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Optical Transmission Systems Using Polymeric Fibers

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1. Introduction

Polymer Optical Fibers (POFs) offer many advantages compared to alternate data communication solutions such as glass fibers, copper cables and wireless communication systems. In comparison with glass fibers, POFs offer easy and cost-efficient processing and are more flexible for plug interconnections. POFs can be passed with smaller radius of curvature and without any mechanical disruption because of the larger diameter in comparison with glass fibers.

The clear advantage of using glass fibers is their low attenuation, which is below 0.5 dB/km in the infrared range (Fischer, 2002; Keiser, 2000). In comparison, POF can only provide acceptable attenuation in the visible spectrum from 450 nm up to 750 nm (Fig. 1). The attenuation has its minimum with about 85 dB/km at approximately 570 nm, which is due to absorption bands of the used Polymethylmetacrylat (PMMA) material (Daum, 2002). For this reason, POF can only be efficiently used for short distance communication up to 100 m. The large core diameter combined with higher Numerical Aperture (NA) results in strong optical mode dispersion, see Fig. 2.

Sources both LEDs and laser diodes in the 650 nm window have been available for some time. It is only recently that LED and Resonant Cavity LEDs (RC-LEDs) sources have become available in the 520 nm and 580 nm windows.
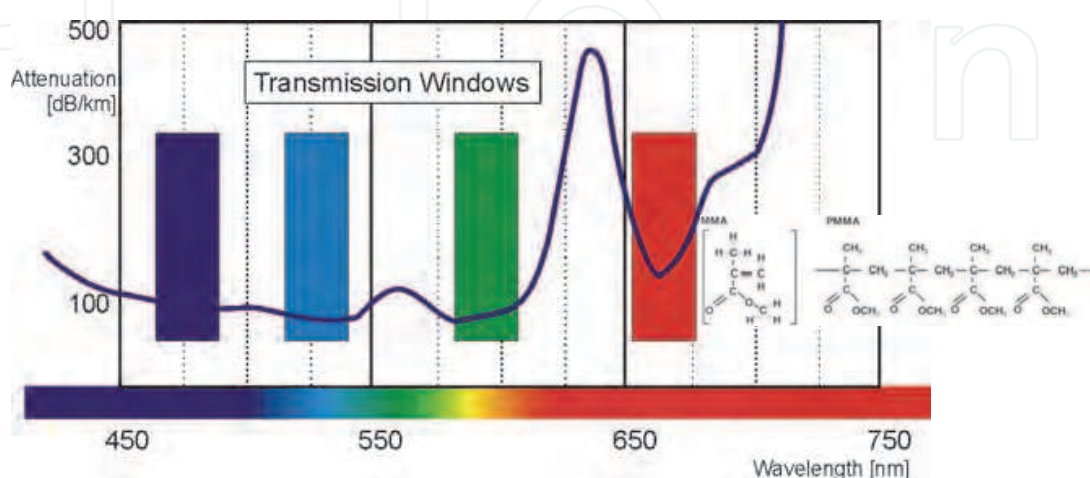

Fig. 1. Attenuation of POF in the visible range, insert: structure of PMMA.

The Numerical Apertur is directly given by the difference of the refractive indices of core and cladding material of the waveguide.

$$NA = (n_1^2 - n_2^2)^{1/2} \qquad (1)$$

$$\Theta = \arcsin(NA) \qquad (2)$$

The aperture angle of the waveguide is defined by the arcsin of the NA, which is the amount of input light that can be transferred by the waveguide by total reflection (Senior, 1992). For polymeric fiber systems, the NA calculates to 0.5, which results in the aperture angle of 30°. The difference of the core and cladding refractive indices is in comparison to glass fibers very high : 5%. The numerical aperture NA is correlated to the so-called V-parameter, which gives a correlation to the number of optical modes in the fiber waveguide. The number of the modes allowed in a given fiber is determined by a relationship between the wavelength of the light passing through the fiber, the core diameter of the fiber, and the material of the fiber. This relationship is known as the Normalized Frequency Parameter, or V number. The mathematical description is:

$$V = 2\pi NA\, a / \lambda \qquad (3)$$

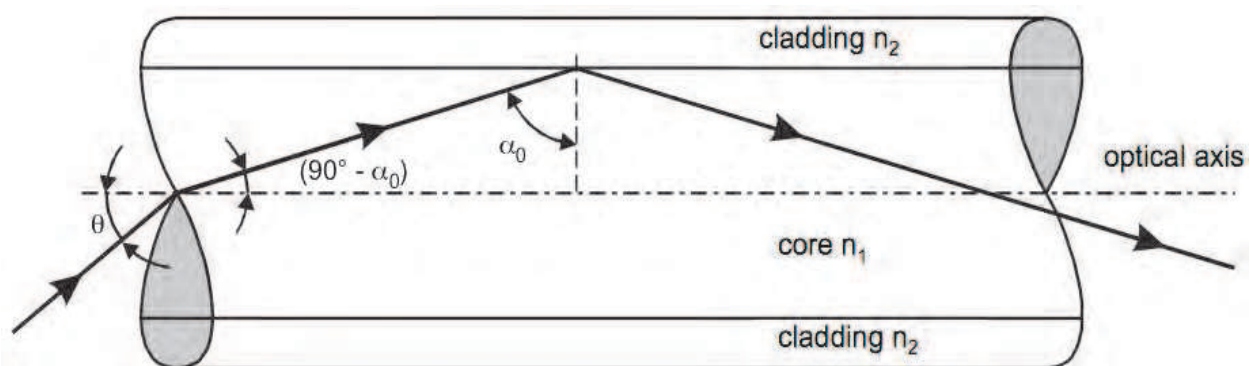where NA is the Numerical Aperture, a is the fiber radius , and λ is wavelength.

Fig. 2. Optical fiber waveguide.

A single-mode fiber has a V number that is less than 2.405, for most optical wavelengths. It will propagate light in a single guided mode. The multi-mode step index POF has a V number of 2,799, by a given optical wavelength of 550 nm, core radius of 490 μm, and NA of 0.5. This is more than 1000 times larger than for single-mode fiber Therefore the light will propagate in many paths or modes through the fiber. The number of optical modes can be calculated by:

$$N = 0.5\, V^2\, g/(g+2) \qquad (4)$$

where g is the index profile exponent, which is infinity for step index fibers. For step index POF the mode number can be calculated to $N \cong V^2/2 = 3.917$ Mio modes. For longer wavelengths the number of modes will reduce to 2.804 Mio modes at 650 nm. The number of modes will reduce the usable bandwidth by mode dispersion, which can be calculated by the difference of the optical path of the mode which is lead through the fiber without reflection t_1 at the core/cladding interface and the path of the mode t_2 which is most reflected due to a high aperture angle of 30°.

$$\Delta t_{mod} = t_1 - t_2 = L_1\, NA^2/(2\, c\, n_2) \tag{5}$$

The skew between the two modes in a POF step index fiber can be calculated to $\Delta t_{mod} \cong 25$ ns for $L_1 = 100$ m and c = velocity of light in vacuum. The bandwidth length product for uniform Gaussian pulses (Ziemann, 2008b)

$$B\, L \cong (0.44/\Delta t_{mod})\, L_1 \tag{6}$$

will result in a theoretical bandwidth of 14 MHz for 100 m fiber length. A reduced NA will magnify the bandwidth length product BL up to 100 MHz for a step index POF with a NA of 0.19. To increase the BL product, other types of POF, which are described in detail in chapter 3., are introduced

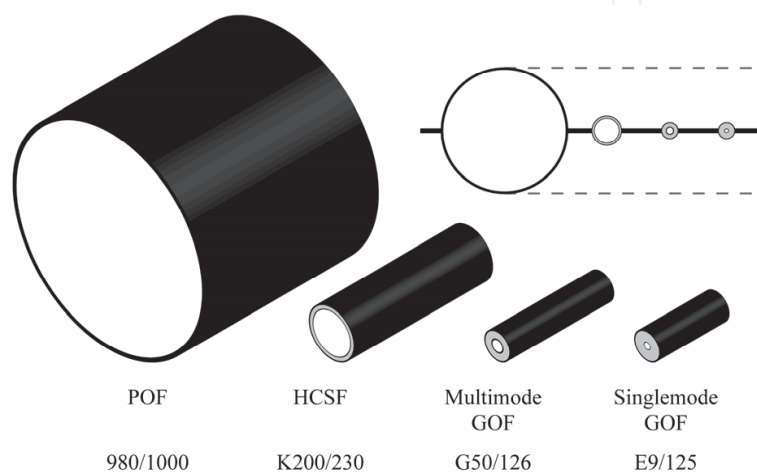POF 980/1000   HCSF K200/230   Multimode GOF G50/126   Singlemode GOF E9/125

Fig. 3a. Polymeric step index fiber, b. Comparison of the dimension of different optical fiber types.

Like all optical transmission systems, at the beginning of the transmission an electro-optical conversion in a transmitter turns the electrical modulated signals into optical signals (see Fig. 4). This is typically performed by the use of a LED for data speeds up to 150 Mbit/s. For higher data speeds the use of a Laser diode like a VCSEL or edge emitter is necessary.

Modulation format in the existing Fast Ethernet systems is direct modulation by ASK: Non-Return-to-Zero (NRZ). NRZ means that the transmitter switches from maximum level to zero switching with the bit pattern. The advantage is the very easy system set-up. The disadvantage is the large required bandwidth. Usually a minimum bandwidth corresponding to the half of the transmitted bit rate is needed (e.g. 50 MHz for a bit rate of 100 Mbit/s).

For 1 Gbit/s Ethernet direct modulation techniques are not possible for use in POF systems, because of the high mode dispersion of the SI POF. Here, different higher modulation techniques must be implemented:

2. Pulse Amplitude Modulation (PAM)

In pulse-amplitude modulation there are more than two levels possible. Usually 2^n levels are used, with $4 < n < 12$. Due to every symbol transmitting n bits, the required bandwidth and the noise is reduced by $1/n$. A great advantage of PAM is its flexibility and adaptability to the actual signal to noise ratio (Gaudino et al., 2007a, 2007b; Loquai et al., 2010).

2.1 Discrete Multi Tone (DMT)

At DMT the used spectrum is cut into many sub-carriers. Each sub-carrier can now be modulated discrete by quadrature amplitude modulation QAM. Strong signal processing must be implemented with a fast analog-to- digital converter and forward error correction, which makes the overall system expensive. Nowadays, many communication systems like DSL, LTE or WLAN use this method (Ziemann, 2010).
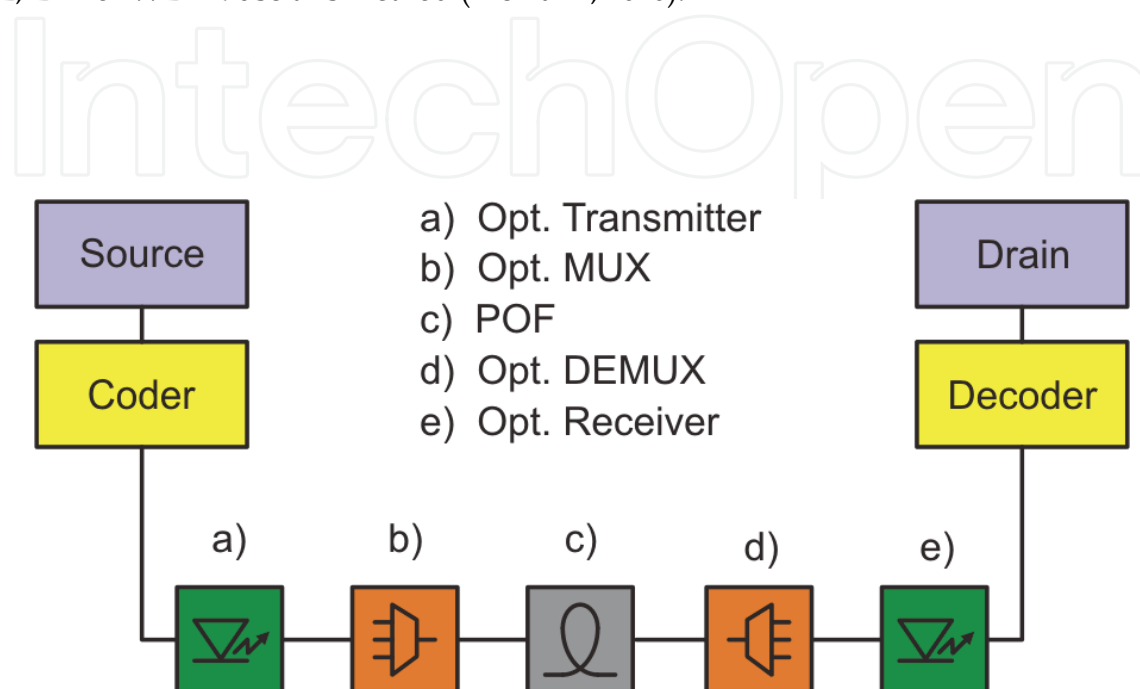

Fig. 4. Basic key elements of an optical transmission line.

At the end of the optical transmission path, an optical/electrical converter must be used. Typically, pin-photo diodes with large active areas are used. In between, the POF medium is situated using multiplexers (MUX) and demultiplexers (DEMUX) for higher effective data rates in the optical pathway. In this paper special optical DEMUX und MUX for wavelength multiplexing are described to extend the data rate of the whole systems for a factor of 4 – 10 in comparison to todays one channel transmission.

The use of copper as communication medium is technically out-dated, but still the standard for short distance communication. In comparison, POF offers lower weight, 1/10 of the volume of CAT cables and very low bending losses down to 20 mm radius. Another reason is the non-existent susceptibility to any kind of electromagnetic interference.

Wireless communication is afflicted with two main disadvantages:

* electromagnetic fields can disturb each other and probably other electronic device,
* wireless communication technologies provide almost no safeguards against unwarranted eavesdropping by third parties, which makes this technology unsuitable for the secure transmission of volatile and sensitive business information.

For these reasons, POF is already applied in various applications sectors. Two of these fields should be described in more detail in the next sections: the automotive sector and the in house communication sector.

2.2 Application areas of POF
2.2.1 Automotive

Since 2000 POF displaces copper in the passenger compartment for multimedia applications, see Fig. 5. The benefits for the automobile manufacturers are clear: POF offers a high operating bandwidth, increased transmission security, low weight, immunity to electromagnetic interference, and ease of handing and installation (Daishing POF Co., Ltd, n.d.). This vehicle bus standard is called Media Oriented Systems Transport (MOST). It is based on synchronous data communication and is used for transmission of multimedia signals over polymer optical fiber (MOST25, MOST50, MOST150) or via electrical conductors (MOST50). The technology was developed, standardized and up to date regularly refined by the MOST Cooperation founded in 1998. MOST was first introduced by BMW in the 7er series in 2001. Since then, MOST technology is used in almost all major car manufacturers in the world, such as VAG Group, Toyota, BMW, Mercedes-Benz, Ford, Hyundai, Jaguar and Land Rover (Wikipedia, 2011). In 2011 there are more than 50 different car types on the market which use the POF in the passenger cabin network structure for multi media data services.

The MOST specification covers all seven layers of the ISO/OSI Reference Model for data communication. On a physical layer polymer optical fiber is used as a media. A light emitting diode (LED) is used for transmission in red wavelength area at 650 nm. PIN photo diode is used as receiver (Grzemba, 2008).

The basic architecture of a MOST network is a logical ring, which consists of up to 64 devices (nods). The logical ring structure is usually implemented on a physical ring, which is however not mandatory. Combined ring, star network or double ring (for critical applications) can also be realised. Plug and play functionality enables easy adding or removing of devices.

In a MOST network one MOST device handles the role of the Timing Master which feeds MOST frames into the ring at a sampling rate of 44.1 kHz (frame is transmitted 44,100 times a second) or 48 kHz. The latest MOST specification recommends sampling rate of 48 kHz. The exact data rate depends on the sampling rate of the system. One after another Timing Slaves on the logical ring receive the signal, synchronize themselves with the preamble, parse the frame, process the desired information, add information to the free slots in the frame and transmits the frame to their successor. Since the MOST system is fully synchronous, with all devices connected to the bus being synchronized, no memory buffering is needed. Each Time Slave contain a fiber optic transceiver - received light signals are converted into electrical domain, processed, converted back into the optical domain and forwarded further.

A MOST frame includes one area for the synchronous transmission of streaming data (audio and video data), one area for the asynchronous transmission of packet data (TCP/IP packets or configuration data for a navigation system), and one area for the transmission of control data. MOST25 frame consists of 512 bits (64 bytes). 60 bytes are used for transmission of data. 6 – 15 quadlets (qualet consists of 4 bytes) of the data can be synchronous data, while the rest of the 60 bytes (0 – 9 quadlets) hold asynchronous data. Two bytes transport the part of the control message which spreads over 16 frames (one block). The first and the last byte of the frame contain the control information for the frame. MOST25 provides a data rate of 22.58 Mbit/s at a sampling rate of 44.1 kHz. This allows up to 15 uncompressed stereo audio channels in CD quality (2x16 bits per channel) / 15 MPEG1 channels for audio-video transmission or up to 60 1-byte connections to be established simultaneously. Maximal data rate is 24.58 Mbit/s at a sampling frequency of 48 kHz.
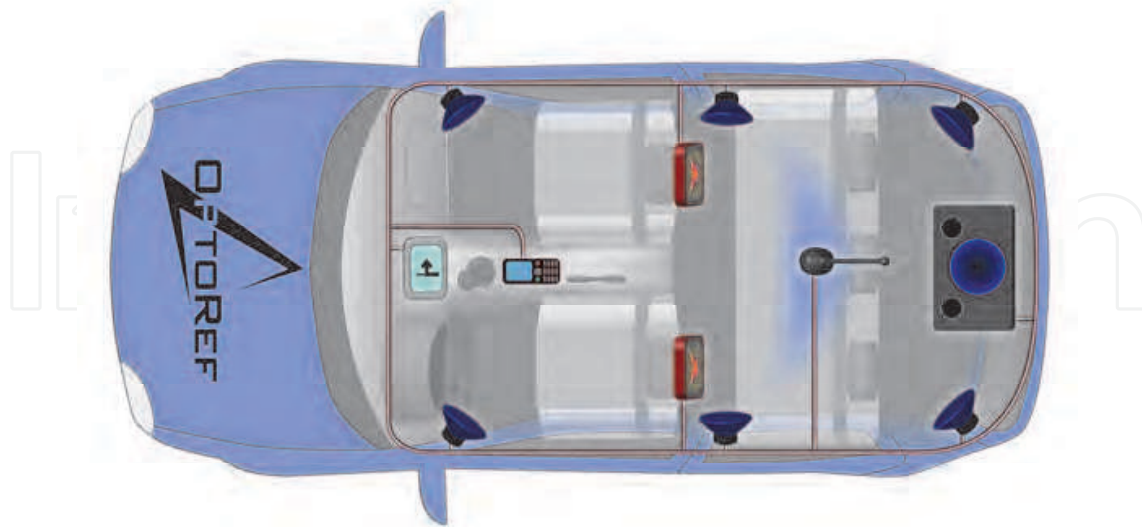
Fig. 5. Multimedia Bus System (MOST-Bus) with POF.

Next MOST generation uses a bit rate of just under 50 Mbit/s for doubling the bandwidth. The name MOST50 derives from this fact. Each frame consists of 1024 bits (128 bytes): 11 bytes for header, which also includes the control channel, and 117 bytes for the payload. The border between synchronous and asynchronous data can be adapted dynamically to the current requirements. The synchronous area can have a width of 0 to 29 quadlets plus one byte (0 to 117 bytes) and the asynchronous area can have a width of 0 to 29 quadlets (116 bytes). Control message consists of 64 bytes.

The latest MOST version (MOST150) was presented in October 2007. MOST150 is designed for high data rate of just under 150 Mbit/s and has a frame of 3027 bits (384 bytes): 12 bytes for header, which also includes the control channel, and 372 bytes for streaming and packet data transfer. It also has access to the dynamic boundary. Both, synchronous and asynchronous areas can have a width in between of 0 and 372 bytes. Besides the three known channels, an Ethernet channel with adjustable bandwidth and isochronous transfer on the synchronous channel for HDTV were introduced. This enables the transmission of synchronous data that require a different frequency than that given by the frame rate of the MOST. MOST150 thus a physical layer for Ethernet in the vehicle (MOST Cooperation, 2010).

Not just multimedia functions can exploit POF. For example, BMW has developed a 10 Mbit/s protocol called ByteFlight, which it uses to support the rapidly growing number of sensors, actuators and electronic control units within cars. Unlike MOST, which employs real-time data transfer, ByteFlight is a deterministic system in which the focus is on making sure that no data is lost (BMW, n.d.). The glass temperature of POF (below 85°C) makes using the fiber in the engine compartment impossible, although this problem might be solved in the foreseeable future. Up to date, a number of different in-car networks for multimedia and security applications has been developed, see Fig. 7.

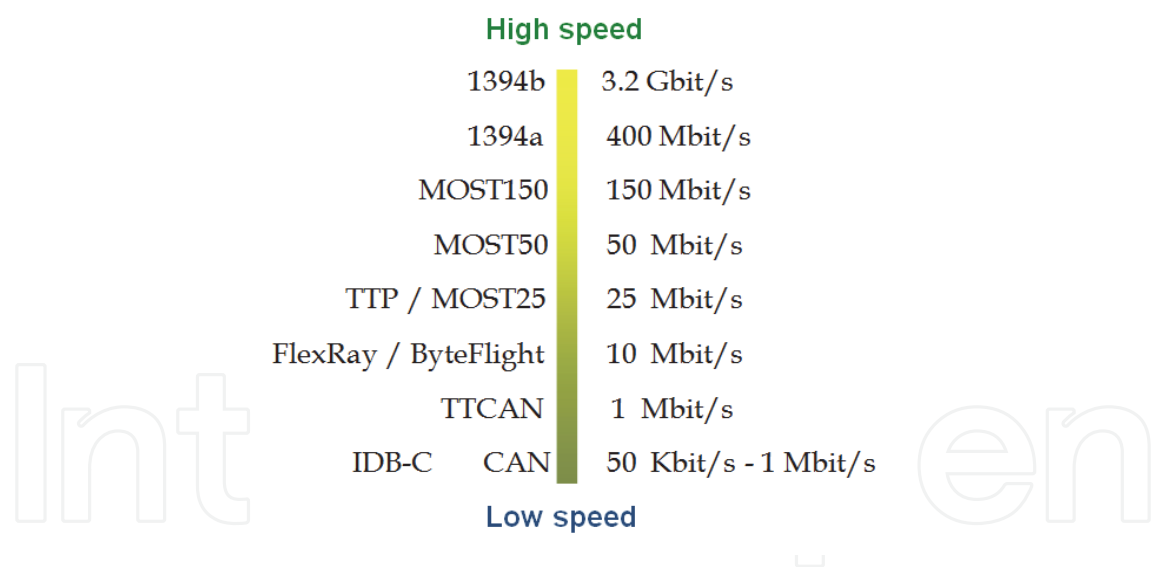Fig. 6. MOST applications in the multimedia bus.

Fig. 7. In-Car network data rates.

2.3 Use of POF in aircraft

To use POF as the transmission media for aircrafts is under the research of different R&D groups due to its specific advantages. The DLR (German Aerospace Center) researches this kind of fiber under the conditions in civil aircrafts. They concluded that "the use of POF multimedia fibers appears to be possible for future aircraft applications" (Cherian et al., 2010). The Boeing Company develops special measurement setups to investigate and analyze POFs for the application under the conditions of daily use in aircrafts. Especially the low weight and the easy and economic handling make this kind of fiber the first choice. But

for now the data rates and the temperature range are too low to replace copper for multimedia purposes.

To build aircraft with less weight, all big aircraft manufacturers will use carbon fibers for the aircraft body in all the new aircraft models. Because of its better weight performance, the aviation will loose a lot of its resistance against EMV and outer space radiation. To use optical cables like glass fibers or polymeric fibers is a good approach to bypass the problems of EMV in signal transmission. One coming solution will be the replacement of the electrical copper cables by POF and the application of the bus protocols FlexRay or MOST, which is widely used in the automotive industry (Lubkol, 2008; Strobel, 2010).

In aviation, strong test procedures are introduced for high reliable operation of all system components. High and low temperature operation starting from –60°C up to +130°C must be considered. Also high vibration stability in case of using optical connectors is required. For system relevant usage in the airplane, it is necessary to design the cable in the aircraft for POF use fire- and heat resistant and also waterproof, respectively. Additionally, high temperature POF must be implemented to force stable operation at temperatures in the aircraft up to +130°C, which can occur in the cockpit system unit.

To implement MOST technology in the airplane in the cabin for multimedia usage, the normal standard fiber can be used, because of the not relevant system impact of multimedia provision of the passengers. Up to now, the usage of POF in the airplane is focused in the research area and it will take years to test the reliability for everyday use in the airplane industry.

2.4 In-house

Another sector where POF displaces the traditional communication medium is in-house communication, although the possibilities of application are not confined to the inside of the house itself. In the future, POF will most likely displace copper cables for the so-called last mile between the last distribution box of the telecommunication company and the end-consumer (Koonen et al., 2005, 2009). Today, copper cables are the most significant bottleneck for high-speed Internet.

"Triple Play", the combination of VoIP, IPTV and the classical Internet, is being introduced to the market with force, therefore high-speed connections are essential. It is highly expensive to realize any VDSL system using copper components, thus the future will be FTTH (Fischer, 2007a).

For in-house communications networks data rates between 10 Mbit/s and 100 Mbit/s are typically in use. Copper-cables (Category 5/6) are most widely used in office networks in combination with structured wiring system of DIN EN 50173-1 and DIN EN 50173-2. The 8-core wire in combination with the RJ45 plug can transmit 100/1000 Mbit/s over distances up to 100 meters using Ethernet protocol. Due to the mass-market application of Ethernet (IEEE 802.3), this technique has become very cheap. Most broadband home networks today focus on the combination of Ethernet and RJ45 data cable interface. The disadvantage of this technique depends on the lack of structured cabling in most apartments. The possibilities for re-installation of the thick and inflexible CAT cables are very limited, while most of the wiring has no professional electrical grounding.

In the following the available in-house network technologies are depicted and compared in detail with their specific advantages and disadvantages with POF applications in Table 1:

- Twisted-pair cables belong to the Ethernet standard CAT 5/6 with a star network topology and data rates up to 1 Gbit/s up to 100 m, but due to very thick cables (Ø 7 mm)

wide cable channels and complex plug required. They have no electrical isolation, which also leads to a high EMC sensitivity. This disturbing especially in the industrial and automotive environment the transmission.

- Coaxial cables, as they are known from the TV connection, have a diameter of 5 mm and a much higher bandwidth up to 1 GHz for 30 m with large bend radii. However, the electrical isolation from the 230 V power is problematic, which can lead to problems. The EMC problem is related critical as the twisted-pair cable.

- Glass fibers are the media with the highest range and data rate, but expensive compared to alternative techniques, also because of expensive connector assembly and low possible bending radii. Additionally, the small core diameter of 9 microns for single mode fiber is highly vulnerable to pollution. This leads to significant problems in the industrial environment, but without EMC problems.

- Polymer fibers can be easily laid with small bend radii, are very tolerant in terms of buckling and pollution (large core cross-section), without the need of using connectors. It can be shown that POF have a high future potential for increased data rate without having to install additional fibers. Like the glass fiber, POF has a fiber optic to electrical isolation and has a very low EMC sensitivity.

- WLAN is a pure wireless technology with a possible range up to 20 m. Due to absorption by walls, and ceilings the effective range is poor. Furthermore due to interference by third parties, the transmission is not secure. In addition, neighbouring networks will reduce the data rate significantly. This leads especially in the industrial environment to a very large problem, if there are installed WLAN nodes in a very large number. Data rates from 2 up to 100 Mbit/s data rate are possible under optimal conditions, most of the achievable data rates remains well below it.

- Powerline uses the 230 V-house power grid. The range is very limited and depends on the power grid. However, there are only low installation costs, but the high electromagnetic radiation and the uncontrolled distribution over the network are major disadvantages, which makes this network technology for in-house use unattractive.

Technique	Data rate	Range	Security	Costs	Handling	Deployability	Total
Twisted-Pair cable	+	0	0	++	-	0	2+
Coax cable	0	0	0	+	0	0	1+
Glass fiber	++	++	++	--	--	-	1+
POF	0	-	++	+	+	+	4+
WLAN	--	-	--	++	++	++	1+
Powerline	-	-	--	+	+	++	0

Table 1. In-house networks in comparison, division between particularly poor -- and particularly well: ++

In Table 1 an overview is summarized to assess the respective qualities of the alternative networks in view of the most important criteria. It turns out that the most widely used networking technologies such as wireless or twisted pair are leader in the field in terms of costs, but in total the polymer fiber technology shows superior overall properties and combines many advantages of the other transmission media, without their main drawbacks. Keeping these reasons in mind, the further potential of POF seems to be very high.
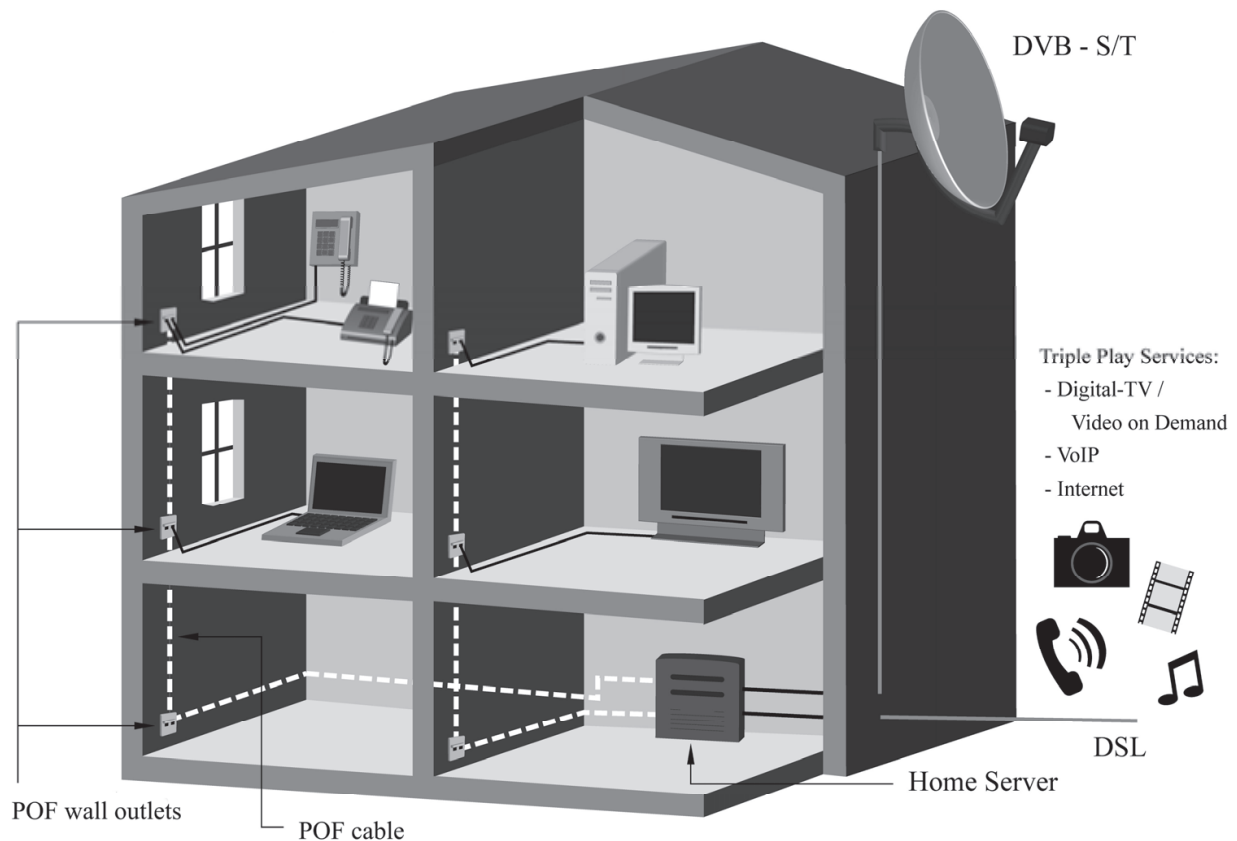
Fig. 8. In-house communication scenario with POF –Ethernet system.

3. State of the art in POF transmission systems

3.1 POF fiber types

Plastic optical fibers for data transmission until recently were limited to step index PMMA fibers that had bandwidths of 38 MHz-100 m (Mitsubishi Eska). More recent results by Mitsubishi with an Eska-Mega fiber shows a three fold increase in bandwidth to 105 MHz-100 m. Increases in bandwidth are also possible with the use of dual step index (DSI), multi-step index (MSI) profiles, multi-core (MC), or combinations of these (Poisel et al., 2003). Here, only the most relevant used POF types are described.

For POF there are in general three fiber types existing, which are on the market available (Table 2).

3.1.1 Step index fibers SI POF

The SI POF (Fig. 9) is already standardized in a IEC 60793-2-40: and IEC 60794-2-40: specification for A4 fiber cables and also in an ETSI recommendation TS 105 175-1. The SI POF fiber is called in the specification as A4.a1 and A4.a2, respectively. Optical properties and also mechanical ones are strictly defined to guaranty a international reliable high level of fabricated fibers. Optical specs are 980/1000 µm diameters, temperature range of -40 °C - +85 °C, and A4a1 is a fiber with attenuation 180 dB/km at 650 nm and bandwidth 4 MHz-km, which is of course the performance of the standard 1 mm, high NA, SI POF. A4a2 refers to the nominally 0.5 mm PF-GI-POF which has an attenuation of less than

100 dB/km in the red, but more significantly, transmits at 850 nm with an attenuation of 40 dB/km. The bandwidth of this fiber is very high, typically of that of GI POF fibers, ~200 MHz-km, but is not in use in cars or in-house networks.

3.1.2 Gradient index fibers GI POF

Here the core-refracting index is distributed in a quadratic behaviour (Fig. 10). This reduces the mode dispersion significantly and relates to a better BL than in step index fibers. BL products of more than 2 GHz-100 m are realized with OM Giga from Optimedia Inc. in Korea. Specifications of different POF types are shown in Table 2:

Specs/Fiber type	SI POF (IEC 60793-2-40)	GI POF (Park 2006)	MC POF (Asahi Chem.)
Diameter (core) mm	1.0 (0.9)	1.0 (0.9)	1.0 (0.9)
Variation of Diameter %	± 5	± 5	± 5
Tensile at break N	> 65	> 65	> 65
Bending Radius mm	> 20	> 35	> 15
Operating Temperature °C	-40 ~ 85	-30 ~ 70	-40 ~ 85
Attenuation dB/km	< 180 at 650 nm	< 200 at 650 nm	< 180 at 650 nm
Bandwidth Mbps	~ 40 @ 100 m	~ 2000 @ 100 m	> 500 @ 100 m

Table 2. Specifications of different POF types.

3.1.3 Multicore fiber MC POF

In this approach, the fiber can be made of many tiny cores, a multi-core POF (Fig. 11). The partition of the core into many individual light guiding areas allows for very small bending radii, helping to ease the installation of the fiber. The numeric aperture and the bandwidth is nearly the same as of the SI-POF. Up to now, there is no international standard available for this new type of POF. In the market available is the fiber from Asahi Chemical, shown in Fig. 11. 19 multi cores of PMMA are introduced in one complete fiber. The NA of this fiber is 0.27 with 1 mm outer diameter and bandwidth length product of 500 Mbit/s-100 m. Operating temperature ranges from –40 °C up to +85 °C. This fiber is an excellent candidate to replace in the next future the SI POF in the mass market, because of its good bandwidth performance and comparable price. On the other hand, standardizing procedures must be realized to make this MC POF acceptable for international network markets.
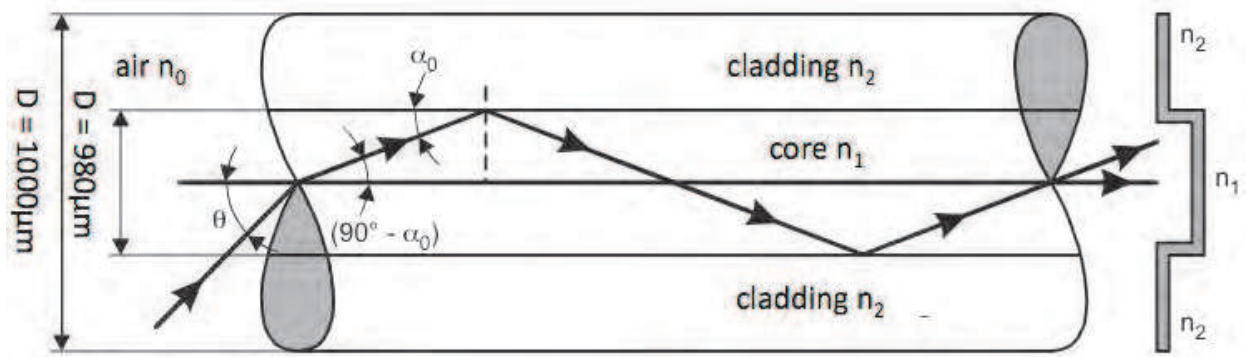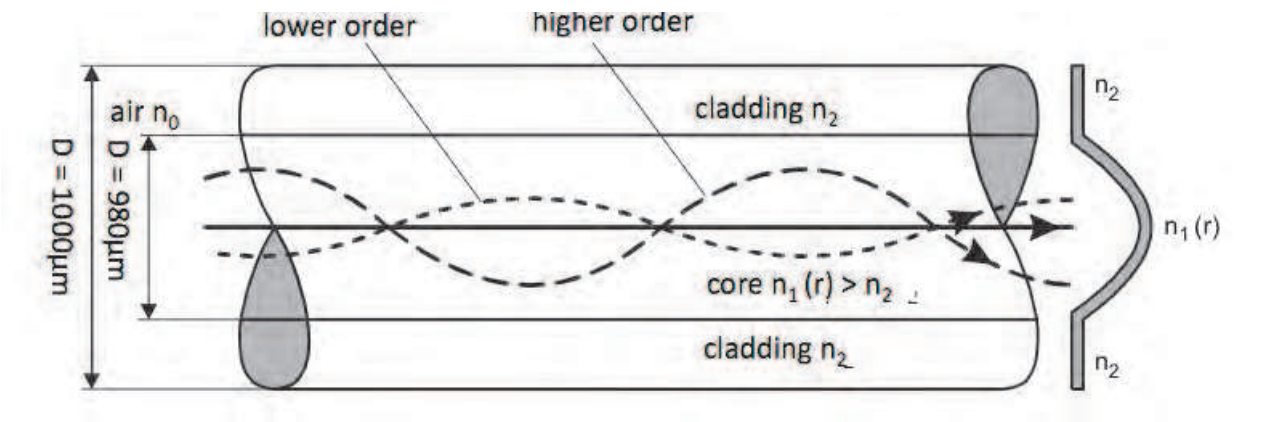

Fig. 9. Step index POF.
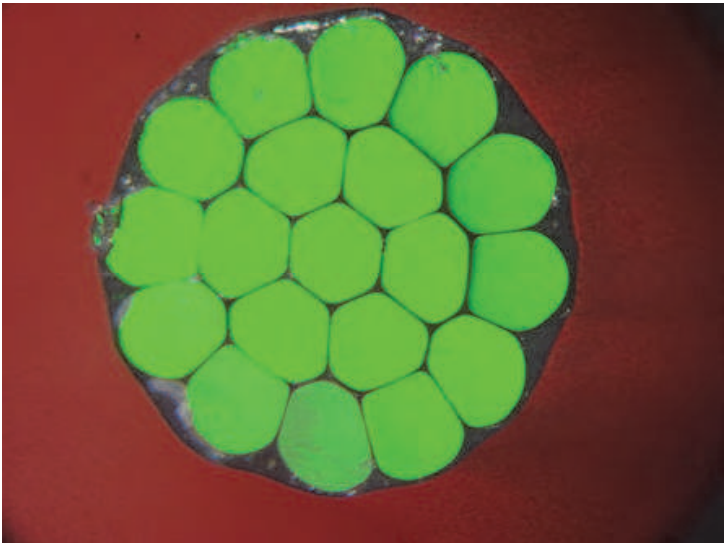
Fig. 10. Gradient index POF.

Fig. 11. Multi core POF (Asahi Chemical) 1 mm diameter, 500Mbit/s-100 m.

3.2 Standardization of POF

As shown in this chapter, SI POF is standardized by the International Electrotechnical Commission (IEC) as the A4 category of fibers. In completion, this category contains four types (families A4a-A4d) of SI POF having core diameters ranging from 490 microns to 980 microns for different applications in networks, multimedia sources and sensor systems. This standard also defines other dimensional requirements for these fibers, as well as minimum mechanical and transmission properties (Ziemann 2008). The existing IEC POF standards do not specify any environmental requirements, however.

OFS and Nexans have recently proposed to modify the A4 category fiber standards to include perfluorinated GI POF. According to this proposal, four new fiber families (A4e-A4h) are be added to the A4 category. These families will have core diameters of 500 µm, 200 µm, 120 µm, and 62.5 µm, and are intended to serve a wide variety of applications ranging from consumer electronics to multi-Gb/s data communication.

In Germany, the DKE as the Standardization Division of the VDE Germany has established a POF working group DKE 412.7.1, which is responsible for the international standardisation of Gbit/s POF transmission systems with active and passive elements.

4. WDM over POF

Several sectors will be introduced, where POF offers advantages when compared to the established technologies. Other possible industrial sectors include the aviation or the medical sector. All these applications have one thing in common – they all need high-speed communications systems. The standard communication over POF uses only one single channel. To increase bandwidth for this technology the only possibility is to increase the data rate, which lowers the signal-to-noise ratio and therefore can only be improved in small limitations.

Fig. 12. Advantages of extending the overall transmission capacity using WDM.

Wavelength Division Multiplexing (WDM) is a technique that combines multiple, unique optical signals at different wavelengths (colours) onto a single strand of fiber. At the receiving location, these optical signals are split back out, or demultiplexed, into separate fibers. Essentially, the bandwidth capacity of the fiber is multiplied by the number of wavelengths multiplexed onto the fiber. Fig. 12 conceptually shows the principal benefits of the WDM technique. The WDM system capacity (T) depends on three basic parameters, which are open to modify:

Bit Rate per Channel (C)
Optical Bandwidth (B)
Channel Density (D)

$$T = B \cdot C \cdot D \tag{7}$$

In comparison to single channel transmission systems that only extend the capacity by the help of higher bitrates per channel, WDM will allow to boost up the overall transmission capacity by two additional factors:

• the channel density and
• the optical bandwidth of the system.

Both factors in combination will lead to the total number of wavelength channels which are possible to implement in the whole system. For glass fiber systems the optical bandwidth is characterised by the fibers attenuation curve between 1300 nm and 1650 nm. Here using

POF the bandwidth ist allocated beween 400 nm and 800 nm. Assuming a bandwidth of B = 380 nm and a channel density of D = 1/40 nm, a bit rate per channel of 1 Gbit/s the total capacity will be   T = 1 Gbit/s x (380 nm/40 nm) = 9,5 Gbit/s. The application of fixed reference channels for POF systems will be described in chapter 4.6.

For the use of different channel densities, a international system was established for glass fiber systems which defines fixed channel spacing for long distance, metro and short haul networks: this variations of WDM that are commonly used for glass fiber systems: Broad WDM, Coarse WDM, and Dense WDM. Each variation has different capabilities, costs, and operational friendliness.

4.1 Broad WDM

Broad WDM (often just called WDM) utilizes two wavelengths with are parted by more than 200 nm. Broad WDM is very simple to implement. Off-the-shelf optical transmitters without tight control of wavelengths can be used. These applications also utilize low-cost optical multiplexers and demultiplexers with low insertion loss, but are not useful for higher speed systems.

4.2 Coarse WDM

Coarse WDM (CWDM) utilizes multiple wavelengths spaced at 20 nm in the infra red region. The International Telecommunication Union (ITU) in G 694-2 specifies 18 CWDM wavelengths from 1271 nm to 1611 nm for metro networks using optical glass fibers. Transmitters, optical multiplexers, and demultiplexers are at defined wavelengths, but they do not need to be tightly controlled, which translates into lower equipment costs compared to Dense WDM.

4.3 Dense WDM

Dense WDM (DWDM) utilizes many wavelengths spaced narrowly, and they are most commonly located in the C-band, the wavelength range from 1530 nm to 1565 nm. ITU G 694-1 in specifies the center of the DWDM wavelengths. Practical deployments of DWDM today are spaced at 100 GHz frequencies (or approximately 0.8 nm spacing), which allow about 40 wavelengths in the C-band. DWDM requires that the optical transmitters, multiplexers and demultiplexers have very tight control over the wavelength under all operating temperature conditions.

This contribution presents a possibility to open the WDM technique to the POF world. This basic concept can – in theory – also be assigned to POF. However POF shows different attenuation behavior, see Fig. 1. For this reason, only the visible spectrum between 400 nm – 780 nm can be applied when using POF for communication.

For WDM, two key-elements are indispensable: a multiplexer and a demultiplexer. The multiplexer is placed before the single fiber to integrate every wavelength to a single waveguide. The second element, the demultiplexer, is placed behind the fiber to regain every discrete wavelength. Therefore, the polychromatic light must be split in its monochromatic parts to regain the information. These two components are well known for infrared telecom systems, but must be re-developed for POF, because of the different transmission windows.

One technical solution for this problem is available, but it cannot be efficiently utilized in the POF application scenario described here, mostly because this solution is afflicted with high costs and therefore not applicable for any mass production.

4.4 Basic concept of the demultiplexer

As mentioned before, a demultiplexer is essential for WDM (Daum et al., 2008; Chen & Lipscomb, 2000). Several preconditions must be fulfilled to create a functional demultiplexer for POF. First of all, the divergent light beam, which escapes the POF, must be focused. This is done by an on-axis mirror. In the first attempt, a spherical mirror is used. To get perfect results without any spherical aberrations, an ellipsoid mirror should be used.

The second function is the separation of the different transmitted wavelengths (Fischer et al., 2007b). In Fig. 13, this principle is illustrated for three wavelengths (red, green, blue). This is not a limitation for possible future developments, but rather an experimental basis from where to run the various simulations described below. The diffraction is done by a diffraction grating. The diffraction is split into different orders of diffraction. The first order is the important one to regain all information. There a detector line can be installed to detect the signals.
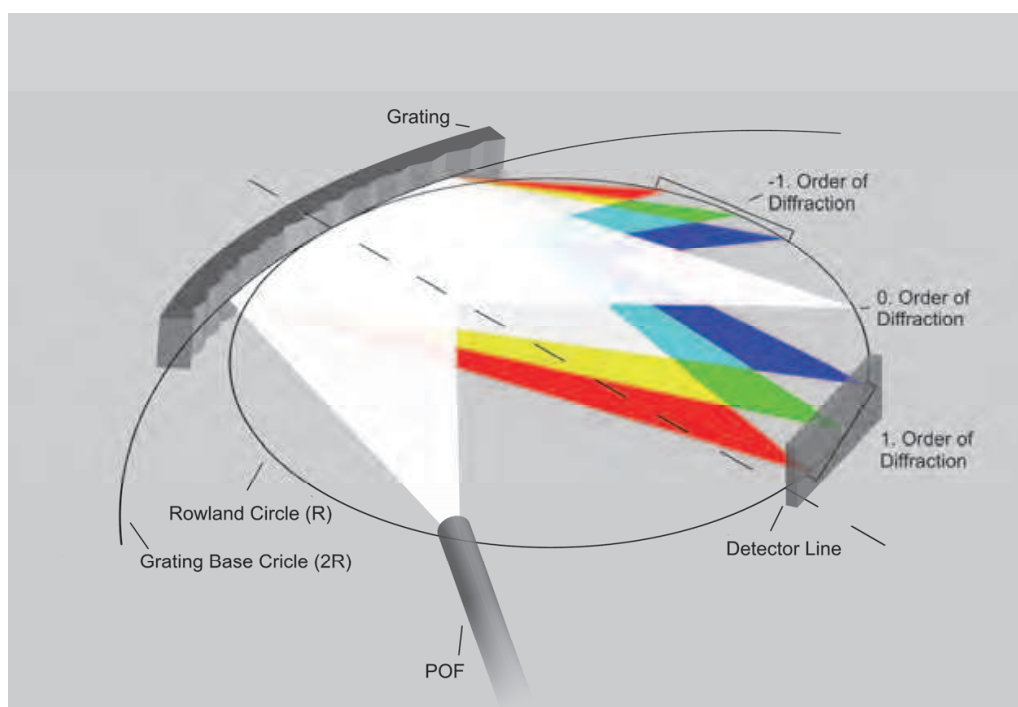

Fig. 13. Principle sketch of a Rowland Spectrometer.

Because the grating is attached to a bended basement only one element can cover both functions, the focusing and the diffracting. Hence the light is not afflicted with any aberrations or attenuations of a focusing lens or other refractive elements, which are necessary for any other setup. The diffraction is split into different orders of diffraction. The first order ($z = 1$) is the important one for data transmission. The higher the grating constant g of the diffraction grating, the more accurate the shape of the maxima of the different diffraction orders. The diffracted light interferes positively on the detection layer for (Demtröder, 2008):

$$z\lambda = g(\sin\alpha + \sin\beta) \tag{8}$$

with α angle of incidence, β emergent angle and g the grating constant. The following figure illustrates this formula (Fig 14).
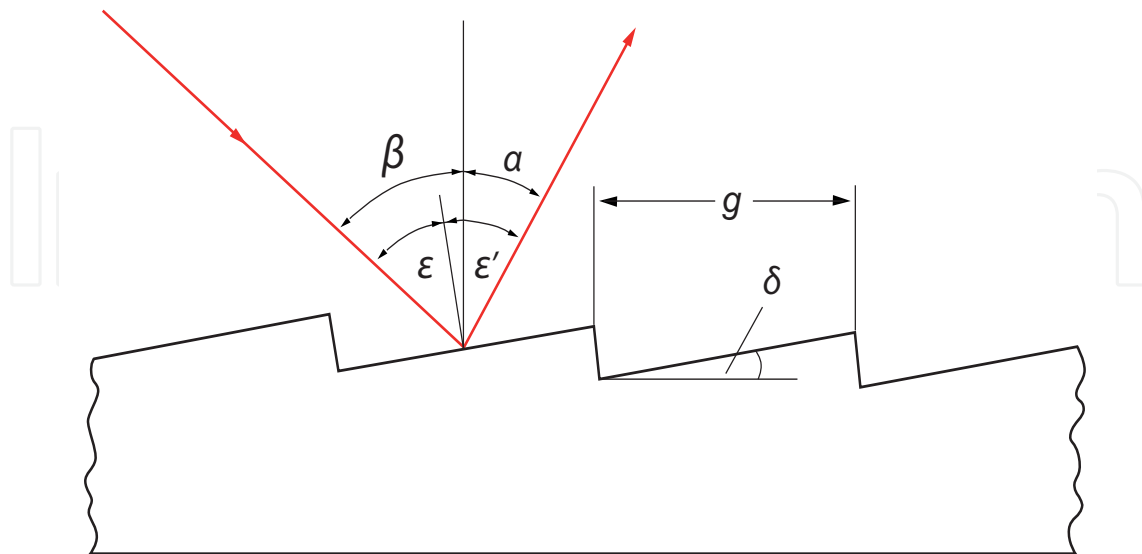
Fig. 14. Grating and behavior of light.

The resolution of the diffraction grating follows the Rayleigh Criterion and depends on the complete number of grating steps N and not on the grating constant (Hecht, 2009):

$$(\lambda/\Delta\lambda) \leq zN \qquad (9)$$

This means for the first order of diffraction (z=1) and a number of grating steps N = 3000 (300 lines/mm) that the resolving power is $\Delta\lambda$ = 0.196 nm for λ = 589 nm.

One other characteristic of key elements for POF communication is the three dimensional approach. Key elements of glass fiber communication are usually designed planar. This simplification cannot be adopted for POF communication, because of POF's large numerical aperture and therefore large angle of beam spread.

4.4.1 Results of the simulation

In the following steps, a software program is used to design a demultiplexer based on the general concept outlined above. For the current task, the software OpTaLiX, which is based on the raytracing method, provides all needed functionalities (Blechinger, 2008; Hecht, 2009; Demtröder, 2008). This approach offers different advantages, it is easy to design, analyze and evaluate the simulated results. Also, effective improvements of the configuration can be simulated fast.

4.4.2 Results of the simulation for different line densities

In figure 15, the 2D plot for the reference wavelength (520 nm) of the demultiplexer with an ellipsoid mirror and grating is shown. The multicolored light is emitted by a polymeric fiber. It hits the mirror, where it is focused and diffracted in its monochromatic parts. The light is focused onto a POF- or detector-array.
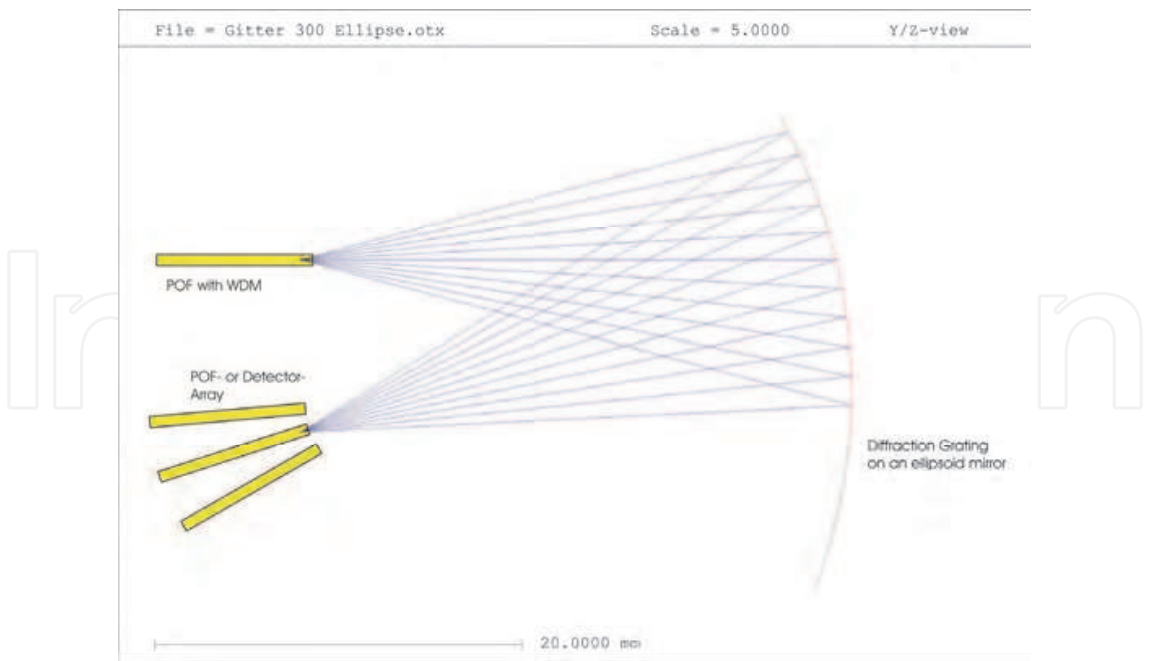
Fig. 15. 2D plot of the demultiplexer.

Without a grating, a perfect point to point mapping (without any aberrations) is possible with an ellipsoid mirror because of the two foci, but there is no separation of the different channels. With a grating stamped on the mirror, the separation of the multicolored light in its monochromatic parts is possible. But this grating distorts the optical path of light dramatically. The first change is the gap of the different colors in the image layer (here the POF- or Detector Array) increases with the line density of the grating. This can be noticed for an ellipsoid mirror (Fig. 16) and for a spherical mirror (Fig. 17) as well. The spherical mirror has the advantage, that the shape can be produced for injection molding easier.

| 300 lines/mm | 600 lines/mm | 1200 lines/mm |

Fig. 16. 2D Plot of the demultiplexer with an ellipsoid mirror and different line densities.

d=2mm

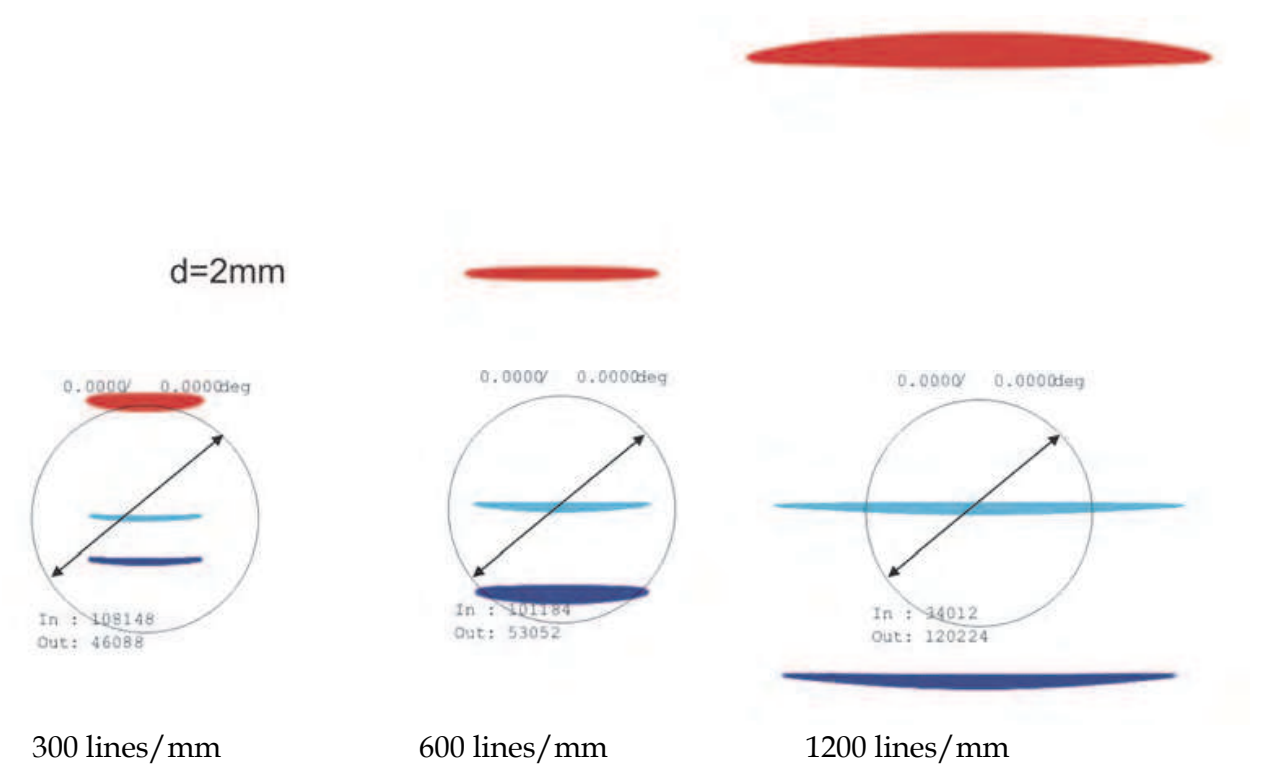300 lines/mm   600 lines/mm   1200 lines/mm

Fig. 17. 2D Plot of the demultiplexer with a spherical mirror and different line densities.
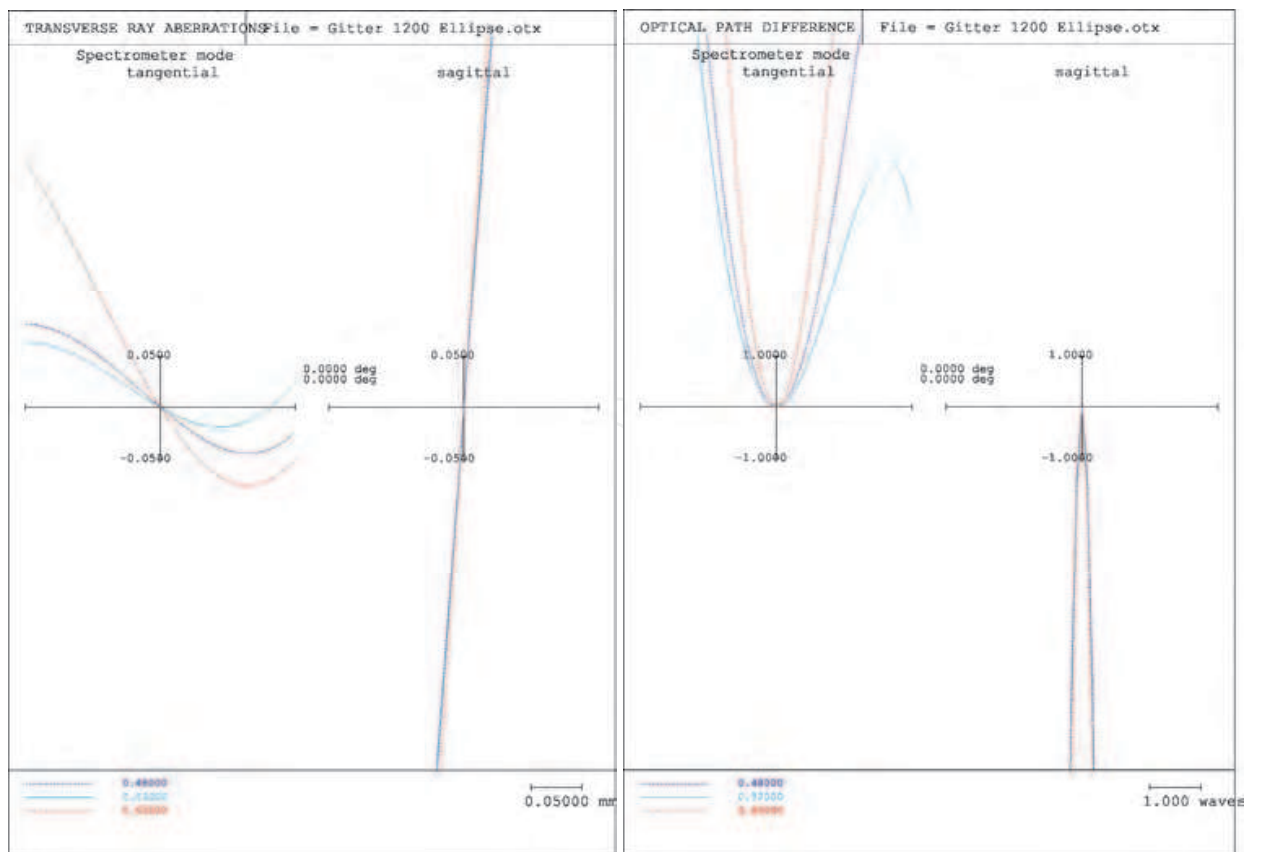

Fig. 18. TRA and OPD for the ellipsoid demultiplexer with 1200 lines/mm.

The second changes are the great aberrations especially for the demultiplexer high line density. To underline this result and to analyze the aberrations in detail, the transverse ray aberration (TRA) and the optical path difference (OPD) in spectrometer mode are shown in figure 18 for the demultiplexer with an ellipsoid mirror and 1200 lines/mm. The chief ray coordinates are irrespective for the TRA and OPD to overlap the different colors.

The TRA shows a slight defocusing for the meridional section, but a very strong defocusing for the sagittal section. The graph of the function in the meridional section exhibits a predominant third order Seidel coefficient. Therefore the slight defocusing in the meridional section compensates the astigmatism. The OPD shows as expected strong deviation from the ideal waveform especially in the sagittal section. This defocusing leads to high losses for the coupling efficiency for the POF- or detector- array in the image layer.

It is obvious that the grating changes the focal length especially of the sagittal section; therefore the shape of the mirror must be improved. It is necessary to change the radius of curvature notable in the sagittal section. Hence the basic shape of the mirror is not longer a sphere or ellipsoid. To meet the demands a higher order shape, which is nearly cylindrical, is used.

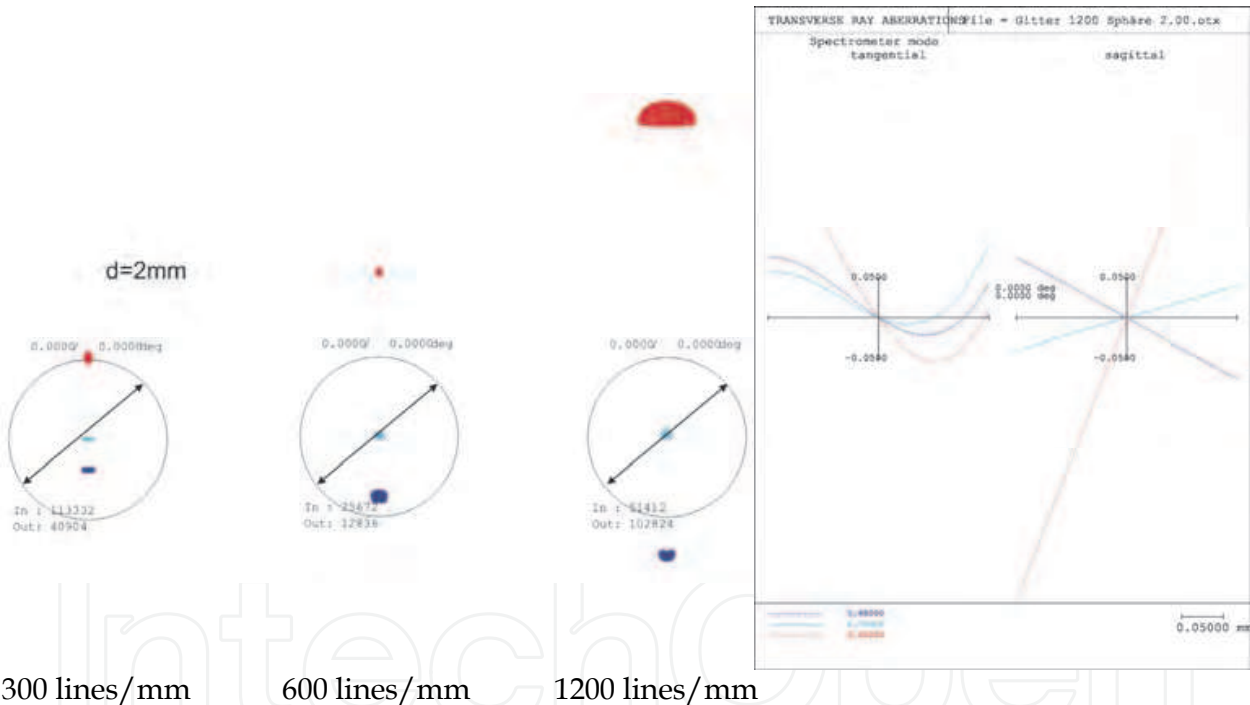300 lines/mm   600 lines/mm   1200 lines/mm

Fig. 19. Spot Diagram and TRA for the improved DEMUX.

The change of the mirror shape improves the imaging quality substantial. The spot diagram and the TRA for the improved demultiplexer are shown in Fig. 19.

The spot diagram shows three dividable colors. The gap between every color is larger than 2 mm. The TRA shows a marginal shift of the focus of all wavelengths to offset the astigmatism in the meridional section. Because of the spectrometric function of the demultiplexer it is not possible to focus all three colors simultaneously. There is always a combination of over and under correction for the different colors. Hence the radius of the mirror in the sagittal section is optimized to focus the colors completely as much as possible.

This improved demultiplexer can separate three colors with enough space between them to regain the information with a POF- or detector-array. The shapes of the foci feature low coupling losses and the shape of the mirror is easy to produce in injection molding.

4.5 WDM reference comb

Different analyses will be shown in the full chapter including TRA and OPD. The way to the optimized setup will described in detail. Further on a first attempt to standardize the different wavelengths in visible spectrum will be discussed. As described in the previous chapter, WDM has a great chance to expand the overall bandwidth of POF transmission systems. Therefore it is necessary to standardize the WDM channels in frequency or wavelength, based on proven the glass fiber system channel allocation map of ITU recommendation G.694.2-1/2.

4.6 Optical channel allocation map proposal for POF

The usable transmission window in the visible spectrum of POF is located between 400 – 700 nm, which leads to the possible optical bandwidth of 300 nm for POF. Now the ITU proposes a frequency allocation map for WDM in its recommendation G 694.2. Assuming the correlation between wavelength and frequency of electro magnetic waves

$$\lambda\,f = c_{vac} \tag{10}$$

where f = frequency λ = wavelength and c_{vac} = speed of light in vacuum. Calculating the equivalent frequencies to 400 nm and 700 nm will result in 750 THz and 461.5 THz combined with a bandwidth of 320 THz for true WDM transmission. Additionally, a so-called anchor frequency (for glass fiber systems 193.1 THz) will be proposed as 750 THz. The possible transmission windows for WDM channels are dependent on the attenuation of the PMMA based standard SI POF. A possible transmission channel at 490 THz (610 nm) must be omitted because of the attenuation of the OH-Peak at 610 nm at that frequency (see Fig. 20).

The region of low attenuation of less than 90 dB/km is apportioned between 510 THz and 750 THz. In total 9 WDM channels, which are listed in Tab. 3, can be fixed with channel spacing of 40 THz.
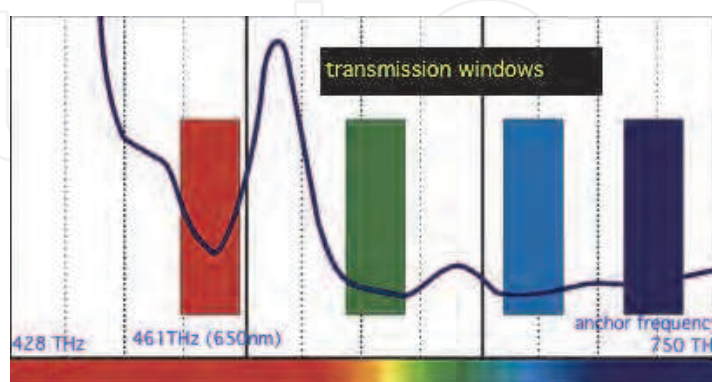

Fig. 20. Proposed optical frequency comb window.

The channel frequencies are calculated by:

$$f_{ch} = 750\text{THz} – n\,(40\text{THz}) \tag{11}$$

where n is the number of the channel.

In total a WDM system data rate of 9 x 2.5 Gbit/s = 22.5 Gbit/s seems to be possible assuming the todays data rates of POF systems using GI POF for transmission medium for a transmission length of 100 m. In this proposal for a new international POF WDM grid, most of the channels are located in the short wavelength region where the attenuation of POF is lower than in the long wavelength region. On the other hand, the "old red" window is already included at channel no 7: f_7 = 470 THz (638 nm).

In Fig. 21 a schematic view of the optical band pass behavior of the WDM filters of the DEMUX/MUX devices are depicted. Supposing a typical X-talk suppression of 30 dB for optical channel separation, a 3 dB filter width of 20 THz for each filter is needed.

Channel	Frequency / THz	Wavelength / nm
0	750	400
1	710	423
2	670	448
3	630	476
4	590	508
5	550	545
6	510	588
7	470	638
8	430	698

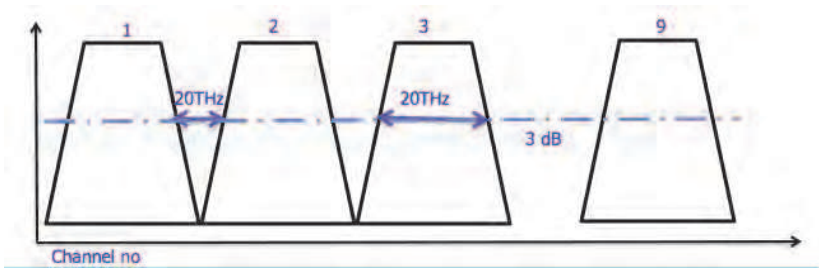Table 3. Proposed optical frequency channels.

Fig. 21. Proposed optical frequency comb window.

5. Outlook

The simulation results show, that it is possible to build up a mass production convenient demultiplexer for polymeric fiber systems by means of a diffraction grating. A special shape of the mirror is needed to suppress most of the aberrations which results of the grating. The improved demultiplexer can separate all three colors with a gap of 2 mm and crosstalk lower than 30 dB. This demultiplexer has the chance to break through the limitation of standard POF communication also with broad range of usability in optical spectroscopy for sensor systems in automotive and medical applications due to its low cost realization. It can be implemented in combination with all in the market existing POF types like SI POF, MC POF or GI POF with 1 mm outer diameter and a Numerical Aperture of 0.3 – 0.5. The high number of modes in the fibers gives no restriction to optimal function the developed multiplexer for WDM transmission of minimum three different wavelength channels. In the future the device will be extended to multiplex 8 channels.
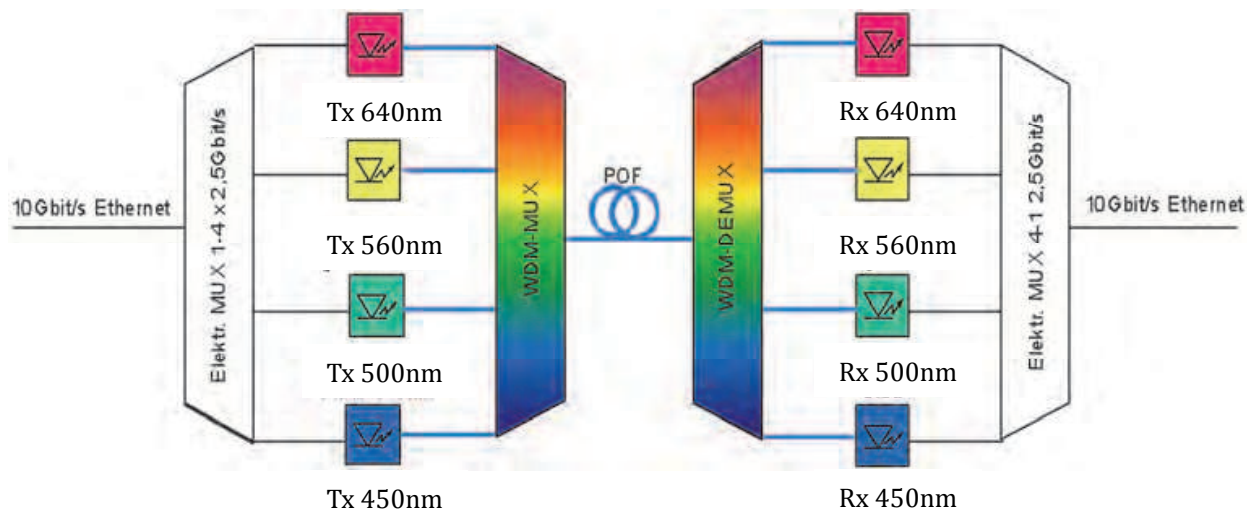
Fig. 22. Possible 10 Gbit/s via POF using WDM technique.

In the next years WDM over POF will expand the total bandwidth of POF transmission systems up to more than 20 Gbit/s. A channel allocation map for 9 WDM channels in the visible range is proposed as an input for the international standardisation organisations IEC and ITU to define a new optical reference standard for POF WDM systems like the ITU recommendation for glass fiber systems G 594.
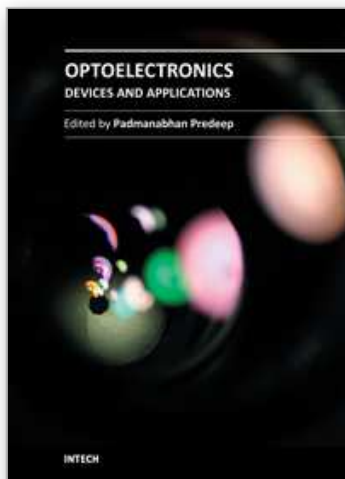
Soon it would be possible to transmit 10 GbEthernet data via SI POF with the help of the here described WDM over POF technology, shown in Fig. 22. The electrical data stream of 10 GbEthernet will be electrically demultiplexed to four sub data streams of 2.5 Gbit/s. Each of this sub streams will modulate an optical laser diode source with different WDM wavelengths. In a WDM MUX all four colored signals will be combined to be transferred simultaneously via the POF fiber link up to 100 m. At the receiver side an optical DEMUX will spread the optical channels to dedicated photo diodes. The out coming electrical 2.5 Gbit/s data can be electrical multiplexed to the full 10 Gbit/s Ethernet bit stream at the output side.

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