Phase-locked controlled filament laser

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A broad area semiconductor laser with induced self-focusing in the form of a phase-locked array of filaments is demonstrated. The multifilamentary laser has a single lobed and nearly diffraction limited far-field pattern, for injection currents up to $I \simeq 1.85 I_{\text{th}}$.

In the quest of a high power semiconductor laser, considerable effort has been devoted recently to the development of phase-locked injection laser arrays.

Uniformly spaced laser arrays with net loss in the interchannel regions usually prefer lasing in a lateral supermode other than the fundamental one, which results in an undesired twin-lobed far field. In cases in which the discrimination between the supermodes is low (comparable modal gain), the phased array emission may take place in a superposition of several lateral supermodes. In these cases, the spatial coherence of the array is degraded and the far-field divergence angle is further increased.

Recently, several approaches have been demonstrated for achieving fundamental supermode operation of phased arrays. These include laser arrays with net gain between the elements[1-3] "chirped" and gain tailored arrays,[4-6] and offset-stripe arrays.[7] However, all these structures are susceptible to gain saturation in the lasing supermode, and the resulting appearance of higher order supermodes as the injection current is increased.[8] It appears that any structure with a built-in (gain or index guided) waveguide, resulting in a nonuniform modal field across the waveguide will suffer from the same problem, since the gain depression (by saturation) of the lasing mode inevitably pushes, with increasing current, initially nonoscillating modes above threshold causing them to oscillate. This problem has yet to find a satisfactory solution.

In this letter, a new approach is demonstrated, by which a nearly diffraction limited beam is obtained from a 120-μm-wide laser, which is *not* an array. The laser maintains nearly the same angular spread when the injection current is increased up to $I \sim 2I_{\text{th}}$. Our starting point is the observation that a broad area semiconductor laser is susceptible to regenerative self-focusing, and the formation of filaments.[9] A generally accepted model for the filamentary nature of semiconductor lasers[10] invokes the dependence of the refractive index on free carriers,[11] and the local depletion of carriers by the stimulated emission. According to this model, a local *maximum* in the optical field intensity produces a *minimum* in the free-carrier density, and therefore induces a *maximum* in the refractive index (self-guiding). An interesting feature of this model is the fact that the gain, which is proportional to the free-carrier density, is lower at the center of the filament than in the wings. Close to threshold, the filamentary lasing field $E(x,z) = \psi(x,z)e^{i\beta z}$ can be described approximately as the solution of the nonlinear Schrödinger equation,

$$2i\beta \frac{\partial \psi}{\partial z} + \frac{\partial^2 \psi}{\partial x^2} + \left[k_0^2 (n_0^2 + 2_0 n_2 |\psi|^2) - \beta^2 \right] \psi = 0, \quad (1)$$

where x and z are the lateral and longitudinal dimensions, respectively; the index of refraction was assumed to be of the form $n(x) = n_0(x) + n_2|\psi|^2$ with $n_2|\psi|^2 \ll n_0$, k_0 is the wave number in vacuum, β is the propagation constant, and $\psi(x,z)$ is a slowly varying (envelope) amplitude. Diffusion of carriers has been neglected, and the transverse (y) variation was taken out by making an effective index approximation.

A solitary, steady state solution of Eq. (1) is the well known filamentary field of the form $\psi(x) = \cosh^{-u} bx$ with b being a scaling factor determining the filament width, and the exponent u is a complex number determined by the ratio of the real part to the imaginary part of n_2[12] (this ratio is called the α parameter).[13] Next, we note that a profile $\psi(x)$ consisting of several filaments is also a solution of Eq. (1).[14] For simplicity, we may view this solution as *an array of phase-locked filaments*. Such an array boasts a higher gain in the interchannel regions where carrier saturation is weaker. Consequently, we expect the locking of neighboring filaments to be *in phase* and a resulting far-field intensity distribution which is single lobed.[1] The above arguments and the possibility of implementing a self-focused laser array operating in the fundamental supermode were suggested recently by us, and preliminary experiments to induce a controlled single filament and multiple filament operation of a broad area device were also reported.[15]

In the work reported here, a controlled phase-locked filament laser array 120 μm wide was fabricated. To induce a controlled multifilament "mode" we introduced a periodic perturbation in the lateral direction, in the reflectivity of one of the mirrors. This was accomplished by means of multiple ridges extending some 10 μm along the longitudinal direction (normal to the facets). The ridges were 4 μm wide and with 9 μm intercenter separation. The resulting laser geometry is illustrated in Fig. 1(a). A schematic drawing of the device is shown in Fig. 1(b).

We may consider the plane AA' in Fig. 1(b) as an effective mirror plane, so that the absolute value of the reflectivity, R, is spatially modulated. The total (incident + reflected) field close to plane AA' is then $\psi(x)[1 + R(x)]$. The resulting lateral modulation of the total intensity will preferentially nucleate self-focused filaments in the regions of high

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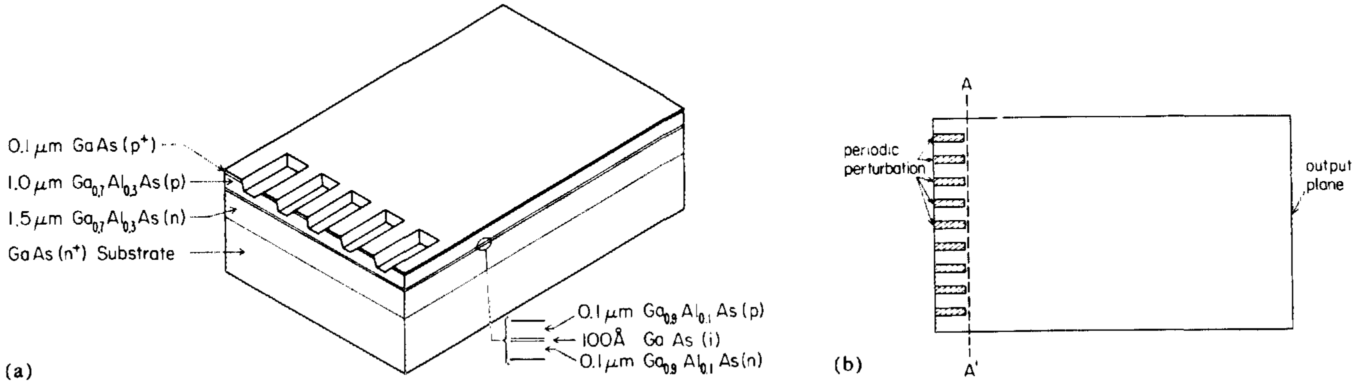

FIG. 1. Controlled filament laser array: (a) Implementation of the induced filaments by multiple ridges near one facet. (b) Schematic drawing of the device. Plane AA' is a reference mirror plane with spatially modulated reflectivity.

intensity. This serves to stabilize the filaments. The actual implementation of the facet reflectivity modulation is not crucial and other schemes employing proton implantation, ion mixing, or a channeled substrate, to name a few, can be used.

The lasers were fabricated from a modified single quantum well double heterostructure wafer grown by molecular beam epitaxy, and operated in 200-ns pulses at 1-kHz repetition rate. The near-field intensity distribution of the controlled filament array, at the unmodulated output plane (see Fig. 1), is in general nearly constant across most of the laser width, with a small periodic lateral modulation consistent with the periodicity in $R(x)$. In Fig. 2 three examples of the spectrally resolved near-field intensity distribution from different devices are shown. A characteristic of nearly all the measured lasers, is the operation, at first, with 8–9 coupled filaments (70% of the total laser width). Complete phase locking is indicated by the fact that an exact replica of the near-field pattern is observed for several longitudinal modes (this is confirmed by the far-field measurements, as explained below). At an injection current $I \simeq 1.2 I_{th}$, a second lateral mode, spanning the total width of the laser starts lasing at a different wavelength. Further increasing the injection current causes additional longitudinal modes to lase, but the general pattern of two lateral modes, as shown in Figs. 2(a) and 2(b), is maintained up to $I \sim 2.5 I_{th}$. The near-field patterns shown in Fig. 2 might have been interpreted as those corresponding to a high order lateral mode of the waveguide, but in this case, a twin-lobed far-field pattern would be expected. In contrast, single-lobed far fields, on axis, were always measured. Figure 3 shows the far-field intensity distribution for various values of the injection cur-

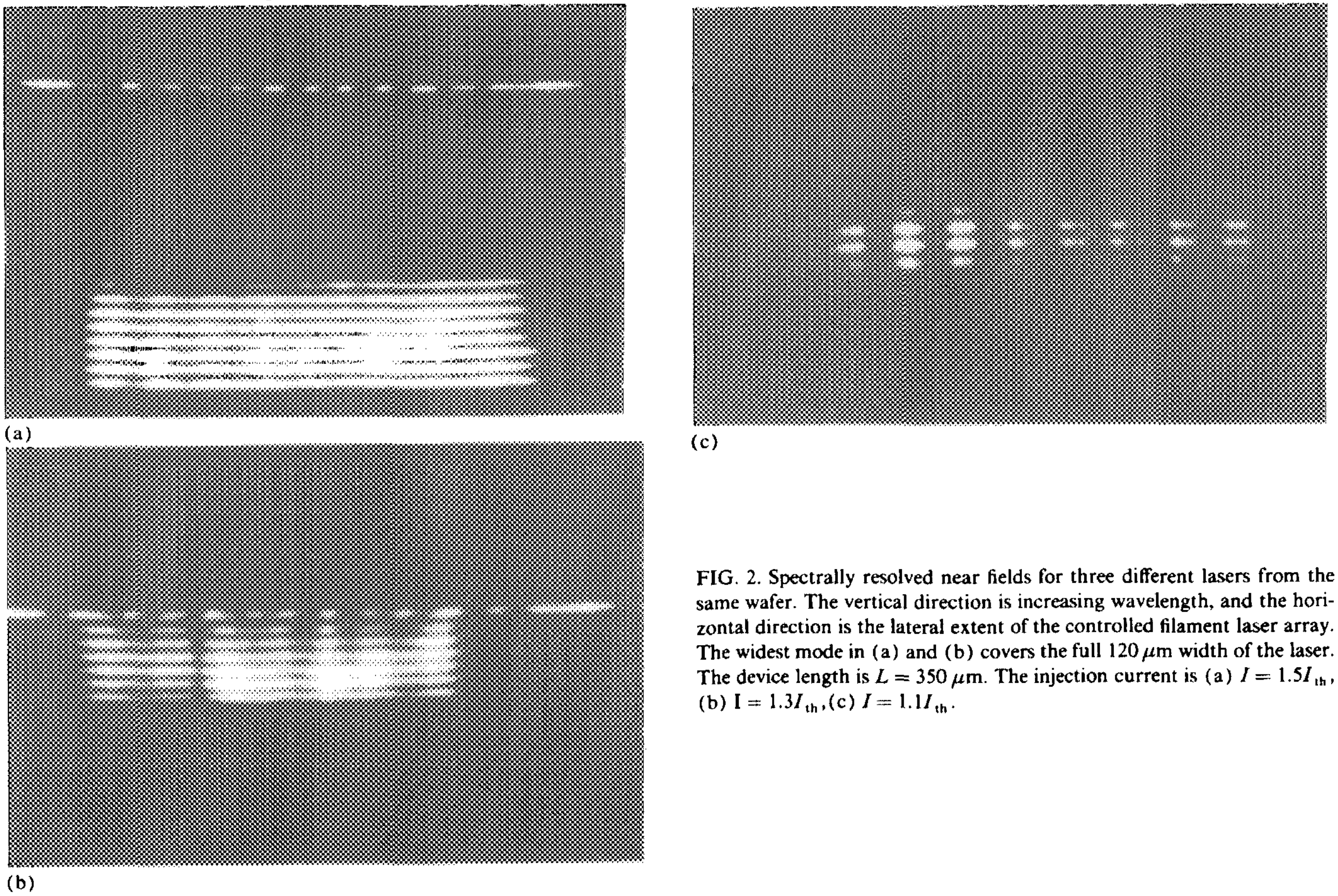

FIG. 2. Spectrally resolved near fields for three different lasers from the same wafer. The vertical direction is increasing wavelength, and the horizontal direction is the lateral extent of the controlled filament laser array. The widest mode in (a) and (b) covers the full 120 μm width of the laser. The device length is $L = 350\ \mu$m. The injection current is (a) $I = 1.5 I_{th}$, (b) $I = 1.3 I_{th}$, (c) $I = 1.1 I_{th}$.

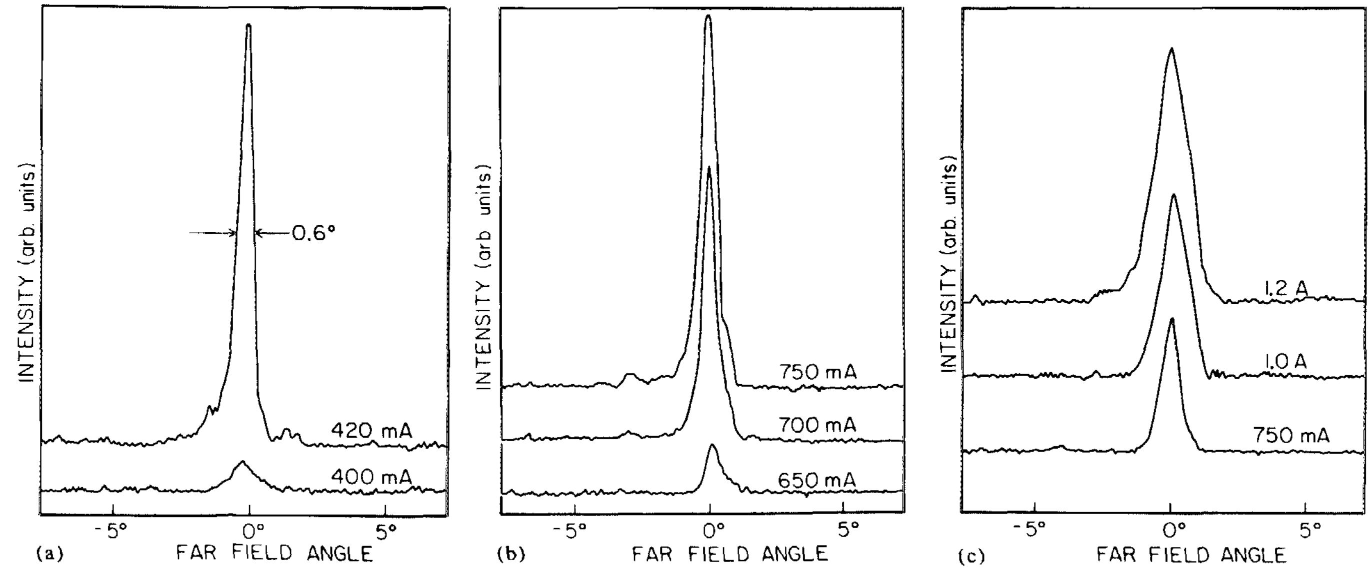

FIG. 3. Far-field intensity distribution of the controlled filament laser array for different values of the injection current [arbitrary re-scaling in (b) and (c)].

rents. A beam divergence of $\theta = 0.6^\circ$ full width at half-maximum (FWHM) was measured at $I = 1.05I_{\text{th}}$, and no broadening was observed up to $I = 1.85I_{\text{th}}$, [Fig. 3(b)]. (The diffraction limited beam divergence for a uniform distribution over a width $D = 120\mu\text{m}$ is $\theta \sim \lambda / D \sim 0.4^\circ$.) At $I = 3I_{\text{th}}$ the far-field angle FWHM is $\theta = 1.5^\circ$ and it continues broadening up to $\theta = 5^\circ$ at $I = 6I_{\text{th}}$.

A stable, single lobe, nearly diffraction limited far-field pattern similar to the one observed in our controlled filament array (Fig. 3) has been a primary goal of previous research in phase-locked laser arrays. Even in cases where the phased array operated in the fundamental supermode close to threshold, a superposition of supermodes was observed when the injection current was increased over $I \gg 1.5I_{\text{th}}$. In the case of the controlled filament array, the nonlinearity in the index of refraction represented by the term $n_2|\psi|^2$ in Eq. (1) is essential to the formation of the filaments and their locking. Therefore, the concept of a lateral mode of the passive waveguide (i.e., without the oscillating field) does not apply and the functional form of the solution is intensity dependent.

A relevant question would be: Is the gradual broadening of the far-field pattern with increasing current related to an increase in phase front curvature of the *coherent* oscillating field, or to the onset of independent (unlocked) filaments? A partial answer to this question can be obtained by measuring the spatial coherence of the light output of the controlled filament array as a function of injection current. This has been performed by employing a simple shear interferometer, in which the laser near field, and a spatially inverted version of this near field were superimposed[16] and the interference pattern monitored with a vidicon camera. High visibility of fringes was observed over the total laser width, up to injection currents of 1.5–$2.0I_{\text{th}}$ in close agreement with the injection level at which the far-field pattern started broadening. This suggests that the increased broadening is due to the onset of independent filamentary fields.

In conclusion, we have demonstrated the operation of a multifilamentary laser, with single lobed and nearly diffraction limited far-field pattern. The controlled filaments have been induced by a lateral periodic perturbation on one side of the broad area laser, and complete phase locking was observed up to injection currents of $\sim 1.85I_{\text{th}}$. A detailed theoretical study was performed which extends, self-consistently, the nonlinear Schrödinger equation to the high power regime. This solution results in an *ab initio* derivation of the effective nonlinear constant n_2 and leads among other things to an expression for the filament spacing. This study will be published separately.[17]

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