Investigation on spectral grids for VIS WDM applications over SI-POF
Untersuchung von Spektralen Gittern für VIS WDM-Anwendungen über SI-POF

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Abstract

In recent years, a growing interest to develop wavelength division multiplexing (WDM) systems over large core Polymer Optical Fibers (POFs) is present. WDM technology for POF is already under investigation and development by several working groups. Besides key WDM components (e.g. demultiplexer (DEMUX)), which are essential to the success of WDM over POF, an important aspect is establishing a unique set of WDM transmission channels for the realization of standardized commercial WDM devices and systems. Among different types of POF, the 1 mm polymethylmethacrylate (PMMA) Step-Index POF (SI-POF) is the best known and by far the most widely used type of POF. In this paper spectral grids for visible spectrum (VIS) WDM applications over SI-POF are investigated. The criteria for evaluating the applicability of a spectral grid are first established. These refer to: attenuation in individual channels, performances of different multiplexer (MUX)/DEMUX solutions, availability of optical sources, capacity of the WDM system, and long-term compatibility. New-generated wavelength and frequency grids in 400 nm – 700 nm region, but also extensions of existing grids from infrared into VIS (Dense and Coarse WDM grid according to ITU-T Recommendations G.694.1 and G.964.2 respectively) are analyzed. The grid that best satisfies set criteria is proposed for further international discussion and revision.

Kurzfassung

In den letzten Jahren besteht ein wachsendes Interesse an der Entwicklung von WDM-Systemen über POFs. Die WDM-Technologie für POF wird bereits von mehreren Arbeitsgruppen erforscht und entwickelt. Neben den Schlüsselkomponenten (z.B. DEMUX), die wesentlich zum Erfolg des WDM über POF beitragen, ist die Festlegung eines eindeutigen Gitters von WDM-Übertragungskanälen ein weiterer wichtiger Aspekt für die Realisierung von standardisierten kommerziellen WDM-Systemen. Unter den verschiedenen Arten von POF, ist die 1 mm PMMA SI-POF die bekannteste und mit Abstand die am weitesten verbreitete POF. In diesem Beitrag werden spektrale Gitter für den sichtbaren Bereich für WDM-Anwendungen über SI-POF untersucht. Zunächst werden die Kriterien zur Bewertung der Verwendbarkeit eines spektralen Gitters dargestellt. Diese beziehen sich auf: Dämpfung in den einzelnen Kanälen, verschiedene MUX/DEMUX-Lösungen, die Verfügbarkeit von optischen Quellen, Kapazität des WDM-Systems und die langfristige Kompatibilität. Neu generierte Wellenlängen und Frequenzgitter im 400 nm – 700 nm Bereich, aber auch Erweiterungen der bestehenden Gitter von Infrarot in VIS (Dense und Coarse WDM-Gitter gemäß ITU-T G.694.1- bzw. G.964.2-Empfehlungen) werden analysiert. Ein Gitter, das die festgelegten Kriterien am besten erfüllt, wird für die weitere internationale Diskussion und Überarbeitung vorgeschlagen.

1 Introduction

POF is very attractive for the use in short-range communication systems. Among different types of POF, the 1 mm PMMA SI-POF is the best known and by far the most widely used type of POF. SI-POF offers many advantages in comparison to alternative data communication media such as glass fibers, copper cables, and wireless systems. It is pliable, durable, and cost effective, has small weight and short bend radius, allows easy installation and quick troubleshooting, and provides immunity to electrical noise. Due to its numerous advantages SI-POF is already applied in various application sectors (in-house networks, automotive and aerospace industry, industrial control) [1].

Present communication systems over POF use a single channel for data transmission. Commercial systems with SI-POF can deliver a bandwidth of 100 Mbit/s over 50-100 m. The standard for 1 Gbit/s over up to 50 m of SI-POF is being developed within German DKE/AK 412.7.1 working group. Multi-Gbit/s transmission over SI-POF was demonstrated in laboratory conditions [2]. However, the standard SI-POF has the lowest bandwidth among all POFs. This small bandwidth limits the maximum data rate that can be transmitted through the fiber.

One possibility to open up this bottleneck is to implement WDM approach. In recent years, a growing interest to develop WDM technology for POF is present [3-5]. Besides the bandwidth increase, the argument used to introduce WDM technique in POF communications is the advantage

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of parallel over serial transmission in some applications. In glass fiber communications WDM has already been established for 15 years in the infrared (IR) range, and represents a key technology in modern optical communications [6]. Immense success of WDM technology in the IR range further justifies implementation of WDM principles in POF communication.

WDM technology for POF is already under investigation and development by several working groups. The working group at the Harz University is currently running a project within which key-components for high-speed communication over POF, especially optical MUX/DEMUX element, are researched and developed (Figure 1) [7].

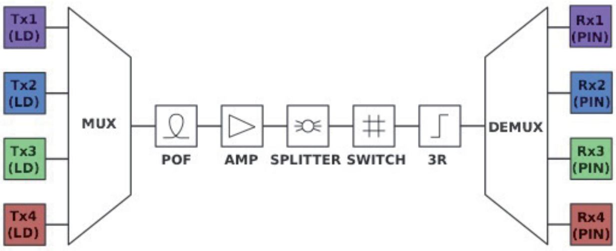

Figure 1 Basic structure of an optical four-channel high-speed WDM transmission system over POF with the key-components

Besides these key-components, which are essential to the success of WDM over POF, an important aspect is establishing a unique set of WDM transmission channels in VIS for the realization of standardized commercial WDM devices and systems. Spectral grids are already established in the IR part of the spectrum by the ITU-T Recommendations (Recs.). Therefore, having a spectral grid in VIS would be nothing more but following a good practice established through these Recs. In this paper spectral grids for VIS WDM applications over SI-POF are investigated. The criteria for evaluating the applicability of a spectral grid for intended applications are first established. A number of grids is evaluated and proposal for a spectral grid for further international discussion and revision is presented.

2 Existing spectral grids in IR

ITU-T Recs. G.694.1 and G.694.2 provide frequency and wavelength grid in the IR part of the spectrum to support dense WDM (DWDM) and coarse WDM (CWDM) applications respectively [8,9].

2.1 DWDM grid

ITU-T Rec. G.694.1 provides a frequency grid for DWDM applications. Term *dense* refers to narrow optical frequency spacing. The grid is anchored to 193.1 THz (1552.52 nm). It specifies channel spacing of 100 GHz (0.8 nm), 50 GHz (0.4 nm), 25 GHz (0.2 nm), and 12.5 GHz (0.1 nm), and covers frequency range from 186 THz (1611.79 nm) to 201 THz (1490.50 nm). Because of the narrow channel spacing, very precise temperature control of the laser transmitters is necessary. DWDM systems tend to be used at a higher level of network hierarchy, typically in backbone networks and metro rings with high capacity.

2.2 CWDM grid

ITU-T Rec. G.694.2 provides a wavelength grid for CWDM applications. Term *coarse* refers to wide channel spacing. The grid specifies channel spacing of 20 nm, and consists of 18 wavelengths between 1271 nm and 1611 nm (Table 1). Flexible system design is here achieved through a combination of uncooled lasers, relaxed laser wavelength selection tolerances, and wide passband MUX/DEMUXs. CWDM systems are less expansive than DWDM systems and are better suited for short-haul communications, typically metro/access networks.

Ch. No.	1	2	3	4	5	6
λ [nm]	1271	1291	1311	1331	1351	1371
Ch. No.	7	8	9	10	11	12
λ [nm]	1391	1411	1431	1451	1471	1491
Ch. No.	13	14	15	16	17	18
λ [nm]	1511	1531	1551	1571	1591	1611

Table 1 CWDM grid according to ITU-T G.694.2 Rec.

3 Requests for spectral grids

To evaluate the applicability of a grid for intended applications, appropriate criteria are first defined. These criteria refer to:

1. channel distribution with respect to the spectral attenuation of SI-POF,
2. performances of different MUX/DEMUX solutions, and
3. availability of optical sources in VIS.

Based on these criteria, a high-performance grid that is compatible with current state-of-the-art technology, but will also be future-compatible with oncoming technologies, should be established.

3.1 Channel distribution with respect to the spectral attenuation of SI-POF

A grid should have channels at wavelengths (frequencies) or at least wavelength regions where spectral attenuation of SI-POF has local minima.

The spectral attenuation of SI-POF shows local minima at 476 nm, 522 nm, 568 nm, and 650 nm (Figure 2). The attenuation slightly varies around 568 nm, 522 nm and 476 nm, while it rapidly increases for wavelengths around 650 nm. Therefore, a grid should have one channel very close to 650 nm, and channel spacing that will place channels near to 568 nm, 522 nm, and 476 nm. All channels should be defined within the wavelength range from

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400 nm to 700 nm. This wavelength range is referred to as VIS, and within it SI-POF offers acceptable attenuation.

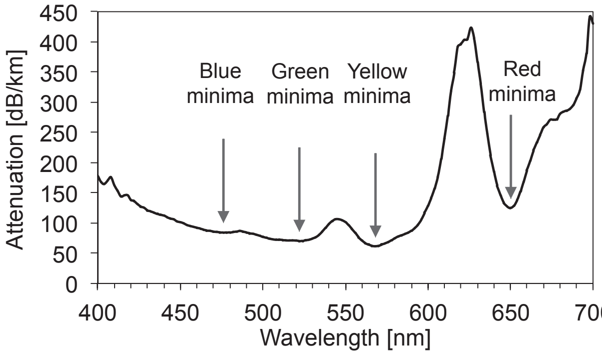

Figure 2 Spectral attenuation of SI-POF with the attenuation minima

3.2 Performances of different MUX/DEMUX solutions

A proposed grid should provide sufficient channel spacing for near-future WDM systems, but also the possibility of high channel density to ensure long-term compatibility and high capacity.
Different approaches for realization of MUX/DEMUX for POF, including prisms, dichroic and color filters, and diffraction gratings have been shown [10-12]. Both filter and grating based MUX/DEMUX can be used for the realization of three to four-channel high-speed WDM systems. Such systems are to be expected in the near future. For more than four channels, only the grating based solution can provide acceptable insertion loss (IL) [13]. Such components are not to be expected in the next few years mainly due to the complex manufacturing process. However, the spectral grid must ensure long-term compatibility and high capacity. This primarily means high channel density. A proposed solution is to define a grid with high channel density, while near future WDM systems would use only some, previously specified, channels of that grid. Filter and grating based DEMUXs are described more in detail below.

3.2.1 Filter based DEMUX

The bulk optics technology can be used to realize a bulky but low-loss DEMUX setup in the laboratory conditions. The operating principle of a four-channel DEMUX established in bulk optics at Harz University is shown in Figure 3. Multi-wavelength light exiting the sending fiber is first collimated with a lens. Collimated light is partially transmitted and partially reflected from the dichroic mirrors such that desired wavelength components reach the thin-film filters in each channel. Thin-film filters reduce the crosstalk by filtering out the remaining light at undesired wavelengths. Filtered light is then focused on the receiving fibers and fed to the corresponding photodiodes.

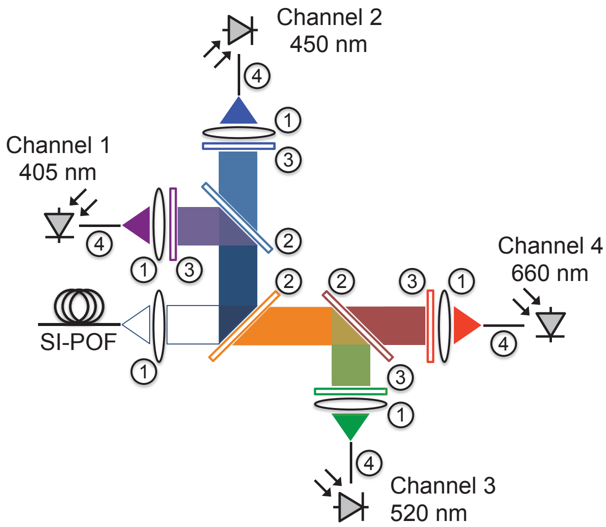

Figure 3 Basic operating principle of a four-channel DEMUX (1 – lens; 2 – dichroic mirror; 3 – thin-film filter; 1 m SI-POF)

Transfer function of the DEMUX is shown in Figure 4. Due to the very complex positioning and adjustment process of the individual DEMUX components (which is still not fully performed), the optimal DEMUX performance is expected to be much better than the one presented here. However, the measurement results verify the potential of the DEMUX setup to produce low IL per channel. As can be seen from the graph, the crosstalk coming from adjacent channels is very high. This is because the thin-film filters are still not acquired and included in the setup. The target performances that are expected to be achieved when all components are available and adjusted are narrower passbands, the IL of less than 7 dB and crosstalk of less than –30 dB.

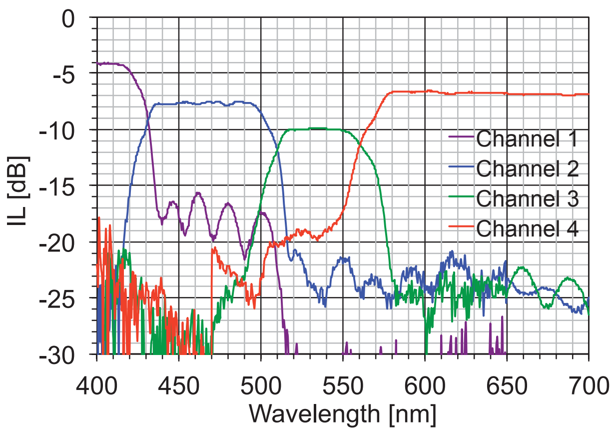

Figure 4 Transfer function of a four-channel DEMUX realized in bulk optics technology at Harz University

3.2.2 Grating based DEMUX

Several preconditions must be fulfilled to create a functional grating based DEMUX for SI-POF. First of all, the divergent light beam, which escapes the POF, must be focused. This can be done with an on-axis mirror. To prevent any spherical aberrations, a toric mirror should be used.

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Second of all, different transmitted wavelengths must be separated. This can be done with a diffraction grating, as illustrated in Figure 5 for four different colors. The diffracted light is split into different orders of diffraction. There the outgoing POFs or a detector array can be positioned to detect the signals.

Both functions can be combined, so that the grating is directly located on the toric mirror. Hence, the light is not afflicted by any aberrations or attenuation of a focusing lens or other diffractive or refractive elements [14], which would be necessary for any other setup.

In case of a DEMUX for glass fiber, the Rowland grating can be designed planar. But SI-POF has a large numerical aperture, which leads to a higher opening angle of the emitted light. A planar setup would result in high losses. Therefore, a three dimensional design is necessary.

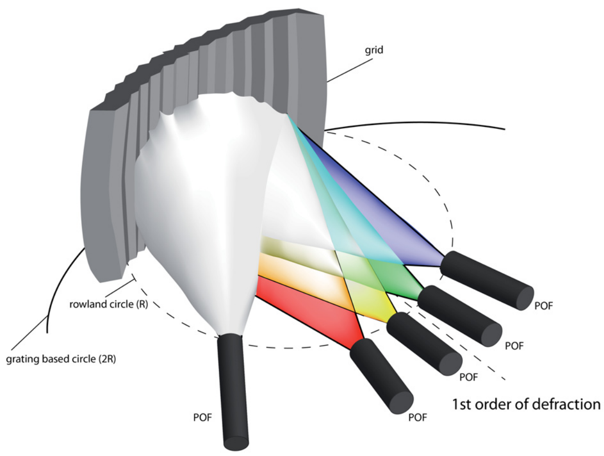

Figure 5 Schematic of a Rowland spectrometer

As shown in [15], for a grating based DEMUX first diffraction order is of the highest interest for detection, but the required grating line density of 1200 l/mm is too high for mass production. According to simulation results in [15], the DEMUX can separate three colors with enough space between them on the detection layer, so that the information can be regained with POFs or a detector array. This result is given for a second diffraction order, which offers good manufacturing possibilities due to the reduced line density of the grating (500 l/mm).

3.3 Availability of optical sources in VIS

A proposed grid should have channels at wavelengths or at least wavelength regions where laser diodes (LDs) are currently available.

The WDM system should be capable of transferring high data rates. This requires the utilization of high-power high-speed LDs. Unlike light-emitting diodes, which are available within whole spectral range where SI-POF is used, LDs are currently available only at certain wavelengths: 405 nm, 450 nm, 488 nm, 520, and at and around 650 nm. These LDs are good candidates to form the basis of the three to four-channel high-speed VIS WDM system.

Basic parameters of four LDs acquired by Harz University for the realization of a four-channel high-speed WDM transmission system over SI-POF are listed in Table 2.

Ch. No.	1	2	3	4
Type Name	DL-5146-101S	PL 450B	/	HL6544FM
Manufacturer	Sanyo	Osram	/	Opnext
λ_{peak} [nm]	405	450	520	660
I_{th} [mA]	35	30	60	60
I_{bias} [mA]	70	100	160	115
P_{op} [mW]	40	80	50	50
Housing	TO-56	TO-38	TO-38	TO-56
Commercially available	yes	yes	no	yes

Table 2 Basic data of LDs acquired by Harz University

4 Establishing and evaluating grids in VIS

Spectral grids in VIS can be established in two ways:

1. extend existing grids from IR into visible spectral range, and
2. establish independent wavelength and frequency grids.

4.1 Extension of DWDM grid into VIS

Extending DWDM frequency grid into VIS results in 3213 channels between 428.3 THz (700 nm) and 749.5 THz (400 nm) for channel spacing of 100 GHz. In wavelength domain channel spacing reduces from 0.163 nm for channels in 700 nm region, to 0.053 nm for channels in 400 nm region. For channel spacing of (100/n) GHz, where n=2,4, or 8, the number of channels in the same spectral region equals n*3212+1.

Since demands for WDM systems are far more modest in visible than in IR spectral range, it can be stated that DWDM concept cannot be applied for WDM systems over SI-POF.

4.2 Extension of CWDM grid into VIS

Extending CWDM wavelength grid into VIS results in 15 channels between 400 nm and 700 nm (Figure 5), thus making a good utilization of the available spectral range. Having channels in high attenuation regions cannot be avoided (Ch. 11, 12, 14, and 15). Channels in low attenuation regions are those at 471 nm (Ch. 4), 511 nm (Ch. 6), 571 nm (Ch. 9), and 651 nm (Ch. 13). Having a channel at 651 nm is particularly important since most of the commercial SI-POF systems work in red window.

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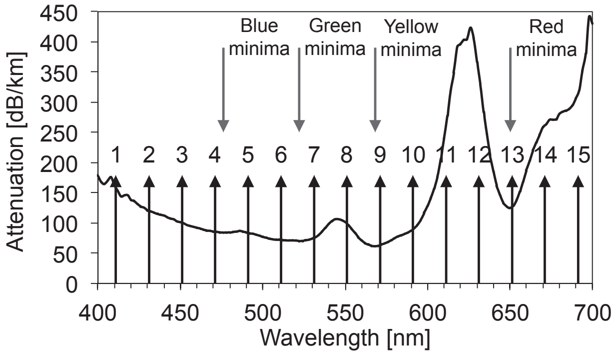

Figure 5 Extension of CWDM grid into VIS

Parameters of the grid are listed in Table 3. Here λ denotes the nominal central wavelength, f is the corresponding frequency, and L is the attenuation of SI-POF at a given wavelength.

Ch. No.	1	2	3	4	5	6
λ [nm]	411	431	451	471	491	511
f [THz]	729	696	665	637	611	587
L [dB/km]	158	120	100	85	84	72
Ch. No.	7	8	9	10	11	12
λ [nm]	531	551	571	591	611	631
f [THz]	565	544	525	507	491	475
L [dB/km]	75	99	63	89	259	349
Ch. No.	13	14	15			
λ [nm]	651	671	691			
f [THz]	461	447	434			
L [dB/km]	126	261	313			

Table 3 Extension of CWDM grid into VIS

Good channel allocation, high channel density, and availability of LDs make extension of CWDM grid a strong candidate for a grid in VIS. For near-future WDM systems the utilization of some of the odd-numbered channels is of interest (marked blue in Table 3). Because of the higher attenuation and lack of sources for channels 11 and 15, the choice would likely be reduced to channels 1, 3, 5, 7, 9, and 13. The overall attenuation in all channels is 2253 dB/km.
The main requirement for WDM systems in VIS is cost-effectiveness. Like in CWDM systems, cost- effectiveness in VIS should be achieved through a flexible system design, and 20 nm channel spacing allows that.

4.3 Independent grids

Independent grid is any wavelength or frequency grid defined in VIS. Because of the obvious CWDM nature of VIS WDM systems over SI-POF, it is convenient to have a wavelength grid with equidistant channel spacing. One approach to establish and optimize such a grid is presented here. The idea is to establish grids with channel spacing from 10 nm to 50 nm in increments of 1 nm. The position of each grid on the wavelength axis should be optimized. Finally, the grid with the best performances is determined based on the criteria set above.
The following procedure was used. Let the distance in nm between the first and the last nominal central wavelength equal D, $D \leq 300$ (700-400). If D is not a prime number it can be prime factorized. Depending on the prime factors obtained, one or more $a*b$ products can be derived (D=a*b). Here a represents number of channels decremented by one, and b represents channel spacing. Among all possible $a*b$ products only some of them are of interest. For example, let D equal 280. Prime factorization of this number results in $280=2^3*5*7$. Applicable $a*b$ products are 10*28, 14*20, 8*35, and 7*40, meaning that for 8*35 case grid consists of 9 channels with 35 nm channel spacing. The grid is then centered on the wavelength axis with respect to 550 nm and shifted left and right by

- no more than $\pm(300–a*b)/2$ if $(300–a*b)<b$, or
- less than $\pm(b–(300–(a+1)*b))/2$ if $(300–a*b)\geq b$,

in order to find the optimal position. To establish and evaluate grids with channel spacing of 50 nm and less, and thereby for the same channel spacing have a grid with odd and even number of channels, numbers from [215, 300] interval were prime factorized. In case of identical solutions, only the grid with the highest number of channels was taken into consideration (i.e. 300=15*20, 260=13*20, only 15*20 is considered; 280=14*20, 240=12*20, only 14*20 is considered)
Among all examined independent grids, the grid that best satisfies set criteria is a wavelength grid that specifies channel spacing of 20 nm, and consists of 15 channels between 410 nm and 690 nm. Parameters of the grid are listed in Table 4. The extension of CWDM grid differs by only 1 nm from this grid. Everything stated for the extension of CWDM grid (good channel allocation, utilization of odd-numbered channels, etc.) applies here as well. The overall attenuation in the channels is 2249 dB/km, which is as low as with the extension of CWDM grid.

Ch. No.	1	2	3	4	5	6
λ [nm]	410	430	450	470	490	510
f [THz]	731	697	666	638	612	588
L [dB/km]	162	121	101	86	85	72
Ch. No.	7	8	9	10	11	12
λ [nm]	530	550	570	590	610	630
f [THz]	566	545	526	508	491	476
L [dB/km]	74	102	62	87	240	367
Ch. No.	13	14	15			
λ [nm]	650	670	690			
f [THz]	461	447	434			
L [dB/km]	125	259	306			

Table 4 Independent grid that best satisfies the criteria for evaluating the applicability of a grid in VIS

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5 Proposal for a grid in VIS

The independent grid presented above best satisfies the criteria for evaluating the applicability of a grid in VIS. Extension of CWDM grid differs from this grid by only 1 nm, which makes it almost equally good solution for a grid in VIS. We propose these two high-performance grids to be further internationally discussed and revised.

Besides SI-POF, fibers of a particular interest for POF communications are PMMA graded-index (GI)-POF (named OM-Giga), polystyrene based GI-POF [16], and perfluorinated GI-POF made of CYTOP (a completely fluorinated polymer). It seems that two presented CWDM grids (extended in near IR) have also a strong potential to be used for these types of POF. This could potentially lead to having a unique CWDM grid applicable for all types of POF.

6 Conclusions

Growing interests and intensive activities to develop WDM systems over SI-POF are present in recent years. Besides developing WDM components, which are essential to the success of WDM over SI-POF, an important aspect is establishing a unique set of WDM transmission channels in VIS. In this paper spectral grids for VIS-WDM application over SI-POF were investigated. It is shown that CWDM concept is appropriate for WDM applications over SI-POF. Two solutions for a grid are proposed for further international discussion and revision. One of them is the extension into VIS of the existing CWDM grid defined in ITU-T Rec. G.694.2. The other one is the independent grid established on the technical aspects of SI-POF technology. For upcoming POF WDM systems it is highly required to define a wavelength grid for interworking possibilities and industry standards. It is an important rule that the market needs sources with identical center wavelength from independent suppliers. With the use of one of these two grids it will be possible to obtain an international recommendation for future SI-POF WDM systems with possible capacity of nearly 40 Gbit/s, assuming 2.5 Gbit/s per channel and 15 WDM channels.

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