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Elements of Light-Wave Communications over Fiberguides

By S.C. Kitsopoulos

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The state of the art of solid-state light sources, photodetectors, and fiberguides is reviewed with emphasis on how they fit together for light-wave communications over fiberguides. A few recent applications as well as future possibilities are briefly mentioned. The study starts with a short historical introduction and ends with a bibliography of recent articles in the field.

Der gegenwärtige Stand von Halbleiterlichtquellen, Photodetektoren und Glasfaser-Wellenleitern wird beschrieben, unter besonderer Berücksichtigung ihrer Zusammenfügung zu Lichtübertragungssystemen. Einige neuere Anwendungen sowie Zukunftsmöglichkeiten werden kurz erwähnt. Die Arbeit enthält eine kurze geschichtliche Einführung und eine Liste von Veröffentlichungen aus den letzten Jahren.

On décrit l'état actuel du développement des sources de lumière et des photodétecteurs en semiconducteurs ainsi que des guides d'ondes optiques en fibres de verre, en considérant en particulier la mise au point de systèmes de transmission optique à partir de ces elements. Quelques applications présentes et des possibilités futures sont mentionnées. On inclut une courte introduction historique et une liste de publications récentes.

1. Introduction

In his very first attempts to communicate instantaneously at a distance, man used light as the transmission medium; he 'modulated' fire, smoke or the position of his hands at the 'transmitter' and used his own eyes as the 'receiver'. For millenia before the dawn of the technological era, he used optical communication for long-haul and sound (drums etc.) for short-haul transmission. It is worth noting that these primitive communication systems were digital.

Pioneering experiments to transmit speech by modulating the intensity of a light beam were conducted successfully by none other than the father of telephony, *Alexander Graham Bell* himself. Bell received a patent in 1880 for his 'photophone', even before Hertz had published his fundamental work on electromagnetic waves and well before Marconi's experimental success with radio waves [1...3][1]. These attempts have been repeated and refined over the years as better light sources and light detectors became available.

However, wire transmission and radio have up to now totally dominated the field of communications because, unlike light beams, they are not impeded by snow or fog and can carry signals around corners. The development of the laser and the recent advent of low-loss light guides in the form of glass fibers – 'fiberguides' is the preferred term – is now bringing us back full circle to digital light-wave communications. A good historical introduction is contained in [4] which is an excellent, comprehensive treatise on the subject of fiberguide transmission and also includes an exhaustive bibliography.

In telephony, light-wave communication over fiberguides offers tremendous advantages over electrical transmission on metallic cables. Fiberguides are made of silica, one of the most abundant and most easily mined materials on earth. Their size and weight are orders of magnitude less than those of copper cables. Their information carrying capacity far surpasses anything copper can offer at the same cost. They practically eliminate the effects of cross-talk and they totally eliminate the effects of lightning and electromagnetic interference. This latter property is likely to translate into very substantial cost savings at the point where electronic switching offices interface with the present metallic telephone subscriber loops when the time will come to meet this need with fiberguides. Traditionalists are sure to ask at this point how power will be transmitted to the telephone sets to insure their operation when commercial power fails. Adventurous minds have speculated that even this could be done over the fiberguide. One more realistic possibility may be that when we will 'go back' to light communication, the time will have come to also go back to local battery for telephones, or copper could still be used just for powering.

The essential elements of a fiberguide transmission system are shown schematically in the block diagram of Fig. 1. The signal s_i to be transmitted is assumed to be in electrical form, either analog or digital. This signal is first coded or modulated in one of various ways (e. g. FM, PPM, PCM, etc.)[2]. The electrical output of the corresponding box modulates the intensity of light generated by the Light Emitting Diode (LED) or laser. This light is then coupled as efficiently as possible into the fiberguide. There is always a finite coupling loss l_t at this point. Often there is a feedback path from the light source to the electrical modulator which serves either to stabilize the laser output or to counteract certain nonlinear properties of the LED. Lasers, being threshold devices, are used for digital systems; LEDs are easier to modulate and are used for both digital and analog transmission.

The fiberguide transmission medium itself may extend over a few meters or over hundreds or even thousands of kilometers and presents a loss of l_f per unit length. It may include one or more splices, each of which has some finite loss l_s. It may also be outfitted with repeaters at regular intervals when the distance to be bridged so requires. Such repeaters restore the light signal to the original form it had when it left the transmitter but not without adding some impairments of their own: mostly noise in analog transmission, mainly time jitter and errors in digital transmission. Repeaters consist essentially of a receiver driving directly a transmitter contained in the same enclosure.

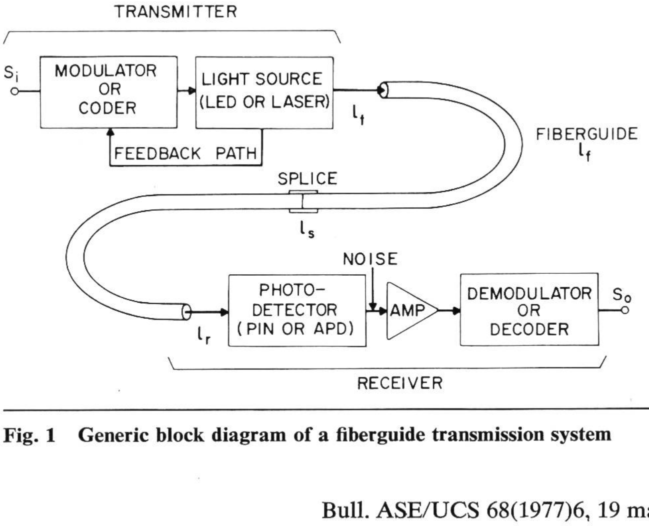

Fig. 1 Generic block diagram of a fiberguide transmission system

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[1] See the bibliography at the end of the paper.

[2] FM = Frequency Modulation;
PPM = Pulse-Position Modulation; PCM = Pulse Code Modulation.

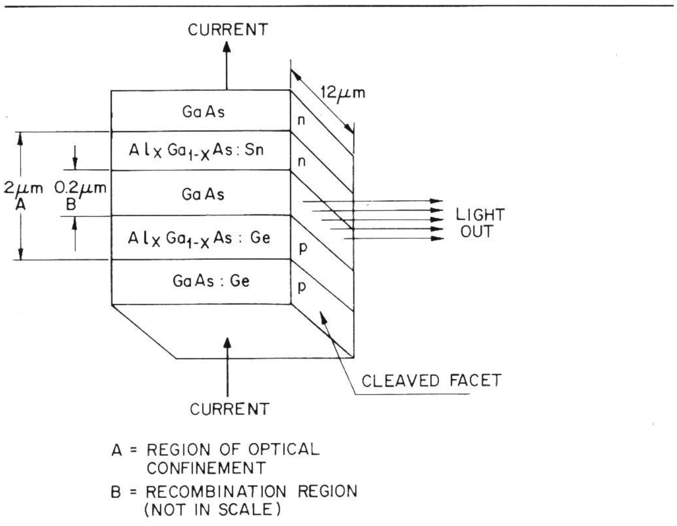

Fig. 2 Schematic diagram of an AlGaAs double-heterostructure laser

At the receiving end, a photodetector (usually either a PIN or an avalanche photodiode) transforms the impinging light signal into an electric current, again with a coupling loss l_r. The current is amplified and then demodulated or decoded to reconstruct the output signal s_0 which should reproduce, within certain fidelity criteria, the original signal s_i.

The subsequent four sections are devoted to the description of transmitters, fiberguides, receivers and system applications, respectively. Transmitter and receiver sections are restricted to solid-state devices. Developments of new elements for fiberguide communication systems as well as their future applications and impact are summarized in the final section.

2. The Transmitter

Whatever the device used as the light source and whatever modulation or coding method is adopted, the fundamental concern at the transmitter is how to inject the maximum possible average light-signal power into the fiberguide, consistent with acceptable electrical power dissipation, modulation bandwidth and signal impairments.

Maximum light power coupling as well as maximum bandwidth is achieved when a coherent light source or single-mode laser is injecting into a matching single-mode fiber. However, the nonlinear effects of stimulated *Raman* and stimulated *Brillouin* scattering, always present in the fiberguide material, impose limits to this power; if a power threshold is exceeded, the wavelength will be shifted and other undesirable effects will occur. 'Matching' the light source to the fiberguide means a number of things that may also depend upon whether the transmission is digital or analog and other system aspects. For example, there is the question of matching the source wavelength to that at which the fiberguide exhibits minimum attenuation or minimum dispersion; this wavelength may in turn not be the one at which the source has its maximum quantum efficiency; or a practical source geometry may not yield maximum coupling to the fiberguide; or again high quantum efficiency may be incompatible with the required emission response time as determined by the required system bit rate.

Light sources, both laser and LEDs, that have been highly developed and are presently in use, are based on double heterostructures of the ternary alloy system $Al_xGa_{1-x}As$. By choosing the appropriate value of the stoichiometric variable x, these structures can be made to emit at between 0.75 and 0.9 μm, which happens to be a region of low fiber loss and dispersion.

An $Al_xGa_{1-x}As$ double-heterostructure injection laser [5] consists of layers of this material, grown by the process of liquid-phase epitaxy, and appropriately doped to obtain the desired conductivity type as shown in Fig. 2. For efficient operation, the minority carriers as well as the radiation must be confined within the optical *Fabry-Pérot* cavity defined by the cleaved facets of the structure in the recombination region. The potential barrier due to the band-gap difference between the materials that form the heterojunction effects the carrier confinement, while radiation confinement is achieved by the discontinuity in refractive index. Continuous wave operation at room temperature has been achieved with threshold current densities of 500 A/cm². At this value, the cavity cross-section of Fig. 2 can produce 10 mW of output power on one side. A typical curve of radiated power output from one facet versus diode current is shown in Fig. 3. A fundamental advantage of the laser over LEDs is the relatively small beam width of the laser which allows efficient coupling into the fiberguide. For example, at least half the power emitted from one facet of the laser in Fig. 2 can be coupled into a multimode step-index fiber with a numerical aperture[3] of 0.14 and a core diameter of 80 μm [6]. Thus, the coupling loss would be $l_t = 3$ dB. As mentioned earlier, the quasi-monochromatic, single-mode laser (spectral width can vary from 0.15 to 30 Å) is capable of providing the highest bandwidth in conjunction with single-mode fibers. Thus, bit rates of 300 Mbit/s have been achieved in experimental digital communications systems, while operation into the Gbit/s range is theoretically possible. Lasers, being threshold devices, are used in the pulsed mode for digital communications. The highest bit rate is achieved with the device dc biased just below threshold. In order to improve the long-term stability of injection lasers, the light emerging from the cleaved facet opposite the one coupling into the fiberguide is measured with a local photodetector and used in a feedback system to adjust the dc bias current so as to counteract variations in light output. Laser lifetimes in excess of 20000 hours and approaching 100000 hours have been reported.

High-radiance LEDs are made of the same fundamental double heterostructure. Although edge-emitters have been

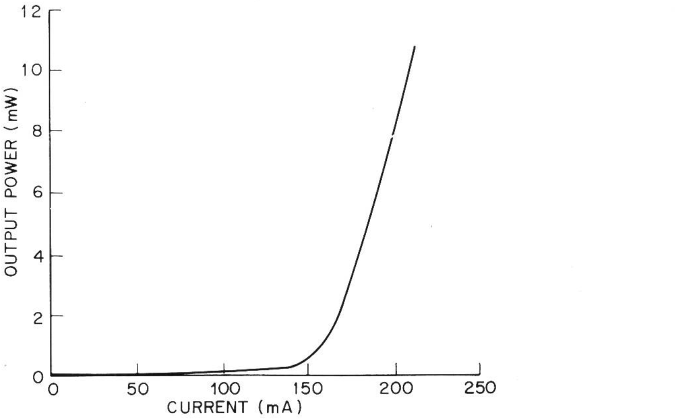

Fig. 3 Typical curve of radiated power of an AlGaAs double-heterostructure laser as a function of current

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[3] Defined in Section 3.

used to improve the directionality of the emitted light, most LEDs are of the *Burrus* type; the latter have a well etched on one face of the substrate into which the fiber end is affixed with a clear epoxy as shown in Fig. 4. Because the radiation is omnidirectional, only a relatively small portion of the available power is coupled into the fiber; the coupling loss l_t into a multimode 80 μm diameter step-index fiber with a numerical aperture of 0.14 is 17 to 20 dB. The spectral width of the LED is quite large (300 to 600 Å at room temperature) compared to that of the laser and, therefore, LEDs are used only with multimode fibers of as large a numerical aperture as possible. Practical LEDs would, for example, couple about 0.1 mW of light power into the previously mentioned fiberguide. If parasitic circuit elements are neglected, the highest frequency of operation of an LED is obtained when the lifetime τ of the injected carriers in the recombination region is as small as possible. However, reducing τ by using high doping levels also reduces the internal quantum efficiency. Typical practical bandwidths (3 dB point) range to about 100 MHz, while the maximum reported is about 500 MHz [7]. The light intensity of an LED is easily modulated by the current through it, since the corresponding characteristic is quasi-linear over a substantial range even at low currents, unlike the abrupt characteristic of lasers. However, for most analog applications the linearity is not sufficient to keep distortion and intermodulation products within the required low range. An ingenious recent scheme which dramatically improves this linearity makes use of a local photodiode in a feedback loop as shown in Fig. 5 [8]. LED lifetimes are reaching the 1000000-hour mark.

3. The Fiberguide

Optical communication did not come to its own until hair-thin glass fibers with low attenuation and dispersion were developed. *Kao* and *Hockman* [9] were first to suggest that glass fibers might become usable in long-distance communications. This happened at a time when the best optical glasses had attenuations of several thousand dB/km. In 1970, attenuations of 20 dB/km were reported [28]. By 1974, glass fibers with attenuations as low as 2 dB/km were announced [10; 11]. The lowest attenuation value yet observed is 0.5 dB/km at 1.2 μm [12].

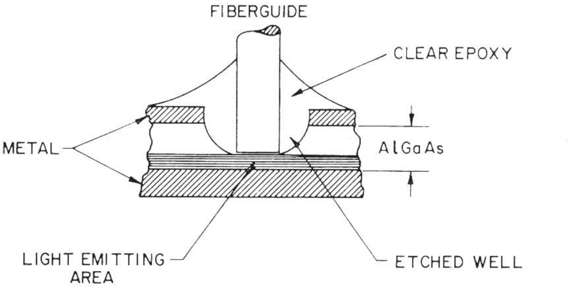

Fig. 4 A Burrus-type LED

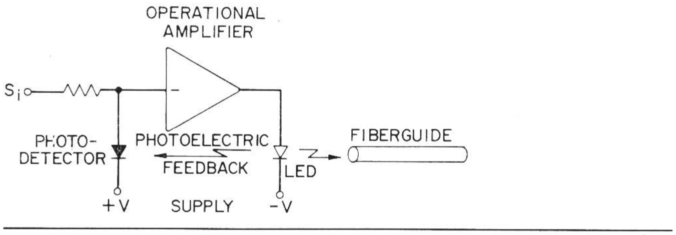

Fig. 5 Schematic of LED transmitter circuit with photoelectric feedback

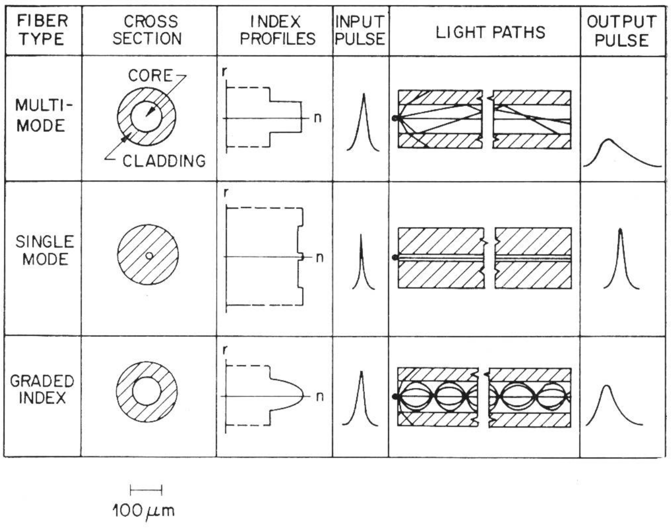

Fig. 6 Types of fiberguides [13]

The basic structure of a fiberguide consists of a thin cylindrical glass core surrounded by a glass cladding of slightly lower (1 to 2%) index of refraction. The light wave propagates by internal reflection or refraction at the core/cladding interface. For such a step-index fiber of large core diameter (e.g. > 10 μm), a large number of modes propagate, each at a different angle of internal reflection, resulting in different times of arrival of the wavefront at the other end of the guide. This mechanism of dispersion causes multimode fibers to spread the pulses carrying the signal information by an amount of time proportional to the fiberguide length. One way to minimize this dispersion is to make the core diameter very small (e.g. ≈ 5 μm) and also to minimize the index difference between core and cladding; both steps are difficult to control but feasible. This then results in a single-mode fiber, the type that offers the highest bandwidth when used with a coherent monochromatic source. A more ingenious way to combat dispersion is to increase gradually the refractive index of the core in the radial direction so as to force rays traveling away from the axis to pass through progressively lower index material which results in higher propagation velocity. For a parabolic index profile (with maximum on the axis) the rays periodically converge and the dispersion is radically reduced. This graded-index fiberguide appears at the present time to offer the most overall advantages. These three types of fiber profiles – multimode, single-mode and graded index – are shown in Fig. 6 with typical dimensions, light paths and transmission pulse shapes [13].

Low-loss glass materials were developed mostly through empirical research, aided by the availability of techniques for obtaining extremely pure materials for the semiconductor industry and by the recognition that important applications in telecommunications were at hand. Glass fibers consist fundamentally of silica, one of the most abundant and inexpensive materials on earth. There are two families of glasses that have been used: multicomponent glasses containing a number of transition element oxides and fused silica glasses doped with boron or germania to change their refractive index. Once the

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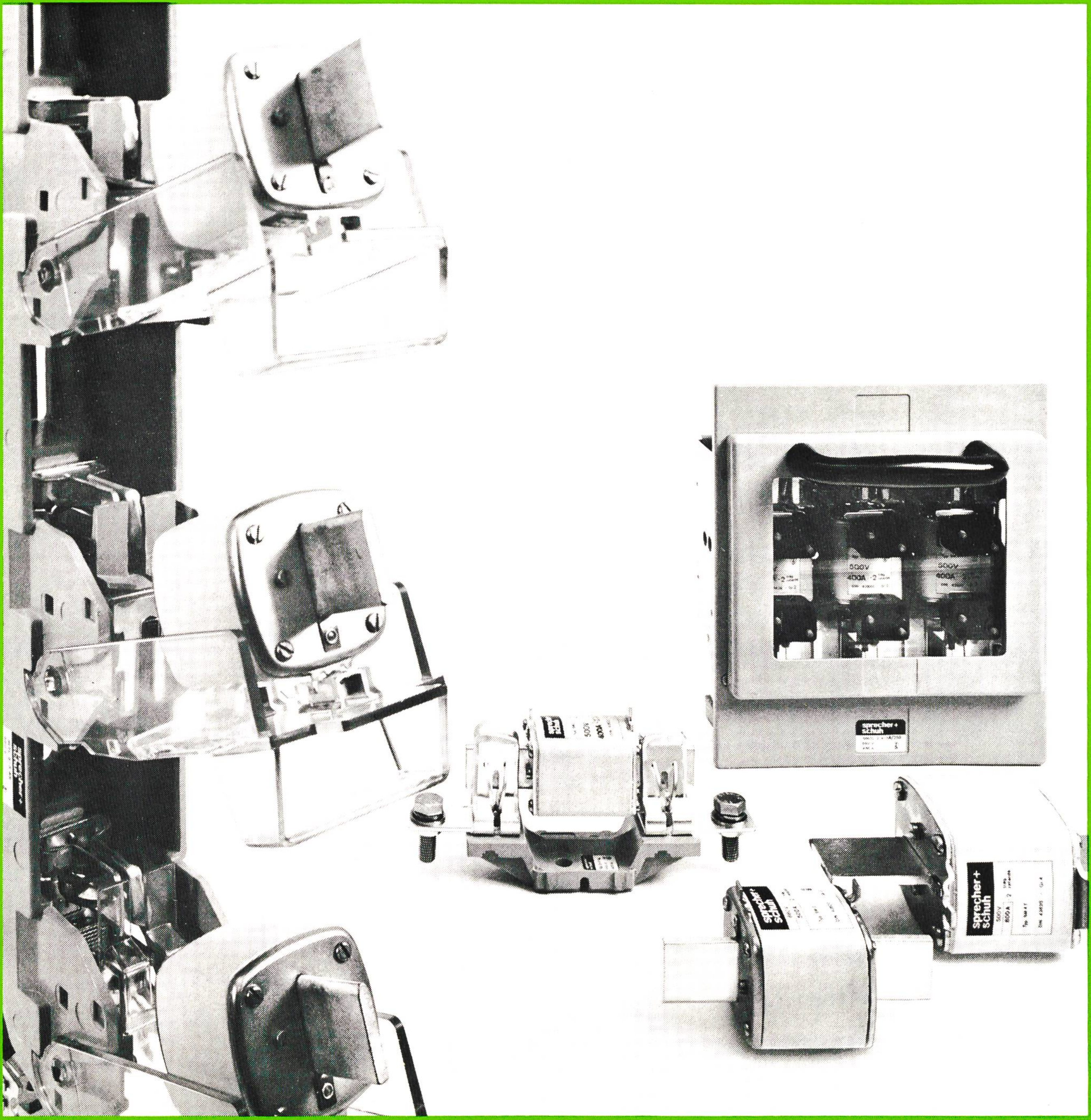
NH-Sicherungen nach DIN und Kabelverteilerschränke

NH-Sicherungseinsätze — NH-Sicherungsunterteile —
NH-Sicherungsleisten — NH-Sicherungs-Lasttrennerleisten
Norm-Kabelverteilerschränke



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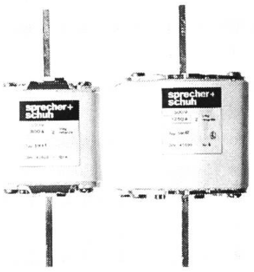
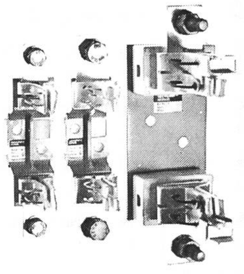


NH-Sicherungseinsätze nach DIN 43 620. Träge Charakteristik

Grösse	Nennstrom	Bezeichnungen
00	6A— 160A	SM 00 T / 6...
1	80A— 250A	SM 1 TF/ 80...
2	125A— 400A	SM 2 TF/125...
3	315A— 630A	SM 3 TF/315...
4 a	500A—1600A	SM 4 TF/500...

Technische Daten — Hinweise

Max. Betriebsspannung 660 V a. c., Schaltleistung bei 500 V a. c.: >100 KA;
Auf Anfrage Ausführungen für:
500 Volt, träg, mit Schlagbolzenmelder;
500 Volt, überflink, für Halbleiterschutz.

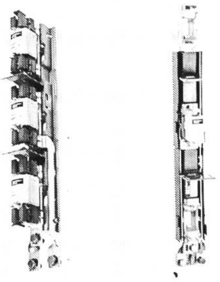


NH-Sicherungsunterteile, Schiebetrenner, 1polig nach DIN 43 620

Grösse	Nennstrom	Bezeichnungen
00	160A	SU 00-1 lg...
1	250A	SU 1-1 lg...
2	400A	SU 2-1 lg...
3	630A	SU 3-1 lg...
4 a	1250A, (1600A)	SU 4-1 ...

Technische Daten — Hinweise

Max. Betriebsspannung 660 V a. c.; Schiebetrenner 160—2000 A. Anschlussvarianten: Bockklemmen, Sechskantschrauben, Rahmenklemmen. Berührungsschutzhauben, Trennwände für Reihenmontage, Abdeckungen aus Isolierstoff, Bedienungsgriffe mit oder ohne Armschutz für Sicherungseinsätze. Für SEV-Sicherungseinsätze Gr. 2 und Gr. 4.

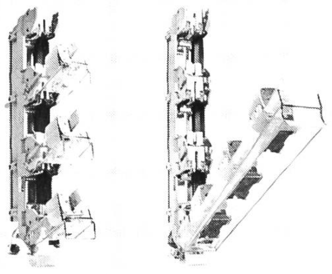


NH-Sicherungsleisten, 3polig, nach DIN 43 623, Sammelschienenabstand 185 mm

Grösse	Nennstrom	Bezeichnungen
00	160A	SUL 00-3 AS/185
1	250A	SUL 1-3 AS/SS...
2	400A	SUL 2-3 AS/SS...
3	630A	SUL 3-3 AS/SS...
4	1250A	SUL 4-3 AS/1250

Technische Daten — Hinweise

Max. Betriebsspannung 660 V a. c.; Schaltleistung: 1,25 In, 500 V, cos δ 0,7. Isolierstoffträger mit stark versilberten Kontaktstücken. Direkte Montage auf Sammelschiene. Verschiedene Anschlussarten, schaltsichere (isolierstoffverkleidete) Kontaktstücke, Trennstege, Berührungsschutz, Montagehaube.

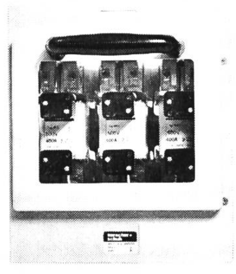


NH-Sicherungs-Lasttrennerleisten, 3polig, nach DIN 43 623, Sammelschienenabstand 185 mm

Grösse	Nennstrom	Bezeichnungen
1	250A	SLTL 1-3 AS/...
2	400A	SLTL 2-3 AS/...
3	630A	SLTL 3-3 AS/...
4	1250A	Auf Anfrage

Technische Daten — Hinweise

Max. Betriebsspannung 660 V a. c.; Schaltleistung: 500 V, 3× In. Direkte Montage auf Sammelschiene. Spannungslose Fixierung der Sicherungseinsätze im ein- oder dreipoligen schwenkbaren Oberteil, Löschkammern zur Funkenlöschung. Verschiedene Anschlussvarianten. Ausführung für SEV-Sicherungseinsätze. Gr. 2 und Gr. 4, dreipolig.

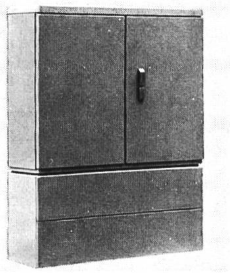


NH-Sicherungsunterteile, 3polig, Sicherungs-Lasttrenner, 3polig

Grösse	Nennstrom	Bezeichnungen
1	250A	SGU 1-3/100/...
2	400A	SGU 2-3/100/...
00	160A	SNLTL 00...-3...
1	250A	SNLTL 1...-3...
2	400A	SNLTL 2...-3...
3	630A	SNLTL 3...-3...

Technische Daten — Hinweise

Sicherungsunterteil SGU.../100... für direkte Montage auf Sammelschiene 100 mm nach DIN 43 623; schaltsichere Kontaktstücke, verschiedene Abgangs-Anschlussarten.
Sicherungs-Lasttrenner für Einbau und Aufbau, mit Löschkammern, elektr. Verriegelung, Ausführung für SEV-Sicherungseinsätze Gr. 2 und Gr. 4, dreipolig.



Norm-Kabelverteilerschränke

Nenngrösse	für Anzahl Leisten	Bezeichnungen
00	3	NKVS-00/850
0	4	NKVS- 0/...
1	6	NKVS- 1/...
2	8	NKVS- 2/...
3	12	NKVS- 3/850

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Genève 022 - 21 13 12,
Sion 027 - 22 16 92

high-temperature, high-purity processing techniques required for the latter were mastered, the fused silica glasses became dominant. Bell Laboratories, for example, has developed a new chemical vapor deposition (CVD) process for despositing silica on the inner wall of a fused silica tube which avoids contamination since no crucibles are used. The fused silica tube is slowly rotated around its axis while mixtures of reactant gases flow through it at controlled rates. An oxyhydrogen torch traveling back and forth along the tube heats the gases at up to 1750 °C. The oxidation products form a melt on the tube's inner walls. By changing the composition of the gases a parabolic profile is formed. When the desired deposition thickness is obtained, the tube is collapsed by heating into a solid cylinder (a preform) from which the fiberguide is drawn [13].

Typical loss vs. wavelength characteristics of a multimode and a single-mode fiberguide produced by the CVD process are shown in Fig. 7 [29], which also includes the intrinsic *(Rayleigh)* scattering limit (the peaks are due to OH absorption). The figure includes the intrinsic dispersion limit which also decreases with increasing wavelength. It is seen that the loss is of the order of 3 dB/km at 0.9 µm, the wavelength of AlGaAs lasers and LEDs. Minimum loss occurs at about 1.06 µm; lasers emitting at this wavelength exist but are not as highly developed as AlGaAs sources. The multimode, parabolic-index fiber of 50 µm core and 100 µm outer diameter exhibits a pulse dispersion of less than 2 ns/km. The single-mode fiber has two loss minima of 2.2 dB/km, one at 0.85 µm and one at 1.02 µm. Its pulse dispersion is 0.4 ns/km.

An important parameter which is an indirect measure of the amount of light power that can be coupled into a fiberguide is its numerical aperture NA given by

$$\mathrm{NA} = \sin\theta = (n_1^2 - n_2^2)^{\frac{1}{2}} \approx n_1 \sqrt{2\Delta}$$

where θ is the maximum angle to the axis at which a ray can be accepted, n_1 is the refractive index of the core, n_2 that of the cladding and Δ is defined by $n_2 = n_1(1 - \Delta)$. Typical NA values range from 0.14 to 0.22.

Good optical properties are extremely important but not sufficient for practical telecommunications systems. These require that fibers be made into cables of sufficient strength to be pulled through ducts, that they be spliced in the field, connected to transmitters and receivers. They must also have high reliability; i.e., that over a period of, say, 20 years, the optical properties of the cables remain constant. All these problems are being worked on – several have been solved already – and progress has been remarkably rapid.

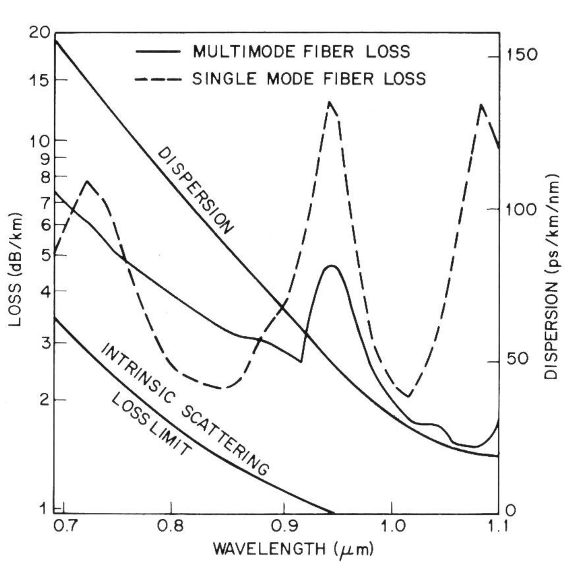

Fig. 7 Typical loss versus wavelength characteristics of a multimode and a single-mode fiberguide [29]

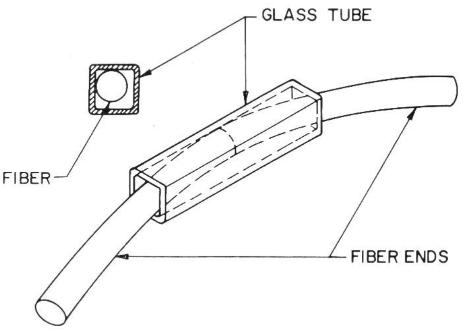

Fig. 8 The loose tube splice

One effect that adds loss, for example, is bending. Where the fiber deviates from a straight line, some light enters and gets scattered in the cladding. However, this effect is insignificant for a radius of curvature of more than about 10 cm. Much more severe is the effect of microbends which produce tiny cracks that can propagate, mostly on the surface. They do not affect so much the loss as the tensile strength of the fiber. For a pristine fiber the latter is as high as a million pounds per square inch but can be less by one or two orders of magnitude unless the fiber is coated with a polymer plastic soon after drawing. This coating also seems to prevent corrosion effects resulting from the interaction of water with the microcracks [13]. The question of long-term reliability, however, remains, because polymers are not hermetic but allow water eventually to reach the fiber. These effects are of a random character which necessitates specifying strength in a probabilistic way, a departure from standard practice with copper wires [14].

Splicing methods have been developed using simple tools and fixtures that can be used by unskilled personnel. The most critical parameter in splices and connectors is the lateral misalignment rather than the gap between the two fiber ends. For low splice loss, the fiber ends must be cut perpendicular to the fiber axis and polished. A very simple and efficient way for low-loss splicing in the field, that was developed at Bell Labs, is the loose-tube splice of Fig. 8. The polished fiber ends are inserted into the rectangular tube shown, after it is filled with an index-matching epoxy. The two ends are slightly bent so as to sit against the inner corner of the tube, pushed against each other until they touch, and held in this position until the epoxy cures. This method yields an average splice loss l_s = 0.1 dB [15]. Metal and plastic connectors have been developed not only for single fibers but also for cables of fiber bundles. Connector losses vary from 0.5 to 3.5 dB [16; 17].

4. The Receiver

The photodetectors used in the receiver circuitry of fiberguide communication systems are simple, silicon semiconductor devices either of the PIN or the avalanche (APD) type. The most desirable property of the photodetector is to provide

Typical Photodetector Device Parameters 4) Table I

Parameter	APD	PIN
Diameter, µm	200	320
Quantum Efficiency at 0.85 µm	$> 80\,\%$	$> 80\,\%$
Gain	100 at 300 V	1
Dark Current, A	$< 10^{-8}$ total at 300 V	$< 10^{-9}$ at 20 V
Capacitance, pF	< 1 at 300 V	< 1.5 at 20 V
Risetime, ns	1	5 at 20 V

4) Courtesy of *R. G. Smith*, Bell Laboratories

as high a sensitivity as possible at the wavelength of emission of the sources considered (0.75 to 0.9 µm) and a response consistent with the desired bandwidth or bit rate of the system. The fundamental limitation at the receiver, both for analog and digital transmission, is the noise introduced by the detector and the first stage of the following amplifier. Were it not for this excess noise, the limiting factor would be the quantum noise, which practical receivers hardly ever reach. Noise limits the signal-to-noise ratio in analog transmission and determines the error rate in digital transmission.

PIN photodiodes are reverse biased and absorb photons in a depleted region where these photons generate electron-hole pairs. These are separated and swept away by a high electric field, thus inducing a current in the load circuit. This photo current is proportional to the incident light power. Peak quantum efficiencies of such diodes exceed 90%. Fig. 9 shows the quantum efficiency vs. wavelength for a PIN photodetector with wide depletion region, optimized for maximum response at 0.9 µm. The figure also includes contours of constant responsivity (i.e. photodetector current in mA/W of incident light power). The sensitivity of these diodes to weak signals is limited by their dark current. With care in fabrication, dark currents as low as 10^{-8} A/mm^3 of depleted volume can be achieved.

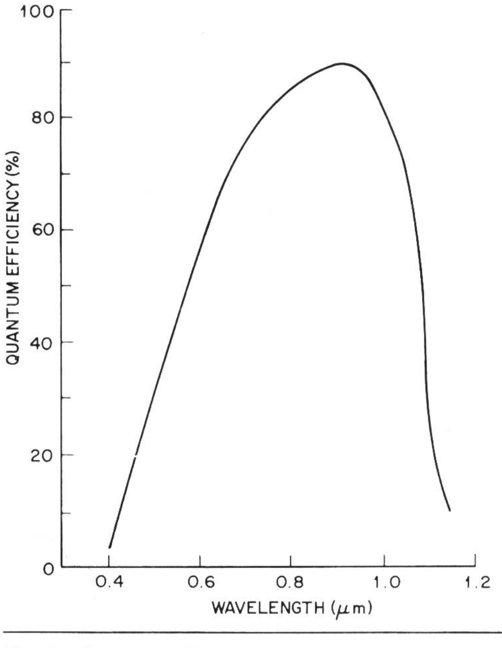

Fig. 9 Quantum efficiency as a function of wavelength for a PIN Photodetector with wide depletion regions, optimized for maximum response at 0,9 µm [18]

Avalanche photodiodes (APD) are based on the same principle as PIN photodiodes but are designed to include internal gain. They require a highly reverse-biased junction to produce a high field which accelerates carriers sufficiently to produce an avalanche effect through impact ionization. APDs can thus achieve carrier multiplication by factors up to 200 at 0.9 µm. Current gain-bandwidth products of up to 100 GHz have been achieved. The gain-bandwidth advantage of APDs over PINs must be paid for by a more complicated, i.e. more expensive, device and by the necessity of a stabilized, high-voltage supply of 200 to 500 V. Table I shows typical device parameters for both types of photodetectors. An excellent exposé on the subject is given by *Melchior* in [18].

The maximum length of a transmission link is ultimately determined by the sensitivity and noise performance of the receiver. In the case of digital transmission, by far the most important application, an important parameter at the receiver is the minimum number of primary photoelectrons that must be generated at the detector per bit interval of incoming information to guarantee a desired error rate. This parameter is plotted in Fig. 10 as a function of bit rate for a fixed error probability of 10^{-9}. The upper band represents the region of operation with PIN photodetectors, while the lower band corresponds to APDs with optimal gain. These bands assume state-of-the-art FET 5) or bipolar device noise at the first stage of the receiver amplifier. The dots represent the performance various experimental systems have achieved. The dotted lines are contours of equal average optical power at the receiver [19].

Efficient coupling of the fiber end to the photodetector with a loss $l_r < 0.1$ dB is easily achieved by making the photosensitive area somewhat larger than the fiber core cross-sectional area.

5. System Applications

Analog system applications in voice and television transmission have been reported using direct intensity modulation (baseband), frequency modulation (FM) and pulse-position modulation (PPM). In a study by *Horak* [20], for example, it was shown that with a 5 dB/km fiberguide, baseband transmission can satisfy the required TV signal-to-noise ratio for distances up to about 4.4 km. The corresponding maximum distances for FM and PPM are 8.0 km and 8.4 km, respectively.

However, the most important application of fiberguide systems is in digital transmission, which takes advantage of the inherently wideband fiberguide medium and the high-speed sources and detectors described in previous sections. Short-haul applications include interconnections between mainframes and peripherals in large computer installations as well as interframe connections in digital central offices. The important advantages in this case are achieving electrical isolation and avoiding ground loops. Such systems are nearly operational at bit rates of tens of Mbit/s [27].

The most important application of digital transmission is in telephone systems, at the toll plant and the exchange plant levels with exciting future possibilities in the distribution and subscriber loop plant. An experiment by the Bell System in Atlanta, Georgia, has been performed to assess fiberguide transmission in all its practical aspects, in an environment closely approximating actual plant conditions. The results of this

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5) FET = Field Effect Transistor.

experiment have exceeded all expectations. One hundred forty-four fiberguides are enclosed in a 2100-foot, half-inch-diameter cable, installed in ducts and manholes. Some of the fibers are joined at their ends to form transmission paths up to 40 miles long. Each fiber carries PCM signals at a bit rate of 44.7 Mbit/s which corresponds to 672 simultaneous telephone conversations. Measured average fiberguide loss is 6 dB/km *after* cabling and installation. This allows repeater spacing of more than seven kilometers. From this, other experiments and fiberguide cost trends, one can safely conclude that fiberguide transmission systems are not only technically feasible but that they will also make good economic sense in the near future.

6. Outlook

In trying to predict what the future may bring, let us look first at light sources. A recent article [21] indicates that a new, mixed crystal material has been used to make a double heterostructure injection laser emitting between 0.98 and 1.07 µm. These new GaAsSb/AlGaAsSb lasers have been operated continuously at room temperature and have delivered 10 mW of power at 1 µm with 100 mA of threshold current. The significance of this event will be appreciated if one recalls that the lowest fiberguide loss observed to date was 0.9 dB at 1.06 µm, a wavelength at which the dispersion is also very low. The neodymium-doped yttrium-aluminium-garnet (Nd: YAG) laser, which emits at 1.06 µm, has been available in the past, but its use is not practical since it needs optical pumping and an external optical modulator. While the new GaAsSb laser is as simple as the GaAlAs one, it has not yet attained the latter's lifetime.

A very active field of study which may have a large impact on future fiberguide communication systems is 'Integrated Optics' [22; 23]. This term refers to one- and two-dimensional thin film techniques which integrate several optical functions on a single substrate. These functions include light generating, guided-wave optics for transmission within the substrate, modulation, switching, mixing, up conversion, directional coupling, etc. One development of interest, for example, is the operation as end-pumped lasers of short lengths of fused silica fibers with Nd-doped cores reported in [24]. This is a true integration of the light source and fiberguide but is still far from finding practical applications. Another advance in the direction of integrating several functions in a single material has been reported in [25; 26]. They describe a laser coupled into a lightguide through a tapered region and a grating mirror as well as an electrooptic modulator. All these elements are included within a single GaAs crystal.

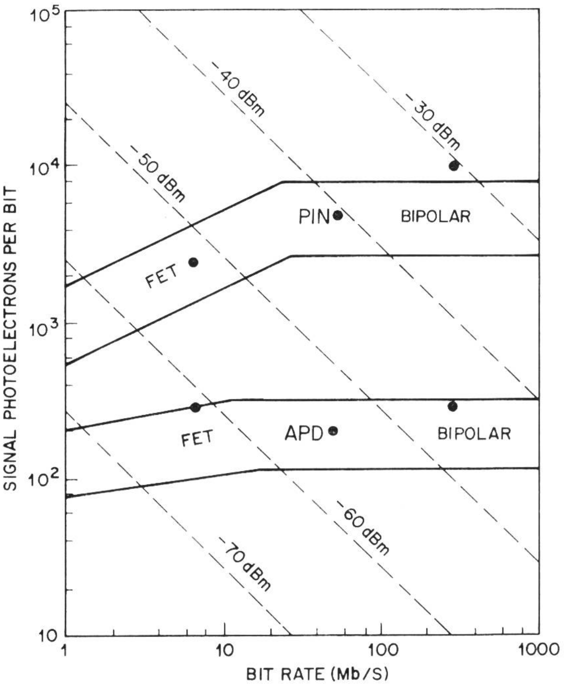

Fig. 10 **Minimum primary photoelectrons generated at the photodetector per bit interval of incoming information as a function of bit rate, for a fixed error probability of 10^{-9} [19]**

Concerning the fiberguide itself, the main thrust of near future developments is expected in manufacturing, cabling and splicing methods. Cabled fiberguides are already cost competitive with coaxial cable, while their transmission (loss-bandwidth) properties are superior and their size and weight much less. It is the strong personal opinion of the author that someday, in the not-too-distant future, fiberguide cables are going to be less expensive than twisted-pair cables of copper wires.

When it comes to solid-state photodetectors, nothing exciting appears on the horizon at this time; moderate improvements and incorporation into integrated optical systems are, of course, possible. On the other hand, ternary and quaternary photoemitters with high quantum efficiency for electron emission into vacuum are being actively pursued.

The really revolutionary impact of fiberguide communications will occur when this medium will be inexpensive and widespread enough to reach large numbers of business and private customer premises. Its tremendous bandwidth potential may make visual two-way communication as simple as the telephone of today. It may make retrieval of information practical and affordable to everyone: Entire encyclopedia articles, including high-resolution colour pictures, will then be transmitted in microseconds. However, this assumes that appropriately inexpensive display and other terminals will also have been developed by then, perhaps with the help of integrated optics.

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Circuits logiques M.S.I. et L.S.I. Par *R. Lyon-Caen.* Paris e.a., Editions Masson, 1976; 8°, X/190 p. 122 fig.

Das Buch bildet eine neue, erweiterte Fassung des vor acht Jahren erschienenen Werkes des Verfassers «Circuits logiques intégrés», bereichert um viele Ergebnisse der ausserordentlich schnellen Entwicklung der letzten Jahre. Es steht eigentlich an der Grenze zwischen zwei sich gegenseitig beeinflussenden Gebieten, nämlich dem umfangreichen Anwendungsbereich der integrierten logischen Schaltungen und der Technologie von integrierten Halbleiterschaltungen. Für beide Bereiche ist es als gleichermassen aufschlussreich anzusehen. Der behandelte Stoff ist in vier Kapitel gegliedert.

Zuerst wird das für die Anwendungen Wesentliche über den Booleschen Verband systematisch dargelegt und an Beispielen schaltungstechnischer Realisierung von logischen Verknüpfungen erläutert. Die Wirkungsweise von typischen Gattern (OR, AND, NOR, NAND) sowie von zusammengesetzten Gebilden, wie verschiedene Typen von Flipflops, Vorwärts- und Rückwärtszähler, Schieberegister u. dgl. wird dabei eingehend behandelt. Kapitel II ist den physikalischen Beschaffenheiten der integrierten logischen Schaltungen, wie Störanfälligkeit, Schaltgeschwindigkeit, Verlustleistung u. dgl., gewidmet. Anschliessend werden Familien von derartigen Schaltungen und deren Kompatibilität besprochen.

Im nächsten Kapitel wird zuerst die Entwicklung der Technologie über den mittleren Integrationsgrad (MSI: middle scale integration) bis zu hochintegrierten Schaltungen (LSI: large scale integration) geschildert. Die für MSI typischen Schaltungen mit bipolaren Transistoren und Widerständen werden anschliessend ausführlich besprochen. Das letzte Kapitel IV ist der für LSI wesentlichen Verwendung von Schaltungen ohne Widerstände und mit unipolaren Feldeffekttransistoren (FET) gewidmet, wobei sowohl p- und n-Kanal-Transistoren (MOS: metal oxide semiconductor) als auch komplementäre FET-Schaltungen (CMOS) berücksichtigt werden. Die diesen, heute am häufigsten verwendeten Technologien eigenen Vor- und Nachteile werden einander gegenübergestellt und ausführlich besprochen.

Trotz des beschränkten Umfanges des Buches kann es allen im Nachrichtenwesen und auf benachbarten Gebieten Tätigen als sehr nützliches Einführungs- und Nachschlagewerk empfohlen werden. Die Darstellungsweise ist lückenlos und klar. Der bibliographische Anhang mit über 100 Titeln enthält wertvolle Hinweise für ein weiteres Studium der im Buch behandelten Probleme. *J. Fabijanski*

DK: 621.316.1 SEV-Nr. A 623

Einführung in die Netzwerktheorie. Berechnung des stationären und dynamischen Verhaltens von elektrischen Netzwerken. Von *Dietrich Naunin.* Braunschweig, Friedrich Vieweg Verlag, 1976. – Unitext – 8°, VIII/200 S. Fig., Tab. Preis: kart. DM 18.80.

Das Buch bildet einen systematisch aufgebauten Lehrgang für Hochschulstudenten der Elektrotechnik, die sich in die Analyse des stationären und dynamischen Verhaltens elektrischer Netzwerke einarbeiten wollen. Einleitend werden die mathematischen und elektrotechnischen Grundlagen, deren Beherrschung an sich vorausgesetzt wird, wiederholt: Signalformen, Netzwerkelemente, Matrizenrechnen.

Im Zentrum des Buches steht die Einführung in die Graphentheorie und deren Anwendung auf elektrische Netzwerke. Die Grundbegriffe Schleife, Schnittmenge und Baum werden eingehend erläutert und anschliessend Schritt für Schritt auf die verschiedenen Netzwerkelemente angewandt. Die Gleichungssysteme des dynamischen Verhaltens führen zur Laplace-Transformation und deren Anwendungen sowie zur Lösung der Zustandsgleichungen mit der ein Netzwerk kennzeichnenden Übergangsfunktion. Den Abschluss bilden Kapitel über Stabilitätsprobleme sowie über die Möglichkeiten von Lösungen mittels Analog- resp. Digitalrechner.

Die eingehende Behandlung der Graphentheorie ist von um so grösserer Bedeutung, als dieses Verfahren auf alle Arten elektrischer Netzwerke, aber auch auf andere Regelsysteme angewandt werden kann. Bekanntlich führt die Analyse schon bei relativ einfachen Netzwerken zu umfangreichen Gleichungssystemen und aufwendigen Rechnungen. Das ganze Buch stellt denn auch hohe Anforderungen an das mathematische Denkvermögen des Lesers und setzt gründliche Kenntnisse des Verhaltens der einfachsten Schaltungen voraus. Eingestreute Beispiele sowie Übungsaufgaben am Ende jeden Kapitels, deren Lösungen allerdings fehlen, vermitteln Hinweise auf praktische Anwendungen.

Als begleitendes Lehrmittel oder zur Vertiefung einzelner Kapitel ist das einfach und übersichtlich gestaltete, didaktisch sehr gut aufgebaute Buch bestens zu empfehlen. *Eb*