Chapter 7

Step-Index PMMA Fibers and Their Applications

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Additional information is available at the end of the chapter

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1. Introduction

With the general term “Optical Fibers” it is quite common to refer to a specific type of fibers, in particular Glass Optical Fibers (GOF), that can then be divided into several categories depending on the type of applications they are needed for (communications, sensing, lasing, etc.); but optical fibers are not only glass-based: a wide variety of Polymer-based Optical Fibers (POF), that can be mainly classified based on the specific material and the index profile, exists, for several applications.

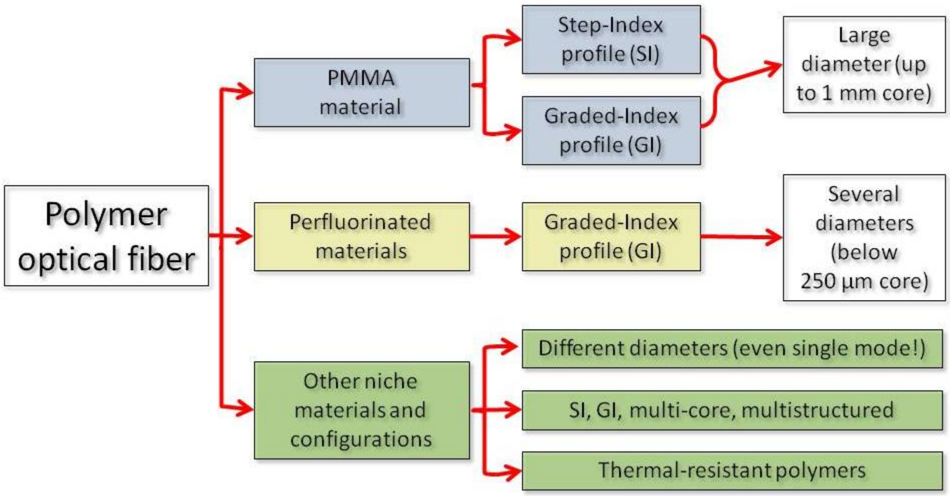

Figure 1. Overview of the different types of POF available.

Two major classes of POF can be identified: Step-Index POF with large core and Graded-Index POF. It is quite common to identify the first type of fiber as POF and the second one as PF-POF (made of perfluorinated material) or GI-POF, however in the following, for sake of clarity, PMMA-SI-POF will be used to address large core step index fibers made of PMMA material. Some other variants exist but are not commonly used, so we will not address them in this chapter.

The use of polymers instead of glass gives certain advantages in terms of mechanical robustness and installation in hostile environments (such as in presence of water or high humidity), so many studies are still in progress to reduce the transmission performance penalty that POF pay with respect to GOF. Since the behavior of the best performing GI-POF are getting very similar to multi-mode GOF, purpose of this chapter is to focus only on PMMA-SI-POF.

This chapter is organized as follows: first, we will give an overview on the fiber itself, describing the material, the production process, the main characteristic; secondly, we will describe components and tools for PMMA-SI-POF handling and using; then, we will analyze their adoption for communication systems and sensing applications.

2. Basics of PMMA-SI-POF

The most widely available PMMA-SI-POF has a core diameter of 980 μm and a global (core plus cladding) diameter of 1mm, while a variant with a diameter of 500μm is gaining interest; however, only the first type of fiber is standardized [1].

The success of 1mm fiber is due to the wide range of applications (Hi-Fi, car infotainment systems, video-surveillance, home networking) and to the interesting mechanical characteristics with respect to GOF. In particular, we can highlight the following main advantages that this type of POF has with respect to other fibers (we will not discuss about all the intrinsic advantages of optical propagation compared with electrical communications, that are maintained moving from GOF to POF):

- High mechanical resilience: the flexibility of the plastic material allows rough handling of the fiber, such as severe bending and stressing, without causing permanent damages. This enables brownfield installation (for example in existing power ducts, being an electrical insulator), also thanks to the 2,2 mm diameter of conventional PMMA-SI-POF simplex cable;
- High mechanical tolerances: the 980 μm core and the 0,5 numerical aperture allow a certain aligning mismatch in connection processes with transmitter and receivers of among fiber spools. This tolerance avoids the use of expensive precision tools for connectorization. Moreover, dust on the fiber ends is less compromising than with small-core fibers;
- Low bending losses: the core diameter also allows a certain bending tolerance. It has been demonstrated [2] that more than 20 bends at 90° with a radius of 14 mm are requested to cause a loss over 5dB for a 1 Gbps transmission system, even if standards foresee 0,5dB for every bend with a bending radius of 25 mm;

- Easy tooling: fiber cut can be made via conventional scissors, and polishing via sand paper, however very simple tools that avoid polishing after cutting exist. Connectorization is fast and easy via crimping or spin connectors, while also connector-less connection via clamping is foreseen in recent transceivers;
- Use of visible sources: the PMMA material works efficiently in the visible wavelength, namely red, green and blue (650 nm, 520 nm and 480 nm respectively). This actually helps unskilled personnel to have a preliminary evaluation of the good functioning of the components (you can actually see the light);
- Ease of installation: the previous characteristics result in a certain ease of installation for unskilled personnel and users, then yielding a consistent reduction in installation time and cost;
- Water resistance: PMMA is also very resistant towards water and salted water. This makes POF suitable for marine applications.

These advantages are reflected in 500 μm PMMA-SI-POF, with the obvious note that alignment tolerances are lower.

In turn, PMMA-SI-POF suffer of high attenuation and low bandwidth; while the attenuation is due to the material, the bandwidth limitations are due to the size of the core and the index profile: in 1 mm PMMA-SI-POF around 1 million modes are propagating in the operational wavelengths.

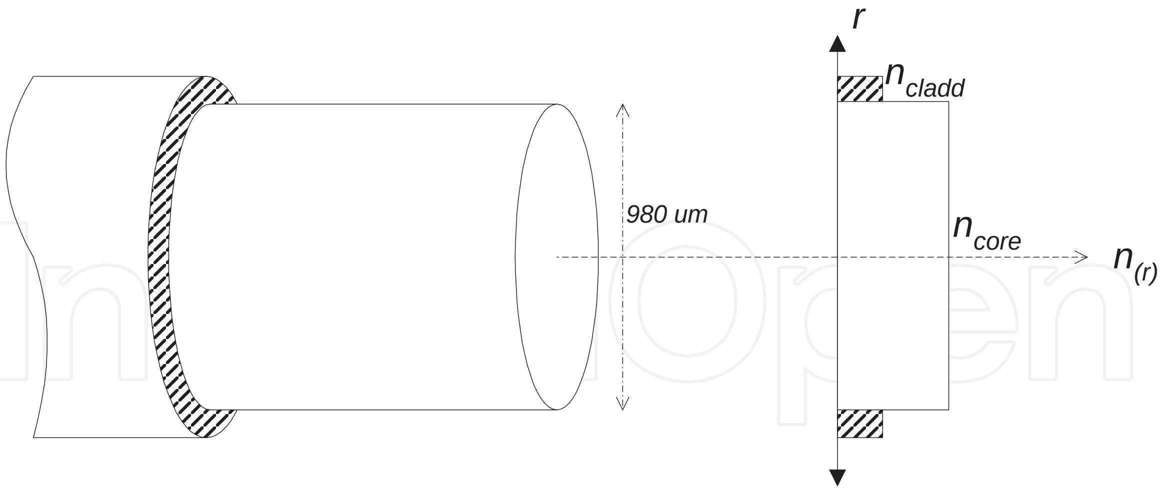

Figure 2. PMMA-SI-POF dimensions and index profile

We can then summarize that PMMA-SI-POF are not to be considered as competitors to GOF, but are rather competitors to copper, with the advantage of being a suitable medium for hostile environments. In Figure 3 it is possible to see a comparison among standard UTP Cat. 5e cable and a PMMA-SI-POF duplex cable.

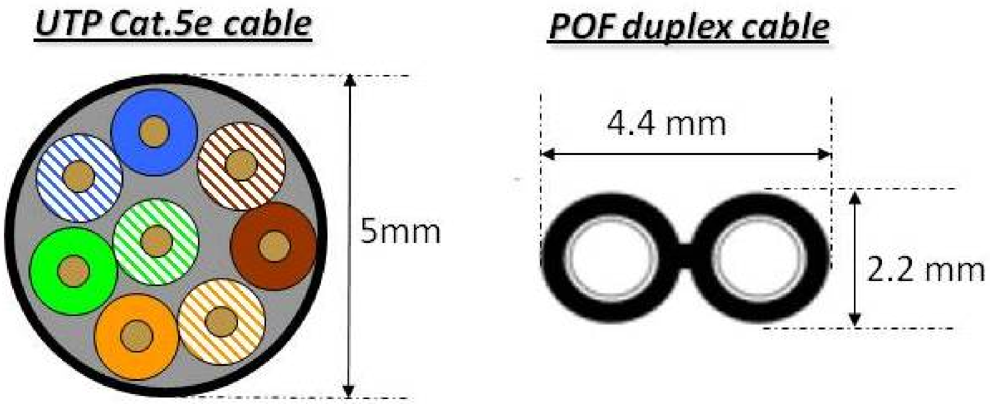

Figure 3. Comparison among a standard UTP Cat.5e copper cable and a PMMA-SI-POF duplex cable. POF cable is smaller and can easily replace copper cable.

2.1. Materials and production processes

2.1.1. Core materials

The most common material for POF is PolyMethylMethAcrylate (PMMA), also known as Plexyglas; it's refractive index is 1,492 and its glass transition temperature is around 105°C. PMMA based POF usually work with visible light (red, green and blue), however the attenuation can be very high (up to 200dB/Km for commercial fibers). Other materials have been investigates: Polystyrene (PS) has an higher refractive index than PMMA (1,59) but its attenuation performances are not expected to be better, so currently no mass production employing this polymer exists; Polycarbonate (PC) has a refractive index of 1,58, is interesting for special applications thanks to its high glass transition temperature (150°C) but its very high attenuation makes it not suitable for telecom/datacom applications.

MMA structure can be seen in Figure 4.

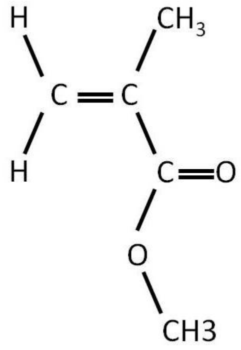

Figure 4. MMA momomer

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2.1.2. Cladding materials

The other main materials for POF are Fluorinated Polymers; they can also be used for the core, since their performances are very interesting in terms of attenuation: in theory it could be comparable with the one achieved for glass fibers, and the refractive index is in the order of 1,42;to date, the best results have been achieved with CYTOP polymer, working at 850 nm and 1300 nm and used for GI-POF. However, from the point of view of PMMA-SI-POF, PF polymers are adopted as cladding materials.

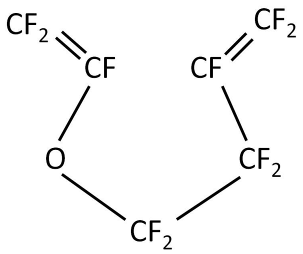


Figure 5. CYTOP momomer

PMMA can be used as cladding material when the core is made with PC.

2.1.3. Manufacturing by fiber drawing

The most well-known method for fiber productions is drawing from a preform, with a proper drawing tower; this method is used for mass production of glass fibers and can be easily adapted to polymer fibers.

A cylinder of polymer (the preform), having the very same structure and refractive indices difference of the fiber we want to draw has to be prepared, usually with an extrusion process; this cylinder has dimensions orders of magnitude bigger compared to the fiber it is meant to generate. The preform is then mounted on top of the drawing tower and heated through a specific furnace to a temperature that makes the polymer starts to soften, so that it becomes possible to reduce its diameter via controlled traction by a take-up winding drum. During the process, the diameter is controlled and it is eventually possible to deposit the coating (however this operation can also be performed in a subsequent phase).

Some variants of the process foresee the preform to be suitable for core drawing only, with the cladding applied subsequently via extrusion.

This way, the length of the fiber that can be obtained is limited by the dimension of the original preform.

With respect to GOF drawing towers, due to the lower melting temperature of polymer with respect to glass, POF towers are lower and also the ovens have a lower working temperature. Also the drawing speed is significantly lower, being in the order of 0,5 m/s while for GOF the conventional production speed overcomes 10 m/s.

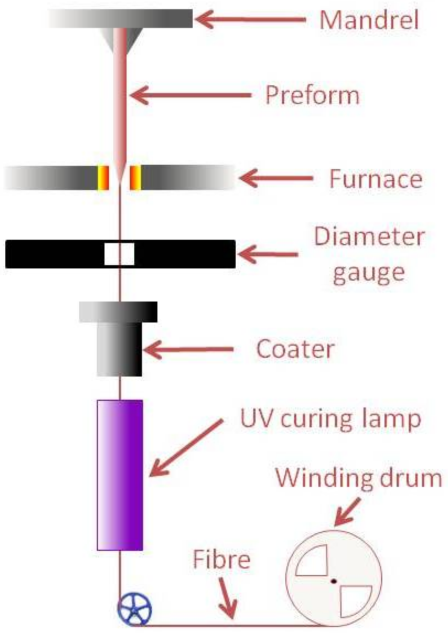


Figure 6. Fiber drawing.

2.1.4. Manufacturing by extrusion

Producing the fiber by extrusion requires the whole process to start from the monomer, that by means of a distillation process is inserted into a proper reactor together with the initiator and the polymerization controller. Once the process is concluded (at a temperature of about 150°C), the polymer is pushed through a nozzle by pressurized nitrogen injections, in order to control the diameter, and the cladding is applied (the cladding is extruded at around 200°C).

The extrusion is quite simple for PMMA-SI-POF, and is the most promising manufacturing process since it is quite cheap and allows continuous production starting from the monomer, thus enabling mass-production.

2.2. PMMASI-POF characteristics

2.2.1. Attenuation

Attenuation is a very important factor in determining the maximum length of a fiber link, and depends on the material properties and the transmission wavelength. The PMMA attenuation spectrum is depicted in Figure 7. It can be seen that, as happens with glass, three transmission windows can be clearly identified, even if with very different attenuation values: around 500 nm, 570 nm and 650 nm, starting from at least 80dB/Km; being in the visible wavelength interval, these windows can be associated to colors, respectively blue-green, yellow and red.

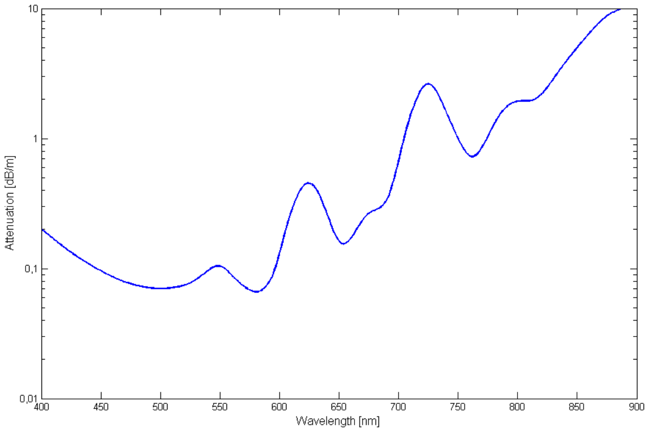


Figure 7. PMMA attenuation spectrum. Different windows can be identified.

The availability of components and the shape of the windows actually suggests to identify the transmission windows as follows: blue (480 nm), green (520 nm) and red (650 nm). Green and blue windows are characterized by the lowest attenuation, in the order of 80dB/Km (together with yellow, in which the attenuation is even lower but there is lack of components, and thus this window will be neglected in the following of this chapter), while in red the attenuation is nearly doubled but where there is a significantly higher availability of components at higher speeds. It has to be mentioned that standards [1] use to define the attenuations as reported in Table 1 for PMMA-SI-POF dubbed of category A4a.2.

Wavelength (nm)	Attenuation (dB/Km)
500	<110
650	<180

Table 1. Attenuation of PMMA-SI-POF according to IEC 60793-2-40 A4a.2

It is then evident that, when dealing with PMMA-POF, transmission length is limited to a few tens or a few hundred meters, depending on the baud-rate.

Given the attenuation of the fiber and the fact that home/office networking is one of the most interesting market for data-communications over PMMA-POF, bending loss becomes a parameter of paramount importance when dimensioning and then installing the system. As previously mentioned, standards foresee 0,5dB for a bend with a radius of 25 mm, but better results have been achieved; Figure 8 shows measured value of extra-losses for 360° bends, when the modal equilibrium is reached.

It can then be said that 0,5dB of extra-loss has to be considered for each 10 mm bend, while there is virtually no extra-loss to be considered when the bending radius exceeds 25 mm.

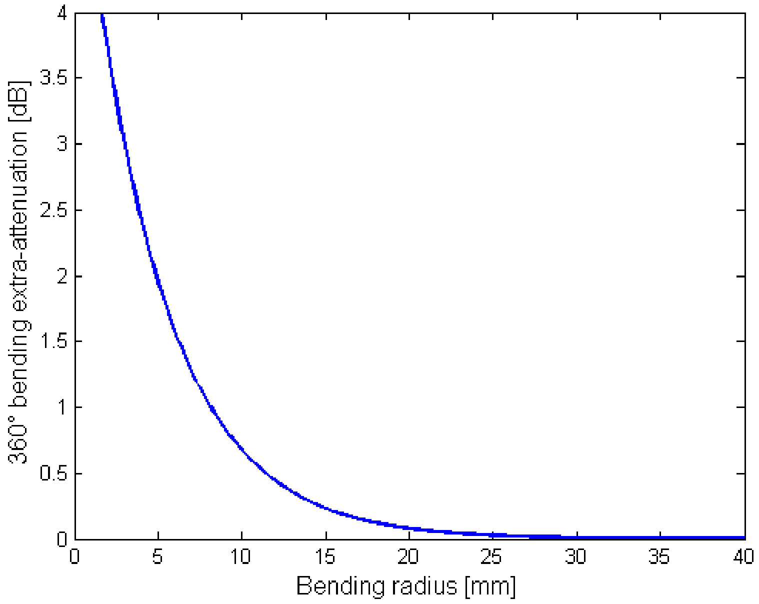


Figure 8. Extra attenuation vs. bending radius

As briefly mentioned, the modal equilibrium condition is important while measuring attenuation: due the multimodality of the fiber, the launching conditions are important especially for short lengths. In order to avoid having length-dependent attenuation measurements (after a certain length the Equilibrium Mode Distribution EMD is naturally obtained), usually two methods are adopted: differential measurement with consistent fiber lengths or the insertion of a mode scrambler at the transmitter side. An example of mode scrambler is reported in Figure 9.

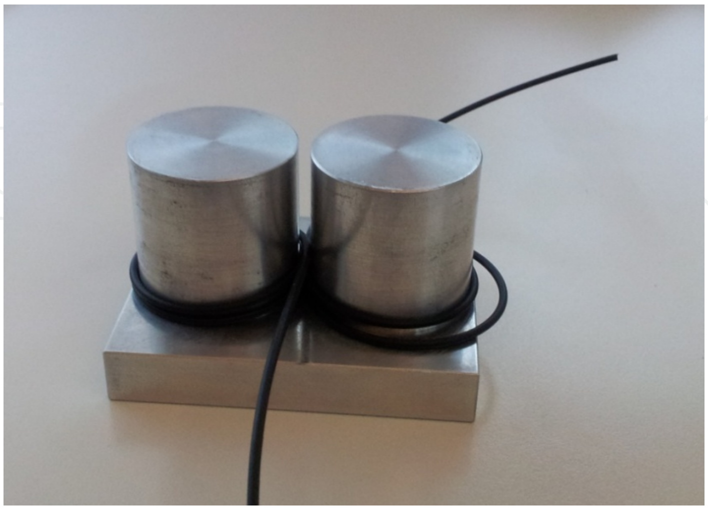


Figure 9. Mode scrambler. Two cylinders with a radius of 21 mm are separated by 3 mm. The fiber is wounded in a 8-shape 10 times around those cylinders. The total attenuation of such an arrangement is about 10dB.

2.2.2. *Bandwidth*

PMMA-SI-POF are highly multi-modal (in the order of 1 million modes), and in the wavelength regime we consider, for what concerns bandwidth performances, multi-modality is by far the most limiting factor, while chromatic dispersion becomes negligible. It is not target of this chapter to perform a deep theoretical analyses of bandwidth in POF, then we will now focus only on experimental measurements, pointing out the fact that, as GOF, POF have a low-pass characteristic that can be approximated with a Gaussian curve.

A bandwidth measurement technique has not yet been defined in any standard; in literature, we can find results exploiting the following methods:

1. Frequency-domain direct spectral measurement with network analyzers;
2. Time-domain measurement with narrow pulse generation;
3. Optical Time Domain Reflectometry (OTDR).

The most comprehensive results available in literature [3] have been obtained with method 1, while results obtained with the other methods are usually a lot more limited in the length of the link [4], [5].

Frequency-domain measurement setup is quite simple: an electrical network analyzer drives an high-speed laser source connected to the fiber under test, then an high-bandwidth optical receiver closes the loop into the network analyzer, so that a direct bandwidth measurement can be performed. The results shown in Figure 10 are referred to a fiber with a declared NA=0,46. It is evident how POF systems can also be bandwidth limited, since we range from 30 MHz for 100 m of fiber to 9 MHz for 400 m of fiber. Also in this case it is useful to reach the EMD condition to avoid measurement being affected by launching conditions, such as transmitter numerical aperture.

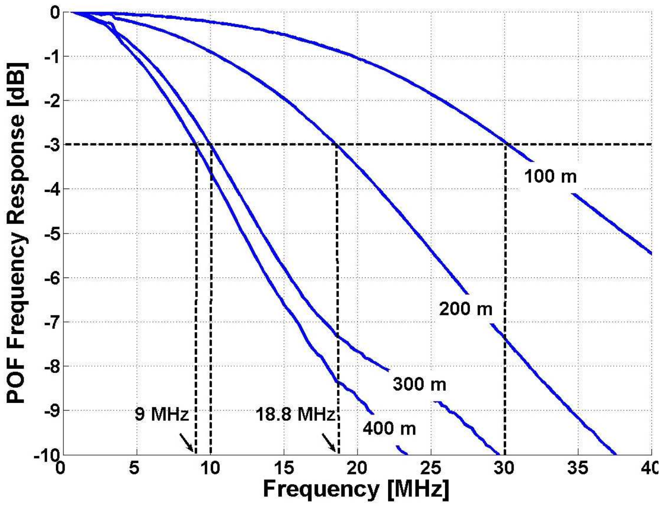


Figure 10. Electrical-to-electrical PMMA-SI-POF response for different link lengths with indication of 3dB bandwidth. Courtesy of the authors of [3].

It is not purpose of this chapter do go into deep analysis of the theoretical aspects of fibers bandwidth, and we suggest to refer to [6] if interested.

2.2.3. Handling, tooling and connectorization

The big advantage of 1 mm POF are due to their easy handling: this does not require expensive equipment and allows do-it-yourself installation; in particular:

- PMMA-SI-POF is robust and flexible, with good bending properties, and thus suitable for careless handling;
- its core dimension and numerical aperture allow certain mechanical tolerances and low sensitivity to contaminations;
- connectorization is easy, requiring simple tools (such as even conventional scissors) and, taken to the extreme, also allows connector-less contact.

Workmanlike connectorization of PMMA-SI-POF foresees the following steps:

- cutting and stripping the fiber with a proper tool, such as in Figure 11;
- inserting the fiber into the chosen connector (different types of connectors can be seen in Figure 12) and locking it (the connectors are usually self-crimping or screw-type);
- putting the connector into a polishing disk (Figure 13) and cleaving by moving the disk on delicate sand paper forming several times a 8-shape.

Figure 11. Cutting and stripping tools. On the left, a conventional copper cable stripper; on the right, a proper tool courtesy of Firecomms.

For such a connection, a 1 dB penalty is usually taken into account. Fusion splicing is not available with POF, so splicing is obtained facing to end-connectors into a proper in-line connector, and thus a 2 dB attenuation has to be taken into account.

Figure 12. Different type of 1 mm POF connectors. ST, SMA (2 versions), V-pin. Other type of connectors exist.

It is worth nothing that connectorless installation is gaining real interest since the induced penalties with respect to the previously mentioned procedure can be really negligible if the cutting is made with a certain care. If cutting and stripping is done with tools such as the ones shown in Figure 11, allowing a certain plain cut of the end face, then special transceiver housings such as the Optolock™ (by Firecomms, Figure 14) can be used, simply inserting the fiber into it and then locking.

Figure 13. Polishing disk for 1 mm POF. This disk will be moved forming several times a 8-shape on sand paper for final cleaving.

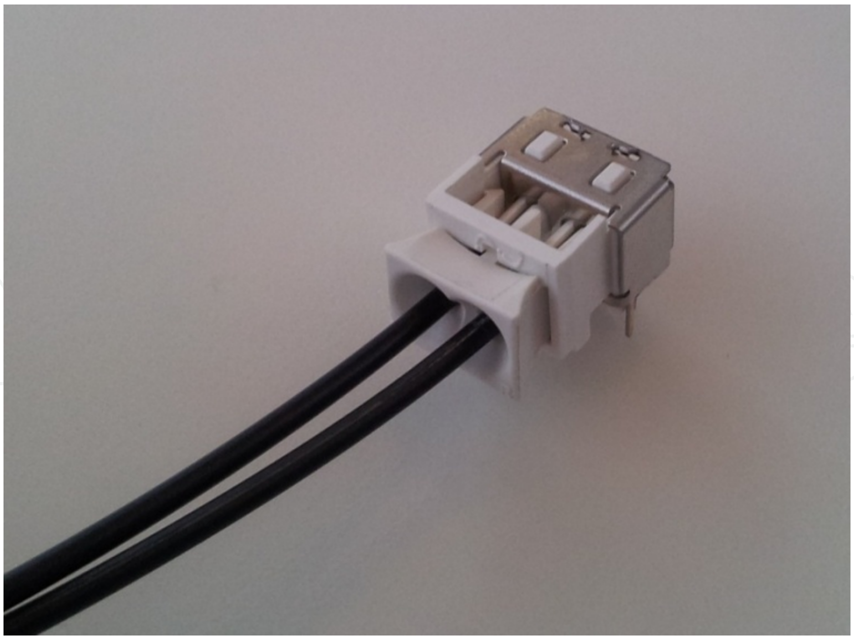


Figure 14. Optoloc™ transceiver housing, courtesy of Firecomms.

2.3. Overview on components

It is not in the scope of this chapter to present a full treatise on optical components, that would deserve a full book itself, so we suggest to consult [7] for this purpose and we will give a very general overview on what type of optical components are available for PMMA-SI-POF applications, given that the most interesting novelties of PMMA-SI-POF components are related to the optical sources only.

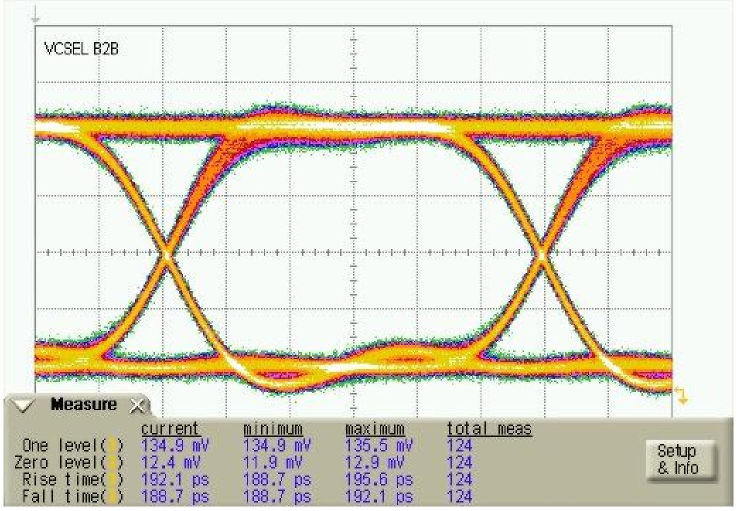
2.3.1. Sources

LEDs are the most common optical source to be employed with PMMA-SI-POF. LEDs are available for all the main wavelengths (red, green and blue), and can guarantee high output power and long lifetime. Components with an output power of up to +6 dBm can be found on market, and modulation bandwidths usually are in the order of the tenth of megahertz; thus, they usually are suitable for low-speed transmissions, such as 10 Mb/s, or require complex modulation formats of equalization techniques for higher speeds. Typical linewidth of LED sources is in the order of 40 nm.

A wide variety of red lasers exist, mostly developed of CD and DVD drives and laser pointers; usually, sources developed for such applications hardly meet the speed requirements for data communications but might be suitable for sensing applications. High power edge emitting lasers suitable for high-speeds exist, but not yet available in mass production or for low-cost applications. Vertical Cavity red lasers (VCSELs) are gaining interest since they can achieve interesting performances in terms of bit-rate [14], however low-cost commercial units usually have their peak wavelength at 665 nm, that remains in the red region but experiences a little attenuation penalty with respect to sources working at the optimal wavelength of 650 nm. The spectral width of VCSELs is of course very narrow, and the typical output power is in the range of -5 dBm to -2 dBm.

Resonant Cavity LEDs (RC-LEDs) are gaining increasing interest for communications, since they join the robustness of LEDs with the high bandwidth provided by the resonant cavity. Commercial components work at 650 nm, with a spectral width in the order of 20 nm. Commercial RC-LED have 2 or 4 Quantum Wells (2QW or 4QW); in general 2QW sources are faster while 4QW sources are more powerful. On average, the typical bandwidth of a RC-LED source is in the order of 250 MHz, while the output power goes up to 0 dBm.

For comparison purposes, in Figure 15 and 16 are reported the eye diagrams at the output of commercial low-cost VCSEL and a RC-LED when transmitting 1,1 Gb/s.



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             current    minimum    maximum    total meas
 One level( ) 134.9 mV   134.9 mV   135.5 mV   124
Zero level( ) 12.4 mV    11.9 mV    12.9 mV    124
 Rise time( ) 192.1 ps   188.7 ps   195.6 ps   124
 Fall time( ) 188.7 ps   188.7 ps   192.1 ps   124
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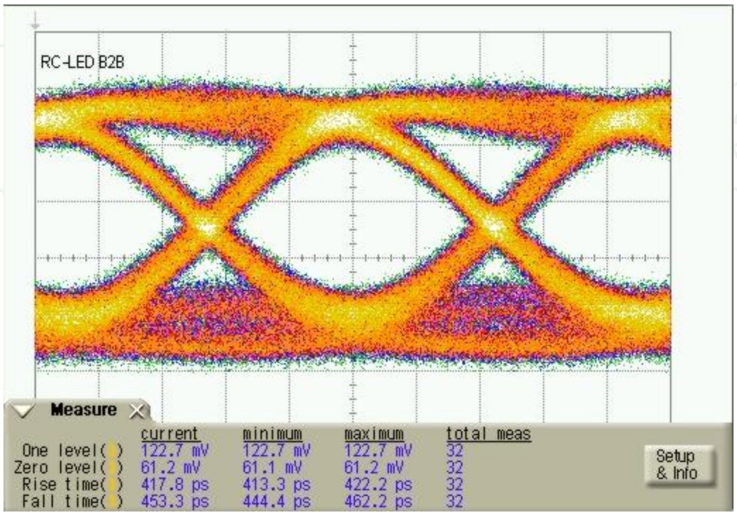
Figure 15. Gb/s transmission, eye-diagram at VCSEL output



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             current    minimum    maximum    total meas
 One level( ) 122.7 mV   122.7 mV   122.7 mV   32
Zero level( ) 61.2 mV    61.1 mV    61.2 mV    32
 Rise time( ) 417.8 ps   413.3 ps   422.2 ps   32
 Fall time( ) 453.3 ps   444.4 ps   462.2 ps   32
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Figure 16. Gb/s transmission, eye-diagram at RC-LED output

As a summary, it is worth reminding that when needing high-speed components, such as VCSELs and RC-LEDs, then working in red wavelength is the only option.

2.3.2. Photodiodes

Typically, silicon photodiodes are used with PMMA-SI-POF. Their highest responsivity is usually around 950 nm, but their efficiency usually remains quite high also at 650 nm; some variants having their best performance at 800 nm exist. The performances decay when working at shorter wavelengths, but the lower attenuation of the fiber in green and blue.

Typical photodiodes have an area of 500 μm, up to 800 μm; considering the fiber diameter of 980 μm, it is quite common to use spherical coupling lenses in the photodiode package for improving coupling efficiency.

Pin structures are the most common to be found on market, but some Avalanche Photo Detectors (APD) can also be found.

2.3.3. Passive components

In the POF world there is not the same variety of passive components as in the GOF world. In particular, it can be said that only POF couplers exist off-the-shelf. The reasons for this lack of components is mainly due to the relatively low market needs. In particular, it can be said that only couplers/splitters exist off-the-shelf, mainly used for measurements setups or sensing applications. Couplers for PMMA-SI-POF are in general quite simple to be produced, mainly starting from the fiber itself: the most common structure foresees to polish two fibers, match and then glue them. It has to be mentioned that such couplers usually exhibit an excess loss in the order of 3 dB (to be added to the 3 dB due to the power splitting).

It is then worth mentioning that, however filtering in the visible regime should be quite common, no filters for PMMA-SI-POF exist. At the same time, no attenuator are available, and the common way to obtain (uncontrolled) attenuation is to insert in-line connectors into a fiber link and then creating an air-gap among the two facing fibers.

3. Data communications with PMMA-SI-POF

Considering attenuation and bandwidth characteristics illustrated in paragraph 2.2 and the performances of the components described in paragraph 2.3, it becomes quite evident that, if we consider the speeds defined by the Ethernet standard, 10 Mb/s systems are mainly attenuation limited, while transmitting at 100 Mb/s and over suffers of severe bandwidth limitations. Communications with PMMA-SI-POF then require the adoptions of mechanisms that are not usual to the optical community but that are widely adopted for example in copper or radio communications, such as multi-level modulation schemes or equalizations. In the following we will rapidly describe the most interesting multilevel modulation formats currently adopted for PMMA-SI-POF transmission, then we will report on the architectures that in literature have demonstrated the best bit rate vs. length results, considering the data-rates defined by the Ethernet standard.

3.1. Amplitude modulations: binary and multilevel

Amplitude modulations are the only formats reasonably applicable to PMMA-SI-POF systems, due to the unavailability of external modulators.

Conventional optical communications adopt On-Off Keying (OOK), that is a binary amplitude modulation, thus transmitting one bit per symbol and that in optics can be simplified switching the source ON when transmitting symbol 1 and OFF when transmitting symbol 0. In recent years more complex modulation formats, able to transmit more bits per symbol, have gained interest also when dealing with single-mode GOF for ultra-high capacity backbone systems. When dealing with PMMA-SI-POF, also due to the absence of proper optical modulators, only direct modulation of the source power can be adopted, thus introducing *Pulse Amplitude Modulation* (PAM).

PAM) consists in transmitting one of M possible amplitude levels (the "symbols") in each time slot. It is a well-known technique outside the fiber optic community, while it has found so far little (if any) application in fiber transmissions. For this reason, we briefly review its basic principle and terminology.

The number of levels M is set to $M=2^{N_{bit}}$, where N_{bit} is the number of transmitted bits per symbol. Being T_s the duration of a symbol, the quantity $D=1/T_s$ is the number of transmitted symbols per second, also called baud-rate, and the resulting bit rate is $B_r = N_{bit}*D$. The only reason for choosing multilevel is that, for a given available bandwidth B_{av} (related to the cascade of the transmitter, channel and receiver transfer functions), the maximum data rate that can be transmitted without excessive Inter-Symbol Interference (ISI) increases with the number of levels M. As a rule of thumb, the relation:

$$B_{av} > 0.7\ D$$

should be satisfied to have acceptable ISI level (the constant 0.7 comes from the SDH standard; it can vary a little depending on filter types, without qualitatively affecting the following considerations nevertheless). Thus, for the same available bandwidth B_{av}, the resulting maximum bit rate increases with N_{bit} following the relation:

$$B_{r\_max} < N_{bit} * B_{av} / 0.7$$

When adopting OOK, this means that for example 70 MHz are required for a line-rate of 100 Mb/s, while for multilevel modulations with the same bandwidth 100 Mbaud can be transmitted.

The use of multilevel transmission is very interesting for any bandwidth-limited system. On the other side, the drawbacks are:

- for a given Bit Error Rate and a given receiver noise floor, the required received power (or "receiver sensitivity") increases with N_{bit}

- the entire transmission channel, from the transmitter to the receiver, should be as linear as possible
- the complexity of the TX-RX pair is clearly increased with respect to binary transmission.

Multilevel transmission is then an appealing approach to improve the maximum bit rate without changing the optical part of the system. This key advantage has to be weighted up together with the previously mentioned drawbacks. In particular:

- regarding receiver sensitivity, for the same total bit rate, the penalty of multilevel compared to binary is equal to 1.76 dB for M=4, 3.93 dB for M=8 and 5.74 dB for M=16, if the receiver bandwidth is properly optimized. Without receiver bandwidth optimization, the penalty is respectively 4.77 dB, 9.03 dB and 12.04 dB. These penalties should clearly be taken into account.
- Regarding POF channel linearity, the only significantly nonlinear optoelectronic device is the LED, while the POF itself and the photodiode are linear to a fairly good approximation. Multilevel POF transmitter should therefore properly compensate for potential LED nonlinearity
- Regarding TX-RX electronic complexity, the cost of high-speed electronics is decreasing so much that there is a rationale to move “logical complexity” from the optical level to the electronic level, by using suitable digital signal processing (using programmable devices such as DSP and FPGA).

PAM has been described in deep since it is one of the options that is being considered for the standardization of 1 Gb/s PMMA-SI-POF systems, however other multilevel formats, such adduobinary [8], [9], [10] can be of interest and easy to be introduced.

Increase of performances could also be obtained using adaptive equalization; this topic is too complex to be fruitfully addressed in this chapter, so we will only mention when in literature equalization has been adopted and we suggest the reader to consult [11] for the theory of equalization.

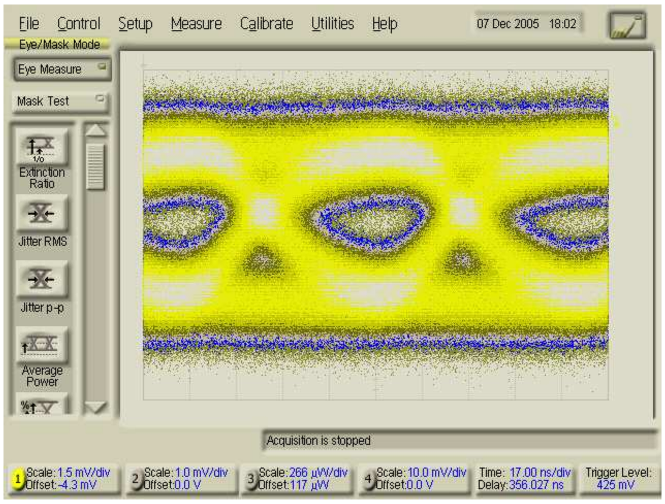
3.2. Best results available in literature

3.2.1. 10 Mb/s transmission

According to the frequency response depicted in Figure 10 and the rule-of-the-thumb reported in the previous paragraph about the relationship among bandwidth and baud-rate, a conventional OOK modulation at 10 Mb/s could easily overcome, in terms of bandwidth, a distance of 400 m. In terms of attenuation, it makes sense then to use green wavelength due to the lowest attenuation it presence: the lack of fast components is not a limiting factor at this bit-rate. However, overcoming 400 m implies a power budget of over 40 dB, impossible with the best receivers available on market. Thus, we can affirm that at 10 Mb/s the system is attenuation limited.

UTP to POF Ethernet media converters currently available on market usually have a maximum reach in the order 200/250 m. They are mostly obtained by using standard Ethernet chipsets and directly driving the optical source. With the same technique, analog video-surveillance systems are being produced.

The best result available in literature [3] shows the possibility of transmitting 10 Mb/s over a distance of 425 Mb/s, by properly choosing the optical components (for mass production) and introducing Reed Solomon Forward Error Correction (FEC). Ethernet transport over such distances has required to correct the standard at level 1 and level 2, removing the Manchester line-coding (that doubles the line rate with respect to the bit-rate) to adopt a 8B / 10B line coding, and transforming the data stream from bursty to continuous in order to apply the FEC.



07 Dec 2005 18:02

Acquisition is stopped

1 Scale: 1.5 mV/div
Offset: -4.3 mV

2 Scale: 1.0 mV/div
Offset: 0.0 V

3 Scale: 266 µW/div
Offset: 117 µW

4 Scale: 10.0 mV/div
Offset: 0.0 V

Time: 17.00 ns/div
Delay: 356.027 ns

Trigger Level:
425 mV

Figure 17. Eye-diagram of 10 Mb/s transmission over 400 m of PMMA-SI-POF, with one intermediate connector. Courtesy of the authors of [3].

3.2.2. *100 Mb/s transmission*

Severe bandwidth limitations occur when transmitting at 100 Mb/s: from a power-budget point of view, transmitting in green could target 250 to 300 m, while over these distances the available bandwidth is well below the 20 MHz. This is then the typical case in which multi-level transmission techniques become of paramount importance. Adopting bandwidth-efficient modulation formats can allow, also in this case, the adoption of green components even giver their lack of speed with respect to red components. In fact, the best result available in literature [11] adopts a green LED with a bandwidth of 35 MHz and an average output power of +2 dBm at the transmitter side and a large area photodiode with integrated transimpedence amplifier, with a bandwidth of 26 MHz, at the receiver side, and reaches a distance of 275 m. The authors of the paper have opted for 8 levels PAM (8-PAM), and due to the linearity requirements mentioned in 2.4.1, LED non-linearity compensation has been implemented; even with these techniques, the received eye-diagram after a link in the order of 200 m resulted completely closed, showing that also equalization techniques [12] should be studied in order to recover the signal. In fact, the authors of [11] have adopted adaptive equalization (adaptive to cope with the intrinsic stochastic properties of multimodal dispersion), and the power budget has been increased with the adoption of FEC. In Figure 18 it is shown the eye-diagram of the 8-PAM signal after 200 m of PMMA-SI-POF when LED non-linearity compensation and adaptive equalization are adopted. Moving modulation formats with even more levels would be practically unfeasible for stricter linearity requirements.

It is worth mentioning that, when it is not requested to reach long distances, so that the available fiber bandwidth is bigger, it might be useful to employ red components, faster (such as VCSELs or RC-LEDs) than the ones working in green, and multilevel modulations might be avoided.

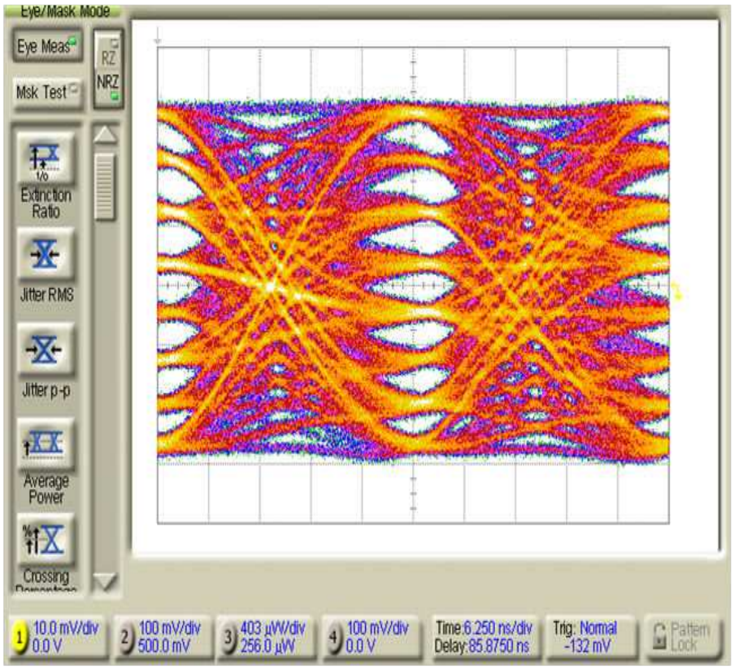


Figure 18. Received 8-PAM signal after 200 m of PMMA-SI-POF, with LED non-linearity compensation and adaptive equalization. Net data rate of 100 Mb/s. Courtesy of the authors of [11].

3.2.3. 1 Gb/s transmission

1 Gb/s transmission over PMMA-SI-POF experiences huge bandwidth limitations, and there is no other chance than using red components and strong equalization. The best results available in literature are due to the POF-PLUS European Project [13], in which it has been shown that in this case complex modulation formats do not give significant advantage with respect to OOK when already equalization is adopted. In [14] it has been shown that with a RC-LED OOK modulated and proper equalization and error correction it is possible to obtain a system overcoming 50 m (75 m with no margin have been obtained). Some little additional margin has been shown in [15] adopting duobinary modulation, a multilevel modulation that has a more complex theoretical background but an easier implementation,

with the current electronic capabilities, than PAM, and is feasible with low cost components. Transmissions over 100 m have been achieved using an edge-emitting laser with an output power of +6 dBm, but such a system cannot be acceptable for practical systems since not eye-safe.

A standardization process is currently going on inside the VDE/DKE initiative, for standardizing 1 Gb/s systems. Since adopting lasers at the transmitter side becomes of interest at this bit rate, then exploiting at most their linearity makes sense, and in fact a solution that adopts Discrete Multi-Tone (DMT) with PAM that adjusts the speed according to the channel performances is currently under investigation [16]: as previously mentioned, PAM vs OOK does not give significant advantages in terms of maximum distance, but in conjunction with DMT inserts in the system rate-adaption capabilities.

3.3. What about WDM over PMMA-SI-POF?

Wavelength Division Multiplexing (WDM) is a very common multiplexing technique adopted for high capacity optical communications with glass fibers; it might appear as an interesting chance with POF as well, but actually it is not a practical solution [17] for high-speed or long-distance applications for the following reasons:

- Array Waveguides (AVG), Mach-Zehender Interferometers (MZI) or Fiber Bragg Gratings (FBG) cannot be used with multimode fibers, so dense wavelength filtering is not possible;
- Red, Green and Blue (RGB) multiplexing is possible but no integrated wavelength splitter exists; experimental units with high insertion losses (5 dB), but in absence of in-line amplifiers this consistently reduces the distance.
- The different performances in terms of attenuation and speed of the components in the three transmission windows would make RGB WDM systems very unbalanced.

In turn, it is possible to say that RGB WDM on PMMA-SI-POF is of interest when low aggregate speeds and short distances are requested; in particular, video systems or medical applications could take advantage of such a technology.

When requiring high speeds and longer distances, the parallel optics approach can be a viable solution, for example for optical interconnects applications [18].

4. Sensing with PMMA-SI-POF

The peculiar characteristics of plastic optical fibers have attracted also the interest in sensing applications, and especially for measuring physical quantities in structural health monitoring [19]. Indeed, using multimode PMMA-SIPOF it is possible to realize fiber based sensing systems that balance costs and performances, since this type of fibers does not require complex machines for splicing and polishing, and makes use of simpler connectors and of visible LED sources. Although several sensing techniques have been described in the literature (and some are described in other chapters of this book), PMMA-SI-POF are best suited for the development of sensors that exploit the variation of the received light intensity with the quantity under measurement, which are the so-called intensiometric sensors, and in this paragraph we will address this technique only.

Typical PMMA-SI-POF intensiometric sensors are based on the variation of: (i) the propagation loss along the fiber (either for local microbending, as for example in [20] and [21], or in distributed form, as in [22]); (ii) the light collected after a free space propagation (as in [23], [24], and [25]); (iii) the interaction through evanescent field tails (as in [26], [27] and [28]). The first two approaches are most often used to measure physical quantities like displacements, vibrations and acceleration, whereas the latter for detecting chemicals.

Intensiometric sensors are conceptually very simple – hence the low cost – because their implementation in principle requires just an LED source and a receiver that acts as a power meter. They are, however, very sensitive to disturbances since any fluctuation in the received power (e.g. due to fluctuations in the source or to fiber degradations) is indistinguishable from actual changes in the quantity under measurement. This sensitivity to parasitic quantities is particularly relevant for long-term monitoring of slowly changing quantities, so in these cases proper compensation techniques using reference sensors [29], or more complex interrogation schemes with signals at different wavelengths [30], must be considered.

Limiting our analysis to the sensors used to measure static or dynamic displacements (vibrations), one of the simplest intensiometric sensors can be realized by facing two fibers along a common axis as in Figure 19. The displacement is measured by exploiting the change of the received power with the separation between the two fiber tips due to the beam divergence form the transmitting fiber (Figure 19 - right). This principle of operation has also been applied in early realizations with glass fibers, but with limitations in the measurement range, unless fiber bundles are used. Despite the simplicity, such a transducer, made using standard step-index 1 mm plastic fibers, has been successfully used to develop a sensing system with working range and accuracy within the typical specifications required for long term crack monitoring in cultural heritage preservation applications [23], [29]. In this case the use of PMMA-SI-POF allowed having most of the advantages of fiber sensors, and above all the impossibility to start fires, without the usual costs and complexities, both in terms of manufacturing and deployment.

Given the propagation loss in plastic optical fibers and the free space attenuation, the distance between the sensor and the interrogators is limited to some tens of meters, but this is typically enough to allow placing the electronics in a remote and safe place. Moreover, if unjacketed fibers are used, the visual impact is dramatically reduced, making the sensing system almost invisible.

An example of the results obtained with sensors arranged as in Figure 19 is shown in Figure 20, where a picture of a sensor mounted across a crack and the readings for a period of 18 months are reported. The data in Figure 20-right are corrected to compensate for the environmental parasitic effects using a “null” (reference) sensor, as reported in [29]. The null sensor is a sensor identical to the others but not fixed to edges of the crack under measure. This is an approach common to most types of the sensors and is effective provided that the reference sensor is exposed to the same kind of disturbances as the measuring sensor; so for meaningful readings, particular care must be devoted to ensure that the two sensors are exposed to the same parasitic phenomena (e.g. temperature, stray light, bending, etc.). The strict correlation between seasonal temperature fluctuations and the crack opening/closing are quite evident from the reported plots.

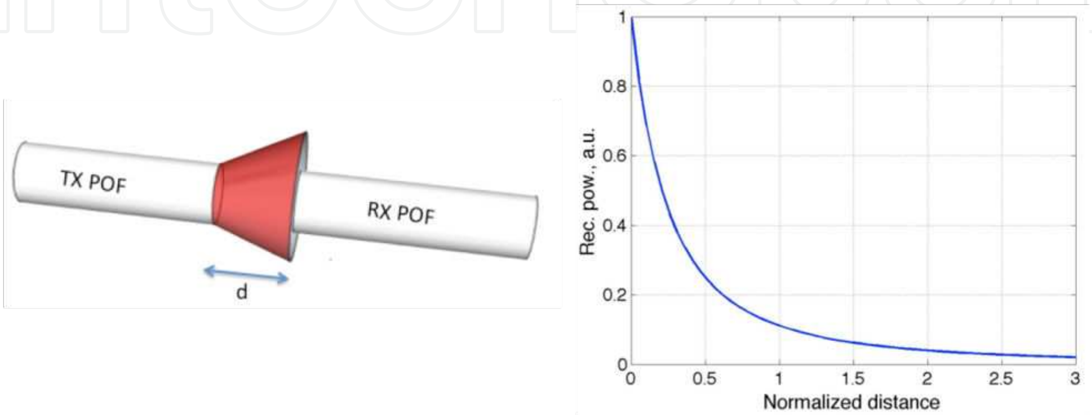


Figure 19. Schematic representation of a POF displacement sensor working in transmission mode (left) and the received power against distance curve (right).

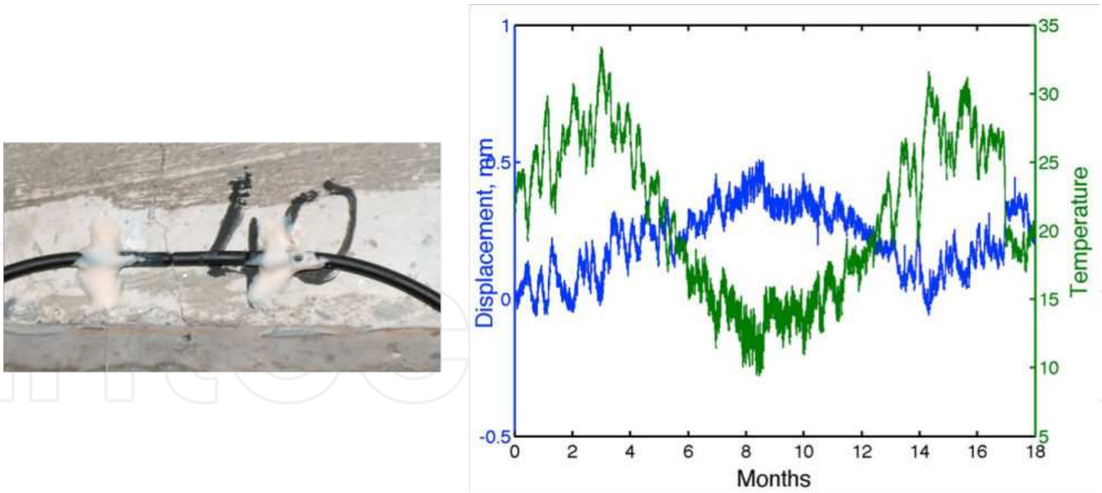


Figure 20. Example of practical POF displacement sensor arranged as in Figure 1 (left), and of the readings of a crack evolution for 18 months, after proper compensation with the null sensor technique as in [11] (right).

A variation of the same working principle is reported in Figure 21, where the light is collected by the receiving fiber after reflection from a target. This configuration can be reduced to the previous one working in transmission mode by considering an image receiving fiber positioned at a double distance and with a lateral offset. The transducer response curve can be modified by changing the sensor geometry (e.g. fiber diameters and separation), but, in any case, it exhibits a maximum that identifies two working regions. The leftmost part of the curve, which is characterized by higher sensitivity, though in a reduced working range, can be used to measure extremely small displacements, such as in high frequency vibrations; however, it requires positioning the sensing head very close to the target. For this reason, in most cases the sensor is arranged to operate exploiting the rightmost part of the curve. This type of sensor can be used both to measure displacements and for non-contact distance measurements.

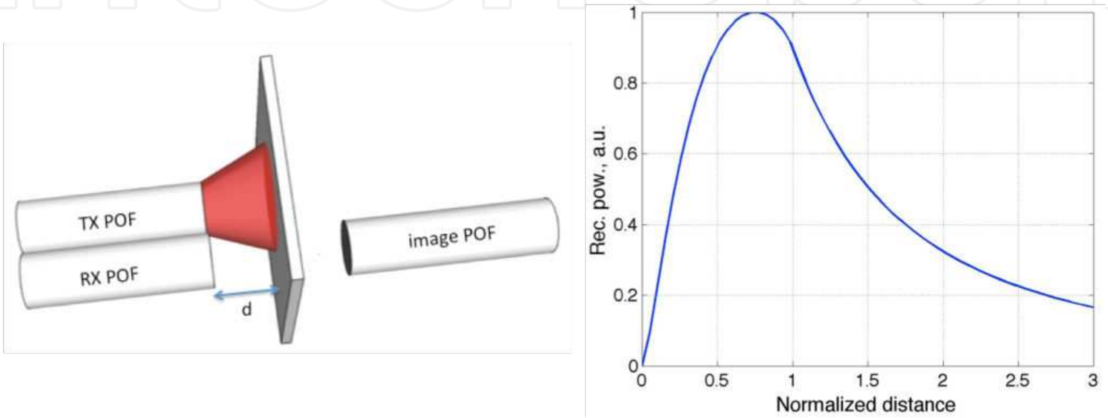


Figure 21. Schematic representation of a POF displacement sensor working in reflection mode (left) and the received power against distance curve (right).

An example of the use to measure displacements is an evolution of the crack monitoring system already shown in Figure 20. Indeed, using the reflection based sensor configuration it has been possible to develop compact transducers having the fiber connections on one side only, as depicted in Figure 4. These new sensors are currently used in a monitoing network deployed inside the chapel hosting the Holy Shroud of Turin in the framework of the Guarini's Project [31], a pilot project devoted to develop new technologies to support the restoration works after the fire that destroyed the Chapel in 1997. In this particular application the POF sensors are integrated within a wireless network to take advantages of both technologies.

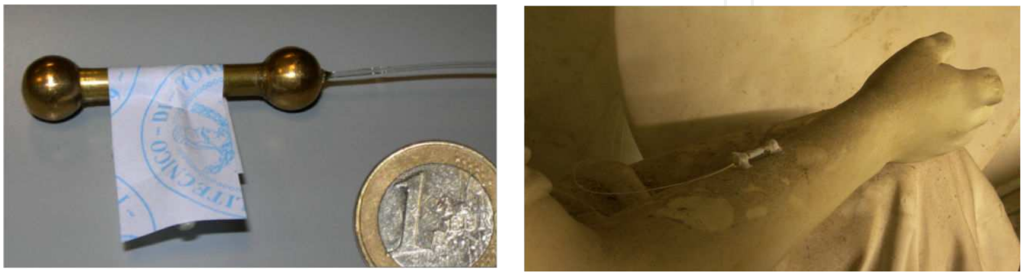


Figure 22. Picture of a crack evolution POF sensor using the principle sketched in Figure 3 (left) and example of application in the Guarini Chapel to monitor a crack on a marble statue in a quite dusty environment (right) [13].

The reflection-based sensor configuration is also particularly well suited for the application of a dual-wavelength compensation technique, which turned out to be much more effective than the null sensor one, though slightly more complex to implement because it requires a dichroic mirror to be inserted in the setup sketched in Figure 22[30]. In this case two signals, at two different wavelengths, are coupled inside the transmitting fiber, then the reference signal is reflected at the fiber tip by a dichroic mirror, while the other wavelength is reflected by the target. This way, the two signals share the same path, hence the same perturbations, except for the sensing region. As for the use in non-contact distance measurements, it is important to highlight that the sensor response depends also on terms that cannot be calculated through theoretical models or may change in time, such as the target reflectivity, so they require continuous characterizations and subsequent calibrations. A sensor for static non-contact distance measurements with response independent from reflectivity changes has been studied in [32], while a calibration technique particularly effective in vibration tests, including cases when the surface has non-uniform reflectivity or non-flat profile, is presented in [33]. An example of a possible application is the mapping of the vibration amplitudes of a printed circuit board under vibration tests. An example of the system setup is pictured in Figure 23.

Recent developments of PMMA-SI-POF displacement sensors include the realization of a possible replacement of conventional crack gage based on sliding plates to measure crack evolutions in two dimensions [34].

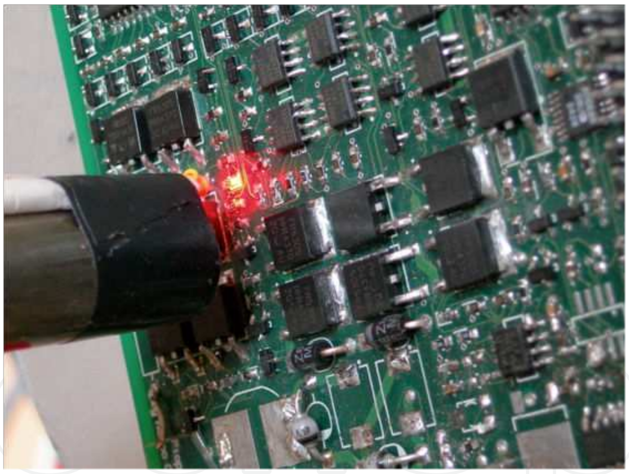


Figure 23. Picture of non-contact system for the mapping of the vibration amplitudes of printed circuit boards under vibration tests using the procedure described in [15].

5. Conclusions

In this chapter we have given a general overview of the most interesting applications of optical fibers made of PolyMethylMethAcrylate material, with a core diameter of 980 μm and with Step-Index profile. We have shown that, given the fact that the communication performances are orders of magnitude lower than the ones of the more common single-mode glass fibers, PMMA-SI-POF can address interesting niche markets such as automobile entertainment, local networking, sensing, provided that some complexity is added to the electrical part of the system, while the rules of optical propagation remain unchanged with respect to more common, yet more powerful, optical fibers.

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