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457-nm radiation source based on a diode laser for precision spectroscopy of magnesium atoms

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Abstract. **We report on the development of a highly stable source of 457-nm radiation based on a diode laser and a tapered amplifier operating in a double-pass scheme. The diode laser frequency was stabilised by a high-*Q* reference Fabry–Perot interferometer and doubled in a PPSLT nonlinear crystal placed in an enhancement cavity. At a maximum output power of 200 mW at a wavelength of 457 nm, the laser linewidth was less than 5 kHz. The radiation source operation was demonstrated in experiments on precision spectroscopy of cold magnesium atoms in a magneto-optical trap.**

Keywords: *frequency standards, magnesium, diode laser, tapered amplifier, magneto-optical trap, precision spectroscopy.*

1. Introduction

Optical frequency standards based on cold atoms are of great interest both for various applications in navigation and metrology and for fundamental physics. At present, optical frequency standards based on cold ytterbium, strontium, mercury, thulium, and magnesium atoms have already been created or are being developed [1]. Magnesium atoms have some attractive properties for application in optical frequency standards, namely, a small frequency shift of the clock transition due to black body radiation; a simple electronic configuration; the existence of a strong closed transition, which allows rapid and effective cooling to temperatures of 3–5 mK and localisation of atoms in a magneto-optical trap (MOT); and the presence of narrow optical transition between the ground $^1S_0$ transition and the $^3P_{0,1,2}$ triplet states. The $^1S_0 - {}^3P_1$ intercombination transition with the natural linewidth of $\sim$30 Hz is the narrowest intercombination transition among alkali-earth atoms, which are of interest for optical frequency standards. This transition can be used for achieving a high long-term stability of optical frequency standards. Despite some problems in creation of optical frequency standards based on magnesium atoms related to deep cooling of atoms to temperatures of $\sim$10 μK [2–4] and a relatively strong quadratic Zeeman effect [5], recent encouraging results demonstrate that magnesium atoms are promising for developing frequency standards with relative uncertainty of $10^{-17} - 10^{-18}$ [6].

To create an optical frequency standard with the use of the $^1S_0 - {}^3P_1$ intercombination transition of magnesium atoms, one needs a highly stable source of radiation at a wavelength of 457 nm. Today, such a source can be developed based on a dye laser [7], the second harmonic of a Nd:YVO_4 laser with λ = 914 nm [8], the second harmonic of a Ti:sapphire laser [9], the second harmonic of a diode laser with λ = 914 nm [10], and the direct emission of a diode laser with λ = 457 nm [11]. The diode laser emitting at λ = 457 nm can be most compact. However, a highly stable radiation with a power of $\sim$100 mW is required for frequency standards. At present, it is difficult to obtain such powers for laser diodes in the region of 457 nm. Moreover, there exist problems in the fabrication of mirrors highly reflecting in the blue region for interferometers used for preliminary stabilisation of laser frequency. Also, the transfer of the metrological characteristics of optical frequency standards from the blue spectral region is also problematic due to the operation of the conventional conventional femtosecond optical frequency combs in the near-IR region.

It seems that a system based on the second harmonic of a 914-nm diode laser is today most promising for creating a compact highly stable source at a wavelength of 457 nm for a frequency standard. For efficient conversion to the second harmonic, the radiation at 914 nm should have a sufficiently high power, of the order of 1 W. However, the output power of single-frequency laser diodes is usually several tens of milliwatts. One of the effective methods for increasing a laser system power from several milliwatts to 1 W was demonstrated in [12]. In the present work, we used this method and developed a laser system consisting of a laser diode emitting at a wavelength of 914 nm and a double-pass tapered amplifier (TA). The amplified radiation was used for second harmonic generation in a periodically poled stoichiometric lithium tantalate (PPSLT) nonlinear crystal. The obtained parameters of the radiation source allow one to perform experiments on high-resolution spectroscopy of cold magnesium atoms localised in a MOT and to use it as a clock laser in an optical frequency standard.

2. Experimental setup

The radiation source is a laser system based on a master oscillator and a power amplifier (MOPA). The experimental setup scheme is shown in Fig. 1.

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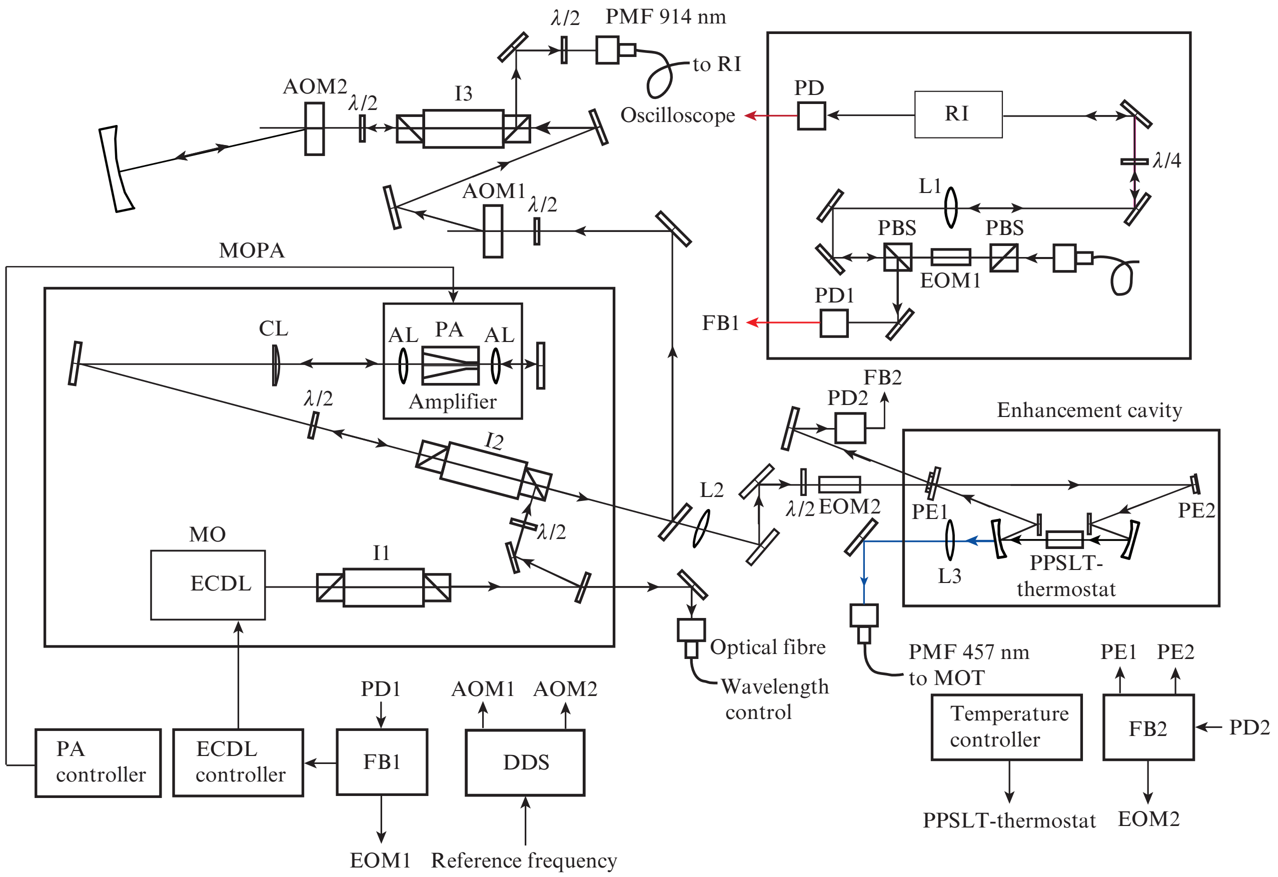

Figure 1. Scheme of the experimental setup:
(MO) external-cavity diode laser (ECDL); (PA) power amplifier (tapered amplifier); (AOM) acousto-optic modulator; (PMF) polarisation-maintaining fibre; (RI) reference interferometer; (PBS) polarising beam splitter; (EOM) electro-optic modulator; (DDS) direct digital synthesiser; (PD) photodetector; (FB1, FB2) feedback loops; (I1, I2, I3) optical isolators; (PE1, PE2) piezoelectric ceramic elements.

As a master oscillator, we used a diode laser with an external cavity designed according to the Littrow scheme (ECDL). The radiation wavelength was tuned by rotating the diffraction grating, by changing the voltage on piezoelectric ceramics on which the diffraction grating was mounted, and by changing the temperature and current of the laser diode. The laser power at a wavelength of 914 nm was 25 mW. The diode laser radiation propagated through an optical isolator I1, and a small part of radiation (~2 mW) was deflected by a beam splitter to a wavelength meter. The laser radiation was coupled into the amplifier using an optical isolator I2. Half-wave plates $\lambda/2$ were used to orient the polarisation and control the radiation power incident to the amplifier. The beams of the master oscillator and the amplifier were matched using two lenses, i.e., a cylindrical lens CL with a focal length $f = 75$ mm and an aspherical lens AL with $f = 4.5$ mm. The beam passed through an amplifier chip was collimated by another AL ($f = 4.5$ mm) and sent back using an optically dense plane mirror. We used a TA-0920-1000 chip (Coherent-Dilas) as an amplifier. The aspherical lenses and the amplifier chip were assembled in one housing mounted on a Peltier element, which allowed us to stabilise the temperature inside the amplifier housing. The maximum amplifier power, according to the manufacturer specification, may reach 1 W at a current of 2.6 A. The dependences of the amplified power on the current and on the power incident on the amplifier are shown in Fig. 2.

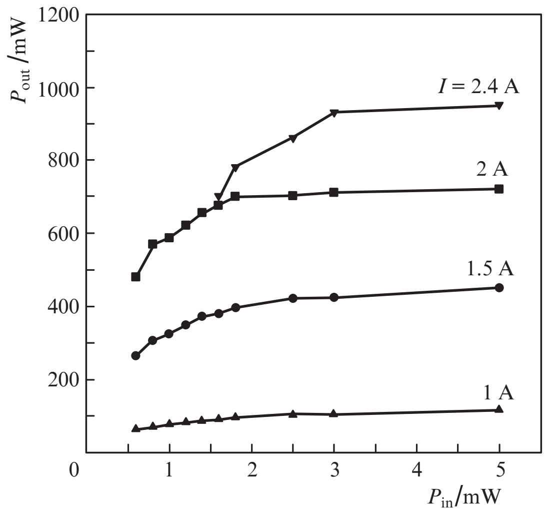

Figure 2. Dependences of the output amplifier power P_{out} on the power at the input to the amplifier P_{in} at different currents.

One can see that the amplifier at powers $P_{in} > 3$ mW is saturated at all current values. A part (approximately 10%) of the amplifier output power was deflected by a beam splitter to a frequency stabilisation system, while the main part of radiation was directed through a matching lens L2 to an enhancement cavity with a PPSLT nonlinear crystal. The cavity was assembled in a butterfly configuration with a 100-m radius of curvature of spherical mirrors. A nonlinear PPSLT crystal (Deltronic Crystal Industries Inc.) was placed in the beam waist between the spherical mirrors of the cavity. Both crystal faces were antireflection coated for wavelengths of 457 and 914 nm. The phase-matching temperature for λ = 914 nm at the structure period Λ = 4.9 μm was 87 °C and maintained using a TC-200 temperature controller (Thorlabs). The enhancement cavity transmission peak was stabilised to the diode laser frequency with the Pound–Drever–Hall technique [13].

The dependence of the second harmonic (λ = 457 nm) power on the power incident on the enhancement cavity (914 nm) is shown in Fig. 3. The second harmonic radiation was coupled out through one of the spherical mirrors of the enhancement cavity, collimated by lens L3, and coupled into a single-mode polarisation-maintaining fibre (PMF) for further experiments with cold magnesium atoms.

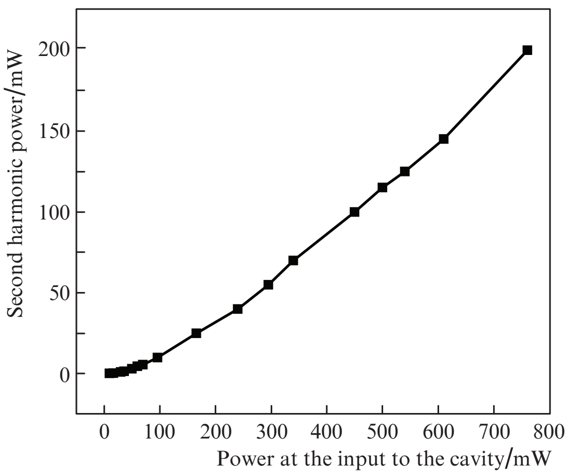

Figure 3. Dependence of the second harmonic power on the power of 914-nm radiation at the input to the enhancement cavity.

The laser system frequency was stabilised by the Fabry–Perot interferometer using the Pound–Drever–Hall technique [13]. The reference interferometer base was a sitall cylinder 20 mm long and 80 mm in diameter with an axial hole 10 mm in diameter and interferometer mirrors glued to its faces. The interferometer mounted in a copper heat screen was placed into a vacuum chamber whose temperature was maintained at 30 °C using a digital thermostabilisation system [14]. The vacuum chamber with the interferometer was mounted on a Minus K 100BM-4 vibration isolation table. The free spectral range (FSR) of the interferometer was FSR = 740 MHz and the finesse was F = 700. Since the frequency of the closest peak of the reference interferometer differed from the frequency of the clock transition $^1S_0$ – $^3P_1$ of the magnesium atom by approximately 30 MHz, the radiation was coupled into the interferometer through acousto-optic modulators AOM1 and AOM2. The first AOM, which operated at a frequency of 180 MHz, was used to provide a constant frequency shift. The double-pass AOM2 with an average frequency of 75 MHz was used to shift and tune the laser system frequency. The modulators were aligned so that the frequency shifts were divided. By changing the frequency of AOM2 by several megahertz, it is possible to precisely tune the laser frequency to the absorption line of the $^1S_0$ – $^3P_1$ clock transition of the magnesium atom. The frequencies of the modulators were set using a computer-controlled four-channel direct digital synthesiser (DDS). The diffracted radiation after the second pass through AOM2 was coupled out using an optical isolator I3 and directed to the reference interferometer through the fibre PMF.

The diode laser frequency stabilisation system (Servo Lock1) had two (slow and fast) control loops. The control signal of the slow loop was fed to the piezoelectric element of the diode laser, and the fast-loop signal controlled the LD current. The total bandwidth of the feedback system bandwidth was 900 kHz. The diode laser system linewidth obtained as a result of frequency stabilisation was estimated from the spectrum of the beat signal of the diode laser and a highly stable Ti : sapphire laser with a linewidth smaller than 100 Hz [15]. The beat signal spectrum is shown in Fig. 4. The obtained diode laser linewidth is determined by noises and parasitic signals in the feedback system and can be considerably decreased by using a reference interferometer with a higher Q-factor.

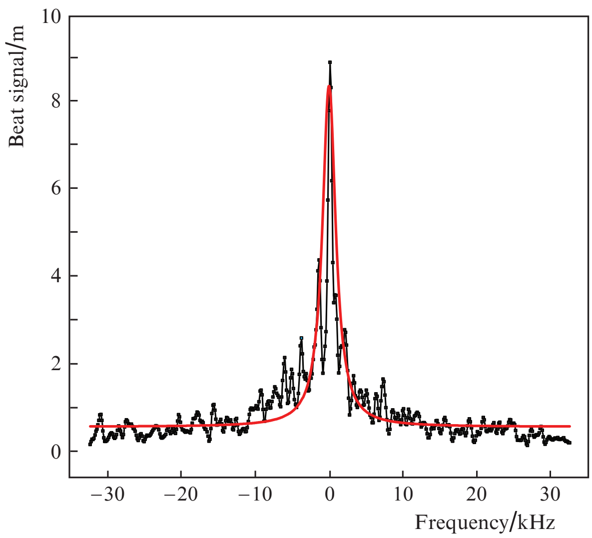

Figure 4. Spectrum of the beat signal of diode and Ti : sapphire lasers. The scanning time is SWT = 5 s, the resolution bandwidth (RBW) of the spectrometer is 100 Hz. The solid curve is the approximation by a Lorentzian function with a FWHM of 2.5 kHz.

To test the operation of the developed radiation source, we performed experiments on recording Ramsey–Borde resonances in time-separated laser fields interacting with cold magnesium atoms in a magneto-optical trap [7]. The scheme of the setup for recording the Ramsey–Borde resonances in a MOT is shown in Fig. 5. In this method, a cloud of cold magnesium atoms successively interacts with four light field pulses (two pulses from one side and two pulses from the opposite side), which are formed by the acousto-optical modulators. The width of the recorded resonances depends on the duration of light pulses and on the time delay between unidirectional pulses in a pair [15].

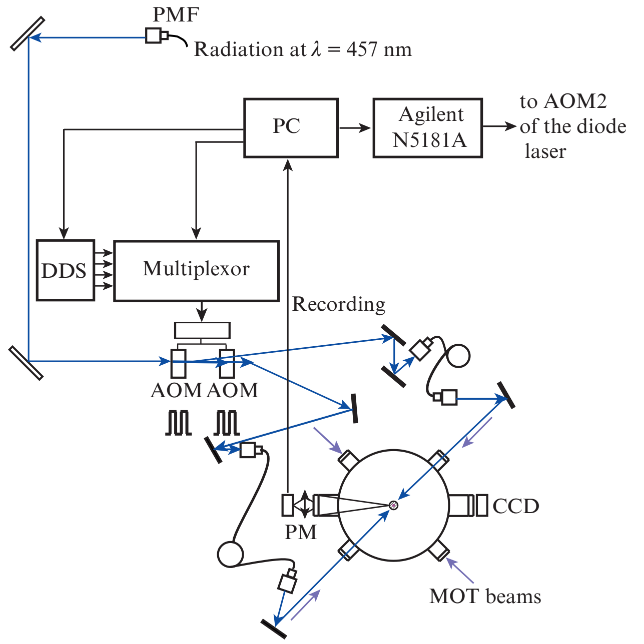

Figure 5. Scheme of the setup for recording the Ramsey–Borde resonances in a MOT:
(DDS) four-channel direct digital synthesiser; (PM) photomultiplier; (CCD) CCD camera; (PC) personal computer.

The diode laser system radiation (λ = 457 nm) was fed to the setup through a single-mode PMF. The setup for recording the Ramsey–Borde resonances is described in detail in [16]. This recording was performed by tuning the frequency of the diode laser system using an Agilent N5181A synthesiser, which controlled the AOM2 frequency. The luminescence signal of cold magnesium atoms at the $^1S_0 - {}^1P_1$ transition at a wavelength of 285 nm was recorded by a photomultiplier. The Ramsey–Borde resonances recorded using the diode laser system are shown in Fig. 6. The good contrast of

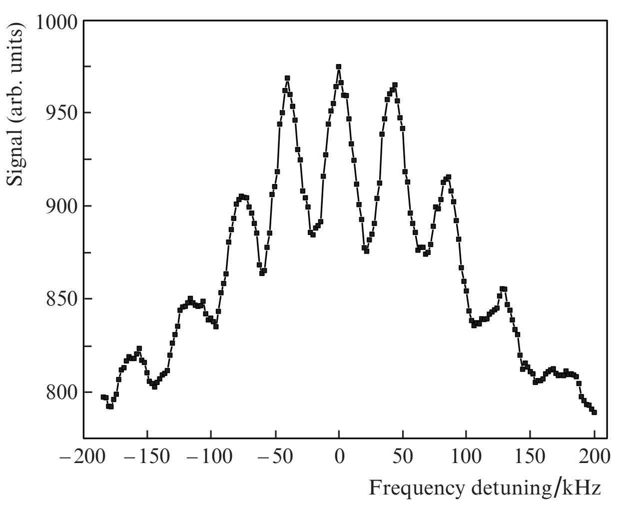

Figure 6. Ramsey–Borde resonances in time-separated fields interacting with a cloud of cold magnesium atoms in a MOT. The delay time between pulses in the pair of unidirectional waves is 7.5 µs, which corresponds to the resonance width $\Delta \approx$ 20 kHz. The integration time for each point (200 points) is 0.1 s.

the Ramsey–Borde resonances allows us to conclude that the developed radiation source can be used as a clock laser in experiments on high-resolution spectroscopy of cold magnesium atoms localised in a MOT.

Presently, the radiation linewidth Γ < 5 kHz of the developed source is limited by the reference interferometer used for frequency stabilisation. The obtained power $P \approx$ 200 mW at a wavelength of 457 nm is sufficient for spectroscopy of the magnesium clock transition oand for creating a magnesium frequency standard.

3. Conclusions

Thus, we developed a frequency-stabilised 457-nmr adiation source based on a diode laser and a tapered amplifier with parameters that allow one to use it in experiments on developing a frequency standard based on cold magnesium atoms. In comparison with a system based on a Ti:sapphire laser, the developed radiation source is easier to operate and has smaller dimensions and a considerably lower cost. In the future, we plan to considerably increase the frequency stability of the developed source by using a reference interferometer with a higher Q-factor and by improving the frequency stabilisation system.

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