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ABSTRACT

The measurement of distances by optical techniques relies on the knowledge of the speed of light in the atmosphere, i.e. the air refractive index. The meteorological conditions must be very well-known to make measurements down to the level of 1×10^{-7} by tracking along a measurement path the ambient conditions and using them for correction methods. The relative uncertainties during measurements through the atmosphere are therefore limited by the major challenge to determine the refractive index.

A method for finding *in situ* the absolute distance and refractive index takes advantage of the dispersive characteristic of air when simultaneously measuring distances with multiple wavelengths. This approach results in much less dependence on accurate determination of atmospheric parameters and does not require their cumbersome recording via sensor networks. To measure long distances with this technique, the PTB has been developing such distance measuring interferometer systems for more than 10 years. The latest system, the so-called TeleYAG-II, has conceptually been designed to serve as a standard to disseminate the SI-unit meter over baseline distances up to 5000 m with an uncertainty below 1 mm.

INTRODUCTION

The gold standard for length measurements over hundreds of meters at baselines is still represented by the white light interference comparator proposed by VÄISÄLÄ in 1923 [1]. The fundamental scale in this comparator setup is embodied by a 1-m quartz gauge whose absolute length is determined with an expanded uncertainty of 71 nm (k=2) [2]. Taking the highly reliable Nummela Standard Baseline as an example, standard uncertainties of length measurements from 24 m to 864 m range from 44 µm to 148 µm can be achieved with this interference technique [3]. Since the length can be traced back to the definition of the meter, this method has a significant metrological advantage over other methods, such as electronic distance meters (EDM). High-precision EDMs can be calibrated at such baselines and then used as a transfer normal between different baselines. However, such interference measurements require a period of 3 months [4] and a considerable amount of manpower, which makes them hardly economically viable [5].

One objective within the European research project "GeoMetre" [6] was to improve this complex traceability chain for geodetic length measurements. Specifically, a field-capable standard was planned to be developed to disseminate the SI-unit meter over standard baselines. CNAM and PTB have developed two different prototypes that can measure long distances up to 5000 m, inherently compensating for the refractive index of air.

Inspired by EARNSHAW [7] and the predecessor TeleYAG-I developed by MEINERS-HAGEN [8], which already united large parts of the feasibility, the present work focuses on PTB's new multiwavelength interferometer. We introduce its four subsystems: laser source, optical & mechanical setup, and phase evaluation electronics. Finally, we briefly show experimental results.

MULTIWAVELENGTH LASER SOURCE

For the heterodyne interferometer concept of our TeleYAG-II system we have developed a multi-wavelength laser source, which is depicted in Fig. 1. a). The synthetic wavelengths are generated by two diode-pumped solid state (DPSS) Nd:YAG lasers stabilized on each other. Each laser unit provides two wavelengths at 1064 nm and 532 nm and an optical power of 1 W and 20 mW, respectively. Their energy efficiency, size, lifetime, robustness, coherence characteristics [9] and intrinsic noise levels, render DPSS lasers like Nd:YAG lasers ideal for the use in multi-wavelength interferometry.

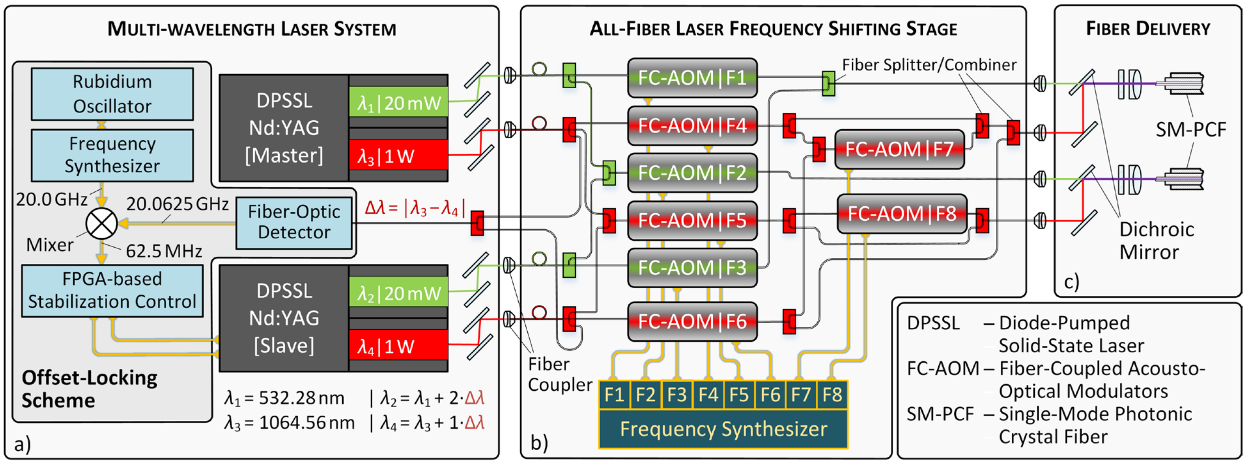

FIGURE 1. Scheme of the TeleYAG-II laser source based on two Nd:YAG lasers each with 532-nm and 1064-nm wavelength outputs. All laser wavelengths are fed into a frequency shifting stage based on fiber-coupled acousto-optical modulators to generate beat frequencies for heterodyne signal processing. Both frequency-shifted signals are superposed and are coupled into polarization-maintaining single-mode photonic crystal fibers. Both lasers are offset-locked to each other by an optical phased-locked loop (OPLL) with a tunable offset of about 20 GHz.

Both independent laser oscillators, the so-called master and slave laser, are phase-locked using their 1064-nm outputs by the well-known offset-locking technique. The heterodyned optical signal is converted into a microwave signal using a fiber-coupled photo detector (Model: New Focus 1414, Bandwidth: 25 GHz). To precisely tune the frequency offset between both phase-locked lasers, a frequency synthesizer (Model: R&S SMA-100B) with low noise characteristics (Type: R&S SMAB-B710; single-sideband (SSB) phase noise: typ. −111 dBc at 1-kHz offset), is employed as an offset stage to down convert the 20-GHz beat signal with a mixer to an intermediate frequency of 62.5 MHz. The down-mixed signal is then sampled with a sample rate of 250 MSPS by a 14-bit analogue-to-digital-converter (ADC, ADS62P49) equipped on a transceiver board (Model: NI-5782), which is connected to an FPGA-based controller (Model: NI-7935R, Kintex-7-410T). The FPGA executes an I/Q demodulation algorithm to extract the phase information from the data stream with a low latency of about 0.5 µs. The data processing is based on a 256-tap FIR filter with a 125-kHz bandwidth. Finally, the phase information is used to process two output signals with a cascaded PID control method. While a 16-bit fast DAC (Type: DAC5682Z, SFDR: 77 dB) is fed to the PZT actuator, a slower 20-bit DAC (AD5791, SFDR: 100 dB) is used to precisely control the crystal temperature. It turned out that without any averaging a stability of about 2 kHz (FWHM) can be achieved for the 20.0625-GHz beat note, which is equivalent to a relative value of 1×10^{-7}. For averaging times of 1 s, the standard deviation was reduced to be below 250 Hz.

The laser frequency shifting stage needed for the heterodyne detection of six beat frequencies was realized by a fully fiber-coupled setup, which is highlighted in Fig. 1. b). The assembly consisted of eight acousto-optical modulators (AOM) and 14 fiber splitters and combiners. The frequencies for controlling the AOM modules were generated by a synthesizer system consisting of two four-channel synthesizer boards (Model: Analog Devices EVAL-AD9959) and were then amplified with 30 dB by eight amplifiers (Model: Becker AMP590033H). After the laser light was frequency shifted and recombined, the optical power at each fiber output was measured to be 250 µW (λ = 532 nm) and 1500 µW (λ = 1064 nm).

Finally, we have implemented a laser light delivery system (see Fig. 1. c) that allowed us to superimpose two colors using dichroic mirrors and achromatic optics to couple both colors together into a polarization-maintaining (PM) single-mode (SM) photonic crystal fiber (PCF). Thus, perfect spatial co-centricity and collinear propagation direction are ensured for the two colors on the interferometer head [10].

Both, fiber-coupled shifting and delivery, provided an improved stability and handling of the optical light source compared to previous free-space versions [8].

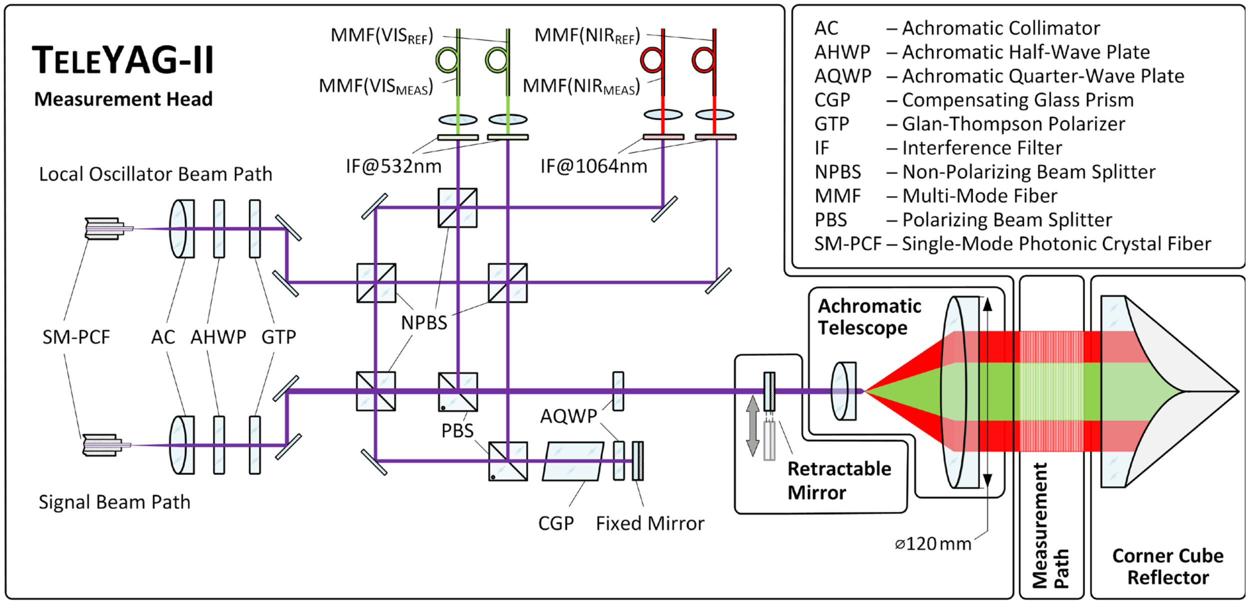

FIGURE 2. Scheme of the optical interferometer principle which was built in the measurement head to form two sub-interferometers. Two SM-PCF guide the frequency-shifted radiation of the multiwavelength laser source to the optical setup. After propagating through the optics, the beams are coupled into four multi-mode fibers to guide the interfered light to the phase evaluation electronics.

OPTICAL SETUP

The optical principle of the TeleYAG-II measurement head relies on a heterodyne interferometer with spatially separated input beams and is depicted in Fig. 2. A signal beam is divided into a reference and a measurement beam. The former beam remains in the interferometer head, while the latter one traverses the path to be measured. After being reflected at the corner cube reflector, the measurement beam propagates back to the measurement head and interferes with the local oscillator beam whose frequency is slightly shifted, in our case 1.95 MHz and 2.99 MHz for 532 nm. This highly differential interferometer principle was originally proposed by TANAKA *et al.* [11] and enables to suppress nonlinearities down to the 10-pm level [12].

Two practical problems had to be considered for the optical design of the TeleYAG-II:

(i) The light of two colors is guided to the measuring head by fibers. As a result of the joint emission out of the fibers, the beam size emerging from both fibers is almost twice as large at 1064 nm as at 532 nm. This property of an almost perfect overlap now had to be maintained during propagation through the following optical elements. Dispersion also comes into play here because the refractive index of optical elements depends on the wavelength of light and leads to a shift in focal lengths (chromatic aberration). For the optical concept, this meant that any variation in chromatic aberration between the two colors had to be avoided by using achromatic elements, see AC, AHWP, AQWP in Fig. 2. So optical components were carefully selected and anti-reflection coated for both 532 nm and 1064 nm. In summary, the lens systems were designed and manufactured specifically for the TeleYAG-II interferometer.

(ii) It is a well-known fact that laser beams do not propagate as planar wavefronts, but as Gaussian beams in curved wavefronts. An unfavorable consequence of this is that Gaussian beams cannot be collimated in the sense of linear optics, but their beam waist undergoes an easily predictable change over the propagation distance. This effect can be suppressed by choosing a large beam diameter, which was at TeleYAG-II expanded to a diameter of about 30 mm and 80 mm for 532 nm and 1064 mm, respectively. In our case, a clear diameter of 120 mm was chosen for the telescope aperture to avoid clipping up to a measurement distance up to 3500 m. We would like to point out that the alignment of the interferometer under field conditions is anything but trivial. To give an example, the distance between ocular and objective lens is crucial for the imaging properties of the laser beam expansion. To avoid significant degradation of the laser beam collimation, an alignment error of less than 100 µm must be

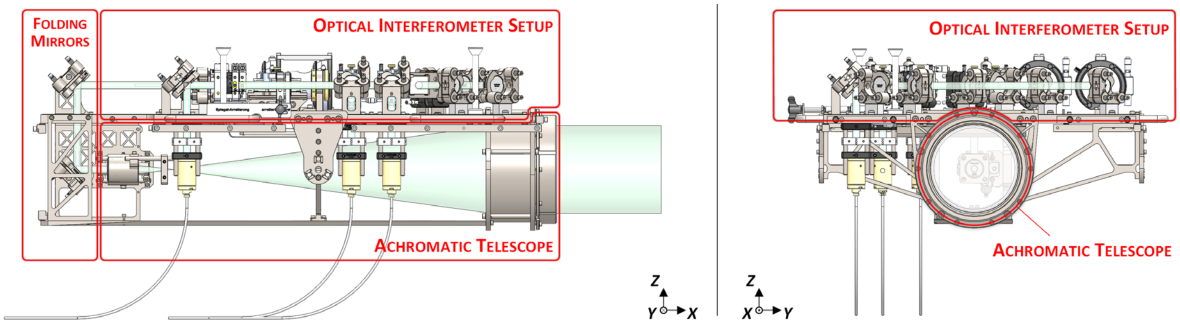

Figure 3. Scale presentation of the mechanical structure of the measurement head. The total length of the head is about 0.75 m. The head is mounted in a protective housing, which allows thermal as well as mechanical decoupling to the optical assembly. A total weight of 45 kg also includes the base for the head.

achieved and preserved under changing ambient conditions by the mechanical design to be discussed in the next section.

In addition, a retractable mirror was used within the setup to provide a mechanical reference to determine changes in the offset of the optical interferometer, such as when the geometry has changed due to thermal expansion. Future improvements in optical alignment will be achieved by using a Shack-Hartmann sensor.

MECHANICAL SETUP

The distance measuring interferometer system should be capable to operate outdoors in a temperature range of 5 °C to 35 °C, even under adverse conditions. During long range measurements, longer averaging times are essentially needed to reduce the effects of turbulence. Therefore, the mechanical design must ensure geometric stability, especially thermal stability, even over tens of minutes at the micrometer level. Also important for mechanical robustness against shock or vibration during transport and assembly was a low-stress mounting of the optical components of the interferometer to ensure long-term stability. During target acquisition and beam alignment, it must be ensured that the emitted laser light hits a retroreflector with an aperture of 127 mm. This results in an alignment accuracy of less than 0.5-arc seconds in both the horizontal and vertical axes. Finally, the weight of the instrument should allow its mounting by two people on geodetic pillars.

Thermal drift effects were minimized by using a material (FeNi36) with a low coefficient of thermal expansion (CTE, $\alpha_{\mathrm{FeNi36}} \approx 1.2 \times 10^{-6}\ \mathrm{K}^{-1}$) for all critical parts. In addition, the housing is both thermally and mechanically isolated from the optical assembly to eliminate the influence of the environment during measurement. For a better handling during transport and installation, the system was divided into two units:

1. the interferometer head including the optical interferometer setup (see Fig. 3), which was arranged in a folded sandwich structure for compactness, and
2. the base for measurement alignment. This part is compatible to standard geodetic tribrach mounts, so that it can be fixed highly reproducible on geodetic pillars to be measured.

PHASE EVALUATION ELECTRONICS

After passing through the interferometer optics, the interfered light was coupled into 200-µm multimode fibers (MMF) for delivery to the phase evaluation electronics. For each color a pair of fiber-coupled photo receivers (Model: Femto HCA-S-200M, Transimpedance: 20 kV/A) was employed to convert the optical to a voltage signal. The voltage signals contained the beat frequencies and were fed to an in-house developed phase meter (ADC board NI-5762, SNR: 75.5 dB). It was capable of single out the phase information for each carrier by applying a multi-carrier lock-in technique. Since atmospheric fluctuations have a power spectrum extending from very low frequencies up to about 500 Hz [7] the signal processing was designed in two steps. First, the incoming data stream was processed with a 512-tap FIR filters to reduce the bandwidth down to a value of 40 kHz. Second, a further averaging process enabled us to save values with a 3.8125-kHz rate. We tested our phase meter using a frequency generator (Model: Tektronix AFG3102) and measured a noise level of less than 5 pm at a 40-kHz bandwidth and a 1.95-MHz carrier frequency. In the post-processing step, the phase and power information were used to unfold the multiple wavelengths to determine the absolute value of each distance measurement.

PERFORMANCE EVALUATION

Latest TeleYAG-II measurements were conducted during a campaign in Warszawa, Poland, at a 250 m outdoor baseline together with other national metrology institutes. During those measurements mostly at night we used a meteorological station to track the relatively stable ambient conditions for redundancy coverage. The temperature changed by up to 8.4 K and the atmospheric pressure varied between 988.2 mbar to 992.6 mbar over an observation time of 29 hours.

Our measurement results were corrected using a modified Edlén method, since a visible discrepancy was found between the two colors: Significantly less scatter was observed for the 532-nm signals than for the 1064-nm signals, although the 1064-nm signal performance was comparable. However, the 532-nm data results within a time slot of 12 minutes demonstrated that the multiwavelength interferometer was capable to resolve an absolute distance over 224 m with a precision of 1.9×10^{-7}.

The primary instrumental limitation to an improvement in this capability was the infrared path. We are currently investigating the possible causes of this effect.

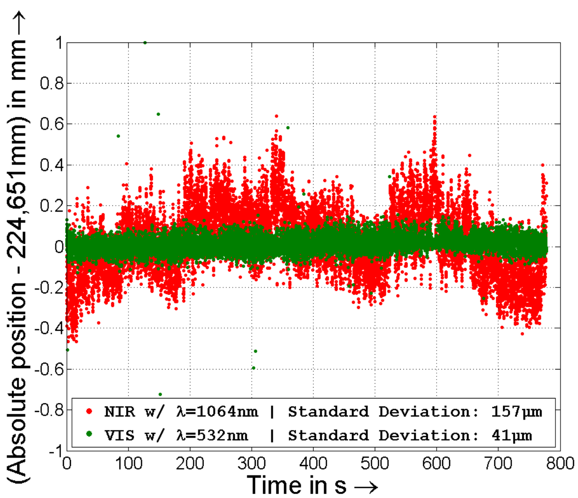

FIGURE 4. Absolute position results at the WUT200 campaign over a distance of 224,651 mm measured with PTB's multi-wavelength interferometer. The standard deviation of 41 µm at 532 nm corresponds to a relative accuracy of 1.85×10^{-7}.

CONCLUSION

A new multiwavelength interferometer system for geodetic length measurements was built by PTB. Its subsystems including laser source, opto-mechanical setup and phase evaluation electronics were presented.

During the latest measurement campaign at a new baseline in Warszawa, a relative measurement accuracy of 1.9×10^{-7} has been achieved. PTB's TeleYAG-II system is still undergoing test and modifications. The portable optical head and the rest of the equipment inside a mobile trailer have proven their suitability for harsh environments.

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The authors would like to thank F. Pilarski, F. Schmaljohann, S. Weinrich, and M. Peglow for the mechanical design and manufacture of the interferometer head. This work was performed within the EMPIR projects 18SIB01 GeoMetre and 20IND02 DynaMITE. These projects 18SIB01 GeoMetre and 20IND02 DynaMITE have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

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