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Single-frequency tunable laser for pumping cesium frequency standards

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***Abstract*. A single-frequency tunable laser for pumping the cesium frequency standard is studied. It is shown experimentally that the laser emits at a single frequency despite the fact that a few longitudinal modes of the external cavity fall within the reflection band of a fibre Bragg grating (FBG) written in the optical fibre. The laser wavelength can be tuned by varying the pump current of the laser, its temperature, and the FBG temperature. The laser linewidth does not exceed 2 MHz for 10 mW of output power.**

Keywords: *single-frequency tunable laser, frequency standards, fibre Bragg grating.*

1. Introduction

In the last 10 – 15 years a technical innovation has literally rushed into our life and has become widespread at once, having found wide applications not only in complicated scientific and technological studies but also in homes. This novelty is global navigation satellite systems: the American Global Positioning System (GPS) and Russian Global Navigation Satellite System (GLONASS). The global operation of these systems is provided by a set of satellites visible from any point on the Earth, which continuously transmit highly accurate measurement signals. In this way, as if the information coordinate-temporal field is produced around our planet from which a user can obtain the data on its position in space and time by using a special receiver [1].

A basic instrument providing a high-precision navigation and temporal operation of global positioning systems is a cesium frequency standard based on an atomic-beam tube (ABT). At present, commercial ABTs with a magnetic selection of atomic states have been developed almost to perfection. The parameters of ABTs can be significantly improved only by using a fundamentally new scheme of laser excitation and detection of the atomic beam.

The use of optical methods in ABTs makes it possible to replace the magnetic selection of atoms over their states by more efficient methods of optical pumping and optical detection. As a result, the design of the device is simplified, its weight is decreased, and the efficiency of using the working substance and the output signal amplitude are considerably increased.

The most promising for using in ABTs are single-frequency semiconductor injection lasers, which have a very small size and weight, are simply pumped, and possess a high conversion efficiency of electric power to coherent radiation in the wavelength range from 850 to 895 nm covering the region of resonance optical transitions in cesium atoms.

To obtain the single-frequency regime in a semiconductor laser, several variants of its design have been proposed.

2. Designs of single-frequency lasers

2.1 Short cavity laser

The single-frequency operation in lasers of this type is achieved by decreasing the cavity length, which results in the increase in the mode interval

$$\delta\lambda = \lambda_m - \lambda_{m-1} = \frac{\lambda^2}{2n_{gr}L}, \qquad (1)$$

where λ_m is the wavelength of the mth mode; n_{gr} is the group refractive index; and L is the cavity length.

As the mode interval increases, the gain of the side modes decreases and the laser generates one longitudinal mode [2].

2.2 External cavity lasers

The design of a laser diode with an external cavity whose waveguide layer was grown from a material transparent for laser radiation is described in [3]. The laser diode was fabricated of the InGaAsP/InP heterostructure ($\lambda =$ 1.3 μm), while the external cavity was made of the specially grown GaAlAs/GaAs heterostructure ($\lambda = 0.8 - 0.9$ μm). The waveguide-layer thickness was ~ 2 μm, which made it possible to bring automatically the active region of the laser diode into coincidence with the waveguide layer of the external cavity upon soldering them on a heat sink.

The laser cavity length L_1 differed from the external cavity length L_2. When the difference $\Delta L = |L_1 - L_2|$ in the cavity lengths is small compared to L_1 and L_2, the interference maxima of each of the cavities are periodically coincident in such a system. In the spectrum of coupled cavities the beatings appear with the interval

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$$\delta\lambda = \frac{\lambda^2}{2(L_1 n_{1\text{gr}} - L_2 n_{2\text{gr}})}, \quad (2)$$

where $n_{1\text{gr}}$ and $n_{2\text{gr}}$ are the group refractive indices of the laser and external cavity.

By selecting appropriately the lengths of the laser diode and external cavity, single-frequency lasing is provided due to the 'nonius' effect.

2.3 C^3 lasers

Unlike the previous scheme where the laser and external cavity were fabricated of different materials, C^3 lasers consist of two optically coupled sections made of the same material, each of the sections being pumped by its own current.

A composite cavity laser with optically coupled sections was studied in detail in [4].

2.4 Periodic structure lasers (distributed feedback and distributed Bragg reflector lasers)

Distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers were studied in many papers (see, for example, [4, 5] and references therein).

The cavities of these lasers are a modification of a plane Fabry–Perot resonator to which a periodic spatial modulation structure is added. The periodic structure in DFB lasers coincides with the active region, while in DBR lasers it lies outside the active region. The periodic structure in DFB and DBR lasers affects their radiation parameters and reduces the dependence of the laser wavelength on the injection current and temperature compared to that in Fabry–Perot lasers. An advantage of DFB and DBR lasers is that their radiation can be modulated almost by 100 % without changing the spectrum.

Any parameters of the laser affecting the propagation of an electromagnetic wave in it (the refractive index of the medium, the decay coefficient or gain, the waveguide cross section, etc.) can be spatially periodically modulated.

Reviews of studies on single-frequency DFB and DBR lasers are presented in [6–8].

2.5 External diffraction grating laser

Radiation from a laser diode is directed with the help of a collimating optics to a diffraction grating tilted at a certain angle to provide feedback with the laser. The diffraction grating of the laser diode cavity is covered with an AR coating, and the second mirror of the laser diode is covered with a reflection or protection coating. The laser can be continuously tuned by rotating the diffraction grating.

A compact laser diode for spectroscopy and metrology was considered in [9]. In [10], a vertical silicon diffraction grating laser was studied. The continuous tuning ranges of external selective cavity injection lasers were considered in detail in [11, 12].

2.6 Fibre Bragg grating laser

The scheme of this laser is similar to those considered in section 2.5, the only difference being that the Bragg grating is produced in an optical fibre [13, 14]. The radiation dynamics of the laser with a strong feedback was studied in [15].

2.7 Vertical-cavity surface-emitting laser (VCSEL)

Lasers of this type operate in the single-mode regime and use a very short cavity (of the order of 1 μm) for which the longitudinal-mode interval is greater than the gain bandwidth. A laser emitting at $\sim$ 850 nm and having the pump current threshold of 310 μA is described in [16]. The output power of this laser was 1 mW for the pump current of 1.6 mA.

2.8 Other designs of single-frequency lasers

Single-frequency single-component lasers with a plane Fabry–Perot resonator emitting up to 20 mW in the region from 780 to 850 nm were developed and studied in [17].

An external dispersion cavity semiconductor laser in which partial discrimination is performed with a loop fibre reflector with a spliced selective single-mode coupler was developed in [18].

A highly coherent injection laser with an optical feedback via a whispering-gallery mode microcavity was studied in [19].

In [20], the scheme of an external cavity with a waveguide-diffraction mirror was proposed for a wide-aperture semiconductor laser.

Thus, one of the main methods for selecting modes of a laser diode is the use of a diffraction grating that can be rotated to change the laser wavelength. A disadvantage of this method is that the grating is rotated with the help of a mechanical system, which has a poor reliability. Piezoelectric ceramics that can be used to adjust the position of the diffraction grating requires high-voltage power supplies. The applications of tunable DFB and DBR lasers are restricted by their complicated manufacturing technology.

In this paper, we propose the laser design based on a diffraction grating produced in an optical fibre.

A diffraction grating produced in a fibre is mounted on the opposite side to the output mirror of the laser cavity (Fig. 1). This makes it possible to increase the reflectance of the diffraction grating up to 100 % and to decrease the lasing threshold, thereby reducing the energy consumption in the laser. The fibre with the grating written in it is mounted on a separate microcooler, so that the grating temperature can be varied independently of the laser crystal temperature, which cannot be done in DFB and DBR lasers.

We used laser diodes made of single-quantum well GaAlAs/GaAs heterostructures grown by the method of MOS hydride epitaxy. The width of a mesostrip was 3 μm and the cavity length was 600 μm. The laser diode was soldered on a copper heat sink by its active side up. The

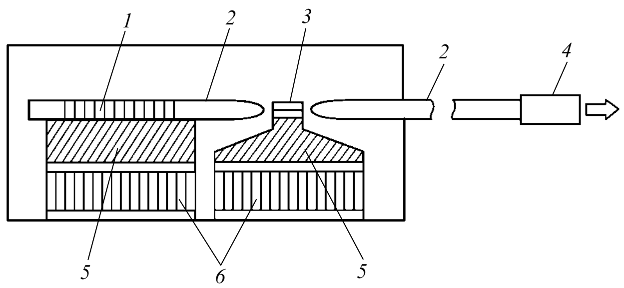

Figure 1. Design of the active element of a laser with a diffraction grating and a collimator: (*1*) fibre diffraction grating; (*2*) optical fibre; (*3*) laser crystal; (*4*) collimator (gradient lens); (*5*) copper mount; (*6*) microcooler.

crystal facet facing the grating was covered with an AR coating and the opposite facet had a protective coating.

The reflectance of the FBG was $\sim 90\,\%$. This grating, together with the crystal facet with the protective coating ($R \sim 30\,\%$) forms a cavity which determines the basic parameters of the laser such as the emission wavelength, linewidth, output power, and pump current. A gradient lens collimator determines the angular divergence and cross section of the laser beam.

The emission wavelength was tuned by heating (or cooling) the FBG by a microcooler. The selected operating temperature of the grating was maintained with a high accuracy by using an electronic stabilisation system.

The radiation parameters were stabilised by mounting the laser diode on a separate microcooler. By varying the pump current of the laser diode, its temperature or grating temperature, the laser wavelength was tuned to the D_2-line of cesium. Figure 2 presents the general view of the radiation source.

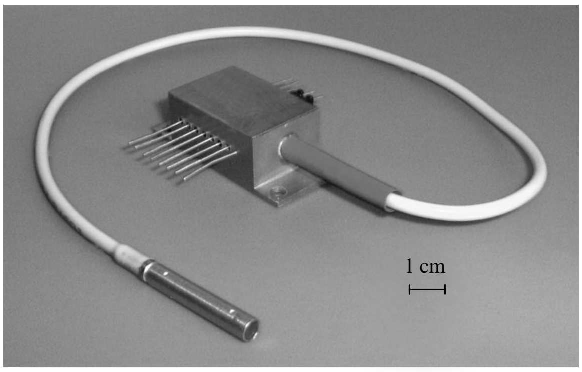

Figure 2. General view of the radiation source.

3. Results of the study of the radiation source parameters

Figure 3 shows typical light – current characteristics of the laser diode with a cavity formed by cleaving a heterostructure along the crystallographic axes. Curve (*1*) corresponds to the operation of the laser without coatings,

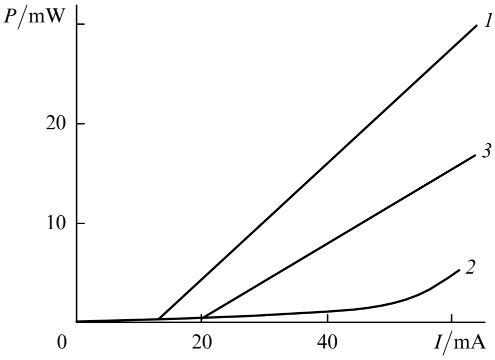

Figure 3. Light – current characteristics of the laser diode with the reflectance of the front and back facets $\sim 30\,\%$ (*1*), with the front- and back-facet reflectances $R \to 0$ and $\sim 30\,\%$, respectively (*2*), and of the fibre grating radiation source (Fig. 1) at the collimator output (*3*).

when the reflectances of the front and back facets of the cavity are equal to $\sim 30\,\%$. Curve (*2*) shows the light – current characteristic of the laser fabricated of the same heterostructure in which an AR coating ($R \to 0$) is deposited on the front facet of the cavity and the back facet has a protective coating (the reflectance of this facet remaining $\sim 30\,\%$). Curve (*3*) shows the light – current characteristic of the laser with the FBG recorded at the collimator output.

The AR coating of the cavity facet drastically increases the lasing threshold of the laser and transfers it to the superluminescence regime. This is well demonstrated by the emission spectra of the laser with the reflectance of facets of $\sim 30\,\%$ and with the reflectance of the first facet $R \to 0$ (Fig. 4b). In the latter case, the FWHM of the emission spectrum exceeds 20 nm.

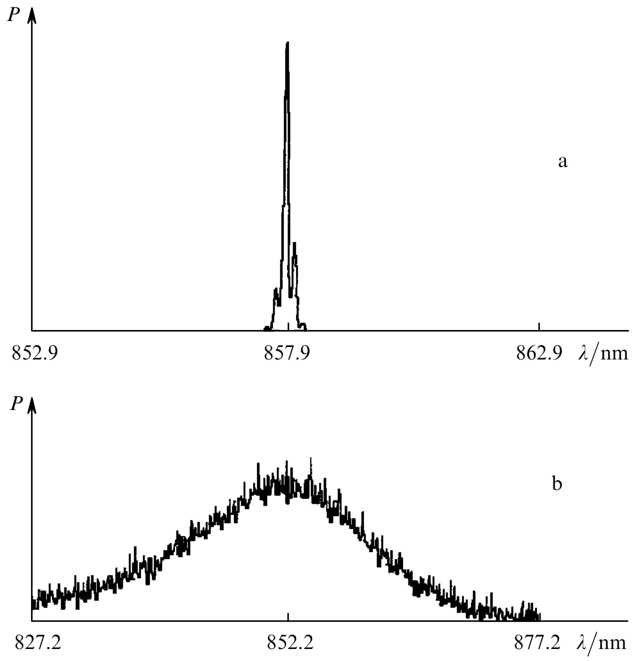

Figure 4. Emission spectra of the laser diode with the reflectance of facets $\sim 30\,\%$ (a) and the reflectances of the front and back facets $R \to 0$ and $\sim 30\,\%$, respectively (b).

The maximum of the electroluminescence spectrum (Fig. 4b) is shifted with respect to the laser line (Fig. 4a) to the blue by 5.7 nm.

Of most interest are the spectral characteristics of the radiation source. The matter is that several modes of the external cavity formed by the external facet of the laser crystal without the AR coating and the FBG fall into the reflection band (of width 0.15 nm) of the FBG. Because the gain bandwidth is much greater than the mode distance in the external cavity, it can be expected that generation will occur at several longitudinal modes. However, our experiments showed that this is not the case. Figure 5a presents the emission spectrum of the laser recorded with an AQ631B optical spectrum analyser (Ando) with a spectral resolution of 0.01 nm. One can see that parasitic optical lines are absent and the suppression of side modes exceeds 30 dB; however, the longitudinal modes of the external resonator are unresolved. The spectrum in Fig. 5b was recorded with a Q8347 spectrum analyser (Advantest) with a better reso-

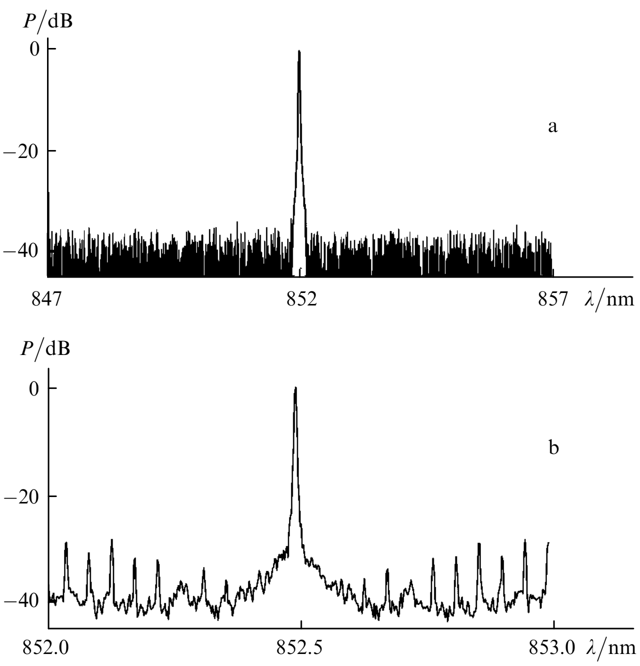

Figure 5. Emission spectra of the laser recorded with an AQ6317B optical spectrum analyser (Ando) with a resolution of 0.01 nm (a) and a Q8347 spectrum analyser (Advantest) with a resolution of 0.002 nm (b).

lution of 0.002 nm. Now the external-cavity modes are well resolved. One can see that the side modes of the external cavity are almost completely suppressed, which can be probably explained by the spectral burning of carriers theoretically described in [5, 21, 22].

Our experiments showed that the laser wavelength changed at the rate $\Delta\lambda/\Delta I = 4.5 \times 10^{-2}$ Å mA^{-1} depending on the pump current. The laser linewidth measured with a scanning confocal interferometer with a free spectral range of 200 MHz did not exceed 2 MHz for 10 mW of output power.

The laser wavelength changed as $\Delta\lambda/\Delta T_{\text{grat}} = 4.8\times 10^{-2}$ Å K^{-1} depending on the FBG temperature. The angular divergence of the output laser beam was $\sim 10^{-3}$ rad.

Thus, the additional possibility to tune the emission wavelength by varying the grating temperature (not only the pump current) simplifies tuning to the D_2-line of cesium in an atomic-beam tube.

In addition, the radiation source developed in this study can find wide applications in magnetometers, high-resolution spectroscopy, metrology, and systems for coherent data communication and processing.

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