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Characteristics of 32 × 32 Photonic Quantum Ring Laser Array for Convergence Display Technology

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디스플레이 융합 기술 개발을 위한 32 × 32 광양자테 레이저 어레이의 특성

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Abstract We have fabricated and characterized 32 × 32 photonic quantum ring (PQR) laser arrays uniformly operable with 0.98 ㎂ per ring at room temperature. The typical threshold current, threshold current density, and threshold voltage are 20 mA, 0.068 A/cm^2, and 1.38 V. The top surface emitting PQR array contains GaAs multiquantum well active regions and exhibits uniform characteristics for a chip of 1.65 × 1.65 mm^2. The peak power wavelength is 858.8 ± 0.35 nm, the relative intensity is 0.3 ± 0.2, and the linewidth is 0.2 ± 0.07 nm. We also report the wavelength division multiplexing system experiment using angle-dependent blue shift characteristics of this laser array. This photonic quantum ring laser has angle-dependent multiple-wavelength radial emission characteristics over about 10 nm tuning range generated from array devices. The array exhibits a free space detection as far as 6 m with a function of the distance.

• Key Words : Photonic quantum ring laser array, Vertical cavity surface emitting laser, Metal oxide chemical vapor deposition, GaAs quantum well, 3 dimensional whispering gallery mode, Laser and display convergence technology

요 약 상온에서 단일소자의 경우 0.98 ㎂ 문턱전류를 나타내는 32 × 32 광양자테 레이저 어레이를 제작하였다. 제작된 어레이의 전체 소자들의 문턱전류 및 밀도, 전압은 20 mA, 0.068 A/cm^2, 1.38 V의 값을 나타내었다. 발광 광양자테 어레이는 GaAs 물질이 다중-양자 우물 활성 영역을 구성하고, 칩이 차지하는 면적은 1.65 × 1.65 mm^{2}였으며, 소자들의 피크파워 파장은 858.8 ± 0.35 nm, 상대적인 레이저 세기는 0.3 ± 0.2, 선폭은 0.2 ± 0.07 nm로 비교적 균일한 특성을 보였다. 또한, 레이저 어레이의 각도 의존적 청색 이동 특성을 이용한 파장 분할 멀티플렉싱 시스템 실험을 진행하였고, 각도에 따라 10 nm 정도 파장이 변하는 현상을 발견하였으며, 거리에 따른 레이저 세기를 측정한 결과 6 m에서도 감지할 수 있음을 확인하였다.

• 주제어 : 광양자테 레이저 어레이, 수직 공동 표면 발광 레이저, 금속유기화학기상증착장치, GaAs 양자 우물, 3차원 속삭이는 갤리리 모드, 레이저와 디스플레이 융합 기술

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1. INTRODUCTION

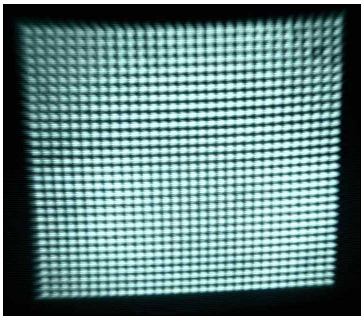
Photonic Quantum Ring (PQR) lasers, achieved from a toroidal microcavity of three-dimensional (3-D) whispering gallery modes (WGMs) in the peripheral Rayleigh band of the active multi-quantum-well planes of vertical cavity surface emitting laser (VCSEL)-like structure, differ from VCSEL [1,2,3,4,5]. They exhibit ㎂ range threshold currents, squar-root-T-dependent spectral shift, which thus suggest potential applications for digital interconnects, spatial light modulators, displays, and parallel optical computing systems [6,7,8,9,10]. Indeed, the PQR laser lends itself easily to large-scale integrations, and the ultralow threshold currents permit room-temperature CW operation of high density arrays [11,12,13,14]. While we demonstrated the uniformity of lasing threshold, spectrum, and light vs. current of the 8 × 8 PQR laser arrays [15], we report in this letter our recent results on the design, fabrication, and integration of ultralow-threshold top-emitting 32 × 32 GaAs/AlGaAs PQR arrays.

2. Experimental Details

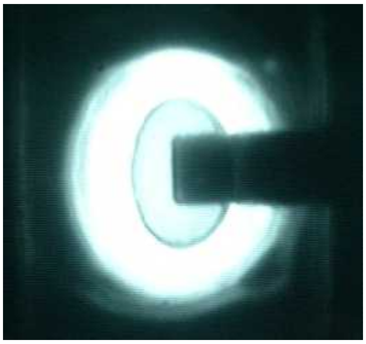
The PQR structure was grown by metal-organic chemical vapor deposition (MOCVD) on a n+-GaAs substrate. The PQR, which has a similar structure as a VCSEL, consisted of 39.5 periods for the Si-doped (at a concentration of 1~5 × 10^{18} cm^{-3}) bottom mirror and 22 periods for the C-doped (at a concentration of 1~5 × 10^{18} cm^{-3}) top mirror. The active region is composed of three 8-nm-thick GaAs quantum wells for an emission wavelength of about 850 nm. Quantum wells were implemented in order to blue shift the gain with respect to the Fabry-Perot transmission. This causes the transmission peak and the gain maximum to achieve resonance above room temperature. The fabrication of single devices and 2-D array is very similar. The device was processed by the following step. A 5 ㎛ index-guiding was patterned below the active region as an elliptical mesa (major axis length = 23.4 ㎛, minor axis length = 15.6 ㎛) by chemically assisted ion beam etching (CAIBE) [6], while using in situ laser reflectrometry to monitor the etching. A silicon nitride (SiNx) film was used as a passivation layer to support electrical tracks. To achieve planarization, a polyimide coating was next carried out for the upper side. A photoresist is then deposited and is patterned by photo-lithography. The polyimide is etched using reactive ion etching method until the protective SiNx is reached and the mesa surface is exposed by removing the SiNx with a CF4 plasma. Subsequently, p-side metal contact (Cr/AuGe/Au) and n-side metal contact (AuGe/Ni/Au) were formed on each side to derive good ohmic contact. Individual chips containing a 32 × 32 array of lasers are separated by cleaving and the substrate is bonded to a 64-pin package using silver epoxy. The array pitch and chip size were 50㎛ (center-to-center spacing) in both the x- and y- directions and 1.65 × 1.65 mm^2, respectively. Bonding pads are 120 × 1560 ㎛^{2} about the periphery of the active devices, thus being convenient for gold wire bonding. The widths of the conducting lines are 10 ㎛. In laser arrays, we typically operate all devices at the same time with approximately the same average dissipated input power.

3. Results and Discussions

A microscopic picture of the completed PQR array is given in Fig. 1(a). Clearly all the lasers in the array are active. The array exhibits 1 mA current, which is converted to 0.976 ㎂ per each PQR element with fairly uniform intensities. Fig. 1(b) shows a near field microscopic picture for one PQR device of the 32 × 32 array taken with a total threshold current of 20 mA corresponding to a very low threshold current density of 0.068 A/cm^2. A threshold voltage for all array devices is also V_{th} = 1.38 V. The near field micrograph shows the external emission due to the carrier crowed gain ring, taken near the lasing threshold after transparency

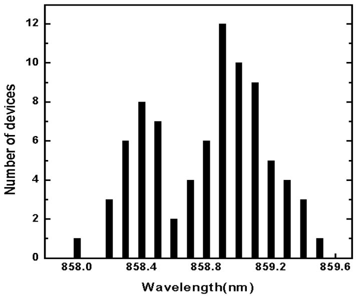


(a)

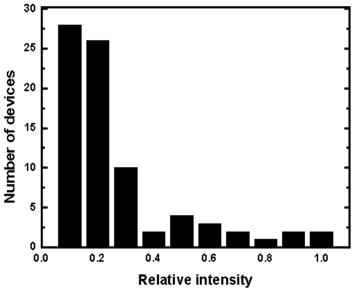


(b)

[Fig. 1] Microscopic pictures: (a) 32 × 32 PQR laser array with 23.4 ㎛ for major axis length, and 15.6 ㎛ for minor axis length at 1 mA injection, (b) A discrete PQR near the threshold. The emission is partly blocked due to the stripe electrode.



(a)



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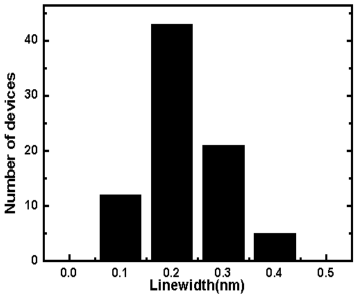


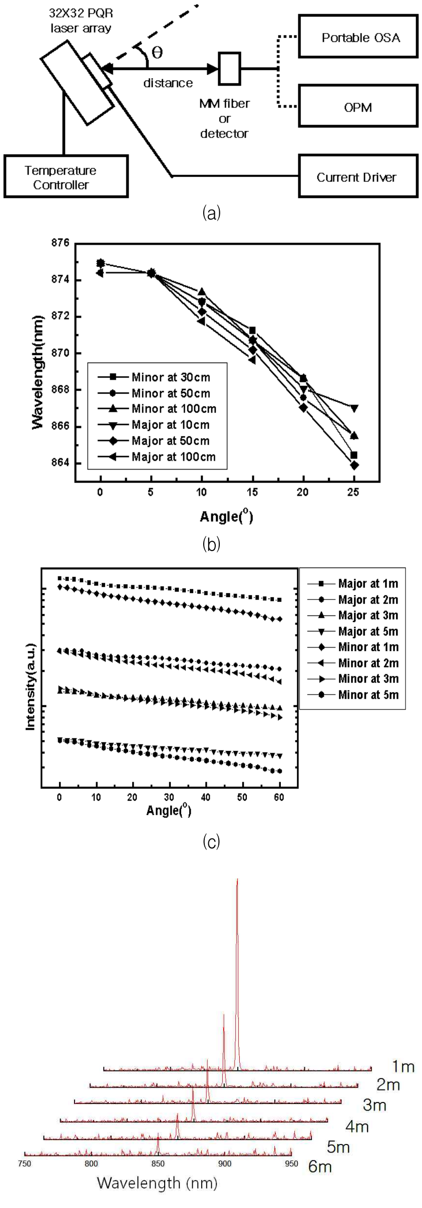
(c)

[Fig. 2] Histogram of 81 PQR elements. (a) Peak power wavelength; average = 858.8 nm, standard deviation = 0.35 nm , (b) Relative intensity; average = 0.3, standard deviation = 0.2, (c) Linewidth; average = 0.2 nm, standard deviation = 0.07 nm.

condition. A significant fraction of the light is emitted through the evanescent region. Based on the 3-D WGM characteristics in the Rayleigh-Fabry-Perot cavity, the PQR modes always give rise to free propagation outside the disk after tunneling through the evanescent region, with crossover ranges from 55 - 80 ㎛ for device diameters of 15 ㎛ - 36 ㎛ [5]. Therefore, the optical intensity is concentrated on an about several-㎛ wide annulus near the disk edge. In addition to low threshold current, uniformity is another important issue for successful PQR arrays. To quantify array uniformity, the measurements on 81 lasers regularly sampled over the array are summarized in Fig. 2(a). The spectrum is taken with a single mode fiber probe and spectrum analyzer (HP 70951A) at 1 A injection current. A histogram of the 81 PQR elements is presented in Fig. 2(a) for peak power wavelength, Fig. 2(b) for relative intensity, and Fig. 2(c) for full width at half maximum (FWHM). The average peak wavelength is 858.8 nm with a standard deviation of 0.35 nm, the average relative intensity, divided by peak intensity, is 0.3 with a standard deviation 0.2, and the average FWHM is 0.2 nm with standard deviation of 0.07 nm, where the small variations in intensity, peak wavelength, and FWHM indicate a good chip uniformity [16,17,18]. The uniformity of the PQR array characteristics depends on four parameters; 1) reflectivity of the distributed Bragg reflector (DBR), 2) the overlap between an active region and an electric field standing wave pattern within the cavity, 3) the high quality vertical facet of the active region, and 4) the gain peak wavelength [3,9]. The wavelength deviation, which ranges 858 – 859.5 nm, is caused by the natural nonuniformity of MOCVD thickness over the wafer that varies the gain peak wavelength.

Nonetheless, the wavelength over the entire array varies by less than ±0.5 nm, exhibiting sufficient uniformity for numerous applications. The overlap between an active region and an electric field standing wave pattern corresponds to the output intensity. The narrow linewidth is attributed to the high-reflectivity mirrors and the high quality vertical facet of the active region. Sharpened linewidth about 0.1 nm at normal detection is achieved, indicating a successful cylindrical PQR surface roughness control obtained with CAIBE method and a high quality DBR grown by MOCVD. The standard deviations for peak wavelength and linewidth are only 0.35 nm and 0.07 nm, which easily meet the requirements of PQR arrays for the parallel optical interconnects [19,20,21].

We have obtained angle-emissions by varying the view angle (Θ) of the probing fiber directed to various distance without using any guiding optics as shown in Fig. 3(a). The light intensity is collected to the optical power meter with a calibrated detector and the spatial distribution of the emission is measured by the portable optical spectrum analyzer through the optical fiber probe. These spectra exhibit continuous blue shift from 875 nm to 864 nm, giving rising to a good tuning range for an angle sensing application, where increased from 0° to 25°. The total tuning span is 11 nm around 870 nm. Similar angle-dependent multi-wavelength emission characteristics are observed and compared in Fig. 3(b) for the different major axis distance and minor axis, respectively, while Fig. 3(c) is angle-dependent intensity variation. These blue shift and intensity variations are found to be associated with off-normal Rayleigh-Fabry-Perot condition from a toroidal cavity



[Fig. 3] Angle dependent multiple-wavelength emission of the fabricated PQR array. (a) Schematic diagram of measurement setup, (b) Peak wavelength, (c) Relative intensity, (d) Free space spectral data in normal direction of the array.

naturally formed due to a photonic quantum corral effect [7]. Small but systematic deviations in the intensity variation, in Fig 3(c), are obtained from the major and minor axis directions. These deviations are associated with different interference effects between the coherent elliptic PQR sources with different spatial arrangements between the two axes. Fig. 3(b) also shows the calculated resonance peak wavelength, e, is given by $e = e [1 - (\sin /n)^2]^{1/2}$ where , the angle, is defined as in Fig. 3(a). We previously demonstrated 30 nm continuous wavelength tuning range from a toroidal cavity for a single PQR device [2]. The calculated angle-dependent Fabry-Perot resonance spectra agree very well with the observed spectra, which support the 3D characteristics [22]. Fig. 3(d) represents the free space spectral data in normal direction (Θ = 0°) of the array taken with a fixed injection current of 1.75 A (1.7 mA/cell). It is notable that the array exhibits a good free space detection range as far as about 6 m [23,24].

4. Summary

In summary, an integrated 2-D array of a 32 × 32 PQR laser array with 50-㎛ pitch was successfully fabricated and tested. The electrical and optical characteristics of the lasers were found to be fairly homogeneous over the array area. Laser diodes with an active area diameter of 23.4 ㎛ for major axis length, and 15.6 ㎛ for minor axis length show an threshold current density of 0.068 A/cm^2. The lasers show good uniformity across the 32 × 32 array in respect to peak power wavelength, relative intensity, and FWHM. We obtain an angle-dependent multiple-wavelength emissions over 10 nm range due to simple off-normal Fabry-Perot condition from a toroidal cavity naturally formed in a PQR array. The array exhibits a good free space detection range as far as about 6 m. Angle dependent intensity variations show transverse intensity modulations due to interference effects. The development of these high-count PQR arrays will enable new PQR applications in the areas of imaging, sensing, and communication, offering potential benefits to markets ranging from health care to computing. In addtion, the market of flat panel display is dominated by liquid crystal display (LCD) and active matrix organic light emitting diode (AMOLED) TVs. The PQR laser is an attractive candidate for next generation display. Therefore, we are currently developing a panel-less laser image chip for TV application using addressable PQR laser-pixels.

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