

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.25.Kb; 42.55.Px; 42.60.Jf; 42.82.Et
DOI: 10.1070/QE2012v042n06ABEH014826

Coherent summation of the radiation of a single-mode laser diode array

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Abstract. **We report the phase-locked lasing of an array of 25 single-mode laser diodes in an external resonator with the use of a waveguide grating mirror providing angular and spectral selectivity. The laser array was found to generate on the out-of-phase supermode with a stabilised wavelength of 930.8 nm and an output power up to 0.75 W. The output beam exhibited a near diffraction-limited quality ($M^2 \approx 1.2$) in both directions.**

Keywords: *laser-diode array, coherent radiation summation, waveguide grating mirror, out-of-phase oscillation mode of a laser array.*

The problem of coherent radiation summation of an array of laser sources has attracted the attention of researchers for many years. The solution of this problem permits making a high-power small-size high-efficiency light source with a high brightness. The method of coherent radiation summation of laser emitters with the use of a common external resonator has gained the widest acceptance. This method was employed to phase-lock waveguide [1], solid-state, and CO_2 lasers [2] as well as laser diodes [3, 4]. When use was made of an external resonator, advantage was primarily taken of the methods for the selection of the collective mode of a laser source array like the diffraction coupling of the laser set, the Talbot effect, and Fourier filtering. Implied in all these methods is an external resonator of substantial length. In recent papers, a volume Bragg mirror is employed as the selecting element of the feedback of the external resonator of a linear laser diode array [3, 4]. Two techniques of selecting the collective mode were investigated: with the help of the Talbot effect and with the use of the angular selectivity of the volume Bragg mirror. In both cases it was possible to obtain coherent summation of radiation, but the directivity pattern of the output radiation retained its multilobe structure. It is also pertinent to note that the angular selectivity of the volume Bragg mirror depends only slightly on the radiation–mirror interaction length l: $\Delta\varphi \approx \sqrt{\lambda/l}$. Therefore, only the selection of a single collective mode possessing a single-lobe output directivity pattern will permit the laser systems of this type to generate the radiation of high quality and consequently of high brightness.

In the present work, for the selective element of the feedback of a single-mode laser diode array we propose the use of a waveguide grating mirror (WGM) possessing a high angular and spectral selectivity [5–7]. Two objectives are reached in this case: first, the length of external resonator may be as short as permitted by the optics collimating the radiation along the fast axis and, second, the optimal angular selectivity of the mirror permits realising the single-lobe output radiation directivity pattern.

A WGM was earlier employed as an external resonator for laser diodes with a broad stripe contact for stabilising the spectrum and raising the radiation brightness [8, 9].

In our experiments, use was made of an array of 25 single-mode laser diodes (Polyus Research and Development Institute, Moscow) radiating at a wavelength of 930 nm. Each laser diode measured 4 μm in width; the diodes were periodically spaced at distances p = 8 μm. The semiconductor crystal was 1 mm long. The crystal was pumped through an electrode array (4 μm in width, with a period of 8 μm); in this case, a single-mode structure with a lateral gain confinement. The rear crystal face possessed a high reflectivity ($R > 95\%$) at the laser wavelength. The front face had an AR coating ($R < 0.5\%$) to prevent lasing with the faces of the semiconductor crystal itself.

Our experimental setup is shown in Fig. 1. The radiation of the laser diode array was collimated in the fast axis (which was perpendicular to the plane of the p–n junction) with an aspheric cylindrical lens (LIMO, Germany) with a high numerical aperture (NA = 0.8) and a focal distance of 0.29 mm. A highly stable stage was specifically designed for positioning the lens, which made it possible to adjust the lens in three linear

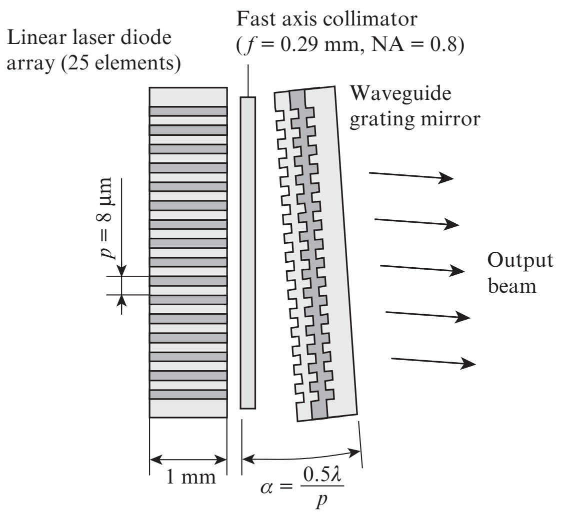

Figure 1. Schematic of the phase-locking of a laser diode array in an external resonator with a WGM.

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Received 8 February 2012; revision received 27 March 2012
Kvantovaya Elektronika **42** (6) 561–564 (2012)
Translated by E.N. Ragozin

and three angular coordinates ($X, Y, Z; \alpha, \theta, \varphi$). The external WGM was aligned in five coordinates ($X, Y, Z; \alpha, \theta$), the Z axis being directed along the resonator axis. To eliminate the parasitic reflection from the rear face of the WGM substrate, use was made of an optical wedge with an apex angle of 3°, which was attached to the substrate with the help of a water–glycerine mixture.

In the general case, N single-mode coupled lasers support N (25 in our instance) independent oscillation types (modes). By way of example, Fig. 2a shows the distributions of the fields of the zero, 23rd, and 24th modes of the linear laser diode array along the p–n junction. The mode field distributions in the plane of the p–n junction were calculated using the method of effective refractive index in a multilayer structure with a weak contrast of refractive index, which is well known in integrated optics. To obtain coherent output radiation requires selecting one mode. Best suited for the selection is the highest-order mode (the 24th mode), or the out-of-phase mode. In this mode, field phase shift for neighbouring lasers is equal to π.

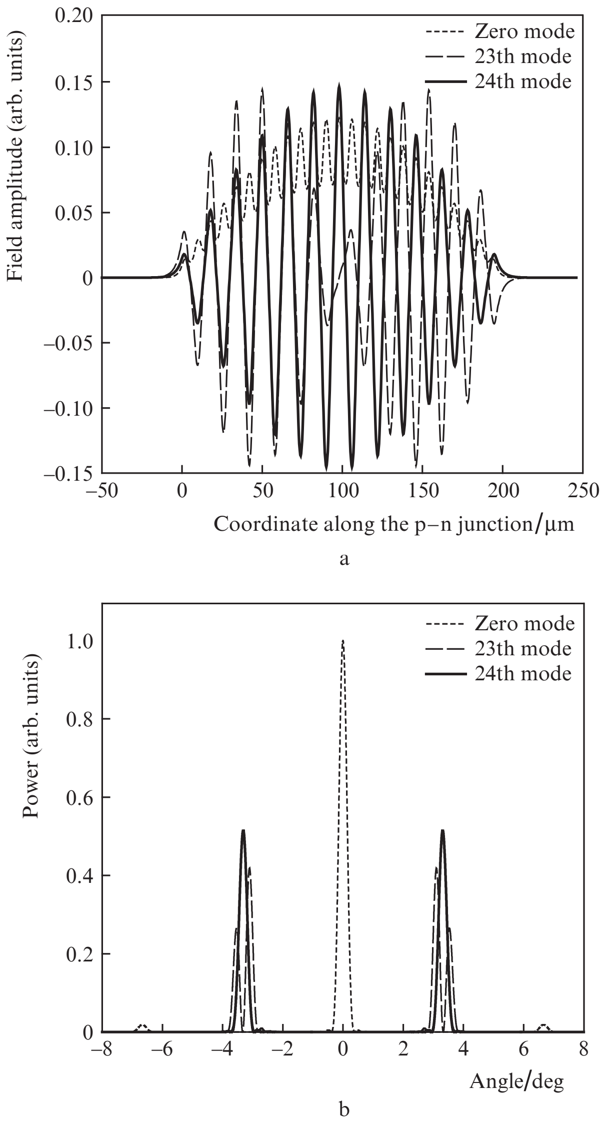

Figure 2. Distribution of the field amplitude in the linear laser diode array in the plane parallel to the p–n junction, along the output aperture (a) and far-field angular power distribution in the plane parallel to the p–n junction (b).

Figure 2b shows the far-field distributions of the zero, 23rd, and 24th mode fields of the linear laser diode array. It is noteworthy that the radiation distribution of the out-of-phase mode has two principal peaks located at angles of $\pm\lambda/2p$ relative to the normal to the output face of the linear array. One of these peaks is reflected back into the resonator with a nearly 100% efficiency, while the second peak makes up the output radiation, because the WGM is transparent to it. In each peak the radiation beam profile has a distribution proportional to $\sin^2$, and the theoretical value of the output beam quality parameter M^2 lies in the range between 1.1 and 1.2.

The angular and spectral selection properties of the WGM at normal light incidence on it are related to the simultaneous excitation of waveguide modes propagating in the planar corrugated waveguide in the opposite directions. For loss-free dielectric structures the peak reflectivity of such a mirror is always equal to unity. The angular width of the WGM reflectivity distribution is approximately inversely proportional to the propagation distance L of these modes along the waveguide ($\Delta\varphi \approx \lambda/L$) or proportional to the squared corrugation depth [5]. This circumstance enables an easy selection of the requisite angular selectivity of the mirror. The waveguide mode propagation distance L and, hence, the angular reflectivity distribution are responsible for the possibility of selecting a single collective mode.

The waveguide grating mirror was calculated using a software tool simulating diffraction processes in periodic structures [10]. The waveguide in the WGM* was formed by two layers: Ta_2O_5 (of thickness 178.2 nm, n = 2.193) and SiO_2 (of thickness 102.9 nm, n = 1.483) evaporated on a corrugated (undulating) surface of a substrate made of quartz of high optical quality (n = 1.451). These layers also constitute an antireflection coating for off-resonance radiation. The corrugation period and its depth are equal to 580 and 39 nm, respectively.

Figure 3a shows the angular distribution of the WGM reflectance as well as the angular distribution of the 24th and 23rd mode radiation of the linear laser diode array incident on the mirror. It is noteworthy that the 23rd mode reflection efficiency is far lower than the efficiency of 24th mode reflection. The reflection efficiency of the remaining modes is still lower. Therefore, the WGM affords a simple way of selecting a single collective mode without lengthening the external resonator (as contrasted with alternative selection methods). By employing the WGM, the length of external resonator can be made as short as permitted by technical conditions. Figure 3b depicts the spectral selectivity of the WGM in use.

In our work we used the most promising lasing scheme involving the selection of a single out-of-phase mode, which implies the total reflection of one radiation peak back into the resonator (which corresponds to a feedback efficiency of up to 25%) and extraction of the working radiation via the second peak.

Without the WGM, the linear laser diode array did not lase throughout the pump current range; with the WGN, the threshold of lasing was equal to 0.45 A. The maximum output power equal to 750 mW in one output radiation peak in the cw regime was obtained for a pump current of 3.5 A. The power in the second suppressed peak of the out-of-phase mode was significantly lower than in the principal peak. The differential efficiency of lasing of the linear laser diode array in the external resonator with selection of a single out-of-phase supermode

*The WGM samples were fabricated at the Laboratoire Hubert Curien, Université Jean Monnet, Saint-Etienne, France).

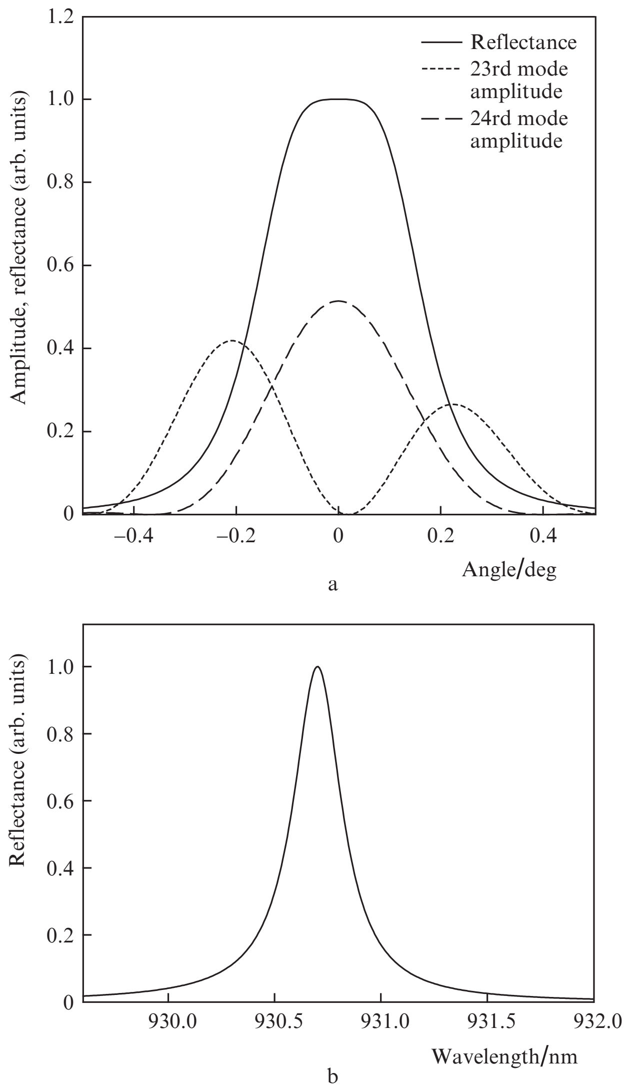

Figure 3. Angular dependence of the WGM reflection efficiency for a plane wave with a wavelength of 930.7 nm (a) and spectral dependence of the reflectance at normal radiation incidence (b).

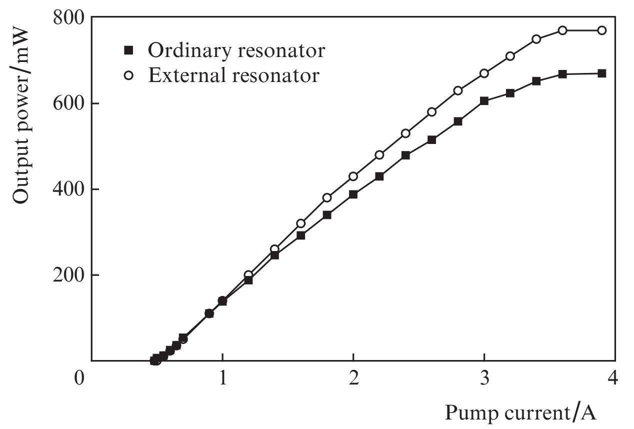

Figure 4. Output power of the linear laser diode array as a function of pump current for two resonator versions.

was equal to 0.25 W A^{-1} (Fig. 4). For comparison, also shown in this figure is the differential efficiency of the linear laser diode array of the same length and with the resonator formed by the faces of the semiconductor crystal itself, which possessed reflectivities of 100% and 10%. We attribute the higher efficiency of the configuration with the external mirror to the optimal feedback strength. In both cases, the output energy saturation is related to the imperfect heat removal from the semiconductor crystal.

The far-field angular radiation distribution for two similar linear diode arrays, which had either an ordinary resonator (mirrors on the semiconductor crystal faces) or an external resonator involving the WGM, is depicted in Fig. 5. One can see from this figure that the diode system with the external resonator and the WGM generates a single out-of-phase mode. In these two cases the output intensities differ strongly; for comparison of the angular distributions of the output power, the plots are normalised to their peak values. In both case, the pump current was equal to 1 A.

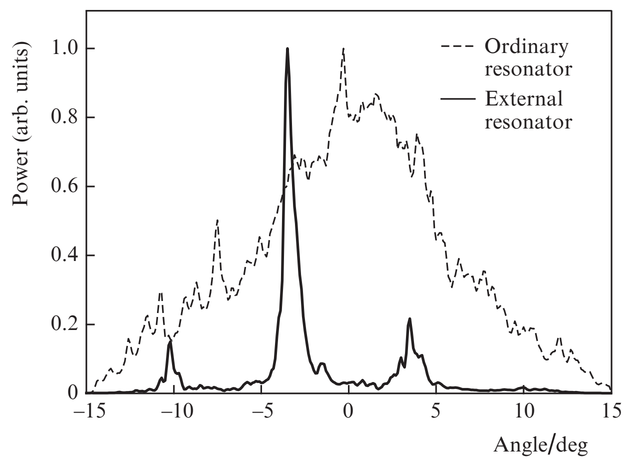

Figure 5. Far-field distribution of the output radiation power of the linear laser diode array for two resonator versions.

The output power of the linear array with the ordinary resonator is distributed over a broad (up to 30°) angular range, while the output power of the linear array with the external resonator and the WGM is primarily confined in a single narrow −0.5 diffraction order peak (for an out-of-phase grating the phase difference between the neighbouring grating elements in the direction of diffraction orders should be equal to an odd number of 0.5λ). Also, one can clearly see the second +0.5 diffraction order peak, which is strongly, but not completely, suppressed by the resonance mirror, which is attributable to the comparable angular widths of the WGM and the principal peaks. A stronger suppression of this peak would be expected in linear laser diode arrays with a larger number of single diodes.

The power in +1.5 order diffraction peaks, for which the WGM is transparent, is relatively low, the ratio between the output power in these peaks and the principal peak power becoming lower with increase in pump current.

The output beam quality and the principal peak's power depend only slightly on the external resonator length in its variation from its minimal values to several centimetres. Figure 6 shows the far-field diagram of the output beam for a pump current of 3.5 A. In addition to the principal peak, weak satellite peaks are observed in both directions. The emergence of peaks in the direction perpendicular to the plane of the p–n junction is caused by the aberration of the collimating lens.

The existence of small peaks in the direction lengthwise of the p–n junction is a natural consequence of the radiation diffraction of a finite number of coherent laser diodes. The M^2 value of the principal peak is close to 1.2 in both directions; for the direction in the p–n junction plane it is very close to the theoretical value of M^2 of the single radiation peak of the out-of-phase laser array mode (1.1–1.2).

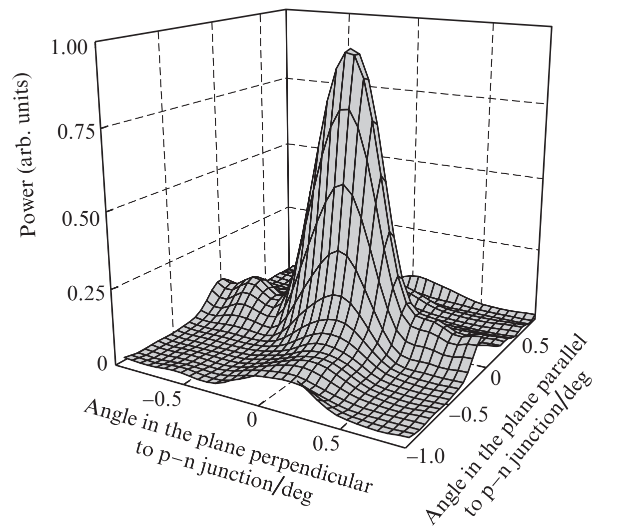

Figure 6. Two-dimensional far-field distribution of the output power of the linear laser diode array with the external resonator.

Figure 7 shows the emission spectra of the linear laser diode array in the cases of external and ordinary resonators. These measurements were carried out with the help of a monochromator with a 0.1-nm resolution and a CCD camera. The spectral distribution of the radiation of the linear array with the ordinary resonator depends strongly on the pump current and the crystal temperature, while the spectrum of the linear array with the resonance mirror contains one narrow line with a fixed wavelength throughout the range of pump currents and cooling system temperatures. The radiation wavelength and the spectrum width are determined by the parameters of the WGM.

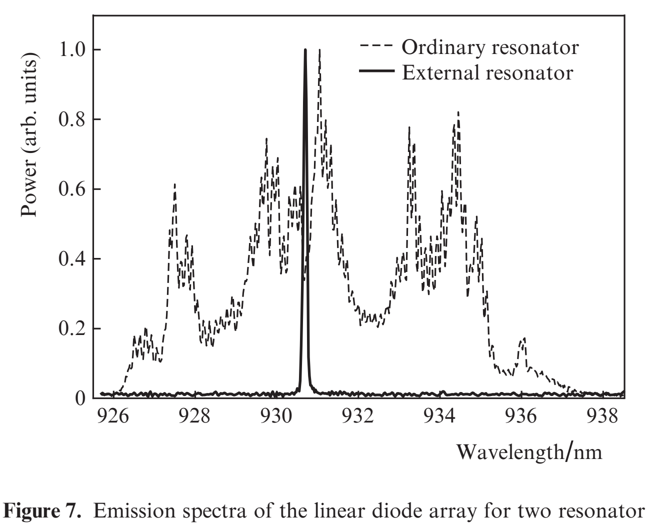

Figure 7. Emission spectra of the linear diode array for two resonator versions.

Therefore, we have demonstrated the collective lasing of a linear array of single-mode laser diodes in an external resonator with an output waveguide resonance mirror. Owing to the high angular selectivity of the WGM it was possible to obtain lasing on a single collective (out-of-phase in our case) mode. The output radiation quality is nearly diffraction limited. The physical WGM properties permit employing the ultimately short external resonator (with the potentiality of positioning the collimating lens and the WGM directly on the semiconductor crystal). An output power of 750 mW was obtained, which was limited by the semiconductor crystal length (1 mm) and the moderate heat extraction capacity of the heat exchanger. The output power may be further improved by increasing the number of the diodes and their length as well by improving the properties of the heat exchanger.

Acknowledgements. The authors express their appreciation to O. Parriaux and S. Tonchev of Laboratoire Hubert Curien, Université Jean Monnet, Saint-Etienne, France, for the fabrication of the WGM as well as to S.M. Sapozhnikov and A.I. Danilov of the Polyus Research and Development Institute, Moscow, for the fabrication of semiconductor active elements.

This work was supported by the New Energy Technologies Ltd. under State Contract No. 14.740.11.0073.

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