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A tunable diode laser emitting orthogonally polarised radiation modes

A.B. Fadyushin, V.L. Velichansky, M.D. Lukin, N.V. Senkov, M.O. Skully, M. Fleischauer

***Abstract*. A new scheme of the external cavity of a diode laser is described. The scheme provides emission of two closely spaced ($\Delta\lambda < 10^{-3}$ nm) orthogonally polarised modes, which can be tuned within the gain line, with the mode interval continuously changed.**

Keywords: *diode laser, external cavity, two-mode lasing, orthogonal polarisation.*

1. Introduction

Applications of lasers in spectroscopy require a strict control of their lasing modes. In particular, single-mode [1], or less commonly, two-mode lasing [2] is used in high-resolution spectroscopy. On the other hand, a high time resolution [3] and a high detection sensitivity of the intracavity absorption [4] are provided upon multimode lasing.

In the case of diode lasers, single-mode and multimode regimes have been studied in detail and operate reliably, the latter – in the phase-locking regime. The stationary continuous two-mode generation of diode lasers has not been virtually investigated, especially for small mode intervals (lees than 10 GHz). However, the two-mode lasing has many applications. For example, gas and dye lasers operating in this regime provide a combination of a high spectral resolution with a high sensitivity of the heterodyne detection. Bichromatic radiation is required for cooling and trapping of atoms of alkali metals [5] and for the creation of microwave frequency standards using the coherent population trapping [6].

A simultaneous oscillation at two or three longitudinal modes of the same polarisation in diode lasers with an external cavity is hindered by a strong competition between them. The latter is caused both by the local homogeneity of a spectral line and its small-scale spatial homogeneity due to the smoothing effect produced by the electron diffusion. This mechanism operates at distances of the order of the diffusion length, which only slightly exceeds the wavelength λ. For the width of the active waveguide of an injection laser equal to $(5 - 10)\lambda$ and above, the spatial homogeneity is destroyed, resulting in an uncontrollable lasing at many transverse and longitudinal modes. The stability of a stationary two-mode generation in gas, dye and colour centre lasers is related to the spatial inhomogeneity of an active medium due to burning out of the inversion at the antinodes of the lasing field (a fast diffusion of active centres is absent).

The free-running oscillation of a diode laser at many longitudinal modes of the same polarisation was described in Ref. [7], where a strong competition of the modes resulted in a substantial increase in the radiation noise compared to this in the single-mode lasing regime. In this case, different modes occupied incompletely overlapping regions of the active medium, thereby decreasing the competition and correlation of the radiation noise of different modes. Note that a classical study [8] of the anomalous interaction between the modes was performed under conditions that differed from our conditions in that pulsed pumping was used and lasing occurred at two groups of the modes of a composite resonator of the same polarisation. The distance between these groups was determined by two independent diffraction gratings and was no less than 100 GHz. Two-mode diode lasers with the mode interval of the order of 0.1 – 10 GHz were not described in the literature, the only exclusion being paper [9] in which a laser with a cavity containing two quarter-wavelength plates was studied (Fig. 1a). Such cavities were used initially in gas lasers [10].

Lasing at the modes with mutually orthogonal polarisations is attractive because it can strongly reduce the interaction and competition of the modes caused by intermode beats, which result in the anomalous interaction and generation of new frequencies, and enhances noise [7]. Note that a 'stationary' competition related to the inversion common for both modes and feeding them is retained irrespective of the mode polarisation and can affect the stability of the regime.

The aim of this paper is to build a tunable diode laser generating simultaneously two modes with mutually orthogonal polarisations and to study its noise. We proposed a new cavity scheme, which allows us to change both the mode interval between two closely spaced simultaneously generated modes and their wavelengths within the gain line (Fig. 1b).

A.B. Fadyushin, V.L. Velichanskii, N.V. Senkov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prosp. 53, 119991 Moscow, Russia; web-site: www.lebedev.ru
M.D. Lukin Department of Physics, Harvard University, 17 Oxford st., Cambridge. MA, 0138, USA;
M.O. Skully Texas A&M University, Physics Department, College Station, TX 77843-4242, USA; web-site: www.physics.tamu.edu
M. Fleischauer Fachberech Physik, Uni Kaiserlautern, Erwin-Schroedinger Str. D-67663 Kaiserslautern, Germany;
e-mail: mfleish@physik.uni-kl.de

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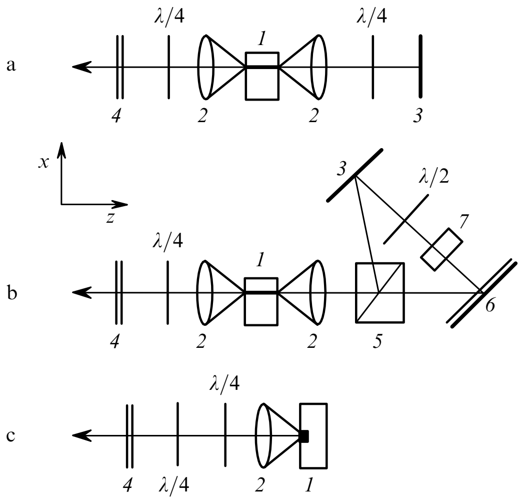

Figure 1. Initial scheme of a two-mode laser (a), the scheme proposed in this paper (b), and the resonator scheme proposed for a surface-emitting two-mode laser (c): (*1*) diode laser with antireflection coatings; (*2*) microobjective with a numerical aperture of 0.65 and a focus distance of 6.2 mm; (*3*) mirror ($R = 100\,\%$); (*4*) semitransparent mirror ($R = 60\,\%$); (*5*) Glan prism; (*6*) 1800 line mm^{-1} diffraction grating; (*7*) Fabry–Perot etalon; $\lambda/4$ plate; $\lambda/2$ plate.

2. Model of the proposed resonator

Consider a simplest model of the polarisation properties of a resonator in which an active medium and a waveguide have isotropic polarisation of radiation. Dynamic processes in the active medium and the stability of lasing regimes are not analysed, phase shifts during the propagation of two modes outside optical elements are assumed identical, and phase-anisotropic optical elements ($\lambda/2$ and $\lambda/4$ plates) are assumed perfect.

Let us introduce the system of coordinates in which the y axis is directed perpendicular to the figure plane, the axis of a half-wavelength plate is turned by an angle of 45° with respect to the x axis, while the axis of a quarter-wavelength plate is turned by $45^\circ + \alpha$. Therefore, the plate axes observed along the optical axis prove to be turned with respect to each other by an angle α in a plane perpendicular to the optical axis. The Jones matrix for a round trip in the resonator, beginning from the output mirror, has the form

$$\Gamma\begin{bmatrix} \cos 2\alpha(1 + \mathrm{i}\sin 2\alpha) & \mathrm{i}\sin^2 2\alpha \\ \mathrm{i}\sin^2 2\alpha & \cos 2\alpha(1 + \mathrm{i}\sin 2\alpha) \end{bmatrix},$$

where Γ is the effective (taking losses into account) gain of radiation during the round trip in the resonator. The eigenvectors $\Psi_{1,2}$ and eigenvalues $\lambda_{1,2}$ of this matrix are

$$\Psi_1 \propto \begin{pmatrix} -\sin\alpha \\ \cos\alpha \end{pmatrix}, \quad \lambda_1 = \Gamma(\cos 2\alpha - \mathrm{i}\sin 2\alpha),$$

$$\Psi_2 \propto \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix}, \quad \lambda_2 = \Gamma(\cos 2\alpha + \mathrm{i}\sin 2\alpha).$$

When the axes of the quarter-wavelength and half-wavelength plates are parallel, i.e., the angle $\alpha = 0$, modes of any polarisation cab be excited in the resonator. When one of the plates is rotated around the optical axis, each of the longitudinal eigenmodes of the resonator splits into two orthogonally polarised modes, their polarisations being circular in the active medium between the plates and linear between the plates and mirrors. The subscripts 1 and 2 refer to the waves that are linearly polarised at small angles ($\alpha < 0.1$ rad) along axes x and y, respectively.

For large angles α, polarisations of the modes, remaining linear and mutually orthogonal, turn by α with respect to coordinate axes. The losses for both modes are identical and are inversely proportional to $\cos\alpha$. The resonance radiation frequencies ω_n for the longitudinal mode of the order n are determined by the expressions

$$\omega_n^{(1)} = \frac{2n\pi c}{L} + \frac{2\alpha c}{L}, \quad \omega_n^{(2)} = \frac{2n\pi c}{L} - \frac{2\alpha c}{L},$$

where L is the optical path per round trip in the resonator and n is an integer. The differences of frequencies of two mutually orthogonal modes of the same order (n) and of nearest neighbouring orders (n and $n+1$) are determined by expressions

$$\Delta\omega_{n,n} = \frac{2\alpha}{\pi}\,\Delta\omega_0, \quad \Delta\omega_{n,n+1} = \left(1 \pm \frac{2\alpha}{\pi}\right)\Delta\omega_0,$$

where $\Delta\omega_0 = 2\pi c/L$ is the free spectral range of the resonator.

Returning back to a real planar waveguide of a diode laser, which has a strong polarisation anisotropy, note that the propagation of circularly polarised waves should be accompanied by a strong perturbation of their polarisation. The effective refractive indices for the waves with orthogonal polarisations (in the $p-n$ junction plane and perpendicular to it) are generally different, and a circular wave is not a waveguide mode at all.

However, it is important that a mode is self-reproduced after a round trip in the active medium, its polarisation changing to orthogonal between the forward and opposite trips. Thus, the perturbations introduced by the polarisation anisotropy of the active medium during the forward trip are compensated after the opposite trip. However, when the effective reflection coefficients are not equal to each other, resulting in the different intensities of counterpropagating waves in the active medium of the laser, such compensation can be incomplete because of nonlinear effects.

3. Experiment

The scheme described in Ref. [9] allows one to control the difference of frequencies of the generated modes, but not their position within the gain line of the laser. To control the mode position, we placed a diffraction grating into the resonator. The efficiencies of diffraction of radiation with different polarisations are generally noticeably different, although they can be identical at some wavelength for a certain position of the grating [11]. The efficiencies of diffraction from a 1800-line mm^{-1} grating for waves at 850 nm, which were polarised parallel or perpendicular to the grating lines, were substantially different and were 7 % and 75 %, respectively. To equalise these efficiencies for any wavelengths, one of the quarter-wavelength plates and a mirror corresponding to it (Fig. 1a) were replaced by a loop containing a Glan prism, a half-wavelength plate, a diffraction grating, and a mirror (Fig. 1b). Such a scheme provides the same diffraction efficiency for any polarisation of radiation coupled to the loop.

The Glan prism divides radiation into two beams with mutually orthogonal polarisations. The beam passing around the loop counter-clockwise is incident on the grating having polarisation that corresponds to the maximum diffraction efficiency. The polarisation of the beam passing around the loop clockwise is turned by 90° in front of the grating with the help of the half-wavelength plate. As a result, both these beams are incident on the grating having the same polarisation and the same high diffraction efficiency.

To tune lasing modes within the gain line, the diffraction grating is turned, as usual, around the axis parallel to its lines.

In the resonator of such a design, the lasing modes coincide spatially everywhere in the resonator (if the broadening of a radiation beam along one coordinate upon its diffraction from the grating is neglected), which should result in a high degree of correlation of the technical noise of the resonator between the lasing modes. To increase the stability of two-mode lasing, we placed into the resonator a Fabry–Perot etalon of thickness $d = 13$ mm, with the refractive index equal to 1.45 and reflectivity of both mirrors $R = 65\,\%$. The radiation was outcoupled from the resonator through a semitransparent mirror.

The adjustment of a laser resonator in the case when both ends of the active element have antireflection coatings is more complicated than the adjustment of a laser with a unidirectional feedback. It is important that the presence of an optical feedback only in one (any) of the resonator arms was insufficient for lasing even in the case of the optimal linear polarisation. In a spontaneous regime, the adjustment of the loop with the diffraction grating was also complicated; therefore, we placed initially an auxiliary mirror with a reflectivity of 0.6–0.8 in front of the loop, which allowed us to rapidly obtain lasing. Then, the loop with the grating was adjusted using the laser beam and the auxiliary mirror was removed. To obtain stable two- and three-mode lasing regimes, the etalon placed in the loop was slightly tilted in the vertical plane.

The emission spectrum was roughly analysed with a monochromator. The number of modes was controlled with a confocal scanning interferometer with a free spectral range of 1.5 GHz and a resolution of 15 MHz, and their polarisation was determined with an analyser, which was placed in front of the scanning interferometer.

The beat spectrum was detected with a photodiode with a bandwidth of 1.5 GHz. To observe the beat signal, a Glan prism was placed in front of the photodiode, which was oriented at 45° with respect to coordinate axes. In the absence of the Glan prism, beats were also observed, but their amplitude was 2–3 times smaller.

To enhance the influence of the external elements of the resonator, the resonance properties of a laser diode should be suppressed. We used two variants of the suppression: the covering of both facets with an antireflection coating and the same procedure upon tilting a stripe contact at an angle of 12° with respect to cleaved facets. Because radiation sources of this type are not standard products, the choice of the structure of an active waveguide was limited. In particular, we tested only one quantum-well structure, which was used in several samples with a two-sided antireflection coating. The overall effective amplification of the TM mode in this structure was substantially lower than that for the TE mode, and no lasing was observed in the scheme shown in Fig. 1b.

The results presented above are related to lasers with a bulk active region, which generate TE modes in standard resonators. A diode laser having antireflection coatings on both facets of the active element (the reflectivity $R < 1\,\%$) and emitting at 850 nm was mounted on a heatsink, which allowed the use of microobjectives with a large aperture (NA = 0.65) for outcoupling radiation from both faces of the active element.

In the experiments with the laser whose facets were perpendicular to the optical axis, we observed three lasing regimes:

(i) single-mode lasing when $\alpha = 0$;

(ii) two-mode lasing when two modes with the same longitudinal indices at the resonator output have linear polarisations that are almost orthogonal with respect to each other;

(iii) three-mode lasing when two longitudinal modes with the same index have mutually orthogonal linear polarisations, while the longitudinal index of the third mode differs by unity and its polarisation coincides with that of one of the first two modes.

In all three cases, the wavelengths of the lasing fields were determined in the first approximation by the position of a diffraction grating, while the mode splitting in the second and third cases was determined by the orientation of the axis of the quarter-wavelength plate.

In the two-mode regime (Fig. 2), we obtained the following results. The intermode beat frequency changed virtually linearly with the coefficient equal to 3.6 MHz$\times$ deg^{-1} when the quarter-wavelength plate was rotated (Fig. 3). The amplitude of the intermode beat signal also changed (Fig. 4). In this case, the lasing modes retained the degree of mutual orthogonality at the resonator output. The maximum ratio of the mode intensities observed upon rotation of the quarter-wavelength plate was 7–10. The degree of orthogonality was checked with the help of a polarising prism, which was placed into the output beam and was rotated around its axis. For the pump current of 84 mA, the overall radiation power in both modes was 1.7 mW (the mode powers were 1.48 mW and 0.22 mW). The overall radiation power didn't virtually change upon rotation of the $\lambda/4$ plate.

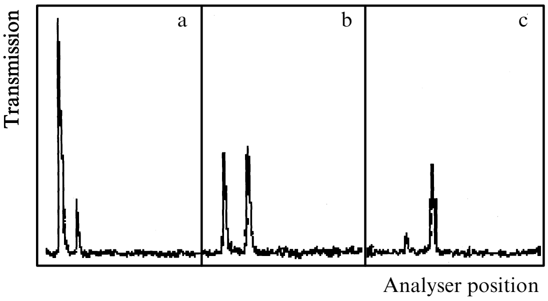

Figure 2. Transmission of a confocal interferometer for different positions of an analyser placed in front of the interferometer. (a) One of the modes is suppressed, and the transmission axis is set at an angle of 7° to the x axis (Fig. 1); (b) both modes are transmitted; (c) another mode is suppressed.

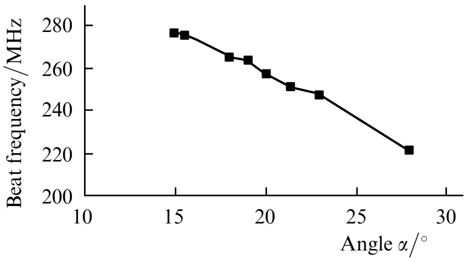

Figure 3. Beat frequency in the two-mode lasing regime as a function of the angle α between the axis of a quarter-wavelength plate and the x axis (Fig. 1); the $p-n$ junction plane in the active medium of the laser is parallel to the x axis.

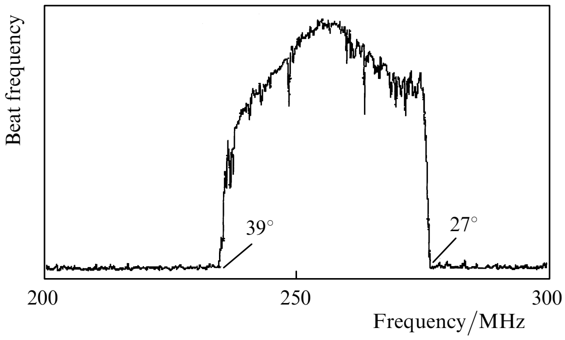

Figure 4. Beat amplitude in the two-mode lasing regime as a function of the angle between the axis of a quarter-wavelength plane and the x axis (Fig. 1).

The extrapolation of the dependence $f(\alpha)$ (Fig. 3) shows that the beat frequency should be $\sim$ 340 MHz at $\alpha = 0$. At the same time, for perfect phase-isotropic elements, it should be equal to the intermode interval of the resonator (about 300 MHz). This discrepancy can be explained by the fact that the quarter-wavelength plate is not perfect [12].

When the voltage applied to piezoelectric ceramics controlling the resonator length was changed, optical frequencies changed linearly with the coefficient equal to 3.9 MHz V^{-1}, while the beat frequency for modes with different polarisations changed linearly with the coefficient equal to 0.1 MHz V^{-1}. As the pump current was changed, the mode frequencies changed with the rate 20 MHz mA^{-1}, and the beat frequency was changed with the rate 0.5 MHz mA^{-1}. Therefore, variations in the difference frequency caused by fluctuations of the optical lengths of the active waveguide and the external part of a composite resonator should be 40 times smaller than the corresponding variations in the frequencies themselves. The minimal width of the beat spectrum for the orthogonal modes measured with the help of a spectrum analyser was 150 kHz (Fig. 5).

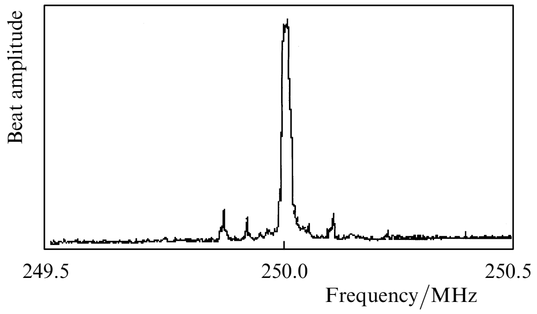

Figure 5. Beat spectrum of the modes generated in the two-mode regime.

We also observed three-mode lasing, when two adjacent longitudinal modes of the resonator split into orthogonal components (Fig. 6). In this case, beats between lasing modes at four frequencies should occur. One of the frequencies (f_1) is independent of the rotation angle of the quarter-wavelength plate and is equal to the interval $\Delta\omega_0$ between the adjacent longitudinal modes of the resonator. When the plate was rotated in the angular range from $\alpha = 0$ to $\pi/2$, three other frequencies varied linearly as follows: f_2 – from zero to $\Delta\omega_0$, f_3 – from $\Delta\omega_0$ to zero, and f_4 – from $\Delta\omega_0$ to $2\Delta\omega_0$. We observed lasing at two components of one longitudinal mode and at the adjacent component of the other longitudinal mode. The observed dependences of the intermode beat frequencies f_1, f_2, and f_3 on the rotation angle of the quarter-wavelength plate correspond to this scheme. One of the splitting components was not generated possibly because of large losses at its wavelength compared to those for generated components.

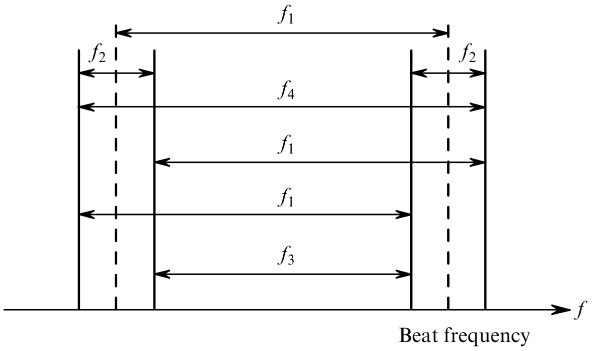

Figure 6. Formation of beats in the four-mode lasing regime.

The tuning coefficients upon three-mode lasing were approximately the same as those upon two-mode lasing; however, the width of the beat spectrum for modes of adjacent orders was 20 kHz. This lasing regime existed for several hours without any additional adjustment of the resonator, the width of the beat spectrum being invariable (Fig. 7). The beat frequencies f_2 and f_3 changed linearly with the rotation angle of the plate (Fig. 8).

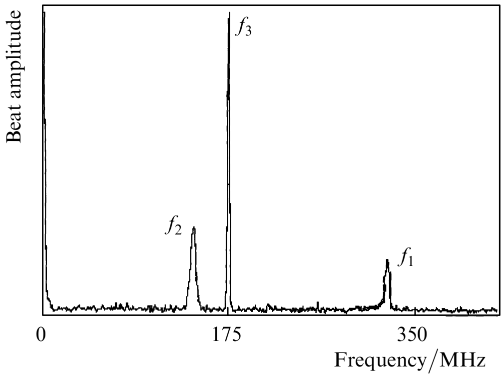

Figure 7. Beat spectrum of the modes generated in the three-mode regime. The beats between modes of the same polarisation and their beats with the mode orthogonal polarisation are observed.

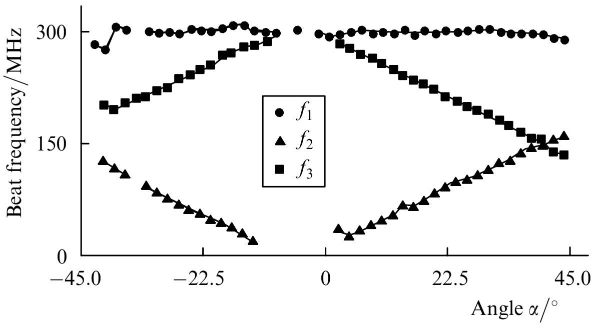

Figure 8. Dependence of the beat frequencies of the fields of generated modes on the angle between the axis of a quarter-wavelength plate and the x axis in the three-mode regime.

In experiments with lasers of the second type (with facets with antireflection coatings and a tilted stripe contact), two- and three-mode lasing could be obtained much more easily because the sensitivity to the resonator misalignment was lower, and a stable two-mode lasing was observed even without an intracavity etalon. The difference of frequencies of the orthogonal modes was greater than 1 GHz upon two-mode lasing, exceeding the intermode interval of the resonator.

4. Discussion of results

We did not find any substantial (down to several kilohertz) narrowing of the intermode beat spectrum due to a high correlation of technical noises in both lasing modes. The minimal detected width of the beat spectrum was of about 20 kHz. The possible source of uncorrelated fluctuations can be the presence of the longitudinal components of the field in an active medium due to their transverse confinement in the waveguide. The unidirectional components reduce the degree of orthogonality, resulting in the dynamic competition between modes. This effect can be reduced by a proper choice of the transverse sizes of the laser waveguide, i.e., by increasing at least one of them. At present, we obtained two-mode generation in a surface-emitting diode laser. The design of the external cavity is similar to this described in Ref. [6], the only difference being that two quarter-wavelength plates are located at one side of the active medium (Fig. 1c).

Thus, we have designed a two-mode diode laser with a course wavelength tuning (by rotating a diffraction grating) in the range exceeding 10 nm. The frequency interval between modes with mutually orthogonal polarisations can be continuously varied in the range corresponding to about 20 % of the free spectral range of the resonator. It is interesting to compare the parameters of a beat signal for two independent lasers with an external cavity and the beat signal for two modes of the same laser considered in our paper. For the latter, a high correlation of frequency fluctuations was observed in the low-frequency region, whereas this correlation is virtually absent at frequencies above 1 kHz, and the widths of the beat spectra only slightly differ from those observed in the case of two lasers.

Note that the ratio (~ 40) of the changes in the beat frequency and the frequency of each of the modes caused by the change in the resonator length indicated in section 3 strongly differs from the value obtained from simple theoretical considerations ($L/\lambda \approx 10^5$, where λ is the emission wavelength). The reasons for such a discrepancy, as well as sources of uncorrelated fluctuations call for further investigations.

Note that the intended application of the two-mode laser requires an interval between lasing modes of the order of a few gigahertz, which can be achieved using an intracavity etalon with an appropriate intermode interval. In this region, the degree of correlation may be higher due to the reduction of the dynamic competition.

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