Effective phase locking of an array of lasers

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It is predicted theoretically and verified experimentally that an effective phase locking of a two-dimensional array of lasers can be achieved by making use of the reproduction of the wavefront of a periodic structure of coherent radiators.

Laser systems containing a large number of laser oscillators have recently attracted considerable interest.[1–3] If there is no coupling between the individual lasers, the output of each laser has its own independent polarization, frequency, and mode structure. The emission from an array of uncoupled laser oscillators has a large angular divergence, determined by the aperture of a single element. If the laser oscillators are phase-locked, the angular divergence can be reduced significantly, and the resulting multibeam lasers will have more possible fields of application.[3]

Our purpose in the present study was to experimentally and theoretically determine the conditions for an effective phase locking of a two-dimensional array of CO_2 waveguide lasers with an external coupling mirror through variation of the distance between this mirror and the laser aperture.

Let us examine the transformation of the fields in an array of waveguide lasers after a complete traversal of the resonator. If the field distribution at the aperture of an array of N laser oscillators is $\mathbf{E}(\mathbf{r}) = \Sigma^N E_n \mathbf{e}_n f(\mathbf{r}-\mathbf{r}_n)$, then the field amplitudes are transformed as follows after a complete traversal of the resonator:

$$E_n(t+\tau_p) = R\hat{A}_n \mathbf{E}(t) \exp(gl) \exp(i\varphi_n), \tag{1}$$

Here $f(\mathbf{r}-\mathbf{r}_n)$ is the normalized waveguide mode function; $f(\mathbf{r}-\mathbf{r}_n) f(\mathbf{r}-\mathbf{r}_m) = \delta_{nm}$; $\mathbf{e}_n$ is the polarization vector of the given mode; $\mathbf{r}_n$ is the position of the center of the aperture of the n-th waveguide; R is the amplitude reflection coefficient of the output mirror; g and l are the gain and length of the waveguide; and φ_n is the change in the phase of the field over the traversal of the waveguide. The coupling operator $\hat{A}$ describes the transformation of the radiation field during the traversal of an empty gap:

$$\hat{A}_n \mathbf{E} = \int f(\mathbf{r}-\mathbf{r}_n) \mathbf{e}_n d\mathbf{r} \frac{ik}{2\pi L} \int \mathbf{E}(x_1, y_1) \exp[ikL(x, y, x_1, y_1)] dx_1 dy_1 . \tag{2}$$

In the case $L = 0$, with $\hat{A}_n \mathbf{E} = E_n$, each laser operates independently since there is no coupling. If the distance to the mirror is small, $L \ll d^2 \lambda$ (d is the period of the waveguide array, and $\lambda = 2\pi/k$ is the wavelength of the radiation), there is a diffractive coupling between nearest neighbors. The resonant frequencies of the individual lasers differ and there is a threshold value of the coupling coefficient at which the array of lasers is locked. The problem of determining the threshold coupling coefficient, at which lasers separated by a substantial distance are phase-locked, is analogous to Anderson's problem[4,5] of the states of excitation in the field of periodically distributed potential wells with a random scatter in energy levels. The condition for phase locking of lasers is the same as the condition for an Anderson transition in a two-dimensional lattice[4,5]: $(\langle \Delta\varphi^2 \rangle)^{1/2} < \beta |A_{n,n+1}|$, where $A_{n,n+1}$ is an off-diagonal element of the coupling operator, β is a coefficient of order unity, and $(\langle \Delta\varphi^2 \rangle)^{1/2}$ is the average scatter of the phase shifts in the waveguides. Under the condition $L \ll d^2\lambda$, an increase in the distance leads to an increase in the coefficient of the coupling between different waveguides, but there is a simultaneous increase in the loss. The reason is an increase in the fraction of the radiation which falls in the region between waveguides. For lasing to occur, the condition $R \exp(g_0 l)_{max} |a_n| > 1$ must be satisfied, where the a_n are the eigenvalues of the operator $\hat{A} \exp(i\varphi_n)$, and g_0 is the unsaturated gain. The eigenvalues of the coupling operator for periodically spaced radiators depend in a nonmonotonic way on the distance L. As L is increased, the eigenvalues initially fall off, but later on they increase. At the value L corresponding to the reproduction of the original periodic structure, the moduli of the eigenvalues are equal to unity (if edge effects are ignored). This fact stems from the well-known effect of a reproduction of a periodic field structure.[6,7] In this case, there is no loss due to matching of the fields. If all of the radiators in the periodic array are in phase, then the field structure at the aperture, after the radiation has propagated to the coupling mirror and back, will be the same as the original structure at the distance corresponding to the reproduction length. In this case we have the best condition for multibeam systems, specifically, a high coefficient of the coupling of the lasers in the absence of a field-matching loss.

In the present experiments we use a multibeam CO_2 waveguide laser[3] consisting of 61 glass tubes in a honeycomb arrangement with a period $d = 0.85$ cm. This laser operates in a quasisteady state with an output pulse length ~ 0.1 s. The energy and power of the output are measured with an IMO-2N calorimeter and a Ge:Au photoresistor. The spatial distribution of the output in the focal plane of the lens is monitored with an IR visualizer. The wavelength of the radiation is determined with the help of a spectrum analyzer.

Figure 1 shows the power (P) of the output radiation from the multibeam laser as

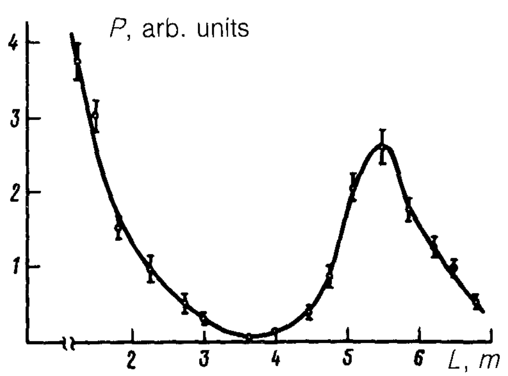

FIG. 1. The output power P as a function of L.

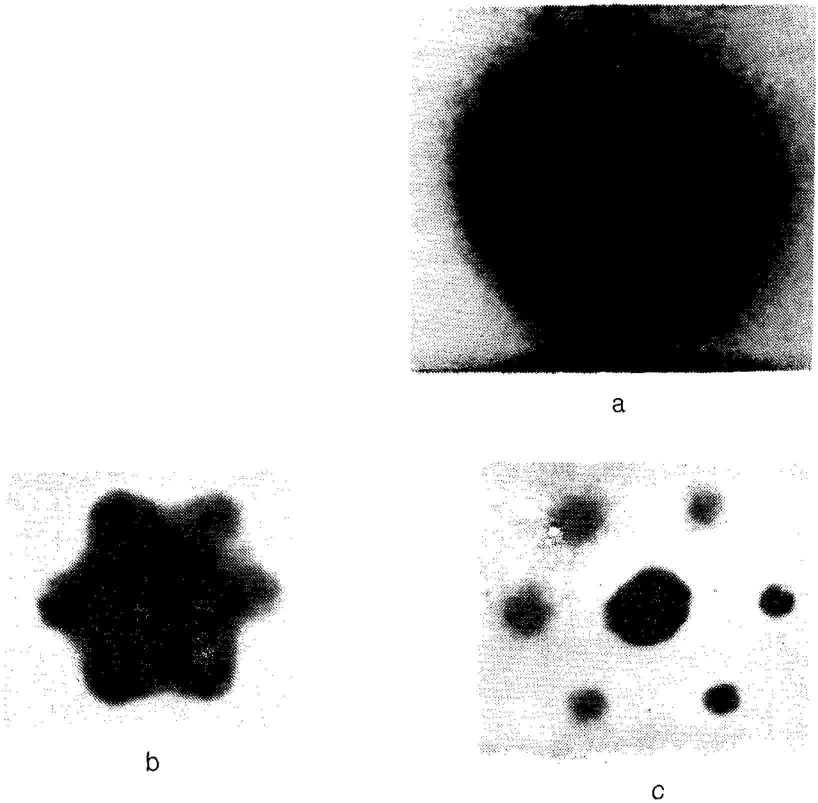

FIG. 2. Photographs of the focal spot of the output from the multibeam CO_2 laser. a—$L < 1$ m; b—1 m $< L < 3$ m; c—4 m $< L < 7$ m.

a function of the distance (L) between the aperture of the array of tubes and the coupling mirror for a constant level of the pumping of the active medium. As L is increased to 3.5 m, the output power falls off monotonically because of an increase in the in-resonator loss. As L is increased further, a peak appears on the plot of the output power, reflecting the reproduction of the periodic wave fields. A possible explanation for the smaller size of the peak at $L = 5.5$ m in Fig. 1 is that five tubes of the array were covered by a screen because they had suffered malfunctions. Figure 2 shows the output intensity distribution in the focal plane of the lens for various values of L. The divergence is at its lowest when the coupling mirror is at the position corresponding to the reproduction distance of the periodic structure, indicating the most effective phase locking of the array of lasers. In the interval 4 m $< L < 6$ m, the lasing occurs on transitions of the P and R branches in the 10-μm region of CO_2, while at $L > 6$ m it occurs on transitions of the P and R branches in the 9-μm region. When the coupling mirror is adjusted well ($L = 4.5$–7.0 m), the lasing occurs on a single rotational transition of CO_2, and the brightness of the focal spots is noticeably higher than at $L < 3.5$ m, indicating a complete phase locking of the array of lasers.

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