$$

L Link length [km]

For a 500m link the modal bandwidth is therefore 320MHz.

2.1.3. Chromatic Dispersion

Chromatic or material dispersion is due to the refractive index of the fiber material being a function of the wavelength. Therefore, different wavelength of the transmitted light spectrum travel at different speeds. So chromatic bandwidth of the fiber depends mainly on the source spectral width. The approximate relationship for chromatic dispersion (FWHM pulse broadening) is :

$$\sigma_C = D_C \cdot \Delta\lambda \cdot L$$

D_C Material dispersion constant [ps/(nm*km)]

$\Delta\lambda$ Full half maximum (FWHM) spectral width of the source [nm]

L Link length [km]

The chromatic bandwidth can then be calculated as :

$$B_C = \frac{0.44}{\sigma_C}$$

Using D_C = 127ps/(nm*km) [**1**] and $\Delta\lambda$ = 75nm as maximum spectral width (see 2.7), the chromatic bandwidth for a 500m link is B_C = 92.4MHz.

2.1.4. Fiber Bandwidth

The total 3dB optical power bandwidth of the fiber depends on modal and chromatic dispersion effects. It is calculated as the geometric sum of modal and chromatic bandwidth :

$$B_F = \frac{1}{\sqrt{\frac{1}{B_M^2} + \frac{1}{B_C^2}}} = 89\text{MHz}$$

From this the optical rise/fall time (10% - 90%) can be derived as follows :

$$t_F = \frac{0.318}{B_F}$$

Using the values from 2.1.2 and 2.1.3, the fiber rise time becomes t_F = 3.6ns.

2.2. Optical Transmitter (OTX)

The optical emitter used is an 820nm LED from Hewlett-Packard packaged in an ST-connectored housing (HFBR1414T) [**2**].

The OTX circuit consists of driver for the LED, which converts from differential ECL input. The driver uses LED prebias and current peaking to speed up the frequency response of the emitter [**3**]. The OTX also includes a DCD correction circuit (see 2.6.1).

Figure 1 shows the block diagram of the OTX. The detailed schematic can be found in appendix A.

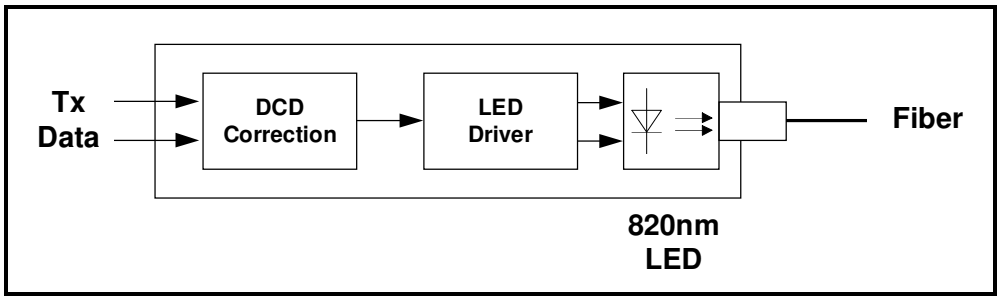


Figure 1 : OTX block diagram

2.3. Optical Receiver (ORX)

The optical detector used is a PIN diode from Hewlett-Packard, mounted together with a transimpedance preamplifier in an ST-housing (HFBR2416T) [**4**]. The output of the PIN-preamp has to be converted to ECL logic levels. The ORX circuit therefore consists of a postamplifier and a discriminator (also called decision circuit). The amplifiers are AC-coupled, allowing simpler circuit design. This is possible because a DC-balanced code will be used.

Figure 2 shows the block diagram of the ORX. The detailed schematic can be found in appendix A.

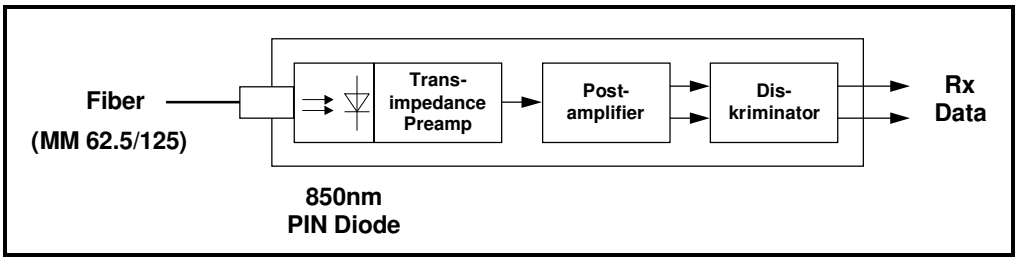


Figure 2 : ORX block diagram

2.4. System Planning

2.4.1. Optical Power Budget

The following table shows the specified power budget for the fiber optic link. All optical power values are given as average optical power (dBm,avg) :

Worst case transmitter optical launch power	-16dBm,avg	
Receiver sensitivity (@ BER = 10E-12)		-26dBm,avg
Power margin for BER	3dB	
Fiber attenuation loss(500m @ 4dB/km)	2dB	
Connector loss (2 x 0.6dB)	1.2dB	
Splice loss (2 x 0.2dB)	0.4dB	
Dispersion penalty	0.4dB	
Total	-23dBm,avg	-26dBm,avg
Unaccounted system margin	3dB	

Table 1 : Power budget

2.4.2. System Bandwidth

The maximum bit rate of a fiber optic system is limited by the response time of the optical transmitter and receiver, as well as by dispersion in the fiber. The total system response time (10% to 90% rise/fall time) can be calculated as :

$$T_S = \sqrt{T_T^2 + T_F^2 + T_R^2} = 5.6ns$$

T_T	OTX rise/fall time	3ns	(see 2.7)
T_F	Fiber response time	3.6ns	(see 2.1.4)
T_R	ORX rise/fall time	3ns	(see 2.7)

The maximum bit rate for NRZ-pulse transmission can be estimated as :

$$R_B = \frac{0.7}{T_s}$$

With the above values the maximum bit rate is 125MBaud. This means that the theoretical speed-distance limit for the chosen optical components is around 500 meters at 125MBaud.

2.5. Bit Error Rate (BER)

Bit error rate is a useful measure for characterizing the reliability of a transmission system. It is defined as the ratio of errored bits to the number of transmitted bits :

$$BER = \frac{N_{Error}}{N_{Bit}}$$

The occurrence of bit errors in a regenerative transmission system can be related to several effects :

- Noise
- Intersymbol interference (ISI)
- Jitter (see 2.6)

2.5.1. BER as a Function of Signal-to-Noise Ratio

Additional noise disturbance at the receiver input is one fundamental reason for bit errors to occur. The main noise sources in the ORX circuit are the optical detector and the receiver amplifiers.

Assuming noise with Gaussian probability density function (e.g. thermal noise), the relationship between BER and optical signal-to-noise ratio (SNR) can be evaluated, see [**5**] for the detailed reduction. The resulting formula is (SNR is defined as peak-signal to RMS-noise power ratio) :

$$BER = \frac{1}{2} \cdot \mathrm{erfc}\left(\frac{SNR_{OPT}}{2 \cdot \sqrt{2}} \right)$$

with the complementary error function defined as :

$$\mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \exp\left(-u^2\right) du$$

Figure 3 shows a plot of this function.

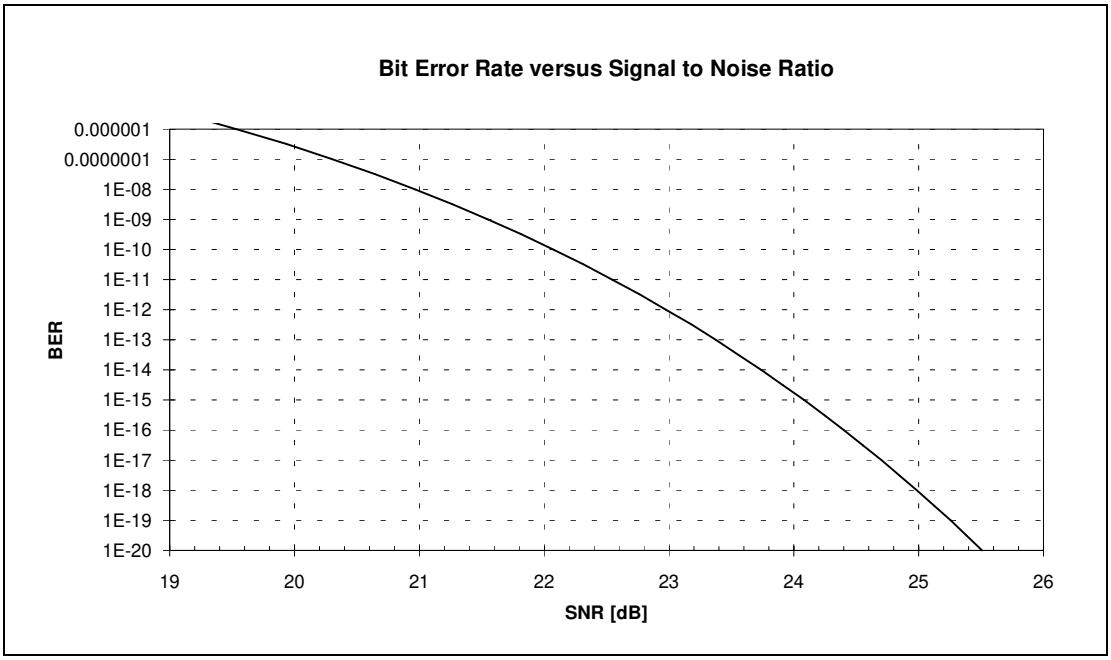


Figure 3 : BER versus SNR

One notes that the above curve is very steep, a change of only 1dB in receiver sensitivity corresponds to a 3 orders of magnitude in BER at error probabilities around 10^{-15}.

The relationship between BER and SNR expressed in dB can be reasonably well approximated by a straight line when BER is plotted on a double logarithmic scale [**6**]. The linear approximation is valid for BER values smaller than 10^{-4}, which is no restriction, as the BER levels of interest are much lower.

To save time, it is common practice to use this relationship to measure at higher error probabilities (e.g. 10^{-8}) and then to extrapolate to the desired BER value [**7**]. This can be done by fitting the linear approximation to the measured data points.

The extrapolation remains valid as long as there is no noise floor, caused for example by EMI or ESD. This can only be verified by long BER test runs (e.g. a test run of 1000 hours is necessary to check that the error rate is smaller than $2.2 \cdot 10^{-15}$).

2.6. Jitter

Jitter in data communications is defined as the deviation of the pulse edges from their nominal position. The types of jitter can essentially broken up into two categories : deterministic jitter (see 2.6.1 and 2.6.2) and random jitter (see 2.6.3).

An excessive amount of jitter will degrade the BER performance of the transmission system. The impact on error probability cannot be estimated independently from the clock recovery circuit though.

2.6.1. Duty-Cycle Distortion (DCD)

Duty cycle distortion, also called pulse width distortion, is caused by the propagation delay difference for low-to-high and high-to-low transitions. It is measured as the deviation of the symbol duration (at 50% level) from the nominal value (i.e. 8ns at 125MBaud), with a continuous square wave of 50% the bit rate (i.e. 62.5MHz) being transmitted. Excessive values of DCD will cause closure of the time domain eye opening.

2.6.2. Data Dependent Jitter (DDJ)

Data dependent jitter is related to the data pattern and is caused by the limited bandwidth characteristics of the transmission channel.

DDJ in the OTX is mainly due to the nonlinear characteristics of the LED. DDJ at the ORX output results from AC-coupling in the receiver circuit (causing base-line wander) and the low-pass characteristics of the optical components and the fiber (causing intersymbol interference, ISI).

2.6.3. Random Jitter (RJ)

Random jitter is caused mainly by thermal noise in the ORX circuit. Essentially, amplitude noise from the optical detector (PIN diode) and the receiver amplifiers is transformed into time domain noise (random jitter) by the decision circuit.

RJ is usually assumed to be a Gaussian process. It can be given as peak-to-peak jitter at an associated error probability or expressed as RMS value.

2.7. System Characteristics

An overview of the most important characteristics of the fiber optic link is given below.

Parameter	Typical value	Unit	Notes
Bit Rate	125	MBaud	
Data format	NRZ		
Transmission code	3-of-6		
BER	10^{-12}		with 3dB optical power margin
Optical fiber			
Type	Multimode		
Core/cladding diameter	62.5/125	µm	
Attenuation	4	dB/km	
Modal Bandwidth	160	MHz·km	
Maximum link length	500	m	
Maximum link loss	4	dB	fiber, connectors, splices
Transmitter			
Type	LED		
Spectral center wavelength	820	nm	
Full width half maximum	75	nm	maximal
Output optical power	-16	dBm	worst case, out of 1m of 62.5/125µm fiber
Rise/Fall time	3	ns	10% - 90%
Receiver			
Type	PIN-Diode		
Sensitivity	-26	dBm	for BER = 10^{-12}
Rise/Fall time	3	ns	

Table 2 : F.O. transceiver specifications

3. Test Procedures

3.1. Test Equipment

3.1.1. Bit Error Rate Tester (BERT)

The instrument used for BER measurements is a Wandel & Goltermann PF5 Bit Error Rate Test Set. It can generate programmable bit patterns of up to 32 bits and also Pseudo-Random-Bit-Sequences (PRBS) of different length. The maximum bit rate is 175MBaud.

3.1.2. Digital Oscilloscope

A Tektronix TDS540 digital sampling scope was used for measurement of eye diagrams (see 3.5) and jitter. The scope can sample data at 1GS/s in real time mode and up to 100GS/s in sequential sampling mode for repetitive signals. The input amplifier bandwidth is 500MHz, which is equivalent to a transition time of 700ps.

Very important for the measurement of eye diagrams (see 3.5), is that the instrument provides a static persistence mode, in which the traces from all trigger events are accumulated on the display.

3.1.3. Optical-Electrical Converter (O/E Converter)

A Tektronix P6701A opto-electronic converter was used for characterizing the transmitter optical pulse shape. The bandwidth of the converter is DC to 850MHz, allowing accurate measurement of optical waveform parameters.

3.1.4. Pulse Generator

A pulse generator was needed for initial tests and as an highly accurate variable delay, to align the clock at the receiver input with the middle of the data eye. The instrument used is a LeCroy 9210 mainframe with a 9211 250MHz plug-in unit.

3.1.5. Variable Optical Attenuator

The programmable optical attenuator is needed for the BER measurements. An Anritsu MN938A has been used for this purpose. The resolution for setting the attenuation is 0.1dB.

3.1.6. Optical Power Meter

An Anritsu ML9001A power meter mainframe with the MA9611A optical sensor were used for accurate measurements of optical power at the OTX and ORX optical ports.

3.2. Optical Power

The average optical power is measured in dBm,avg at the OTX and ORX fiber connector using the optical power meter. The pattern transmitted is a square wave signal at 10% of the bit rate (i.e. 12.5MHz). By adding 3dBm to the average value, the approximate peak optical power (dBm,pk) can be estimated.

3.3. Optical Waveform

Optical waveforms at the OTX output and ORX input are measured using the O/E-converter and the oscilloscope. The digital sampling scope is operated in averaging mode, to reduce noise from the O/E converter. The test pattern used is a square wave signal at 50% the bit rate (i.e. 62.5MHz).

3.4. BER Test Setup

Figure 4 shows the setup used for BER measurements. An optical attenuator is inserted in the fiber path, in order to set the receiver optical input power value.

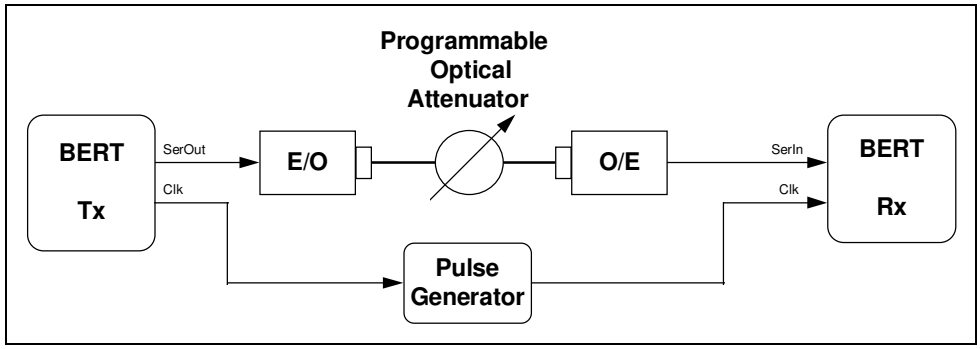


Figure 4 : BER test setup

There are two ways to supply the clock signal to the receiver section of the BERT. The first is to use the external clock input. The bit clock from the BERT transmitter has to be delayed then, so that the sampling instant (e.g. rising edge of clock) coincides with the center of the bit interval. A high-speed pulse generator was used for this purpose.

The second method is to use the built-in clock recovery (CR) feature of the BERT to generate the necessary receive clock signal. The BER performance will be degrade due to jitter of the recovered clock signal.

The results of the first and the second method can be compared, to estimate how much the receiver sensitivity is degraded by the clock recovery process. This can also be thought of an optical power penalty for regenerating the clock

from the serial data stream. Of course the final clock recovery circuit will have different characteristics, but the results can be used as an estimation.

3.5. Eye Measurements

The eye diagram (or eye pattern) results from the superposition of the waveforms for all pattern combinations over one bit interval. The eye opening is defined as the boundary within which no waveform trajectories lie, i.e. the region of the eye where the correct bit value can be regenerated.

The time domain eye opening defines the time interval, in which the sampling instant must lie. It can also be expressed as bit period minus peak-to-peak jitter.

3.5.1. Eye Measurements with an Oscilloscope

The oscilloscope method is simple and provides comprehensive plots of the eye diagram, but the scope does not display events occurring with low probabilities, i.e. low error rates (BER < 10^{-4}).

The eye pattern is measured directly on the display of the digital sampling scope triggered by the serial bit clock (125MHz). The BERT is used as pattern generator. The scope has to be placed in infinite persistence mode.

For the OTX output and ORX input optical eye diagrams, the O/E converter was used.

3.5.2. Eye Measurements with a BERT

The eye opening can be measured with a BERT at any desired error probability. This method is more accurate than the scope measurement, especially at low error rates. A common practice is to measure the eye opening at higher probabilities (e.g. 10^{-8}) and then extrapolate to the desired BER level (see 3.4.1).

The test setup is the same as for the BER measurements, but the decision point is varied by changing the clock delay with the pulse generator. This is how the time domain eye opening (TDEW) can be measured.

3.6. Test Patterns

3.6.1. Square Wave

A square wave signal at 10% or 50% the bit rate is used for average optical power measurements and for OTX and ORX optical waveform testing. The duty cycle of the square wave has to be 50%.

3.6.2. Pseudo-Random Bit Sequence (PRBS)

Short PRBS patters are used for BER testing and eye measurements. The short sequences PRB6 (63 bits, maximum run-length 6) and PRB7 (127 bits, max. RL 7) were used because their characteristics are close to the 3-of-6 code which has a maximum run-length of 4 or 5, depending on the allocation of the code tokens.

3.6.3. 3-of-6 Code IDLE Pattern

As the BERT can generate programmable bit patterns of up to 32 bits, short sequences of valid 3-of-6 code patterns could be tested. For more information on the code see [**8**].

The IDLE pattern is the bit sequence that is transmitted over the link when no data is available. The 24 bit pattern used is :

IDLE	0	1	0	1	0	1	0	1	0	0	1	1	1	0	1	0	1	0	1	0	1	1	0	0

3.6.4. 3-of-6 Code Worst Case Pattern

Patterns having long run-length followed single bits turn out to be worst-case. The long run-length allows for example parasitic capacitance's in the OTX and ORX circuits to charge/discharge, while isolated 1's and 0's are attenuated due to the bandwidth limitation of the system. The worst case patterns used are :

RL5	0	0	1	0	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	0	1	0	0

RL4	0	0	1	0	1	1	1	1	0	1	0	0	0	0	1	0	1	1	1	1	0	1	0	0

4. Test Results

Most of the tests were done with a breadboard version of the optical transceiver circuit. A few of these tests were repeated for the PC-board implementation, mainly to verify its functionality.

All tests were carried out at room temperature (25°C). The results were obtained at nominal power supply voltage (Vcc = 5V), unless otherwise noted.

4.1. OTX optical output

4.1.1. Optical output power

The average optical output power for the two HFBR1414T LED emitters tested is shown below :

HFBR1414T	Po,avg [µW]	Po,avg [dBm]
Part 1	27.0	-15.7
Part 2	27.4	-15.6

Table 3 : OTX average optical output power at Vcc = 5V

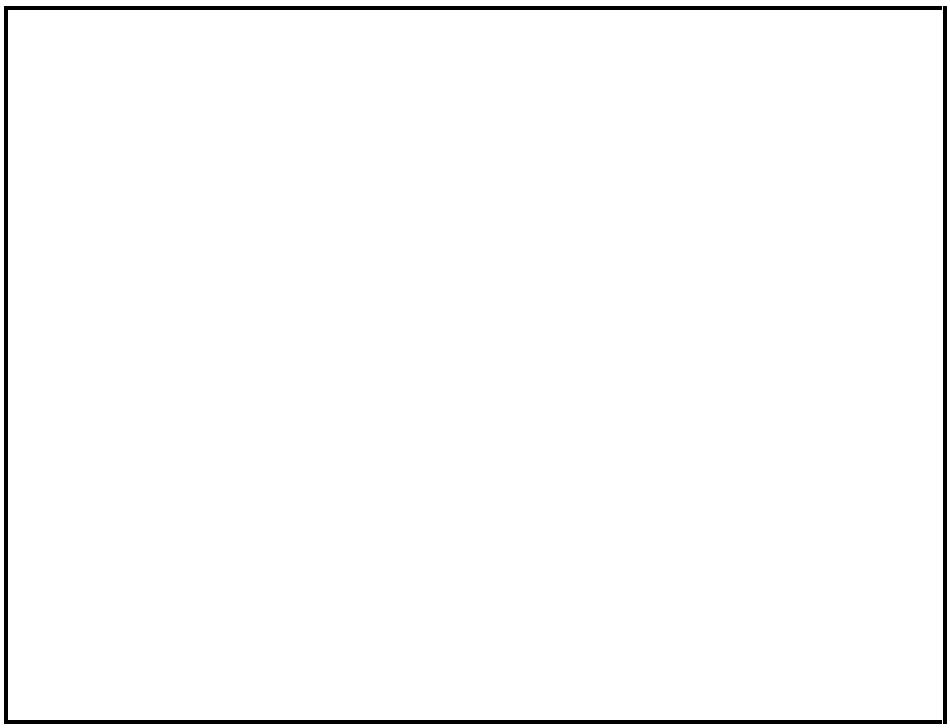
The change in optical power variation for power supply voltage variations is 1.9dB/V for both parts. This translates to a 0.48dB power penalty for a ±5% power supply (Vcc = 4.75V to 5.25V).

4.1.2. Optical waveform

The OTX optical waveform was measured with the O/E converter through 1 meter of 62.5/125µm fiber (see 3.3). Figure 5 (see below) shows the output optical waveform of the transmitter. The measured parameters are :

Parameter	Symbol	Value	Unit
Rise time (10% - 90%)	tr	2.3	ns
Fall time (10% - 90%)	tf	2.4	ns
Duty cycle distortion	DCD	0.2	ns

Table 4 : OTX optical waveform parameters



BER	BEC	Pattern	Baud rate [MBaud]	Link length [m]	Gate interval [hours]
$<3.7*10^{-14}$	0	PRS6	125	500	61
$<3.55*10^{-14}$	0	IDLE	125	500	60
$<4.6*10^{-15}$	0	IDLE	125	200	480

Table 6 : Bit error rate test results

The above results only show that BER is below a certain value, but give no information how big the margin is. One can also see that run times for error rates lower than 10^{-15} become prohibitively long.

4.2.2. ORX Optical Input Sensitivity

The error rate (for BER in the range of 10^{-6} to 10^{-12}) has been measured for several values of optical input power (see 3.4) and this data was used to estimate the ORX sensitivity at an error rate of 10^{-20} by extrapolation (see 2.5.1).

An overview of the most important test results is given below. Plots of the measured data points can be found in appendix C. All tests were run at nominal bit rate of 125MBaud.

Figure	ORX Sensitivity [dBm]	Test Pattern	Fiber length [m]	Clock	Notes
1	-30.1	IDLE	200	Ext.	Breadboard
2	-27.3	PRS7	200	Ext.	Breadboard
3	-28.3	RL5	200	Ext.	Breadboard
4	-29.9	PRS7	200	Ext.	PCB
5	-30.7	RL5	200	Ext.	PCB
6	-28.2	RL5	200	Int.	PCB

Table 7 : ORX optical input sensitivity at BER = 10^{-20}

By comparing the above results, the following conclusions can be drawn :

- The sensitivity values correspond to those expected from the data sheet (receiver sensitivity of -27dBm,pk at BER = 10^{-9}).
- The sensitivity difference between a short pseudo-random pattern and a 3-of-6 code pattern with bounded disparity is 0.8 to 1.0 dB.
- The power penalty for clock recovery is around 2dB for the IDLE pattern to 2.5dB for the worst-case RL5 pattern.

4.3. Fiber Bandwidth

OTX output and ORX input optical power was measured at different bit rates. With this data, a plot of relative fiber attenuation over line rate frequency was produced (see figure 6). From this graph, the 3dB optical bandwidth the fiber was estimated to be 95MHz (i.e. 190MBaud). This compares quite well with the calculated value of 89MHz (see section 2.1.4).

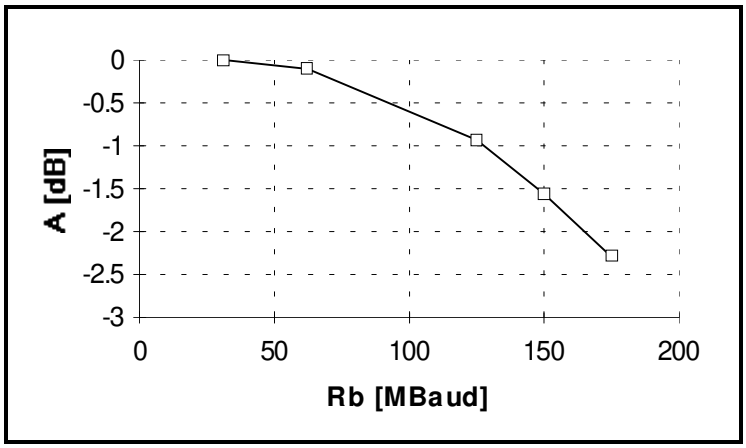


Figure 6 : Fiber attenuation versus bit rate

4.4. Eye Measurement Test Results

4.5.1. ORX Output Eye

The ORX ECL output eye was measured with the oscilloscope (see 3.5.1). The measurements were done with a PRS6 pattern and a 62.5MHz square wave. Table 8 shows the test results. All measurements were made with 200 meters of fiber and at nominal bit rate of 125MBaud. The actual scope traces can be found in appendix D.

Pattern	Eye Opening	
PRS6	7.0	ns
0101	7.5	ns

Table 8 : ORX output eye width

Comparison of these results with the OTX output eye (see 4.1.3) show that the fiber and the ORX introduce only and additional 0.3ns of jitter (for the PRS6 pattern). The overall peak-to-peak jitter is therefore as small as 1ns. The limitations of the scope method for measuring eye patterns have to be considered though (see 3.5.1).

4.5.2. ORX Output Eye Opening

The ORX ECL output time domain eye opening was measured with the BER method (see 3.5.2), providing a more realistic estimate of jitter than 4.5.1. The measured data was used to extrapolate to the eye opening at 10^{-20} BER.

The test results are presented here in tabular form, for plots of the measured data see appendix E.

	Pattern	Fiber length [m]	Po,avg [dBm]	Eye opening [ns]
1	0101	200	-27	5.8
2	PRS7	200	-27	4.2
3	RL5	200	-27	4.6

Table 9 : ORX output time domain eye opening at BER = 10^{-20}

One can see that the eye opening for the PRS7 and RL5 pattern is smaller than for the regular square wave signal, due to DDJ. The worst case 3-of-6 code pattern results in 0.4ns less jitter than the pseudo-random pattern.

All the values of the eye opening are quite large (e.g. FDDI specifies worst case peak-to-peak jitter of 5.87ns at the ORX output), leaving enough margin for the clock recovery circuit.

5. Conclusions

The measurement carried out on the fiber optic link have shown that virtually error free transmission is possible with the chosen components and circuitry over distances of up to 250m.

The bandwidth-distance limit for the chosen low cost 850nm optical components with 62.5um core multimode fiber lies at about 500m for the requested bit-rate of 125MBaud.

Links of up to 500m length could be realized by using a different transmitter. An LED which delivers 3dB more optical power than the used component at the same diode current is available from Hewlett-Packard, but has not been tested.

The influence of the clock recovery on error rate performance of the link remains to be tested. This will be done as soon as the clock recovery circuit is available.

6. References

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