Lasing on higher-order whispering gallery modes at room temperature

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Abstract: We report a direct method to observe higher-order whispering gallery modes in vertical cavity surface emitting lasers (VCSELs) at room temperature. Instead of introducing any defect mode, we show that suppression of lower-order cavity modes can be achieved by destroying vertical reflectors with a surface micro-structure. Perfect whispering gallery modes with an azimuthal number as large as 41 are observed in experiments through collecting near-field radiation patterns, as well as in numerical simulations.

OCIS codes: (140.7260) Vertical cavity surface emitting lasers, (140.3948) Microcavity devices.

Whispering gallery (WG) modes are almost grazing incidence patterns confined by the total internal reflection at the interface [1, 2]. With advantages of a ultrasmall mode volume and a strong confinement WG modes have attracted lots of attentions in photonics, quantum electrodynamics, and telecommunications, due to their potential applications to enhance spontaneous emission and make threshold-less lasing. Applications based on WG modes, which act as filters, delay lines, couplers, and sensors, cover a broad areas from optical communications, information processing, to bio-photonics [3]. Consequentially, the control of WG modes in optical resonators plays a crucial role for every specific applications. Given a refractive index in 2D disks or rings, the order of modes in the azimuthal direction is proportional to the radius of disks or rings and inverse to the lasing wavelength. Following this guideline, the WG modes surrounded in photonic crystal defect cavities are typically lowest-order modes due to that the defect geometry is usually on the same order of magnitude to the lasing wavelength. To excite WG modes with a larger azimuthal number, microdisks or microrings with a large area have been introduced, which also act as an interesting platform for studying optical pattern formation in mesoscopic system.

Due to the competitions between different modes, a cryogenic system is needed to suppress lower-order cavity modes in a large area VCSEL. In this work, we propose another simple but powerful method to directly excite required transverse optical patterns by a 2D micro-structure on a VCSEL surface [4–6]. Instead of forming a defect cavity, we show that it is possible to use the surface structure as a deterioration mechanism for the desired lasing characteristics. As most of the vertical emission windows in the central region are destroyed by the surface micro-structure, we report direct observations of a ultra-high-order WG mode lasing, with an azimuthal number as large as 41. And all demonstrations of WG mode lasings are directly collected by their near-field radiation intensities at room temperature, and verified by a 2D mode solver in simulations.

The schematic diagram and the corresponding SEM image of the surface micro-structure for the VCSEL used in our experiments are shown in Fig. 1(a) and (b), respectively. And Fig. 1(c) shows the L-I curve, light versus current of the VCSEL with a photonic crystal structure on it. The threshold current for lasing operation is about 17mA. Then we show the measured near-field intensity electromagnetic intensity distribution on the surface of

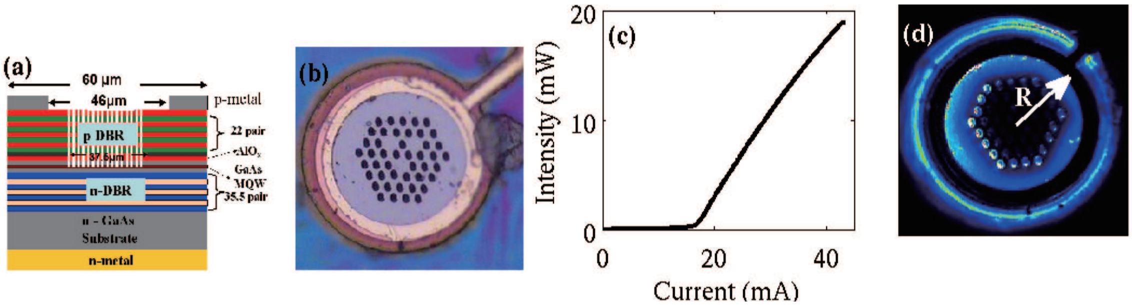

Fig. 1. (a) The schematic diagram, (b) corresponding SEM image of the surface micro-structure, and (c) L-I curve for our VCSEL. (d) The near-field collected spontaneous emission patterns operated below the threshold current.

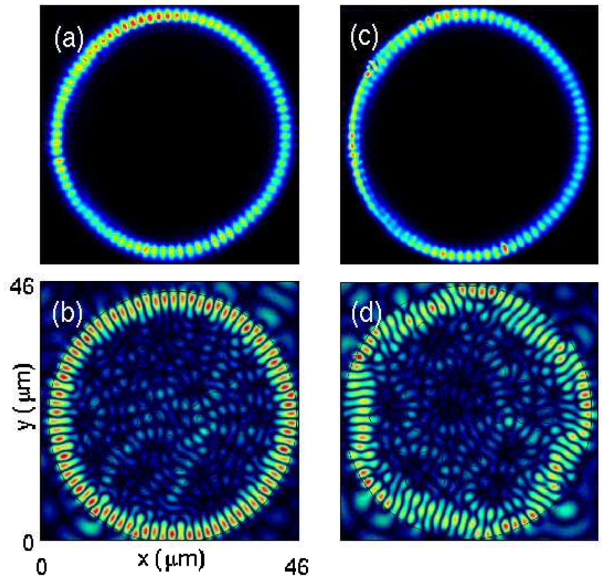

Fig. 2. Near field intensity distributions on the surface of aperture of our micro-structured VCSEL at different injection currents. Experimental data: (a) 19mA and (c) 20.5mA; corresponding simulation results (b) and (d) with the same azimuthal number, 41.

device by a charge-coupled device (CCD) camera through a standard microsope with a $100X$ lens. While the VCSEL is operated below threshold, it can be seen clearly in Fig. 1(d) that the radiation pattern just emits around the region outside the photonic crystal structures.

As the injection current increases, the VCSEL is operated above threshold and begins to lase. Owing to the destruction of top DBR reflector induced by the surface micro-structure, lower-order cavity modes are totally suppressed and the surrounding WG modes have a chance to lase. In Fig. 2(a) and (c), operated at 19mA and 20.5mA, perfect ultra-high-order WG grazing patterns confined by the total internal reflection with multiple lobes in the azimuthal direction are directly observed at room temperature. By counting the number of lobes, we report the recorded experimental demonstration of highest-order WG mode to the best of our knowledge, up to the azimuthal number of 41. To illustrate the experimental observation of a chaotic mode lasing in such a micro-structured VCSEL, we perform a 2D mode solver based on the standard finite element method for electromagnetic waves to calculate the corresponding eigenmodes of this laser cavity. The lateral geometry defined by the native oxide layer is drawn according to the observed spontaneous emission pattern below the threshold current, as shown in Fig. 1(d). Then photonic crystal structures are embedded with the real lattice geometries. The calculated eigenmodes for two possible WG mode patterns with the same azimuthal number, 41, as well as asymmetric intensity distributions along the outer rings are shown in Fig. 2 (b) (a nearly perfect WG mode) and (d) (a chaotic WG mode), respectively. From direct numerical simulations, the observed asymmetric intensity distributions in the azimuthal direction comes from the inter photonic crystal geometry, which overall is in the shape of a hexagon and break the rotation symmetry of the emission pattern.

In conclusion, at the expense of higher threshold current, a native oxide laterally confined whispering-gallery mode in VCSELs can be directly observed at room temperature. Up to the 41rd azimuthal order vertical emission WG mode is reported by collecting the near-field intensity on the surfaces of aperture and emission window. The observed slightly asymmetric WG mode patterns are explained and identified by a direct numerical simulation. The experimental observations and the simulation results provide an alternative but easy approach to access WG modes in VCSELs at room temperature.

1. References

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