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Short-haul fibre-optic communication link with a phase noise compensation system for optical frequency signal transmission

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Abstract. **A 5-m-long fibre link with a phase noise compensation system for optical frequency signal transmission at a wavelength of 1.14 μm is demonstrated. The stability of the noise compensation system in the presence of harmonic mechanical perturbations is assessed and the relative transmitted signal frequency instability is shown to be 3.8×10^{-15} at an averaging time of 1 s and 3.5×10^{-20} over 850 s.**

Keywords: *fibre-optic communication links, frequency signal transmission, phase noise compensation.*

1. Introduction

In the last decade, progress in the technology of optical frequency standards has led to rapid advances in frequency and time metrology, as well as in many other areas of modern basic and applied physics. The relative uncertainty and instability of modern optical clocks has been reduced to a few parts in 10^{18} [1, 2], which opens up new possibilities for satellite navigation and geodesy and makes it possible to test fundamental theories at a new level of accuracy [3]. Concurrently, studies have been initiated to improve methods for transmitting highly stable frequency signals, which would allow a required stability level to be reached in a short time.

The most widely used satellite-based methods for the transmission of highly stable signals (GPS and TWSTFT) enable frequency signal transmission with a relative instability at a level of 10^{-16} at an averaging time of the order of 24 h [4, 5]. This is insufficient for maintaining stability of frequency signals of modern optical clocks in the case of long-haul transmission.

One promising approach to the transmission of highly stable frequency signals is to use optical fibres. Recent work has demonstrated radio frequency signal transmission using amplitude modulation of a cw laser output with a relative instability of 5×10^{-15} at an averaging time of 1 s [6] and the transmission of femtosecond laser pulses with a relative instability of 4.6×10^{-15} [7] over distances of up to 100 km. At the same time, the highest frequency signal transmission stability has been reached using information about the phase of the carrier, which has made it possible to increase the transmission distance to 1000–2000 km [8, 9] without impairing the stability of the signal.

At present, intensive research effort is concentrated on producing a network of fibre links between European institutions, which would allow one to compare different frequency standards and use them in various applications [3, 10]. An important step was the transmission of highly stable frequency and time signals over commercial links used for Internet traffic [11] and the advent of open optical frequency signal transmission channels, e.g. through satellites [12].

A key technology underlying optical frequency signal transmission over fibre-optic communication links is the compensation for the phase noise accumulated by the propagating signal. In particular, refractive index fluctuations caused by temperature changes and acoustic vibrations give rise to optical path length fluctuations and, as a consequence, to phase noise [13]. Such noise, referred to as Doppler noise, should be detected and compensated for.

Researchers at the Department of Spectroscopy, P.N. Lebedev Physical Institute (LPI), Russian Academy of Sciences, focus on creating a frequency reference based on an ensemble of cold thulium atoms [14]. To transfer the high stability of a reference cavity (with a relative frequency instability of 2×10^{-15} at averaging times of up to 100 s) [8] to an atomic ensemble being interrogated, we produced and characterised a 5-m-long fibre link with a phase noise monitoring and compensation system. In this paper, we describe this link and report a study of the stability it ensures for optical frequency signal transmission at a wavelength of 1.14 μm. A similar link can be used for highly stable optical signal transmission to other laboratories in order to compare different frequency standards.

2. Experimental setup

Figure 1 shows a schematic of the experimental arrangement. Phase noise in the fibre is detected using autodyning. The beam of a Toptica DL-100 cw diode laser emitting at a wavelength of 1.14 μm is split into two using a half-wave plate and polarising beam splitter. One part of the beam is used as a reference and is directed through the short arm of the interferometer. The other part passes the fibre link in both directions, being reflected from the mirror at the far end. This beam contains doubled noise of the fibre link. The frequency of this beam is shifted by 58 MHz after it passes twice through the acousto-optic modulator (AOM). The reference beam and the beam that passed through the fibre combine in the polarising beam splitter. Next, the beat signal at the difference fre-

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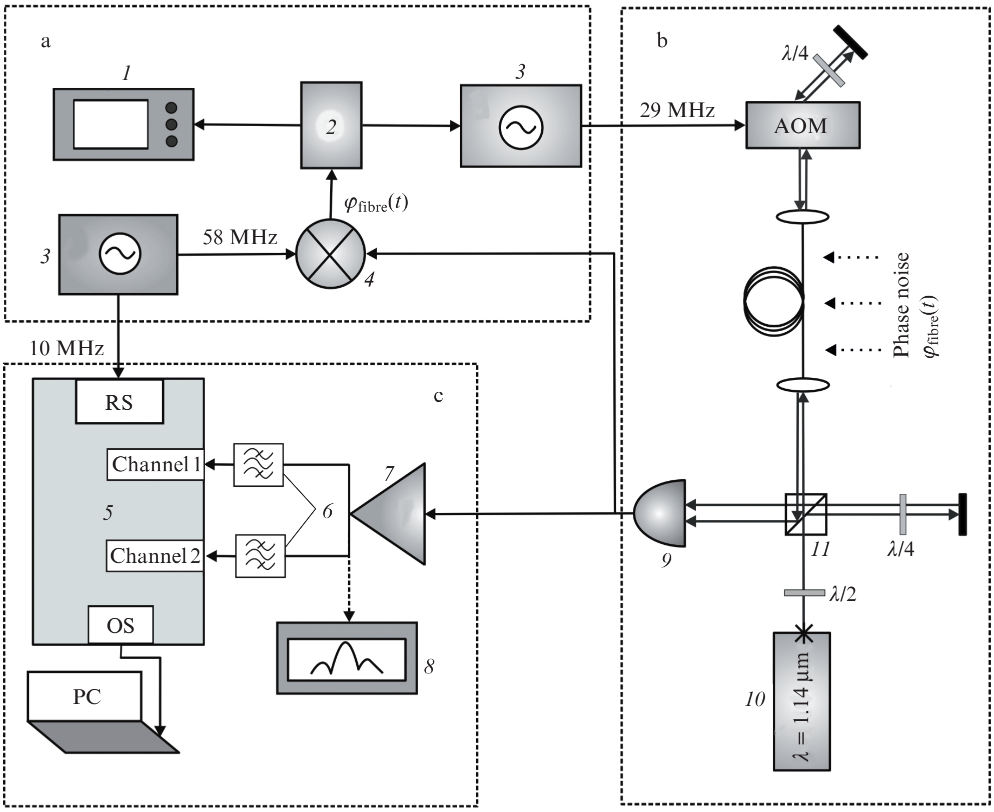

Figure 1. Schematic of the experimental setup for phase noise detection and compensation in fibre, comprising (a) a feedback loop, (b) optical scheme and (c) transmitted signal stability measuring system: (*1*) oscilloscope; (*2*) proportional–integral amplifier; (*3*) oscillator; (*4*) phase detector; (*5*) counter; (*6*) passband filters; (*7*) amplifier; (*8*) spectrum analyser; (*9*) photodetector; (*10*) laser source; (*11*) polarising beam splitter; (AOM) acousto-optic modulator; (RS) reference signal; (OS) output signal; (PC) personal computer; (λ/2) half-wave plate; (λ/4) quarter-wave plate.

quency (58 MHz) is detected by a photodetector. One part of the signal from the photodetector is used in the feedback loop for noise compensation, and the other part is amplified and fed to a frequency counter for assessing signal stability.

That part of the signal used for noise compensation and the reference signal from an oscillator at a frequency of 58 MHz are fed to a phase detector. The error signal at the output of the detector is proportional to the phase difference between the input signals and is used to produce a servo signal in a proportional–integral amplifier. The band of the proportional–integral amplifier should exceed the band of frequencies to be compensated for. We used a single-stage amplifier with a 100-kHz bandwidth, made in our laboratory and similar in many respects to an SRS SIM960 commercially available amplifier. The servo signal is fed to a voltage-controlled oscillator, which in turn controls the AOM frequency. The AOM frequency is adjusted so as to maintain the error signal at zero, thus compensating for the noise originating from the fibre link.

The beat frequency is measured using a dead-time free multichannel Π-type counter (without internal averaging), which allows signal stability to be characterised using the Allan deviation. Additional information about the types of phase noise in the transmitted signal can be obtained by using a Λ-type counter. For synchronisation, a 10-MHz signal from the oscillator used to generate the error signal is fed to the reference input of the counter. The beat frequency (58 MHz) was chosen to be not a multiple of the master frequency of the counter in order to prevent cross talk. The signal is fed to two channels of the counter through filters with different passbands, which is necessary for cycle slip detection. Coincidence of results in the two channels attests to adequate operation of the counter and reliability of the data obtained. Data containing cycle slips are left out of consideration.

To adequately detect the phase noise introduced by the fibre, the contribution of the self-noise of the laser source should be negligible, i.e. the coherence length of the light should far exceed the doubled fibre length. In experiments with a short-haul (5 m) fibre link, additional source frequency stabilisation is unnecessary. Subsequently, for noise compensation in longer haul links the transmitting laser will be additionally stabilised to a high-finesse Fabry–Perot cavity in order to increase the coherence length of the laser.

3. Frequency transfer stability

To assess frequency stability, we used the Allan variance:

$$\sigma_y^2(\tau) = \frac{1}{2}\langle(\overline{y_2(t)} - \overline{y_1(t)})^2\rangle,$$

where t is time; τ is the averaging time; and $\overline{y_i(t)} = \overline{\Delta\nu_i(t)}/\nu$ ($i = 1, 2$) are the average relative deviations of frequency ν at different averaging times [15]. For a more detailed analysis, we calculated the phase noise spectral power density (SPD) $S_\varphi(f)$, where f is the frequency of the Fourier component. In variance calculation, we used analysis with overlapping data ranges, which allows one to more effectively utilise measurement results and obtain the Allan variance at longer averaging times [16]. From the slope of a log–log graph of the Allan

Table 1. Noise contributions to frequency transfer instability [$\sigma_y(\tau)$ is the Allan deviation and $S_\varphi(f)$ is the phase noise spectral power density].

Type of noise	Frequency stability assessment	
	$\sigma_y(\tau)$	$S_\varphi(f)$
Random frequency drift	$\propto \tau^{1/2}$	$\propto f^{-4}$
Flicker frequency noise	const	$\propto f^{-3}$
White frequency noise	$\propto \tau^{-1/2}$	$\propto f^{-2}$
Flicker phase noise	$\propto \tau^{-1}$	$\propto f^{-1}$
White phase noise	$\propto \tau^{-1}$	const

deviation $\sigma_y(\tau)$ against averaging time, one can assess the contributions of different types of noise (Table 1). White and flicker phase noises lead to similar time dependences of the deviation, so a modified Allan deviation should be constructed to differentiate them [17].

The relative signal frequency instability measured for signal transmission over a 5-m-long fibre link and the phase noise SPD are shown in Fig. 2. Without noise compensation, at averaging times over 1 s we observe a significant effect of flicker frequency noise, which is probably caused by temperature variations in the laboratory. Active noise compensation makes it possible to reach a relative instability of 3.8×10^{-15} at an averaging time of 1 s and 3.5×10^{-20} over ~1000 s. In the case of the active stabilisation of the link, at averaging times shorter than 10 s the modified Allan deviation varies as $\tau^{-3/2}$, which corresponds to white phase noise. With increasing averaging time, its behaviour changes to $\tau^{-1/2}$ (white frequency noise).

4. Effect of perturbations

To verify the stability of our system to perturbations, we measured transmitted frequency signal stability for fibre exposed to mechanical stimuli at various frequencies in the range 5–120 Hz. The Allan deviation of a harmonic signal of frequency f_m is [16]

$$\sigma_y(\tau) \propto \frac{\sin^2(\pi f_\mathrm{m}\tau)}{\pi f_\mathrm{m}\tau}.$$

The data obtained in our experiment with a perturbation at a frequency f_m = 5 Hz are presented in Fig. 3. Without noise compensation, the Allan deviation has maxima at averaging times that are multiples of $1/(2f_\mathrm{m})$, which corresponds to the contribution of the perturbation. The noise spectrum has a characteristic peak at f_m. With the noise compensation system turned on, the contribution of the perturbation is significantly suppressed.

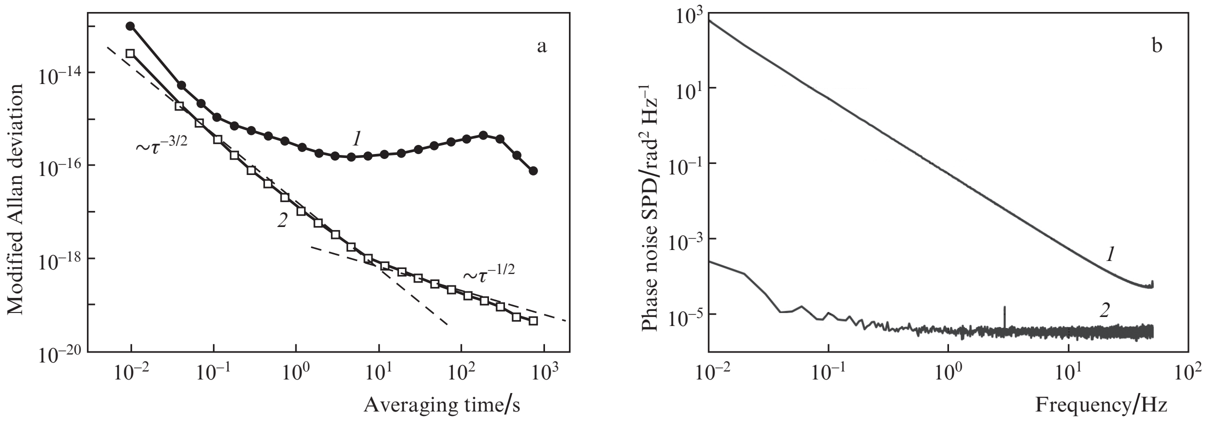

Figure 2. (a) Modified Allan deviation and (b) phase noise spectral power density for signal transmission (*1*) without noise compensation and (*2*) with active noise compensation.

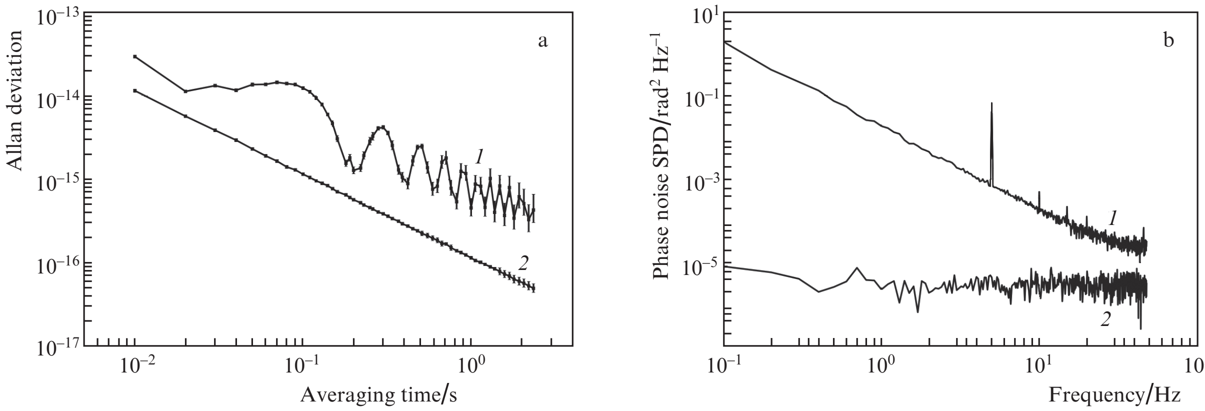

Figure 3. (a) Allan deviation and (b) phase noise spectral power density for signal transmission in the case of a mechanical perturbation at a frequency of 5 Hz (*1*) without noise compensation and (*2*) with active noise compensation.

5. Conclusions

The short-haul fibre link with an active phase noise compensation system ensures a relative optical frequency signal transmission instability at a level of a few parts in 10^{20}, which enables the transmission of ultrastable frequency signals of optical clocks within a laboratory. This is attractive for making a clock laser stabilised to a high-finesse Fabry–Perot optical cavity and for optical signal transmission to an ultracold atomic ensemble being interrogated. In the frequency range of harmonic mechanical perturbations studied here (5–120 Hz), a feedback loop allows the phase noise spectral power density to be reduced to a level of 10^{-5} rad^2 Hz^{-1}. Further work is planned to study signal transmission over long-haul links, up to 4 km in length, to produce a fibre-optic network on the LPI scale.

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