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TESTING TIME AND FREQUENCY FIBER-OPTIC LINK TRANSFER BY HARDWARE EMULATION OF ACOUSTIC-BAND OPTICAL NOISE

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Abstract

The low-frequency optical-signal phase noise induced by mechanical vibration of the base occurs in field-deployed fibers. Typical telecommunication data transfer is insensitive to this type of noise but the phenomenon may influence links dedicated to precise *Time and Frequency* (T&F) fiber-optic transfer that exploit the idea of stabilization of phase or propagation delay of the link. To measure effectiveness of suppression of acoustic noise in such a link, a dedicated measurement setup is necessary. The setup should enable to introduce a low-frequency phase corruption to the optical signal in a controllable way. In the paper, a concept of a setup in which the mechanically induced acoustic-band optical signal phase corruption is described and its own features and measured parameters are presented. Next, the experimental measurement results of the T&F transfer TFTS-2 system's immunity as a function of the fibre-optic length vs. the acoustic-band noise are presented. Then, the dependency of the system immunity on the location of a noise source along the link is also pointed out.

Keywords: Time and Frequency fiber-optic transfer, phase noise in optical fiber, timing jitter, fiber-optic transmission.

1. Introduction

In long-distance *Fiber-Optic* (FO) links, the phenomenon of low-frequency optical-signal phase noise may be observed. Especially, the clear phenomenon occurs when an FO cable runs along highways or railways [1]. Typical telecommunication data transfer is insensitive to this type of noise, but it may influence precision of dedicated FO transfer of the metrological reference signal. In several recently published papers on the fiber-optic T&F transfer, the low-frequency acoustic-band optical phase noise has been reported [2, 3]. An example of such a phase noise spectrum is shown in Fig. 1. It was calculated from the measurement of experimental FO transmission of the frequency reference in field-deployed FO cables. The measurement was performed for the ca.100 km fiber-optic cable installed along the rail track between Kraków and Wadowice [1]. In the time domain, the received signal displayed the phase noise in a form of jitter. A very good agreement between the noise and the railway timetable was observed, thus confirming that the noise is induced mechanically, as described in [4]. The phase noise spectrum is mainly located in the low acoustic-band frequencies and the spectrum curve shows a visible bump of around tens of Hz [3]. The above described phenomenon indicates that for modeling and practical application of the T&F transferring systems knowing their low-frequency response may become significant. The measurements of transfer stability (Allan, time deviation *etc*.) are time-consuming and do not give answers on effectiveness of the acoustic phase noise suppression.

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The resistance of the *Fiber-Optic T&F* transfer system to the phase noise results directly from the low-frequency response of the system. As a coarse tool analytical modeling [10] may be used, but the final verification requires the hardware measurement.

The aim of building a laboratory setup was to obtain the possibility to introduce the phase modulation to the *Intensity Modulated* (IM) optical signal. The setup enables to measure, quantitatively characterize and further optimize the low-frequency response of the *Fiber-Optic T&F* transfer system.

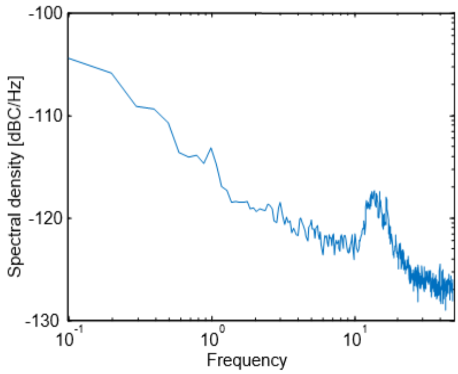

Fig. 1. An example of the acoustic-band optical phase noise spectrum.

2. A concept of the phase-modulated signal

We decided to build a setup in which a continous harmonic phase modulation of the IM optical signal with a low-frequency modulating sinusoid would be generated.

The basic technical assumptions were as follows:

- to use a narrow-band harmonic phase modulation;
- to employ the optical way length modulation by stretching a piece of standard single mode fiber as the method of optical-signal phase modulation.

According to the theory of modulation [5], the approximated formula for the harmonic narrow-band phase-modulated signal is:

$$a(t) \cong A_0 \sin 2\pi f_0 t + A_0 \frac{\Delta\phi}{2} \sin 2\pi (f_0 + f_m) t - A_0 \frac{\Delta\phi}{2} \sin 2\pi (f_0 - f_m) t, \qquad (1)$$

where: f_0 is the frequency of transferred signal, which may be interpreted as the carrier; f_m is the modulating signal frequency; and $\Delta\varphi$ is the phase deviation. To keep the narrow-band condition [5], the deviation should meet the condition:

$$\Delta\phi \leq 0{,}3\, rad. \qquad (2)$$

For the complete description of the modulation effect, it is sufficient to specify the peak level of side lines. By changing the modulation frequency we can obtain a series of signals which - point by point - may serve to measure the frequency response of the band-pass filters, *Phase-Locked Loops* (PLL) or *Delay-Locked Loops* (DLL).

3. The fiber stretcher

The essential part of the measurement setup is the fibre stretcher. A block diagram of the stretcher is shown in Fig. 2.

It uses a 270 cm long piece of SMF-28 type bare fiber folded in half and suspended on the support. At the bottom, both fibre ends are fixed together and fastened to a violin string. The second end of the string is hooked to a type 4809 Bruel-Kjaer Vibration Exciter [6]. To ensure the return movement of the fibre, a preliminary tension is applied. The combination of fibers and string is pulled and stretched by the exciter which vibrates vertically. The vibration is proportional to the amplitude of the electric driving signal delivered from the type 2706 Bruel-Kjaer Power Amplifier. The modulating sinusoid is generated by the function generator.

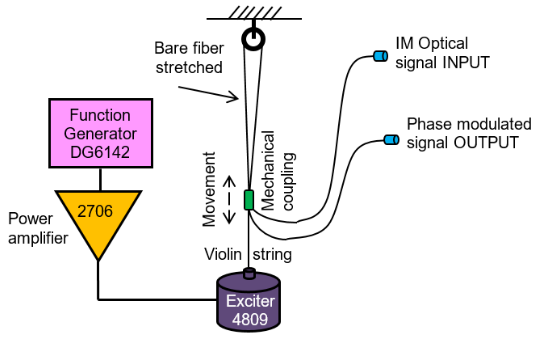

Fig. 2. A block diagram of the fibre stretcher.

As the result, stretching the fibre modulates the length of optical way and thus the time delay of the optical signal propagating along the fibre. The modulating frequency was selected from the range between 5 Hz and 80 Hz. We also assumed that the optical signal propagating in the stretched fibre would be a sine-wave IM optical signal of the frequency f_0 = 10 MHz. The mechanically induced time-delay increment Δt modulates its phase with the deviation:

$$\Delta\phi = 2\pi\ f_0\ \Delta t. \tag{3}$$

We also predicted that the combination of the taut fibre with the violin string may exhibit many undesired transversal resonances, so to get rid of them the whole vertical part of the stretched section of the fibre was wrapped in a sponge tube with the cotton wool filling. The suppressor effectively reduced all transversal vibrations not disturbing the longitudinal stretch of the fibre.

4. Modulation parameters and calibration

Before starting the measurements we had to establish the setup basic operation parameters, such as the modulating frequency range and the phase deviation. After some preliminary tests of the exciter we decided to operate within the modulation frequency range from 5 Hz to 80 Hz.

Next, the length of stretching, and thus the value of phase deviation had to be established. According to [7], to avoid breaking the fibre, the stretch length should not exceed one percent of the total stretched fibre length. The upper limit is also due to the capability of the used exciter. We assumed stretching the fibre by a few millimetres, and checking the result of it by carrying out the measurements in the time and frequency domains.

Both mentioned parameters can be controlled by the DG4162 function generator. The phase deviation depends on the amplitude of modulating signal. The higher amplitude, the longer the stretch length, and thus the time delay and the phase deviation.

To calibrate the stretcher we created the experimental setup, as shown in Fig. 3. The simplex FO link transmitting the reference 10 MHz sine-wave, the stretcher and two 2 m long patchcords in the optical path have been used. To improve the signal to noise ratio in the received and modulated signals, an X100 frequency multiplier was applied.

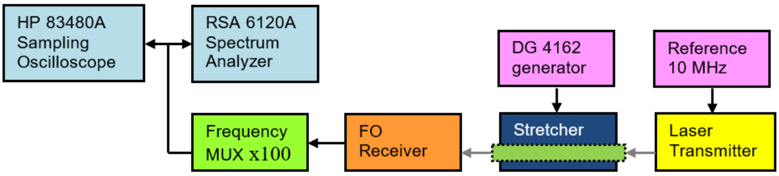

Fig. 3. The first setup.

The output signal slope position histogram and the spectrum of received signal, when phase-modulated with the frequency of 5 Hz, are shown in Fig. 4. The histogram is typical for the sinusoidal modulation and shows two peaks with the approximate time deviation of a little below 20 ps. It means that the fiber was stretched by about 4 mm. Using (3) we also checked that the deviation meets the condition (2). The record also showed that, using an HP83480A sampling oscilloscope, we can measure the value of deviation with a limited precision which results from both the noise component and the histogram time quantization error, introduced by the oscilloscope.

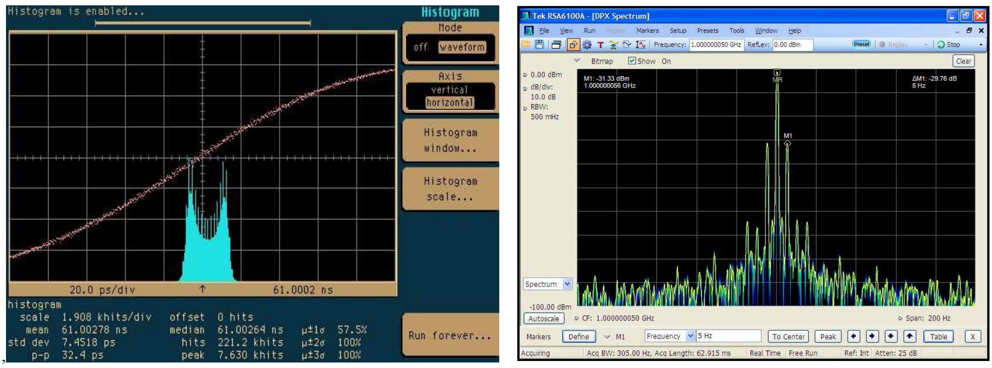

Fig. 4. The modulated signal histogram (left) and the spectrum (right).

A better precision of the measurements is achievable in the frequency domain. In accordance to (1), the measured spectrum shows the central spectral line of transmitted 10.00000056 MHz reference signal frequency multiplied by 100 what gives the frequency of 1.000000056 GHz, and two symmetrical spectral side lines with frequencies of 1.000000051 GHz and 1.000000061 GHz as the result of phase modulation. The peak levels of both spectral side lines are equal and may be controlled by the modulating signal amplitude.

In the first measurement, the modulating 5 Hz signal at the input of the exciter was set at 1.21 V RMS and under these conditions the measured peak level of spectral side lines was equal to –30 dBc ±0,5 dB.

It was necessary to calibrate the stretcher driving voltages for the range of frequencies from 5 Hz to 80 MHz. To maintain a constant effect of modulation and keep the side line peak level at –30 dBc ±0.5 dB, the exciter driving RMS voltage increases when increasing the modulating signal frequency. The results are shown in the calibration table (Table 1).

Table 1. The stretcher driving voltage calibration table.

f_{mod} [Hz]	5	10	15	20	25	30	35	40
U [V_{rms}]	1.21	1.53	1.84	2.12	2.42	2.77	3.10	3.38

f_{mod} [Hz]	45	50	55	60	65	70	75	80
U [V_{rms}]	3.66	4.33	4.57	4.95	5.37	5.85	6.38	6.86

The spectrum of the modulated optical signal shows also other higher order modulation and noise products but their levels are low enough to neglect their impact on the measurement results.

5. Tests with the T&F Transfer System TFTS-2.

After calibration, the measurement setup has been used to research the low-frequency response of the dedicated *T&F Transfer System* TFTS-2 developed in our laboratory [8, 9].

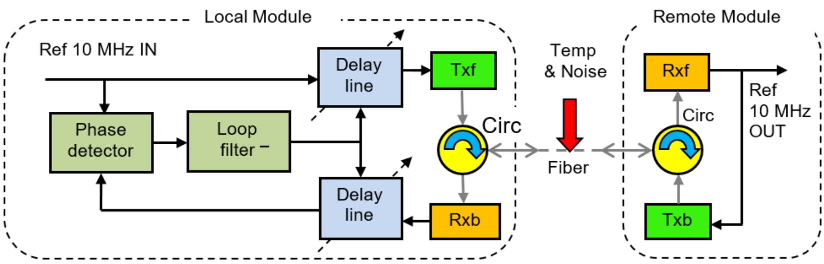

Fig. 5. A simplified block diagram of the TFTS-2 system.

A general block diagram of the T&F transfer system TFTS-2 is shown in Fig. 5. The system consists of two modules: Local Module and Remote Module, which are playing, respectively, the role of transmitter and receiver of the transferred 10 MHz reference signal. Both modules are connected with one fiber, in which the signal is transferred in both directions at a time. The signal received in Remote Module is then back-transmitted to Local Module, and there compared - by the phase detector - with the original reference. The result of phase comparison controls the matched Delay lines. When the loop (DLL) is locked, the system tracks and stabilizes the time delay between the Local Module input and the Remote Module output. The primary task of the system was to compensate the thermal fluctuation of time delay in the fiber, but – by the way – the loop compensates also the low-frequency noise generated in the fiber [8, 10].

We decided to check the immunity of TFTS-2 [8, 9] to the low-frequency phase noise generated in the fiber for 3 different distances.

First, we replaced the simplex transmission link shown in Fig. 3 with the TFTS-2 transfer time stabilizing link. Local Module was installed instead of Laser Transmitter and, respectively, Remote Module – instead of FO Receiver. The length of the fiber including the stretcher was about 7 m. Next, we tested the TFTS-2 link with a 50 km fiber spool inserted between Local Module and the stretcher. A schematic diagram of this experiment is shown in Fig. 6.

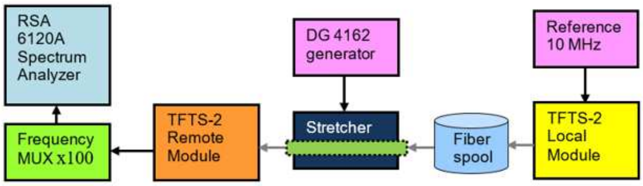

Fig. 6. Testing the TFTS-2 system with 50 km of fibre.

The spectra of the transferred reference signal have been measured in the presence of optical signal modulation by the stretcher. Selecting the modulating frequencies from the range between 5 Hz and 80 Hz, we could calculate the low-frequency phase-noise suppression frequency characteristics of TFTS-2 link for different distances. The suppression curves are shown in Fig. 7.

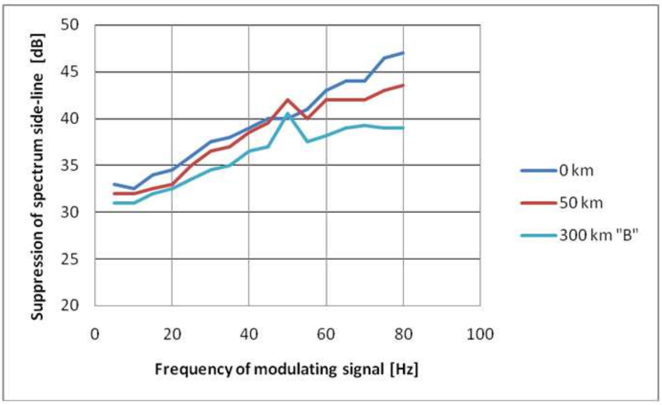

Fig. 7. The low-frequency noise suppression in TFTS-2 links.

All suppression curves have a similar characteristic and display the growth of suppression of spectrum side lines in a function of the modulating signal frequency. The highest suppression and sharpest slope is displayed by the shortest link. The 300 km link suppresses least, but in general the suppression of the spectrum side lines within the whole considered low-frequency bandwidth is better than 30 dB. For the 50 Hz modulating frequency, curves for 50 km and 300 km links show some irregularity caused by low levels of measured signals and the disturbing presence of the mains spectral line.

The last measurements were done with the long-haul 300 km link equipped with five specially developed erbium-doped fiber amplifiers, called Single Path Bidirectional Amplifiers (SPBA) [9], installed every 50 km. First, the long-haul link experiment was done in configuration "B". The 300 km link was inserted between Local Module and the stretcher, as shown in Fig. 8.

In the last setup, the 300 km link was switched between the stretcher and Remote Module to the placement X – configuration "A".

A very interesting relation may be observed between two suppression curves in configurations "B" and "A". Both curves shown in Fig. 9 are of the same type, but the one obtained in configuration "B" is shifted upwards related to the other. The effectiveness of suppression for configuration "B", where the stretcher is close to Local Module, is about 6 dB better than for configuration "A", where the stretcher is close to Remote Module. This phenomenon can be explained by the DLL theory [10]. The transmittance of the loop for the corrupting signal depends on the location of the corrupting source. The suppression ranges from 24 dB to 40 dB.

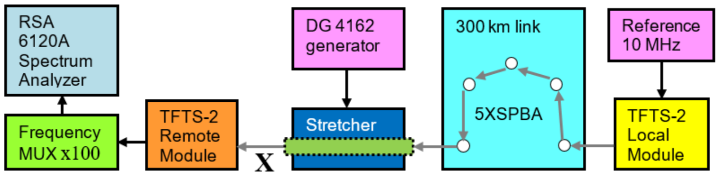

Fig. 8. Testing the TFTS-2 system with a long-haul link – in configuration "B".

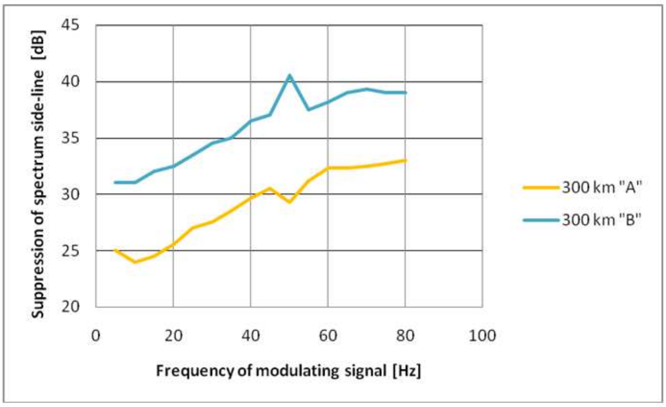

Fig. 9. The suppression curves for long-haul OSTT-2 links in configurations "A" and "B".

6. Conclusions

The concept of generating a harmonically phase-modulated signal is based on the natural springiness and elasticity of typical telecommunication optical fibers. We show that by slight stretching a fiber with a low-frequency vibration it is possible to generate a special phase-modulated optical test signal. We also show that it can be employed as a dedicated means to characterize immunity of specialized T&F transfer systems to the low-frequency phase noise observed in long-haul FO links. As an example, some basic tests of the TFTS-2 system operating at different distances are presented.

The system effectively suppresses the spectrum side lines for the modulation frequencies within the range from 5 Hz to 80 Hz. It means that the TFTS-2 should also exhibit effective immunity to the real phase noise which may happen in field-deployed FO links.

A very interesting remark arise from the dependence of suppression on the stretcher location. It is shown that the suppression effectiveness depends stronger on the location of the noise source along the link than on the link length.

Acknowledgement

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