Coupling mechanism of gain-guided integrated semiconductor laser arrays

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It is shown that a gain-guided laser array couples via propagating fields rather than the evanescent mode coupling typically responsible for directional coupling in passive (directional couplers) and active (laser array) devices. We show that these phase-locked modes exhibit an interference pattern, in the junction plane, which arises from the curvature of the phase fronts of optical fields of the interacting lasers. The experimental results are interpreted with the aid of a simple theoretical model, and the effect of the observed mode pattern on the coupling of gain-guided lasers is discussed.

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The understanding of the coupling mechanism between integrated nearest neighbor lasers is important for the design of high-power diode-laser phased arrays[1–5] and of diode lasers with frequency control that are based on such coupled devices.[6,7] The exact nature of this coupling mechanism, however, has not been investigated thus far. The coupled modes of lasers which interact in parallel are commonly visualized as odd and even combinations of the individual laser modes. It is usually argued that such lasers couple in the odd or even combinations depending on whether the coupling region between their stripes is lossy or not, in order to maximize the modal gain. In this work we show that, generally, the coupling mechanism of semiconductor lasers is more involved. In particular, the coupled modes of gain-guided lasers were found to exhibit spatial (lateral) patterns which result from the interference of their individual, radiating modes. The specific intensity distribution in the junction plane of these "supermodes" determines the modal gain, which in turn determines the pattern of the lasing mode. A simple theoretical model is employed to calculate the mode patterns of coupled gain-guided lasers, which are found to be in qualitative agreement with the experimental results.

The coupling features of narrow stripe ($\sim 4\ \mu$m wide) gain-guided lasers were investigated using the recently developed GaAs/GaAlAs laser array with separate contacts.[5] The laser stripes were delineated by using proton implantation, the separation between the centers of adjacent stripes being $9\ \mu$m. Separate contacting was accomplished by using two-level metallization.[5] The threshold current of each individual laser was, typically, 60 mA (pulsed operation).

The spectrally resolved near fields of pairs of coupled lasers, separated by various multiples of $9\ \mu$m, were obtained by imaging the near field of the lasers on the entrance slit of a spectrometer and displaying the output on a monitor using a silicon-vidicon TV camera. The spatial intensity distribution of the coupled modes at a given frequency could then be obtained by scanning a selected line of the video signal.

Generally, the phase-locked modes of the coupled lasers appeared at wavelengths which were $\sim$50–100 Å longer than the wavelengths of the individual laser modes, and the spectral width of the phase-locked lasers was considerably smaller than that of the individual ones.[6] When the interacting lasers were separated by more than $18\ \mu$m, gain had to be introduced into the coupling region between them by pumping current through the intervening stripes, in order to obtain phase-locked modes.[8] The near-field pattern of a phase-locked mode consisted of two main lobes, located approximately below the centers of the coupled laser stripes, and secondary peaks in the intervening coupling region. An example of such a phase-locked mode is shown in Fig. 1. Figure 1(a) shows schematically the layered structure and the contacts configuration. Figures 1(b) and 1(c) present the intensity pattern in the junction plane and the spectrally resolved near field of two coupled lasers separated by $18\ \mu$m,

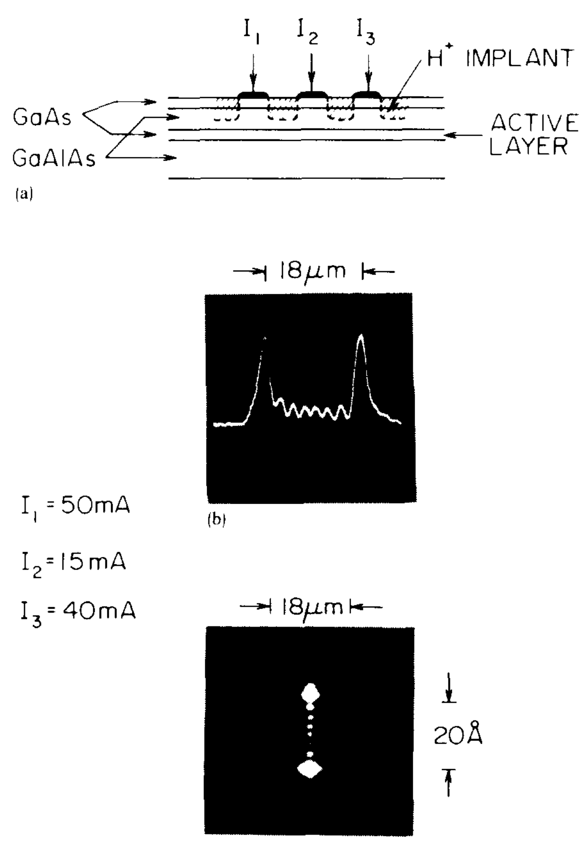

FIG. 1. (a) Schematic illustration of the layer structure and the contact configuration of the coupled lasers. (b) Intensity pattern (in the junction plane) of a phase-locked mode of two lasers separated by $18\ \mu$m, with $I_1 = 50$ mA, $I_3 = 40$ mA, when the intermediate stripe is pumped with $I_2 = 15$ mA. (c) Spectrally resolved near field for the same parameters as in (b).

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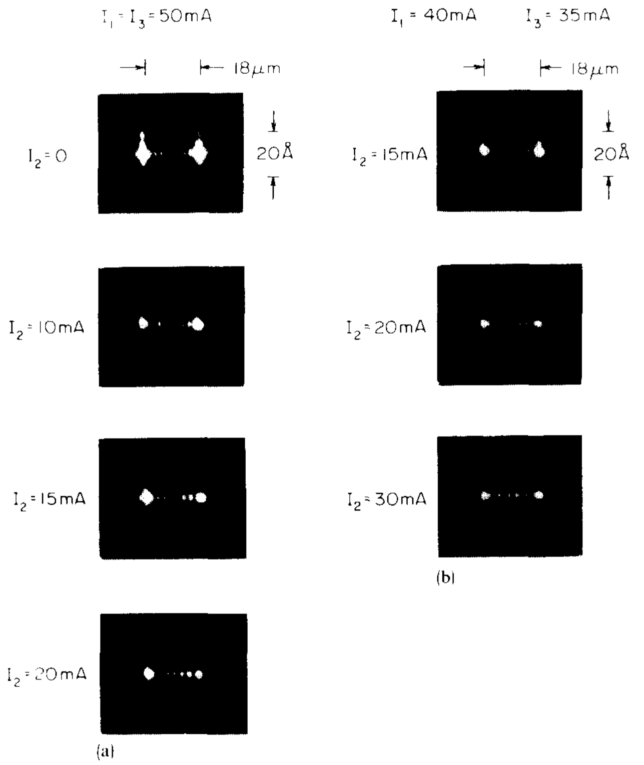

FIG. 2. Evolution of the intensity pattern of the phase-locked modes of two coupled gain-guided lasers separated by 18 μm, as a function of the current I_2 through the stripe between them. (a) $I_1 = I_3 = 50$ mA, (b) $I_1 = 40$ mA, $I_3 = 35$ mA.

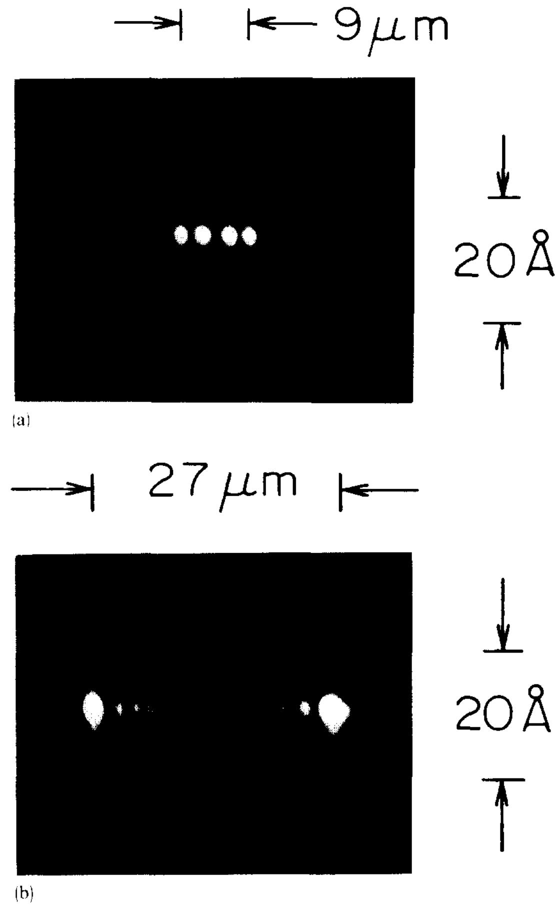

FIG. 3. Spectrally resolved near fields of two coupled gain-guided lasers with various separations s. (a) $s = 9$ μm, (b) $s = 27$ μm.

with the laser between them biased below threshold. The coupled lasers operated in essentially a single longitudinal mode, at $\lambda \approx 0.88$ μm.

As the current through the contact between the coupled lasers was increased, the lasing modes hopped to shorter wavelengths, resulting in tuning range of ~ 50 Å (Ref. 6). When this current was further increased, the lasing mode hopped back to longer wavelengths, but the spatial mode pattern was now different. This behavior repeated at still higher currents through the intermediate stripe. Figure 2 shows the evolution of the spatial mode pattern of the phase-locked modes of two lasers separated by 18 μm for two sets of the laser currents I_1 and I_3. For all the spectrally resolved near fields in Fig. 2, the wavelength is $\lambda \approx 0.88$ μm. It is clear that the separation between the secondary peaks in the mode pattern increases with increasing current I_2 [Fig. 2(a)]. Also, this separation was larger when the laser currents I_1 and I_3 were lowered [Fig. 2(b)]. Essentially the same behavior was exhibited by coupled lasers which were separated by different distances s. Figures 3(a) and 3(b) show the near-field pattern for $s = 9$ and 27 μm, respectively.

The near-field patterns presented above can be understood by recalling that gain-guided lasers are characterized by optical fields whose phase fronts are curved in the junction plane.[9,10] Thus, the radiating modes of two adjacent gain-guided lasers interfere to form a lateral standing wave pattern in the intervening region in which the fringe periods depend on the angle between the phase fronts of the interfering fields. The angle at which the gain-guided mode radiates (with respect to its propagation direction) increases with increasing difference between the peak gain under the laser stripe and the gain in the region outside the laser stripe. Thus, the period of the interference fringes in the pattern of the phase-locked modes increases when the region between the coupled lasers becomes less lossy, as shown in Fig. 2.

The above discussion can be rendered more quantitative by employing a simple model to evaluate the modes of the coupled gain-guided lasers. The analytic expression for the optical field of each individual laser is obtained using the asymmetrical gain profile of Streifer *et al.*,[11] which can account for the difference in loss between the two sides of each coupled laser. In the case of well confined individual modes (in the junction plane), the coupled modes can be well approximated by the superposition of the optical fields supported by each asymmetrical gain distribution. An example of such calculated field patterns (for $s = 18$ μm) is given in Fig. 4, for two values of gain in the intermediate region. Notice the decrease in the number of fringes for the case of higher intermediate gain, which is in agreement with the experimental results. A more accurate model, in which the two coupled lasers were modeled as a single waveguide made up of several lamelar regions, each with a different constant, complex ϵ, yields essentially the same results.[12]

The data that we presented and its interpretation reveal the details of the formation of phase-locked modes of coupled gain-guided lasers. As discussed elsewhere,[6] the phase-locked multiwaveguide array laser prefers to oscillate at a wavelength where the individual guides have the same phase velocity. This is responsible for the wavelength selectivity

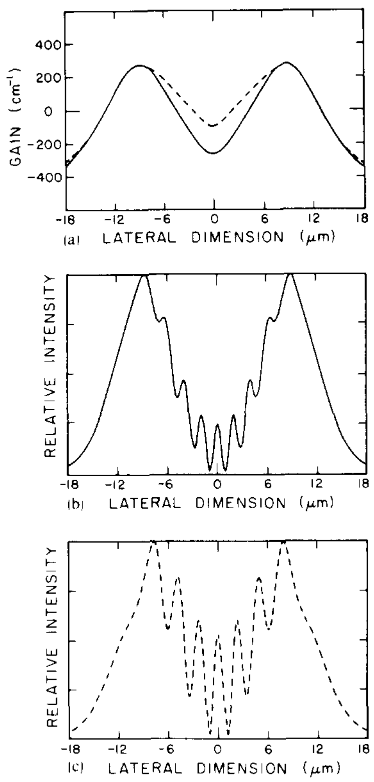

FIG. 4. Model for two coupled gain-guided GaAs/GaAlAs lasers separated by 18 μm. (a) Gain distribution for two cases of intermediate gain. (b) Near-field patterns corresponding to the gain distribution described by the solid line in (a). (c) Near-field pattern corresponding to the gain distribution described by the dashed line in (a). The near-field of each individual laser was calculated using the model of the asymmetrical gain profile described in Ref. 11, assuming an antiguidance factor $b = 2.5$.

exhibited by lasers that are coupled side by side.[6] This phase-matching requirement explains the tuning of the phase-locked modes as described in connection with Fig. 2: a change in the value of the intermediate gain results in the shift of the phase-matching domain and, thus, of the oscillation, to different wavelengths.[6]

The occurrence of high intensity peaks *between* the pumped stripes of coupled gain-guided lasers [see, e.g., Fig. 3(a)] may give rise to saturation effects. These may result in a virtual transparency of the (usually unpumped) regions between the stripes of gain-guided laser arrays which, in turn, increases the effective coupling between the elements in such arrays. It should be noted that, since the phase-front curvature of index-guided lasers is negligible, these effects are less important in that case.

In conclusion, we showed that semiconductor gain-guided lasers couple by forming phase-locked modes which exhibit interference pattern due to the curvature of the phase fronts in the coupled optical fields. A simple theoretical model was used to calculate the near fields of the phase-locked modes of two coupled gain-guided lasers, and the results were found to agree with the experimental data. This investigation may be utilized in the design of high-power phase-locked laser arrays which, to date, employed mostly gain-guided lasers.

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