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Application of lasers of metrological appropriation as working standards

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Abstract. Today laser measuring systems and sets, interferometers and other measuring units, which principle of operation is based on the use of stabilized laser radiation sources, are actively used to solve urgent problems in metrological laboratories of advanced enterprises of various industries and in leading scientific institutes. This article discusses the research results of a number of stabilized radiation sources with the aim of using them as working standards. The research was carried out on the basis of the D.I. Mendeleyev Institute for Metrology (next VNIIM).

Keywords: laser, measuring instrument, State Primary Standard of the unit of length, working standard

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Применение лазеров метрологического назначения в качестве рабочих эталонов

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Аннотация. В настоящее время лазерные измерительные системы и установки, интерферометры и другие измерительные устройства, принцип работы которых основан на использовании стабилизированных источников лазерного излучения, активно используются для решения актуальных задач в метрологических лабораториях передовых предприятий различных отраслей промышленности и в ведущих научных институтах. В данной статье рассмотрены результаты исследований ряда стабилизированных источников излучения с целью применения их в качестве рабочих эталонов. Исследования проводились на базе Федерального государственного унитарного предприятия «Всероссийский научно-исследовательский институт метрологии им. Д. И. Менделеева» (далее ВНИИМ).

Ключевые слова: лазер, средство измерения, государственный первичный эталон единицы длины, рабочий эталон

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Introduction

With the advent of the first laser in the middle of the 20^{th} century, the rapid development of laser technology immediately began, which continues to this day. The laser does not cease to conquer new areas of applications due to its properties and characteristics, it becomes a reliable assistant to doctors, builders, archaeologists, criminologists, etc.

Now lasers are successfully used in modern industry, helping to solve a wide variety of tasks. Lasers are also widely used in metrology. As working measuring instruments, the metrological services of most manufacturing enterprises use laser-based measuring instruments, such as linear displacement sensors, distance measuring equipment, laser systems for shaft alignment, and others, to control their products. The assortment of laser-based measuring instruments are constantly expanding, newly developed measuring equipment are appearing, already available on the market measuring instruments are improving, their accuracy is increasing. Along with unstabilized laser radiation sources, in modern high-precision measuring equipment stabilized lasers are used. The principle of operation of such modern high-precision measuring systems as interferometers, lasers trackers, scanners, total stations, etc. is based on the use of stabilized laser radiation sources. Being the most accurate and capable of solving many technical problems, measuring instruments based on stabilized lasers occupy an important place in the technical control services of products and services and successfully replace the traditional measuring instrument [1].

Stabilized laser radiation sources are successfully used to realize, store and transfer of the unit of length all over the world. Stabilized lasers and systems based on them are successfully used for transfer the unit of length both as independent measuring instruments and as a part of various measuring equipment and systems. This article is devoted to the study of the metrological characteristics of stabilized laser radiation sources with the aim of using them as working standards of 1st and 2nd echelons in accordance with the State verification schedule for measuring instruments of length in the range from $1\cdot10^{-9}$ to 100 m and wavelengths in the range from 0.2 to 50 microns, approved by Order No. 2840 of December 29, 2018 of the Federal Technical Regulation and Metrology Agency.

In accordance with the Recommendation of the International Bureau of Weights and Measures (next BIPM), leading scientific metrological institutes of the world use in national standards stabilized laser radiation sources. In Russia the realization of the unit of length is by two He-Ne/I_2 and one Nd:YAG lasers from the State Primary Standard of the Unit of Length – metre GET 2-2021 (next GET 2). GET 2 provides realization of the unit of length at the wavelength of 0.633 µm with the standard deviation – $1.6\cdot10^{-12}$, and $1.3\cdot10^{-12}$ at 0.532 µm. GET 2-2021 also includes the set for measuring the frequency difference of laser radiation sources, the complex of equipment for measuring a frequency of lasers in the wavelength range from 500 to 1050 nm (optical frequency comb) with the hydrogen standard of frequency and four linear laser interferometers in the range from $1\cdot10^{-9}$ to 30 m, the basis of the measuring system of which are also frequency stabilized lasers [2, 3].

Stabilized laser radiation sources used for realization of the unit of length are developed directly by national metrological institutes or other scientific organizations. Today a serial production of frequency-stabilized lasers of such precision is carried out only by Winters Electro-Optics, Inc. (USA). In accordance with the Recommendation of the BIPM, the absolute frequency accuracy of such lasers is less than $2.5\cdot10^{-11}$ [4].

The metre as one of the seven basic units of the International System of Units is included in a number of derived units, so the realization of many derived units is impossible without the use of equipment of storing and transferring of the unit of length. In the Russia, stabilized laser radiation sources are a part of a number of such State Primary standards as the State Primary Standard of the Flat Angle Unit GET 22-2014, the State Primary Standard of the Unit of the Temperature Coefficient of Linear Expansion of Solids GET 24-2018, the State Primary Standard of the Unit of Pressure GET 101-2011, etc.

To store and transfer of the unit of length to frequency-stabilized lasers, wavelength meters, etc., stabilized laser radiation sources in the range from 0.4 to 11 microns are used as secondary standards. Stabilized laser radiation sources are also as a part of sets for calibration of linescales and gauge blocks are used as secondary standards, and as a part of laser displacement meters in the range from 10^{-9} to 10^{-2} m for transferring the unit of length to laser interferometers and laser displacement meters. The main manufacturers of such lasers today are JSC Plasma (Russia), Meßtechnik GmbH (Germany), Thorlabs Inc. (USA). The absolute frequency accuracy of such lasers is near $10 \cdot 2^{-8}$.

Stabilized lasers are a part of modern high-precision measuring equipment, such as laser measuring systems, mobile coordinate measuring machines (trackers), laser interferometers and others. The operating principle of such measuring equipment is based on the method of laser interferometry, which is one of the most highly accurate method of transferring of the unit of length. Laser measuring systems are widely used to solve a variety of scientific and technical problems in the most important sectors of the national industry. Laser measuring systems of the following manufacturers are mostly used: Renishaw PLC (Great Britain), Automated Precision Inc. (USA), Chotest Technology Inc. (China) [5].

Experimental procedure

Research was carried out using the iodine-stabilized He-Ne laser and the set for measuring the frequency difference of laser radiation sources from the GET 2-2021. The appearance of the laser and the set is shown in Fig. 1.

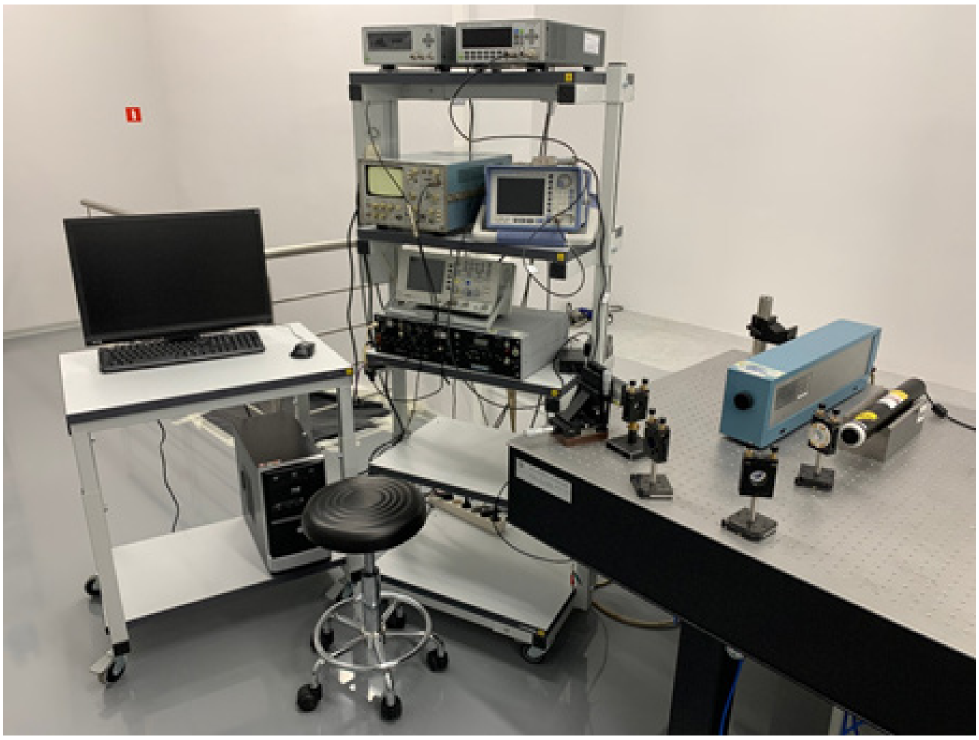

Fig. 1. Iodine-stabilized He-Ne laser and the set for measuring the frequency difference of laser radiation sources

The principle of operation of a iodine-stabilized laser is to automatically adjust the optical frequency of the laser radiation to the center of a certain component of the absorption line of molecular iodine vapor. The frequency of the iodine-stabilized He-Ne laser can be tuned without loss of accuracy within 463 MHz along the components a, b, c, d, e, f, g, h, i, j, k, l, m and n of the absorption line R(127) in iodine.

The cavity of the iodine-stabilized He-Ne laser is based on four invar rods. Ends of bars are connected with end plates with positioners for cavity's adjustment on both sides. There are a low-noise laser tube which length is 210 mm and a iodine cell which length is 100 mm are used in a cavity. A process of a cell is placed in a thermocooler. A thermocooler provide the temperature of the process – (15.00 ± 0.05) °C. The system of automatic frequency control of the laser includes: a low noise high voltage source for power of laser tube; the power supply system and thermistor; generator f-3f; 3f phase detector; a DC amplifier; integrator; sweep generator; an iodine peaks indication system [4].

To obtain and process measurement information, specialized software "Laser-Laser" developed by VNIIM was used. This software package allows you to automatically register the difference frequency of iodine-stabilized and investigated lasers, process the difference frequency and determine the frequency of the investigated laser, determine the stability of the frequency of the investigated laser for various time intervals.

Metrological characteristics of the reference stabilized He-Ne/I_2 laser:

- the frequency of the laser radiation is f = 473612353603.6 kHz, the combined uncertainty of the laser radiation frequency is u_c = 0.2 kHz (calibration certificate No. 8 by the BIPM, BIPM.L-K11. The key comparison of stabilized lasers at a wavelength of 633 nm [6]);
- output power of laser radiation – 100–125 μW.

Experimental researching of widely used stabilized lasers carried out by GET2 at the following conditions:

- ambient temperature, °C 20 ± 3;
- max. temperature's transformation during an hour, °C 0.2;
- relative humidity of the air, %, no more 80;
- atmospheric pressure, kPa 100 ± 6.

For the research, frequency-stabilized laser radiation sources were chosen: Stabilized He-Ne laser LGN-302, Stabilized He-Ne laser SIOS SL 02/1, Differential laser interferometer SIOS SP 2000, Laser measuring system Renishaw XL-80 and Stabilized He-Ne laser Thorlabs HRS015. The following results were obtained, which are presented in Table 1.

According to Part 1 of the State verification schedule, frequency-stabilized lasers with confidence limits from $2\cdot10^{-10}$ to $1\cdot10^{-8}$ can be used as working standards of the 1st category, and from $1\cdot10^{-8}$ to $1\cdot10^{-6}$ as working standards of the 2nd echelon. Thus, based on the data obtained, we can conclude that the stabilized He-Ne laser LGN-302 in its accuracy characteristics corresponds to the 1st echelon operating manual, and the stabilized He-Ne laser SIOS SL 02/1, differential laser interferometer SIOS SP 2000, laser measuring system Renishaw XL-80, stabilized He-Ne laser Thorlabs HRS015 correspond to the 2nd echelon.

Table 1

Results

Model	Wavelength, nm	Relative frequency instability
Stabilized He-Ne laser LGN-302	632.99097	$1\cdot10^{-8}$
Stabilized He-Ne laser SIOS SL 02/1	632.99099	$2\cdot10^{-8}$
Differential laser interferometer SIOS SP 2000	632.99083	$2\cdot10^{-8}$
Laser measuring system Renishaw XL-80	632.99058	$2\cdot10^{-8}$
Stabilized He-Ne laser Thorlabs HRS015	632.99152	$3\cdot10^{-8}$

Conclusion

The dynamics of the global market of metrological services is defined by constantly growing needs for changes in new areas of activity and increasing requirements for their accuracy. The development of new technologies requires constant improvement of the state standards base, the development of new measuring technologies and equipment for the traceability of measurements. Stabilized laser radiation sources are the reliable basis for these goals. Thus, the metrological characteristics of the lasers discussed in this article correspond to the characteristics declared by the manufacturers and can be successfully used as working standards, ensuring the transfer of a unit of length at a high level.

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