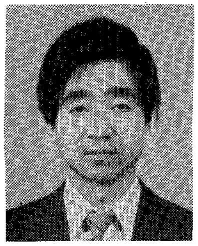

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In 1975 he joined the Ibaraki Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Ibaraki, Japan, where from 1975 to 1977 he had been engaged in research on the measurement method of refractive index profiles in optical fibers. He is presently a member of the Opto-Materials Device Section, and has been engaged in research on fabrication of single-mode fibers since 1977.

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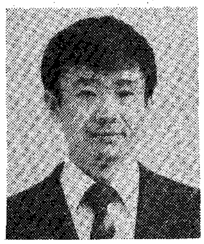

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Dr. Nagai is a member of the Japan Society of Applied Physics.

Tatsuya Kimura (S'63–M'68–SM'78), for a photograph and a biography, see p. 65 of the January 1982 issue of the JOURNAL OF QUANTUM ELECTRONICS.

Optical Digital High-Speed Transmission: General Considerations and Experimental Results

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***Abstract*—Laboratory experiments on digital optical transmission systems at bit rates of 1 and 2 Gbits/s are described. Systems with graded-index and single-mode fibers in the optical short and long wavelength region were investigated. All systems include complete circuits for clock and signal regeneration. Special emphasis was laid on the development of electronic circuits for gigabit signal processing and on the investigations of the noise sources of the optical channel, which appear especially pronounced in broad-band systems. The experimental results confirm the possibility to set up reliable high-speed optical transmission systems under laboratory conditions with available components. The remaining problems are of optical and not of electronic nature, despite the fact that monolithic integrated circuits for gigabit applications are hardly commercially available today.**

I. INTRODUCTION

EXTREMELY rapid progress has been made in the field of optical communications and microelectronics in the last years. This progress allows the engineer to develop future wideband integrated networks, which offer a wide spectrum of narrow- and broad-band services to the subscribers [1], [2].

In cooperation with the German communication industry, an extensive experimental integrated services broad-band communication network was implemented at the Heinrich Hertz Institut (HHI). It consists of optical digital and analog transmission links and applies decentralized as well as centralized switching. Numerous narrow- and broad-band services, for example, picturephone with color TV qualities, are available [3].

This experimental system contains optical links with nearly all bit rates of the European PCM-hierarchy up to 560 Mbits/s. To investigate optical transmission systems at the higher hierarchy levels of 1.12 and 2.24 Gbits/s a second research project was conducted. The aim was to gain practical experience with such systems and to study the limits of available components as well as the problems which are encountered in the implementation of optical gigabit systems. The results of the work will be illustrated in this paper.

Table I gives a survey of the three systems realized in this project. The first experiments were carried out in the short wavelength region ($\lambda = 0.85\ \mu m$) with graded-index fibers at 1.12 Gbits/s (system 1). It was learned that the graded-index fiber is not suitable for high bit rate transmission. By changing from graded-index fiber to single-mode fiber, a transmission rate of 2.24 Gbits/s was achieved (system 2).

As shown in Fig. 1 the attenuation of the fiber at 0.85 μm is about 2 dB/km and the bandwidth of the single-mode fiber is limited by a material dispersion of about 0.1 ns/km · nm. Lowest attenuation of about 0.5 and 0.2 dB/km is obtained in the long wavelength region (1.3–1.6 μm) [4]. Furthermore, material dispersion disappears at 1.3 μm; that means at this wavelength the single-mode fiber has an almost unlimited bandwidth. The wavelength of extreme bandwidth can be shifted to 1.55 μm by appropriate doping and profile shaping of the fiber core. By this means the wavelength of lowest

Manuscript received March 1, 1982; revised May 19, 1982. This work was supported by the German Bundesministerium für Forschung und Technologie.

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TABLE I
Gbit/s SYSTEMS UNDER INVESTIGATION AT THE HEINRICH HERTZ INSTITUT

parameter \ systems in HHI	1	2	3
wavelength (μm)	0,85	0,85	1,3
bitrate (Gbit/s)	1,12	2,24	1,12
fiber - type	graded-index	singlemode	singlemode
- length (km)	3	5,5	21
- attenuation (dB/km)	5	< 2,5	~ 0,7
- manufacturer	Siemens/Siecor	AEG-Tel /SEL	SEL
laser - type	CSP	CSP	BH
- manufacturer	Hitachi	Hitachi	Hitachi
- power (dBm)	6	6	0
- number of modes	1	1	4
- fiber coupling	hemisphere	taper	taper
coupling loss (dB)	3	~ 4	~ 4
transmitting signal	RZ	NRZ	RZ
photodiode	Si-APD (BPW 28)	Si-APD (BPW 28)	Ge-APD (FPD 150 M)
- manufacturer	AEG-Tel.	AEG-Tel	Fujitsu
oe-receiver	TIT	TIT	TIT
systemmargin (dB) (BER = 10^{-9})	not known	~ 3	~ 3

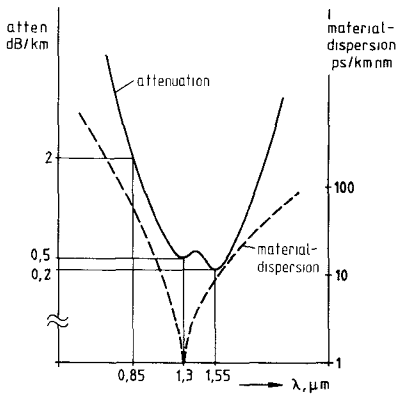

Fig. 1. Attenuation and material-dispersion of glass fibers (principle).

attenuation and the wavelength of highest bandwidth coincide [5]. Components for this wavelength were not yet commercially available. Therefore, the third system (see Table I) was set up for 1.3 μm laser wavelength.

It must be emphasized that the investigated systems were realized using commercially available optic and electronic components except for the fibers. All systems incorporate complete regeneration of the transmitted signals and clock extraction. A main subject of the project was the development of electronic subassembly groups for high-speed signal processing such as laser driver stage, optoelectronic receiver, broad-band amplifier, sampler, and clock extraction as well as multiplexers and demultiplexers. Further efforts were directed at the investigation of sources of interference of the optical channel, e.g., modal noise, optical feedback, and laser mode partition noise. High-speed systems are especially sensitive to such interferences and are therefore particularly suited for their investigation.

Table II finally gives a survey of further high-speed systems mentioned in the literature by other research teams [6]-[12]. These papers deal with laboratory systems in the optical short and long wavelength range with graded-index and single-mode fibers and transmission rates from 560 Mbits/s up to 2 Gbits/s.

II. The Optical Transmission Link

Three optical transmission systems for gigabit application have been investigated at the Heinrich Hertz Institut: system 1 with graded-index fiber in the short wavelength region; systems 2 and 3 with single-mode fibers at 0.85 and 1.3 μm, respectively. The principle underlying all systems is shown in Fig. 2.

The gigabit signals are fed to the driver circuit which modulates the laser. The lightpulses are coupled into the fiber. APD's are used as optical receivers at the fiber end. The amplifier consists of a transimpedance preamplifier and a broadband main amplifier. The amplified signals are split up into two paths, one for clock extraction, consisting of a preprocessing circuit and a PLL circuit, and the other path for signal regeneration. The main parameters of the three systems are listed in Table I.

In the first 1.12 Gbit/s system [13] a graded-index fiber of a length of 3 km was used. The wavelength was 0.85 μm. The mode dispersion of the total fiber was 0.6 ns. Bandwidth limitation by material dispersion was eliminated by using nearly monochromatic index-guided lasers [Fig. 3(a)].

Owing to its large coherence length, severe modal noise arose. Furthermore, this laser is very sensitive to optical feed-

TABLE II
Gbit/s SYSTEMS REALIZED IN DIFFERENT LABORATORIES

parameter \ system ref.	6	7	8	9	10	11	12
wavelength (μm)	0,85	0,85	1,18, 1,31	0,85	1,3	1,3	1,55
bitrate (Gbit/s)	0,56	0,8	0,8	1	1,2;1,6	2	2
fiber - type	graded-index	single - mode	single - mode	single - mode	single - mode	single - mode	single - mode
- length (km)	7,2	4,15	40	1,6	23 ; 15	44,3	51,5
- attenuation (dB/km)	5,7	3,8	0,6	6	< 1,1	0,57	0,54
- manufacturer	Siemens			AEG			
laser - type	oxid - stripe	DH	DH	DH	DH	BH	BH
- power (dBm)	4	5	1,2			2,8	2,3
- number of modes or spectral bandwidth		1	> 4	2,3 nm	5	1,5 nm	multimode
- coupling	hemisph lense	butt	cylindrical lense	butt	cylindrical lense	hemisph. μ-lense	hemisph μ - lense
- manufacturer	Siemens			AEG			
coupling loss (dB)	∽3	21,5	5,2		8 ..11	4	4,5
transmitting signal	RZ	RZ	RZ	RZ	NRZ	RZ	RZ
photodiode	APD	Si - APD	Ge - APD	Si - APD	Ge - APD	Ge - APD	Ge - APD
- manufacturer	RCA			AEG			
oe - receiver	TIT	50Ω	50Ω	50Ω	50Ω	50Ω	50Ω
systemmargin (dB)	6,2					2,9	
BER	$<10^{-9}$	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-10}
clock extraction	yes	yes	yes	yes	no , yes	no	no
company	Siemens Germany	NTT Japan	NTT Japan	AEG - Tel Germany	NTT Japan	NTT Japan	NTT Japan

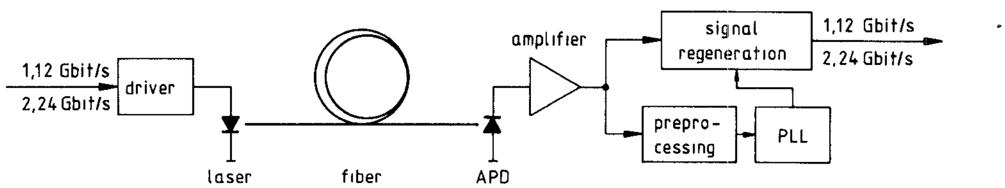

Fig. 2. General concept of the optical transmission links.

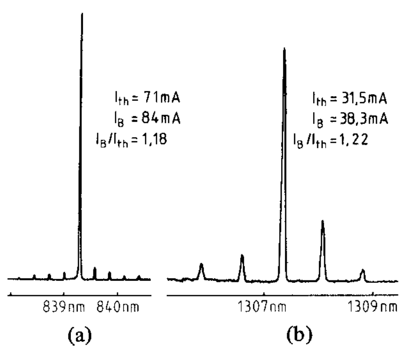

Fig. 3. Dynamic time resolved laser spectrums measured at the top of a single 1.12 Gbit/s "1." (a) CSP laser at short wavelength (systems 1, 2). (b) BH laser at long wavelength (system 3).

back. These problems are discussed in [14]. Therefore, long term stability of the bit error rate (BER) was worse than 10^{-9} [15]. To avoid modal noise and mode dispersion, single-mode fibers were chosen in systems 2 and 3. To minimize optical feedback, a taper coupler with low coupling loss was installed in both systems (see Section II-C).

The optical components and the associated problems will be described in the following sections.

A. Laser

Comprehensive tests of modulation behavior and measurements of the dynamic spectra were performed especially in the short wavelength region [16]. Dynamic single-mode operation was possible with index-guided lasers [Fig. 3(a)]. For the long wavelength region only a few lasers were available. Fig. 3(b) shows the spectrum of the BH laser used.

The lasers had to be biased beyond the threshold current to obtain a narrow laser spectrum and a sufficient modulation bandwidth. This leads to a reduced extinction ratio of the transmitted signal which creates additional noise in the optical receiver. To obtain satisfactory all-system-performance, the lasers were modulated by RZ signals. In system 1, no significant difference between RZ and NRZ modulation was observed. Due to the limited bandwidth of the laser in the 2.24 Gbit/s system, only NRZ modulation was possible. In system 3 RZ modulation led to the best results which agrees with theory and with experiments made by others [17], [18], [11]. In all systems the temperature of the laser and the fiber coupler was stabilized at 20°C. Stability was better than 0.1°C.

B. Fiber

Some parameters of the fibers are quoted in Table I. Mode dispersion for the whole length of the graded-index fiber in system 1 was about 0.6 ns. Core diameter was 62.5 μm. The single-mode fiber for the short wavelength system 2 consisted of two pieces made by different manufacturers with core diameters of 7 and 9 μm, respectively. In the long wavelength system, system 3, a difference between laser wavelength and zero-dispersion-wavelength of the fiber resulted in a residual material dispersion of about 5 ps/km · nm. The core diameter was 7 μm.

C. Coupling

The objectives of laser-fiber coupling are good efficiency and small optical feedback. Both requirements are somewhat contrary and a compromise has to be found. In system 1 the coupler consisted of a bead fused onto the face of the graded-index fiber. The coupling efficiency was about 50 percent. Because of the small core diameter, single-mode fiber coupling is more critical. In this case we chose a small taper [19] drawn easily from the fiber. This allows a coupling efficiency greater than 50 percent and produces less optical feedback [15]. In order to reduce optical feedback even further, the optimum coupling efficiency was reduced to 40 percent. Connection between fiber and APD was achieved by an epoxy adhesive. The different refractive indexes of fiber and APD result in additional optical feedback.

D. Problems

1) Modal Noise: When multimode fibers are fed with laser light, interferences between the different fiber modes occur at a fiber cross section. These interferences generate a speckle pattern. Since the speckle pattern is extremely sensitive to delay variations of the fiber modes, it is generally not stable, but heavily influenced by mechanical vibrations, temperature changes, and, of course, minor laser wavelength changes. If fiber axes are displaced or tilted in a fiber-to-fiber connection (connector, splice) the coupling efficiency depends on the speckle pattern at the intersection. Hence, every practical fiber connection exhibits a varying transmission factor subject to the external disturbances [14], [21], [22]. An undistorted eye-pattern and one distorted by modal noise are shown in Fig. 4. The latter one was generated by randomly bending the fiber between laser and APD.

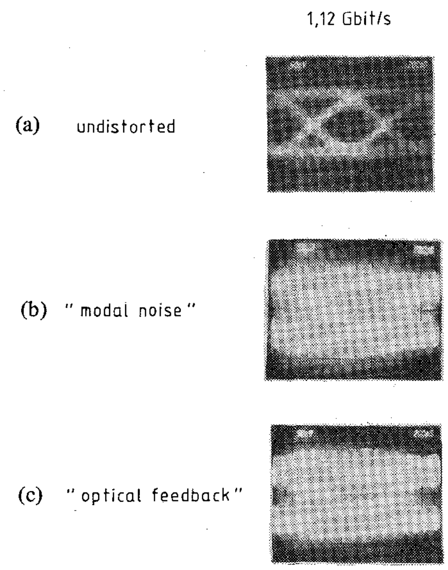

Fig. 4. Modal noise and optical feedback effects in system 1 at 1.12 Gbits/s. Fiber length of graded index fiber is 3 km.

Since we had to use a single-mode laser in system 1, the modal noise problem was especially severe. An elimination of modal noise is only possible by employing single-mode fibers. A reduction, however, can be achieved by using gain-guided lasers with a broad optical spectrum, but in this case the system bandwidth is limited due to material dispersion. This holds even in long wavelength systems where a residual material dispersion in connection with a long transmission distance occurs. Single-mode fibers are the only choice for broadband transmission systems and, therefore, we used them in systems 2 and 3.

2) Optical Feedback: The fiber front face, connectors, splices, and the fiber far end scatter light back into the source. The reflected light deteriorates laser linearity, spectral stability, and noise behavior [20], [23]-[25]. Disturbances are severe when reflections arise within the coherence length of the laser light.

Fig. 4(c) depicts the distortion in the eye-pattern of system 1 due to optical feedback. Distortion was produced by changing the laser-fiber distance. Thus, the external resonator formed by the laser and the fiber front face was changed. According to [20] this leads to mode hopping of the laser which is transformed into the time domain by the material dispersion of the fiber. Heavy phase modulation of the received PCM pattern occurs at the fiber end. Furthermore, mode hopping gives rise to additional modal noise.

Especially in system 2, we experienced the influence of optical feedback on the system performance. The fiber connector on the transmitter front panel is within the coherence length of the laser light and the reflections from the connector caused mode hops which led to system instabilities under certain operating conditions. The application of index-matching liquid reduced the feedback effect, but the best stability was obtained by replacing the connector by a fusion splice.

Reflection from the APD at the fiber far end do not influence the laser spectrum, but only the laser linearity, since the fiber length is longer than the coherence length of the laser light [20]. It is known that gain-guided lasers are less sensitive to optical feedback than index-guided lasers [26]. As mentioned before, a broad optical spectrum limits the transmission bandwidth and produces laser mode partition noise.

The only real cure for optical feedback is the insertion of an optical isolator between laser and fiber. Available devices are quite expensive and massive, but improved devices produced with a new technology will be available soon [27]. The optimum solution to the problem, however, would be a monolithic integrated laser–isolator module, since with all hybrid devices the reflections on the laser–isolator intersection remain a problem.

3) Laser Mode Partition Noise: Another source of noise which is related to the laser spectrum and the material dispersion of the fiber is laser mode partition noise.

In a multilongitudinal mode spectrum of a laser the power distribution in the different modes is not stationary. The noise components of the various spectral lines are of opposite phase so that the noise of the complete laser spectrum is reduced in comparison to the noise power in one line. The relative level of noise power in one mode is more than 20 dB higher than that in the complete laser light.

The transmission along the optical fiber disturbs the correlation, as each individual laser mode travels at a different velocity due to the material dispersion [28]. After a certain travel length, the modes are completely decorrelated and the obtainable signal-to-noise ratio is accordingly degraded.

Since the material dispersion is much lower in long wavelength systems, the fiber length at which the complete decorrelation occurs will be longer. In practical systems the laser wavelength will generally not match the zero-dispersion wavelength of the fiber so that the residual material dispersion will give rise to laser mode partition noise when multimode lasers are applied.

In our short wavelength systems (1 and 2) we used lasers which emitted mainly in one mode [Fig. 3(a)], but the residual power in the other modes generates noticeable laser mode partition noise [29]. The long wavelength lasers we used emit in several longitudinal modes and the total residual material dispersion is about 100 ps/nm so that laser mode partition noise occurred.

4) Modal Mode Partion Noise: A nonideal fiber-to-fiber connection (e.g., connector, splice) in a multimode fiber link exhibits a wavelength-dependent transmission loss [30]. Hence, the different laser modes suffer different attenuation and the above-mentioned correlation of the laser modes is disturbed and mode partition noise occurs. Since this noise occurs even in the absence of material dispersion in all systems operating with multimode lasers and fibers which suffer from modal noise, this noise was called "modal mode partition noise."

To avoid this noise, single-mode lasers in graded-index fiber systems could be used, but then heavy modal noise occurs (system 1). Hence, again single-mode fibers are the best cure for modal mode partition noise (systems 2 and 3).

5) Polarization Effects in Single-Mode Fibers: Even in single-mode fibers "modal noise" occurs [22] because there are actually two orthogonally polarized modes. These two modes cannot produce a speckle pattern, but nevertheless, they give rise to dispersion and noise [31], as their propagation constants are generally not equal due to noncircularity of the fiber core and birefringence. The polarization mode-dispersion at a wavelength of 1.2 μm for a normal single-mode fiber was measured to be about 5 ps/km [33].

To avoid the problems associated with polarization mode-dispersion, two ways are possible. One way is the application of polarization maintaining fibers [32] which exhibit low coupling coefficients between the modes. Another way is the use of fibers with a periodical mechanical stress induced birefringence which averages the two propagation constants, so the overall birefringence is small [33].

In our single-mode fiber systems we observed some influence of the polarization effects which could be noticed when squeezing the fiber.

III. Description of the Electronic Circuits

The design of electronic circuits for Gbit/s application still suffers from several shortcomings. Although there are many publications about logic integrated circuits for Gbit/s use [34] these IC's are hardly commercially available and complete logic families for Gbit/s application do not exist at all. Consequently, only a few digital integrated circuits have been installed in our transmission systems for 1.12 and 2.24 Gbits/s. For multiplexing and demultiplexing purposes at lower bit rates, IC's could be used to some extent. Most of the circuits which will be introduced below are implemented with discrete components. It must be stressed that they were all commercially available.

Before entering a detailed discussion of the electronic circuits, general aspects of our circuit concept are described. To achieve flexibility in our laboratory setup, discrete blocks of the different electronic stages were built. To simplify testing facilities, a 50 Ω technique was used throughout the whole circuit. In this way, direct connection to oscilloscopes and other measuring equipment with their standard 50 Ω input impedance was possible. High impedance probes cannot be used because they introduce strong waveform distortion. All circuits are built in microstrip technology. Except for one MESFET, only Si bipolar devices were utilized.

A. Laser Modulation

The spectral and modulation behavior of the laser is very sensitive to variations of the laser bias current. In view of the overall system performance it has to be kept constant. To achieve flexibility in our experimental setup and to eliminate the influence of dc drift of the driver-circuit in our experimental setup, the modulation signal is delivered by a coaxial cable and a capacitor to the laser (Fig. 5). Impedance matching is accomplished by a 48 Ω resistor in series with the low dynamic impedance of the laser. ac coupling causes a variation of the actual operating point of the laser due to the change of the mean value of the modulation current. To limit these variations, the signals have to be scrambled. The pseudostatistical word of $2^{15}-1$ length supplied by our error rate equipment fulfilled these requirements. For the ratio of bias current to threshold current I_B/I_{th} a compromise between spectral width and extinction ratio has to be found.

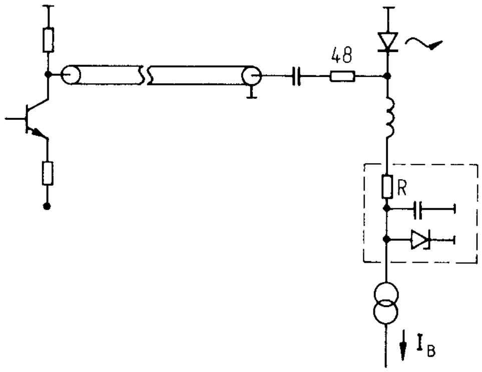

Fig. 5. Laser driving circuit.

In our case, the optimum value was found by measurement of the bit error rate. The driver circuit is shown in Fig. 5. The network drawn in dashed lines protects the laser against current spikes.

B. The Optoelectronic Receiver

The optoelectronic receiver consists of an APD and a low noise preamplifier. Fig. 6 shows the pulse response of the chosen APD's for the short- and long-wavelength region. The following two types of optoelectronic receivers exist [35]:

1) the high-impedance-type (HIT)
2) the transimpedance-type (TIT).

The TIT is advantageous for broad-band optical transmission. It shows higher dynamic range than the HIT and no additional equalizer is needed. The realized preamplifier has two stages, each with negative feedback (see Fig. 7).

Due to the total mismatching between the two stages, stray capacitances between them have no influence. Therefore, the realizable gain bandwidth product approaches the ideal limit f_T which indicates the transit frequency of the transistor [36].

The optimum bandwidth of the amplifier was calculated. Required small signal and noise equivalent circuits of the transistors were modeled after measuring S parameters. Bipolar microwave transistors NE 64480 (NEC) with a transit frequency of 12 GHz were used.

The measured and calculated gain of the preamplifier can be seen in Fig. 8. The gain is 27 dB with a 3 dB cutoff frequency of 2 GHz.

The lower cutoff frequency is 3 kHz. The insert in Fig. 8 shows the measurement procedure with the laser and APD. Here, the gain is defined as the ratio of the current in the 50 Ω load of the amplifier to the current in the 50 Ω load directly at the APD. The frequency response of the laser/APD link alone was measured and taken into account for the graph of amplifier gain in Fig. 8. Measuring was done at a light wavelength of 0.84 μm with a TJS laser (M1-2205) from Mitsubishi. The APD was a BPW 28 (AEG-Telefunken). The broad-band preamplifier was used in all systems.

Noise power calculation and measurement are reported in [37]. The absolute sensitivity for the 2.24 Gbit/s system at the short wavelength was calculated (see Fig. 9). An optical receiving level of −33 dBm was computed to obtain a 10^{-9} error rate with an optimum avalanche gain of 45.

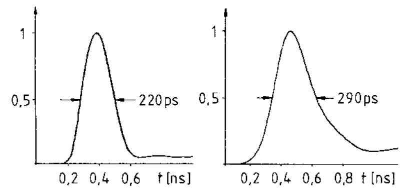

Fig. 6. Measured pulse responses of the APD's used in the transmission experiments. (a) Si APD (systems 1, 2) pulse half-maximum width of the optical input test signal 70 ps. (b) Ge APD (system 3) pulse half-maximum width of the optical input test signal 200 ps.

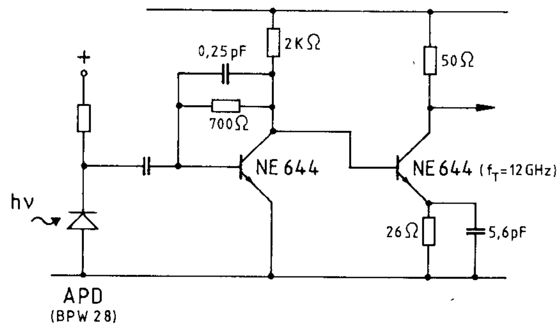

Fig. 7. Circuit of the optoelectronic receiver.

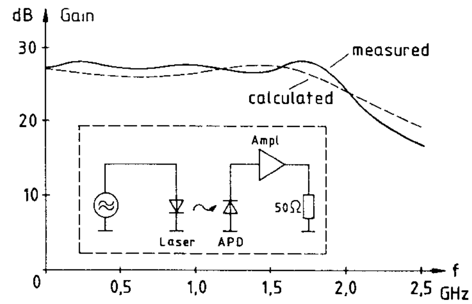

Fig. 8. Amplifier gain of the optoelectronic receiver versus frequency. Inset: measurement conditions.

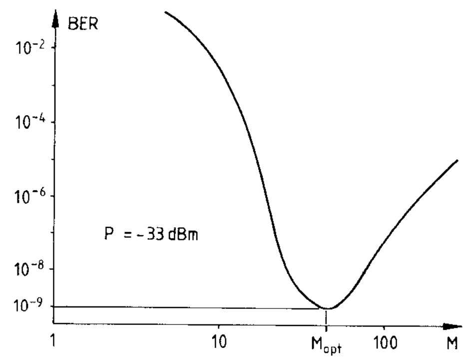

Fig. 9. Calculated bit error rate BER versus avalanche gain M at received optical power P_S of −33 dBm. Transmission rate is 2.24 Gbits/s.

C. Main Amplifier

The main amplifier consists of two stages, each with 28 dB gain (Fig. 10). In a third stage the signals are divided into two branches, one for signal regeneration and the other for clock extraction. The amplifier is built up with bipolar transistors NE 219 35 (f_T = 8 GHz). Fig. 11 presents the principal circuit

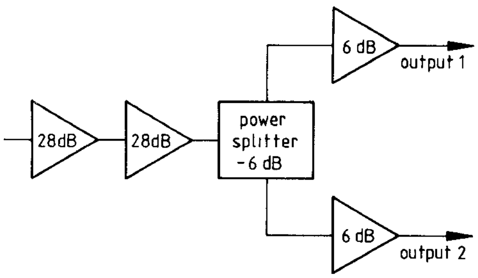

Fig. 10. Block diagram of the main amplifier.

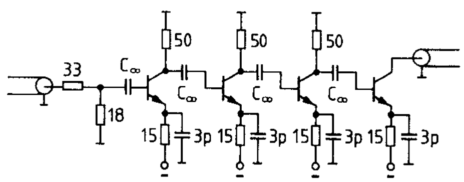

Fig. 11. Circuit of one main amplifier stage.

of the first and second unit consisting of four stages with negative current feedback.

To match the front end of the amplifier to the 50 Ω coaxial cable, a resistive network was installed. This results, on the one hand, in an attenuation of the signal and, on the other hand, in a reduction of the influence of the transistor to the input reflection coefficient. Therefore, the input reflection coefficient (S_{11}) is less than 10 percent up to 2 GHz (Fig. 12). Fig. 12 depicts the transmission coefficient (S_{21}) of the whole main amplifier. Up to 2 GHz a gain of 56 dB was measured. Maximum output voltage was 3.5 V at a 50 Ω load.

D. Clock Extraction

Clock extraction is accomplished in the following two steps (see Fig. 2): preprocessing and the PLL.

1) Preprocessing: Preprocessing for the purpose of clock extraction is indispensable when the transmitted signal has no spectral line at the bit frequency, as is the case with the NRZ signal format, or when the spectral line of the transmitted signal, e.g., at RZ format, is considerably attenuated as in bandwidth limited systems.

Thus, the aim of preprocessing, which is generally carried out by linear prefiltering and subsequent nonlinear treatment, is to perform an efficient conversion of the density spectrum of the received signal to a spectral line at the bit frequency. Beyond that, the phase of this spectral line should be constant and independent of the data pattern, and spectral components due to preprocessing within the bandwidth of the following PLL must be negligibly low.

It has been shown in [38] that, for a squaring nonlinear treatment, these conditions are fulfilled if a single prefiltered pulse is equivalent to the pulse response of an ideal symmetrical bandpass with center frequency $f_b/2$ and a bandwidth up to $f_b - B_L$, where f_b denotes the bit frequency and B_L is the noise bandwidth of the PLL.

At high bit rates, delay-line-clipping is appropriate for prefiltering, since it is simple to implement and leads to preprocessing, which fulfills the above-mentioned conditions exactly for phase, and approximately for magnitude [39]. Fig. 13 shows the preprocessing circuit developed for 1.12 Gbit/s

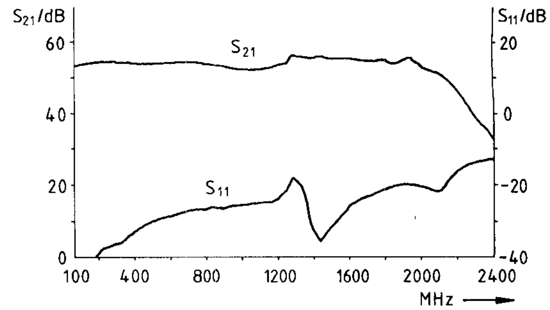

Fig. 12. Measured transmission S_{21} and input reflection coefficient S_{11} of the main amplifier.

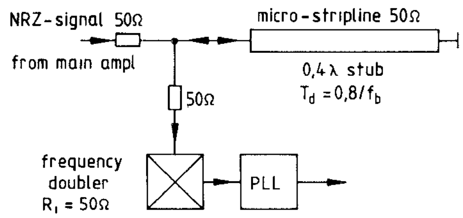

Fig. 13. Preprocessing circuit of the clock extraction in the 1.12 Gbit/s system.

systems. It is noteworthy that the delay time T_d is not $0.5/f_b$, which is the optimum value for rectangular NRZ signals, Fig. 14 shows that for bandwidth limited signal waveforms the maximum clock content is generally obtained at delay times above $0.5/f_B$ with a flat maximum.

For the 2.24 Gbit/s system the same principle has been used for preprocessing, with the variation that nonlinear treatment is carried out by a limiting and a subsequent fullwave-rectifying active stage, which avoids a large variation of the signal level.

2) PLL Design: Generally, a PLL is used to derive a clock signal of constant amplitude and adequately constant phase from the spectral line of the bit frequency contained in the received or in the preprocessed signal. The PLL can be characterized by three main parameters: the damping factor φ, the pull-in-range Δf_p, and B_L. When the repeater is to be used within a chain of repeaters, φ must be $\geqslant 2$ in order to avoid high jitter accumulation due to the resonance peak of the PLL transfer function [39]. This holds especially for the case of an unscrambled data stream since the mean transition density modifies the PLL parameters.

The selection of B_L is a compromise: it must be sufficiently low to obtain adequately low phase jitter and to avoid high-speed electronics in the active PLL filter, but it should not be too low as this would demand expensive crystal-stabilized oscillators (VCXO) and long pull-in times would occur.

For clock extraction at 1.12 GHz, a PLL has been developed with B_L = 0.48 MHz and φ = 2.7. These values are related to a data stream which is rarefied by a factor 0.5 compared to the maximum transition density. A varactor tuned voltage controlled oscillator (VCO) was used. Its main characteristics were center frequency 1.12 GHz, tuning range ±10 MHz, and temperature coefficient −100 kHz/K. A double balanced mixer was utilized as phase meter.

Applying a LAG-filter, this PLL had a pull-in range of about

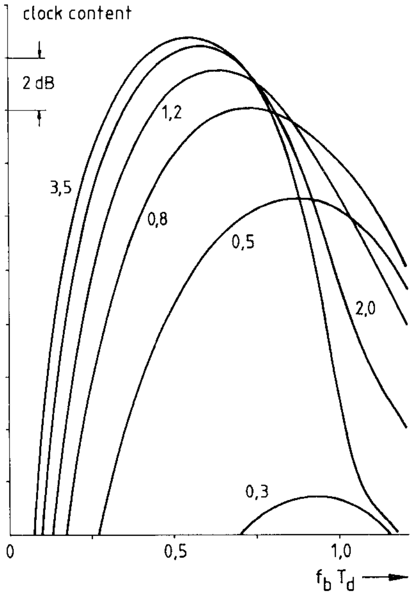

Fig. 14. Relative clock content versus delay time for various ratios of the 3 dB system bandwidth f_{bw} to bit frequency f_b.

1 MHz, which would be further reduced at more rarefied data streams. Considering the above-mentioned temperature coefficient, it is obvious that the VCO must be temperature stabilized. Another possibility is the use of a PI-filter and of an additional aquisition aid by a frequency sensitive loop. At lower bit rates, integrated phase meters with additional frequency sensitivity are available for this purpose. For the Gbit range, a circuit has been developed [40] with a second phase meter which is fed via a delay line of 90°. During the unlocked PLL condition, the output voltage (beat note) of this phase meter is sampled at the instant at which the output voltage of the other phase meter crosses zero with positive slope. By averaging these samples, a voltage is obtained that is proportional to the frequency difference between VCO and bit frequency and that can be used for frequency control. By this the effective pull-in range of the PLL becomes equal to the tuning range of the VCO. Additionally, the use of a PI-filter leads to lower systematic jitter since the phase control has, theoretically, no residual error.

Fig. 15 shows the implementation of a PLL with aquisition aid for 2.24 GHz. In this case, the beat notes have been limited by comparators. The sampling process can be carried out by simple TTL circuits because the maximum processing frequency is given by the tuning range of the VCO.

Measurements of the jitter of the regenerated clock signal show rms values of about 3°. Laser modulation effects have been determined as the predominant jitter source. In the case of mode hopping, considerable phase hops occur which may cause the unlock of the PLL.

E. Signal Regeneration for 2.24 and 1.12 Gbits/s

The electrical signals leaving the APD are distorted due to the impairments of the optical transmission link. They are affected by dispersion, phase jitter, and noise. As the laser, APD, and amplifiers are ac-coupled, baseline wander occurs. In our first 1.12 Gbit/s system we have shown that baseline restoration can be achieved by simple means of quantized feedback equalization. This circuit shall not be considered here. For details, refer to [41]. After reamplification the signals enter the regeneration circuit where amplitude restoration and retiming is performed. Depending on the desired pulse format RZ or NRZ this is done in two or four steps, respectively.

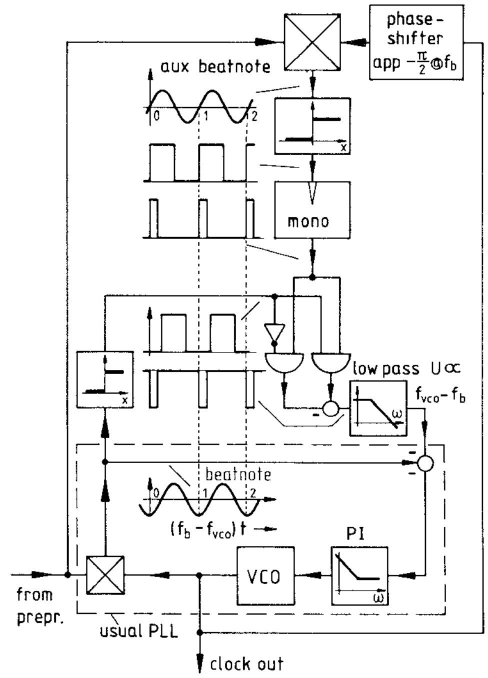

Fig. 15. Block diagram of the 2.24 GHz PLL.

1) Slicer Circuit: Up to 1.12 Gbit/s differential amplifiers have been used successfully as amplitude-comparators [41]. Unfortunately, the slope of the transfer characteristic of the differential amplifier declines with increasing bit rate. For the 2.24 Gbits/s a simple slicer with one transistor was installed (T_1 in Fig. 16). It is a p-n-p transistor which matches the following retiming stage. The bias condition was chosen so that only the lower part of the pulse switches the transistor on. At the inverter output a pulse with a flat "1" line appears. The "0" line is not affected.

2) Retiming Circuit: A single field effect transistor (T_2 in Fig. 16) acts as sampler. When data signals "1" from the slicer and the clock-signal are applied to source and gate response the transistor is switched on. An RZ signal is generated at the output of the transistor. When the data signal is "0" the transistor is not conducting. Depending on the sampling requirements, an output pulse halfwidth of 100 ps can be achieved [42].

3) Changing of Pulse Format: It was shown in Section II that the modulation behavior of the laser and the performance of the various systems depend on the pulse format RZ or NRZ. When NRZ signals are needed, another stage must be introduced which changes the regenerated RZ pulses to an NRZ format. Different circuits for 1.12 Gbits/s are described in [43], [44].

The signal format change at 2.24 Gbits/s is done by the remaining stages of Fig. 16. The regenerated RZ signal is fed

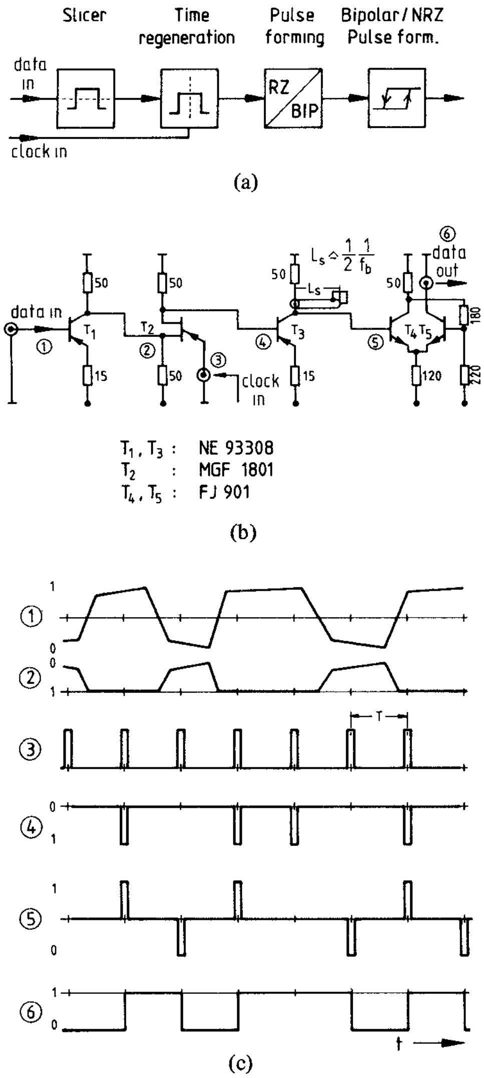

Fig. 16. Regeneration circuit for 2.24 Gbits/s. (a) Block diagram. (b) Circuit. (c) Signal scheme.

to transistor T_3 whose collector is connected to a short-circuited coaxial cable of length L_S. The pulses are reflected at the end of the cable with opposite polarity and are added to the subsequent RZ signals leaving the collector. The roundtrip travel time of the cable is one bit period. A bipolar signal is generated with a positive going pulse at the beginning of a "1" and a negative going pulse at the end of a "1" or at the end of a series of "1." The positive going pulse sets the Schmitt-trigger (T_4, T_5) and the negative going resets it. A NRZ signal is generated.

F. High-Speed Multiplexing and Demultiplexing 0.28 and 2.25 Gbits/s

To demonstrate the capabilities of the three systems 16 and 32 digitized TV channels have been transmitted over the optical links [45]-[47]. Each channel consisted of 70 Mbit/s signals and four were joined to 280 Mbit/s data streams. Multiplexer and demultiplexer circuits operating between 280 Mbits/s and higher levels will be described here. In the multiplexer four 280 Mbit/s signals are combined to a 1.12 Gbit/s signal [Fig. 17(a) and (b)] and the two resulting 1.12 Gbit/s signals then to one 2.24 Gbit/s signal. Demultiplexing is done in the inverse sequence.

1) Multiplexer From 280 Mbits/s to 1.12 Gbit/s: Multiplexing is accomplished in 2 steps (see Fig. 18). By means of integrated circuits two 560 Mbit/s signals are generated. These are combined to a 1.12 Gbit/s signal in the second stage where discrete bipolar transistors in ECL technology were used. The multiplexer does not contain any frequency selective components and therefore offers broad-band capabilities from dc to 1.3 GHz.

2) Multiplexer 1.12–2.24 Gbits/s: Several multiplexers for Gbit/s application are known from the literature. Active switching devices described are step recovery diodes [48], MESFET's [49], or bipolar transistors [50]. Our multiplexer was designed with bipolar transistors which worked properly at bit rates of 1 and 2 Gbits/s. The circuit described here concentrates two 1.12 Gbit/s signals to one 2.24 Gbit/s signal. It consists of two samplers: a summing amplifier; and a limiting amplifier (see Fig. 19). The sampler circuit is shown in Fig. 20. When the data signal is high, transistor T_2 is switched off and the clock signal will switch T_3. An RZ signal appears at the circuit output. When the data signal is low the emitter potential rises and T_3 is turned off. The clock signal then cannot be put through. Furthermore, transistors T_3 and T_4 limit the clock amplitude and signals with rectangular shape are generated as seen in Fig. 21(a). The eye diagram of the 2.24 Gbit/s NRZ signal after the summing amplifier and the following limiter stage is shown in Fig. 21(b). Rise and fall times are 150 ps.

3) Demultiplexing 2.24–1.12 Gbits/s to 0.28 Gbits/s: The first demultiplexing stage from 2.24 to 1.12 Gbits/s is similar to the regenerative circuit described above (Fig. 16). The length of the short circuited coaxial cable at T_3 is in this case equivalent to a round travel time of 1.12 ns. The second stage consists of four IC D-flip-flops which are driven by the 1.12 Gbit/s signals; each input signal is delayed by one 1.12 Gbit/s period. The clock signal is 280 MHz. The block diagram is shown in Fig. 22.

IV. System Performance

Our test setup for error-rate measurements (a Tautron SRX/STX 1001) delivered 1.12 Gbit/s NRZ signals with a word length of $2^{15} - 1$. In the case of the 2.24 Gbit/s transmission experiment, two 1.12 Gbit/s signals were generated by branching and delaying one branch by 17 bits. The two 1.12 Gbit/s streams were multiplexed to 2.24 Gbit/s (see Section III-F) and transmitted over the optical link. After regeneration in the receiver they were demultiplexed to two 1.12 Gbit/s signals (Fig. 23). For error rate measurements one 1.12 Gbit/s channel was used.

Lowest stability was achieved in the short wavelength system 1. Using a graded-index fiber of 3 km length and total attenuation of 15 dB, only a short term bit error rate of 10^{-9} was measured due to the severe modal noise effects. We have learned from our investigations that mainly due to modal noise, the graded-index fiber cannot be recommended for high bit rate optical transmission. For that reason in system 2 a single-mode fiber was used. The fiber of 5.5 km length

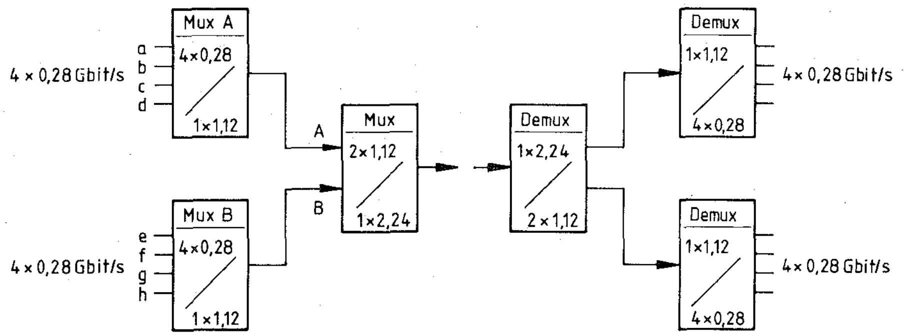

Fig. 17. Multiplexing and demultiplexing scheme 0.28 to 1.12 to 2.24 Gbits/s and 2.24 to 1.12 to 0.28 Gbits/s, all hierarchy level figures in Gbits/s.

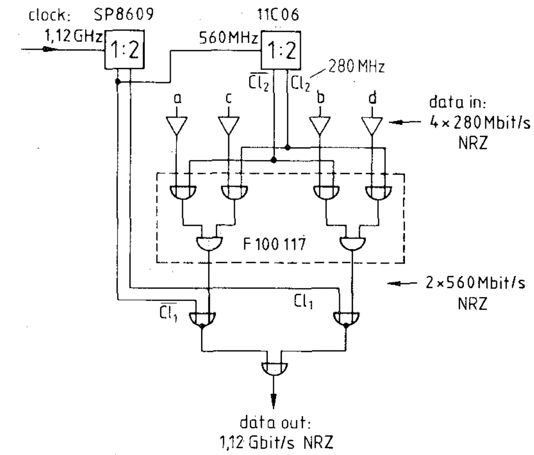

Fig. 18. Block diagram of the multiplexer 0.28–1.12 Gbits/s.

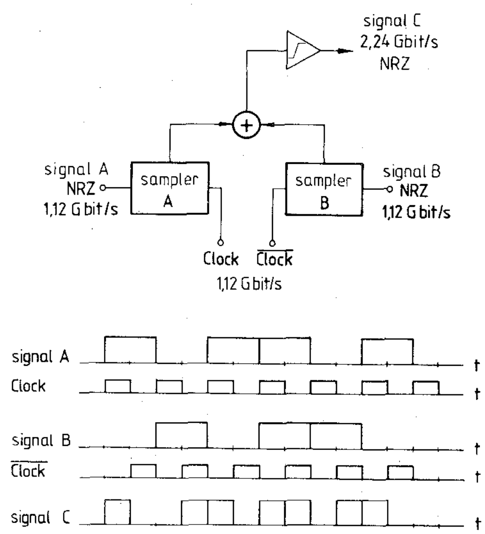

Fig. 19. Block diagram of the multiplexer 1.12–2.24 Gbits/s.

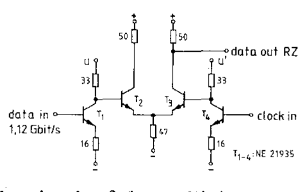

Fig. 20. Sampler circuit of the multiplexer 1.12–2.24 Gbits/s.

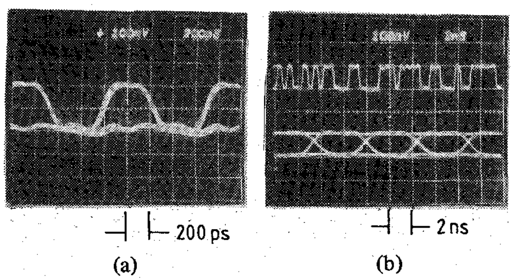

Fig. 21. Eye-patterns of the signal processing in the multiplexer 1.12–2.24 Gbits/s. (a) Sampler output (see Fig. 20). (b) Multiplexer output.

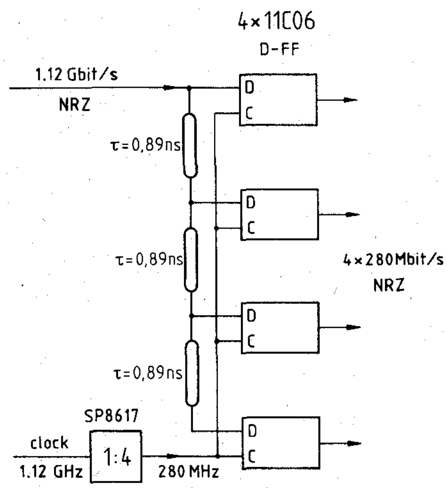

Fig. 22. Block diagram of the demultiplexer 1.12–0.28 Gbits/s.

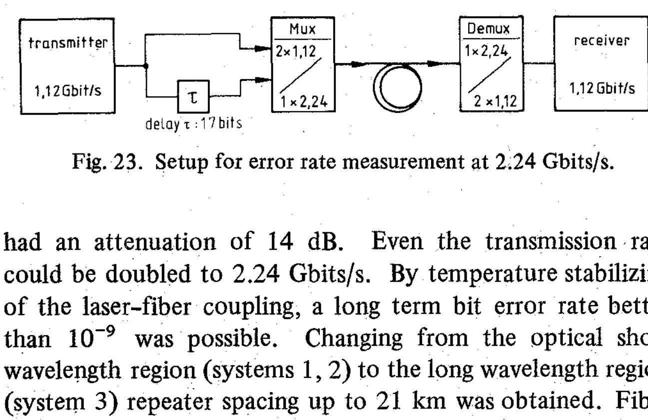

Fig. 23. Setup for error rate measurement at 2.24 Gbits/s.

had an attenuation of 14 dB. Even the transmission rate could be doubled to 2.24 Gbits/s. By temperature stabilizing of the laser–fiber coupling, a long term bit error rate better than 10^{-9} was possible. Changing from the optical short wavelength region (systems 1, 2) to the long wavelength region (system 3) repeater spacing up to 21 km was obtained. Fiber attenuation was about 15 dB. Compared to the systems 1 and 2, best stability was achieved in system 3. The bit error rate was insensitive to variations of the distance between laser and fiber when changed for several μm. There are two reasons. First, the laser emitted several spectral lines [see Fig. 3(b)] and the material dispersion of the fiber was low (about 5 ps/km · nm) compared to the fibers used at short wavelength. Second, due to the broad laser spectrum, optical feedback and polarization noise in the fiber was reduced. Because of the low material dispersion mode hops which were evoked by modulation and/or optical feedback led to less phase jitter at the far end of the transmission links. In Fig. 24 eye-patterns of systems 2 and 3 are shown.

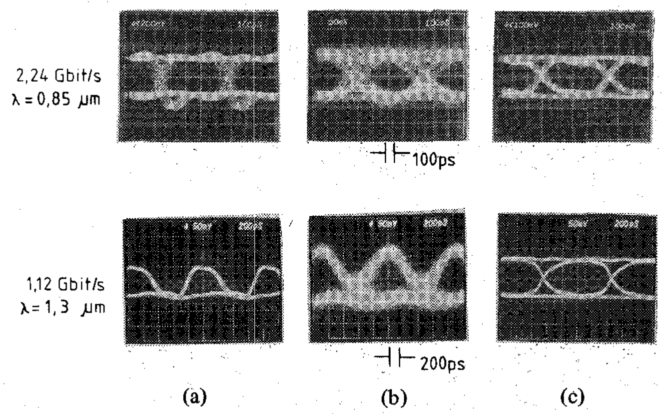

Fig. 24. Eye-patterns, measured in systems 2 and 3 at 1.12 and 2.24 Gbits/s. (a) Input to the laser. (b) Output of the receiver amplifier. (c) Regenerated signals.

V. Conclusion

For future digital broad-band communication systems, optical high-speed transmission links are of great interest. In this paper transmission experiments at 1.12 and 2.24 Gbits/s were reported. Graded-index fibers at the short wavelength and single-mode fibers at the short and long wavelength region were used.

For the practical application of optical broad-band transmission systems to future communication networks, long wavelength single-mode polarization maintaining fibers, stable single-mode lasers, and optical isolators should be used. Such an arrangement eliminates the discussed sources of interferences and allows us to make reliable use of the capacity of optical transmission.

1) The long wavelength single-mode polarization maintaining fiber exhibits lowest attenuation, broadest bandwidth, and cancels interferences like modal noise, modal mode partition noise, and polarization related effects.

2) The single-mode laser, in connection with an optical isolator, avoids laser mode partition noise, bandwidth limitations due to a residual material dispersion of the fiber, and distortions by optical feedback.

Polarization maintaining or low birefringent single-mode fibers and suitable optical isolators were not at hand for our experiments, monochromatic lasers only for the short wavelength region. Instead of the isolator, a taper coupler between laser and single-mode fiber was utilized. This coupler allowed us to reduce optical feedback while maintaining a sufficient coupling efficiency. With the laboratory systems, an appropriate long term stable bit error rate could be achieved especially after changing to 1.3 μm transmission wavelength where the material dispersion related effects are reduced and the attenuation is much lower.

The remaining problems in our high-speed optical transmission systems are caused by optical and not electronic components. The impressive laboratory experiments conducted by NTT in Japan, where 2 Gbits/s have been transmitted over 44 km ($\lambda = 1.3$ μm) and 52 km ($\lambda = 1.55$ μm) fiber [11], [12], demonstrate that these problems may be solved satisfactorily.

Electronic signal processing in the 1 and 2 Gbit/s region is possible with available discrete bipolar transistors and MESFET's. For practical and economic applications of such systems, however, the development of high-speed monolithic integrated circuits at reasonable prices is mandatory.

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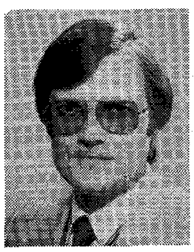
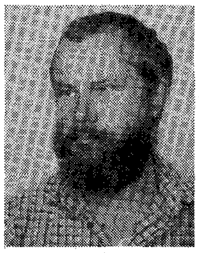
Clemens Baack was born in Meschede, Germany, on May 3, 1937. He received the B.S. degree in electrical engineering from the Rheinische Ingenieurschule Bingen in 1959, the M.S. degree in communication engineering, and the Ph.D. degree in phased array antennas theory from the Technische Universität Berlin, Berlin, Germany, in 1967 and 1974, respectively.

From 1968 to 1970 he was with the Hahn-Meitner-Institut for Nuclear Research, Berlin, Germany, where he was engaged in the development of electronic circuits. From 1970 to 1974 he was a Research Associate at the Institute for Electronic Engineering, Technische Universitat Berlin. From 1974 to 1975 he was with the Forschungsinstitut für Funk und Mathematik, Wachtberg-Werthoven, Germany, where he worked in the field of phased array radar systems. In 1975 he joined the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, where he headed a group which was engaged in broad-band transmission techniques. In 1980 he became head of the Transmission Switching Department, Heinrich Hertz Institut. For several years he has lectured in the field of optical broad-band communications at the Technische Universität Berlin. In May 1982 he was appointed to Professor for wideband communications at the Technische Universität Berlin and nominated as Scientific Director of the Heinrich Hertz Institut.



Gerhard Elze was born in Berlin, Germany, on May 19, 1948. He received the diploma degree in physics from the Technische Universität Berlin, Berlin, Germany, in 1975.

Since 1972 he has been working in the field of fiber optics and optical wideband transmission. In 1975 he joined the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, where he is presently Section Head for optical transmission systems.



Bernhard Enning was born in Ahaus, Germany, on February 10, 1947. He graduated from the Technische Universität Berlin, Berlin, Germany, in 1975.

In 1975 he joined the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, and is presently working in the field of broad-band optical communications.

Günter Heydt was born in Berlin, Germany, on January 8, 1933. He received the Ing. degree from the Staatliche Ingenieurschule Gauß Berlin, Berlin, Germany.

In 1956 he joined the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, where he worked in the fields of remote sensing, electronic aids for the handicapped, optical broad-band transmission, and broad-band switching. Presently, he is Section Head for digital broad-band switching.

Lutz Ihlenburg was born in Graudenz, Westpreußen, Germany, on October 16, 1943. He received the Dipl.-Ing. degree in electrical engineering from the Technische Universität Berlin, Berlin, Germany, in 1978.

From 1971 to 1976 he was a Research Associate at the Technische Universität Berlin, where he worked on control theory. From 1976 to 1977 he was with Project Elektronik, Berlin, Germany, where he was engaged in electronic circuit design. Since 1977 he has been with the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, where he has been active in various fields.

Godehard Walf was born in Berlin, Germany, on December 2, 1947. He received the Dipl.-Ing. degree in electrical engineering from the Technische Universität Berlin, Berlin, Germany, in 1975.

Since joining the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, in 1976, he has worked in the field of broad-band optical communications.

Gerhard Wenke was born in Melle, Germany, on July 2, 1949. He received the diploma degree in physics from the Technische Universität Berlin, Berlin, Germany, in 1978.

At the Technische Universität he was engaged in work on laser physics and optics. In 1979 he joined the Physikalisch-Technische-Bundesanstalt, Berlin, Germany, where he worked in plasma spectroscopie. He joined the Heinrich Hertz Institut für Nachrichtentechnik, Berlin, Germany, in 1980 and is presently working in the field of optical broad-band transmission systems.