Fiber-Optic Transmission – an Overview

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Invited Paper

***Abstract* – The idea of this paper is to give an overview on fiber-optic communication. The most important devices for fiber-optic transmission systems are presented, and their properties discussed. In particular we consider such systems working with those basic components which are necessary to explain the principle of operation. Among them is the optical transmitter, consisting of a light source, typically a high speed driven laser diode. Furthermore, the optical receiver has to be mentioned; it consists of a photodiode and a low noise high bit rate front-end amplifier. Yet, in the focus of the considerations you will find the optical fiber as the dominant element in optical communication systems. Different fiber types are presented, and their properties explained. The joint action of these three basic components leads to fiber- optic systems, mainly applied for data communication. The systems operate as transmission links with bit rates up to 40 Gbit/s.**

I. INTRODUCTION

Since the beginning of the sixties, there has been a light source which yields a completely different behavior compared to the sources we had before: This light source is the LASER. The first realized laser was the bulk-optic ruby laser [1]. Short time after this very important achievement, diode lasers for use as optical transmitters have already been developed (see Fig.1) [2]. Parallel to that accomplishment in the early seventies, researchers and engineers accomplished the first optical glass fiber with sufficient low attenuation to transmit electromagnetic waves in the near infrared region [3].

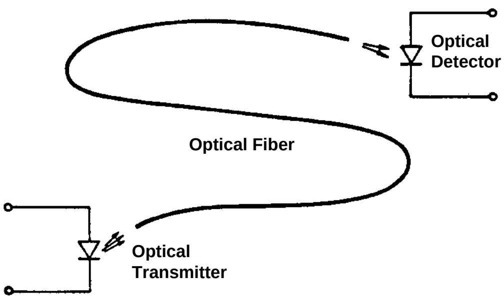


Figure 1 – Basic arrangement of a fiber-optic system.

The photodiode as detector already worked [4], and thus, systems could be developed using optoelectric (O/E) and electrooptic (E/O) components for transmitters and receivers as well as a fiber in the center of the arrangement. The main fields of application of such systems are found in the area of fiber-optic transmission and fiber-optic sensors (see Fig.2).

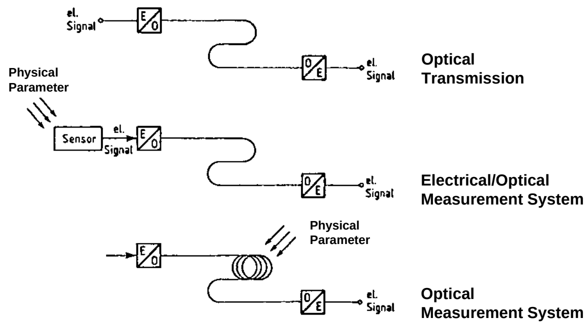


Figure 2 – Application of fiber-optic systems.

However, the first optical transmission is much older. Indians for instance, had already communication by smoke signals long time ago (see Fig.3, [5]). Furthermore, it was a very sophisticated and modern system, because it was already a digital system, consisting of "binary 1" and "binary 0" (smoke/no smoke).

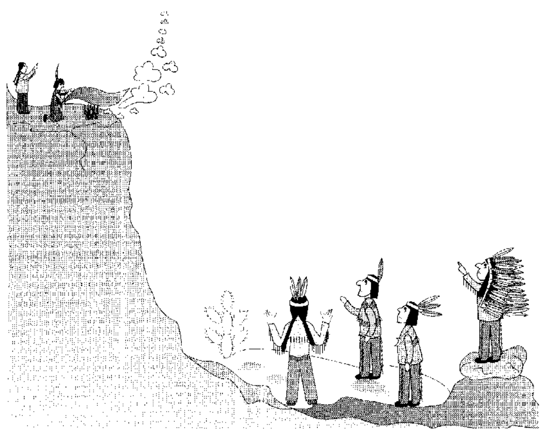


Figure 3 – Digital optical transmission by use of smoke signals.

As inventors of fiber-optic transmission systems can be regarded Charles Kao (1963, [6]) and Manfred Börner (1964, [7]). Nowadays, their invention would not be very spectacular: Take a light source as transmitter, an optical fiber as transmission medium, and a photodiode as detector (see Fig.1)! Yet, in 1963, it was a revolution, because the attenuation of optical glass was in the order of 1000 dB/km, and therefore totally unrealistic for use in practical systems. Today's fibers achieve an attenuation below 0.2 dB/km which means otherwise that after 100 km, there is still more than 1% of light at the end of the fiber. This low value of attenuation is one of the most attractive advantages of fiber-optic systems, compared to conventional electrical ones (see Fig.4). In addition, low weight, small size, insensitivity against electromagnetic interference (EMI), electrical insulation and low crosstalk must be mentioned. Apart from low attenuation, the enormous achievable bandwidth must be pointed out. That leads to a high transmission capacity in terms of the product of fiber bandwidth and length. One of the most important goals is to maximize this product for every kind of data transmission. Figure 4 depicts the attenuation behavior. In particular we observe an independence on modulation frequency of fiber-optic systems in contrast to electrical ones which suffer from the skin effect.

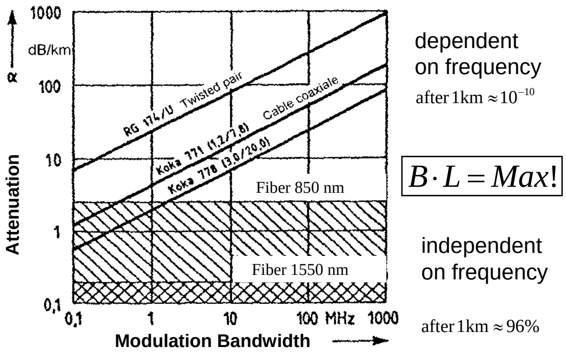


Figure 4 – Attenuation of coaxial cables and optical fibers.

II. Optical fibers

Most important demands on optical fibers are a proper waveguiding, low loss of optical power and low distortion of the transmitted optical signals. The principle of operation of guiding a light wave can be explained by Snell's law (see Fig.5). If light is incident on an interface between two media with different refraction indices (n_1 and n_2) in general there is a reflected and a refracted ray. But for the special case that light is incident from a media

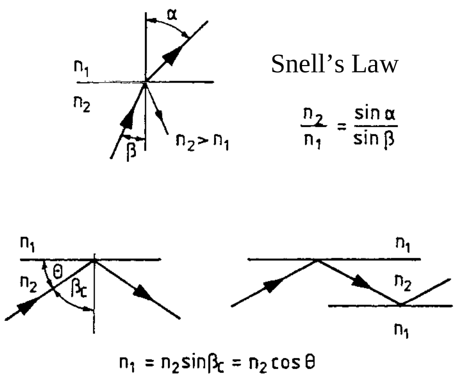


Figure 5 – Refraction, reflection and total internal reflection for light transition between two different media.

with higher refraction index ($n_2 > n_1$) as compared to the following one and furthermore the angle β exceeds a certain value (the cut-off angle β_c) there is no refraction anymore. We get reflection exclusively, the whole light is totally reflected; this effect is called "total internal reflection".

If this total internal reflection is repeated at a second interface a waveguide is achieved [8]. Figure 6 depicts this behavior. In particular it has to be pointed out that there is no loss due to the multiple reflection because it is a total internal reflection; the coefficient R = 1 holds for every repeated reflection. Thus, the attenuation of the fiber is only due to losses inside the fiber.

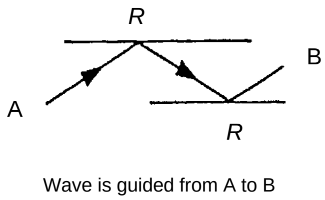


Figure 6 – Total internal refraction and waveguiding.

The most important attenuation mechanisms are Rayleigh scattering and OH^- absorption. The scattering effect is due to inhomogeneities in the molecular structure of glass (silicon dioxide: SiO_2). Hence, statistical refraction index changes are caused. This leads to a scattering effect of the traveling light wave in the fiber, causing loss. The loss strongly depends on the wavelength of the light wave (scattered power P_S, see Fig.19). Lord Rayleigh discovered and explained that due to this effect the color of the sky is blue. When we look at the sky, we see the scattered light of the white sunlight. Blue light is much more scattered than red. The same reason causes much higher losses in glass fibers for blue light than for red one (see Fig.19). Therefore, fiber-optic systems operate even beyond the red area, in the infrared (see below).

Figure 19 depicts also high attenuation peaks. These peaks are due to light absorption at undesired molecules in glass. The most important enemy in a fiber is water which appears as OH^- ions in the silicon dioxide structure. The OH^-molecules are brought to oscillations by light waves. This effect is in particular dominant when resonance occurs at wavelengths which fit (see peaks). Hence, the energy of a light wave traveling in the fiber is absorbed, which leads to high attenuation. To achieve low fiber attenuation, the demand of purity is very high, the OH^- concentration must not exceed a value of 1 ppb. This was one of the reasons why it took a long time from the first idea of fiber transmission, in about 1963, to the first produced fiber in about 1972. Furthermore has to be mentioned that the fiber also suffers from SiO_2-self absorption in the ultraviolet (UV) and infrared (IR) region, which in principle cannot be avoided. Whereas the UV-absorption can be neglected compared to the much higher value caused by Rayleigh scattering, the IR-absorption is responsible for the attenuation rise beyond 1600 nm (see Fig.19).

Besides the attenuation, there is a second cardinal problem concerning data transmission in optical fibers. Light rays in the fiber are not only traveling under one single angle. Figure 7 shows three representative existing rays (among hundreds or thousands). The existing rays are called "modes" in fibers. It is obvious that they do have different geometrical path lengths L. Yet, the determining effect for data transmission is not the geometrical but the optical path length $g = nL$, the product of the refraction index and the geometrical path length L. However, this optical path length differs for the three mentioned modes, too, because the refraction index in the fiber core is constant.

Different transit times for different modes

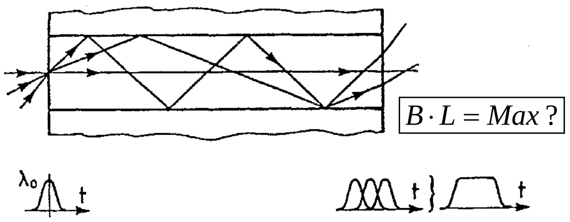


Figure 7 – Pulse broadening by modal dispersion.

Therefore, an optical pulse travels along all the three paths in the fiber. The consequence of this is, that they have different transit times and reach the fiber end at different arrival times. The three pulses superimpose and thus, we receive a broader output pulse as compared to the narrow input pulse (see Fig.7), the effect is called "pulse broadening". This behavior causes serious consequences. Since, if we want to transmit a high data rate, we have to place the second input pulse immediately after the first one. As a result, the pulses at the end of the fiber will overlap in such a manner that both pulses cannot be separated any longer. To avoid the overlap, it is necessary to place the second pulse with a greater distance from the first one which reduces the achievable bandwidth *B*. The second opportunity is to reduce the fiber length *L*. Both measures derogate the transmission capacity, the product of fiber bandwidth and length, the most important goal of every data transmission.

To avoid (reduce) this problem, scientists invented the graded-index fiber (see Fig.8). In contrast to the above described fiber, called "step-index fiber", the refraction index is not any longer constant across the fiber [9]. The latter reveals a gradient behavior in the fiber core, whereas it still remains constant in the envelope, the cladding.

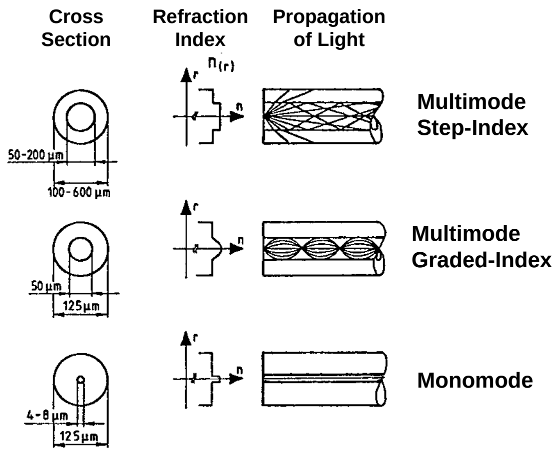
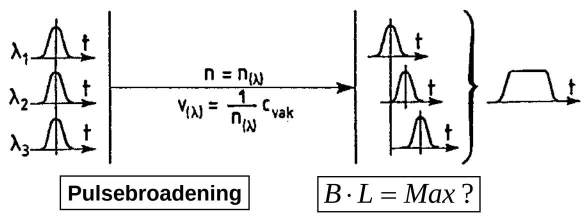


Figure 8 – Fiber types.

As a consequence, the optical path length $g = nL$ is now constant for each mode, because in the fiber center, one can remark the shortest geometrical path length *L* and the highest refraction index *n*. In contrast to this result near the cladding you find the longest geometrical path length linked with the lowest refraction index. Thus, with a properly chosen index profile we achieve a constant optical path length for all modes. At this stage, it has to be pointed out that it is not possible to achieve this goal completely, we obtain only a good approximation and thus there is still a certain modal dispersion left, resulting in a non negligible remain of transmission capacity reduction [10].

To overcome this problem, another invention was made, the construction of a monomode fiber: If we reduce the fiber core to a diameter below about ten micrometers, there will be only one ray, the ray along the optical axes transmitted and the modal dispersion problem vanishes per se [11]. For very high data rates (about 40 Gbit/s) we have to confess that this disappearance is not completely correct due to polarization effects. Very accurate investigations lead to the result that there is a difference between two perpendicularly oriented axes in the fiber concerning the refraction index. This fact again results in different optical path lengths, and finally as described before, in the same process of pulse broadening; this dispersion is called "polarization mode dispersion" (PMD [12]).

Different transit times for different wavelengths



(n: Refraction Index, λ: Wavelength, c_{vak}: Free Space Velocity, v: Velocity in Media)

Figure 9 – Pulse broadening by material dispersion.

Furthermore, another important dispersion is to mention, the material dispersion [11]. Due to the fact that there is no light source emitting at a single wavelength (see Fig. 15), there is no monochromatic but always polychromatic light traveling through a fiber. Moreover, taking into account the dependence of the refraction index on the wavelength, it is obvious that we have always different refraction indices, and therefore, different optical path lengths according to different velocities of pulses traveling along the fiber.

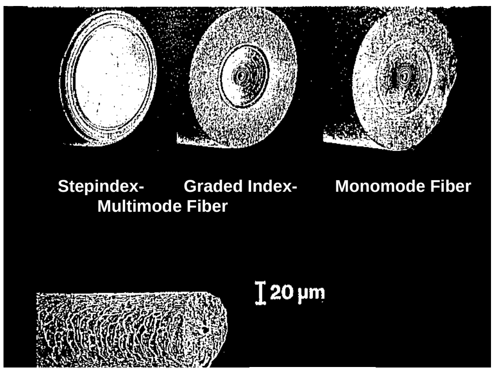


Figure 10 – Comparison of fiber types and a woman's hair.

Figure 9 shows three pulses having three representative wavelengths. They suffer from different transit times and reach the fiber end at different times of arrival. The three pulses superimpose as described above for the modal dispersion process and thus, we again obtain a broader output pulse as compared to the narrow input pulse (see Fig.9). The result is the same as for modal dispersion, just the mechanism is different, the effect is again pulse broadening and reduction of the transmission capacity.

Figure 10 visualizes the three common fiber types in comparison with a woman's hair. Table 1 shows an overview on fiber types depicting most important fiber data. Furthermore, two more fiber types must be mentioned. There are also low cost applications concerning fiber-optic transmission, i.e. plastic fibers and PCS fibers (plastic cladding and silica core) are used, too. Their transmission capacity is much lower as compared to pure glass fibers in particular monomode fibers. However, there are applications for such fibers, e.g. if you have low data rates and only some ten meters of spacing. For example to watch a machine tool in an EMI relevant area, why not use a cheap plastic fiber transmission set-up in the kHz-region?

Type	Profile	Size	Attenuation	Bandwidth x Length
Plastic Fiber	Step Index	950/1000 µm	0,2 dB/m	< 100 MHz·m
PCS Fiber	Step Index	100 - 600 µm	6 dB/km	< 10 MHz·km
Multimode Glass	Step Index	> 100 µm	3 - 5 dB/km	20 MHz·km
Multimode Glass	Gradient Index	50/125 µm	2 dB/km (0.85 µm) 0,4 dB/km (1,3 µm) 0,2 dB/km (1,55 µm)	500 MHz·km
Monomode Glass		5 - 10 µm		> 100 GHz·km

Table 1 – Fiber types.

III. Optical Sources and Detectors

Most important demands on optical sources are a high optical output power as well as a small electrical input power. With regard to the fiber, the wavelengths should be in a proper range (see Fig.19). The spectral width has to be small, and for a sufficient coupling efficiency, the beam divergence should be low and the geometrical size should be small. Furthermore, a modulation capability of the injection current at high speed is favorable. To understand the principle of operation concerning optical sources and detectors, fundamental considerations about the interaction between photons and electrons have to be taken into account.

Figure 11 shows the energy band model of the semiconductor material, applied for the optical components. E_1 is the energy level of the valence band, whereas E_2 denotes the level of the conduction band. The difference ΔE between both levels is the energy gap E_g. There are three dominant effects to be considered:

A photon is incident onto the semiconductor material. Thereby, an electron is lifted from the valence to the conduction band followed by transportation in an external circuit if a voltage is applied. Thus, electric charge is moving, i.e. this is current which is generated, caused by the absorption of a photon. This is the desired behavior in a photodiode. The second effect goes the other way round, an electron transition from the conduction band to the valence band occurs spontaneously. The energy difference ΔE is converted into a photon. In particular, the process of a following electron transition causing a second photon has nothing to do with generation of the first photon, i.e. there is a statistical behavior, named "spontaneous emission". This process occurs in an LED [13]. In contrast to this process, the third one is completely different. The electron transition from conduction to valence band is not any longer a statistical process, but an induced or stimulated one. This process is stimulated by an already existing photon, e.g. produced by the spontaneous process. The two photons are not any longer strangers. They know each other, they are coherent, we receive a coherent radiation caused by stimulated emission. This is the desired behavior in a laser. The two photons, now and again, cause new transitions and multiply themselves. Thereby an avalanche is produced; we receive a large amplification after exceeding a certain threshold (see Fig.12), we receive a LASER: Light Amplification by Stimulated Emission of Radiation [14].

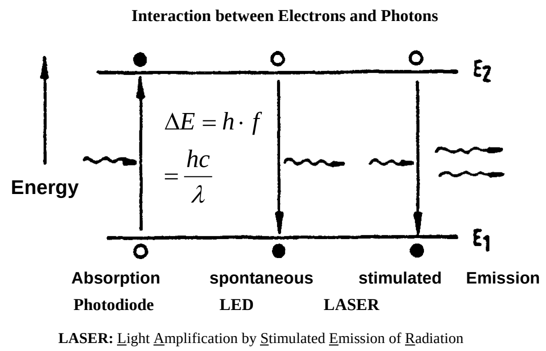


Figure 11 – Absorption and emission of photons.

Figure 12 depicts the optical power versus the injection current of a semiconductor laser. Below threshold the laser operates as an LED, after exceeding a certain injection current, the threshold current, stimulated emission takes place. Unfortunately there is a strong dependence of the threshold current on temperature. Hence, additional measures are necessary, such as temperature control or control by a monitor diode in order to stabilize the optical output power.

Figure 13 shows the far field distribution of a typical Fabry-Perot semiconductor laser. Unfortunately, semiconductor lasers show beam divergence and astigmatism, whereby the divergence is different in two perpendicular directions. Both effects make the coupling into a fiber in particular in a monomode fiber difficult. The laser chip is mounted up side down on a silicon substrate. This mounting enables a close contact of the active area to the heat sink. The chip size is about 300 µm long, 200 µm broad and 100 µm high, the active area is in the order of 1µm^2. Figure 14 visualizes a comparison between LED and laser farfield. The LED is a Lambertian light source, and thus it emits the radiation in the half sphere which makes the fiber coupling even more difficult.

A further interesting comparison between laser and LED is concerned with coherence properties. Figure 15 shows that the spectral width of a laser diode is much smaller than that of an LED, i.e. the laser coherence length is much larger as compared to the LED.

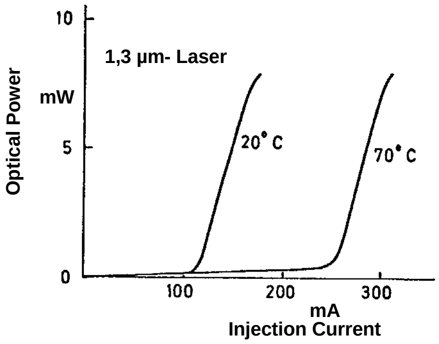


Figure 12 – Optical power versus injection current.

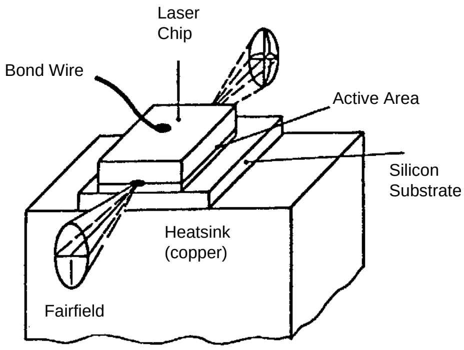


Figure 13 – Schematic arrangement of a semiconductor laser.

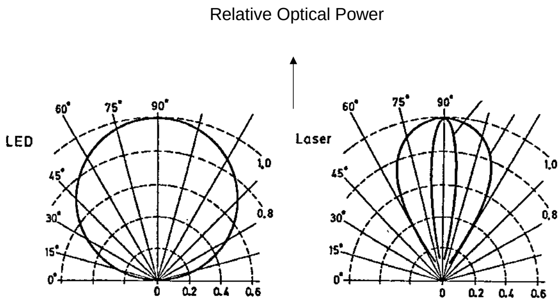


Figure 14 – Farfield characteristics of LED and Laser.

To depict both spectra in a single diagram, the laser power had to be reduced by a factor of 50. Moreover, it has to be mentioned that the 2 nm of laser width is just a rough idea. It could also be smaller by several decades. This results in a much better behavior concerning the material dispersion of a fiber. Thus, optical power, farfield behavior and spectral size enable the laser much more for highly sophisticated optical transmission systems, and hence for high speed long distance systems exclusively lasers are applied. In contrast to the laser, LEDs are used for low cost, low bit rate and low distance systems.

Most important demands on optical detectors [15, 16] are high sensitivity, low noise, linearity (for analog systems only) and small geometrical size. Most famous components are pin-photodiodes (see Fig. 16 and 17) and avalanche photodiodes (APDs). All photodiodes for transmission systems are used in reverse voltage operation. This operation applies an electric field to the semiconductor material and thus an electron produced by photon absorption is experiencing a force and will be accelerated. This effect is even enlarged by introducing an intrinsic zone into a pn-diode, which results in a pin-diode. This design guaranties a constant and high electric field over the whole absorption zone whereas the pn-diode has only a maximum directly at the pn-junction which leaves most part of the absorption area in a low electric field. Therefore the pin-diode is able to operate as a high speed component.

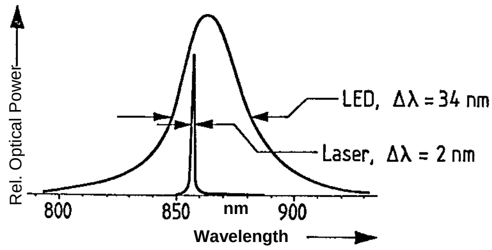


Figure 15 – Spectral width of LED and Laser.

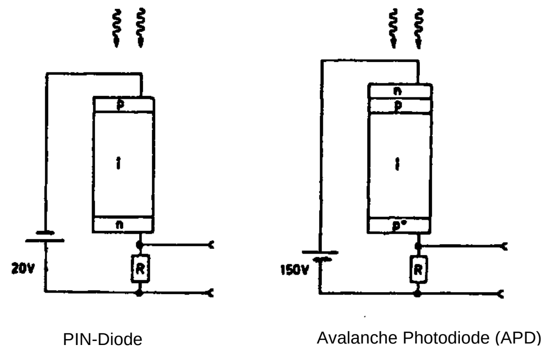


Figure 16 – Photodiodes for optical systems.

Figure 16 depicts an APD, this component has except for the pn-junction and the intrinsic zone a highly doped p+-zone. In this case we receive besides the constant electric field in the i-zone a very high field at the pn-junction (see also voltages for comparison).

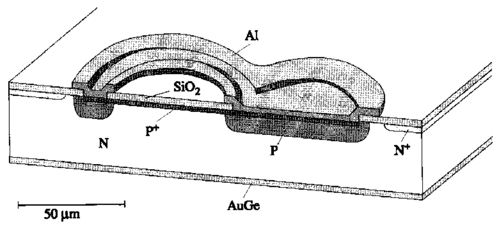


Figure 17 – Schematic structure of a Ge-APD [17].

This arrangement causes such a high acceleration of charge carriers that collisions occur between the electrons, produced by the absorption process, and the atoms of the semiconductor material. Thus, further electrons will be freed from the atoms (lifted from the valence band into the conduction band) and we receive secondary electrons. This effect is called “impact ionization”. The secondary electrons are now also accelerated and generate tertiary electrons and so on, which leads to an avalanche. As a result the APD possesses an internal gain and thus it is a very proper component for optical systems. The small geometrical size enables small junction capacities (see Fig. 17) and therefore, high cut-off frequencies are gained. Typical diameters of high bit rate photodiodes are in the order or 50 µm.

Most common materials for application in photodiodes are silicon (Si), germanium (Ge) and gallium indium arsenide phosphide (GaInAsP). Figure 18 shows the proper use according to the relative sensitivity versus wavelength (see also Fig. 19).

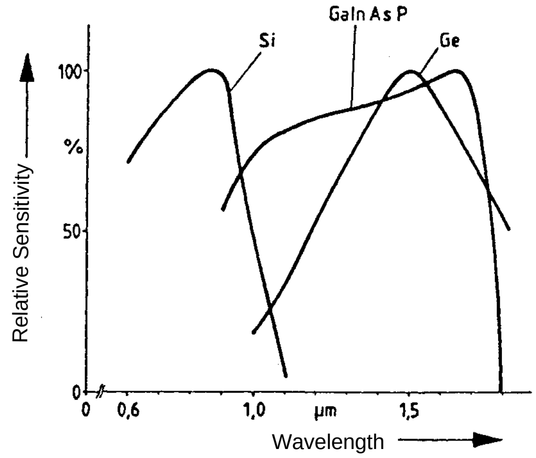


Figure 18 – Spectral sensitivity of photodiodes.

Fig.19 shows a summary of the most important components and their properties for fiber-optic transmission systems: In 1973 there was a fiber featuring a first minimum at a wavelength of about 850 nm in the order of 5 dB/km. Therefore, fiber-optic transmission started at the area of this wavelength and thus, this area is called the “first window”. In 1981, the attenuation lowered to about 0.5 dB/km and 0.3 dB/km at 1300 nm and 1550 nm respectively. Hence, the areas at these wavelengths are called the “second” and the “third window” where fiber-optic communication systems operate: Today’s fibers reach an absolute minimum of 0.176 dB/km due to principle physical effects as described above: Rayleigh scattering and infrared self-absorption.

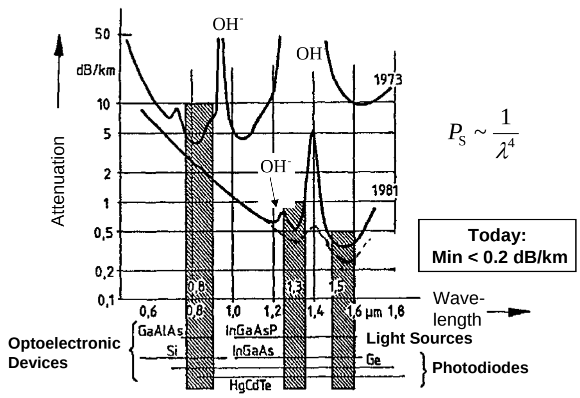


Figure 19 – Spectral attenuation of optical fibers and useful wavelengths of optoelectronic devices.

As optoelectronic components for light sources, we apply GaAlAs LEDs and laser diodes for the first window and InGaAsP devices, for the second and the third one. Photodiode materials are the well known Si for 850 nm, Ge and InGaAsP for the wavelength range of about 1200 nm to over 1600 nm. Furthermore, mercury cadmium telluride (HgCdTe) materials are very promising compounds for future optical detectors [35].

IV. FIBER-OPTIC TRANSMISSION SYSTEMS

Using the devices described above, fiber-optic transmission systems could be developed applying optoelectric and electrooptic components for transmitters and receivers as well as a fiber in the center of the arrangement (see Fig.1).

However, an optical communication system is more than a light source a fiber and a photodiode. There is a laser driver circuit necessary to provide a proper high bit rate electric signal; this driver combined with a laser or an LED build the optical transmitter. As well the photodiode (pin or APD) together with the front-end amplifier form the optical detector, also called “optical receiver” (see Fig.20).

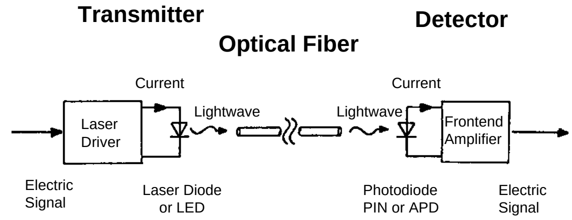


Figure 20 – Optical fiber transmission principle.

This front-end amplifier consists of a very highly sophisticated electric circuit. It has to detect a high bandwidth operating with very few photons due to a large fiber length and it is struggling with a variety of noise generators.

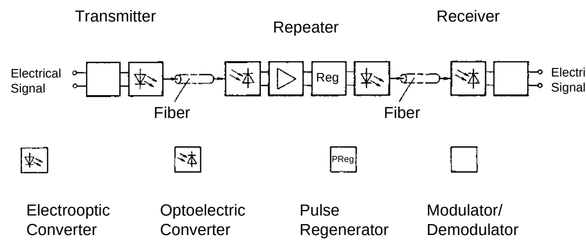


Figure 21 – Transmitter, repeater and receiver.

However, if the desired link length cannot be realized, a repeater will be inserted consisting of a front-end amplifier and a pulse regenerator (see Fig.21). This pulse regenerator is necessary to restore the data signal before it is fed to a further laser driver followed by another laser. Figure 22 visualizes the immense capability of the data regeneration: Directly at the front-end amplifier, (1) the eye pattern and the data signal cannot be detected as those. After a first following equalizer circuit, eye pattern and data signal are hardly recognized (2), whereas both are quite well restored after a second equalizer step (3). The non-return to zero signal at 168 Mbit/s can be seen clearly. Finally, a low pass filter is applied to suppress very high frequency noise (4).

At this point, it must be mentioned that an optical communication system is still more than discussed in this paper: There are further electric circuits to be taken into account, such as circuits for coding, scrambling, error correction, clock extraction, temperature power-level and gain controls [19].

Furthermore, until now, we have described a unidirectional system exclusively (see Fig. 23), i.e. we think of a telephone link at which a person at one side of the link is able to speak. At the other side of the link a second person can listen exclusively, but the system does not operate the other way round. To overcome this insufficient situation, optical couplers on both sides of the link are inserted. Therefore, we achieve a bi-directional system [20]. The two counter propagating optical waves superimpose undisturbed, they separate at the optical couplers on the other side of the link and reach the according receivers. To improve the transmission capacity drastically, wavelength selective couplers are applied, called "multiplexers" and "demultiplexers". Several laser diodes operating at different wavelengths are used as transmitters; their light waves are combined by the multiplexer and on the other link end separated by the demultiplexer.

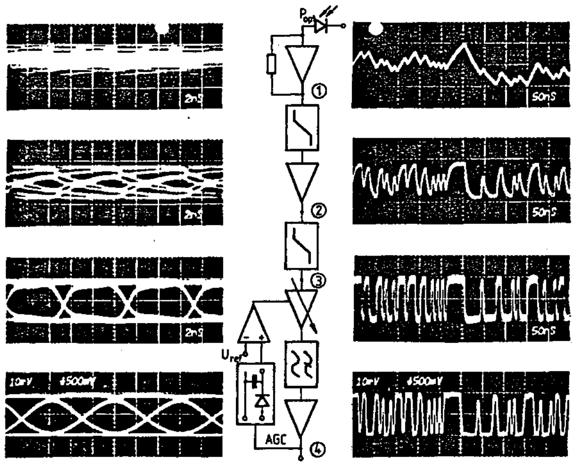


Figure 22 – Eye pattern and data signal [18].

The set-up is named "wavelength division multiplex system" (WDM). If we apply this arrangement again in the two counter propagating directions, we achieve a bi-directional WDM system [21]. The transmission capacity is risen by the number *N* of the channels transmitted over one single fiber.

Figure 24 depicts a scheme to describe the limits of optical transmission systems. For a single channel system two basic limitations occur. Such systems are called "direct detection systems", consisting of one laser one fiber and one detector.

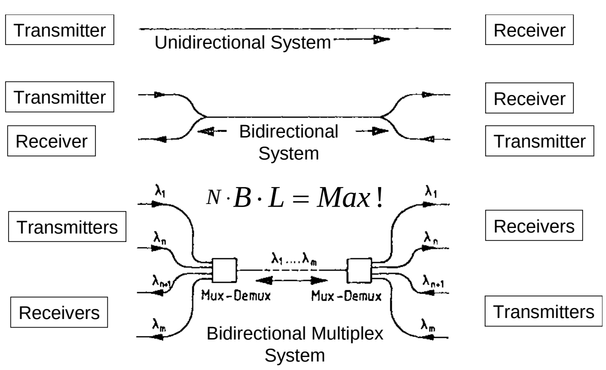


Figure 23 – Variety of optical transmission systems.

The limitations are divided into two groups, the systems suffer from attenuation limitation and dispersion limitation. The attenuation limited arm is governed by the transmitter power of the applied laser diode, the fiber attenuation and the receiver sensitivity of the detector. The dispersion limited arm is governed by the modulation bandwidth of the applied laser diode, the fiber dispersion and the demodulation bandwidth of the detector.

Thus, for high bit rate long distance transmission systems, exclusively high speed lasers and photodiodes will be installed as well as a monomode fiber. Figure 25 shows the eye pattern of a 43 Gbit/s data signal transmitted over a single channel high bit rate system. The data rate corresponds to the cut-off frequency of about 30 GHz which is approximately the highest frequency a single laser diode can be modulated.

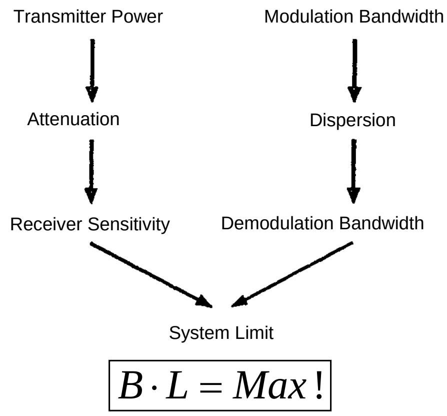


Figure 24 – Limits of optical transmission systems.

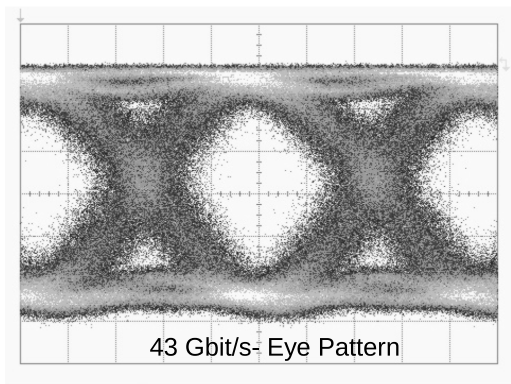


Figure 25 – Eye pattern of a high bit rate data signal [22].

V. Conclusions and Outlook

The aim of this paper was to give an introduction to fiber transmission systems, working with basic components. The reader should be familiarized with the fundamental optical techniques for communication systems. However, for more comprehensive considerations there are further components to be dealt with [23], e.g. the optical amplifier to enhance the link length over the conventional limits described above. In order to do that, Erbium and Raman amplifiers [24 -26] have been developed to overcome the problem of attenuation in fibers.

Moreover, it is also necessary to avoid signal distortions caused by the dispersion mechanisms in optical fibers. The solution to that problem could be the use of soliton transmission [27, 28]. The principle idea has been developed more than 20 years ago but it came just recently as product on the optical telecom market. For very high data rates such as over 40 Gbit/s, polarization problems in fibers have to be considered. There is a further distortion called "polarization mode dispersion (PMD)" which leads again to pulse broadening and therefore to bandwidth reduction with impact on the transmission capacity, the product of bandwidth and fiber length [12, 29]. In this paper only point-to-point links have been discussed. Further applications for future optical systems must be taken into account - such as optical networks [30-32] (LAN and MAN).

Finally, the subject of opening up the last mile for fiber communication is of great interest. Yet, more than ten years this idea of fiber to the home (FTTH) is discussed but it is still too expensive and therefore still waiting to reach the commercial market. May be new plastic fibers [33] with sufficient low attenuation and gradient profile together with high-speed LEDs [34] could solve this problem in the near future.

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