In-Phase Hexagonal Implant-Defined Coherently Coupled Vertical Cavity Surface Emitting Laser Array

Meng Xun, Chen Xu, Kun Xu, Jun Wang and Guoqing Jiang

***Abstract*—Hexagonal in-phase implant-defined coherently coupled array was presented. The array exhibited high beam quality with divergence angular of 2.5degrees. The array can maintain in-phase single mode in a considerably wide current range from 10mA (I_{th}) to 35mA ($3.5\times I_{th}$). The maximum output power of the array is 4.9mW under pulse wave condition. Simulation of far-field profile was carried out to match the in-phase operation test results. The modal behavior of the array was also investigated.**

***Index Terms*—In-phase coupling, hexagonal, semiconductor laser arrays, surface-emitting laser,**

I. Introduction

Vertical cavity surface emitting lasers (VCSELs) are very attractive light sources for many applications such as printing, telecommunication and data storage [1]-[2]. High power single mode operation is required in many areas. Different approaches were employed to achieve the purpose. They include surface shallow relief [3], etching of hole structures [4], or combinations of oxide-defined and implanted apertures [5]. An array of lasers may indeed produce the requisite power but the incoherent source will result in a large emission angle. The elements must be coherent with one another to produce a narrow beam. If the entire array is oscillating in the in-phase mode, the beam width varies inversely as the entire array size [6]. The coherently coupled array may be used in many applications, such as laser radar, optical communications, image processing and steerable sources. [7]-[9].

A variety of approaches have been tried to achieve coherent coupling among elements in an array. The first demonstration of a coherent 2-D VCSEL array was reported by Yoo et al [10]. Evanescent coupling was achieved by 0.1-0.2μm air gap between elements. Subsequently, reflectivity-modulated VCSEL array was fabricated using pattern metal on the DBR mirror surface [11]. Both of the two kinds of arrays operated out-of-phase mode. To achieve in-phase operation, an integrated phase-corrector was employed to match the phase between neighbor elements [12]. A similar in-phase far-field profile was observed. Cavity induced anti-guided array can exhibit strong in-phase coupling and large coupling distance [13]. However, the processing of multi-step epitaxial growth is complex. Proton implantation provides an effective method to fabricate coherently coupled array. The implanted inter-element region implements both the electrical isolation and optical coupling among the elements without fabrication complexity. In-phase mode can be easily obtained through suitable choice of implantation energy and inter-element spacing. A 1×2 in-phase implant-defined VCSEL array was firstly reported by Choquette et al. [14]. Later we reported 2×2 and 3×3 in-phase implant-defined VCSEL arrays [15]-[16]. Modal behavior dependence on inter-element spacing of 2-D VCSEL array was also investigated [17]. The implant-defined arrays reported previously were all square structure. Hexagonal arrays exhibited stronger element coupling because of more nearest neighbors [18].There is also better symmetry in these arrays. A hexagonal array was reported by Y. Yadin et al [19]. The array elements are laterally defined by the mirror patterning method. The inter-element spacing was only 1μm. The arrays exhibited out-of-phase mode characteristic. Bao Ling et al. fabricated hexagonal VCSEL arrays using cavity induced anti-guided structure [18]. The array exhibited high output power under pulse wave.

In this paper, we produced the 7-element hexagonal array using proton implantation. The array can exhibit in-phase mode operation, exhibiting excellent beam quality. The complex mode of hexagonal array was also analyzed.

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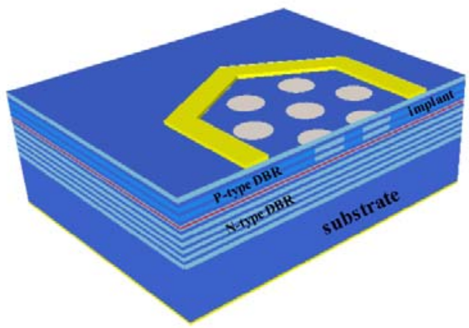

Fig. 1 Schematic representation of seven-element hexagonal VCSEL arrays

II. EXPERIMENT AND RESULTS

A schematic representation of seven-element hexagonal VCSEL arrays is shown in Fig. 1. The procedure is identical to that in [17]. The array consists of seven elements with element diameter of 6μm and inter-element spacing of 3μm. Typical light power-voltage versus current characteristics of the hexagonal array is depicted in Fig. 2. The array shows the maximum output power of 3.4mW under continuous wave condition. The series resistance is 14.78Ω.The threshold current of the array is 10.5mA.

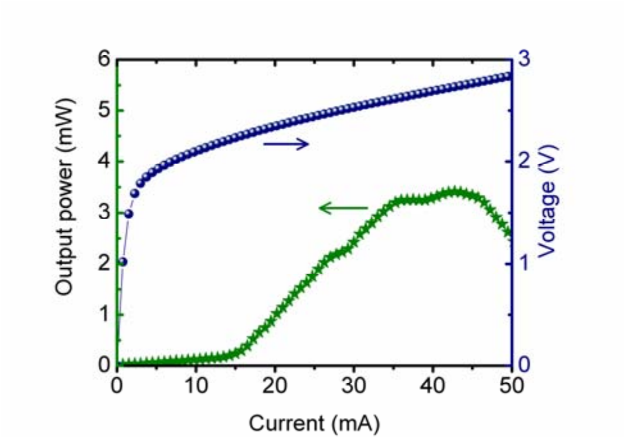

Fig. 2 Typical light-voltage versus current characteristics of a 7-element triangular array

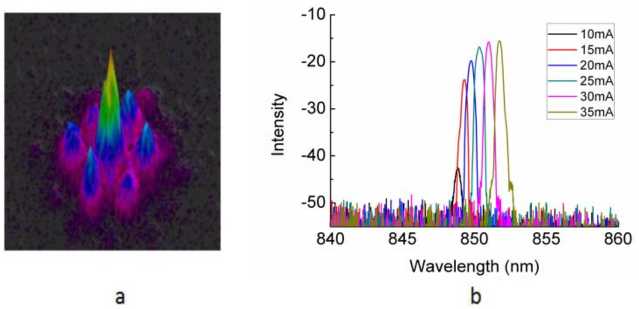

Fig. 3 (a) The measured far-field profile at 20mA and (b) the measured spectra from 10mA to 35mA

The measured far-filed profile acquired with laser beam profiler (Spiricon SP620) under injection current of 20mA is shown in Fig. 3(a). From the far-field profile, the main power is localized in the central lobe, which represents the in-phase coupling characteristics [20]. The divergence angular is 2.5degrees, showing excellent beam quality. The measured spectra under continuous wave condition are shown in Fig. 3(b). The array can operate in in-phase mode from threshold to 35mA (3.5×Ith). It shows a wide in-phase operation current range.

Another device with the same size in different location in the same wafer was shown in Fig. 4. Small central lobes appear between the elements at the injection current of 12mA. In far-field profile, the power in central lobe is slightly larger than subsidiary lobes. The array operates in the single mode, which is evident from the measured spectrum. When the injection current increases to 15mA, a symmetrical flower-like profile appears. The on-axis is null in the far-field profile. The array exhibits multi-mode operation. We believe that the lateral distribution of refractive index is affected by

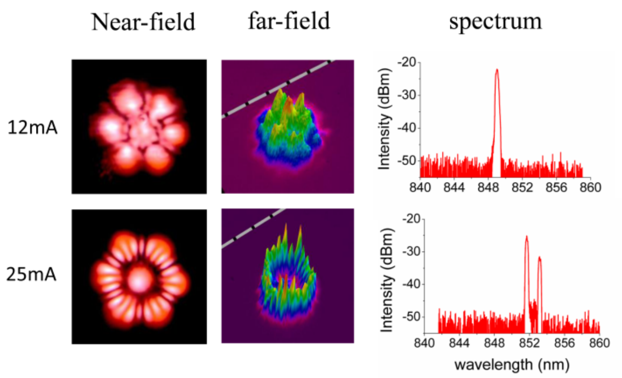

Fig. 4 near-field (left column), far-field (middle column) and spectrum (right column) of an array with tame size in different location in the same wafer

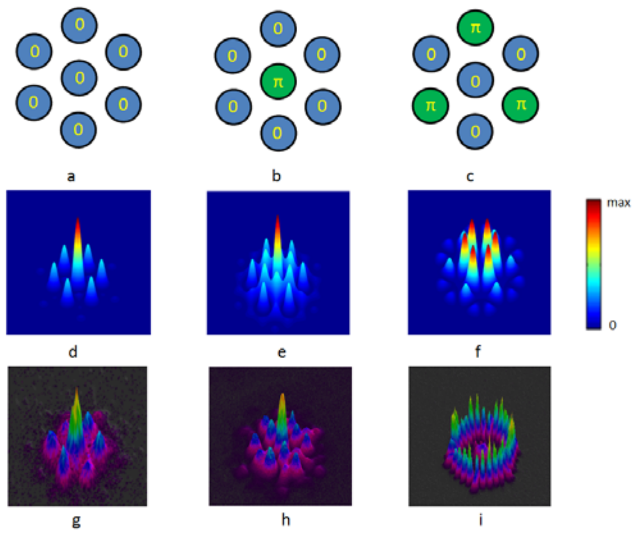

Fig. 5 (a)-(c) phase distribution, (d)-(f) corresponding simulated far-field profiles and (g)-(i) measured far-field profiles, respectively.

both thermal and carriers distributions. The refractive index gets complex with the increased current, which results the variation of the array mode.

The far-field distribution of seven-element hexagonal array of 850nm laser emitters with 6μm element diameter, 3μm inter-element spacing was simulated using FDTD solution software. The virtual light sources in each element were set to be Gaussian distribution. The phase of every element was set as shown in Figs. 5(a)-(c). The calculated data was transferred to MATLAB software to plot a 3-D view far-filed profile. The corresponding results were shown in Figs. 5(d)-(f), respectively. The in-phase mode far-field profile always has the main power in the center lobe with six surrounding smaller lobes, as shown in Fig. 5(d). The measured in-phase mode far-field profile was shown in Fig. 5(g). Fig. 5 (b) shows the case the central element is 180° difference from the surrounding elements. The corresponding simulated far-field profile was shown in Fig. 5(e). It is similar to the experimental result as shown in Fig. 5(h). Fig. 5(c) shows the case there is 180° difference between the surrounding neighbor elements. The corresponding simulated far-field profile was shown in Fig. 5(f). It is similar to the experimental result as shown in Fig. 5(i). The appearances of the different phases are probably because of the phase difference among the elements. The asymmetric in fabrication process may produce non-uniformity in the element size and thermal distribution, leading to the phase difference among the elements.

III. CONCLUSION

We have produced seven-element hexagonal VCSEL arrays operating in in-phase mode using proton implantation. The divergence angular of the array is only 2.5° in far-field profile. The array can maintain in-phase mode from threshold to 35mA, showing a considerably wide in-phase single mode operation range. Structure optimization and the design of the heat dissipation are still needed to increase the scale of the coherently coupled array.

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