Three-dimensional Characteristics of the Photonic Quantum Ring Laser

Received March 31, 2020; revised July 7, 2020; accepted July 9, 2020

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ABSTRACT

The three-dimensional (3D) wave propagation properties due to the chirality and broken z-axis symmetry of the photonic quantum ring laser are investigated by the apparent evanescence-propagation crossing action with various viewing angles. The radiant intensity profile of a laser with a disk size of 15–35 μm shows that the 3D whisper gallery mode inside the device emits a radial propagation mode outside the device with an intersecting range of 26.1–69.5 μm and an offset value of 8.2–19.5 μm , which appeared experimentally. The crossover and offset are related to the viewing angle and device size. Our results are compared with theoretical data obtained from a two-dimensional microdisk laser.

Keywords: Three-dimensional, Photonic quantum ring laser, Evanescence-propagation

1. Introduction

Two-dimensional (2D) whispering gallery mode (WGM) in semiconductor microdisk lasers has been intensively studied due to low threshold currents and easy integration with photoelectronic circuits. Research on the WGM of quantum dots embedded in quantum well planes is currently being conducted using various pumping methods [1–5]. However, the photonic quantum ring (PQR) laser shows three-dimensional (3D) WGM characteristics with very low threshold current, square-root temperature dependent spectral shift and evanescence-propagation behavior due to quantum-like properties of the PQR device [6,7]. We reported that the 3D WGM on the PQR laser always generates a propagation mode with a cross-range of 55–80 μm for a device diameter of 15–36 μm [7]. This wave behavior originates from the nearly perfect reflection of the 3D toroidal cavity of the PQR, where the spiral waves of clockwise (CW) and counter-clockwise (CCW) are symmetrical with each other, resulting in the vector sum shown in Fig. 1. These two radio waves are fixed in phase, resulting in a normal wave due to a defect in the spiral direction or a defect in the spawning factor [8,9]. Figure 1 also shows the chiral propagation by the active plane inside the cavity due to the distributed Bragg reflector (DBR) vertical limits and in-plane Rayleigh limits. It can be divided into a zigzag form in a space confined by the DBR located above and below the active layer and resonance along an edge like a two-dimensional whispering gallery (WG) [6,7]. The 3D WGM mode is interpreted by quantization rules, and the experimental and theoretical values are almost the same [10]. The optical field is expected to be concentrated on narrow loops with a width of less than 1 μm near the edge of the disk. It is known that external emission other than spiral waves in cavities can generally have z-axis rotational

symmetry. However, the electric field responsible for PQR propagates CW and CCW from the Rayleigh-Fabry-Perot (RFP) cavity and has nothing to do with z-symmetry. Unlike other microdisk lasers, the 3D internal WG mode with broken z-axis rotation symmetry leads to one unique operation of the evanescent tunneling and propagation. 3D models developed primarily for higher lateral modes of vertical cavity surface emission lasers (VCSELs) with z-axis rotational symmetry do not match PQR phenomena [6,8]. Previous reports have shown obviously evanescent-wave behavior of the PQR laser in the 3D RFP cavity with only 45° of detection angle, but the intersection must be fully inspected as the detection angle changes from the vertical direction to one parallel direction of the device [7]. Also, the extrapolated intersection crossover point (CP) offset value between the

Figure 1. Schematic of the chiral propagation in 3D effective toroidal cavity of photonic quantum ring laser. The radial evanescent-propagating field for angle-dependent multi-wavelength emission results from forward and backward helical traveling waves. R is the index-guided outer limit, view angle θ is the angle between z-axis and radiated wave at a particularly selected wavelength λ and r_{in} is the inner reflection limit.

measured and calculated data is too large. In this paper, our focus is on the expression of the evanescence and propagation characteristics for various abnormal angles of the advanced PQR laser, which shows obvious 3D WG characteristics.

2. Experimental details

The PQR structure can be explained as part of the cylindrical waveguide. First, we will discuss the mode solution of a cylindrical waveguide. Assuming that the indexes of refraction $n_2 = 1$ and $n_1 > 1$ are constant inside the dielectric, the form of the wave equation for the electric field in each of these regions is

$$-\nabla^2 E + (k^2 - n^2 k^2)E = k^2 E, \quad (1)$$

where $k = \omega c$ is the wave vector of light in a vacuum. The field mode function is characterized by factor $\exp(ik_z z)\exp(im\phi)$, where the mode degeneracy is 2 (m and $-m$) and $k_z(kn_z)$ is a k vector in the z direction. The number m of azimuth modes represents a sequence of spherical Bessel and Hankel functions describing the partial wave emission field distribution and is approximately the number of wavelengths of light that fit around the PQR device. The matching conditions for E at the interface of the dielectric can be very different from the quantum mechanical conditions for the wave function, but we can consider $V_{EM}(r) = [1 - (n^2(r) - n_z^2)]k^2$. Thus, it can be seen that the dielectric acts like an attractive potential for the scattering of EM radiation. The field's equation of radial change includes the change in effective potential to m^2/r^2 . The total potential is the sum of the potential function V_{EM} and the repulsive angular momentum potential. It is given by

$$V(r) = [1 - (n^2(r) - n_z^2)]k^2 + m^2/r^2 \quad (2)$$

and the energy is determined as

$$E = k^2. \quad (3)$$

Next, we consider the case of the constant refractive index n . The potential in this case is written as

$$V(r) = \begin{cases} k^2(1 - n^2 + n_z^2) + m^2/r^2 & r \leq R \\ k^2 n_z^2 + m^2/r^2 & r > R \end{cases} \quad (4)$$

Whether this potential is attractive or repulsive will depend on the value of device radius R , refractive index n , and free space wave vector k . For example, consider $R = 12.5 \mu\text{m}$, $n_1 = 3.5$ (inside the dielectric constant but $n_2 = 1$ outside), $n_z = 0.456$, and $k = 7.392 \mu\text{m}^{-1}$. The potential cause-and-effect function for this case is also illustrated in Fig. 2 on a scale. There is also a classically permitted area within the dielectric separated by each momentum barrier from the outer area where propagation is also permitted. The PQR area is defined by the bandwidth of Rayleigh, $W_{\text{Rayleigh}} = R - m/(k\sqrt{n^2 - n_z^2}) = R(1 - n_{\text{eff}}/\sqrt{n^2 - n_z^2})$, which occurs in WG mode. Rayleigh's annular band is defined by the radius R of the active disk for the outer boundary and the internal reflection point $r_{\text{in}} = m/k\sqrt{n^2 - n_z^2} = Rn_{\text{eff}}/\sqrt{n^2 - n_z^2}$, in which n_{eff} is the effective refractive index. Waves that propagate freely outward from disk to low index areas pass through the evanescent region during tunneling. The evanescent

Figure 2. Effective potential for 2D WG resonances; $k_{\text{min}} = m/R\sqrt{n^2 - n_z^2}$ and $k_{\text{max}} = m/R(1 - n_z^2)$. The Rayleigh band and evanescent propagation region result from the repulsive potential in combination with attractive potential.

Figure 3. Measured (solid line) and calculated (circles and triangles) emission wavelength with varying view angle θ .

scint area from disk to CP is defined as $W_{\text{evanescent}} = m/(k\sqrt{1 - n_z^2}) - R = R(n_{\text{eff}}/\sqrt{1 - n_z^2} - 1)$.

The PQR laser was fabricated with a GaAs/AlGaAs based VCSEL wafer formed by a molecular beams epitaxy technique, the details of which are described elsewhere [6–11]. Figure 3 shows the resonance peak wavelength shift of a 15, 25, and 35 μm diameter device for various viewing angles with an injection current ($I = 0.75$ mA for 15 μm , 2 mA for 25 μm , and 3 mA for 35 μm) under a continuous-wave operation. As the viewing angle increases from 0° to 75° , the wavelength shows a blue shift from 848 to 815 nm.

The resonant peak wavelength, λ_e , can be represented by $\lambda_e = \lambda_0 \cos \theta_r = \lambda_0 [1 - (\sin \theta/n)^2]^{1/2}$. In this equation, λ_0 is the peak wavelength at angle 0° and θ_r and θ are the angles of refraction in the cavity and free space, respectively [11]. The theoretical and experimental resonance spectrum fits well. This means that the off-normal Fabry-Perot characteristics in small active volumes are embedded in a uniform DBR. The angle dependent emission wavelength is relatively independent of the device diameter.

We observed the spatial direct intensity profile of a PQR laser. The 3D mode profile of the PQR laser is measured from normal ($\theta = 0^\circ$) to off-normal ($\theta = 60^\circ$) using a tapered single mode fiber tip (core diameter: 3–4 μm). The position of the fiber tip is controlled by an electric micro stage with 0.1 μm resolution. Wire-bonded samples are

Figure 4. Schematic diagram and picture of measurement setup.

Figure 5. Field intensity profile as a function of distance for 25 μm diameter PQR. The raw data has exponential decay function, $F(r) = 3.09 \times 10^{-9} e^{-r/32}$, and inverse square function, $G(r) = 0.125 \times 10^{-9} + 1.35 \times 10^{-6}/r^2$. Data were taken at room temperature with a CW current of $0.7 I_{\text{th,VCSEL}}$ (2 mA) level.

driven above the PQR threshold by a constant current source and the fibers can be tapered to measure an explicit field profile (by heat and pull method). As shown in Fig. 4, a charge coupled device camera with a high magnification objective allows the fiber to approach the mesa edge. After the fiber tip nears the mesa edge, it is pushed by using the controlled motor. If the fiber touches the device, it bends. Feedback on the curved fiber is used to contact the tip to the mesa edge of the device surface. Then we move the device back to a fixed angle (0° – 60°) using a computer-controlled DC step motor with $0.5 \mu\text{m}$ steps. As a result, the evanescence and propagation waves are locally converted to propagation waves that are coupled to the aperture and guided through the optical fiber towards the optical power meter. These quantitative measurements provide CP information for angle-dependent multi-wavelength emission.

Figure 5 shows the intensity for the distance from the mesa edge, and describes the fitting results for the exponential and inverse square function of a view angle $\theta = 15^\circ$ for a 25- μm -diameter device. This means tremendous results in visualizing the device's light propagation and monitoring changes in light intensity distribution along this path. CP can be well fitted by distance dependence in the form of $ae^{-r/b}$ inside the CP point and $c + d/r^2$ outside the CP point, where a and c represent intensities at $r = 0$ and $r = \infty$ and b and d are power constants. The values for the a , b , c and d parameters were determined

Figure 6. Width of the evanescently decaying region for various viewing angles. Parameters used in a theoretical 2D plot are $n = 3.5$, $n_2 = 1$, $n_{\text{eff}} = 3.28$, and $n_z = 0.456$ obtained from the boundary condition of the waveguide. The measured offset values approach the 2D WG from $19.5 \mu\text{m}$ ($\theta = 0^\circ$) to $8.2 \mu\text{m}$ ($\theta = 60^\circ$), as shown in the inset.

for matching the experimental power profile.

Theoretical and experimental CPs on PQR devices between the evanescent and propagating areas are provided for various devices of different viewing angles, as shown in Fig. 6. Maximum scanning is limited by the device structure. The offset value as a function of the viewing angle is shown in Fig. 6 as an inset. As θ increases, the angle-dependent CP decreases. These changes are found to be related to off-normal Fabry-Perot conditions and angular dependent emissions, ranging from vertical to short wavelengths, as shown in Fig. 3. The wavelength is converted to the corresponding wavevector, and then the solid line in Fig. 2 moves upwards as the viewing angle increases. This means that the evanescent region decreases. CPs showing a difference of $30 \mu\text{m}$ offsets for older devices are also shown in various PQR lasers ($\phi = 15$, 24 , and $36 \mu\text{m}$) for the viewing angle of $\theta = 45^\circ$. A significant reduction between the older device and the recent device for an offset value of 30 to $9.2 \mu\text{m}$ is noteworthy. In order to manufacture a PQR device, a mesa using a chemically assisted ion beam etching technology is formed [12]. Previously, the process conditions were not perfect, and the side surfaces of the device were rough. However, the roughness of the side became very low by establishing the etching conditions. Therefore, improved fabrication techniques reduce scattering losses, but the small sidewall roughness remaining at the mesa edge provides a few μm offset values at the viewing angle $\theta = 90^\circ$. This mismatch is also affected by uncertainty in the exact physical dimensions of the PQR device and by the apparent distinction between the 3D WG and the 2D WG.

The PQR laser emits 3D WG radiation in all directions in the vertical direction, such as a VCSEL, and in a certain normal direction θ , near the plane of the device like a microdisk laser. These radiated waves have obvious 3D emission characteristics that are influenced by device size and viewing angle. A complicated discussion is needed to explain this phenomenon. We can assume that a carrier trapping phenomenon occurs in the active layer of the PQR laser. The injected carrier is periodically localized at the node or anti-node point of the standing waves (summed by CW and CCW) confined to the Rayleigh band due to carrier-light interaction. The localization period is calculated as $\lambda/2n_{\text{eff}}$. Such carrier-trapping-order effects can be visualized from a trapping force depending on the gradient electric field cal-

culated by Letokhov and Minogin [13]. The spatial motion (trapping) of the carrier at the node or anti-node creates a dipole. This vibrating dipole interacts with waves standing spirally in all directions. In particular at the selected wavelength (λ), the induced dipole excites the radiation field. This particular characteristic of the PQR with broken z-symmetry results in angle-dependent multi-wavelength emission with evanescent and propagating crossover behavior.

3. Conclusions

We demonstrated that after tunneling through the evanescent region, free propagation with different CPs is always generated according to various viewing angles outside the device. The evanescence-propagation properties with 3D WG mode were investigated with an intersecting range of 26.1 to 69.5 μm for device diameters of 15 to 35 μm . In addition, a relatively small offset value of 8.16 μm for viewing angle 60° was obtained by reduced scattering loss. This value will decrease if the angle is larger. The PQR device that can be measured at the viewing angle of 90° in the future will be designed and manufactured to examine the difference between the theoretical and the measured values.

Acknowledgements

This work was supported by INHA TECHNICAL COLLEGE 2020 LINC+ (Leaders in INdustry-University Cooperation) Research Grant.

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