IRUVX-PP

Preparatory phase for the EuroFEL (ex-IRUVX-FEL) consortium

Deliverable N°:	D8.6
Deliverable Title:	Final Report on aging and reliability of optical components used for a laser based synchronization system
Work package :	WP8
Authors:	T. Quast
Contract N°:	211285
Dissemination level:	PU

Project funded by the European Community

Workpackage 8.1 - Deliverable 8.6 Torsten Quast (HZB)

Final Report on aging and reliability of optical components used for a laser based synchronization system

Introduction

Many of the components used in a fiber-laser based timing distribution system are taken from standard telecom applications and are therefore not specified for short pulses application like fiber-laser based synchronization systems. So the idea was to take a closer look into those components in terms of reliability within an accelerator timing system.
But still the choice of components to take a closer look at is by no means trivial. So the focus of investigation was put on those components that have failed repeatedly or have attracted attention by unexpected and suspicious behaviour within an existing prototype setup.

Components of a laser based timing/synchronisation system

In a large accelerator facility the distribution of the timing signals with femtosecond accuracy is done optically. As a master oscillator an optical resonator (pulse laser) is used. By coupling the laser oscillator to a low noise microwave oscillator one can create a source that exhibits lower phase noise than any of them alone.
The distribution of the timing signal via an optical fiber however has to be actively controlled. The length drift with temperature is simply too big. At the outcoupling end of the fiber a fraction of each puls is sent back and detected by an optical phase detector. From the output of the phase detector the feedback signal is generated that controls the motorized delay stage. While the delay stage is slow (and therefore counteracts slow drifts) a second device, a piezo driven fiber stretcher is used for fast length control of the fiber link in the kHz range.
Figure 1 shows the functional blocks of a fiber distribution system.
The synchronization locking of a laser oscillator to a RF master frequency in practical tests worked very reliable and stable once a good set of parameter settings was found.
However the stabilized link suffered from the insufficient accuracy of the motorized delay stage. The high demands on the specification as well as the profile of use often caused unexpected problems in the beginning.
The optical to RF (back-)conversion at the experimental site is easiest done with a photo diode. It was found that fiber coupled diodes from the same production had different amplitude-to phase noise conversion efficiencies.
Especially for long distance connections (km range) the use of a special PSOF (Phase Stabilized Optical Fiber) was taken into account. With this fiber type the special coating counteracts the temperature drift effects. With the high radiation level in an accelerator environment the special cladding of liquid crystal polymer might be damaged and loose its unique compensating features.

Critical components in this system are:

- the mechanical stability of moving components in the delay line
- an appropriate optical design,
- the stability of the laser diodes, used in the master oscillator
- the phase stability of the optical fibers

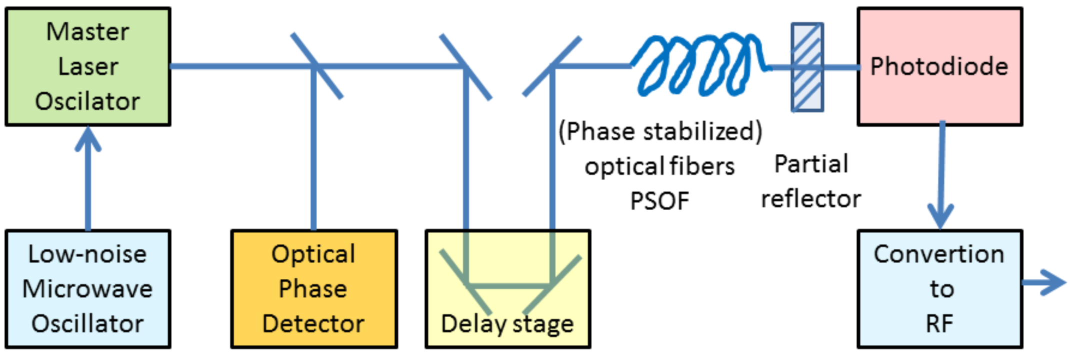

Figure 1: Schematic of an optical timing distribution system. The optical path is stabilized by means of a delay stage (and a piezo fiber stretcher, not shown). At the end station the optical signal is converted into an RF with a photodiode.

Mechanical Stability - Linear Stages for Delay Lines

Motorized linear stages are a standard element in optical delay lines where the optical path length is changed in a free space section (see e.g. [1]). Commercial available delay stages either didn't have enough travel range or needed special development as well which made them unattractive in terms of costs. The first design showed significant pitch and yaw errors which - together with an optical setup utilizing a plane mirror – lead to variations in coupling efficiency of up to 90 % [2].
Not only the design of the linear stage was significantly improved but also the implementation into the optical system. The design of the delay line was significantly improved. On the one hand this concerns the delay stage itself and on the other hand how it is implemented in the setup.

Mechanical Improvements

Considerable changes compared to the old design were realized in the new stage. The force from the motor is transferred with a belt instead of cogs. Critical components like the shaft, arbor, and linear bearings of the stage are high quality, commercial of the shelf parts. It has two guide rods next to the arbor and the guide bushing is just transferring the longitudinal force but is flexible in the transverse direction.
The travel range is about 45 mm which can be extended to about 55 mm if the hall end-sensors are mounted accordingly.

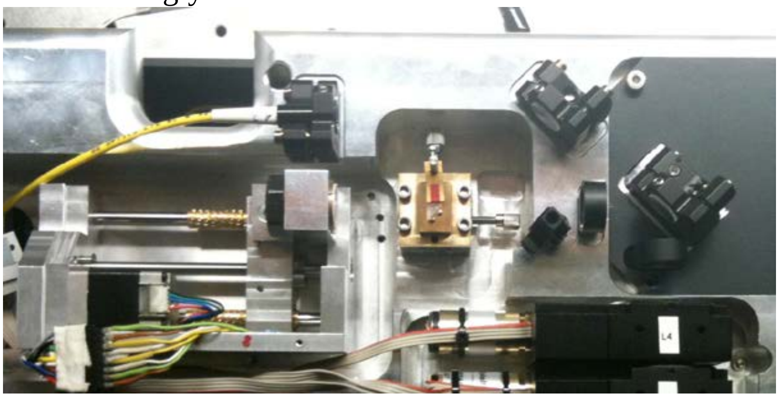

Figure 2 Delay Line - The stage with retro reflector is on the left side of the picture, the prism on goniometer in the center. There is a D-shaped mirror (right side of prism) for reflecting the beam to the in-coupling mirror (top).

Improved Optical Setup

Opposed to the old setup which uses a planar mirror where the delay applied to the laser pulses is two times the travel range because the beam is passing the stage twice, the new design uses a retro-reflector and prism combination allowing for a four pass delay line, see Figure 2. Assuming 50 mm travel range of the stage, the delay range is about 650 ps. Another big advantage of using a retro reflector is that its reflection is only sensitive to transverse motion of the mirror but completely insensitive to pitching and yawing.

The drawbacks of the new design are that the prism has to be mounted on a goniometer in order to adjust the pitch axis and the retro reflector has to be turned such that none of the four laser spots hits an edge. Thus, the alignment is considerably more complex, nevertheless the improvements outweigh this disadvantage.

The in-coupling efficiency to the link collimator is tremendously improved. Variations below 3% over the entire travel range ware achieved as can be seen in Figure 3.

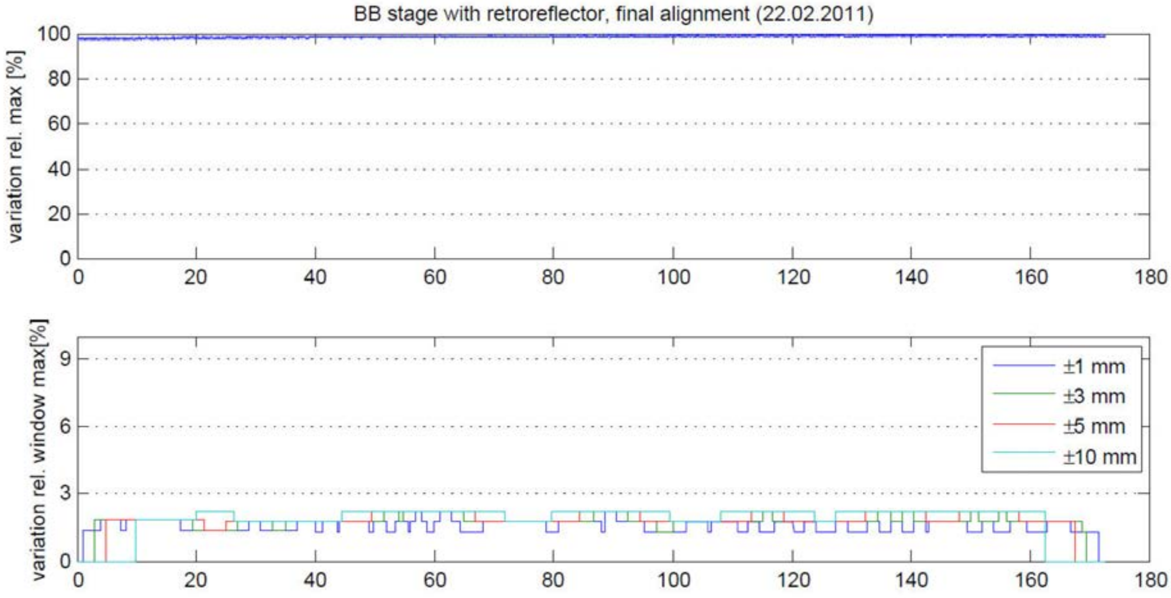

Figure 3: In-coupling efficiency of new delay line

Power Stability of Laser Diodes

With their currently used setup of pump laser diodes (980nm, 500mW, pigtail type) and laser diode driver it was noticed at DESY that sudden jumps in the optical output power of the laser diode modules occurred. While at first it was assumed to be a problem of the laser diode driver or the temperature stabilisation it soon became clear that the occurrence of jumps was not correlated to any of those external parameters. Figure 4 shows the stability of the temperature of the laser diode and the optical output measured on a stable example of the used laser diodes.

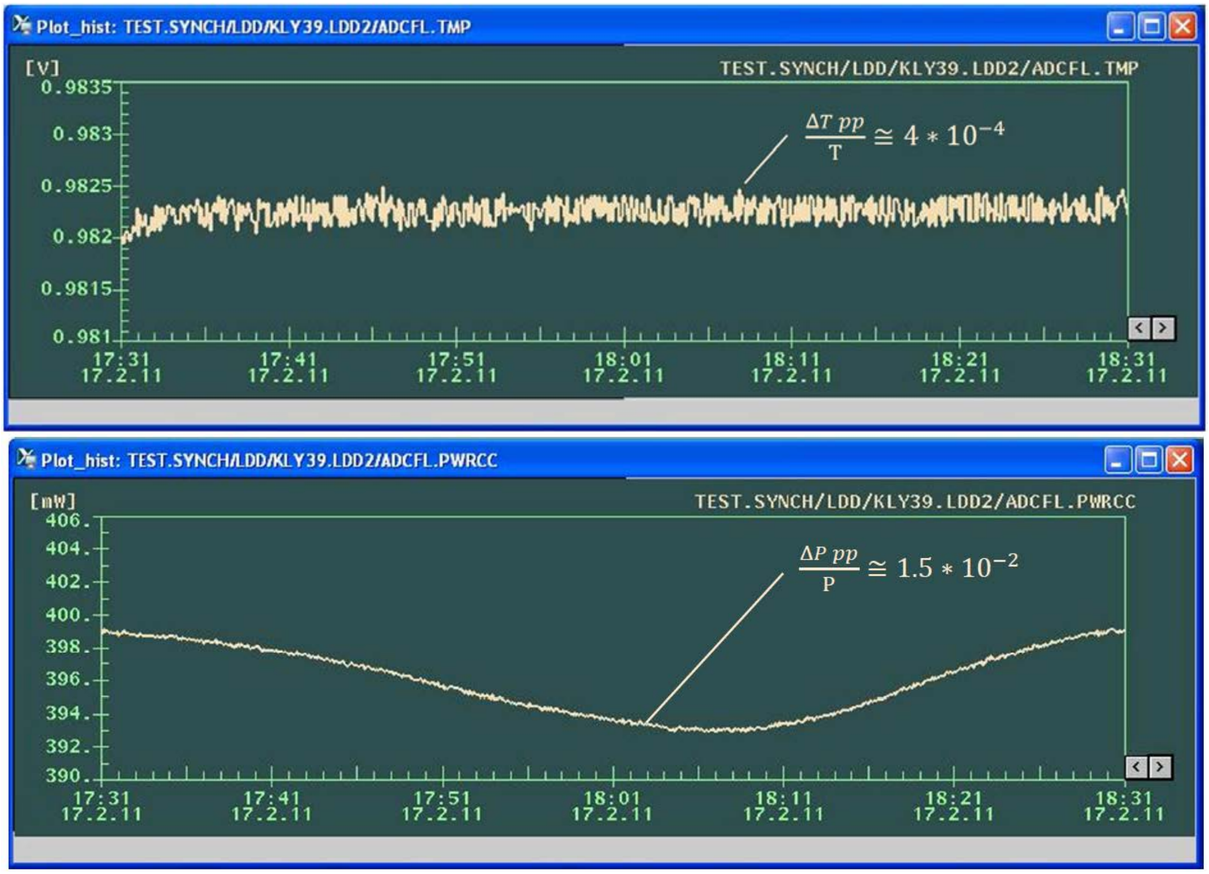

Figure 4: Long time measurement of the temperature of the laser diode measured as voltage on internal resistor (upper).
The optical output power of a stable example of the laser diodes as calculated from the current of the internal photo diode (lower).

The problem stems from the fiber Bragg grating (FBG) that is implemented in the pigtail of the laser module. An FBG is a periodic modulation of the refractive index in the fiber written by illumination with ultraviolet or visible light. While used for many different applications in optical communication here the role of the FBG is to provide a spectrally narrow feedback to the laser diode in order to lock the system to a defined emission wavelength [3].
Figure 5 shows that suddenly the laser power jumps to a different level while the laser diode current stays within its normal range of fluctuation.
During the power jump the optical spectrum of the laser diode changes significantly from a width of 2 nm to a sharp peak of only 0.2 nm as can be seen in Figure 6.
Tests with laser diodes from different manufacturers were made. These were “Bookham”, “Oclaro” and “Lumics”.
It was found that the external optical setup has a tremendous influence on the occurrence of jumps. Wile some of the laser diodes under test did not show any jumps in the test setup they did when operated in the real setup. If spliced with a 1550 nm SMF fiber all of the Oclaro and Bookham diodes produced jumps. Obviously any back-reflection will disturb the stabilizing properties of the FBG.
To help understanding and to overcome the problem of power jumps the company “AOS GmbH” specialized in customizing FBG was contacted [4] but up to now no results have emerged from that cooperation so far.

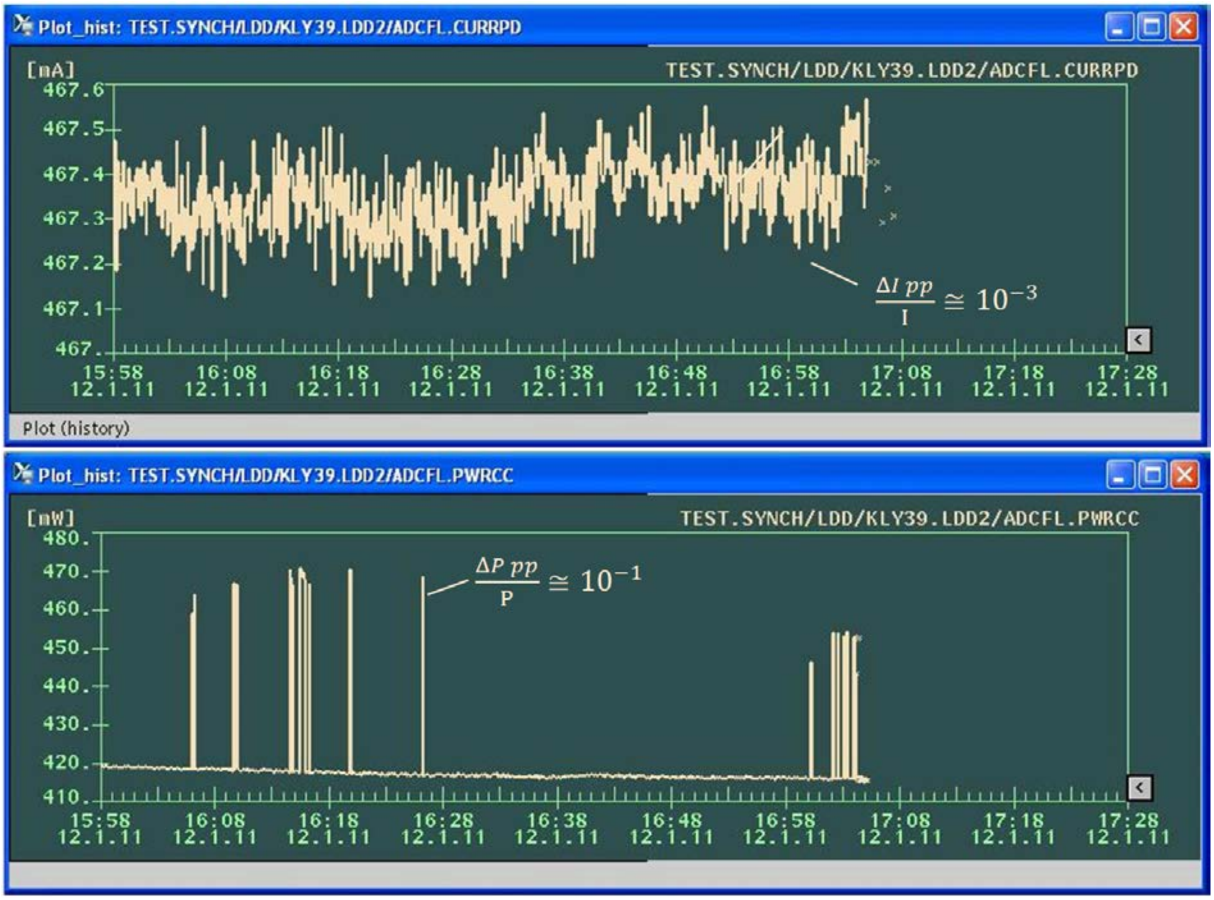

Figure 5: The jumps in the optical output power (lower) are observed without any signature in the laser diode current (upper).

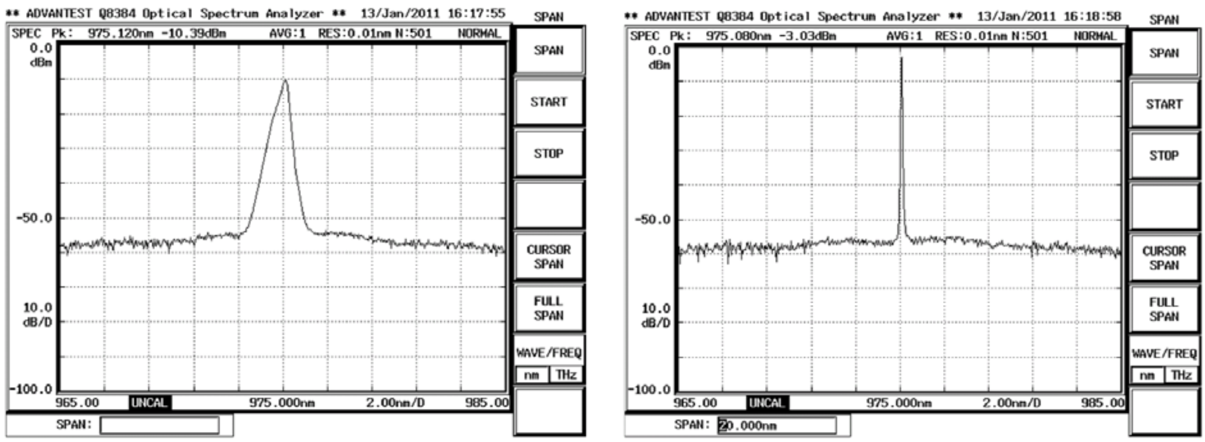

Figure 6: The optical spectrum before (left) and after (right) the power jump has occurred shows a significant narrowing of the spectral width.

Phase Stabilized Optical Fibers (PSOF)

The use of phase stabilized optical fiber (PSOF) offers an easy solution for timing distribution because it needs no active stabilization. Though the temperature drift is not completely compensated the use of PSOF is still very attractive for short distances and for applications where highest stability is not needed.

The company “Furukawa” has developed the technology and is until today the only company that gives specification on the thermal coefficient of delay (TCD). With a specified TDC < 5 ps/km the Furukawa PSOF is kind of a reference for this type of fibers. Unfortunately the Furukawa fiber is rather expensive. With a price of about 13 €/m for the uncoated[1] and 50 €/m for the coated fiber it is quite a large amount when used in a large scale facility. In an attempt to save money the uncoated Furukawa PSOF was coated with a protective coating by “Huber & Suhner”.

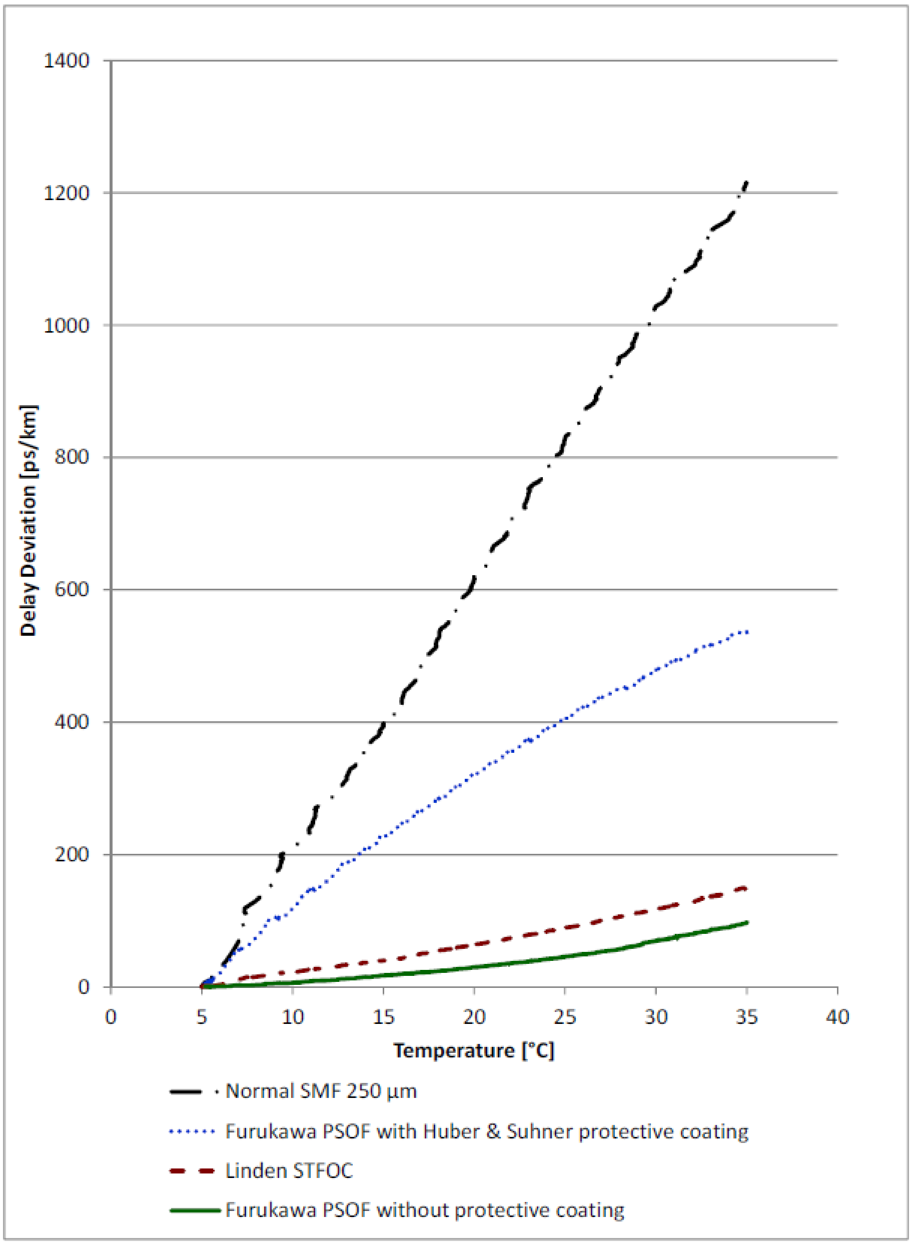

Figure 7: Delay deviation over temperature per kilometer fiber

[1] uncoated: the bare SMF with only the phase stability protective coating

To check whether this coating process keeps the good TCD values this fiber was tested in a climate chamber against an uncoated Furukawa PSOF. A standard SMF fiber for reference reasons as well as a fiber from Company "Linden" (STFOC - Strong Tether Fiber Optic Cable) was tested. This fiber has a primary coating similar to the Furukawa PSOF, but it's TCD is not specified by the manufacturer. With 1 €/m it is much less expensive than the PSOF from Furukawa.
The temperature was varied between 5°C and 35°C.
Figure 7 shows the results for the temperature variation scaled to fiber length of 1 km.
The uncoated PSOF fulfill its specification (TCD < 5 ps/km/K within a temperature range from 0°C to 35°), but the PSOF with Huber & Suhner coating do not. It is only two times better the normal SMF with 250 µm primary coating. But the Linden fiber is nearly as good as the PSOF is specified.
Table 1 summarizes the TDC values for the tested fibers.

Fiber Type	**TCD (Thermal Coefficient of Delay) [ps/km/K]**
Furukawa PSOF without protective coating	3.32
Furukawa PSOF with Huber & Suhner protective coating	17.93
Linden STFOC	5.03
Normal SMF with 250 µm primary coating	40.37

Table 1: TDC values for the tested fibers

In a second test the humidity was changed between 50% and 27%. Up to now only the values for the Linden fiber are available.
The effect of a humidity change from 50 % to 27 % (Figure 8) on the Linden STFOC fiber is depicted in Figure 9 . For the Linden fiber without protective coating the delay change was very slow. It took approximately 24 hours to get the full effect. For the PSOF coating much more time is needed. So at the beginning the measuring time was under estimated and not all fibers have been measured up to now. In the moment only the HCD (Humidity Coefficient of Delay) for the Linden fiber can be given as HCD(Linden) = 1,09 ps/km/%.
The values of the other fibers seem to be in the same order of magnitude.

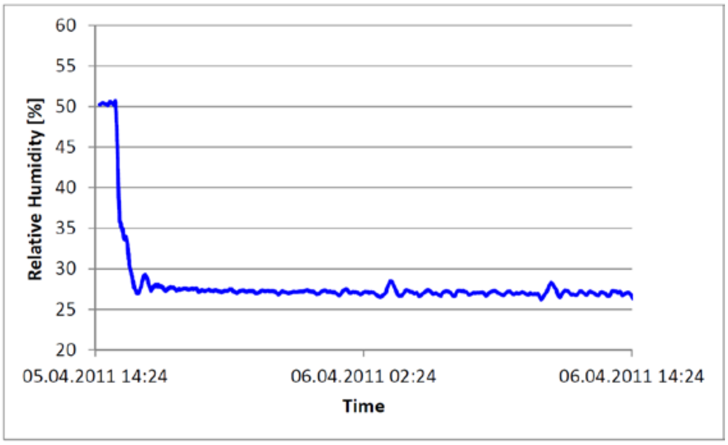

Figure 8: Humidity change

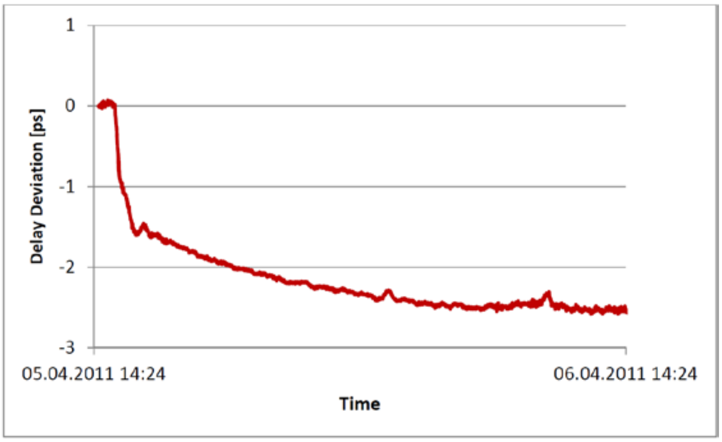

Figure 9: Delay deviation Delay deviation due to humidity change (see Figure 6); DUT: Linden STFOC, length = 100 m

Acknowledgement

I would like to thank M.K. Bock and M. Felber for the measurements on the linear stages. and I would like to thank S. Ruzin for giving his contributions to the paragraph about the laser diodes. M.Bousonville I would like to thank for giving me data and information about the PSOF measurements and P. Gessler and H. Schlarb for general support. This work was partly supported by "IRUVX-PP" an EU co-funded project under FP7 (Grant Agreement 211285).

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