Quantum Electronics **44** (6) 527–529 (2014)

PACS numbers: 37.10.Ty; 42.62.Eh; 42.55.Px; 42.65.Ky
DOI: 10.1070/QE2014v044n06ABEH015450

Laser system for Doppler cooling of ytterbium ion in an optical frequency standard

S.V. Chepurov, A.A. Lugovoy, S.N. Kuznetsov

Abstract. **A laser system for Doppler cooling of ytterbium ion on the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ transition in a single-ion optical frequency standard is developed. The second harmonic of a semiconductor laser with a wavelength of 739 nm is used for cooling. The laser frequency is doubled in a nonlinear BiBO crystal embedded in a ring resonator, which also serves as a reference for laser frequency stabilisation. Second-harmonic power of ~100 μW is generated at a wavelength of 369.5 nm. Diode laser radiation is modulated by an electro-optic modulator at 14.75 GHz to generate a sideband exciting the $^2S_{1/2}$ (F = 0) → $^2P_{1/2}$ (F = 1) hyperfine component of the cooling transition that is not excited by resonant cooling light. The sideband relative intensity of a few percent proved to be sufficient to reduce the ion dwelling time in the $^2S_{1/2}$ (F = 0) state to less than 10^{-4} s and increase the cooling efficiency.**

Keywords: *diode laser, frequency doubling, frequency stabilisation.*

1. Introduction

Frequency standards play a very important role in both fundamental research and various applications. This is primarily related to the fact that the accuracy of modern frequency standards, which implement a reference for one of the basic units of measure of the SI system (second) is several orders of magnitude higher than the accuracy of references for other physical values.

The development of a new generation of high-precision optical frequency standards is a fundamental problem of precise laser spectroscopy. Currently, the standards based on atoms or ions localised in space are considered to be the most stable ones [1–4].

A promising candidate for the use in these optical frequency standards is the ^{171}Yb ion. The specific features of the energy level diagram of ytterbium ion make it possible to develop optical frequency standards based on two transitions (Fig. 1): (i) the $^2S_{1/2}$ (F = 0) → $^2D_{3/2}$ (F = 2) quadrupole transition with a wavelength λ = 436 nm and a natural linewidth of 3.1 Hz and (ii) the $^2S_{1/2}$ (F = 0) → $^2F_{7/2}$ (F = 3) octupole transition at λ = 467 nm with a natural lifetime of several years [5–7]. Ions are localised in traps in the Lamb–Dicke regime using Doppler laser cooling (see, for example, [8, 9]) on the $^2S_{1/2}$ (F = 1) → $^2P_{1/2}$ (F = 0) transition with λ = 369.5 nm and a natural linewidth of 23 MHz. The Doppler limit temperature for this transition is $T_D \sim 0.37$ mK. The possibility of using compact diode lasers in schemes of ion cooling and clock-transition detection, along with the application of fibre lines for delivering laser radiation, makes the ^{171}Yb ion an optimal candidate for designing on-board optical frequency standards. In this paper, we report the results of developing a laser system with a wavelength λ = 369.5 nm for Doppler cooling of ^{171}Yb ion in an optical frequency standard.

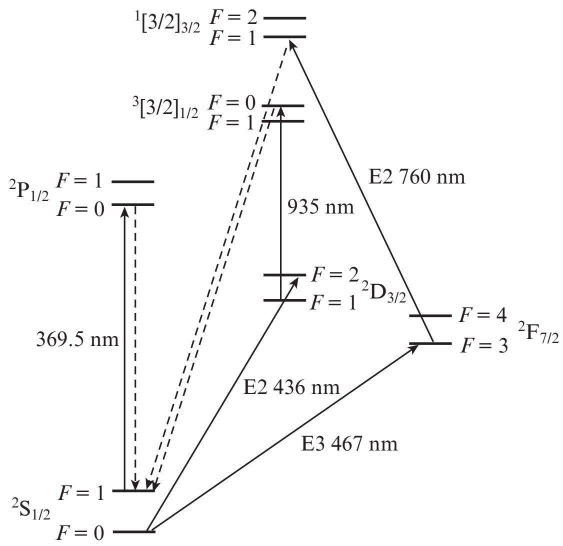

Figure 1. Energy level diagram of Yb$^+$ ion.

S.V. Chepurov, A.A. Lugovoy, S.N. Kuznetsov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: svc04@ngs.ru

Received 3 March 2014; revision received 21 March 2014
Kvantovaya Elektronika **44** (6) 527–529 (2014)
Translated by Yu.P. Sin'kov

2. Laser cooling system

Figure 2 shows a schematic of the laser system for Doppler cooling of ytterbium ion. A trapped ion is cooled by frequency-modulated 10-μW radiation at λ = 369.5 nm, i.e., the second harmonic of a semiconductor laser with a fundamental wavelength λ = 739 nm.

The cooling laser is an external-cavity diode laser, working according to the Littrow configuration (Toptica DL100L). The output (after the optical isolator) laser power at λ = 739 nm is 12 mW. The output beam has a cross section 2.8 × 1 mm; the beam shape was corrected using an anamorphic objective with an anamorphosis coefficient of 3. To cool an ion to the Doppler temperature limit, one must precisely tune the cooling radiation frequency. By changing temperature, as well as

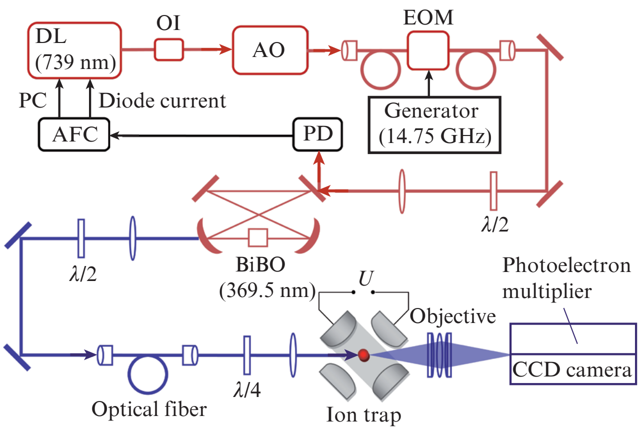

Figure 2. Schematic of the laser system for cooling Yb^+ ion: (DL) diode laser, (OI) optical isolator, (AO) anamorphic objective, (PC) piezoelectric ceramic, (AFC) automatic frequency control system, (PD) photodetector, and (EOM) electro-optic modulator.

the laser diode current, one can tune the laser frequency within the range between the external-resonator longitudinal modes (9 GHz). Continuous frequency tuning within several intermodal ranges (to 20 GHz) can be implemented when the resonator length and diode current change synchronously. The external-resonator laser used in this study has a radiation linewidth of ~100 kHz.

One of the most appropriate materials for frequency doubling in the wavelength range under consideration is bismuth triborate BiB_3O_6 (BiBO). Nonlinear BiBO crystals are characterised by a rather large effective nonlinear coefficient D_{eff} = 3.3 pm V^{-1}, high damage threshold and absence of hygroscopicity. We used a crystal 10 × 3 × 3 mm in size with type-I phase matching; the phase-matching angle necessary for doubling the frequency of radiation with λ = 739 nm is 145.5° for this crystal.

Under optimal phase-matching conditions, the power of generated second harmonic is given by the expression [10]

$$P_2 = \frac{P_1^2(\omega_1^2 k_1 D_{eff} Lh)}{\pi n_1^2 n_2 c^3 \varepsilon_0}.$$

Here, P_2 is the second-harmonic power; P_1 is the fundamental-radiation power; ω_1 and k_1 are, respectively, the optical frequency and modulus of the fundamental-radiation wave vector in the medium; n_1 and n_2 are, respectively, the refractive indices for the fundamental and second-harmonic frequencies; $D_{eff} = d_{31}\sin\theta_m$; θ_m is the phase-matching angle; L is the crystal length; and h is a geometric factor, which takes into account the effects of focusing and limited overlap of the fundamental and second-harmonic beams because of the birefringence. For λ = 739 nm and θ_m = 145.5°, the calculated efficiency of second-harmonic generation is $P_2/P_1 \sim 10^{-4}$.

To increase the efficiency of doubling the diode-laser radiation frequency, a nonlinear crystal was embedded in an enhancement ring resonator, which serves simultaneously as a reference resonator for laser frequency stabilisation. The resonator includes two plane mirrors (the input mirror has a transmittance of 0.01) and two spherical mirrors with a working-surface radius of curvature of 50 mm, which form a beam waist in the crystal with a radius of 21 μm. The free spectral range of the resonator is Δf = 740 MHz. A spherical lens with a focal length of 500 mm was used to implement spatial matching of the input beam with the resonator mode.

Figure 3 shows a change in the radiation power reflected from the input mirror of ring resonator for the case where the diode laser frequency is in resonance with the resonator mode. The FWHM of the resonant dip (transmission peak) is $\delta f \approx$ 1.65 MHz. The resonator finesse F, determined as the ratio of the free spectral range Δf to the transmission peak FWHM δf, amounts to 450. The dip amplitude corresponds to the residual resonator reflectance $R_r = 1 - 6/8.5 = 0.29$. For diode laser radiation with power of ~5 mW at the input of enhancement resonator and electronic laser frequency stabilisation with respect to resonance, the second-harmonic power at λ = 369.5 nm was found to be ~100 μW. Figure 4 presents a dependence of the second-harmonic power on the fundamental-radiation power.

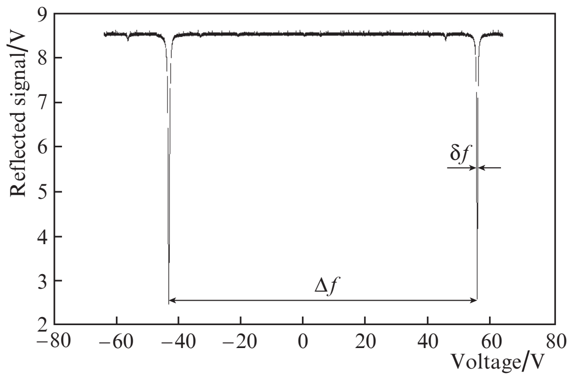

Figure 3. Resonant change in the power of diode laser beam reflected from the input mirror of the enhancement ring resonator, obtained by scanning the laser frequency.

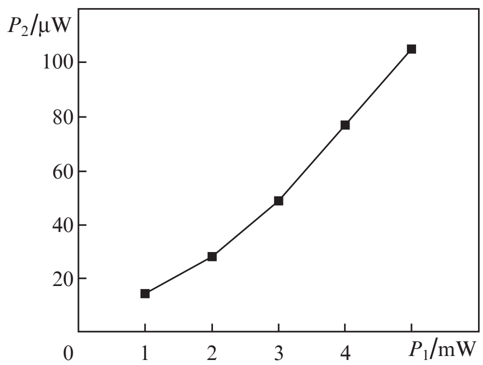

Figure 4. Dependence of the second-harmonic power on the fundamental-radiation power.

The experimentally obtained harmonic power can be compared with the theoretical estimate, based on the calculated conversion efficiency of BiBO crystal, the observed optical power loss and the measured finesse of the enhancement ring resonator. The observed resonator finesse corresponds to a relative power loss per pass through the resonator, $T_{rt} = 2\pi/F \approx 0.014$. The input-mirror transmittance is $T_m = 0.01$; hence, when mode matching is implemented in the resonator, the input-radiation gain is $k = 4T_m/T_{rt}^2 = 204$ and the residual reflectance (caused by the presence of loss and spatial beam mismatch) is $R_L = (T_{rt} - 2T_m)^2/T_{rt}^2 \approx 0.18$. The observed residual reflectance of the enhancement resonator is $R_r \approx 0.29$ (see above).

The excess of R_r above R_L, equal to approximately 0.11, can be explained by inaccurate spatial matching of the laser beam with the resonator mode and the high-frequency noise of diode laser, which is beyond the bandwidth of the automatic frequency control (AFC) system. The intracavity power, with allowance for the input beam power $P_{DL} = 5$ mW, is determined as $P_c = (1 - R_r + R_L)kP_{DL} = 908$ mW. For a BiBO fundamental-to-second-harmonic conversion efficiency of $\sim 10^{-4}$, the calculated harmonic power is $\sim$91 μW; this value is in fairly good agreement with the experimental data.

To implement efficient second-harmonic generation, the spectrum of diode-laser power should be mostly within the enhancement resonator linewidth; active stabilisation of laser frequency must be performed to this end. The laser frequency is stabilised with respect to the transmission peak of enhancement resonator using the AFC system (Fig. 2). The error signal for AFC is formed using weak frequency modulation of laser beam by means of the modulation of diode current at a frequency of 200 kHz and further lock-in detection of modulated power with respect to the signal reflected from the enhancement resonator. The low-frequency (to 1 kHz) and high-frequency (to 20 kHz) error-signal components are used to stabilise the diode laser frequency by controlling (with the aid of piezoelectric ceramic) the length of external laser resonator and the diode current, respectively.

The harmonic frequency is tuned into resonance with the frequency of ion cooling transition by varying the enhancement resonator length using a piezoelectric ceramic. The tuning range is limited by the dynamic range of piezoelectric transducer and amounts to 6 GHz. To reduce fluctuations of the enhancement resonator length, all optical components of the resonator are mounted on a monolithic thermally stabilised base.

The diode laser radiation is modulated by an electro-optic modulator at a frequency of 14.75 GHz to generate the spectral component exciting the hyperfine component of the $^2S_{1/2}$ $(F = 0) \rightarrow {}^2P_{1/2}$ $(F = 1)$ (Fig. 1) cooling transition (the component that is not excited by resonant cooling radiation). Modulation is performed using a lithium niobate electro-optic modulator EO Space PM-0K5-20-PFA-PFA-740 with optical fibre input and output. The free spectral range of the ring resonator is chosen so as to make the modulation and carrier frequencies be in resonance. Thus, the spectrum of radiation at the output of the cooling laser system contains, along with the fundamental (resonant) frequency at 369.5 nm, two sideband frequencies, spaced from the resonant one by 14.75 GHz. The intensity of the sideband components is few percent of the resonant line intensity, which is sufficient to reduce the ion residence time in the $^2S_{1/2}$ $(F = 0)$ state to a value smaller than 10^{-4} s.

Currently, the Doppler cooling of a trapped ion using the laser system, reported here, is under way. Cooling is performed by 10-μW second-harmonic radiation, focused into a waist 50 μm in diameter. The ion fluorescence, induced by cooling radiation, is projected by a multilens objective onto a photoelectron multiplier and a CCD camera (Fig. 2).The camera image is used to determine the number of particles captured in a trap and monitor the ion position in the trap. The photoelectron multiplier signal is used to determine the total fluorescence rate with a high time resolution.

3. Conclusions

Thus, we developed a laser system for Doppler cooling of ytterbium ion on the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ transition in a single-ion-based optical frequency standard. Cooling is performed by second-harmonic radiation of a semiconductor laser with a wavelength $\lambda = 739$ nm. Frequency doubling is implemented using a BiBO crystal embedded in a ring resonator, which serves simultaneously as a reference resonator for laser frequency stabilisation. The second-harmonic output power at $\lambda = 369.5$ nm is $\sim$100 μW. The diode laser radiation is modulated by the electro-optic modulator at a frequency of 14.75 GHz to generate the spectral component exciting the hyperfine component of the $^2S_{1/2}$ $(F = 0) \rightarrow {}^2P_{1/2}$ $(F = 1)$ cooling transition that is not excited by resonant cooling radiation. The sideband component intensities are a few percent of the resonant line intensity. This value is sufficient to reduce the ion dwelling time in the $^2S_{1/2}$ $(F = 0)$ state to less than 10^{-4} s and increase the cooling efficiency.

Acknowledgements. This work was supported by the Presidium of the Russian Academy of Sciences (Extreme Light Fields and Their Applications Programme).

References

1. Huntemann N., Okhapkin M., Lipphardt B., Weyers S., Tamm Chr., Peik E. *Phys. Rev. Lett.*, **108**, 090801 (2012).
2. Madej A.A., Dube P., Zhou Zichao, Bernard J.E., Gertsvolf M. *Phys. Rev. Lett.*, **109**, 203002 (2012).
3. Hinkley N., Sherman J.A., Phillips N.B., Schioppo M., Lemke N.D., Beloy K., Pizzocaro M., Oates C.W., Ludlow A.D. *Science*, **341** (6151), 1215 (2013).
4. Chou C.W., Hume D.B., Koelemeij J.C.J., Wineland D.J., Rosenband T. *Phys. Rev. Lett.*, **104**, 070802 (2010).
5. Fisk P.T.H. *Rep. Prog. Phys.*, **60**, 761 (1997).
6. Roberts M., Taylor P., Barwood G.P., Gill P., Klein H.A., Rowley W.R.C. *Phys. Rev. Lett.*, **78**, 1876 (1997).
7. Schneider T., Peik E., Tamm Chr. *Phys. Rev. Lett.*, **94**, 230801 (2005).
8. Wineland D.J., Itano W.M. *Phys. Rev. A*, **20**, 1521 (1979).
9. Stenholm S. *Rev. Mod. Phys.*, **58** (3), 699 (1986).
10. Boyd G.D., Kleinmann D.A. *J. Appl. Phys.*, **39**, 3597 (1968).