Sensors & Transducers, Vol. 233, Issue 5, May 2019, pp. 21-26

Sensors & Transducers

Published by IFSA Publishing, S. L., 2019
http://www.sensorsportal.com

Experimental Study of Reference Frequency and Time Scales Transmission Systems via Optical Fiber

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Received: 30 March 2019 /Accepted: 30 April 2019 /Published: 31 May 2019

Abstract: The way of reference frequency and time scales transmission via optical fiber is describes in the article. Transmission system is designed to transfer reference signals from clock to remote object's users. It uses two standard communication fiber optical links. One optical channel is used for transfer of reference frequency signal. Second channel is used to compare time scales of remote objects. The results of experimental studies of the transmission uncertainly of reference frequency and time signals using fiber-optic communication lines are listed. The method of radio frequency reference signal transmission by optical fiber line is represented. The scheme of electronic compensation of reference 100 MHz signal phase perturbations in optical fiber is described. The experimental results of Allan deviation measurements of 100 MHz reference signal transmitted to the remote end of fiber line 100 km long are presented.

Keywords: Optical fiber link, Clock, Time signal transfer, Comparison, Synchronization, Reference, Frequency signal transmission.

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1. Introduction

Modern requirement to the accuracy of time scales synchronization of geographically separated clocks, accuracy of transmission reference frequency and time signals from clocks to users, in particular, to metrological ground complexes of global navigation satellite systems, time scales of metrological standards time scales of astronomic laboratories is uncertainly of no more than 100 - 200 ps.

Signal transmission over coaxial cables longer than 100 meters does not meet the accuracy requirements due to significant attenuation and change in the propagation delay depending on the ambient temperature change.

Transmission of time signals using transported quantum clocks or transfer signals via satellites allows to achieve accuracy no better than 0.5 -1 ns [1-2].

It is possible to achieve such accuracy, when distances between clocks and users vary from tens to hundreds of kilometers, only using optical fiber link (OFL) [3-6]. Optical fiber links provide small attenuation of transmitted signals, much better stability and delay variance can be taken into account with bidirectional measurements.

Using a fiber-optic channel to transmit reference signals of time and frequency requires compensation of perturbations of the fiber line. That's why it is necessary to develop special active compensation devices to suppress disturbances introduced by the fiber-optic link.

2. Frequency Stability Analysis

The synchronization of geographically separated clocks or primary clock and users of the signals mostly depends on stability of reference frequency.

Time domain stability analysis of frequency source is concerned in measurement of fractional frequency y(t).

Frequency source output signal can be described by sin wave:

$$V(t) = [V_0 + \varepsilon(t)] \cdot \sin(2\pi \nu_0 t + \varphi(t)), \tag{1}$$

where V_0 is the nominal peak output voltage, ε(t) is the amplitude deviation, υ_0 is the nominal frequency, φ(t) is the phase deviation.

The instability of most frequency sources can be described using variances (deviation). The Allan variance (deviation) is the most common time domain measure of frequency stability, and there are several versions of it that provide better statistical confidence, can distinguish between white and flicker phase noise, and can describe time stability.

In this work the frequency stability will be described by overlapping Allan Variance.

The fully overlapping Allan variance, or AVAR, is a form of the normal Allan variance, $\sigma^2_y(\tau)$, that makes maximum use of a data set by forming all possible overlapping samples at each averaging time τ. It can be estimated from a set of M frequency measurements for averaging time $\tau = m\tau_0$, where m is the averaging factor and τ_0 is the basic measurement interval, by the expression [7]:

$$\sigma_y{}^2 = \frac{1}{2m^2(M-2m+1)} \sum_{j=1}^{M-2m+1} \left\{ \sum_{i=j}^{j+m-1} [y_{i+m} - y_i] \right\} \tag{2}$$

Further will be used overlapping Allan deviation ADEV (which is square root of AVAR). Basically the most important observations time is τ = 1 s (which characterizes the short-term stability) and $\tau = 10^5$ s (which characterizes the long-term stability).

3. Principle of Operation of System of Reference Frequency and Time Scales Transmission (SRFTST)

The SRFTST system consists of reference frequency transmission system (which is used to transfer frequency signal from clock to auxiliary generator), auxiliary generator (which forms 1 PPS (1 pulse per second) signals and can offset them relative to input reference signal) and the system of time scales comparison (which measures time interval between clock 1 PPS signal and auxiliary generator 1 PPS signal).

The system consists of transmission and receiving parts, which are connected with optical fiber link.

The functional scheme of system of reference frequency and time scales transmission (SRFTST) via optical fiber is suggested on the Fig. 1.

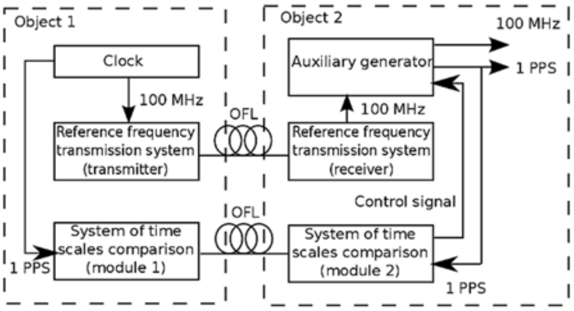

Fig. 1. Functional scheme of SRFTST system.

The operation principle of the SRFTST system is following.

In relatively short fiber-optic links (the length is up to ~ 1 km) it is possible in many cases to transmit a standard RF signal with acceptable level of accuracy without using a special phase perturbation compensation system. But in long links (the length is over 85 km) the frequency of the signal transmitted to the remote end of the line and the reference signal may differ significantly by the value of ~ 10^{-13}.

In order to decrease the error of a reference signal transfer it's essential to use systems of compensation of phase perturbations of transmitted signal, introduced by the link. The system of active compensation in our scheme is based on electronic compensation method. The foundations of this method are: 1) Bidirectional ("both ways") propagation of the reference signal over the same optical fiber; 2) The fact, that both forward and reverse transmissions make the signal undergo substantially the same disturbances.

The scheme of transmission of 100 MHz reference clock signal over an electronically stabilized fiber link via to 200 km length shown in Fig. 2.

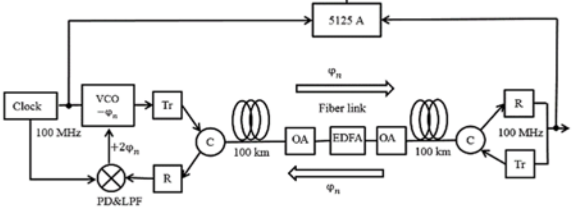

Fig. 2. The simplified scheme, which illustrates the principle of active electronic compensation in the system of transmission of 100 MHz reference signal over the 200 km fiber-optic line.

In the presented scheme 5125A is an analyzer Symmetricom 5125A, PC is a personal computer, VCO is a 100 MHz crystal oscillator (phase shifter), Tr is a DFB laser of optical transmitter, R is a photodetector of optical receiver, C is an optical circulator, OA is an optical attenuator, EDFA is bidirectional erbium doped fiber amplifier, LPF is a low-pass filter, PD is a phase detector. The setup implements a method of asymmetric electronic compensation of disturbances, which are introduced by a fiber-optic line (the length is up to 200 km). In this apparatus a dynamic phase correction is provided by using a 100 MHz variable-frequency crystal oscillator.

This oscillator's signal modulates optical emission of the laser diode.

The comparison of reference signal and signal, which has been transmitted along the "there and back" line, in a phase detector (PD) gives an error signal, which is filtered in low-pass filter (LPF) and controls the frequency of a crystal oscillator. With an operating closed loop the phase of the signal at the remote end of the line will correspond to phase of the reference signal.

In long lines, the optical carrier is significantly attenuated, and the level of phase noise φ_n in the transmitted signal increases and its frequency instability increases. Therefore, for lines longer than 100 km it is imperative to use intermediate optical amplifiers. Since in two-way transmission systems with compensation reference signals are transmitted in both directions, it is necessary use bidirectional optical amplifiers. Performing their useful role, optical amplifiers simultaneously introduce additional noise into the fiber-optic line, which affects the frequency instability of the signal delivered to the end of the line. Since bidirectional amplifiers have optical inputs and outputs combined in one optical connector, this imposes additional requirements on the level of return reflections in the line so that the two-way reference frequency transmission system does not go into self-excitation mode.

In the present work, measurements with 200 km lines were performed using one intermediate bidirectional optical EDFA amplifier, which was installed approximately in the middle of the total length of the line. Measurements with 85 km line [8], which are represented as an example of scheme, working with/without electronic compensation system, in Fig. 3 and Fig. 4, were performed without using an optical amplifier.

By using Symmetricom 5125A Allan deviation of 100 MHz signal relatively to a reference signal of 100 MHz was determined at the output of 85 km line at different averaging intervals without compensation (see Fig. 3). The upper edge of the gray areas in Fig. 3 and Fig. 4 corresponds to a level of resolution of the measurer 5125A.

Fig. 4 shows the results of measurements with the analyzer/measurer of instability Symmetricom 5125A of the Allan deviation of signal of 100 MHz at the output of 85 km fiber optic link relatively to a reference signal of 100 MHz when using active electronic compensation at different averaging intervals.

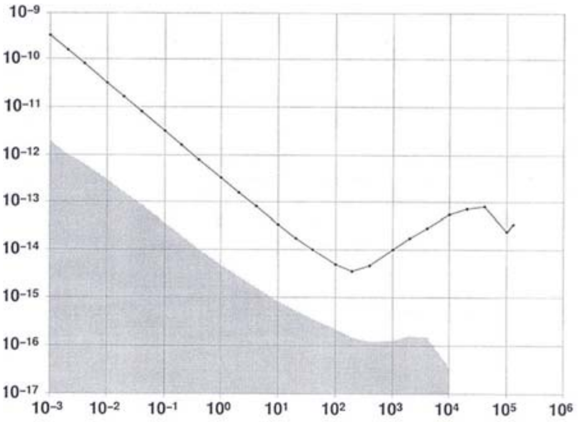

Fig. 3. Allan deviation of signal of 100 MHz, transmitted to the remote end of 85 km fiber link. The abscissa indicates the time of averaging in seconds.

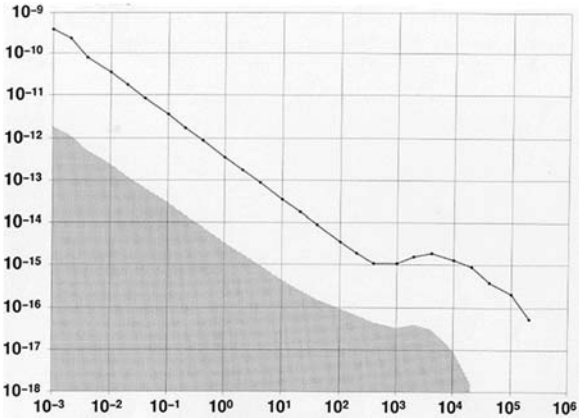

Fig. 4. Allan deviation of signal of 100 MHz, transmitted to the remote end of 85 km fiber link with electronic compensation system. The abscissa indicates the time of averaging in seconds.

Comparison of the results in Fig. 3 and Fig. 4 shows that the transmission error for averaging intervals more than one day is reduced by about two orders of magnitude by using a system of electronic compensation of a reference signal perturbations introduced by 85 km of fiber-optic line.

Fig. 5 shows the results of measurements with the analyzer/measurer of instability Symmetricom 5125A of the Allan deviation of signal of 100 MHz at the output of 200 km fiber optic link relatively to a reference signal of 100 MHz when using active electronic compensation at different averaging intervals.

The performed measurements confirmed Allan deviation (ADEV) of the frequency of reference 100 MHz signal, added by optical fiber link, km lies within the range $(1\div2)\cdot10^{-17}$ on tau $4\cdot10^{5}$ s for distance up to 200 km, when using special compensation systems and one intermediate bidirectional optical EDFA amplifier [9].

The transmitted reference signal is sent to auxiliary generator (AG), which generates time stamps and controls their phase, and can also set the output frequency detuning.

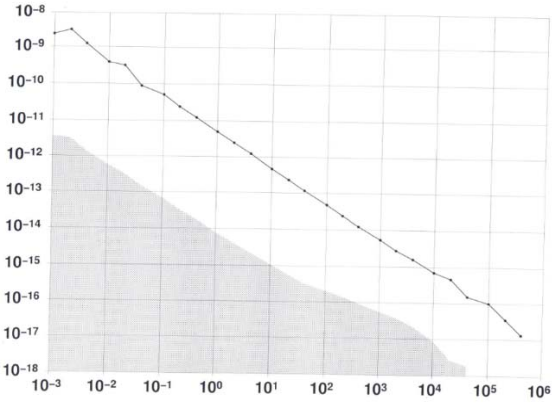

Fig. 5. Allan deviation of signal of 100 MHz, transmitted to the remote end of 200 km fiber link with electronic compensation system, using an optical amplifier. The abscissa indicates the time of averaging in seconds.

4. Time Scales Comparison System

To determine the transmission accuracy of 1 PPS signal, the setup was assembled according to the scheme shown in Fig. 6. One of advantages of this scheme is using of one optical fiber and the same optical signal in both ways. This allows to the use of fiber communication lines leased from operators (so-called dark fibers).

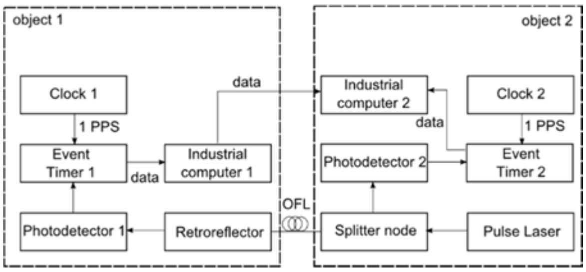

Fig. 6. Functional scheme of system of time scales comparison.

The time interval between the transmitted 1 PPS signal and the reference one is carried out by system of time scales comparison (STSC) [10-11]. The system consists of two separated parts located on different objects. The 1 PPS signals of the compared time scales (reference and remoted) are received at the system input at these object 1 and object 2 (operational principle is shown on Fig. 7).

The operation principle of STSC is following. The pulse laser forms a sequence of pulses. Each optical pulse passes through splitter node, where a small part of the optical pulse power enters the photodetector 2 of object 2 (which consists of a photodetector, amplifier and electronic signal converter). The main part of the pulse's power enters fiber optical link. The electrical signal from the photodetector 1 is fed to the event timer 2 (ET), which measures the moment of time, when pulse is transmitted to the OFL in the time scale (TS) of the object 2 (t_1).

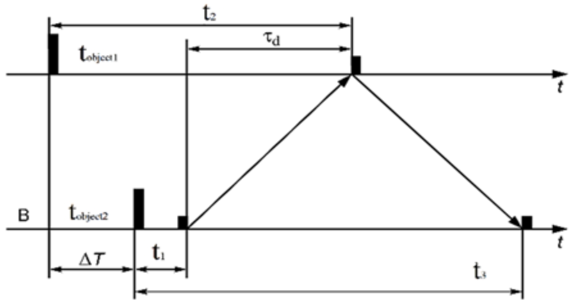

Fig. 7. Time diagram of STSC operation.

The optical pulse, which came through the OFL to object 1 with a certain time delay τ_d, passes through a semitransparent mirror (retroreflector) into the photoderector 1, which converts it into an electrical signal, which is fed to Event Timer 1, which measures the arrival time of the optical pulse in the TS of object 1 (t_2).

Part of the optical pulse's power, which came to object 1, is reflected from the semitransparent mirror and passes along the communication line the opposite way. With a time delay strictly equal to the delay τ_z in the line during the direct passage, the reflected pulse comes through the splitter node and is registered by the photodetector 2 of object 2. The signal from the photoderector is fed to ET2, which measures the time of arrival of the reflected pulse in the TS of object 2.

The computers that process the information are connected to the local network via fiber optic links using Fast Ethernet media converters. Information from the ET1 is transmitted to computer at object 2 via the local network to calculate difference of time scales.

The uncertainty type A of time scales difference depends on jitter of laser, photodectors, time interval counters, it can be decreased meaning n measurements during second measurement cycle.

Time difference can be calculated using the equation:

$$\Delta T = \frac{1}{n}\sum_{i=1}^{n}\left(t_{2i} - \frac{t_{1i}}{2} - \frac{t_{3i}}{2} + \tau_s\right), \qquad (3)$$

where τ_s is the setup correction.

Setup correction is the resulting delay asymmetry of signal propagation in STSC (in splitter node, coaxial cables and etc.).

Setup correction can be measured using scheme on Fig. 2, but equipment from object 1 and 2 should be placed in the same place and using one clock's reference and time signals. The results of experimental measurement of τ_s are shown in Fig. 8.

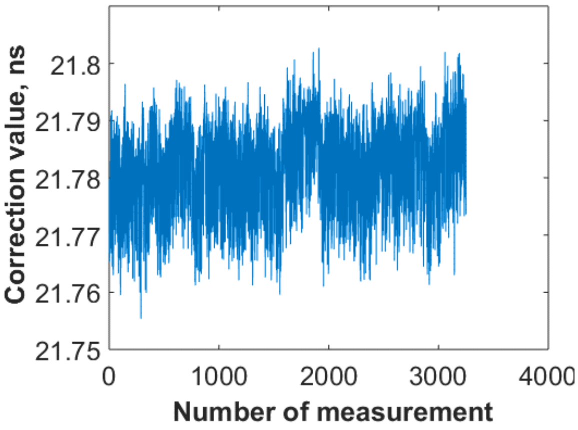

Fig. 8. Measurement results of correction value.

The whole system was tested during the experiment, in which the equipment for transmission of time scales was installed in one rack. Two fiber bays with a length of 3 km were used as OFL.

During measurements the environmental parameters were controlled using the weather station. The temperature variation was ± 2 °C.

The measurement results of time scale transfer were obtained with SRFTST software (Fig. 9) [12]. Based on the measured variance of the reference and transmitted time scales, an amendment was calculated and the control command was applied to auxiliary generator in real time.

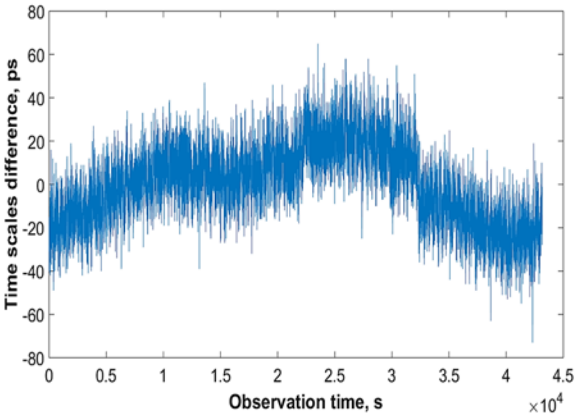

Fig. 9. Result of time scales comparison.

5. Uncertainty Budget of Time Scales Comparison System

The uncertainty type A of the time interval measurement between transmitted and reference time scales is 17 ps (σ).

The sources of Type B uncertainty are: the trigger uncertainty of the event timer counter; the uncertainty in determining the instrumental correction θτ; the correction uncertainty, accounting the effect of attenuation and dispersion in the optical fiber of the pulse's front θ_p; the uncertainty due to the long-term (for 1 year) frequency instability of the reference generator θs, the uncertainty due to the fiber temperature variations θ_T.

The trigger uncertainty due to manufacture's data doesn't exceed 5 ps. The correction uncertainty doesn't exceed 6 ps.

The fiber delay change due to temperature variations in real optical fiber link was measured (Fig. 10).

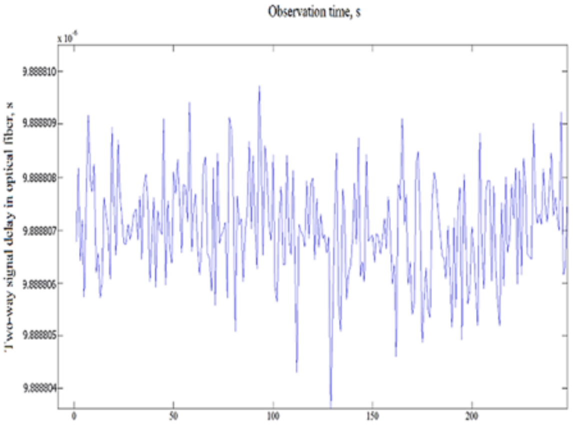

Fig. 10. Two-way signal delay in OFL.

As it can be seen from graphics – measurements uncertainty due to delay variations (temperature is maintained ± 2 °C).

The contribution of the generator instability of the is not more than 10^{-11} when measuring fiber optic to 100 km it is less than units of ps, so it can be ignored.

The type B measurements uncertainty estimation does not exceed 55 ps. The combined standard uncertainty of time scales transmission does not exceed 72 ps.

6. Conclusions

Thus, the work experimentally confirmed the possibility of implementing a system for transmitting time scales via OFL with combined standard uncertainty of no more than 80 ps (while maintaining the temperature at objects within ± 2 °C). The combined standard uncertainty of time scales transfer can be reduced to 30-40 ps if the thermal stabilization of SRFTST devices will be not worse than ± 0.2 °C.

The performed measurements confirmed Allan deviation (ADEV) of the frequency of reference 100 MHz signal, added by optical fiber link, km lies within the range $(1\div2)\cdot10^{-17}$ on tau $4\cdot10^{5}$ s for distance up to 200 km, when using special compensation systems.

References

[1]. Piester D., Rost M., Fujieda M., Feldmann T., Bauch A., Remote atomic clock synchronization via satellites and optical fibers, *Adv. Radio Sci.*, Vol. 9, 2011, pp. 1–7.

[2]. Michito I., Tomonari S., Tadahiro G., Yasuhisa S., Fumimaru N., Yoshiyuki S., Noriyuki K., Two Way Satellite Time and Frequency Transfer, *Journal of the National Institute of Information and Communications Technology*, Vol. 50, Issue 1/2, 2003, pp. 125-133. http://www.nict.go.jp/publication/shuppan/kihou-journal/journal-vol50no1.2/0403.pdf

[3]. Fujieda Miho, Kumagai Motohiro, Nagano Shigeo, Ido Tersuya, Frequency transfer using Optical Fibers, *Journal of National Institute of Information and Communications Technology*, Vol. 57, Issue 3/4, 2010, pp. 209-217.

[4]. Grosche G, Terra O., Predehl K., Holzwarth R., Lipphardt B., Vogt F., Sterr U., Schnatz H., Optical frequency transfer via 146 km fiber link with 10^{-19} relative accuracy, *Optics Letters*, Vol. 34, Issue 15, 2009, pp. 2270-2272. https://arxiv.org/ftp/arxiv/papers/0904/0904.2679.pdf

[5]. Jefferts S. R., Weiss M. A., Levine J., Dilla S., Bell E. W., Parker T E., Two-Way Time and Frequency Transfer Using Optical Fibers, *Transactions on Instrumentation and Measurement*, Vol. 46, Issue 2, April 1997, pp. 209-211.

[6]. Rost M., Piester D., Yang W., Feldmann T., Wübbena T., Bauch A., Time transfer through optical fibers over a distance of 73 km with an uncertainty below 100 ps, *Submitted to Metrologia*, August 2012, pp. 1-13. https://arxiv.org/ftp/arxiv/papers/1209/1209.4467.pdf

[7]. W. J. Riley, Handbook of frequency stability analysis, NIST Special Publication 1065, *U. S. Government Printing Office*, Washington, 2008.

[8]. Fedorova D. M., Malymon A. N., Balaev R. I., Kurchanov A. F., Troyan V. I., Using of optic fiber links for reference frequency transmission over a distance up to 85 km, *Physics Procedia*, Vol. 72, 2015, pp. 227-231.

[9]. Balaev R. I., Malimon A. N., Fedorova D. M., Kurchanov A. F., Troyan V.I., Estimation of the precision of transmission of the standard signal of a hydrogen oscillator along a fiber-optic communication line with electronic compensation of disturbances, *Measurement Techniques*, Vol. 60, Issue 8, 2017, pp. 806-812.

[10]. Kolmogorov O. V., Shchipunov A. N., Prokhorov D. V., Donchenko S. S., Buev S. G., Malimon A. N., Balaev R. I., Fedorova D. M., System for transmitting reference frequency and time signals to measurement resources of the glonass ground complex by optical cable, *Measurement Techniques*, Vol. 60, Issue 9, 2017, pp. 901-905.

[11]. Donchenko S. S., Kolmogorov O. V., Prokhorov D. V., A system of one- and two-way comparisons of time scales, *Measurement Techniques*, Vol. 58, Issue 1, 2015, pp. 18-22.

[12]. Donchenko S. S., Kolmogorov O. V., Prokhorov D. V., System of reference frequency and time scales transmission via optical fiber, *Proceedings of the 2nd International Conference on Optics, Photonics and Lasers (OPAL' 2019)*, Amsterdam, The Netherlands, 24-26 April 2019, pp. 80-82.