Heterodyne determination of the width of the emission lines of injection lasers in the beat frequency stabilization regime

A.M. Akul'shin, N. G. Basov, V. L. Velichanskii, A. S. Zibrov, M. V. Zverkov, V. V. Nikitin, O. G. Okhotnikov, N. V. Senkov, V. A. Sautenkov, D. A. Tyurikov, and E. K. Yurkin

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
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A servo system was used to lock the beat frequency of injection lasers operating under conditions of self-stabilization of single-frequency emission in an anomalously wide continuous tuning range. The width of the beat spectrum was found to be ~500 Hz.

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A method for narrowing the emission line of injection lasers by use of an external resonator was proposed and implemented by Velichanskii et al. Measurements were made by the method of heterodyne mixing of radiation from two injection lasers of the same type. The same method was used to determine the width of the emission line of a laser with an external resonator, which was of the order of 15-50 kHz (Ref. 2). However, investigations reported in Refs. 1 and 2 were concerned with lasers operating under free-running conditions and the precision of the measurements was limited by fluctuations of the difference frequency. In the present study the width of an emission line of an injection laser with an external resonator was determined under conditions of stabilization of the beat frequency.

APPARATUS

All the components of two laser systems with external resonators were identical, they were placed on pyroceramic supports, and included injection lasers operating at 300 K, matching objectives with a numerical aperture 0.65 and a focal length 6.2 mm, rotatable mirrors made of a piezoceramic, and holographic selectors. A similar system was described in Ref. 3. One of the injection laser mirrors was given an antireflection coating to increase the range of tuning by a selector. Since the antireflection effect was incomplete, lasering was possible only when the selector band coincided with the injection laser mode. A complete coverage of the spectrum was achieved when the mode positions were varied by altering the temperature of a heat sink. The laser frequencies were brought together by a diffraction grating and two scanning interferometers with free spectral ranges 40 and 1.5 GHz. The method used to match the wavefronts and the details of the apparatus were described in Ref. 1.

Radiations from the two laser systems were mixed in an avalanche photodiode and the signal of this photodiode was applied to an S4-27 or S4-12 spectrum analyzer and to an automatic frequency control (AFC) unit. In the locking regime the beat frequency was determined by that of a reference AFC oscillator and could be varied within the range 6-20 MHz. The frequency of the “slave” laser system was controlled using two methods: variation of the voltage on a piezoelectric ceramic plate, i.e., variation of the length of the external part of the resonator (with a pass band of 1.5 kHz) and variation of the injection current (with a pass band 20 kHz).

LASER OPERATION REGIME

It is very easy to control the frequency by the self-stabilization single-frequency emission regime, because of its high stability against excitation of neighboring modes and, as reported below, because it can increase considerably the range of continuous tuning of the emission frequency both in the case when the length of the external part of the resonator is varied and when the optical length of the injection laser is modulated. We used injection lasers with a conventional stripe contact as well as lasers with a waveguide buried in a mesastructure. A single-frequency regime was manifested by a strong asymmetry of the characteristic observed when the mode of the injection laser resonator was tuned over the selector profile (Fig. 1a) and a characteristic feature of the self-stabilization regime was the absence of a step structure and an anomalously wide tuning range.

The continuous tuning range was estimated using interferometers (Figs. 1b and 1c). The lower oscillogram in Fig. 1b confirmed the continuity of the frequency tuning in a wide range resulting from variation of the length of the external part of the resonator (mode hopping would have resulted in discontinuities in the curve), whereas the upper oscillogram enabled us to

FIG. 1. Watt-ampere characteristic of a laser with an external resonator (a), resonances of the transmission of interferometers with instrumental widths 16 MHz (upper trace) and 1.2 GHz (lower trace) recorded with the aid of the laser when the length of the external part was varied (b), and dependencies on transmission of an interferometer with an instrumental width 30 MHz (upper trace) and of the output power (lower trace) on the current (c). The resonator length and the current were modulated in accordance with a sawtooth law and the arrow identifies the top of the peak.
measure the tuning range. The maximum deviation of the frequency due to a change in the length of the external part amounted to 2 GHz when the length of the external resonator was \( L = 60 \) cm, which was eight times greater than the tuning range under normal conditions (250 MHz). The corresponding value in the case of tuning by variation of the injection current was 60 MHz, which was two orders of magnitude wider than the usual tuning range.

A transmission resonance of an interferometer (represented by the upper oscillogram in Fig. 1c) was observed when the injection current was varied and it demonstrated the continuity of the frequency tuning. In this case the total tuning range was estimated from the width of an interferometer resonance. A change in the sign of tuning occurring after an abrupt onset of lasing (represented by the watt-ampere characteristics shown in the lower part of Fig. 1c) was due to unsteady cooling because of a corresponding abrupt reduction in the power dissipated in the active region, which gradually changed to an increase in the temperature because of an increase in the current.

**BEAT SPECTRUM**

It was practically impossible to detect the beat spectrum with a high resolution without frequency locking. When the frequency was stabilized by means of the first method, a stable beat signal was obtained on the screen of an analyzer for 10–100 min (depending on the drift of the laboratory temperature). The width of the beat spectrum was then 20–200 kHz for ten pairs of lasers. Broadening of the bands by the second method reduced the width of the beat spectrum. The minimum width at the 0.5 level was 500 Hz (Fig. 2). The spectrum was recorded using an S4–12 analyzer with a resolution of 30 Hz.

**DISCUSSION**

According to Ref. 6, the width of the laser emission line is \( \Gamma = \Gamma_0 \chi^2 + \Gamma'_0 \), where \( \Gamma_0 \) is the contribution of the spontaneous noise, \( \Gamma'_0 \) is the contribution of fluctuations of the number of electrons in the active region to the width of the injection laser line in the absence of an external resonator; \( \chi = Q_0/Qk \); \( Q \) and \( Q_0 \) are the \( Q \) factors of the external and internal (intrinsic) resonators, respectively; \( k \) is the power coupling coefficient of the resonators. This expression is valid in the case of a single-frequency regime when both broadening mechanisms are statistically independent and give rise to a Lorentzian line profile (\( \Gamma, \Gamma_0, \) and \( \Gamma'_0 \) are the total widths) and if the contribution of technical fluctuations is negligible. In the absence of an external resonator the injection lasers operated in the multimode regime, so that it was impossible to determine \( \Gamma_0 \) and \( \Gamma'_0 \) directly. The order of magnitude of \( \chi \) was estimated using the experimental values \( \Gamma'_0 = 20 \) MHz and \( \Gamma_0 = 2 \) MHz (Ref. 7), obtained for the single-frequency regime (it was reasonable to assume that in the case of generation of a specific oscillation mode of a laser with a resonator the broadening mechanisms associated with multimoding were suppressed). In estimating \( \Gamma_0 \) and \( \Gamma'_0 \) an allowance was made for small corrections associated with the difference between the injection laser parameters. The values of \( Q \) and \( Q_0 \) were determined by the resonator lengths and were approximately equal to losses on the mirrors so that \( Q/Q_0 = L/\pi n' = 6 \times 10^5 \) (\( n' \) is the effective refractive index of the injection laser material and \( L \) is the length of the resonator of the injection laser). Then, assuming that \( k = 0.1-0.3 \), we found that \( \Gamma_0 \chi^2 = 0.5 \) kHz and \( \Gamma'_0 \chi = 30-10 \) kHz. Clearly, the sum of these two quantities exceeded the experimental line width. The contribution of the second type of perturbation probably decreased because of AFC. Further narrowing of the line could be achieved by increasing the resonator length or the effective number of transits in the resonator.

One should point out that whereas external resonators reduce the spectra of each of the lasers, electronic self-tuning in the above experiments suppresses only fluctuations of the difference frequency. In practice, the spectra emitted by laser with external resonators are broadened because of technical low-frequency fluctuations of the carriers. However, it is important that in the case of the available systems of resonators with external mirrors and of control components these perturbations can be removed by frequency stabilization using an atomic line with a high-\( Q \) resonator. It is now possible to stabilize the emission frequency of two lasers with external resonators using neighboring modes of a confocal interferometer with a mode spacing 240 MHz.

**CONCLUSIONS**

The proposed method makes it possible to suppress technical fluctuations in the beat spectrum of an injection laser and to achieve a very narrow spectrum of beats with a width amounting to ~500 Hz. The tuning characteristics of lasers with external resonators were obtained for the first time in the self-stabilization regime. Stabilization of the beat frequency of a laser with an external resonator in combination with stabilization with the aid of atomic lines and high-\( Q \) interferometers opens up new opportunities for the use of lasers with external resonators in precision ultra-high-resolution spectroscopy.

1V. I. Velichanskii, A. S. Zibrov, V. S. Kargopol'tsev, V. I. Molochev, V. V. Nikitin, V. A. Sautenkov, G. G. Akul'shin et al.
Influence of temperature on the luminescence spectrum of blue-green algae

F. V. Bunkin, D. V. Vlasov, L. M. Gerasimenko, and V. P. Slobodyanin

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
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An investigation was made of the influence of temperature on the luminescence spectrum of blue-green single-cell algae in water. It was found that the relative intensity of the maxima changed by 30% when temperature was increased from 0 to 23 °C. This dependence could be used for remote determination of the temperature of water.

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One of the most pressing problems in current laser hydrooptics is the development of methods for remote determination of thermodynamic parameters of the surface layer of seawater. One of the known methods for remote determination of temperature, which has been tested under field conditions, involves the temperature dependence of the line representing the OH valence vibrations (3400 cm⁻¹) in the Raman scattering of light in water.

Seawater usually contains phytoplankton with a range of pigments and strong luminescence, for example, different types of chlorophyll $a$, phycocyanin, phycoerythrin, carotenoids, etc. In principle, there are several physical mechanisms that can determine the temperature dependence of the luminescence spectrum of dye-type pigments. In particular, the temperature dependence of the luminescence spectrum may be due to a redistribution of the population of the vibrational levels, changes in the average distance between atoms in a molecule (such a temperature dependence of the luminescence spectrum is observed, for example, in the case of semiconductors), intermolecular relaxation in solutions, etc. Dependences of this kind are used in dye lasers for thermal tuning of the emission line.

Luminescent pigments present in organic objects are components of the photosynthetic apparatus and the temperature dependence may be due to changes in the state and activity of microorganisms. For example, it is well known that in some photosynthetic mechanisms the excitation energy is transferred rapidly from chlorophyll $b$ to chlorophyll $a$ and there are several other chains for transfer of the absorbed light energy. A complex chain of energy migration in pigments may depend strongly on the state of a microorganism, particularly on the temperature of the ambient medium.

We determined the temperature dependence of the luminescence spectrum of blue-green single-cell algae of the Synechococcus type, encountered frequently in natural water reservoirs; our measurements were made in the laboratory.

The luminescence spectrum of blue-green algae and other microorganisms containing chlorophyll are a superposition of components associated with various photosynthetically active pigments (chlorophyll $a$, phycoerythrin, etc.) and, consequently, it depends strongly on the frequency of the exciting radiation (Fig. 1). Luminescence of each group of pigments is deter-