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# System for calibration of the frequency stabilized He-Ne laser

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The frequency stabilized He-Ne lasers are applied as length standard in interferometers used for high-precision measurement of distances and displacements. This paper presents the calibration equipment applied for the definition of real value of the laser radiation wavelength and investigation of stability and reproducibility of the wavelength of the laser radiation in the He-Ne laser interferometers. The laser radiation frequency was measured with the heterodyne method with the help of the developed laser frequency iodine standard 633 nm. The system was used for calibration of the frequency of the He-Ne Zeeman laser used in the two frequency laser interferometer.

## 1. Operating principles of the system

The laser interferometers are intended for high-precision measurement of distances and displacements. The wavelength of laser radiation is used there as initial scale or length unit. The scale has to be kept in fact with proper accuracy during measurements and to be reproducible for a long time. The frequency stabilization of laser radiation can be used to meet the necessary wavelength reproducibility. Practically all He-Ne lasers intended for laser interferometers have a frequency control servo system, which is based on some physical effect. The frequency stability and the value of the wavelength can be different for these lasers. The calibration system can be applied for the definition of rated (real) value of the laser radiation wavelength and investigation of wavelength stability and reproducibility of the laser radiation. It is necessary because of the peculiarity of the physical principle of operation and technical realization of He-Ne 633 nm lasers used in the interferometer. The frequency stabilizing servo system is used to maintain the operation mode of such lasers only near the top of the gain profile. The reproducibility of this position on the frequency axis is rather high; at least its position is stable enough to provide for the required radiation frequency reproducibility. However, the absolute radiation frequency value depends on a number of physical and technical factors such as partial pressure of He and Ne in laser tube, the amount of diffractive loss, *etc*. Therefore, a simple way to determine the rated laser frequency value is to measure it.

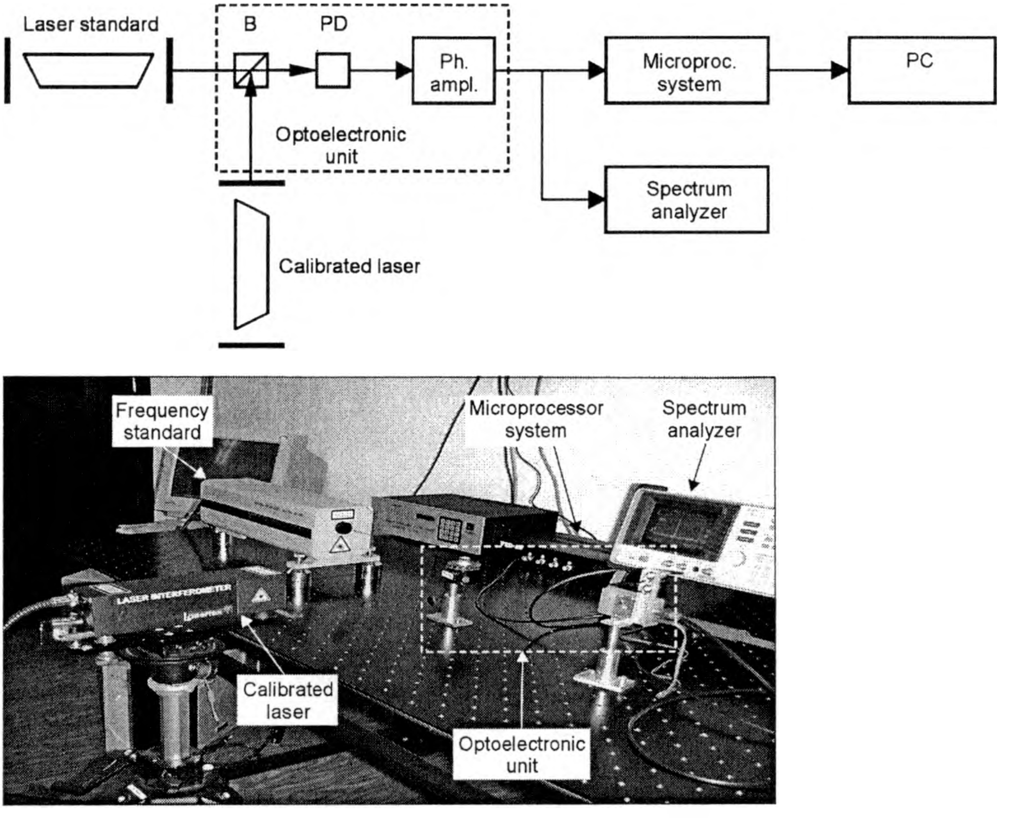


Fig. 1. Laser calibration system.

The laser radiation frequency can be measured with the heterodyne method, in which the frequency of calibrated laser is defined as the measured frequency difference between optical signals of this laser and heterodyne laser of well known stable frequency.

The laser calibration system whose block diagram and photograph are presented in Fig.1 consists of the four elements:

– standard frequency of the iodine stabilized He-Ne 633 nm laser,

– optoelectronic unit to select and amplify the frequency difference signal from the beat signal between radiation of the laser standard and the calibrated laser,

– microprocessor system to measure the frequency difference and calculate the Allan variance,

– computer to collect and record data.

The most important element applied in this calibration system is the iodine stabilized He-Ne laser frequency standard. The frequency stability of the He-Ne laser is measured and calculated with the use of the Allan variance. The measurements are controlled by a microprocessor system, and results are collected and recorded by external PC. The optoelectronic unit consisting of nonpolarising beam-splitter (B),

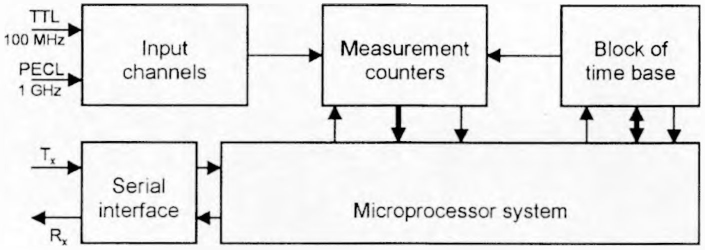


Fig. 2. Block diagram of the microprocessor system.

photodetector (PD) and photodetector amplifier (Ph. ampl.) is used for laser beams heterodyning and interference signal amplification. The spectrum analyzer is applied for the beat signal control and calculation of the value of the measured laser wavelength.

A microprocessor system was developed in order to simplify the measurements of the frequency difference and calculation of the Allan variance. The system, whose block diagram is presented in Fig. 2, consists of five electronic blocks: microprocessor system, a block of the input channels, a block of the measurement counters, a block of the time base, the serial interface RS232C. The input channels transformed the output signal from the photodetector amplifier into TTL signal (0–5 V) and PECL signal (0–1 V). The application of TTL signal enabled the measurement of the frequency difference up to 100 MHz, and the PECL signal allowed taking measurements in the range of 0–1 GHz. The measurement counters were controlled by microprocessor system, programmable counters could count the frequency of signals from channel A or channel B in sampling time ranging from 1 ms to 1000 s. The capacity of the counters was $2^{32}$ pulses, which made it possible to measure the frequency in the range of 0–100 MHz. The frequency of signal from channel B was divided by factor 2.4 or 8 to match the counter frequency range. The microprocessor system controlled the parameters of the device blocks, configured the device, read and stored the results of measurements and communicated with external PC by serial port RS232C.

## 2. Iodine stabilized He-Ne laser standard

The iodine stabilized He-Ne laser, developed by Lasertex Co. Ltd., Poland, was used as a frequency standard for the investigation of the frequency stability of He-Ne 633 nm lasers which were applied in the laser interferometer.

In accordance with a new definition of the meter and the recommendations of the Committee International des Poids et Mesure (CIPM), the primary wavelength standard is the laser standard, the frequency of which has been measured against the primary time and frequency cesium standard [1]. The He-Ne laser, operating at 633 nm and frequency stabilized by a saturated absorption technique using hyperfine transitions in iodine [2], is a relatively simple, cheap and reliable device of known

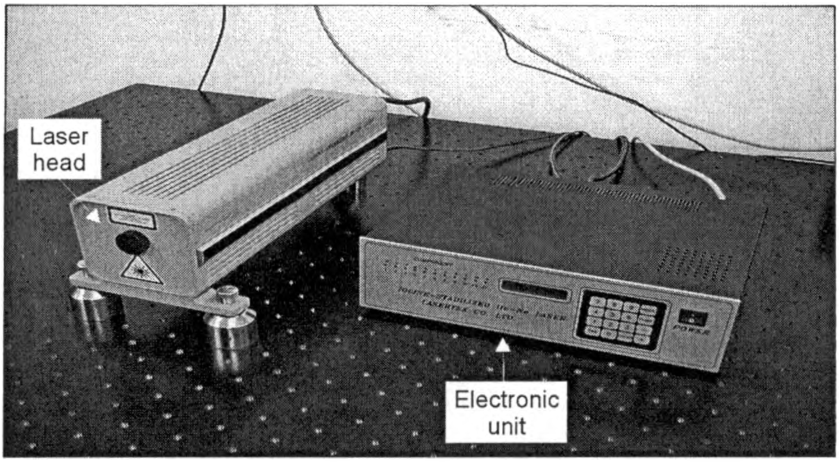


Fig. 3. Iodine stabilized He-Ne laser at $\lambda = 633$ nm.

frequency. Its frequency accuracy, stability and reproducibility are high enough to make an extremely small contribution to the error of the most accurate interferometric length measurements.

The parameters and characteristics of iodine stabilized He-Ne laser (presented in Fig. 3) were closely adjusted to the values recommended by the CIPM:

– Allan variance of the frequency of the laser was 2 kHz in 10 s,

– output power of the laser was 100 μW,

– the laser could be automatically locked to any one of eleven absorption lines of the molecular iodine from $a_{12}$ to $a_{22}$,

– the frequency modulation bandwidth was adjusted to the value of 6 MHz,

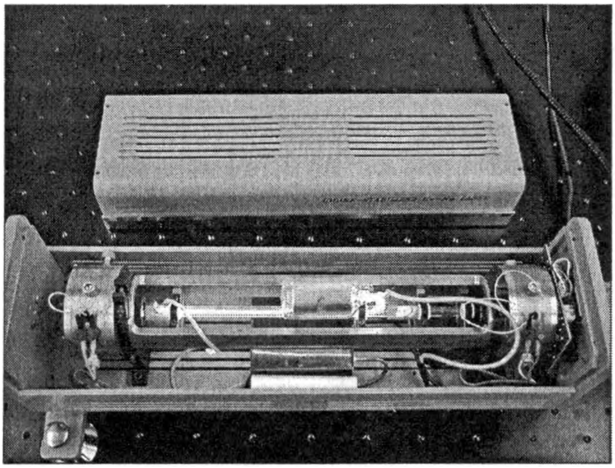

Fig. 4. Laser head of the laser frequency standard.

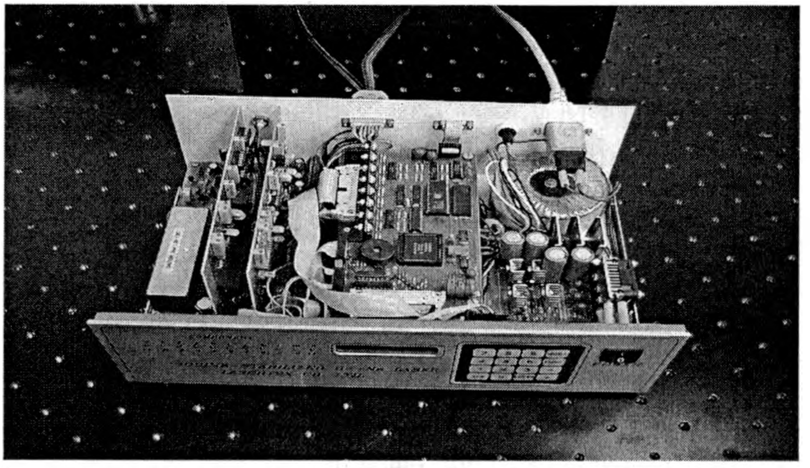

Fig. 5. Electronic unit of the laser frequency standard.

– the temperature of the "cold finger" of the iodine cell was 15 °C,

– construction of the laser is characterized by mechanical compactness, it is portable and easy-to-use with possibility of high modification.

The He-Ne laser frequency standard consists of two main components: the laser head (Fig. 4) and the electronic unit (Fig. 5).

The laser head contains the laser resonator with He-Ne 633 nm discharge laser tube, the iodine cell the "cold finger" of which is cooled with a Pettier element. The electronic board of the photodetector, with the preamplifier and filter is fixed to the back of the resonator. The resonator with the laser tube, the iodine cell and the cooling system were developed and produced by State Scientific Industrial Aassociation (SSIA) "Metrology" Kharkov (Ukraine).

The electronic unit of the frequency standard contains two main blocks: the electronic system of the laser frequency stabilization and the microprocessor control system. The third-harmonic detection technique [3] was used for stabilization of the laser standard frequency. The length of the laser cavity was periodically modulated, using piezoelectric transducer, by the sinus signal of the frequency 1600 Hz. The signal of the third harmonic of the modulation frequency was detected to give a third derivative of the profile. The application of the zero crossing of the line profile enabled very precise stabilization of the laser onto a hyperfine component of the transition R(127) of the $^{127}I_2$ molecular iodine. This precision acquired then determined the precision of the laser radiation frequency. The frequency of the stabilized He-Ne laser could be automatically locked to any one of the eleven components.

The frequency characteristics of a laser used as a frequency standard are conventionally expressed in terms of repeatability, reproducibility and stability, following the nomenclature recommended by the IOS [4]. A regular verification of laser performance for reliable applications is made through international comparisons.

The main objective of such a comparison is to verify the performance of each participating laser as a frequency standard while operating properly under the specifications of the Recommendation 3 (CI-1992) [5]. All measurements are made by the beat frequency technique, which provides very sensitive means of determining the behaviour of stabilized lasers.

The frequency stability of the standard was determined by calculation of the Allan variance. The frequency reproducibility was measured by the commonly used matrix measurement method [6]. The reproducibility is understood as dispersion of the frequencies of lasers compared when working close to the parameters set by Recommendation 3, but with individual intracavity powers, resonator parameters and iodine cells. Repeatability was determined by taking frequency measurements at hourly intervals while keeping the parameters of the lasers as constant as possible.

The Lasertex iodine stabilized He-Ne 633 nm laser standard was calibrated by comparing it with two different state wavelength standards:

– the Polish wavelength standard, which was set by Thompson and compared with BIPM4 standard at Bureau International des Poids et Measures (BIPM) in France 1997,

– the Ukrainian wavelength standard, which was set by SSIA "Metrology" Kharkov (Ukraine) and compared at Bratislava International Laser Comparison in Slovak Meteorological Institute in 1994 and 1998.

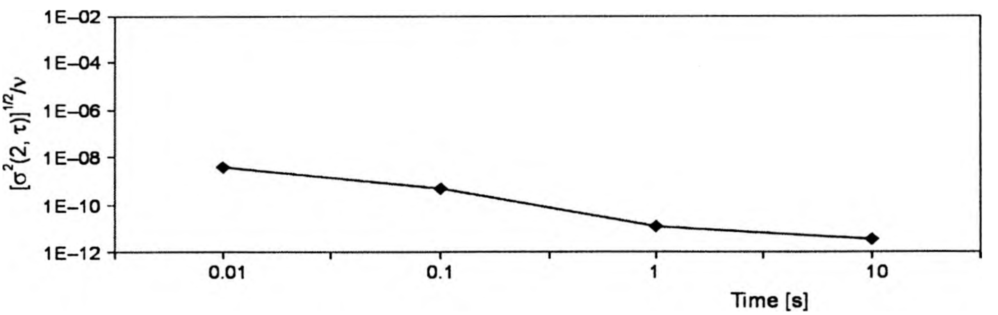


Fig. 6. Results of the measurements of the laser frequency stability of the standard.

The results of the measurements of the Allan variance during the comparison of the developed iodine frequency standard with the state wavelength standard of Poland are plotted in Fig. 6. The standard developed was locked on component *d* and the Polish standard was locked on component *g*. The Lasertex iodine stabilized He-Ne standard had the frequency stability of $10^{-10} - 10^{-12}$ for sampling time from 0.1 to 10 s. The value of the frequency stability achieved by this standard is comparable with parameters of laser standards used by national European standard laboratories.

The reproducibility of the Lasertex laser standard was defined as average frequency difference over the *d, e, f, g* absorption components of the iodine molecular transition 11-5, R(127). The value of reproducibility was measured by comparing the Lasertex

T a b l e 1. Results of reproducibility measurements.

| | Comparisions of Lasertex standard against | |
|---|---|---|
| | Polish standard | Ukrainian standard |
| The averaged frequency difference $\nu_1 - \nu_2$ | 0.33 kHz ($0.6\times10^{-12}$) | 1.25 kHz ($2.5\times10^{-12}$) |
| The standard uncertainty $(1\sigma)$s | 0.71 kHz | 1.5 KHz |

iodine stabilized standard against Polish and Ukrainian wavelength standards. The reproducibility of the frequency of the measured laser standard had the value of $10^{-12}$, the results of the measurements are presented in Table 1.

The repeatability of the Lasertex laser standard was determined by measuring the averaged frequency difference $\nu_1 - \nu_2$ between our standard and the Polish standard. Results of measurements made during a span of 6 hours, are presented in Fig. 7; the repeatability achieved for the measured laser standard frequency had the value of $10^{-12}$.

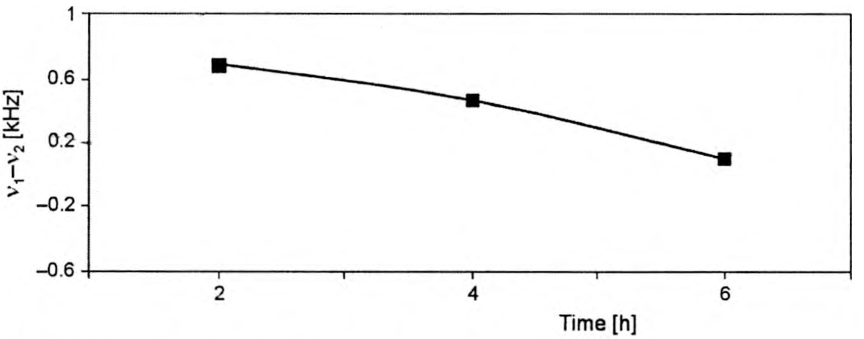


Fig. 7. Average frequency difference versus time.

The Lasertex iodine stabilized He-Ne 633 nm laser frequency standard with its main metrological characteristics meets the requirements and can be applied to calibrate the laser used in the interferometer.

## 3. Results of the laser calibration

The frequency stability and real value of the wavelength of He-Ne lasers 633 nm used in interferometric systems were measured and optimized by the calibration system presented. He-Ne lasers with different systems of frequency stabilization were investigated. The first laser used the digital method of the frequency stabilization [7], the laser frequency was stabilized at the maximum value of the Zeeman laser frequency. For the second laser using the analogue method of the frequency stabilization [8], laser frequency was stabilized using ferroelectric liquid crystal cell.

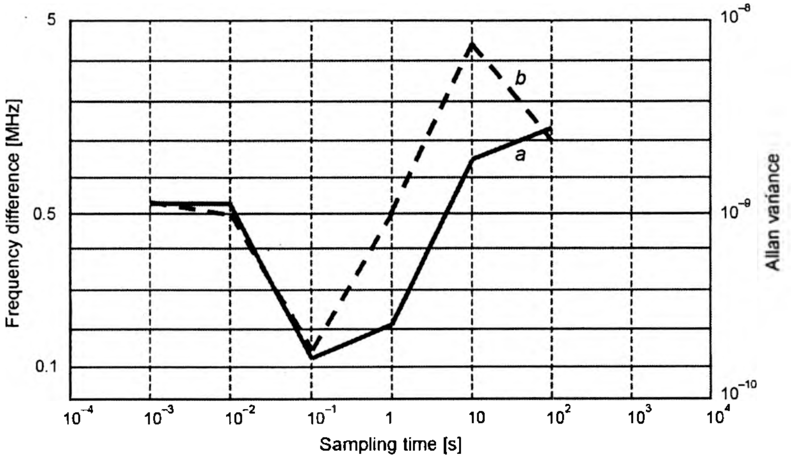


Fig. 8. He-He Zeeman laser frequency stability: digital method (*a*) and analog method (*b*).

T a b l e 2. Results of calibration.

| User of interferometer (in Poland) | Date | Wavelength [nm] | Frequency stability | Frequency stabilization |
|---|---|---|---|---|
| Avia Warszawa | 14.09.2001 | 632.991326 | $6.5\times10^{-10}$ | analog |
| Optical & Laser Service | 21.03.2001 | 632.991209 | $1.3\times10^{-10}$ | analog |
| Politechnika Śląska | 20.11.2000 | 632.991272 | $2.5\times10^{-10}$ | analog |
| OBRSM Tarnów | 31.07.2000 | 632.991251 | $3.0\times10^{-11}$ | analog |
| FAMOT Pleszew SA | 18.03.2000 | 632.991311 | $4.3\times10^{-11}$ | analog |
| OBROiUS Poznań | 27.12.1999 | 632.991261 | $1.9\times10^{-10}$ | analog |
| CHOFUM Chocianów | 12.02.2001 | 632.991324 | $6.6\times10^{-10}$ | digital |
| CHOFUM Chocianów | 02.11.1999 | 632.991331 | $2.2\times10^{-10}$ | digital |
| CHOFUM Chocianów | 25.03.1999 | 632.991334 | $3.7\times10^{-10}$ | digital |

The frequency stability of the laser was determined by measuring the Allan variance between the investigated lasers and the laser frequency standard. The Allan variance was measured for sampling time from 1 ms to 100 s. The results of the Allan variance measurements are presented in Fig. 8. The frequency stability for both measured He-Ne lasers had the values between $10^{-10}$–$10^{-8}$, which is high enough for applications of these lasers in laser interferometers.

The measurements of the wavelength of the investigated He-Ne lasers were made with the use of the heterodyne method. The frequency difference between investigated laser and standard, stabilized to *f* component of iodine, was measured. The difference between wavelength of the measured laser and standard was calculated, using measured frequency difference and known value of the standard wavelength.

Lasertex Co. LTD applied the developed system for measurements of the frequency stability and value of the wavelength of the He-Ne Zeeman lasers used in laser interferometers of type LSP30. The results of measurements are presented in Tab. 2.

The analysis of the results shows that the method of the frequency stabilization of He-Ne lasers affects the parameters of these lasers. The frequency stability of the He-Ne Zeeman lasers stabilized by the analog method is better than for digital method of stabilization, but the reproducibility of the laser wavelength is worse.

## 4. Conclusions

The system presented in this paper can be used for calibration of all kinds of He-Ne 633 nm lasers applied in the one and two frequency laser interferometers.

| **Calibration Certificate** | |
|---|---|
| Date: | 25.04.1999 |
| Order placed by: | CHOFUM Chocinów |
| Laser: | LSP-30 NR 2/96 |
| Result of calibration: | |
| Wavelength $\lambda$: | 632.991334 nm |
| Frequency stability $\delta$: | $3.7 \times 10^{-10}$ |
| Measure condition: | |
| Integration time: | 1 s |
| Laser preheating time: | 2 h |
| The measurements were made by the heterodyne method; the standard used was a He-Ne laser stabilized for iodine absorption lines and tested by Polish National Board of Metrology. | |
| Wroclaw 26.03.1999 Stamp and signature | |

Fig. 9. Calibration Certificate of He-Ne 633 nm laser.

The system is very easy to operate and might be exploited in the industrial laboratory. The software of the system prepares the Calibration Certificate for the measured lasers (Fig. 9).

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## References

[1] *Documents concerning the new definition of the metre*, Metrologia **19** (1984), 163.
[2] Hanes G.R., Baird K.M., Metrologia **5** (1969), 32.
[3] Wallard A.J., J. Phys. E Sci. Instrum. **5** (1972), 926.
[4] *International Vocabulary of Basic and General Terms in Metrology*, IOS, 1984, p. 15.

[5] Recomendation 1 (CI-1983), BIMP Proc.-Verb. Com. Int. Poids Measure, Vol. 51, 1983, pp.25–28.
[6] Bayer-Helms F., Chrtier J.M., Wallard A.J., PTB Bericht Me **17** (1977), 139.
[7] Rzepka J., Maltese P., Proc. SPIE **3186** (1996), 162.
[8] Pienkowski J., Rzepka J., *Laser measurement system LSP-30*, [In] *Proc. of 3rd Mideuropean Symposium and Exhibition on Semiconductors Engineering and Materials*, Warszawa 1992, pp. 32–34.

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