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GENERAL EXPERIMENTAL TECHNIQUES

A Compact Frequency-Stabilized Pulse–Periodic Waveguide CO_2 Laser for Calibration of Wavelength Meters

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Abstract—A compact pulse–periodic waveguide CO_2 laser with high-frequency excitation with automatic assignment of the 10P (14) line and stabilization of the emission frequency in the middle of this line using a sealed-off optoacoustic cell, which is filled with a mixture of C_2H_4 (0.1%) and nitrogen, was developed. It is shown that the laser-frequency instability is within 3 MHz, thus meeting the requirements that are imposed on the calibration tools for high-resolution wavelength meters that are similar to WS-6IR.

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INTRODUCTION

Methods for stabilizing the lasing frequency of CO_2 lasers are presented in detail in the literature [1]. As a rule, the stabilization of continuous-wave (cw) CO_2 lasers is meant. In this case a diffraction grating is used to specify the required lasing line. The continuous lasing mode and the presence of a diffraction grating impose some limitations on the mass and dimension parameters of the laser and its energy consumption.

The issues of the frequency stabilization of lasers that operate in pulse–periodic modes were considered less carefully because of the essentially higher frequency instability, which is caused by changes in the discharge parameters during a pumping pulse. An exception is CO_2 TEA lasers, for which, in order to attain a single-frequency lasing mode, various methods for injecting stabilized radiation, as a rule, from a cw laser source, were developed [2].

Stabilization of the lasing frequency of compact waveguide CO_2 lasers that operate in pulse–periodic lasing modes at low consumed-power levels is important for a number of applications. Such lasers are used in modern portable devices, e.g., in laser leak detectors [3], and can also be used as frequency references for laser wavelength meters (WS-6IR and others).

One of the methods for stabilizing the lasing frequency of a pulse–periodic CO_2 laser is considered in [4], where automatic tuning to the maximum lasing-line power is proposed via determining and subsequently specifying (using a piezoceramic actuator) the minimum laser-pulse delay relative to the triggering pulse, which corresponds to the maximum radiation power. For a delay of 4 μs, the lasing linewidth was ±20 MHz, and for 16 μs, the lasing linewidth was ±100 MHz. The aforementioned stabilization method implies the use of fast photodetectors and a diffraction grating, which is used to select the laser emission line.

When only one known lasing line is required for operation of a device, as was shown in [5], the algorithm for stabilizing the lasing frequency of a pulse–periodic waveguide CO_2 laser using an optoacoustic cell (OAC), which is filled with an absorbing gas with a known absorption spectrum, can be used. In particular, a sealed-off SF_6-filled OAC was used in [5] to specify and stabilize the frequency of the 10P(16) line. To fine-adjust the resonator length, one of the mirrors was placed on the piezoelectric actuator, which was installed in the position that corresponded to the required lasing line. Measurements showed the possibility of obtaining the amplitude instability at a level of 3%, which corresponds to a frequency instability of ±6 MHz.

This study presents a more perfect variant of such a device, which is intended for operating as a frequency reference for calibration of a WS-6IR wavelength meter.

A structural diagram of the instrument is shown in Fig. 1.

As the radiation source, a compact sealed-off waveguide CO_2 laser with microwave excitation and waveguide dimensions of 1.8 × 1.8 × 150 mm is used.

The laser resonator is formed by two flat mirrors that are positioned near the output ends of the waveguide (type I according to the classification that was proposed in [6]). The dense mirror was manufactured on a silicon substrate and is coated with a gold film. The output mirror has a reflectivity of 92% and is mounted on an adjustment device with a piezoceramic actuator (PCA), which allows the resonator length to be varied within a 5-μm interval. The voltage across

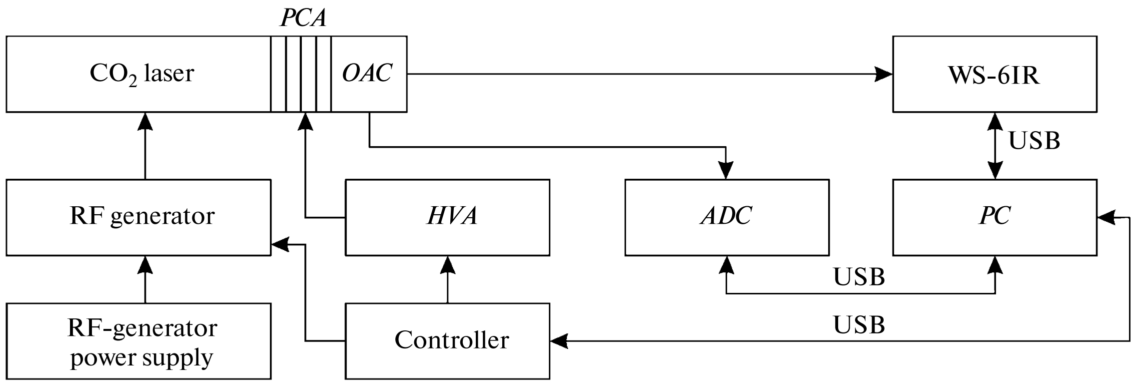

Fig. 1. Structural diagram of the instrument: (*OAC*) optoacoustic detector, (*HVA*) high-voltage amplifier, (*PCA*) piezoceramic actuator, (*ADC*) analog-to-digital converter, and (*PC*) personal computer.

the PCA is set with a PA97DR high-voltage amplifier in response to a microcontroller signal.

The laser is filled with a gas mixture of $CO_2 : N_2 : He = 1 : 1 : 5 + 5\%$ Xe at an operating pressure of 40 Torr. The power of pumping pulses was up to 200 W, the power of lasing pulses was 8–10 W, and the average laser power was ~2 W.

The laser is tuned to the 10P(14) line using a sealed-off nonresonance cell, OAC, which is filled with nitrogen with a small (0.1%) C_2H_4 impurity. The OAC is 1 cm long and is sealed using zinc selenide windows with antireflection coatings. An electret microphone was placed on the cell case.

The laser operating mode is specified via the USB interface from a computer using a specialized controller. In the operating mode, the duration of pumping pulses is 25 μs, the pulse repetition rates in the 10P(14)-line search and locking modes are 850 and 179 Hz, respectively, and the voltage at the actuator changes from 0 to –300 V.

Signals from the optoacoustic detector *OAC* are digitized using one of the channels of a computer-controlled four-channel analog-to-digital converter (*ADC*), where the measurement results are subsequently processed and displayed on the monitor.

The WS-6IR device is a highly sensitive compact wavelength meter for laser sources in a range of 2–11 μm and can operate with both cw and pulse–periodic laser radiation sources. The absolute accuracy of wavelength measurements using WS-6IR is 200 MHz, and the resolution is 50 MHz. The WS-6IR was used to measure the wavelength of laser oscillation. Subsequently, it is planned to use the device described in this paper as a reference for calibrating new wavelength meters from the WS-6IR series.

DESCRIPTION OF THE ALGORITHM FOR SEARCHING THE 10P(14) LASING LINE AND THE AUTOMATIC FREQUENCY CONTROL SYSTEM

According to [5], the necessity of holding a laser-radiation line is based mainly on a change in the refractive index of the laser gaseous medium that results from a monotonic increase in both the temperature and pressure inside the waveguide channel. As a result, a periodic change of the lasing lines occurs. The selection principle involving the determination and subsequent holding of the resonator-length range within the required line is generated. To provide the single-frequency lasing mode, it is essentially important to excite the medium of the laser-radiation source with RF pulses with a duration of at most 25–30 μs [7].

Let us perform a little comparative analysis of the SF_6 and C_2H_4 absorption spectra using the HITRAN data (Fig. 2).

The nonresonance cell of the device is filled with a mixture of nitrogen with a small addition of a marker gas (~40–100 mln^{-1} for SF_6 and 1000 mln^{-1} for C_2H_4) and has the length $l = 1$ cm. The optical thickness of such a cell can be considered small ($\alpha l \ll 1$). The OAC signal is then proportional to the product of the radiation absorption coefficient (α, cm^{-1}) by the laser-pulse power.

In the most general case, the required line is selected by the substantial difference between the absorption coefficient at the reference line and those at other CO_2-laser oscillation lines in the vicinity of 10.6 μm.

The SF_6 absorption spectrum contains several lines with similar absorption coefficients (Fig. 2a). The lasing line can be stabilized by the OAC signal at the strongest absorption peak on the 10P(16) line. In this case, two neighboring peaks on the 10P(18) and 10P(20) lines strongly interfere. Apart from close values of the absorption coefficients, these lines are highly intense. In practice, the OAC signal level at the

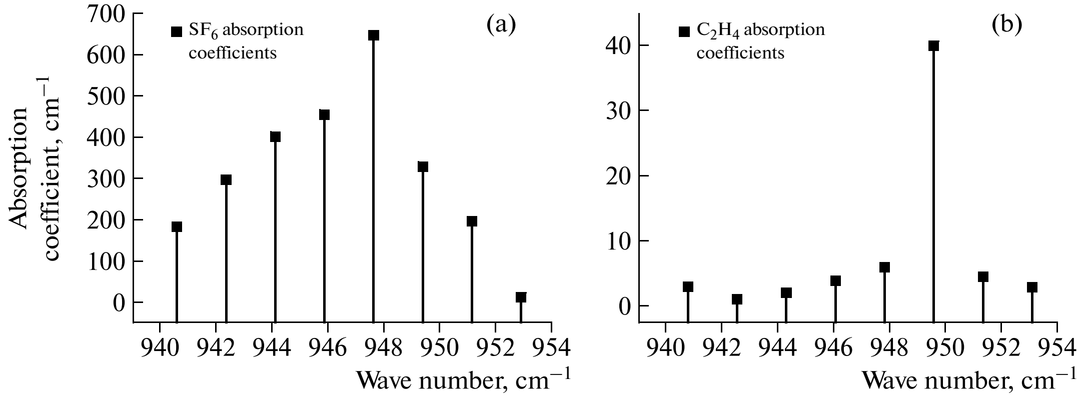

Fig. 2. (a) SF_6 and (b) C_2H_4 absorption spectra at the CO_2-laser emission lines in the range of 943.9–961.5 cm^{-1}.

10P(16) line exceeds the neighboring-line levels by a factor of at most 2–5. Therefore, in order to achieve the correct algorithm operation, periodic scanning of the laser-tuning contour must be performed until lasing is initiated at the 10P(16) line without the 10P(18) and 10P(20) lines within a single scan. In previous studies, a similar system in the form of a laboratory setup allowed us to attain a 10P(16)-line stabilization mode within 3–5 min.

The ethylene absorption spectrum in the region 943.9–961.5 cm^{-1} contains one clearly pronounced peak on the 10P(14) line (Fig. 2b). Because there is no competition with the neighboring lines (the line absorption coefficients at the 10P(14) line and neighboring lines differ by factors of 8–10), the laser stabilization algorithm can operate merely under the condition that the 10P(14) line is present in the tuning contour. During the practical realization, the waiting time of the stabilization-algorithm operation when changing from SF_6 to C_2H_4 remained virtually unaltered (3–5 min), although the laser length decreased from 225 to 150 mm.

Figure 3 illustrates the process of attaining the stabilization mode of the 10P(14) lasing line.

When the line-stabilization algorithm is initiated, a periodic variation in the voltage level across the PCA is performed and the OAC-signal shape and amplitude are simultaneously analyzed. The time interval of one laser-contour tuning cycle is designated with dashed lines in Fig. 3. In each new scan, a gradual increase in the OAC-signal amplitude is observed. This means that due to periodic thermal processes inside the laser resonance volume, the 10P(14) lasing line gradually arises in the emission spectrum.

When the 10P(14) line is fully included in lasing, the curve of the dependence of the OAC signal on the resonator length is virtually a solitary peak (in Fig. 3, the OAC signal from the 10P(14) line is denoted with number *2*), which is accompanied by several weaker signals from other lines. If the amplitude of this peak exceeds the maximum background signal from other lines by a factor of 10 (in Fig. 3, such an OAC signal is denoted with number *1*), the 10P(14)-line searching algorithm terminates and the laser changes to the operating mode at high off-duty factors.

In Fig. 3, after the 6th minute of the 10P(14)-line searching algorithm, the amplitude of OAC signal *1* exceeded the nearest background signal *2* by a factor of 50, and the searching algorithm stopped its operation (the off-duty factor of the laser operation automatically changed from 47 to 235). The necessary and sufficient ratio of the signal amplitudes of no less than 10 is chosen in accordance with the earlier presented theoretical estimates.

To provide the long-term operation at the 10P(14) line after the operation of the searching algorithm and choose the required voltage at the actuator (U_{bas}), an operator can activate the automatic frequency-control (AFC) system. In this case, in response to a control signal from an external program of the PC, the microcontroller begins to sequentially increase and decrease

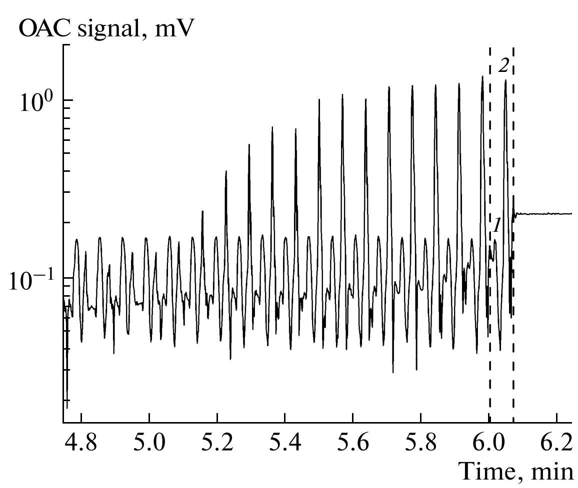

Fig. 3. OAC signal during operation of the 10P(14)-line searching algorithm. Dashed lines denote the time interval of one laser-contour tuning cycle.

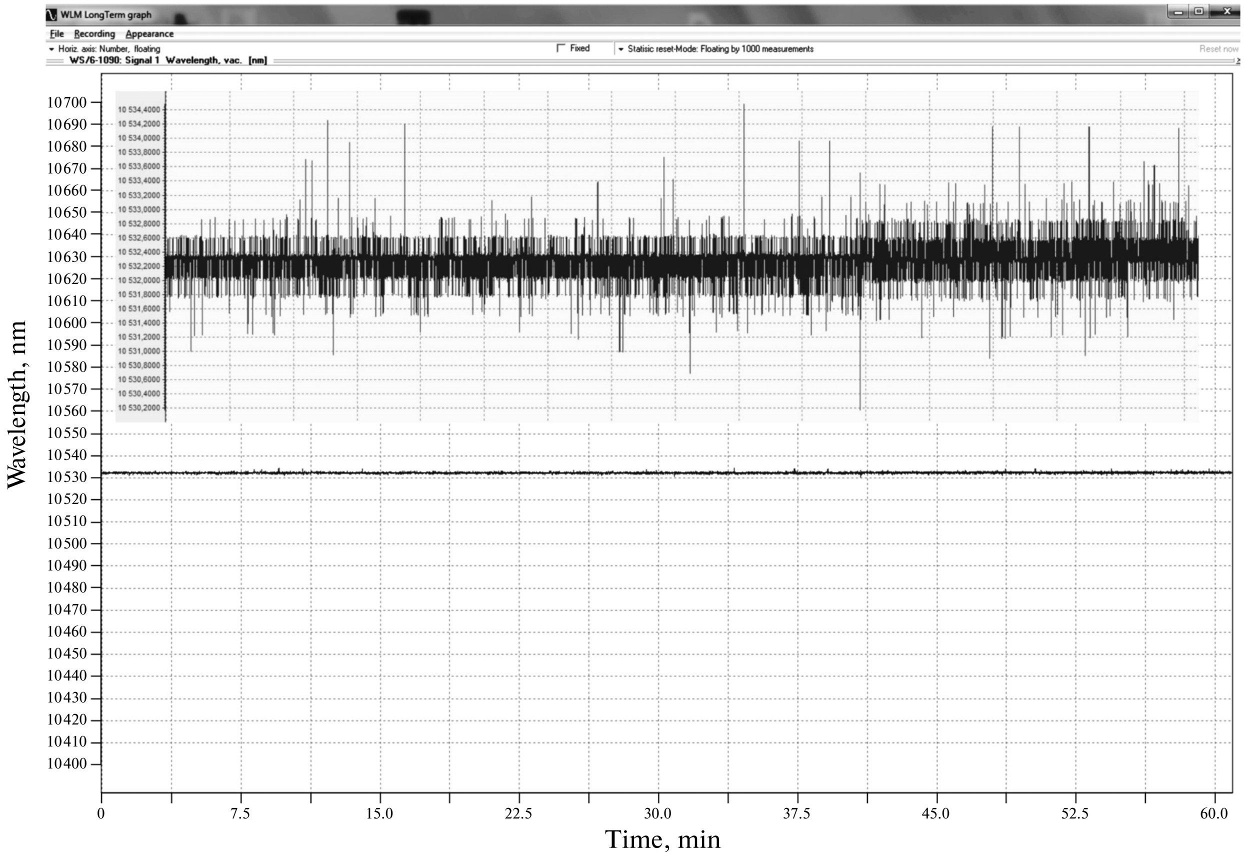

Fig. 4. WS-6IR signal during laser operation in the 10P(14)-line stabilization mode.

U_{bas} by the value U_{add}. The voltage is corrected once a second using the formula

$$U_{bas} = U_{bas} + U_{add}\frac{sdl - sdr}{sdl + sdr},$$

where *sdl* and *sdr* are the OAC signals at the points $U_{bas} - U_{add}$ and $U_{bas} + U_{add}$, respectively.

To determine the correct value of U_{add}, let us theoretically estimate the possible width of the laser-frequency variation during operation of the AFC system.

The spectral-line width for the Lorentz broadening mechanism is found from the formula [8]

$$\Delta v_L = 5.7 \times 10^4 (P_{CO_2} + 0.73P_{N_2} + 0.6P_{He})\sqrt{\frac{300}{T}}, \quad (1)$$

where P_{CO_2}, P_{N_2}, and P_{He} are the partial pressures (in Pa) of carbon dioxide, nitrogen, and helium in the working mixture, respectively, and T is the absolute temperature of the working mixture (as a rule, ~450 K).

For the calculated laser, the working-mixture pressure is 40 Torr. The calculation using formula (1) yields 4.13 MHz/Torr, and the laser-radiation linewidth is then equal to ~165 MHz. Let the amplitude of the voltage variation at the PCA during operation of the AFC system be 9.3 V or 0.148 μm (in wavelengths). In this case, the accuracy of holding the line center is 0.148 μm/10.532 μm × 100% = 1.41% or 1.41% × 165 MHz = 2.33 MHz.

EXPERIMENTAL TEST OF THE ACCURACY OF HOLDING THE LASER-EMISSION FREQUENCY AT THE 10P(14) LASING LINE USING THE WS-6IR WAVELENGTH METER

The results of a practical experiment on the assessment of the laser-stabilization accuracy at the 10P(14) line using the WS-6IR wavelength meter are presented in Fig. 4.

The laser operated in the line-stabilization mode for 1 h. Figure 4 shows that the wavelength is 10.532 μm, and the variation of this value is ±3 MHz (the plot with an enlarged scale), which properly agrees with the theoretical estimate.

Relatively large WS-6IR-signal surges are associated with thermal noises of the photodetector that is included in the structural scheme of the wavelength meter. When the line-holding accuracy was evaluated, only the central part of the signal was taken into consideration.

CONCLUSIONS

This study presents a compact frequency-stabilized pulse–periodic CO_2 laser for calibrating wavelength meters. The stabilization of the 10P(14) lasing line is performed using an external sealed-off nonresonance

OAC, which is filled with a C_2H_4–nitrogen mixture. The 10P(14) laser line is selected using the algorithm for determining and holding the 10P(14) lasing line, which was developed earlier, and the length of the active laser medium was shortened from 225 to 150 mm. As a whole, its effect for the 10P(16) line became even more efficient because the ethylene absorption spectrum in the region of 943.9–961.5 cm^{-1} has a substantially smaller width than that for SF_6. As compared to study [5], the lasing-frequency instability for the 10P(14) line decreased from ±6 to ±3 MHz.

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