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Phase locking of 2D laser arrays by the spatial filter method

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***Abstract*. The efficiency of phase locking of 2D waveguide CO_2 laser arrays as a function of the number of lasers in the array and parameters of the spatial filter is measured. The phase-locking stability is analysed on the basis of far-field-zone intensity distributions obtained.**

Keywords: *2D laser arrays, spatial filter, phase-locking efficiency.*

In order to achieve the radiation phase locking of optically coupled laser arrays, it is preferable to apply the global coupling [1] rather than other types of coupling, because, in this case, the inphase generation of the array is more stable [2, 3]. The simplest way to achieve the global optical coupling is to use a diffraction of radiation in the Talbot resonator [4] or a diffraction from a spatial filter located in the cavity (see, e.g., [5]). The high selectivity of a spatial filter makes it possible to avoid additional methods for supermode selection, and the method of spatial filter was successfully used for phase locking of radiation from both one-dimensional (1D) [5 – 8] and two-dimensional (2D) [9 – 11] laser arrays. In experiments with 2D arrays [10], a phase-locking efficiency of $\sim 50\,\%$ was obtained. The possibility of increasing the axial intensity by several tens of times when correcting the radiation pattern was shown in [12] for 2D arrays.

This work is devoted to an experimental study of the influence of the number of lasers in the array and filter parameters on the efficiency and stability of radiation phase locking of 2D laser arrays. The experiments were performed with hexagonal arrays of waveguide CO_2 lasers with tubes 5.5 mm in diameter and a period $d = 8.5$ mm. By analogy with papers [7, 8], the highly reflecting mirror of the common cavity of the array was formed by a matched telescope that contained a concave spherical mirror with a 90-cm radius of curvature and a focusing lens with a focal length $F = 170$ cm. The number N of lasers in the array was 7, 19, or 37.

One of the three replaceable spatial filters was placed at the telescope focus. Each filter represented an array of periodically arranged holes with equal diameters of holes $d_0 = 1, 1.5$, and 1.9 mm individual for each filter. The holes in all filters were arranged with the same period $d_c = (2/\sqrt{3})\lambda F/d \approx 2.3$ mm ($\lambda = 10.6$ μm is the radiation wavelength). The period of holes and the spatial position of the filters in the telescope focal plane corresponded to the selection of an inphase radiation supermode. The phase-locking efficiency was defined as the ratio of the coherent emission of the laser array with the installed filter to the power in the absence of the filter; the degree of coherence of the output radiation was monitored by the form of the spatial intensity distribution in the far-field zone for the central peak.

As the discharge current in the tubes was rised, the radiation phase-locking efficiency monotonically increased. This increase stopped at currents of 8 – 10 mA in each tube for all d_0 and N. Table 1 presents the phase-locking efficiencies P corresponding to these currents. Characteristic sizes of the intensity distribution peaks calculated from the formula $d_{0f} = 2.44\lambda F/D(N)$ [$D(N)$ is the aperture of the laser array] are also listed in the table (the second column). Depending on N, they may exceed or be below the hole sizes in the filters.

The data of Table 1 show that, as d_0 increases, the efficiency also increases for all N and exceeds 50 % for $N = 7$ at $d_0 = 1.9$ mm. The P change has the same behaviour with increasing N and fixed $d_0 = 1$ mm. The efficiency P increases with increasing d_0 and constant N due to a decreasing radiation loss at the filter caused by a rise of its absolute transmission. The efficiency increases with increasing N for $d_0 = 1$ mm as a result of falling losses due to an increase in the filter relative transmission with decreasing d_{0f}. An inverse dependence is observed for P as a function of N for filters with $d_0 = 1.5$ and 1.9 mm: an increase in the number of lasers N from 7 to 19 and 37 leads to an almost twofold decrease in P.

The radiation intensity distributions in the far-field zone were compared for all d_0 and N. It has been shown that, at $d_0 = 1$ mm, the distributions are characterized by a high contrast for all N, which testifies to a complete radiation phase locking of the laser arrays. On the other hand, for filters with $d_0 = 1.5$ and 1.9 mm, a high contrast distribution

Table 1.

N	d_{0f}/mm	P		
		$d_0 = 1$ mm	$d_0 = 1.5$ mm	$d_0 = 1.9$ mm
7	1.84	0.1	0.47	0.53
19	1.05	0.14	0.23	0.36
37	0.73	0.15	0.25	0.32

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is observed only for the array with $N = 7$, and the contrast decreases for the laser arrays with $N = 19$ and 37. This means that an incomplete radiation coherence for the latter arrays is observed at $d_0 = 1.5$ and 1.9 mm and leads to a reduction of the phase-locking efficiency, although the relative transmission of the filters for these laser arrays is higher than that for the array of seven lasers.

The partial coherence can be associated with a loss in the phase-locking stability [7] or with the fact that some lasers in the array permanently radiate independently of other lasers. In any case, there are two causes that lead to a partial coherence. The first cause is an extending range of the initial frequency spread of separate lasers with increasing N. For example, let the initial dimensionless frequency mismatches Δ between neighbour lasers be equal and the frequency mismatch between any pair of lasers be a linear function of increasing distance. Such a relation between mismatches may correspond well to actual conditions and gives the following estimate for the frequency mismatch (maximum over the array) for the lasers of the 2D array being at the longest distances from each other:

$$\Delta_{\max} = \Delta N^{1/2}. \tag{1}$$

Since the maximum frequency mismatch increases with N, this may result in the fact that the frequencies of a certain number of lasers fall beyond the locking band for the filters with increased absolute transparencies ($d_0 = 1.5$ and 1.9 mm), and, as a consequence, in the partially coherent radiation of the arrays.

Note that most of the experimental conditions do not satisfy the approximation of uniform global optical coupling. In this approximation, according to [13], the condition for coherent oscillation of the ith laser with other lasers of the array has the form

$$\Delta_i < MN, \tag{2}$$

where Δ_i is the initial dimensionless frequency mismatch of the ith laser oscillation with respect to the common frequency equal to the average frequency of individual lasers and $M = \text{const}$ (a positive value) is the coefficient of optical coupling between any pair of lasers. When uniform global coupling is established, all the lasers radiate coherently if $\Delta_{\max}$ is no higher than the product MN. Substituting the frequency mismatch $\Delta_{\max}$ from (1) for Δ_i into (2), we obtain

$$\Delta N^{1/2} < MN. \tag{3}$$

Hence, if condition (3) is satisfied for the array with $N = 7$ at $d_0 = 1.5$ and 1.9 mm, the more so for the arrays with $N = 19$ and 37 at the same d_0. However, this contradicts the experimental results. Probably, the case close to the uniform coupling corresponds to the data of the third column of Table 1, when the stable phase locking was obseved for all three laser arrays at $d_0 = 1$ mm. This assumption is based on the fact that the degree of optical coupling uniformity rises, as the filter absolute transmission decreases [13].

A reduction of the optical coupling with an increase in the filter absolute transmission is another factor causing a partial coherence of radiation for the laser arrays with $N = 19$ and 37 when changing from the filter with $d_0 = 1$ mm to the filters with $d_0 = 1.5$ and 1.9 mm. This is qualitatively confirmed by the results of numerical calculations of the optical coupling coefficients for a 1D laser array with nonshifted spatial filters with various absolute transmissions [7]. As the filter transmission increases, the maximum positive coefficients for neighbour laser pairs decrease, and the array-average absolute values of the negative coupling coefficients increase. Larger magnitudes of the negative coupling coefficients lead to a more significant role of destructive interference of the proper and injected fields in each laser and, together with a decrease in the positive coefficients, cause a reduction of the locking band. Although the calculations in [7] were performed for a 1D array, the tendencies in changes of the optical coupling coefficient mentioned above are quite possible for 2D laser arrays.

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