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High-Power Two-Frequency Laser Source Based on a Semiconductor Laser for Atom Optics

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Abstract—A laser system with a two-frequency radiation spectrum and an output power of up to 80 mW is presented. The frequency difference of laser modes is varied from 2.5 to 4 GHz. The two-frequency lasing is studied for a mode frequency difference equal to the splitting of the hyperfine-structure levels of the ^{85}Rb ground state (3.0357 GHz). This makes it possible to use the system in experimental atom optics. The laser system consists of a master laser (an external-cavity semiconductor laser with a multifrequency radiation spectrum controlled with the microwave modulation of the laser injection current at a frequency of 3 GHz) and a high-power semiconductor diode laser that serves as an amplifier with injection locking.

1. INTRODUCTION

Long-term cyclic interaction of atoms with laser radiation is important in experiments on laser cooling and trapping of atoms and atomic optics. The problem lies in the fact that a real atom exhibits a complicated structure of energy levels, so that, in a few cycles of the photon absorption–emission, the atom is optically pumped upon the interaction with single-frequency laser radiation to one of the energy levels from which it cannot be further excited with the single-frequency laser field.

The long-term cyclic interaction can be somewhat easier to realize for the alkali atoms. These atoms exhibit a relatively simple structure of energy levels and, under certain conditions, a three-level scheme can be used. Therefore, two-frequency laser radiation can be used for the long-term cyclic interaction of atoms. For example, the laser cooling of the ^{85}Rb atoms can be realized at the $D2$ line with the excitation from the $5S_{1/2}$ state to the $5P_{3/2}$ state (Fig. 1). The long-term cyclic interaction with two-frequency laser radiation is possible owing to the hyperfine splitting of the ground ($5S_{1/2}$) state of 3.0357 GHz: one of the frequencies is in resonance with the $5S_{1/2}$ $F = 3 \longrightarrow 5P_{3/2}$, $F' = 4$ transition, whereas the second frequency is in resonance with the $5S_{1/2}$ $F = 2 \longrightarrow 5P_{3/2}$, $F' = 3$ transition.

Additional important characteristics of the laser radiation needed for the atom optics are the high radiation power and the high absolute stability of both laser frequencies, which should be no worse than the natural bandwidth of atomic absorption (5.9 MHz for the ^{85}Rb atom).

It is difficult to obtain radiation with a relatively high power (of greater than 30 mW) and high spectral characteristics using semiconductor lasers. The problem can be solved with two laser systems. The first one (master laser) exhibits high spectral characteristics, whereas the second one (laser amplifier) is a high-power free-running single-frequency laser. The radiation of the master laser is injected into the amplifier, so that the power of the laser radiation is governed by the injection current of the amplifier, while its spectral distribution is determined by the master laser. The application of such injection locking makes it possible to simultaneously achieve high spectral characteristics and a relatively high power of a few hundreds of milliwatts [1–3].

Thus, to construct a high-power laser system we need to obtain (i) two-frequency radiation, (ii) high-power radiation, and (iii) high absolute stability of the laser frequency. To solve the first problem, we may use two laser systems [4], electro-optic and acousto-optic modulators [5], and microwave modulation of the injection current [6]. Based on the method of obtaining

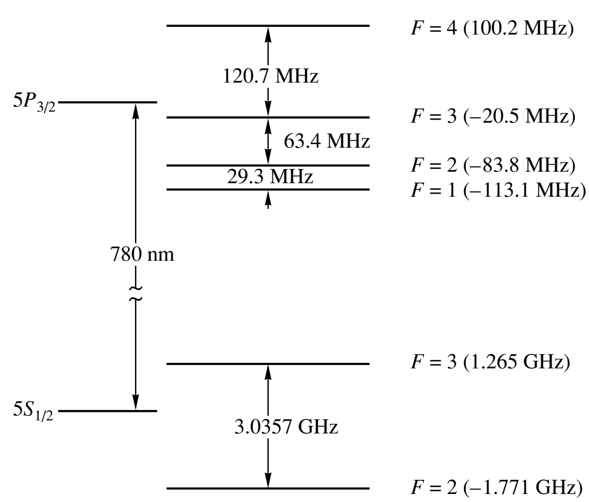

Fig. 1. Energy levels of the D_2 line of the ^{85}Rb atom.

two-frequency laser radiation, we choose the methods to solve the second and third problems.

A conventional approach enabling one to obtain radiation with the above characteristics is as follows. High-power radiation is generated by a system consisting of the master laser and the laser amplifier. The radiation at the second frequency with a lower power is generated by another laser system. Normally, the second radiation is not amplified, since the power of the conventional semiconductor lasers is sufficient for the experiments. The laser frequencies are locked to the atomic absorption lines using active frequency stabilization. This method employs three laser systems and two systems for the active frequency stabilization. The corresponding setup is difficult to construct and to control, especially if a controlled frequency detuning of the laser radiation from the exact atomic resonances is needed.

In another approach, the master laser generates radiation with a two-frequency spectrum that is amplified by two laser amplifiers. The advantage of this method lies in using only one system for the active stabilization of the master-oscillator frequency.

In this work, we propose and realize an alternative scheme of generating high-power two-frequency radiation with a frequency-stable semiconductor laser using only two laser systems: a master laser and a laser amplifier. The two-frequency radiation is generated by the master laser with the resonant excitation of the relaxation oscillations of the active medium of diode laser in the presence of a microwave field [7]. The intermode distance is equal to the hyperfine splitting of the ground state of the ^{85}Rb atom (3.0357 GHz). For the long-term stabilization of the master laser, its frequency is locked to the ^{85}Rb atomic absorption line. To increase the power, we inject the radiation into the laser amplifier. The results obtained show that the radiation spectrum of the laser amplifier is identical to the spectrum of the master laser. Note that the maximum radiation power of the laser amplifier is 80 mW and the amplitude ratio of the two-frequency radiation modes ranges from zero to unity. This setup was used for experiments on laser cooling and trapping of atoms. It can be characterized as reliable and easy-to-use.

2. GENERATION OF THE TWO-FREQUENCY LASER RADIATION

The two-frequency lasing of the semiconductor laser with a cavity in Littrow configuration is realized using the microwave modulation of the injection current. When the diode-laser injection current I is modulated at the frequency ω_m ($I = I_0 + i_m \sin(\omega_m t)$), the dependences of the refractive index of the active medium and the cavity length on the current result in the amplitude and frequency modulation of the radiation spectrum. The side modes emerge in the spectrum on both sides of the fundamental frequency at a distance equal to the modulation frequency ω_m [8]. Thus, the laser radiation spectrum contains modes at three different frequencies. Normally, only two of them are used in experiments.

It is known that, in the case under consideration, the modulation depth of the laser radiation spectrum depends on the modulation frequency of the current: the higher the frequency, the lower the modulation efficiency [8]. This makes it difficult to employ the above method for two-frequency lasing at relatively high modulation frequencies. In this case, deep modulation is possible with large-amplitude ac components of the injection current that lead to the degradation of the laser. The modulation efficiency significantly increases when the modulation frequency equals the frequency of the relaxation oscillations of the laser active medium ranging from 1 to 5 GHz. The hyperfine splitting of the ^{85}Rb ground state lies in the frequency range of the laser relaxation oscillations, which makes it possible to increase the efficiency of the two-frequency lasing. Using the resonant excitation of the relaxation oscillations, we substantially diminish the microwave power supplied to the laser (down to a few tens of milliwatts) [7]. The frequencies of the laser relaxation oscillations depend on the injection current. Hence, to increase the efficiency of the radiation spectrum modulation, we choose the injection current at which the relaxation oscillation frequency is equal to the microwave field frequency.

Using the microwave modulation of the laser injection current, we should choose a safe power of the microwave field. The following condition should be satisfied for the safe operation of the diode laser:

$$I + i_m < I_{max}, \quad I - i_m > 0. \tag{1}$$

Here, I_{max} is the maximum permissible current in the laser diode, I is the laser's working current, and i_m is the amplitude of the microwave current. We assume that the microwave power is fully transferred to the laser diode (in a real experiment, a part of this power is reflected) and that the impedance of the connecting wires coincides with the laser-diode impedance (R = 50 Ω). Then, the microwave power delivered to the laser is $P_{RF} = i_m^2 R$ and the condition for the safe operation of the laser diode is represented as

$$P_{RF} < (I_{max} - I)^2 R, \quad P_{RF} < I^2 R. \tag{2}$$

The hatched region in Fig. 2 shows the range of the permissible microwave power as a function of the laser injection current for the laser diode with the maximum injection current I_{max} ~ 120 mA. It is seen that the maximum permissible microwave power is 180 mW at a laser current of 60 mA. The maximum permissible microwave power decreases with a deviation of the laser current from this value. This type of lasing imposes limitations on the procedures for the laser switching on and switching off that provide for safe

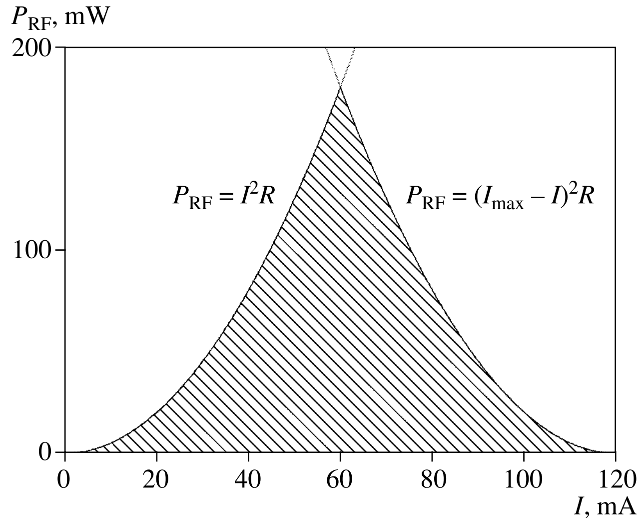

Fig. 2. Diagram that shows how to choose the permissible microwave power for the modulation of the semiconductor-laser injection current. The hatched region corresponds to the safe operation.

operation. When the diode laser is switched on, first the working current is set, and then the microwave power is increased to a safe level depending on the working current. The opposite procedure is used to switch off the laser.

Figure 3 demonstrates a block diagram of the laser setup. The microwave power is fed to the diode laser with a 60-cm-long 50-Ω coaxial cable. One end of the cable is soldered to the diode-laser pins (without matching the impedances of the cable and the laser). Another end is connected to the microwave source with an output power of up to 100 mW and a frequency in the range 2.5 GHz–4 GHz via a 1-pF capacitor. For the isolation of the microwave oscillator from the dc current source, we connect the latter to the laser via an inductance. We study the following commercial diode lasers with a wavelength of 780 nm: Hitachi 50 mW (HL7851G), Hitachi 35 mW (HL7859MG), Sanyo 70 mW (DL7140-201), Mitsubishi 50 mW (ML64114R), and Panasonic 90 mW (LNC708PS). The lasers are placed in an external cavity whose length is chosen in such a way that the distance between the longitudinal cavity modes is equal to the microwave modulation frequency. In this case, the radiation mode at the second frequency is not suppressed [6].

To control the laser frequency, we employ a system consisting of a spherical Fabry–Perot etalon with a free spectral range of 1740 MHz and a finesse of 100, a plane Fabry–Perot etalon with a free spectral range of 14 GHz and a resolution of 300 MHz, and a spectrometer. The spectrometer is interfaced with a CCD array and makes it possible to measure the spectral distribution of the radiation in a spectral window of 34 nm with a resolution of 3 GHz. To tune the laser frequency to the D_2 line of ^{85}Rb, we employ the radiation of a rubidium lamp whose frequency is compared to the laser frequency in the spectrometer. This detection system enables us to tune the laser frequency to the rubidium D_2 line, to analyze the multimode character of the laser radiation, and to measure the laser linewidth with an accuracy of 20 MHz.

Figure 4 shows the Fabry–Perot etalon transmission for the Hitachi 35 mW diode laser in an external cavity with the injection current modulation at a frequency of 2.915 GHz at various microwave powers. The spectra presented are obtained at a laser current of 60 mA and a radiation power of 14 mW. The laser cavity length is 50 ± 3 mm. It is seen that a variation in the microwave power leads to a wide-range variation in the intensity ratio of the radiation modes. The dependence of the laser radiation spectrum on the injection current is the following: at the given microwave frequency, the maximum spectral modulation is reached at a current of 44 mA, while a deviation from this value leads to a decrease in the signal amplitude at the side frequencies (see [7] for the details of this effect).

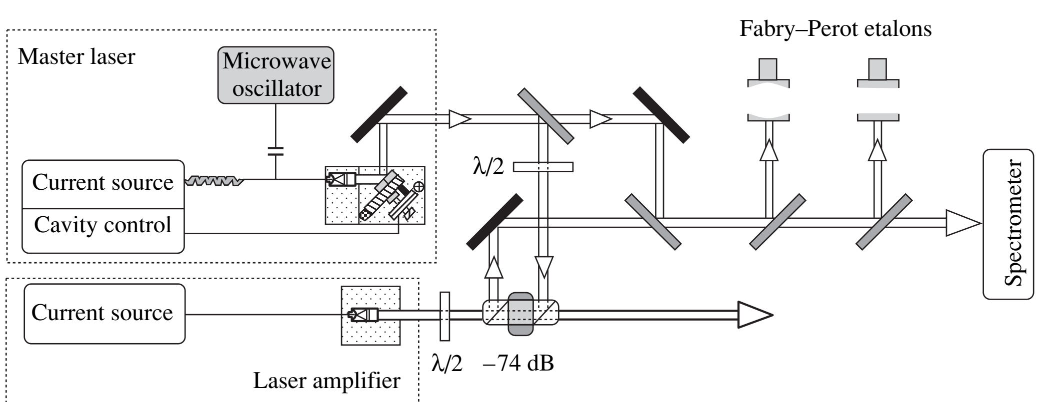

Fig. 3. Block diagram of the experimental setup.

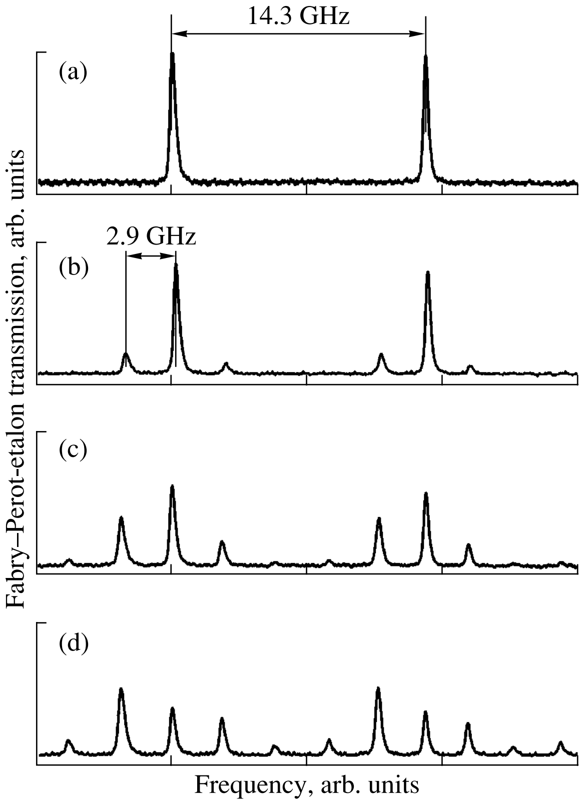

Fig. 4. Spectra of the master-oscillator radiation measured at the microwave powers ranging from (a) 0 to (d) 30 mW.

The analysis of the laser radiation spectrum upon the modulation of the current shows that, at the same injection currents and the microwave powers, diode lasers from different manufacturers exhibit substantially different modulation depths and the lasers of one manufacturer may exhibit a 20% spread in the modulation depths. The results of the study show that in the Hitachi and Sanyo lasers, the spectral modulation is reached at the lowest microwave power (at a microwave power of 30 mW, the radiation amplitudes at the side frequencies are equal to the radiation amplitude at the carrier frequency). In the Mitsubishi diodes, the same modulation is realized at a higher microwave power of about 100 mW. Significant modulation is absent in the Panasonic lasers even at a microwave power limit of 180 mW. A possible reason for this may lie in the difference of the diode-laser impedances resulting in different efficiencies with which the microwave power is fed to the lasers.

Another feature of the laser-current microwave modulation is the dependence of the absolute laser frequencies on the microwave power. In particular, a 10% variation in the microwave power leads to a simultaneous variation in all of the laser frequencies by 50 MHz. We assume that this feature is related to the effect of the microwave power fed to the diode laser on its thermal regime.

The two-frequency lasing of the diode laser causes difficulties in the laser frequency tuning to the atomic resonance. A conventional procedure for the tuning of a single-frequency diode laser to the atomic absorption line is based on choosing the values of current and temperature and the position of the intracavity diffraction grating. In the case of two-frequency radiation, the injection current strongly affects the modulation depth that should take on a fixed value. We employ the following method for the laser frequency tuning. Varying the injection current and the microwave power, we achieve the desired ratio of the radiation powers for the modes of the two-frequency laser. Then, we fix these parameters and set the desired laser frequency using the intracavity diffraction grating and temperature of the diode.

Based on the four-year laboratory application of the above method for obtaining two-frequency radiation with a semiconductor laser, we may characterize it as relatively simple and convenient. Note that the lifetime of diode lasers in our system is equal to the lifetime of conventional laser diodes (from one and a half to two years).

We employ two methods for the active frequency stabilization of the two-mode laser radiation: stabilization at the peak of the nonlinear absorption resonance and the method based on the Doppler broadened dichroic absorption signal (dichroic-atomic-vapor laser lock) [9]. Both approaches make it possible to stabilize the laser frequency with an accuracy of 3MHz for a few hours [12].

3. POWER AMPLIFICATION OF THE TWO-FREQUENCY LASER RADIATION

A method to increase the power of a single-frequency diode laser using injection locking is known from [1–3]. The radiation of the master laser is delivered to the active medium of a semiconductor laser (laser amplifier). The radiation is delivered to the amplifier via an optical diode (Fig. 3) that consists of two Faraday rotators with four polarizers. This makes it possible to decrease the part of the amplifier radiation coming back to the master laser by 74 dB (the corresponding power attenuation factor is 2.5×10^7). The spectral characteristics of the laser amplifier are governed by the characteristics of the laser oscillator, whereas the amplifier radiation power depends only on the amplifier current. We use this approach to increase the power of the two-frequency radiation of the master laser.

Figure 5 demonstrates the master laser radiation spectra (Fig. 5a) and spectra of a frequency locked laser amplifier at various injection currents (Figs. 5b–5f) measured with the Fabri–Perot interferometer. It is seen that the spectra of the amplifier radiation and the master-oscillator radiation are similar. The spectrum of the amplifier radiation contains modes corresponding to

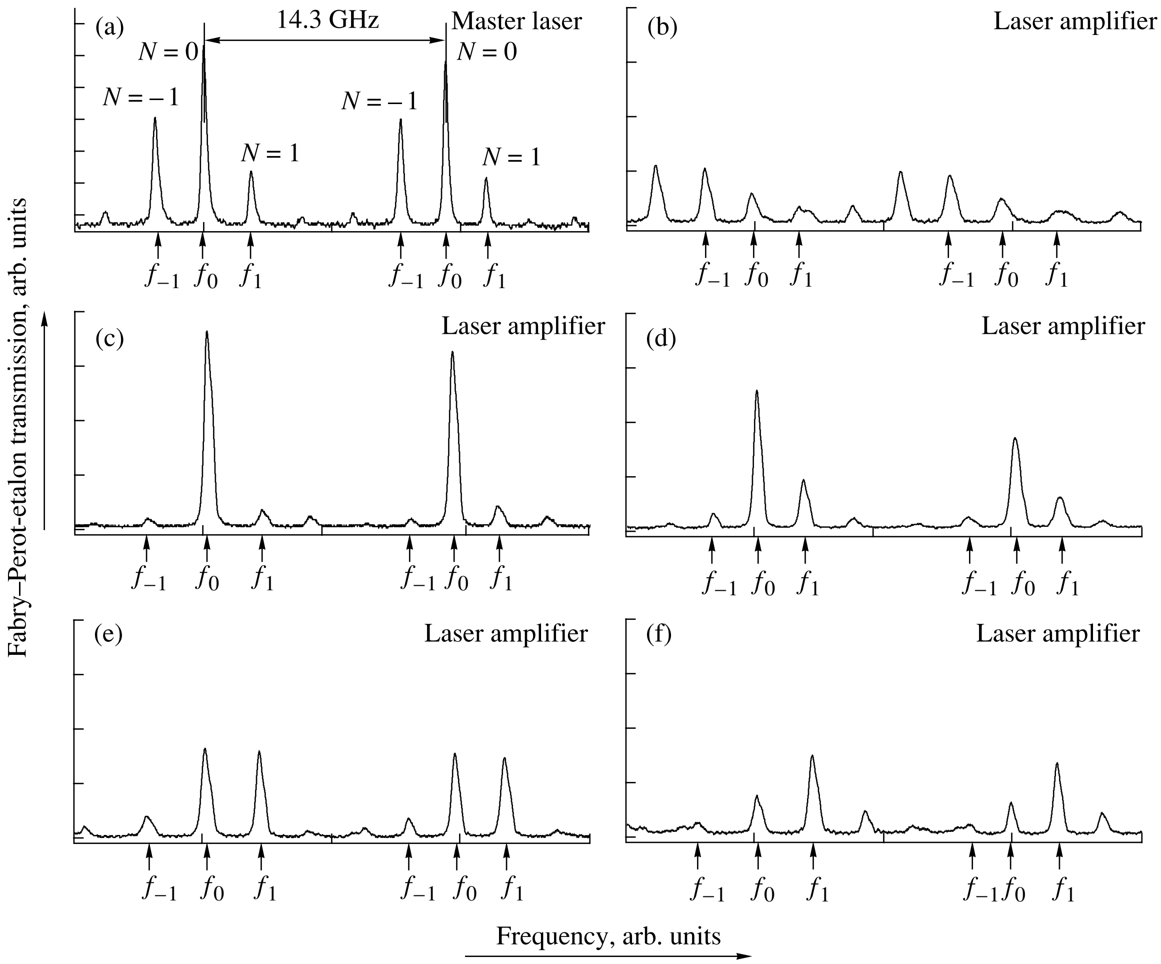

Fig. 5. (a) Spectrum of the master-oscillator radiation and (b)–(f) the corresponding spectra of the amplifier radiation measured upon the injection locking at injection currents of (b) 77.7, (c) 77.8, (d) 78, (e) 78.6, and (f) 81.4 mA.

the fundamental frequency f_0 and the side frequencies f_1 and f_{-1} of the master laser. The spectra shown in Figs. 5b–5f are measured in the range of the laser amplifier injection currents corresponding to stable frequency locking to the master laser. We have also investigated the frequency locking of the laser amplifier to the master laser during the scanning of frequency of the master laser: the scanning of the master-oscillator frequency leads to the synchronous scanning of the amplifier frequency.

It is seen from Fig. 5 that the relative powers of the laser amplifier radiation at the frequencies f_0, f_1, and f_{-1} strongly depend on the amplifier injection current. Specifically, for a current of 77.7 mA, the maximum radiation power corresponds to the modes with the frequencies f_{-1} and f_{-2} (Fig. 5b). The modes at the fundamental frequency f_0 dominate when the injection current is increased to 77.8 and 78 mA (Figs. 5c and 5d). At injection currents of 78.6 and 81.4 mA, we observe an increase in the radiation power at the frequency f_1. Thus, a variation in the injection current of the laser amplifier leads to a wide-range variation in the relative amplitudes of the amplifier modes corresponding to the frequencies of the master laser.

We studied factors that influence the stability of the laser amplifier frequency locking. The most important factors are (i) the closeness of the free-running frequency of the laser amplifier to the frequency of the master laser, (ii) the spatial overlapping of the master laser and laser amplifier beams, (iii) the radiation power of the master laser fed to the laser amplifier, and (iv) the matching of the wave fronts of the lasers. To satisfy the first condition (1), we choose two parameters of the laser amplifier (the values of current and temperature). The minimum radiation power of the master laser providing for stable frequency locking is 100 μW. In this case, the radiation power of the laser amplifier is 80 mW and the power gain is 800.

4. CONCLUSIONS

Microwave modulation of the diode-laser injection current and laser power amplification with injection locking are used to create a laser system with a multifrequency spectrum. Both the frequency difference between the laser modes and the relative intensities of the modes can be controlled in this system. The maximum radiation power is 80 mW. The laser system is successfully used in experiments on the Zeeman cooling of ^{85}Rb atoms in the presence of a transverse magnetic field [10] and a ^{85}Rb atomic beam focusing in a 2D magneto-optical trap [11].

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