Chapter 11

High-Speed Optical In-House Networks Using Polymeric Fibers

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Additional information is available at the end of the chapter

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Abstract

Data communication over polymer optical fibers (POF) is a good alternative method for local area networks to use an optical medium to transmit data in short-range environments like cars or copper in-house networks on the basis of IEEE 802.3. Many companies offer transceivers for the area of Ethernet networks in the visible wavelength range. In the first part of the chapter, a system comparison of manufacturers with interoperability check is presented. Here, the real transfer rates within a manufacturer and between all manufacturers are measured as a cross-check. In the second part of the chapter, the limitation of bandwidth due to the use of only one wavelength channel is discussed. Wavelength Division Multiplexing (WDM) is a promising candidate to significantly increase bandwidth in POF to more than 40 Gbit/s. Here, the problems in the development and manufacture of a demultiplexer (DEMUX) for WDM over POF as well as the results of the optical separation of four wavelength channels are described. At least, the possible extension of a WDM grid of ITU G.694.2 is discussed, which seems to be a hopeful candidate to introduce a standardized WDM grid for POF in the visible range to reach data rates of 40 Gbit/s up to 50 m POF.

Keywords: polymeric fiber transmission, optical networks, WDM over POF, wavelength division multiplex, demultiplexer, injection molding

1. Introduction

Polymer optical fibers (POF) are used in various fields of applications. The core material consists of polymethylmethacrylate (PMMA), while the cover is made of fluorinated PMMA. The whole fiber has a diameter of 1 mm, which is depicted in **Figure 1**. POFs are used for optical data transmission based on the same principle as glass fiber. As a communication medium,

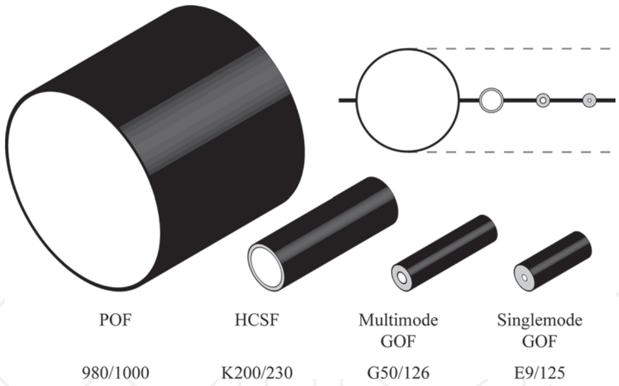

Figure 1. Comparison of optical fiber types.

they offer a couple of advantages related to other data communication systems such as copper cables, glass fibers and wireless systems and have great potential to replace them in different applications.

In comparison with glass optical fibers (GOF), POFs are easy to use in the field because of low bending losses and a large optical core of 980 μm. This makes the POF very insensitive to rough and dusty environments as well as losses on plugs in comparison with glass fibers [1]. However, one advantage of using glass fibers is their low attenuation, which is below 0.2 dB/km in the infrared range. The attenuation of polymeric fibers in the visible spectrum from 350 to 750 nm (see **Figure 2**) is much more higher with its minimum of 85 db/km at a wavelength of 570 nm. For this reason, the use of POF in communication systems is focused on short distance communication from 10 to 100 m. The larger core diameter of POFs leads to high-mode dispersion of more than 2.2 millions of optical modes. Additionally, the high attenuation at wavelengths higher than 700 nm limits the application of the POF to the visible spectrum of light (400–700 nm). Here, POFs can outperform the current standard of copper cable as a communication medium. On the one hand, they feature lower weight, low bending radius and space. On the other hand, POFs are not susceptible to electromagnetic interference [2, 3]. For these reasons, POFs are already used in various application domains, for example, in the automotive sector and for in-house communication [4–7].

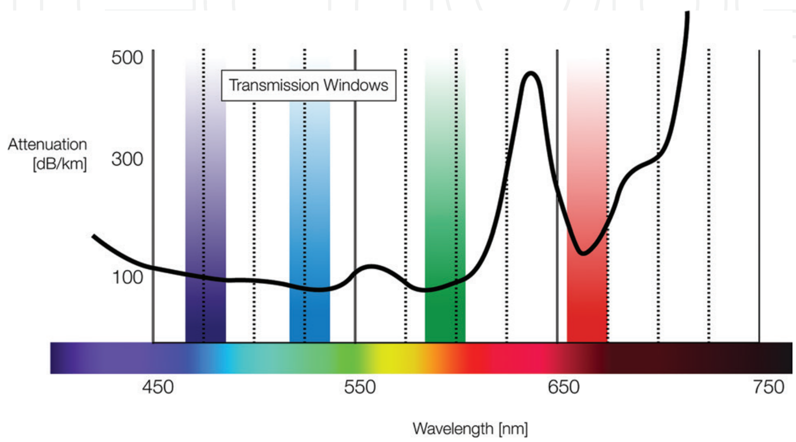

Figure 2. Attenuation of POF in the visible range [1].

1.1. POF in the automotive sector

Typically, copper-wired bus systems are used in the car environment. In the past 15 years, POF has replaced the electrical wiring in many types of car (see **Figure 3**). It was first introduced by BMW in the 7er series in 2001. Since then, not only high-class cars were equipped with POF, actually more than 200 types of volume cars benefit from the advantages of POF [4, 5]. The used bus is called **M**edia **O**riented **S**ystems **T**ransport (MOST), which is a multimedia network optimized for multimedia and infotainment applications. The bus was developed by the automotive industry. It works in three data rate levels with 25, 50 and 150 Mbit/s. MOST defines basically the physical interconnection between devices by using POF as a transport medium. Additionally, it specifies and standardizes a communication protocol to develop complete systems and applications to distribute multimedia content for the car.

The replacement of the communication technique from copper wires to POF leads to lower weight. The low melting temperature of PMMA (95°C) still prevents the use of POF in the engine compartment. However, new types of fiber in the development that have higher glass transition temperature will allow the use of high-temperature POF in the engine compartment in the near future [4]. Another application in the car, where POF most likely will be used in the future, is as sensors for measuring various in-car pressures or forces. Additionally, sides emitting polymeric fibers are interesting devices for future applications for ambient lighting in the passenger cabin.

1.2. POF for in-house communication systems

Another sector where POF displaces the traditional communication medium is in-house communication [6, 7], although the possibilities of application are not confined to the inside of the house itself. In the future, POF can possibly displace copper cables for the so-called last mile between the last distribution box of the telecommunication company and the end consumer. Today, copper cables are the most significant bottleneck for high-speed Internet.

"Triple Play" is called the combination of IPTV, VoIP and the data Internet. The combination is currently introduced into the telecom market; therefore, high-speed connections are essential. It is highly expensive and bandwidth limiting to use Ethernet in-house system using copper components, thus the future will be FTTH, in combination with optical in-house wires of POF or GOF (see **Figure 4**).

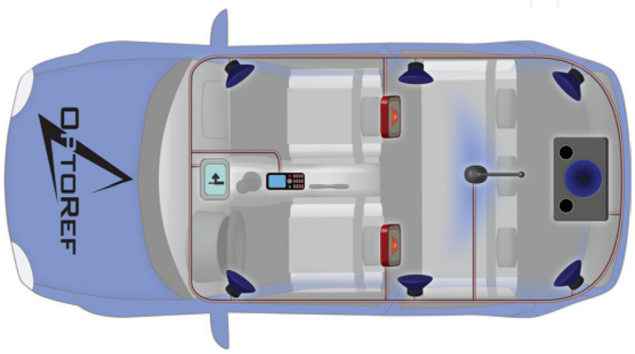

Figure 3. Multimedia bus system (MOST-bus) with POF.

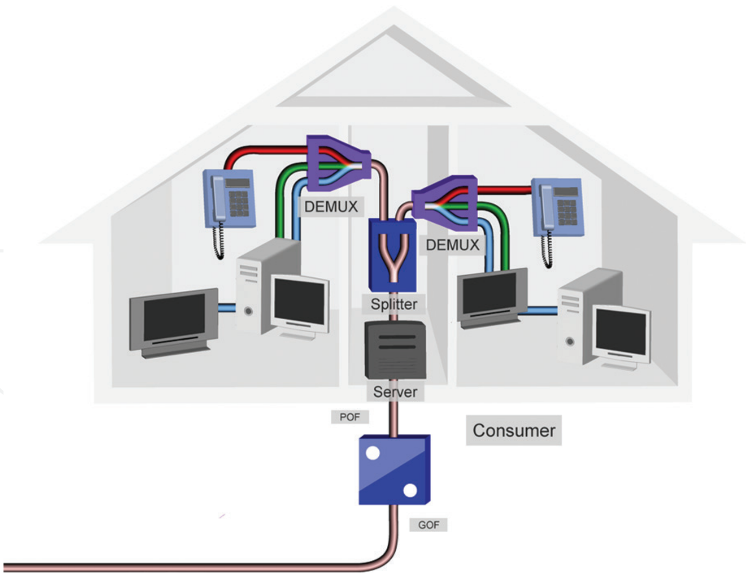

Figure 4. In-house communication with POF.

2. Studies on the interoperability of different transceivers for optical polymer fibers

In this chapter, various transceivers, which can be used for data home cabling with optical polymer fibers, are examined with respect to their interoperability. Eight different devices are tested for their effective data rate over length-varying POF transmission distances. Furthermore, the results are compared with the manufacturer's data regarding performance and the interoperability of all devices is checked.

The Photonic Communications Lab at the Harz University works closely together with manufacturers of various POF components in several projects. From this cooperation, the question of the compatibility of POF devices from different manufacturers among one another has become increasingly important. All devices tested comply with the IEEE 802.3u guidelines for Fast Ethernet. Fast Ethernet is mainly used in local networks and allows data transmission at 100 Mbit/s.

2.1. Devices under test

Table 1 shows the tested media converters or switches with specifications from the manufacturer:

As can be seen in **Table 1** and **Figure 5** devices from various companies are examined. Starting with media converters of German manufacturers (Siemens, Diemount and Rutenbeck) to transceiver-switches from Homefibre (Austria) and BSPCOM (China).

A USB media converter from the company BSPCOM could not be considered for investigations for reasons of problems with the USB driver software for Windows (**Figure 5**).

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Name	Wavelength (nm)	Transmission length (m)	Data transfer rate (Mbit/s)
Speedport OptoLAN	670	30	100
Diemount CS-116	470	70	100
Rutenbeck wall socket	660	70	100
Rutenbeck socket switch	660	50	100
Media converter Rutenbeck	660	50	100
Switch OMS 126S-150 Homefibre	650	50	100
Switch CP8016 BSPCOM	650	50	250

Table 1. Used POF-transceivers.

Figure 5. Tested media converter: Speedport, Diemount, BSPCOM, Rutenbeck and Homefibre.

All the devices tested, except the CS-116 from Diemount, operate at a wavelength in the visible red range. The device from Diemount transmits data at the wavelength of 470 nm in the visible blue range (see **Figure 2**).

2.2. Experimental setup

In the investigations of the POF devices, each existing one is combined with each, connected by a POF of 50 m length and put into operation. The measurements are carried out using a certification scheme developed in the Photonic Communications Lab of Harz University in accordance with the ETSI TS 105175–1 V1.1.1 (220010-01) standard, which establishes an in-house networking of the optical polymer fibers.

The optical polymer fibers are wound up with the aid of two cylinders. These cylinders have different diameters and thus offer different bending radii (see **Figure 6**) in order to apply the typical application conditions of a typical LAN network distribution in an apartment.

Several optical polymer fibers are wound onto this structure. These differ in length and outer cable diameter. However, all have a step index profile with a core diameter of 980/1000 μm. The cable diameter varies between 1.5 and 2.2 mm. The 2.2 mm fibers are being designed for simplex transmissions only. The 1.5 mm fibers are duplex fibers. The lengths of the optical polymer fibers are: 1, 15, 30 and 50 m.

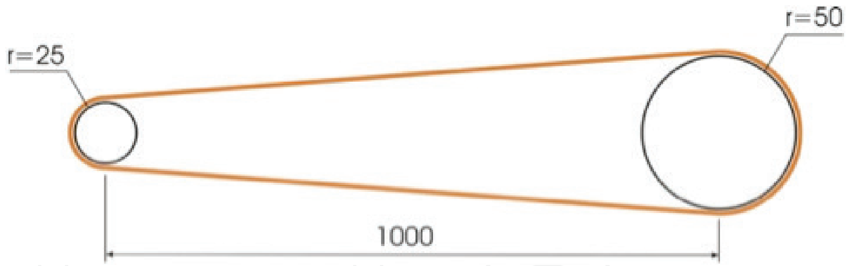

Figure 6. Setup for testing typical laying of a POF with a length of 30 m in an apartment with 15 bends of different radii (in mm).

2.3. Transmission speed measurement with Jperf 2.0.2

Iperf is a command line utility for measuring the performance of networks. Jperf is a graphical interface developed in Java for Jperf. This program is started on two PCs, one of which is the function of the server and the other is assigned to the client (see **Figure 7**). The server accepts connections on TCP port 5001. Data are transferred from the client to the server for the duration of the measurement. Thus, unidirectional data transmission always takes place.

Iperf offers different, adjustable parameters for throughput measurements. Examples of this are the selection of the transmission protocol (TCP/IP or UDP) as well as the modification of the measurement duration. In addition, the buffer size can be changed. The measurements are carried out in transmission control protocol (TCP) [8].

2.4. Transfer rates

At a transmission distance of only 1 m (back to back), all media converters and switches are working together with transmission speeds in the range of 90 Mbit/s (see **Figures 8** and **9**). However, in some combinations, the quality of the transmission rate is lower for this short distance than for a longer distance such as 30 or 50 m. Overdriving at the photodiode due to the excessive light intensity may cause this.

All the transceivers of the different manufacturers have been able to communicate with each other easily and also over the distances of 15 and 30 m, and all tests have been positive. The data rate fluctuates ±1–2 Mbit/s in the range of 92 Mbit/s. A 50 m transmission cannot be positively tested in combinations in which the Diemount CS-116 media converter is used as a client and with a blue transmit diode. This can be explained by the fact that the tolerance window of the photodiodes of the other devices is setup in the red range to this range by 650 nm. However, it should be noted that the light output up to 30 m was still intense enough to achieve a functionality of the two wavelengths without problems.

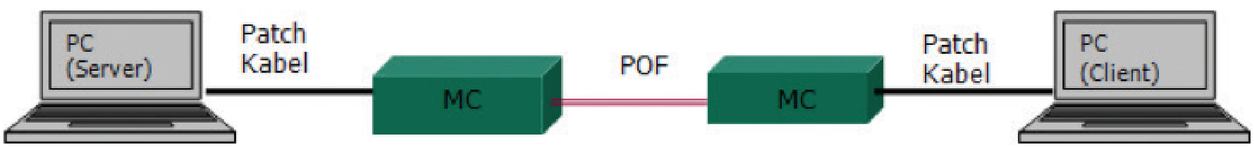

Figure 7. Measurement setup with Jperf (MC (media converter)—DUT.

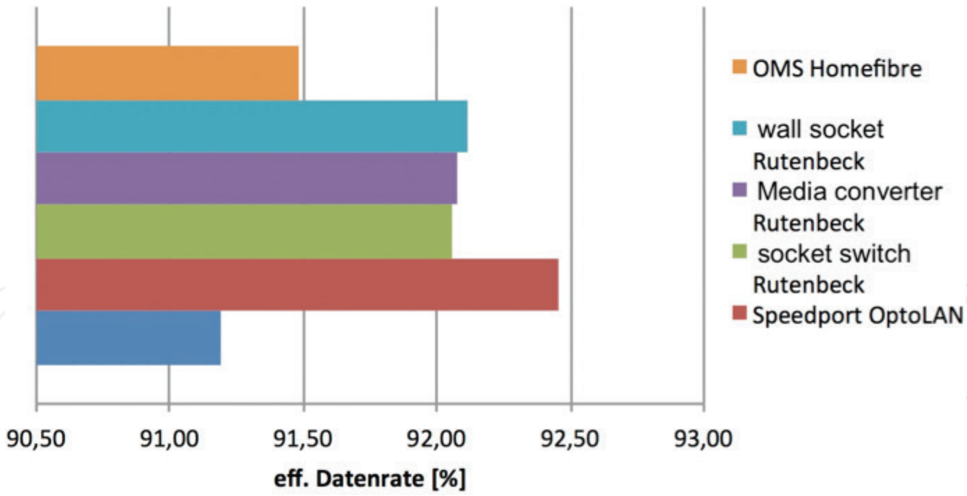

Figure 8. Effective measured data rates within one manufacturer.

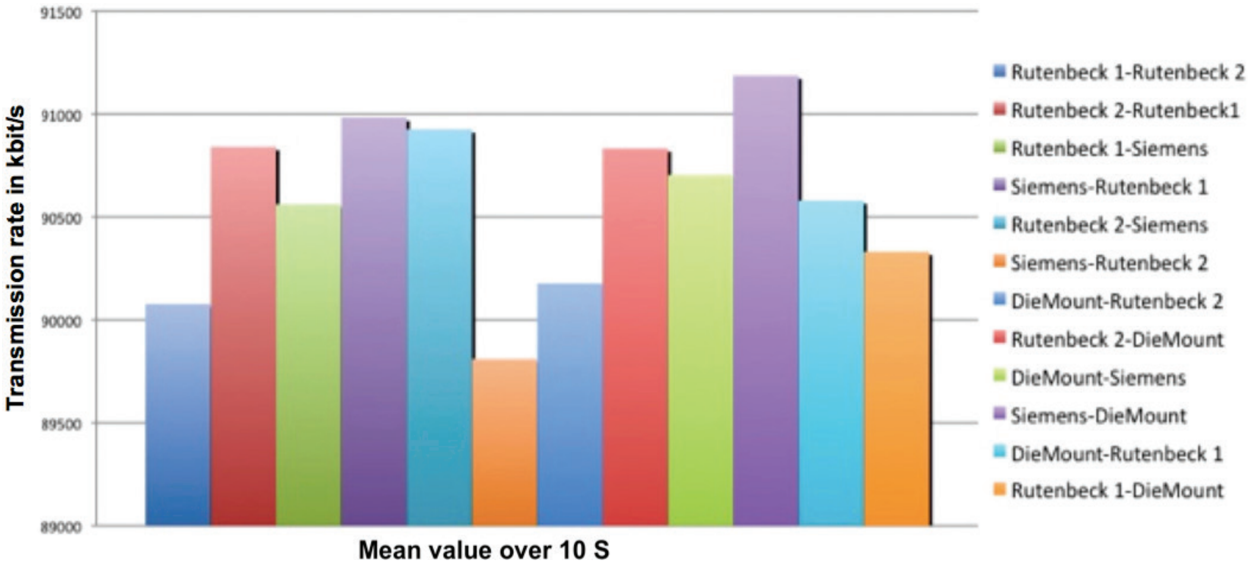

Figure 9. Measured effective data rates with 15 m POF length between different manufacturers.

In addition, the Speedport OptoLAN from Siemens is able to achieve 50 m transmission distances in almost all combinations. In general, it should be mentioned that the data rates reported by the manufacturers of 100 Mbit/s were not achieved by any system. On the other hand, all manufacturers did not provide a minimum data rate to be compared with the measurement results. The POF switch from BSPCOM from China shows the most stable transmission in all combinations and transmission lengths.

2.4.1. Measurement errors in Jperf

During the use of Jperf as a tool for recording the data rate, some points must be noted. On the one hand, higher transmission data values are always detected when the duration of the measurement is set to longer sampling values. This can be explained by the fact that the measuring interval is longer during a longer measuring period than in the case of a shorter measuring duration. Consequently, a mean value formation takes place. The reason is that the output format of Jperf of Mbit/s calculates large rounding errors. In addition, there is an error in the calculation of the average bandwidth over the whole measurement period by recalculation in Excel. The mean bandwidth was always larger than calculated externally. Therefore, the external calculated values are used in the evaluation.

3. WDM over POF

3.1. WDM over POF basics

At present, the great potential of the POF is not available as the alternative techniques offer transmission rates up to 10 Gbit/s over copper and up to 40 Gbit/s over glass fibers in the network area. The WDM technique offers an approach to achieve these high data rates also in the POF range. A sketch of the basic principle is shown in **Figure 10**.

Wavelength division multiplex systems need two basic components of a multiplexer and a demultiplexer (see **Figure 10**). To realize a working DEMUX for POF, several preconditions must be fulfilled. The basic component is a mirror, which focuses a divergent light beam coming from the input fiber. The shape of this mirror must be a toric shape to prevent spherical aberrations [9–11].

To separate the different incoming wavelength channels, a diffraction grating is used. This principle is illustrated in **Figure 11**. The light is split into different orders of diffraction. The first order is the important one to regain all information. There, the outgoing fibers with the different wavelengths channels must be arranged.

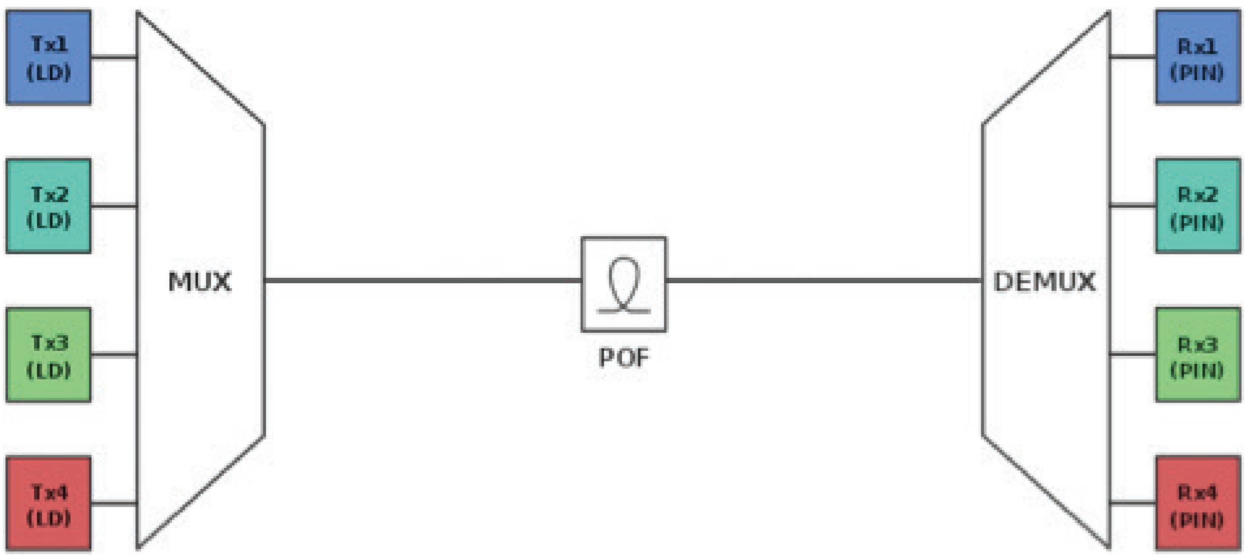

Figure 10. Schematic of the WDM over POF structure.

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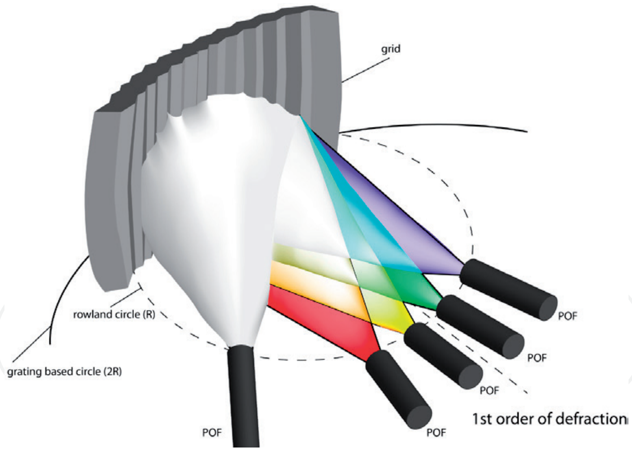

Figure 11. Rowland setup of demultiplexer.

The development of the injection-molding process starts with the production of a master for the imprint of the entire component. This master is milled in micrometer precision by means of a diamond cutting process and created by the diamond turning process. Here, the PMMA material is processed directly. Both the moldings as well as the grid for wavelength separation can be made using this technique (see **Figure 12**). The last step is performed to validate the simulation results with the produced component.

For the injection-molding process, the production of the impression part is the most important factor. Due to the three-dimensional toric structure of the grating planar manufacturing methods like lithography, especially LIGA [a German acronym for Lithographie, Galvanoformung, Abformung (Lithography, Electroplating and Molding)] cannot be used. LIGA is used to manufacture planar spectrometers based on the glass fiber technology [12–15]. In the present approach for using a grating as a WDM element, it is necessary to manufacture the three-dimensional grating with its fine line structure and blaze precisely. In particular, the micro-structure of the grating and the exact shape of the toric surface require high precision. The

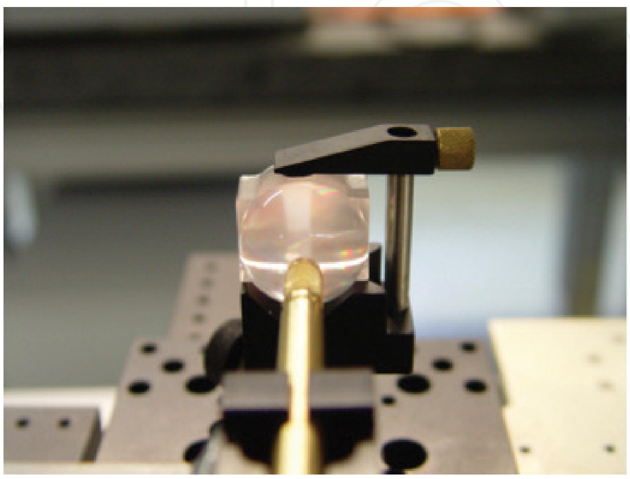

Figure 12. Integrated demultiplexer prototype.

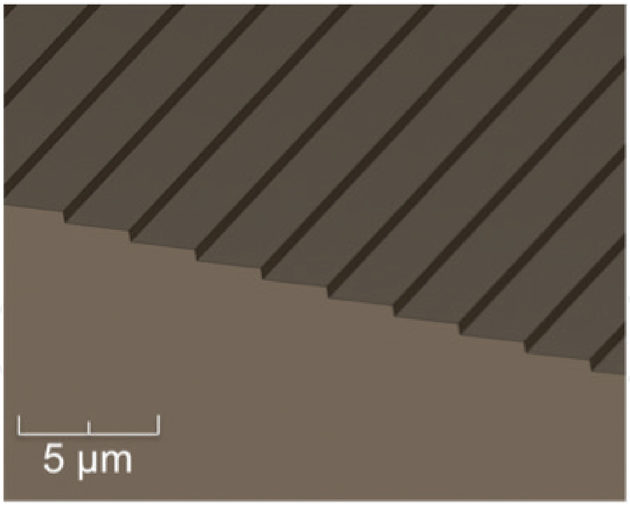

Figure 13. Grating of the demultiplexer.

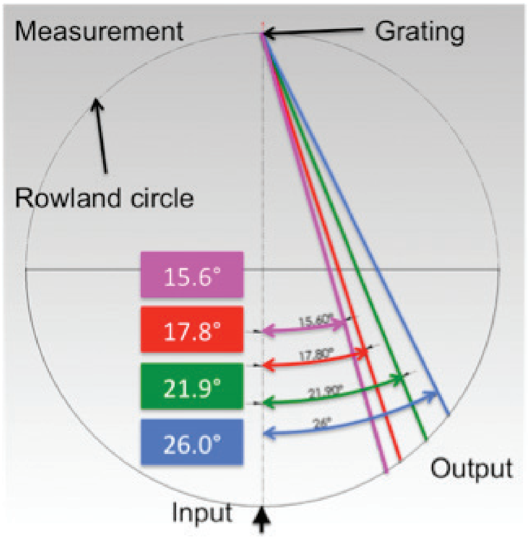

Figure 14. Measurement results of the focal points for different wavelengths (405 nm 15.6°, 450 nm 17.8°, 520 nm 21.9° and 650 nm 26.0°).

blaze with the grating lines is a microstructure in the form of a sawtooth with a distance between the teeth of 2.5 μm. **Figure 13** shows an enlarged 3D model of the grating. After analysis of other microtechnical machining processes to our knowledge, only the diamond turning meets the stringent requirements of the microstructured grating (**Figure 14**).

3.2. Design of the first demonstrator

The DEMUX elements must be manufactured in injection-molding technology. The capability of injection-molding technology for the cost-effective mass production of large volume and micrometer-accurate plastic components has made this technology the industrial standard production method for plastic parts. More and more high-quality optical components

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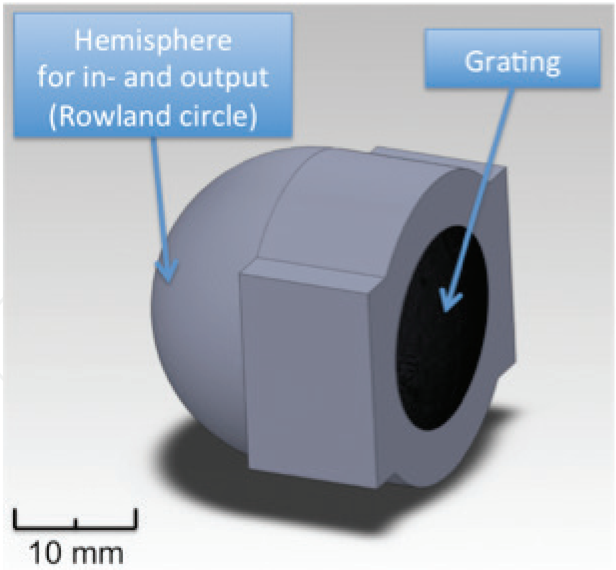

Figure 15. 3D model of the DEMUX demonstrator.

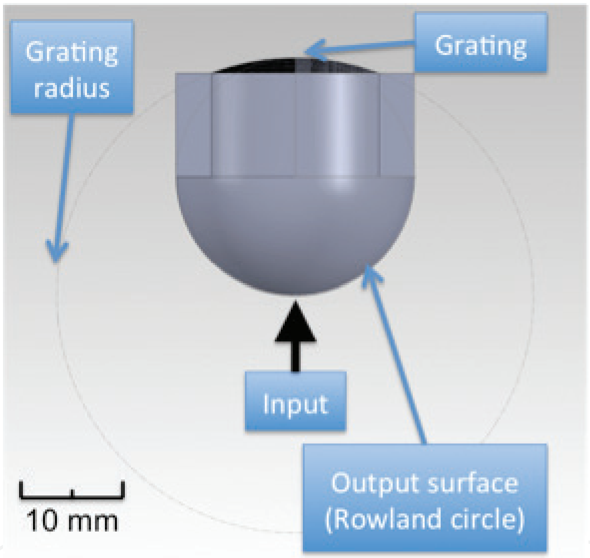

Figure 16. Cross-section view of the DEMUX demonstrator.

are produced with injection molding. With the aid of the injection molding, dimensionally stable and stress-free molded parts can be produced. In particular, the reduction of internal mechanical stress makes this technique ideal for optical mold components [12]. With this cost-effective production, the components for WDM can be made available via POF for a very wide application market. To further reduce the production costs, a self-adjustment of the individual optical components of the DEMUX such as fiber, grating, focusing mirror is necessary. This is why the various functions are combined in a molded part. However, this makes DEMUX technologically more difficult to implement, and therefore the individual process steps are discussed in detail.

In the first step, a demonstrator was produced. In order to verify the concept of the demultiplexer and to compare the simulation results with the real setup, it is necessary to proceed step by step. For this reason, a special optomechanical design was chosen. **Figure 15** shows the new design where a hemisphere at the output of the DEMUX represents the radius of the Rowland circle. This is shown in the cross-sectional view in **Figure 16**. The light reflected from the grating and emanating from the circle is focused on this radius. Therefore, the light is coupled into the center of the hemisphere, and the separated wavelengths can be detected on the surface of the hemispheres. This is illustrated in **Figure 14**. For detection, scanning of the surface is performed to determine the positions of the outgoing, separated light for each wavelength.

4. Materials and methods

Prior to the production of the DEMUX, some preliminary investigations have taken place to find the best suitable material for the demultiplexer. Therefore, both the processability of the material and the optical parameters had to be considered in detail. The injection-molding process was tested with a thick-walled mold. This test tool had the same shape as the final DEMUX, except for the grid. The test runs were carried out with an injection-molding machine from Babyplast 6-10P. This device was able to inject precisely small parts. **Table 1** lists all the materials used for the study. Further, parameters such as the respective melt volume rate (MVR) and light transmittance (according to the manufacturer's specification) are depicted. The test was additionally used to find the optimized injection-molding process parameters for the material.

In addition, the optical quality of the polymer materials must be investigated. Therefore, a mold for injection-molding test plates was designed. The test plates had a thickness of 2 mm. The mold is used to make samples from each material listed in **Table 2**. The DIN EN ISO 13468–2 standard describes the measurement of the optical transmission of polymer materials. Therefore, the test plates are designed to meet this standard.

Transmission measurements were carried out with all test plates. The results are shown for 405 nm in **Figure 17**. It can be seen that both ZEONEX types and PMMA POQ62 show the highest value for the light transmission. PMMA POQ62 is a polymer grade with high purity of polymer granulates. The measurement is made at a wavelength of 405 nm because it is one of the wavelengths used for the WDM system.

4.1. Manufacturing of the demonstrator

By using the injection-molding process, the manufacturing of the mold insert is the most important factor. Due to the three-dimensional toric structure of the grating planar manufacturing methods like lithography, especially LIGA cannot be used [15].

In our case, however, the three-dimensional grating requires a different processing method. The microstructure of the grating and the exact shape of the toric surface require a particularly

Name	Type	MVR [cm^3/10 min]	Transmission [%]
Plexiglas 6 N	PMMA	12	92
Plexiglas POQ62	PMMA	21	92
Topas 5013 L-10	COC	48	91.4
Topas 6013 M-07	COC	14	91
ZEONEX F52R	COP	22	92
ZEONEX 350R	COP	26	92
Makrolon LED2245	PC	35	90

Table 2. Injection-molding materials for MUX/DEMUX-element.

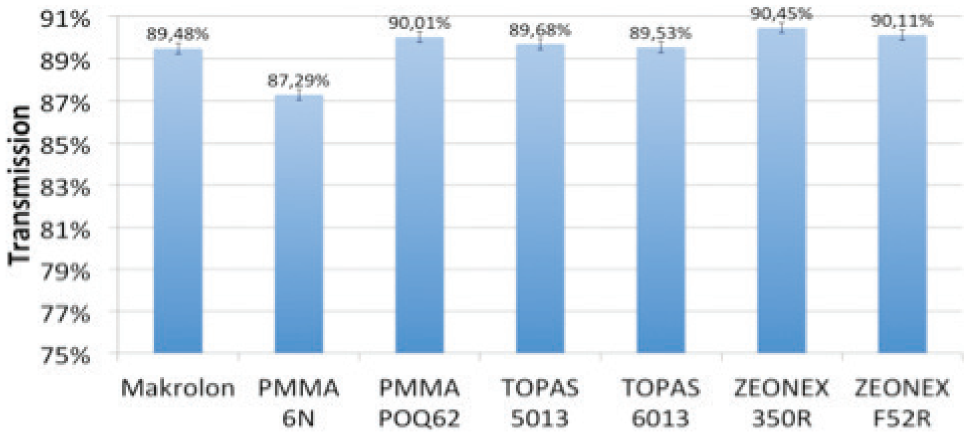

Figure 17. Transmission of different material at 405 nm.

high precision of manufacture. The microstructure has the shape of a sawtooth with a distance between the teeth of 2.5 μm. **Figure 13** shows an enlarged 3D model of the grating. An in-depth investigation of various processing methods has shown that only the diamond turning fulfills the high requirements of the production of the microstructural lattice. The diamond twisting technique is a special machining method using a single crystal diamond cutting tool. It is also possible to produce a surface with an optical quality at the edge of the optical component. It offers several advantages:

- True three-dimensional contour generation.
- Accuracy of one part in 106 with absolute accuracy of 1 part in 108 on a single axis for ideal conditions.
- Surface finish of 5 nm Rz for a range of materials and as good as 1 nm Ra.
- Ability to generate surfaces with variable aspect ratios and
- Feature sizes that exceed the limits of optical microscopy [14, 15].

A metallization process was used to analyze the surface of the lattice. The surface was sputtered with a thin aluminum layer depicted in **Figure 18**. It is now possible to measure the shape of the surface with a white light interferometer and to examine the lattice structure under the scanning electron microscope (SEM). The metallized surface of the grating is shown in **Figure 18**. It can be seen that the structure on the left side has a dull and mat surface instead of the glossy residue of the surface. This is a first indication that the surface roughness in this part is higher and does not meet the requirements for the component precision. The first visual impression was then confirmed by the analysis under the SEM.

The cause of the degradation of the grating quality is the change in the strain as the milling tool passes the highest point in the center of the surface. It changes the way the force is exerted by a pushing movement on the surface. This results in a coarse structure on the other half of the surface. From the measurement of the structure size in **Figure 19**, a width of 2.55 μm can be determined, which is within the tolerances of the reference of 2.5 μm.

In addition to the structural quality, the dimensions of the surface are also important for the functionality of the DEMUX and must be considered in detail. The shape of the radius of the

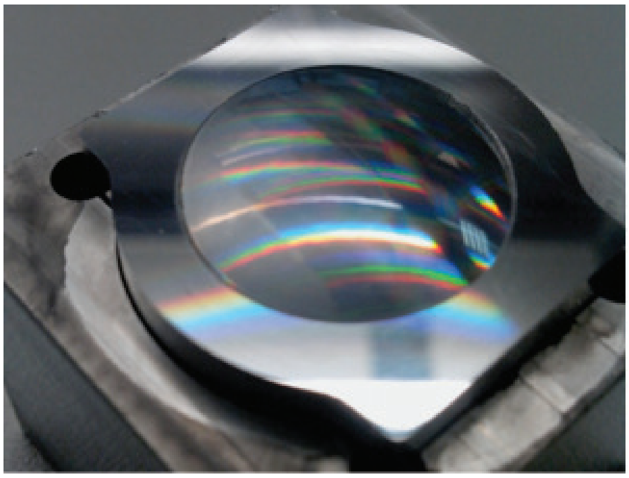

Figure 18. High-quality structures of the grating.

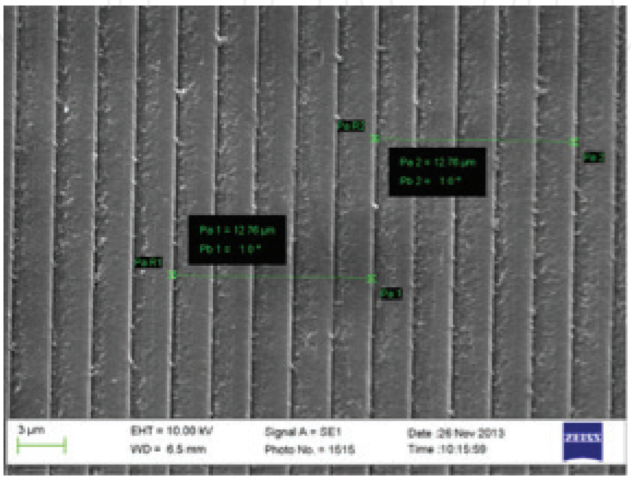

Figure 19. Metallized grating surface of the DEMUX.

toric surface was designed to focus the colored light beams on the Rowland circle. Therefore, it was analyzed using a white light interferometer (FRT MicroProf). The cross-section of the toric surface was measured. The measurement shows that the dimensions of the surface correspond to the tolerances of the DEMUX. An exception can be seen in the diameter in the x-axis, which is somewhat out of tolerance (**Table 3**).

Several parameters have to be optimized in order to correct the manufacturing errors. This is performed in several iterations in close cooperation with the manufacturer. For example, the adjustment of the force applied to the surface was varied and optimized by the diamond tip. The next part with optimized parameters is now in production and is then analyzed in the same way to check the adjustments of the parameters.

4.2. Optical measurements

In order to measure the position of the focal points of the different separated wavelengths on the Rowland circuit, a special measurement setup was chosen. It uses a parallel kinematic precision alignment system to align a POF on the surface of the hemispheres. An input fiber firmly bonded to index matching is used to couple white light into the DEMUX, as shown in **Figure 16**. In this figure, it can be seen that the separated wavelengths are focused on a ring on the hemisphere. This ring is scanned by the fiber on the alignment system. The light from the scanning fiber is analyzed by using a spectrometer.

From the spectra along the Rowland ring, the location of the maxima of the wavelengths is determined. For the first component, the entire measurement was performed and compared with the simulation results. Four different wavelengths that were used to analyze the wavelength separation are as follows: 405, 450, 520 and 650 nm.

The positions of the wavelengths measured by the setup are also depicted in **Figure 14**. In comparison to the simulation, a shift of the positions of 2,3° are found. Nevertheless, the separation of the wavelengths was measured and confirmed the functionality of the demultiplexer.

The derivations to the simulation could be caused through the following reasons:

- Derivation of the blaze angle of the sawtooth grating
- Inhomogeneous structure of the grating
- Manufacturing tolerances

These depend strongly on the precision of the manufacturing process. As mentioned in the previous section, the production of such complex structures on a toric surface is a major

Dimension	Measurement (mm)	Reference (mm)
Diameter x-axis	15.869	>16.000 ± 0.1
Diameter y-axis	15.887	>15.170 ± 0.1
Height of grating	1.862	1.872 ± 0.05

Table 3. Measurement results of the DEMUX dimensions.

challenge. Therefore, the process parameters must be improved and optimized to fully meet the optical requirements of the demultiplexer component.

5. Spectral grids in the visible spectrum for POF WDM applications

Besides developing low-IL cost-effective POF WDM components and fast POF WDM transmission systems, it is also important to allocate a unique set of WDM transmission channels in the visible spectrum to support WDM applications over SI-POF. To evaluate the applicability of a spectral grid to support visible spectrum WDM applications over SI-POF, the appropriate criteria were first established. Those criteria refer to:

- Channel distribution with respect to the spectral attenuation of SI-POF;
- Performances of different demultiplexing techniques;
- Availability of laser diodes in the visible spectrum.

5.1. Extension of ITU-T G.694.2 CWDM grid into the visible spectrum

If ITU-T G.694.2 CWDM wavelength grid would be extended into the visible spectrum, 15 equidistant channels between 400 and 700 nm would be obtained, as shown in **Figure 14**. The parameters of the grid including the nominal central wavelengths are depicted with arrows in **Figure 20**.

The channel spacing of 20 nm makes good utilization of the available spectral range. In the red window, the extension has a channel at 651 nm, which is very close to the attenuation minimum at 650 nm. The channel distribution also corresponds well to three other attenuation windows. The channels experiencing the highest attenuation are those at 611, 631, 671

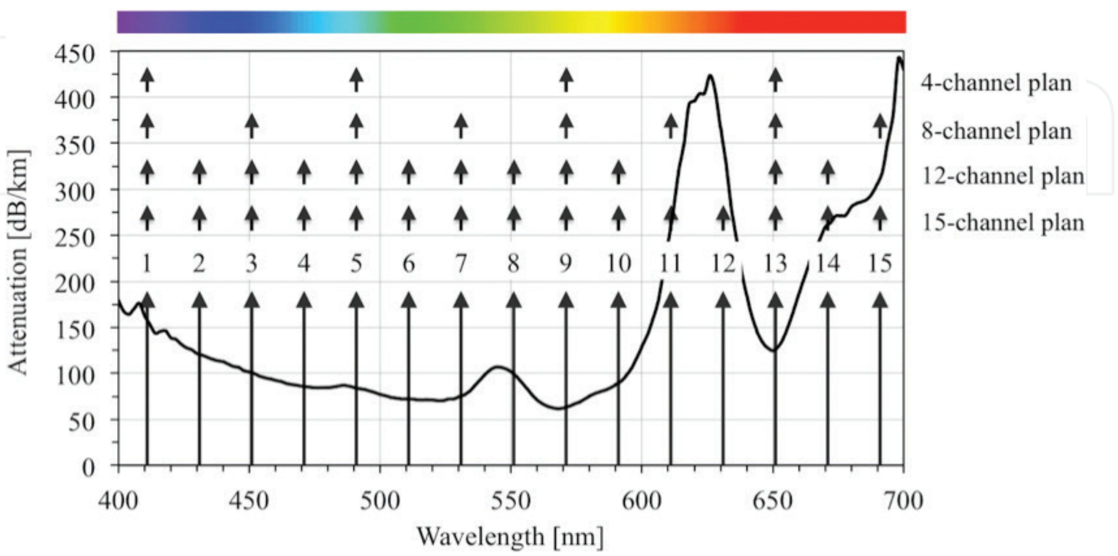

Figure 20. Extension of CWDM wavelength grid into the visible spectrum and channel plans for 4-, 8-, 12- and 15-channel applications.

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and 691 nm. Those channels could be used for distances up to 20 m since they would experience approximately the same attenuation as 651 nm channel over 50 m, but lower intermodal dispersion. Good channel allocation, sufficient channel spacing, high channel count and good availability of the transmitters make the extension of CWDM grid very suitable to support WDM applications over SI-POF.

6. Conclusions

Currently, commercially available POF transmission systems are able to fulfill the needs of IEEE 802.3 requirements with a data rate of 100 Mbit/s. The interoperability between the devices of the different manufacturers is also in a good condition.

To realize higher bitrates WDM over POF will be an interesting application. We produced a DEMUX by injection molding.

The realization of this DEMUX element for POF presents several challenges, in particular the microstructure of the grating on the three-dimensional surface. It is shown that it is possible to realize the structure size and the exact radius for the DEMUX with the current optimized production process. The high challenge of producing the blazed grating leads to some errors in the milling process, which still needs to be improved. This will be done in the future by optimizing the process parameters. The next parts will be produced and analyzed with the optimized parameters.

This hopeful result shows that WDM applications over SI-POF with high Gbit/s transmission are a realistic aim for the next future. The technique will be able to extend the bandwidth in POF systems strongly. It seems to be possible to transmit 40 Gbit/s via 15 channels and a channel rate of 2,7 Gbit/s data rate with WDM over POF. This opens the range of POF applications to existing cloud centers and future in-house networks with to link length up to 100 m.

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References

[1] Daum W, Krauser J, Zamzow PE, Ziemann O. POF Handbook: Optical Short Range Transmission Systems. Berlin, Heidelberg, New York: Springer-Verlag; 2008

[2] Nalwa HS, editor. Polymer Optical Fibres. California: American Scientific Publishers; 2004

[3] Club des Fibres Optiques Plastiques (CFOP) France. In: Marcou J, editor. Plastic Optical Fibres—Practical Applications. Masson: John Wiley & Sons; 1997

[4] Brandrup J, Immergut EH, Grulke EA. Polymer Handbook. 4th ed. Wiley-Interscience; 1999

[5] Chen RT, Lipscomb GF, editors. WDM and photonic switching devices for network applications. Proceedings of SPIE, vol. 3949, 2000

[6] Colachino J. Mux/DeMux optical specifications and measurements. In: White Paper. Lightreading, The Woodland Texas: Lightchip Inc.; 2001

[7] Gnauck AH, Chraplyvy AR, Tkach RW, Zyskind JL, Sulhoff JW, Lucero AJ, et al. One terabit/s transmission experiment. Proceedings OFC'96; 1996

[8] www.nwlab.net/know-how/JPerf/, Website 09-01-2017

[9] Fischer-Hirchert UHP. Photonic Packaging Sourcebook: Fiber-Chip Coupling for Optical Components, Basic Calculations, Modules; 2015

[10] Fischer UHP, Haupt M. WDM over POF: The inexpensive way to breakthrough the limitation of bandwidth of standard POF communication. SPIE Symposium on Integrated Optoelectronic Devices, Photonics; Bellingham WA: West San Jose; 2007

[11] Fischer UHP, Haupt M. Integrated WDM System for POF Communication with Low Cost Injection Moulded Key Components. Access Networks and In-house Communications; 2010

[12] Stricker M, Pillwein G, Giessauf J. Focus on precision—Injection molding optical components. Kunststoffe International. 2009;**4**:15-19

[13] Ferguson JP, Schoenfelder S. Micromoulded spectrometers produced by the Liga process. Searching for Information: Artificial Intelligence and Information Retrieval Approaches, IEE Two-day Seminar (Ref. No. 1999/199); 1999. pp. 11/1-11/4

[14] Davies MA, Evans CJ, Vohra RR, Bergner BC, Patterson SR. Application of precision diamond machining to the manufacture of microphotonics components. Proc. SPIE 5183, Lithographic and Micromachining Techniques for Optical Component Fabrication II, 94; November 2003

[15] Dornfeld D, Min S, Takeuchi Y. Recent advances in mechanical micromachining. CIRP Annals: Manufacturing Technology. 2006;**55**(2):7