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Original research article

Supermode switching and beam steering in phased vertical cavity surface emitting laser arrays

Meng Xun[a,*], Yun Sun[a], Jingtao Zhou[a], Chen Xu[b], Yiyang Xie[b], Hao Wang[c], Qiang Kan[c], Zhi Jin[a], Xinyu Liu[a], Dexin Wu[a]

[a] *Institute of Microelectronics of Chinese Academy of Sciences, Beijing 100029, China*
[b] *Key Laboratory of Optoelectronics Technology, Ministry of Education, Beijing University of Technology, Beijing 100124, China*
[c] *Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China*

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ABSTRACT

We demonstrate electrically controlled supermode switching and beam steering in separate-contact phased vertical cavity surface emitting laser arrays based on proton implantation. The mode switching between out-of-phase and in-phase mode was successfully achieved via controlling the injected currents. The beam steering in two directions is continuous and controllable by proper adjustment of driving currents. The properties of near-field, far-field, optical power and spectra under different currents are analyzed detailedly.

1. Introduction

Controlling of mode in vertical cavity surface emitting lasers (VCSELs) is essential to achieve specific features for different applications, such as single mode, polarization, high power, stable wavelength, beam steering and mode switching [1–4]. Phased VCSEL arrays provides an approach to obtain high output power, low divergence and single supermode [5–7]. In-phase mode with maximum intensity on-axis will be obtained if the elements are with the same phase. The beam width varies inversely with the entire array size [8,9]. Out-of-phase mode appears when the elements are 180 °s difference with each other. The on-axis null will be obtained in far-field beam patterns [10,11]. More recently, implant defined phased VCSEL arrays have been introduced and investigated. Proton-implantation technology has led to the fabrication of close-packed arrays [12–16]. In addition to electronic isolation between elements, the implant region can offer optical coupling. The process to fabricate these arrays is quite simple and of low cost. In particular, such phased array provides a means for beam steering by controlling current injection into individual element [17,18]. The beam steering in implant-defined coherent VCSEL arrays has been firstly reported by Choquette et al. [19].

In this paper, we demonstrate dynamic control of supermode switching in 1 × 2 VCSEL arrays. This is accomplished by fabricating properly designed coherent VCSELs with separate electrical contacts, which makes possible the control of injection currents into each element. Electrically controlled switching of the output power, near-field, far-field patterns, as well as beam steering are observed.

2. Experiment and discussion

The VCSEL arrays used in this work were fabricated starting from a conventional VCSEL wafer grown by metal organic chemical

* Corresponding author.
E-mail address: xunmeng@ime.ac.cn (M. Xun).

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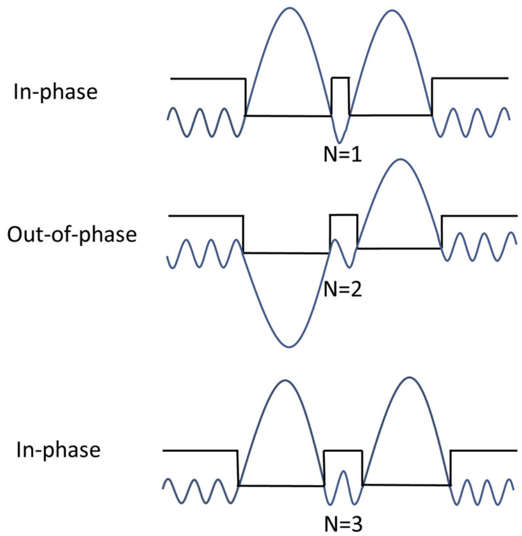

Fig. 1. Field profiles of a 1-D two-element antiguided array.

vapor deposition (MOCVD). The epitaxial structure consists of three GaAs/AlGaAs quantum wells sandwiched between 22.5 pairs of p-type top DBRs and 34.5 pairs of n-type bottom DBRs. The emitted wavelength is 850 nm. The VCSEL arrays were defined by proton implantation. To avoid ion channeling during implantation, the samples were inclined by 7° from normal. Multiple stacked implants with successively decreased energy was used to electrically isolate elements from each other. The largest proton energy is 315 keV and the dose is $1 \times 10^{15}\,cm^{-3}$. Next, the proton-implantation resist masks were removed and Ti/Au was deposited on the top of P-DBRs to form anode. Finally, AuGeNi/Au was deposited on the GaAs substrate to form the cathode.

Firstly, we investigated modal property dependent on inter-element spacing in 1 × 2 VCSEL arrays. Arrays with different inter-element spacing were designed and fabricated. In-phase mode and out-of-phase will be distinguished through the number (N) of small central lobes between main lobes. The refractive distribution of implant VCSEL arrays is similar to that of antiguided VCSEL arrays. Fig. 1 shows the field profiles of a 1-D two-element antiguided array. The dark line represents refractive index distribution. Generally, the array operates inphase mode when N is odd. The array operates in out-of-phase mode when N is even [5].

Then different 1 × 2 VCSEL arrays with different separations were fabricated. The number of central lobes varying with the inter-element spacing is listed in Fig. 2. The corresponding near-field profiles are also inset in the Fig. 2. When the inter-element spacing is 2 µm, 3 µm and 4 µm, one central lobe appears, representing in-phase mode operation. At this moment, the two elements are of the same phase. When the inter-element spacing is 6 µm, two central lobes appear, representing out-of-phase mode operation. With the inter-element spacing increasing, three central lobes appear. The array mode turns to be in-phase mode again. When the inter-element spacing is 5 µm, we found the array will operate in not only in-phase mode but also out-of-phase mode. Some non-uniformity in fabrication process will result a distinction in supermode emitting. In the following experiment, we designed separately electrical contacts to make possible the control of current injection into each element. Then Au nano-layer was deposited on the surface of element and contact to form current route. A schematic illustration of 1 × 2 arrays with separate contacts is shown in Fig. 3. The elements are 6 µm × 6 µm width.

Firstly, we characterized VCSEL arrays with 3 µm inter-element spacing (side to side) with separate contacts to analyze output

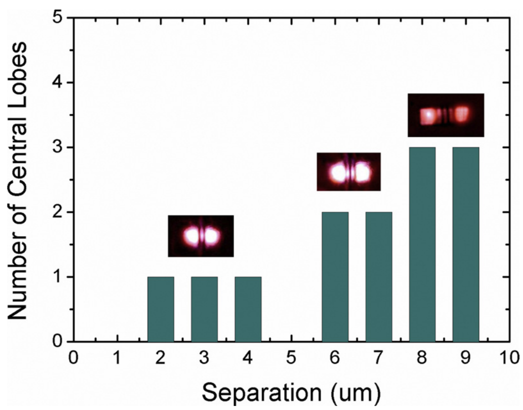

Fig. 2. Number of central lobes between elements dependent on separation.