Phase-locked semiconductor laser array with separate contacts

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A new monolithic phase-locked semiconductor laser array has been fabricated. Employing two-level metallization, each of the eight elements in the array has a separate contact, thus making it possible to compensate for device nonuniformities and control the near-field and far-field patterns. Threshold currents are approximately 60 mA for each 5-μm-wide laser in the array. Phase locking has been observed via the narrowing of the far-field pattern. Experimental results are compared to those obtained from the same arrays operated with all the lasers connected in parallel.

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Coherent combination of the power of several semiconductor lasers operating on the same substrate has been the subject of an intense research effort in recent years.[1-10] The motivation for phase locking is the need, in some applications, to obtain higher power levels than those available from a single semiconductor laser in a stable radiation pattern. The coherent (versus incoherent) combining has the added advantages of narrowing the spatial extent of the radiation pattern in the array plane and also potentially maintaining a narrower output spectrum (since all the phase-locked lasers have the same spectrum). In all the devices demonstrated so far, all the lasers of the array were electrically connected in parallel, i.e., a single contact was applied to the whole array. In recent work, where interaction between only two lasers was investigated[11] each laser had its separate contact.

There are several advantages to constructing an array such that each laser can be addressed—and hence driven—separately and independently of the other lasers in the array. In such a configuration uniform radiation from all the lasers can be achieved—if needed—even when there exist nonuniformities among them. More generally, a separate contact of each laser means an additional degree of freedom in the design of the array and makes it possible to investigate the various aspects of the phase-locking mechanisms. This can provide a better insight into the physics of coherent interaction between lasers. Finally, the current distribution among the lasers can be tailored to produce a predetermined far-field pattern and even beam steering.[12,13]

It is clear that because of the close spacing ($\sim 10\ \mu$m) between the lasers of the array which is needed to achieve efficient phase locking, two-level metallization technology is required in a separate-contact array with three or more elements. In this letter we report primarily on the fabrication of an eight-element monolithic array semiconductor injection lasers, each with its own contact, and on initial tests made on groups of lasers within it.

The array structure is shown schematically in Fig. 1. The eight elements of the array are stripe contact lasers, isolated from each other by proton bombardment (in some devices isolation was obtained by etching). The stripe width is about 5 μm, and the center-to-center spacing between adjacent lasers is 9 μm. Using two-level metallization, separate contact is provided to each laser, as shown in Fig. 1, thus making it possible to apply different currents to each laser in the array.

Fabrication of the device starts with liquid phase epitaxy (LPE) on an n^+-GaAs substrate. The grown layers are n-$Al_{0.4}Ga_{0.6}As$ (2μm), n-GaAs active region (0.25 μm), p-$Al_{0.4}Ga_{0.6}As$ (1.5 μm), and a p^+-GaAs (0.3 μm) cap layer. Groups of eight parallel CrAu stripes are deposited with liftoff. The width of each stripe is 4–5 μm, and the center-to-center spacing is 9 μm. Separation between adjacent stripes is provided via either proton bombardment (energy: 120 keV, dose: 3×10^{15} cm^{-2}) or wet chemical etching (H_2SO_4: H_2O_2: H_2O, 1:1:8). Next, a SiO_2 layer is evaporated and contact holes are etched through it using standard photolithographic techniques. The second level of metallization (CrAu) is deposited and the contact pattern defined by etching. The last processing phase includes the standard steps of wafer lapping, AuGe/Au deposition for the n-side (substrate) contact, alloying and cleaving of individual devices. Typical lengths of individual devices are about 250 μm.

The devices were operated under low duty cycle pulsed conditions. Typical threshold currents of individual lasers in the array are 60 mA. By varying the current through each laser, the near-field and far-field distributions are controlled. Due to limitations of the available testing station, groups of

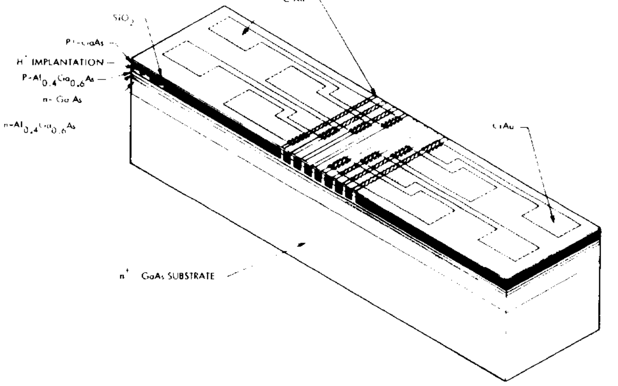

FIG. 1. Schematic structure of the separate contact array.

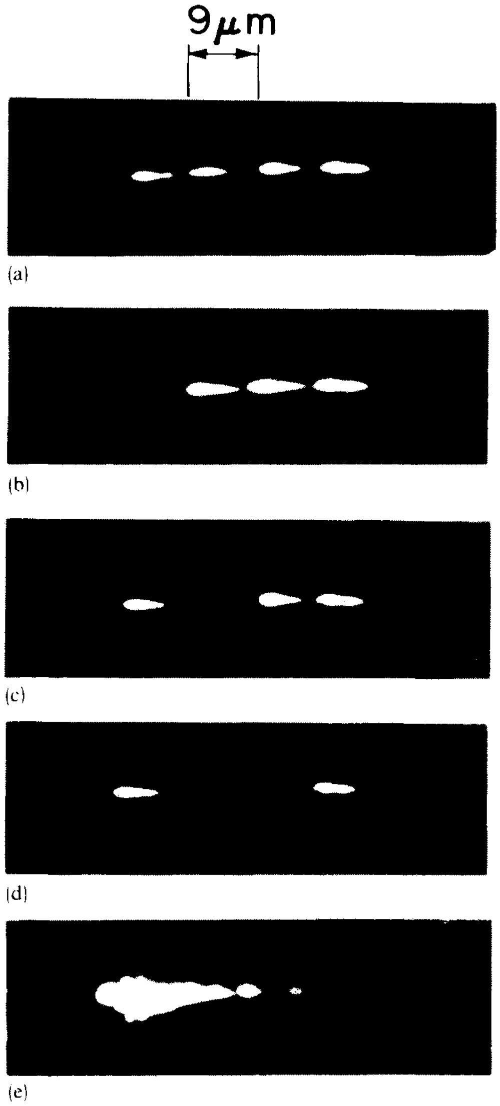

FIG. 2. Near-field pattern of a group of four elements of the array: (a) all four lasers operating; (b), (c) three lasers operating; (d) two lasers operating; (e) all four lasers connected in parallel and fed through one current source.

up to four lasers only in an array were tested simultaneously. Testing of more than four elements simultaneously is now under way. Figure 2 shows several near-field patterns obtained from a typical group of four lasers in an array. In Fig. 2(a) all the lasers are lasing, and the current levels are adjusted to yield as homogeneous distribution as possible. It should be noted again that the center-to-center spacing between the lasers is 9 μm. In Figs. 2(b) and 2(c) different groups of three elements are lasing, and in Fig. 2(d) the currents are adjusted so that only the two lasers at the edges of the group emit light. Figure 2(a) should be contrasted with Fig. 2(e), which shows the same array operated with all four lasers connected in parallel and fed through one current source. The nonuniformity among the lasers is clearly seen: the lasers in the left side of the array are above the lasing threshold, while the two right-most lasers are well below the threshold. This figure clearly demonstrates the benefits of being able to control each laser independently.

As noted earlier, phase locking among the lasers should manifest itself in the narrowing of the spatial extent of the far-field pattern in the array plane. Figure 3(a) shows a photograph of the far field of a typical laser in the array operating by itself. The relevant dimension is the horizontal one, being in the plane of the array. (The fringelike appearance in the vertical dimension is an artifact of the measurement setup.[11]) The angular extent of the beam corresponds to about 8°. Figure 3(b) shows the far field obtained when all the four lasers in the array are operating. It is evident that the far-field pattern has been significantly narrowed to about 2°. This should be compared with the theoretically calculated value[3] of 1.3°. When the array operated with all the lasers connected in parallel, i.e., simulating an array with a single contact, the far field is narrower than that of a single laser, but more than twice as wide as the 2° width achieved before. This can be understood also from Fig. 2(e) which shows the nonuniform near field of the array under these conditions.

By changing the distribution of drive currents through the individual lasers in the array, it is possible to operate in the antiphase mode (i.e., adjacent lasers oscillating with a phase difference of π radians) so that the resultant far-field pattern has the typical double-lobed feature, as shown in Fig. 4. The separation between the two peaks is 7°, which corresponds to an array with a separation of 7.2 μm between adjacent elements. The discrepancy between this value and the contact separation of 9 μm might be due to either displacements of the laser's filaments with respect to the center of the stripe contacts (note that there are only four elements in this array, so the effects of one closer pair can dominate over the

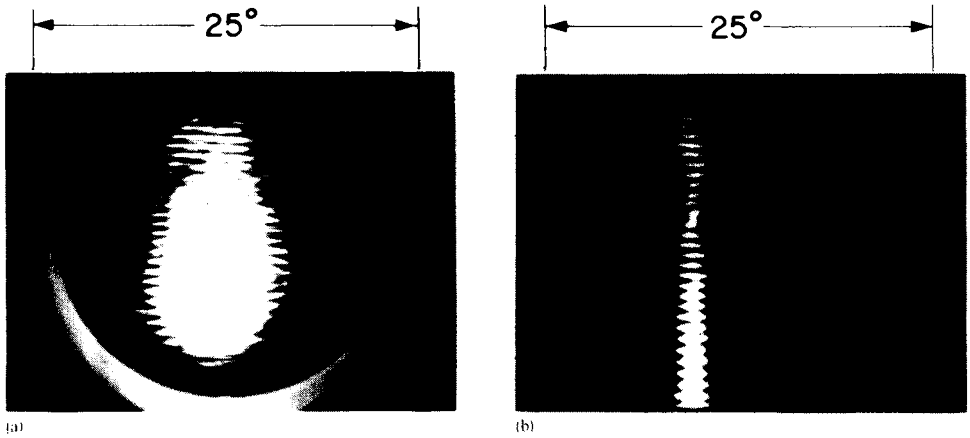

FIG. 3. Far-field patterns: (a) one laser; (b) four lasers operating as a separate contact array.

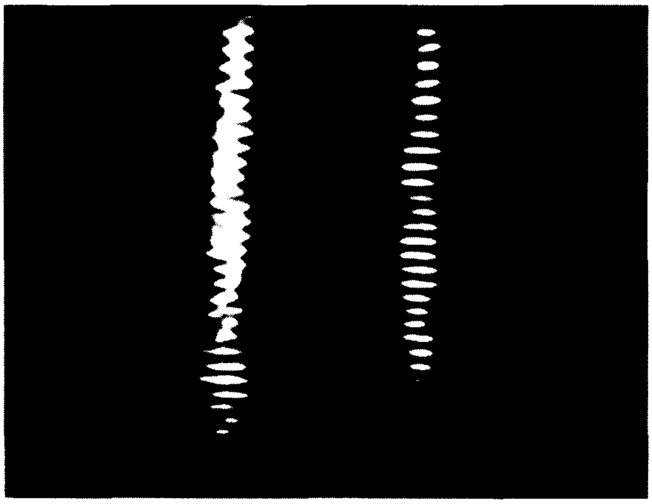

FIG. 4. Far-field pattern of an array with lasers operating in antiphase.

effects of pairs that are more widely separated), or deviations of the phases between adjacent lasers from the nominal value of π radians. Some error might also result from the angle measurement tolerance of the experimental setup. Figure 4 demonstrates the flexibility in controlling the far-field radiation pattern of separate-contact arrays.

In conclusion, we have demonstrated the possibility of operating a monolithic semiconductor laser array where each laser has a separate contact. While requiring the more complex two-level metallization technology, applying a separate contact to each laser provides an additional degree of freedom in monolithic array design, which is used, for example, to compensate for device nonuniformities and control the near-field and far-field patterns. Furthermore, such an array can be employed as a versatile tool in investigating the basic physical mechanisms of phase locking among semiconductor lasers.

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