# Large Core Plastic Optical Fibers and Access Networks

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**Joint Workshop**

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## Agenda

- Introduction: why another type of optical fiber?
- POF technical characteristics
  - Materials
  - Attenuation
  - Dispersion
  - Applications
- The ultimate bit-rate x distance limits of standard PMMA SI POF



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## Plastic Optical Fibers (POF)

- In 1963, DUPONT filed a patent on optical fibers made of poly-methyl meta-acrylate (PMMA)
  - PMMA is a quite common polymer, it has several other applications in polymer chemistry (such as Plexiglass®)
- Starting from 1980, there has been a growing interest in POF
  - At the beginning, mostly for illumination, then (starting in 1990) also for datacom



## Why POF?

- The diameter problem: using a plastic material, the fiber diameter can be significantly increased with respect to glass optical fibers (GOF), without introducing mechanical or bending problems
- The standard for "datacom" PMMA-POF is today a 1 mm diameter (core is 980 μm) using a step index geometry
  - Numerical aperture from 0.4 to 0.6
- Other diameters are anyway available, up to 2-3 mm, though they are mostly used for illumination



## POF and large core

- The key point with POF is the ease of connection
  - Large core
  - Large numerical aperture
  - High resilience
- For this reason, they are currently under investigation for next generation:
  - Access networks
  - Home networks (self-made connectors??)
- The only mass-application so far is in the automotive sector
  - Approx. 10 millions cars equipped with internal POF network (infotainment)

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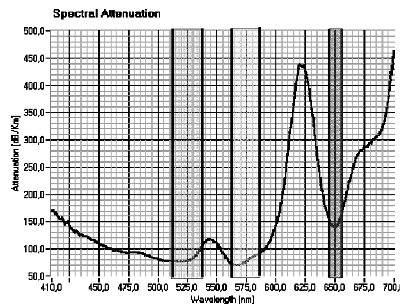
## PMMA attenuation




**Attenuation:**

**@ 520nm** : 90db/km

**@ 570nm** : 80 dB/km

**@ 650nm** : 150dB/km



## PMMA attenuation

- In comparison to GOF, the PMMA attenuation is:
  - Extremely higher (from 0.1 to 0.2 dB/m)
  - Different wavelengths, in the visible rather than in the infrared
    - (visible light is a "plus" for an installer)
- Even if attenuation is high, it allows very low-cost applications in the 100 meters range
  - A 100-meter POF link used with red sources gives approximately 15-18 dB attenuation, which is acceptable (optical TX-RX pair have at least a 20 dB power budget)



## POF attenuation and materials

- Can one choose a better material? Not easy!
- The attenuation of some "optical" materials:
  - A "window" glass: $\approx 10^5$ dB/Km
  - An "optical" glass, used for eyeglasses: ≈1000 dB/Km
  - PMMA: ≈100 dB/Km
  - Silica glass for fibers at 850 nm: ≈2 dB/Km
  - Silica glass for fibers at 1550 nm: ≈0.2 dB/Km
- So we are looking for something that is, for example, much more transparent than "optical" glass



## POF materials

- Several materials have been studied
- The most interesting ones are "Perfluorinated" polymers (same family as Teflon®)
- Using these materials, the absorption peaks are moved to higher wavelengths, so that the intrinsic attenuation may become as low as GOF (theoretically!)
- In practice, best Perfluorinated Fibers (PF) have attenuation as low as 10 dB/Km at 1300 nm (Asashi Glass, Lucina fiber)
  - They can also be used at other wavelengths (850 nm and in the visible)



## Perflourinated POF

- Perfluorinated plastic fibers are "commercially" available from Asashi Glass (Lucina® fiber)
- Other companies are working on PF-POF
  - OFS, Nexans, Digital Optronics

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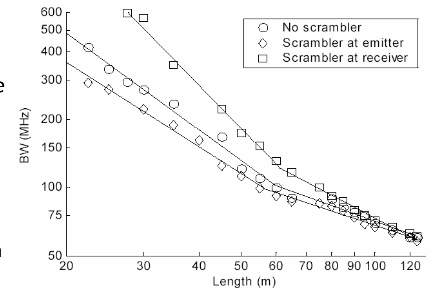
## Standard POF and multimode dispersion

- For standard POF (Step-index, 1 mm diameter, NA≈0.5) the resulting bandwidth decreases significantly with distance
  - For instance: approx. 70 MHz at 100 meters are available
  - For digital applications, we are thus limited at about 100 Mbit/s over 100m




*Data taken from [MATEO_2003] , see bibliography*



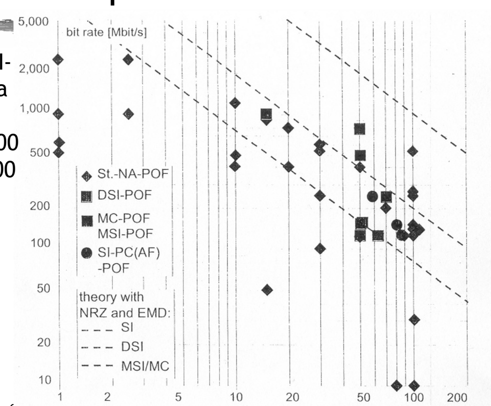
## Optoelectronic components for POF

- Neglecting lasers due to their high cost, the optoelectronic components suitable for standard 1mm SI-POF are:
  - Green and red LEDs
  - Large area photodiodes in the visible window
- These components are available at low cost
  - Red LED: up to 2-3 mW output power, <200 MHz modulation bandwidth (RC-LED)
  - Green LED: up to 1-2 mW output power, <30 MHz modulation bandwidth
  - Photodiodes: large area limit bandwidth, anyway several hundred MHz are possible



## Best published results on SI-POF

- On standard SI-POF, there is a performance wall around 100 Mbit/s over 100 meters




*Data taken from [DAUM_2002] , see bibliography*

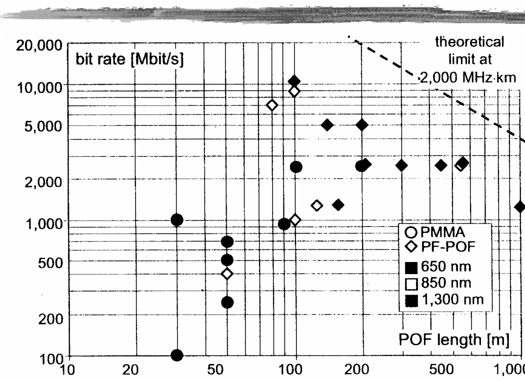


## Graded Index POF

- Graded-Index Polymer Optical Fibers have been demonstrated
- The typical combination is: perfluorinated material (to reduce attenuation) and graded index profile (to minimize multimode dispersion)
  - Perfluorinated GI-POF
- Using PF GI-POF it is possible to obtain excellent results up to 2-3 Km and up to 10 Gbit/s



## Best published results on PF GI-POF




*Data taken from [DAUM_2002] , see bibliography*

## Perfluorinated GI-POF

- The group of Prof. Koike at the Tokio University has shown excellent results using PF GI-POF
- Commercial products: Lucina fiber from Asashi Glass
- Anyway, commercial application is, so far, small
  - The material and production is approximately as expensive as GOF
  - The core diameter is around 250 μm, so that some of the "large diameter" advantages of standard 1mm POF is somehow lost
    - Installation is not much easier



## Comments

- From an application point of view:
- 1mm PMMA SI-POF are a completely different medium with respect to GOF
  - Actually, the competitor is copper, not GOF
  - They are still a "green-field" from an application point of view
- Perfluorinated GI-POF try to "mimick" GOF
  - They still need to show a real cost advantage with respect to GOF
  - Theoretically, they have even higher bandwidth than multimode GOF (due to a compensation between multimode dispersion and chromatic dispersion)



## Comments

- The second part of this presentation focuses on 1mm SI-PMMA-POF only



## Large core POF and distance

- Standard 1mm PMMA-SI-POFs are usually perceived as a useful medium only for short distances, typically below 100 meters
  - The available commercial devices so far usually cover this range
- Is there a technical chance for longer distances (200-400 meters)?
- More important: is there a potential market for this?



## 200-400 meter POF applications

- UTP cables are out of question after 120 meters
- Some FTTH access network architectures may require high-bandwidth low-cost links (100 Mbit/s and more) in the very last part of the link toward each apartment
- In scenario such as the FastWeb FTTH architecture (Italy) these end-user links are in the 50 to 400 meters



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## Bit rate – distance products: TODAY

- Due to the physical characteristics of current 1mm SI-PMMA POF, LED, and photodiode, the typical applications today are:
  - Low bandwidth applications (RS-232, analog video) up to 300-400 m
  - 10 Mbit/s (Ethernet) up to 100 meters
  - 100 Mbit/s (Fast Ethernet) up to 80 meters



## Bit rate – distance products: OUR WORK

- At POLITO-ISMB we are currently investigating techniques to increase reach and bit-rate over large-core POF
- We are focusing on how to achieve this goal by improving the "transmission complexity"
  - Coding
  - Equalization
  - Multilevel transmission



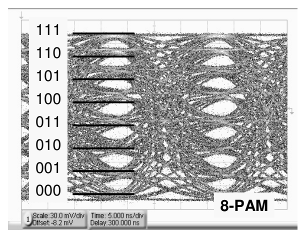
## Demo at the exhibit

- We have a DEMO at the exhibit carrying 10 Mbit/s Ethernet on 1mm SI-PMMA-POF over 350 meters with 3 dB system margin (see Luceat ECOC booth, #404)
  - Commercial LEDs and photodiodes are used
  - Standard binary modulation
  - Proprietary transmission protocol
- The demo shows that bandwidth limitation is not an issue at 10 Mbit/s even over >350 meters



## Binary and multilevel modulation

- 100 Mbit/s transmission would anyway be impossible due to modal dispersion bandwidth limitations
- Anyway, bandwidth limitation can be overcome with several techniques, such as multilevel modulation and/or equalization




- In optics, we are used to approx. 1 bit/s per Hz efficiency
- Remember that in RF modulation, efficiency up to 11 bit/s per Hz are used (such as with 1024-QAM and raised cosine spectral shaping )



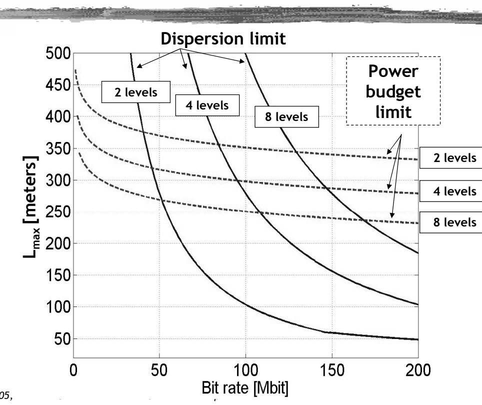
## The ultimate limits

- We carried out a theoretical study on the bitrate-distance ultimate limit on 1mm PMMA-SI-POF (NA=0.4-0.5)
- In our study, we assumed:
  - Transmitted peak power: 0 dBm, green LED
  - POF attenuation: 0.08 dB/m (green window)
  - Bandwidth limited by POF (not by TX-RX optoelectronics)
  - Commercial transimpedance receivers
    - (equivalent noise 1.3 pA/sqrt(Hz), such as MAX3657 )
  - a system margin equal to 2 dB for M=2, 3dB for M=4, and 4 dB for M=8
  - Extrapolated data for fiber bandwidth
    - No experimental data available above 200 meters…

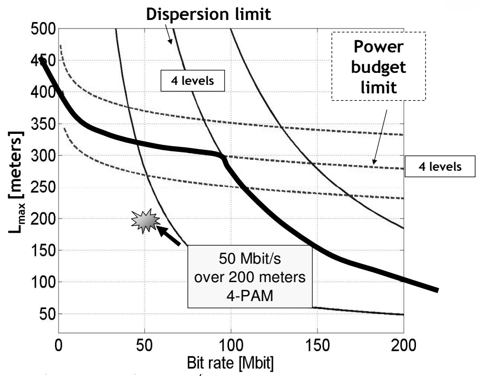
Mateo, M. A. Losada, I. Garcés, J. Arrue, J. Zubia, D. Kalymnios, "High NA POF Dependence of Bandwidth on Fibre Length", POF Conference 2003, Seattle, USA, Sept. 2003



## The bit-rate distance product

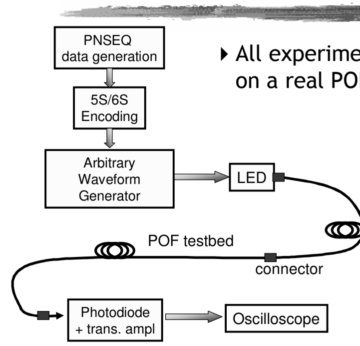


## Our last experimental results: 4-PAM






## Experimental setup

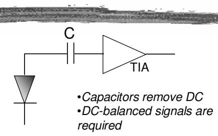


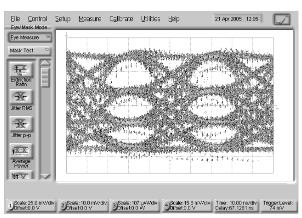

- All experiments have been performed on a real POF testbed at our premises
  - The testbed uses Luceat SI-POF fibers installed in standard LAN ducts
    - Installation was done by the same workers that usually install UTP cables
  - We used commercial optoelectronic components
    - Green LED
    - Large area photodiodes



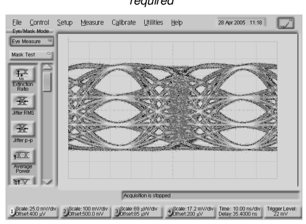
## Optimizations: DC balancing

- We developed a specific DC balancing line coding
- We denominate it 5S/6S coding



**No line coding**

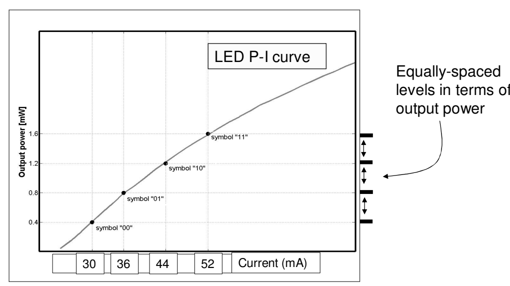


**5S/6S line coding**



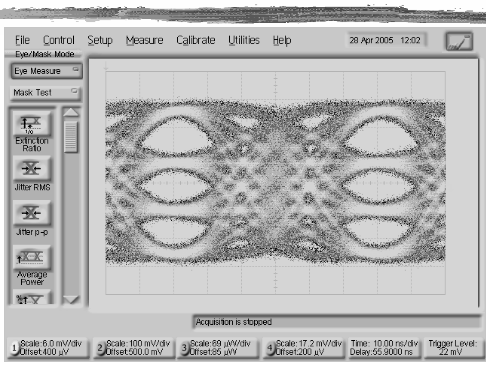
## Optimizations: LED "linearization"

- We need to compensate for the LED P-I curve nonlinearity





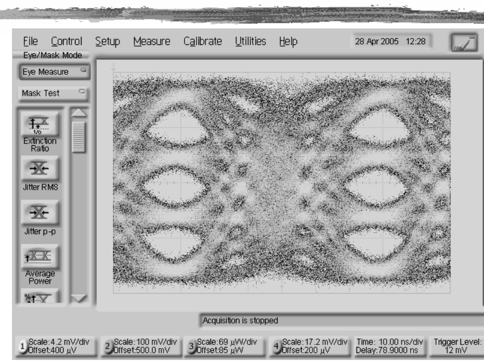

## Results – 50 Mbit/s over 150 meters




Link loss: 17 dB total, one connector



## Results – 50 Mbit/s over 200 meters




Link loss: 21 dB total, one connector

## Future work

- Our current experiments are only preliminary "proof-of-concepts"
- Our short term goals:
  - Optimize the receiver (the current one is noisier than the fundamental limits, due to PCB problems)
  - Introduce A/D and D/A converter at the TX and RX, and suitable digital electronics (prototyped on an FPGA)
  - Develop feedback-loops to compensate for the change of the LED P-I curve vs. temperature, and for the nonlinearities of LED



## POF-ALL project

- Our group is the coordinator of a new EU STREP project (POF-ALL, FP6, 4° call) that will extensively work on "long reach" application of large core POF
- POF-ALL technical targets
  - 100 Mbit/s over >300 m
  - 1 Gbit/s over >100 m
- POF-ALL application targets
  - Access networks
  - Home networks
- **POF-ALL Time frame (currently in the EU negotiation phase):**
  - from January 2006 to June 2008 (likely)



## POF-ALL partners

1. **ISMB** and Politecnico di Torino (R. Gaudino)
2. **Luceat**, ITALY (A. Nocivelli)
3. **DieMount**, GERMANY (H. Kragl)
4. **POFAC**, GERMANY (H. Poisel)
5. **Fraunhofer Institute**, GERMANY (N. Weber)
6. **Duisburg University**, GERMANY (D. Jaeger)
7. **Technical University of Eindovhen**, The Netherlands, (Ton Koonen)
8. **Fastweb**, ITALY (C. Lezzi)
9. **STMicroelectonics** (G. Chiaretti)



## Bibliography


- [DAUM_2002] W. Daum, J. Krauser, P. Zamzow, O. Ziemann, "POF – Polymer Optical Fibers for Data Communication", Springer-Verlag, Berlin, 2002.
- [MATEO_2003] J. Mateo, M. A. Losada, I. Garcés, J. Arrue, J. Zubia, D. Kalymnios , "High NA POF Dependence of Bandwidth on Fibre Length", POF conference, Seattle, 2003.
- [GAUDINO_2004] R. Gaudino, E. Capello, G. Perrone, S. Abrate, M. Chiaberge, "Advanced modulation formats over POF: is there a rationale for multilevel optical transmission?", POF WORLD 2004 conference, San. Jose, June 2004.
- [GAUDINO_2005_1] R. Gaudino, D. Cárdenas, P. Spalla, A. Nespola, S. Abrate, "Multilevel 50Mb/s transmission over a 200m PMMA SI-POF LAN testbed"
- [GAUDINO_2005_2] R. Gaudino, D. Cárdenas, P. Spalla, A. Nespola, S. Abrate, "A novel DC-Balancing line coding for multilevel transmission over POF"
- The interested reader should refer to the act of the annual "POF conferences".




For further informations:

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