Regular paper

Influence of temperature and aging on polarization mode dispersion of tight-buffered optical fibers and cables

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Abstract—This paper presents results of laboratory tests investigating influence of temperature on polarization mode dispersion (PMD) in variety of single mode optical fibers and cables. Research was focused primarily on tight-buffered fibers, where most pronounced effects resulting from buffer shrinkage or expansion were expected. The goal was to verify performance of optical fiber cable exposed to extreme temperatures and to compare behavior of different cables. Very strong temperature dependence of PMD was detected in standard single mode fibers with 0.9 mm tight buffer, commonly used in indoor cables, and in complete cable with such fiber. However, both nonzero dispersion-shifted fibers, spun during drawing and optical unit used in optical ground wire (OPGW), where 12 fibers are stranded showed good stability of PMD during thermal cycling. The same optical unit extracted from OPGW exhibited excellent PMD stability also during accelerated life test.

Keywords*— *single mode optical fiber, polarization mode dispersion, environmental testing, tight buffered fiber, optical fiber cable, optical ground wire, thermal cycling, accelerated life test.

1. Introduction

Polarization mode dispersion (PMD) is an important limit to performance of high speed optical transmission systems, in particular due to its random changes with time and wavelength and resulting difficulty of compensation, as opposed to chromatic dispersion. PMD of fiber is inherently sensitive to external mechanical disturbances, e.g., pressure applied by protective coating and buffer. PMD phenomenon and ways to control it have been extensively studied since around 1993, including monitoring of commercially installed cables [1, 2].

Research work, however, has been focused on PMD performance of fibers in thin (0.245 mm outer diameter) primary coating made of soft acrylate, as delivered (and tested) by fiber manufacturer or fibers used in loose tube and ribbon cables installed in long distance and metropolitan networks of most large operators. Fibers placed inside loose tube or (less commonly used) slotted core cables are suspended in viscous gel, minimizing hard contact with cable components, e.g., tube walls in all but extreme operating conditions. This in turn minimizes influence of external factors like temperature, cable bending, crush forces, etc., on operation of fibers inside. While providing good stability of transmission parameters and reliability, cables of "loose" designs are not suitable for several applications, particularly when small diameter, connectorization, installation in vertical shafts inside high rise buildings, fire safety or resistance to thermal shocks are required.

For such purposes, cables with so called "tight-buffered" fibers are used. The glass fiber with its primary coating is surrounded by one or more layers of solid plastics, providing mechanical strength and protection against humidity, abrasion and other harmful influences. While most products are intended for indoor operation in relatively benign conditions (except for bending), some manufacturers offer outdoor cables of this kind as well.

Another important product is optical ground wire (OPGW) – metallic aerial cable used by electric power utilities. While majority of manufacturers sell loose-tube OPGWs today, some older, but still available designs feature multi-fiber optical units with tight buffers. Over 7000 km of OPGW of such type has been installed in Poland between 1993 and 2004, constituting the core network of major operator.

Hard buffer made of polymers tends to shrink and stiffen at low temperatures, applying temperature-dependent mechanical pressure to glass fiber. This pressure can induce birefringence and significantly change fiber PMD. Aging of plastics can further modify their behavior, e.g., by shrinkage due to loss of plasticizer from poly-vinyl chloride (PVC) compounds, or softening due to decomposition.

Fiber networks are used to carry signals at ever increasing bit rates, currently up to 10 Gbit/s – both in local area networks (LANs) (gigabit Ethernet) and in long distance networks (STM-64), with link lengths in Poland up to 400 km. This makes the issue of PMD stability worthy detailed investigation.

Therefore, a research project was started by National Institute of Telecommunications in 2003 within EU research program COST Action 270 "Reliability of Optical Components and Devices in Communications Systems and Networks" to experimentally verify effects of temperature and accelerated aging on PMD in tight buffered single mode fibers and cables.

2. Tight buffered optical fiber – PMD issues

Indoor cables, commonly used in LANs and to make patchcords usually contain single fibers protected by buffer of 0.900 mm diameter, mechanically strippable and usually made of relatively hard, extruded thermoplastic materials.

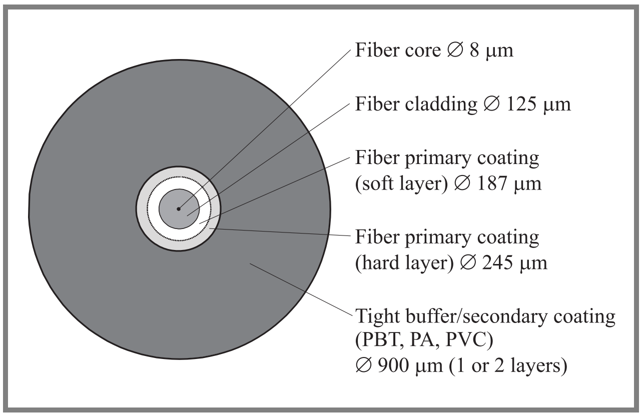

Fig. 1. Tight buffered single mode fiber for indoor cables.

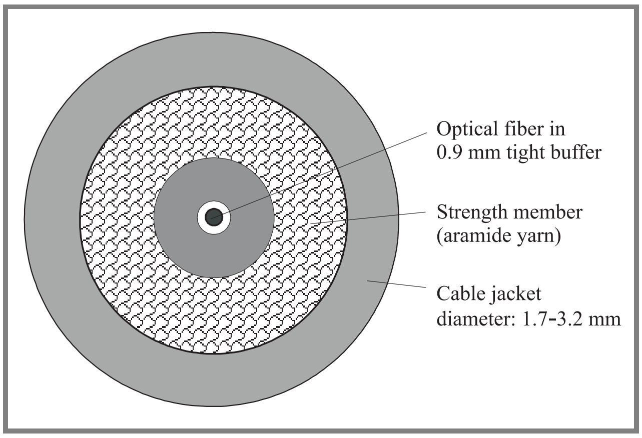

Fig. 2. Cross-section of simplex indoor cable.

The inner layer is sometimes made of soft material like silicone or even gel (in a so called "semi-tight buffer") to make buffer removal easier and faster. Such buffer is the industry standard when fitting optical connectors on the fiber or complete cable is required (Figs. 1 and 2).

Details of OPGW with 12-fiber tight-buffered unit are shown on Figs. 3 and 4. This design is representative of products installed by Polish power companies during the 1990s.

Tight-buffered fiber is surrounded by one or more layers of relatively rigid polymeric materials having much higher thermal expansion coefficient than silica glass (Table 1).

Operation at extreme low temperatures results in considerable mechanical pressure applied in radial direction towards the fiber, while high temperatures cause the buffer to expand and soften, reducing pressure. As long as the pressure remains isotropic, it shall not induce birefringence in glass and increase fiber PMD. When the symmetry is lost, e.g., due to noncircular buffer shape, pressure in one direction becomes dominant and birefringence appears. Soft, inner layers of buffer and primary coating redistribute mechanical forces more evenly (like hydrostatic pressure), mitigating this problem. Efficiency of this mechanism is dependent on materials used and particulars of buffer design [3, 4].

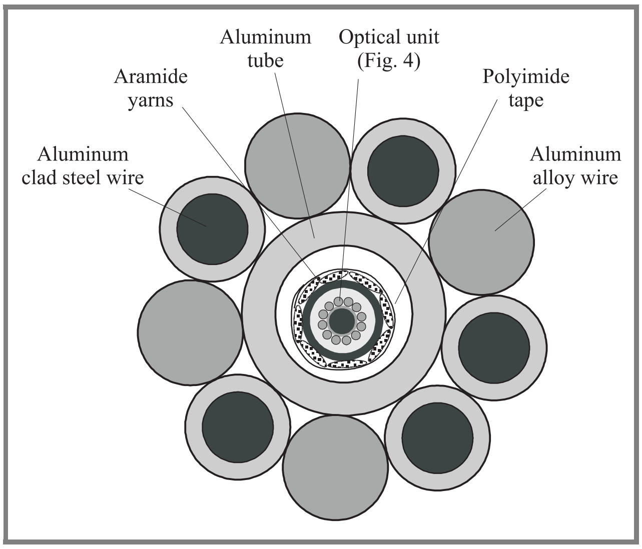

Fig. 3. OPGW tested: AlumaCore OPT-GW 30/38 mm^2/496 (Alcoa Fujikura Ltd.). External diameter: 12.7 mm.

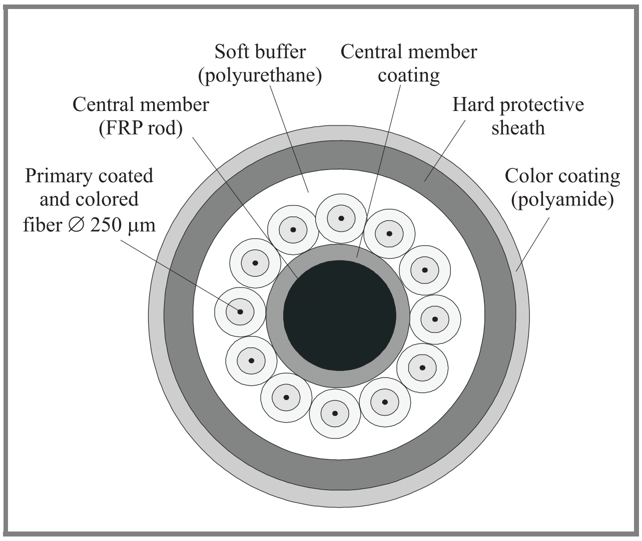

Fig. 4. Optical unit for OPGW with central strength member and 12 fibers. External diameter: 2.5 mm.

So far, temperature (and aging) dependence of PMD in tight-buffered fibers has not been a subject to either a theoretical analysis or experiments in any paper known to the author. The manufacturer has published results of tests and inspection made on similar OPGW after 17 years of field operation [5, 6]. Excellent stability of fiber attenuation was demonstrated, but no PMD measurements were made.

Table 1

Thermal expansion coefficient (TEC) of materials used to make optical fiber cables. Typical values shown; commercial products differ due to variations in manufacturing process

Material	Typical application(s)	TEC (linear)
Fused silica (SiO_2)	Basic fiber material	$+5.5 \cdot 10^{-7}$/K
Fiber reinforced plastic (FRP): glass/epoxy	Strength member – rigid	$+5.5 \cdot 10^{-6}$/K
Aramide yarn (Twaron)	Strength member – fibrous	$-3.5 \cdot 10^{-6}$/K
Fiber reinforced plastic (FRP): aramide/epoxy	Strength member – rigid	$-2.0 \cdot 10^{-6}$/K
Polyamide (nylon 6)	Tight buffer, loose tube	$+8.3 \cdot 10^{-5}$/K
Poly-buthyl-terephtalate (PBT)	Tight buffer, loose tube	$+7.4 \cdot 10^{-5}$/K
Polycarbonate (PC)	Loose tube	$+6.8 \cdot 10^{-5}$/K
High density polyethylene (HDPE)	Sheath – outdoor cables	$+5.9 \cdot 10^{-5}$/K

Table 2

Fiber and cable samples tested for temperature dependence of PMD

Sample	Description of fiber/cable; manufacturer's designation	Manufacturer	Fiber count	Fiber type	Sample length [m]	Year of manufacture	Remarks
A	Fiber in 0.245 mm primary coating, uncolored (SM-02R)	Optical Fibres Ltd.	1	G.652	6409	1997	Wound on plastic spool
B	Fiber in 0.245 mm primary coating, uncolored (SM-02R)	Optical Fibres Ltd.	1	G.652	6458	1997	Wound on plastic spool
C	Fiber in 0.9 mm tight buffer; two lengths spliced (J2B)	TP SA OTO Lublin	1	G.652	4555 1645	2001 2004	UV cured buffer
D	Fiber in 0.9 mm tight buffer; two lengths spliced (J5A)	TP SA OTO Lublin	1	G.655	5034	2005	UV cured buffer – new design
E	Indoor cable – 2 mm diameter, LSZH jacket (W-NOTKSd 1J5A)	TP SA OTO Lublin	1	G.655	4083	2005	UV cured buffer – new design
F	Indoor cable – 2 mm diameter, LSZH jacket (W-NOTKSd J-2,0)	TeleFonika KFK	1	G.652	4040	2004	Extruded buffer
G	OPGW with tight-buffered unit (OPT-GW 14/37 mm^2/443)	Alcoa Fujikura Ltd.	12	G.652	570	1994 (approx.)	Old cable after service (ca 8 yrs.)
H	OPGW with tight-buffered unit (OPT-GW 30/38 mm^2/496)	Alcoa Fujikura Ltd.	12	G.652	460	1994 (approx.)	Old cable after service (ca 8 yrs.)
I	Optical unit from OPT-GW 14/37 mm^2/443; 2 lengths spliced	Alcoa Fujikura Ltd.	12	G.652	170 230	1994 (approx.)	Extracted from old cable

3. Test program

Experiments conducted in 2004 and first half on 2005 included:

- **Temperature cycling of variety of fiber or cable samples with monitoring of fiber PMD and (in most cases) its attenuation**.

  In order to establish a PMD-temperature characteristics a single cycle with multiple, equally spaced temperature values was used. Exposure (dwell) time at each temperature was typically 12 h or 24 h, enough to stabilize temperature inside spool or drum under test. Samples contained standard single mode fibers conforming to ITU-T Rec. G.652 [7] and nonzero dispersion-shifted fibers (NZ-DSF) conforming to ITU-T Rec. G.655 – category A [8]. Following tests, all samples were inspected for signs of deterioration: cracks, discoloration, shrinkage, etc.

- **Accelerated aging test at +85°C, executed on a single sample**.

  This was a simplified, preparatory experiment to verify the principle accelerated life test and equipment used. Nevertheless, results were very useful.

Previous activities carried out in 2003 are described in report [9] and papers [10, 11].
Characteristics of samples are summarized in Table 2.

4. Test equipment

Figures 5 and 6 show general arrangement of test equipment used.

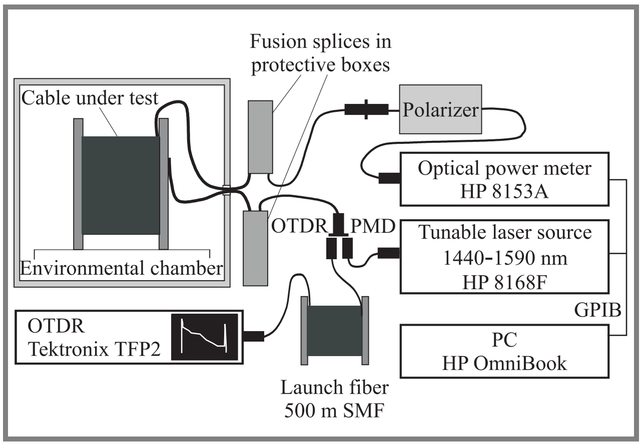

Fig. 5. Test setup for investigation of environmental effects on PMD and attenuation of optical fiber cables.

Fig. 6. Equipment used, including environmental chamber (right).

Polarization mode dispersion measurements were based on the fixed analyzer method defined by ITU-T Rec. G.650.2 [12]. Spectral scan of ratio of optical power transmitted through the fiber only (during loss calibration) and through the fiber and in-line polarizer (during actual PMD measurement), produced a curve with multiple peaks and valleys (Fig. 7), known as "extrema", counted either manually or by program running on PC. For the 150 nm spectral range used, fiber PMD was calculated according to formula:

$$\mathrm{PMD} = n_{EX} \cdot 0.0216 \text{ ps},$$

where n_{EX} is the extrema count.

The lowest value of PMD corresponding to single peak or valley was 0.0216 ps. In order to detect a 25% change in PMD, its initial value had to be greater than 0.1 ps. This required fiber lengths of 4–10 km; unfortunately not all samples available conformed to such requirements. Several relatively old fibers and cables were tested (see Table 2), but their PMD did not significantly differ from products currently available.

In case of multi-fiber cables or optical units, all fibers have been fusion spliced to maximize fiber length, making PMD measurements more accurate and replicating real network conditions, where several cable lengths are spliced. Fibers under test were carefully fixed in order to minimize uncontrolled polarization changes; all splices were located outside environmental chamber.

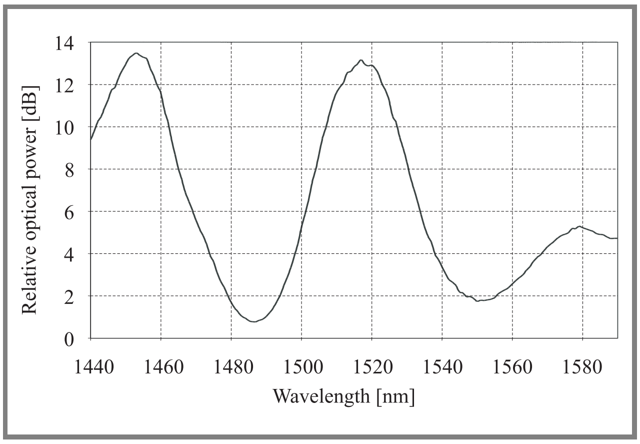

Fig. 7. Example of spectral scan made during PMD measurement. Extrema count: 5. Sample: C.

Spectral scanning was made in 1 nm increments; single measurement took approximately 5 min. During most tests PMD measurements were made repeatedly at fixed intervals ranging from 10 to 120 min.

The purpose of this project was to establish behavior of installed cables, where heat transfer between cable and its environment is relatively fast – unlike testing of coiled cable on drums or spools. Therefore, transient effects were not analyzed, except for establishing PMD stabilization time needed to design test schedule.

A standard test schedule involved the following sequence for each temperature:

- attenuation measurements at 1310 nm and 1550 nm,
- beginning of periodic PMD measurements, e.g., every 15 min for 22 h,
- change of temperature setting to a new value after the first PMD measurement.

Test data representing transients were discarded, and those belonging to steady-state periods were averaged in order to increase accuracy and remove artifacts resulting from vibration, minor fiber movements, etc. PMD values obtained in this way were normalized to initial value measured at +20°C, assumed to be 100%. The final result was a PMD versus temperature plot. For most samples, attenuation changes were negligible.

Temperature ranges were generally in accordance with Polish standards. Ranges for indoor cable and 0.9 mm buffered fiber were extended to investigate performance during possible outdoor use.

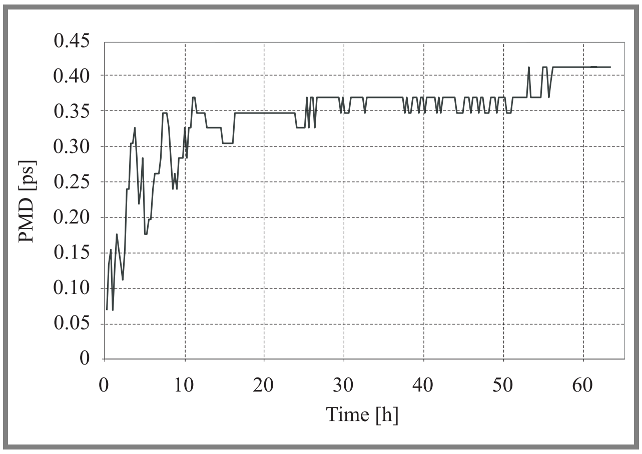

Fig. 8. Changes of PMD in temperature cycled indoor cable. Sample F on plywood drum. Temperature setting was changed from +20°C to −20°C after the first measurement. Due to slow heat transfer between cable layers its PMD has stabilized after 20 h.

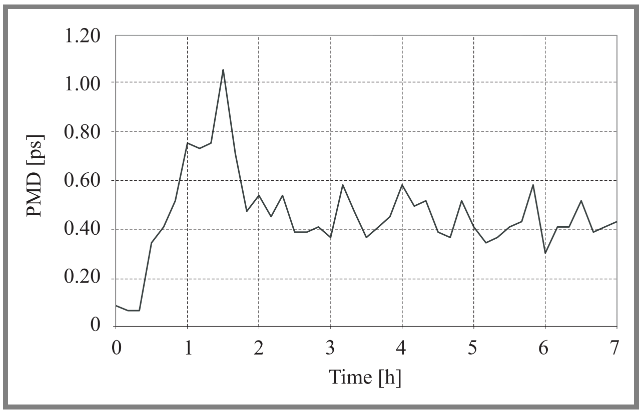

Fig. 9. Changes of PMD in tight buffered fiber during thermal cycling. Sample C on plastic spool. Temperature profile: +20°C (0–0.3 h), −55°C (0.3-1.5 h), −40°C (1.5–7 h).

Reaching a stable PMD at each new temperature required considerable time, ranging from 1 h for 3 kg spool with fiber to about 20 h in case of 15 kg plywood drum holding 4 km of indoor cable (Fig. 8) and 300 kg wooden drum with 570 m of OPGW. Forced air circulation in the chamber was always used. It is apparent (Fig. 9) that response to decreasing temperature is generally slower that to a rising one.

5. Test results

Selected characteristics of PMD changes with temperature for different fiber and cable samples are presented on Figs. 10–16. All results shown are steady-state characteristics.

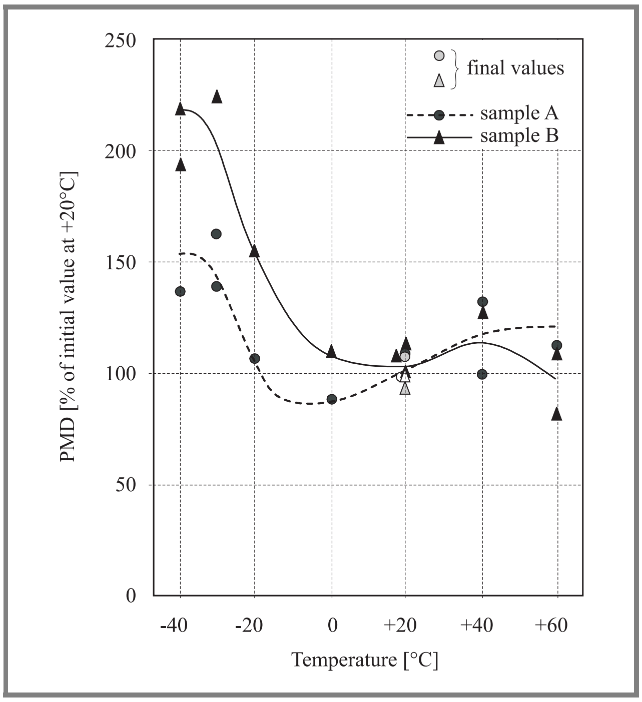

Fig. 10. PMD-temperature characteristics of two lengths of G.652 fiber in primary coating. Samples A and B tested on plastic spools.

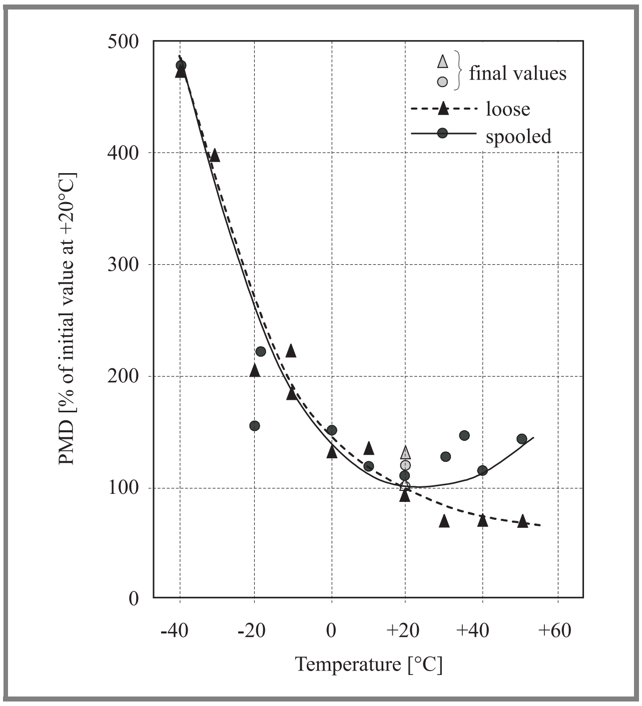

Fig. 11. PMD-temperature characteristics of G.652 fiber in 0.9 mm UV-cured tight buffer. Sample C tested twice: on spool and loose.

The first experiment was performed on primary coated standard single mode fibers, conforming to ITU-T Rec. 652 [7]. Such fibers are used primarily in loose tube cables.

Behavior of two samples (Fig. 10) is very similar. As expected, shrinkage and stiffening of acrylate coating at low temperatures results in increased pressure on glass fiber and higher PMD. However, PMD growth looks to saturate below −30°C, despite continued increase of pressure. The most likely explanation is increased mixing of polarization modes. Changes of PMD were fully reversible, considering measurement uncertainty of about 10%.

Adding harder and thicker tight buffer changes the situation dramatically (Fig. 11 – solid line):

1. Increase of PMD at low temperatures is fast: almost 5-fold at −40°C and 10-fold at −55°C, as predicted.
2. PMD of tight buffered fiber started rise also at elevated temperatures, beginning from about +40°C. This is contrary to expectations, as expanding buffer is expected to exert less pressure on the fiber inside.
3. Despite exposure to very wide range of temperatures, including a brief −55°C transient due to malfunction of environmental chamber (Fig. 9), changes of PMD are reasonably reversible.
4. Fiber attenuation was very stable: 0.191 dB/km before test, 0.196 dB/km at −40°C, 0.192 dB/km at +60°C and 0.193 dB/km after the test; all measurements being done at 1550 nm wavelength.

Effect (2) was surprising, as continued reduction of PMD with rising temperature was expected. To eliminate crush forces between fibers wound on spool, generated when fiber buffer expands, the test was repeated on the fiber removed from spool and freely suspended on 160 mm HDPE tube. Continuous reduction of PMD with temperature was observed, the ratio of extreme values being as high as 7:1 (Fig. 11).

This shows that all tests in elevated temperatures (higher than temperature at which the fiber was originally wound) shall be performed on samples in loose condition. Figure 10 reveals the same problem, too. Cables in which fibers are protected by jacket and strength members against crush forces should not be affected.

Next tests were executed on lightweight indoor cables with single tight buffered fiber and aramide yarn strength member (see Fig. 2), used in LANs and to make patchcords for optical cross-connects. Variants of this design are also used as field-deployable outdoor cables for military use and temporary optical networks.

Two cables of identical design and size, but with different fibers and purchased from two suppliers behave very differently (Figs. 12 and 13).

Sample F had G.652 fiber encased in buffer made of PBT by hot extrusion. The PMD – temperature characteristics (Fig. 12) exhibits minimum at room temperature and dramatic increase at low temperatures. This cable was tested on lightweight plywood drum, as supplied by the manufacturer. Increase of PMD at temperatures starting from +30°C resembles behavior of fiber samples tested on spools (Figs. 10 and 11), so the pressure between layers of cable is probably responsible. Permanent increase of PMD after single thermal cycle is worth further investigation, as this may indicate shrinkage of buffer material or movement of fiber inside cable. Visual inspection of the cable did not indicate any problem.

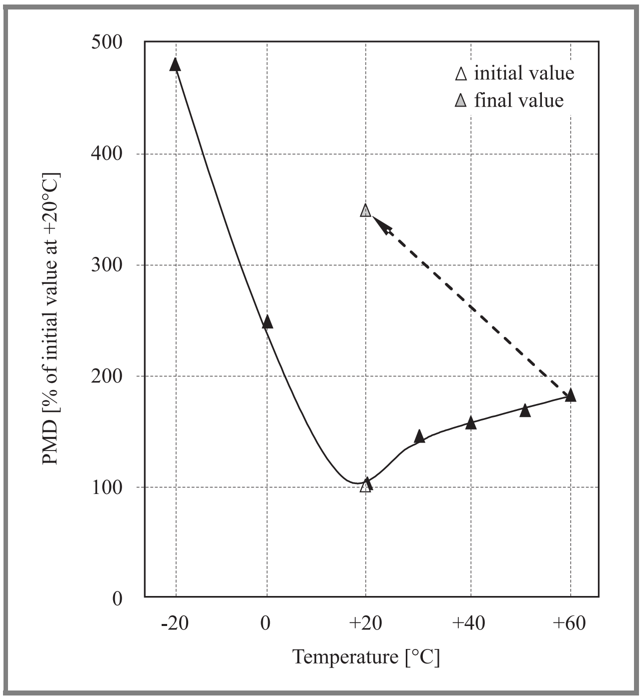

Fig. 12. PMD-temperature curve of 2 mm indoor cable with G.652 fiber. Sample F, wound on plywood drum.

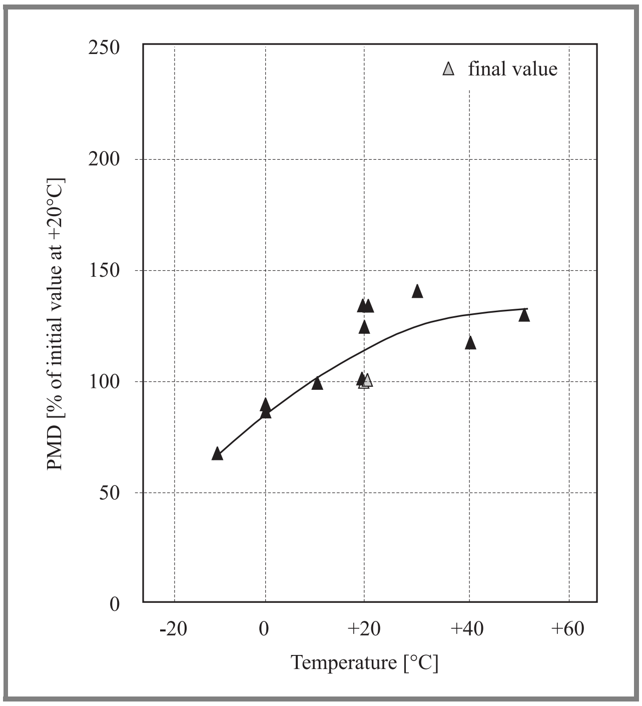

Fig. 13. PMD-temperature curve of 2 mm indoor cable with G.655.A fiber. Sample E, hanged loose on 110 mm tube.

Fiber attenuation at 1550 nm was stable: 0.183 dB/km at +20°C before the test, 0.206 dB/km at −20°C, and 0.187 dB/km at +20°C after test, despite large variations of PMD.

Sample E had a G.655 fiber (OFS TrueWave) buffered with acrylate material UV-cured at room temperature. The cable was loosely suspended on plastic tube to eliminate crush forces between layers. Buffer design was the same as in sample C, but comparison of Figs. 11 (dashed line), 12 and 13 reveals dramatic difference: PMD in G.655 fiber **decreased** at low temperatures and remained stable above +20°C.

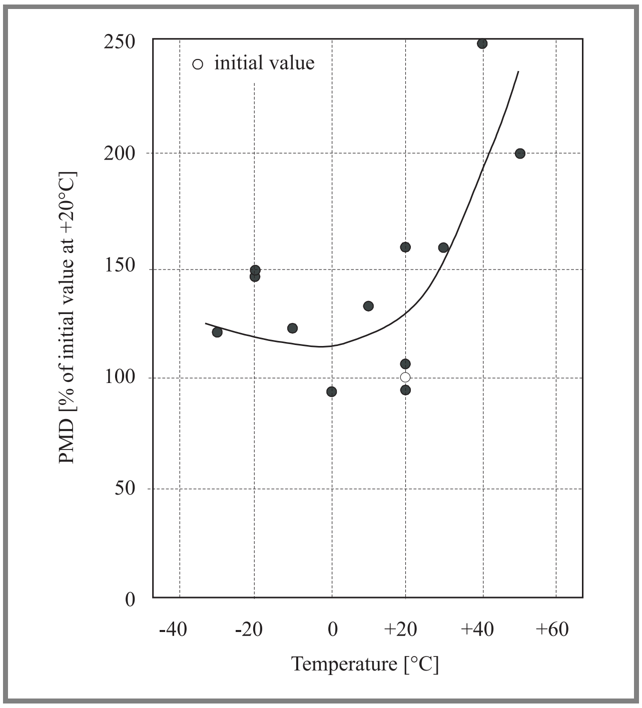

Fig. 14. PMD-temperature characteristics of G.655 fiber in 0.9 mm UV-cured tight buffer. Sample D tested on plastic spool.

Experiment on un-cabled G.655 fiber in tight buffer supplied by the same company (Fig. 14) revealed only small increase of PMD (20–45%) down to −30°C. Rise of PMD at elevated temperatures likely results from testing fiber on spool. Unfortunately, buffer cracked during test at −40°C, this prevented tests on loose fiber.

What caused this difference?

The only tangible explanation is difference in fiber manufacturing process. G.655 fibers are usually spun during drawing from the preform to reduce PMD, because higher concentration of GeO_2 dopant, larger difference of refractive index and increased mechanical strain in core area are all conductive to increased birefringence. Research papers [13, 14] indicate that advanced multi-frequency or frequency-modulated spin reduces PMD to less than 10% of value found in identical, but un-spun fiber. This mechanism is similarly effective at reducing PMD induced by external crush forces.

On the other hand, G.652 fibers are usually drawn without spinning, as their "raw" PMD has been reduced to satisfactory level by improved control of geometry and dopant deposition, so they lack effective defense against external factors increasing PMD.

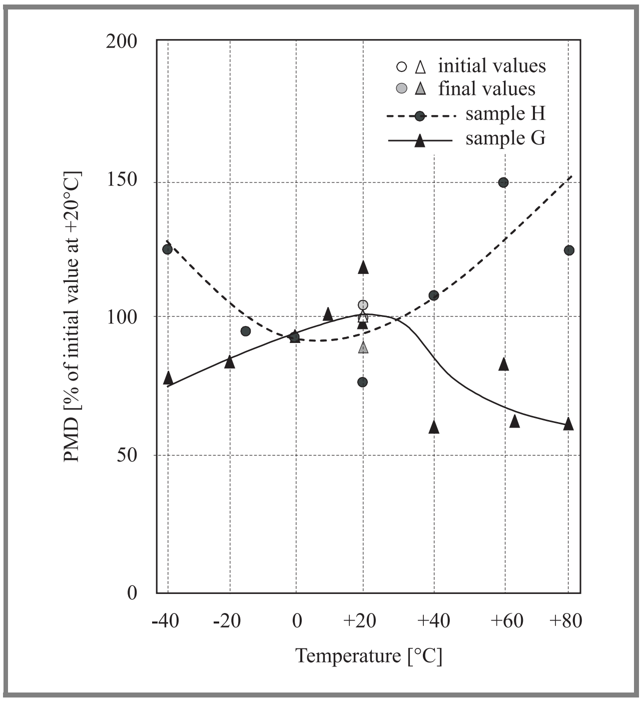

Fig. 15. PMD-temperature characteristics of OPGW cable (see Fig. 3). Samples G and H on wooden drums.

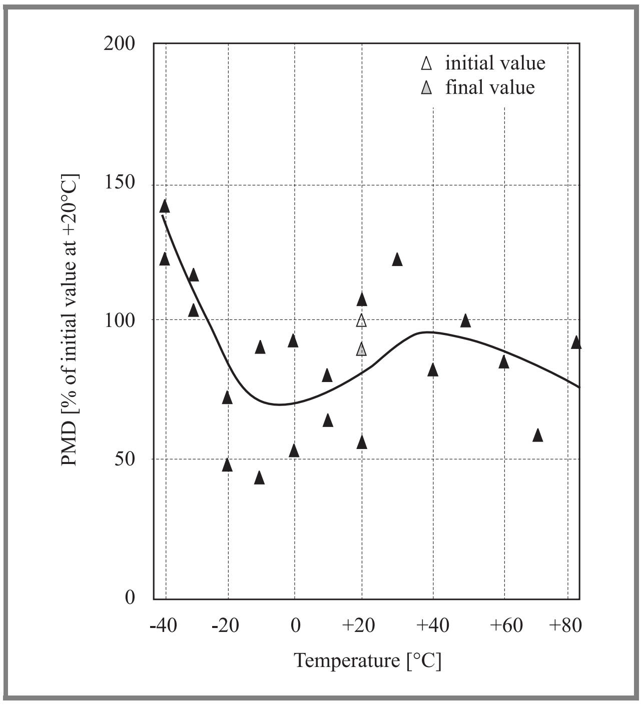

Fig. 16. PMD-temperature characteristics of 12-fiber unit extracted from OPGW (Fig. 4). Sample I, coiled in loose loops.

Optical ground wires are used on aerial power lines in harsh conditions, and have been tested in wide temperature range. Large PMD deviations were expected, especially

Table 3

Results of PMD and attenuation measurements in optical unit extracted from OPGW (sample I) during accelerated life test. Optical loop included 4400 m of fiber and 24 fusion splices. Two fibers from one length were broken and not spliced

Temperature [°C]	Time of measurement	PMD [ps]	Relative value of PMD [%]	Attenuation at 1550 nm [dB]
+20	Before ALT 1	0.076	100	3.69
+85	After 24 h exposure	0.086	114	3.74
+85	After 336 h exposure	0.076	100	3.72
+20	After ALT 1	0.051	71	3.71
+20	Before ALT 2	0.051	71	3.69
+85	After 24 h exposure	0.086	114	3.74
+85	After 336 h exposure	0.065	86	3.78
+20	After ALT 2	0.065	86	3.76

Notes:

1. **Changes of PMD remained within uncertainty of measurement** (±0.022 ps).
2. **A small increase of attenuation:** 0.016 dB/km was detected only in Test 2.
3. Inspection of sample after tests revealed no signs of physical degradation.

as the samples have been degraded by long service and exposure of fiber unit to moisture during post-removal storage. A complete OPGW and the optical unit of the same size removed from OPGW were tested, the results (Figs. 15 and 16) being surprising:

- PMD was remarkably stable between -40°C and $+85$°C, despite differences between two samples. Deviations from room temperature value are within ±50%. Unfortunately, resolution of PMD measurements was hardly adequate for rather short fiber samples.

- Optical unit extracted from OPGW exhibited 50% increase of PMD and increase of attenuation by 0.02–0.04 dB/km (1550 nm) at temperatures between -30°C and -40°C.

- Changes of PMD were fully reversible.

Following thermal cycling, an accelerated life test (ALT) was conducted on the same sample (I) of 12 fiber optical unit extracted from OPGW. The sample was heat-aged at $+85$°C for a 336 h (14 days) twice, with 14 days of storage at room temperature between tests. Telcordia standard GR-20-CORE specifies 7 days (168 h) of heat aging at $+85$°C to simulate 40 years of cable life.

Results of ALT proved excellent stability of transmission parameters (see Table 3).

Good stability of PMD despite the fact that cable manufacturer used un-spun G.652 fibers (Corning SMF-28) is explained by spiral stranding of fibers around strength member during forming of multi-fiber unit. Apparently, this has an effect similar to spinning of fiber during drawing.

6. Conclusions

Results of experiments on variety of fibers and cables are often contrary to assumptions made when the COST-270 research project was initiated in December 2002.

Performance of old type OPGW with tight buffered optical unit is much better than anticipated:

- Stability of PMD across range of temperatures specified in Polish standard (-40°C...$+85$°C) is excellent.

- There was no change of PMD and negligible increase of attenuation during extended accelerated life test.

- Such properties were shown after several years of operation and temporary penetration of moisture.

Fibers in 0.9 mm tight buffers and indoor cables with such fibers can be sensitive to temperature:

- PMD of un-spun G.652 fiber in tight buffer or cable with such fiber starts to rise quickly when temperature drops below approximately 0°C. If the cable must operate in winter conditions, substantial PMD margin must be included during system design.

- Optical fibers, which were spun during drawing are very resistant to induction of PMD by external forces. Use of such fibers in cables intended for low operating temperatures is strongly recommended. Spinning is used mostly during manufacture of fibers conforming to ITU-T Recs. G.655 and G.656.

- PMD in fiber or cable may increase by factor of 5 or more, while attenuation remains very stable.

As only a limited range of products were tested, the results may not be universally applicable.

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