Measurement of optical to electrical and electrical to optical delays with ps-level uncertainty

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Abstract: We present a new measurement principle to determine the absolute time delay of a waveform from an optical reference plane to an electrical reference plane and vice versa. We demonstrate a method based on this principle with 2 ps uncertainty. This method can be used to perform accurate time delay determinations of optical transceivers used in fiber-optic time-dissemination equipment. As a result the time scales in optical and electrical domain can be related to each other with the same uncertainty. We expect this method will be a new breakthrough in high-accuracy time transfer and absolute calibration of time-transfer equipment.

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References and links

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1. Introduction

Relative time delays corresponding to optically generated frequencies can be measured electronically with zeptosecond precision [1]. It has been shown that electrical to electrical (EE) and optical to optical (OO) time delays can be determined with picosecond level precision [2, 3]. However, the absolute time delay between an optical reference plane and an electrical reference plane is much harder to measure. At best, one can estimate the optical to electrical (OE) delay e.g. from the detector geometry and electrical properties, with uncertainties as low as ±7 ps reported [4]. Modern opto-electronic time distribution systems, such as White Rabbit (WR) [5], have become widely used and achieve time interval measurements with picosecond-level precision [5, 6]. A method to directly measure electrical to optical (EO) delay with ps precision has so far been lacking, but is urgently needed to calibrate such systems.

In this publication we present a new method to characterize OE and EO time delay with respect to defined reference planes. A clear advantage of our method is that the photo detector to be characterized is approached as a “black box”, in contrast to the traditional approaches where a detailed knowledge of the photo detector construction is mandatory.

Although the research described in this article was initiated by the demand for WR absolute calibration [7], it enables the absolute calibration of any time transfer system that uses opto-electronic conversions. The presented principle is expected to be generally useful for time and frequency metrology.

2. Theory

Optical communication typically involves modulation of the amplitude, phase, or combinations thereof. Often, amplitude modulation (AM) is used. For the delay calibration method reported we use a LiNbO3 Mach-Zehnder amplitude modulator (MZM). In this device an incident optical field is split and sent into two parallel arms of an optical waveguide interferometer. In one of the arms the optical field interacts with a radio frequency (RF) electric field, co-propagating with the optical field at approximately the same velocity, resulting into nearly instantaneous modulation of the optical field’s phase through the electro-optic (Pockels) effect. At the end of the interferometer the two optical waves are recombined, leading to amplitude modulation (AM) of the emanating optical field. Note that the MZM is essentially a four-port device with two optical and two electrical ports, corresponding to the ends of a bidirectional optical waveguide and a bidirectional electrical stripline, respectively. A photo diode receiver detects the AM of the optical wave and converts it back to the electrical domain. The nearly instantaneous interaction in the MZM from the electrical to the optical wave is used to accurately determine the time delay between the optical reference plane and the electrical reference plane of the opto-electrical receiver.

Figure 1 shows the schematic of the proposed set-up to determine the OE delay, $\Delta OE$, of a receiver. The measurable delays $D_{1-4}$ between the various reference planes in this device are given by

$$D_1 = \Delta E_A + \Delta E_B,$$

$$D_2 = \Delta O_A + \Delta O_B,$$

$$D_3 = \Delta E_A + \Delta O_B + \Delta EO + \Delta OE,$$

$$D_4 = \Delta E_B + \Delta O_A + \Delta EO + \Delta OE,$$

where $\Delta E_A, \Delta E_B, \Delta O_A, \Delta O_B$ are delays from the four MZM ports to a virtual reference plane $R$, and $\Delta EO, \Delta OE$ are internal EO and OE delays of respectively the MZM and opto-electrical receiver.
receiver. Combining Eqs. (1) - (4) yields

\[ \Delta EO + \Delta OE = \frac{D_3 + D_4 - D_1 - D_2}{2}. \]  

(5)

Assuming that the delays \(D_1\ldots D_4\) can be measured, and under the assumption that \(\Delta EO\) is very small and can be measured or estimated from the physical dimensions and composition of the MZM traveling wave device, \(\Delta OE\) can be determined from this equation. Its uncertainty is determined by measurement uncertainties and the uncertainty in \(\Delta EO\). Once calibrated, the known delay \(\Delta OE\) of the receiver can be used to determine an unknown EO delay \(\Delta EO_t\) of a transmitter, by direct EE delay measurement of \(\Delta EO_t + \Delta OE\).

3. Method

EE and OO delays can be determined with high precision using interpolated cross-correlation [3, 8, 9] (see also Appendix A). First the delay between the input and output signals of a reference measurement chain is determined. Then a Device Under Test (DUT) is inserted into the reference measurement chain. The DUT delay is determined by the difference between the measured delay and the delay of the reference measurement chain.

In general cross-correlation is insensitive to amplitude variation and can be reliably used for signals under noise level. Moreover, cross-correlation is less sensitive to signal rise and fall times. It is known that cross-correlating signals may introduce systematic shifts for bandwidth limiting components. In our experiment the bandwidth limitation is given by the directly modulated laser (3.5 Gbit/s), which is much larger than the signal bandwidth. Therefore no systematic effects due to bandwidth limitations are expected.

Fast random signals are advantageous for delay estimation with high time resolution through cross-correlation. In our experiment a 1.25 Gbit/s Pseudo Random Binary Sequence (PRBS-7) signal is used. The choice for the PRBS-7 signal was made because it has similar power spectral density and group delay as that of the IEEE 802.3-BX gigabit Ethernet signal used in the time transfer systems to be calibrated. Given the fact that a coarse estimation can be made from the expected delay with sufficient accuracy, the correct correlation peaks can always be found within a PRBS-7 sequence period (\(T = 101.6\) ns).

For the measurement of the delays defined by Eqs. (3) and (4), both the optical waveguide and electrical stripline need to be bidirectional. This is in principle the case for every MZM. However, most packaged MZMs have an internally terminated electrical transmission line that only allows a single measurement (either \(D_3\) or \(D_4\)). For this experiment a MZM was modified. The internal termination was removed from the electrical stripline, and replaced by an SMA connector. The
resulting device allows us to make the proposed measurements. The modified MZM has two female electrical connectors (SMA) and two optical connectors (FC/APC).

Suitable connectors need to be selected because proper impedance matching is a requirement. SMA and 3.5 mm connectors are found to have sufficient connection repeatability for time transfer purposes with picosecond precision [10]. The electrical reference planes for the measurements are taken at the connectors as specified in MIL-STD-348B. The optical reference planes are taken at the physical contact plane of the FC/APC connectors.

Device delays are measured as outlined in Figs. 2 - 4. Figure 5 shows the symbols used throughout these figures. Wide band directional couplers (50 MHz to 6 GHz, type: Mini Circuits ZHDC-10-63-S+) are used to measure “in-line” with a fixed phase relation to the reference planes. A directional coupler on the output is not necessarily needed, but is used in order to keep the transfer function for both reference planes to the oscilloscope as equal as possible. Two 16 inch phase stable coaxial SMA cables (Huber+Suhner Mini141-16) are used to connect the oscilloscope.

An Ethernet transceiver evaluation board (Texas Instruments TLK1221) was used as PRBS-7 generator, together with a wide band RF amplifier (Multilink Techn. Corp. MTC5515-751) to drive the MZM (OEQuest.com LN-CHIP-12.5G). The MZM needs a bias voltage which determines the optical phase shift for optimum modulation. A DFB laser at 1490 nm (Agilecom WSLS-149003C1424-20) was used for the optical delay measurements. This laser can either be directly modulated up to 3.5 Gbit/s (lowest bandwidth component), or modulated by the MZM modulator. Note that most SFP module lasers cannot be used since one of the measurements needs Continuous Wave (CW) light and usually SFP module lasers cannot be operated in CW. Without data input, the SFP laser driver tends to oscillate and thereby modulate the laser.

The polarized laser light is fed through a fiber polarization controller (Thorlabs FPC560) in order to optimize the coupling to the polarization sensitive MZM. The delay of the optical to electrical converter can depend on the received optical power. Therefore, the received optical power is monitored by measuring the DC current through the photo diode and held constant during the delay measurements.

The mainline loss of the directional couplers is 4 dB while the coupled output is -10 dB. The electrical loss of the MZM is in the order of 3 dB. This means that the source coupler output signal is -10dB while the destination coupler is -17 dB. The loss of optical MZM path is in the order of 6 dB. These losses have no impact on the measured delay using the cross-correlation method. The optical signal at the reference receiver was kept stable at -8 dBm to avoid an error source due to photodiode power dependency.

![Fig. 2. Electrical delay chain reference measurement A (= electrical reference delay plus the delay of an F–F coupling device). Measurement B is used to determine the MZM EE delay $D_1$ using reference measurement A.](image-url)
Figure 2 shows the set-up to measure the electrical delay $D_1$ which is determined by a differential measurement. The blue dashed lines in Fig. 2 are the measurement reference planes. A differential measurement consists of two measurements. The set-up needs to be changed between the reference planes but the overall test set-up must be kept as stable as possible (i.e. no re-connections or large cable movements). Repeating these measurements is a way to check the stability of the measurement set-up.

Due to the fact that SMA electrical connectors are not genderless, the EE reference delay measurement A (Fig. 2) has two reference planes connected by a F–F coupling device. The delay ($\Delta_f$) of the F–F coupling device needs to be subtracted from the EE reference delay measurement A, and is determined by using the auxiliary measurement described in Appendix B. The electrical delay $D_1$ of the MZM is determined by measurement B of Fig. 2 minus the electrical reference delay.

The optical reference delay is determined with the set-up shown in Fig. 3. The optical delay $D_2$ of the MZM is determined by measurement D of Fig. 3 minus the optical reference delay measurement C. Measurement B and D are repeated in both directions of the MZM by exchanging the MZM electrical ports, respectively the optical ports. Figure 4 shows the set-up to measure delays $D_3$ and $D_4$ (Eqs. (3) and (4)). $D_4$ is measured by changing the MZM direction (i.e. exchange the MZM ports).
The order of measurements D, E and F (Figs. 3 and 4) is important. Before starting measurement E, the light polarization through the MZM is optimized for maximum modulation depth with the polarization controller. Thereafter, measurement D is performed in the same MZM direction, with the same polarization (i.e without touching the fiber circuit). In the same manner the light polarization is optimized for measurement F and D in the other direction of the MZM.

Figure 6 shows an overview of the measurement set-up. The labels show the various components.

4. Systematic effects and uncertainties

Table 1 gives a summary of the systematic error sources and their contributions. The Pockels effect in a LiNbO$_3$ MZM is nearly instantaneous and the speed is governed by the photon–phonon coupling [11] through the electrically induced displacement of the atoms in the crystal. The lowest energy resonances lie in the order of 30 cm$^{-1}$, determining the refractive index, and thus
Table 1. Type B (systematic) measurement uncertainties with standard deviation $u_j$.

<table>
<thead>
<tr>
<th>Type B uncertainty</th>
<th>mean (ps)</th>
<th>$u_j$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MZM ($\Delta EO$)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>MZM bias voltage</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>MZM light polarization</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>RX power dependency</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Electrical reflections</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>VOA attenuation</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>thermal laser</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>thermal MZM</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>thermal PIN</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>mechanical accessory tool</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>stability</td>
<td>0.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

group delay for microwave signals [12]. With a separation between the electrical stripline and optical waveguide of at most 100 $\mu$m [13], and a refractive index $n = 6.6$ [12], the worst case EO delay is approximately $nL/c \approx 2.2$ ps and we estimate this delay therefore as $1.1(1.1)$ ps. It is expected that for MZMs specifically designed for this task, $\Delta EO$ can be kept small and that the device parameters needed for its determination can be accurately measured.

The MZM bias voltage is adjusted for optimal symmetric modulation. The delay versus bias voltage around the operating point is 1.9 ps/V and contributes an uncertainty of 0.1 ps.

The maximum observed delay change due to changing light polarization over a wide range was 11.1 ps. The polarization was optimized and controlled during the measurements with the MZM. Under these conditions the contribution due to polarization is small (0.5 ps).

In our set-up the MZM is not perfectly matched to 50 ohms. Electrical reflections are therefore expected to influence the delay measurements. A maximum relative delay variation of less than 0.1 ps was measured (see Appendix D).

Furthermore, it was checked that the delay measurements are not influenced by the Variable Optical Attenuator (VOA). The maximum relative delay variation observed was 0.1 ps/dB. In our set-up the VOA is used over a 6 dB range (uncertainty 0.6 ps).

Thermal effects in the electronics potentially influence the delay measurements. During multiple measurement sessions the temperature was $x \pm 1$ degrees Celsius. Delay variations due to temperature changes are evaluated to be 0.9 ps/K for the MZM modulator and 0.4 ps/K for the laser diode. Delay variations due to temperature changes of the PIN diode was evaluated to be 0.1 ps/K. Thermally induced delay changes of the optical fibers and microwave cables are negligible.

The length measurement of the coupling devices is described in Appendix B and corresponds to a timing error of less than 0.1 ps.

It has been taken care of creating a mechanically stable set-up that is fixed onto an optical breadboard. Multiple OE delay measurements over several weeks contribute to a spread of 1.8 ps with a $u_i$ of 0.5 ps. A number of small error sources, such as electrical/optical connector reconnection and cable/fiber stability are included in Table 1 under "stability".
Table 2. Measurement A to F and $\Delta f$, including Type A (statistical) uncertainties, of a single measurement series with standard error $s_i$, and degrees of freedom $v_i$ (here, number of measurements-1).

<table>
<thead>
<tr>
<th>measurement</th>
<th>mean (ps)</th>
<th>$s_i$ (ps)</th>
<th>$v_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>936.5</td>
<td>0.059</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>1296.3</td>
<td>0.041</td>
<td>49</td>
</tr>
<tr>
<td>C</td>
<td>53086.2</td>
<td>0.228</td>
<td>24</td>
</tr>
<tr>
<td>D</td>
<td>71908.7</td>
<td>0.386</td>
<td>49</td>
</tr>
<tr>
<td>E</td>
<td>12949.8</td>
<td>0.177</td>
<td>24</td>
</tr>
<tr>
<td>F</td>
<td>13926.7</td>
<td>0.162</td>
<td>24</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>85.4</td>
<td>0.1</td>
<td>24</td>
</tr>
</tbody>
</table>

5. Experimental results

Results for the delays A to F (Figs. 2 - 4) of one of the measurement series, together with $\Delta f$, are shown in Table 2.

Delays $D_1$ to $D_4$ (see Eq. (5)) can be calculated from measurements A to F and $\Delta f$ according to

$$D_1 = B - (A - \Delta f),$$  \hspace{1cm} (6)
$$D_2 = D - C,$$  \hspace{1cm} (7)
$$D_3 = E - (A - \Delta f),$$  \hspace{1cm} (8)
$$D_4 = F - (A - \Delta f).$$ \hspace{1cm} (9)

Rewriting Eq. (5) and substituting Eqs. (6) - (9) yields

$$\Delta OE = -\frac{A - B + C - D + E + F + \Delta f}{2} - \Delta EO.$$ \hspace{1cm} (10)

The sources of Type B error are assumed to be uncorrelated, all Type A and Type B errors are summed quadratically to arrive at a total uncertainty ($\sigma$) of 2 ps. A total of 15 measurement series were performed, showing a standard deviation for $\Delta OE$ of 0.5 ps. The optical-to-electrical delay ($\Delta OE$) is therefore determined as 2953 ps, with a conservative uncertainty of 2 ps. Knowing this delay, the EO delay of the MZM in either of its directions is known as well.

6. Discussion

It is clear that the MZM used in our set-up was not optimized for the method presented. It should have a well defined, impedance matched, electrical transmission line which is accessible at both ends. It should have polarization maintaining fiber on both ends. A geometrically optimized MZM with physical parameters that are measurable in order to determine its $\Delta EO$ delay by use of an appropriate model is envisioned. Critical parameters can be made measurable using test structures integrated on such a device. A MZM that is specifically designed and optimized for this measurement method could thus dramatically lower the contribution of the $\Delta EO$ delay error.

Impedance mismatch of the electrical transmission line of the MZM causes distortion of the waveforms used for cross-correlation, resulting in a timing offset. Due to the fact that all waveforms are available digitally, one could correct for MZM impedance mismatch. The same holds for differences in rise- and fall-times. Future research focused on these aspects might therefore lead to smaller attainable uncertainties.
7. Conclusion and outlook

We have introduced a new principle to determine the signal delay from an optical reference plane to an electrical reference plane of an opto-electrical receiver, and thus of the electro-optical transmitter used for its determination. We have shown a method based on this principle resulting in a \( \Delta OE \) determination with 2 ps uncertainty.

Based on the experience gained during the presented experiment the authors think that precisions in the sub-picosecond regime are feasible. The individual measurements already show repeatable sub pico-second accuracy (see Table 2). The main error source (see Table 1) is the uncertainty of the \( \Delta EO \) of the MZM. Second and third error contributions can be addressed by thermal stabilization of the set-up and using a full polarization maintaining fiber light path between laser and MZM.

The introduced method enables cross-domain comparison of time codes and absolute calibration of optical transceivers for fiber-optic time-dissemination equipment with ps-level uncertainty. As indicated in Sec. 2 the EO delay of other transmitters can be determined by EE delay measurement and the receiver with now known OE delay only. This also holds for the OE delay of other receivers, using the transmitter with now known EO delay. This method can be extended to other signals, modulation types and optical line codes as long as these can be generated using MZMs.

The introduced principle enables the direct comparison of optical time signals with their electrical counterparts.

The presented method also enables high accuracy time transfer of optical clocks and their comparison with electrical time standards. Therefore we expect it to be an enabling technique for future generations of high accuracy time-transfer systems.

Appendices

A. Measurement of EE delays using cross correlation

Cross-correlation was done on waveforms, sampled by a 33 GHz DSAV334A Infiniium V-Series Oscilloscope. Waveform samples were 800 kSa long and sampled at 12.5 ps intervals. Both decreasing sample length and increasing sample interval have an effect on the correlation result. Full and reduced sample length correlation results, as well as different sample interval correlation results were compared. Reduction of the waveform sample length to ~8 kSa (a reduction factor 100) does not significantly increase the error. Increasing the sample interval to ~88 ps (a reduction factor 7) does not significantly increase the error. Note that these comparisons were based on the same dataset and thus on the same oscilloscope bandwidth and time-base quality.

In general [8, 9, 14] show that interpolation to find the cross-correlation peak is sensitive to the sampling interval to less than a few %. This means that for our experiment the results for measurements A to F and \( \Delta e \) can be trusted up to about 0.60 ps (5%).

B. Measurement of the F–F SMA coupling device

The electrical delay chain measurement shown in Fig. 2 includes the delay of an F–F coupling device. The auxiliary measurement set-up shown in Fig. 7 is needed to measure the delay of the F–F coupling device. However, this cannot be done directly. The difference between the delay measurements shown in Figs. 2 and 7 is the delay of a F–F plus M–M (male-male) coupling device (\( \Delta_e \)).

The propagation speed of 3.5 mm coupling devices that use air as dielectric, is defined by the speed of light (c). The F–F delay (\( \tau_f \)) and M–M delay (\( \tau_m \)) are determined by measuring their mechanical lengths (\( l_f \) and \( l_m \)) with the aid of an accessory tool (see Fig. 8).

The actual electrical delay \( \Delta_e \) is ~7 ps (\( \Delta_{ex} \)) longer than the sum of \( \tau_f \) and \( \tau_m \) (Eq. (13)). This excess delay is due to a small mechanical center conductor support of dielectric material. Under the assumption that both mechanical supports for F–F and M–M coupling devices are equal...
(i.e. use coupling devices from one manufacturer) the excess delay is equally divided over the coupling devices. The electrical delays ($\Delta_f$ and $\Delta_m$) of the F–F and M–M coupling device can thus be expressed as

\begin{align}
\Delta_f &= \tau_f + \frac{\Delta_{ex}}{2}, \quad (11) \\
\Delta_m &= \tau_m + \frac{\Delta_{ex}}{2}, \quad (12)
\end{align}

where

\begin{equation}
\Delta_{ex} = \Delta_e - \tau_m - \tau_f, \quad (13)
\end{equation}

and

\begin{align}
\tau_f &= \frac{l_f}{c}, \quad (14) \\
\tau_m &= \frac{l_m}{c}. \quad (15)
\end{align}

The length determination of the F-F and M-M SMA coupling devices is done using two separate mechanical length measurements. The electrical reference plane of a 3.5 mm SMA connector as specified in MIL-STD-348B is mechanically difficult to access in order to enable mechanical length measurement. The tool shown in Fig. 8 trans-locates the mechanical reference plane outside the mechanical envelope of the coupling device under test. First, the length of both accessory tools clamped together is measured. Next, the length of F-F or M-M is measured after inserting an accessory tool at each end. The first measurement is subtracted from the second to obtain the length of the F-F or M-M SMA coupling device.

The precision of each of the two measurements is 0.01 mm. Therefore, the measurement of the F-F or M-M SMA coupling device has an error of 0.014 mm which corresponds to 0.045 ps.

**C. Variable optical attenuator**

The type of Variable Optical Attenuator (VOA) should be chosen with care. Air-gap type attenuators are expected to generate variable delay as function of attenuation. Neutral density
filter type attenuators have a constant optical path length. Therefore, in the test set-up we used the neutral density filter type attenuator to minimize delay variation. Delay variation as function of attenuation was characterized. Both attenuator types were placed in series (Eigenlight Power Monitor 410; air-gap type and Wandel&Goltermann OLA-25; neutral density filter type). We measured the delay variation by changing the individual attenuators while keeping the attenuation sum constant. Individual attenuation was changed over a range of 11 dB which resulted in a 0.9 ps delay change. It was not possible to measure the individual contribution of each attenuator.

D. Electrical reflection

The influence on the delay measurement of MZM electrical impedance mismatch is measured with the set-up shown in Fig. 9. A reference delay measurement is performed between the PRBS source and the coupled output of the 50 ohm terminated directional coupler (A). A second measurement is performed with the MZM connected to the directional coupler while the other electrical MZM port is 50 ohm terminated (B). The measured delay difference was less than 0.1 ps.

Fig. 9. set-up to measure delay influence due to electrical reflection caused by MZM impedance mismatch.

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