An easy-to-fabricate radially polarized surface-emitting single mode laser

Xiang Ma, Quanan Chen, Ye Liu, Qiaoyin Lu* and Weihua Guo

Wuhan National Laboratory for Optoelectronics & School of Optical and Electronic Information, Huazhong University of Science and Technology, 1037 Luoyu Rd, Wuhan 430074, China
*luqy@mail.hust.edu.cn

Abstract: A new design of radially polarized surface-emitting laser (RPSEL) is presented for the first time. RPSEL which has a second-order grating shallowly etched on top of a microcylinder cavity, is easy to fabricate. The grating selects a specific whispering-gallery mode (WGM) with the proper emission pattern (radially polarized emission) to lase and simultaneously scatters the mode vertically to form the surface emission. Through numerical simulations, RPSEL is predicted to be a single mode laser with radially polarized surface emission. RPSEL can be rather easily realized at different wavelengths such as the near infrared 1310 and 1550 nm wavelength bands. Furthermore, it can be fabricated with microcylinder cavities with very small radii even down to wavelength-scale, therefore it has the potential to realize very high modulation bandwidth and very low threshold current.

Index Terms: Surface-emitting lasers. microcavity devices. diffraction gratings.

1. Introduction

The booming in data traffic during recent decades is now facing severe restrictions due to its exponentially increasing energy and bandwidth demand. Semiconductor lasers with low threshold current, high direct modulation bandwidth and low packaging cost are always pursued. Vertical-cavity surface-emitting lasers (VCSELs) possess these metrics and have found wide applications in optical interconnect. Long-wavelength such as 1310 and 1550 nm VCSELs have attracted particular interest for their applications in data center, sensing and local-area optical fiber networks [1, 2]. However, due to the lack of lattice matched Bragg mirrors with high index contrast at long wavelengths, the development of VCSELs in these wavelength ranges was hindered, although progress has been made recently by using dielectric mirrors or still GaAs/AlAs mirrors.

Circularly shaped microcavities, such as microcylinder or microdisk resonators, are well known for supporting high quality (Q) whispering-gallery modes (WGMs). These resonators can have very high Q factors even when their radii are reduced down to a few microns [3]. Lasers with very low threshold current based on these resonators have been demonstrated [4]. However, these lasers normally have isotropic emission in plane and are very difficult to be made to emit directionally and efficiently [5].

Recently, a surface-emitting laser structure based on the microcylinder cavity has been proposed [6]. The laser has two second-order gratings etched on the top and side of the microcylinder cavity, respectively. The side grating selects a specific WGM with preferred emission pattern to lase while the top grating scatters the mode vertically to form the radially polarized surface emission. Radially polarized vector beams has attracted growing attention for their applications in optical manipulation [7] and optical microscopy [8]. The laser is based on the transverse-electric (TE) WGM that has a limitation on the minimum cavity radius that can be used. Normally the minimum radius of 5 to 6 microns is required for the TE WGMs to keep high Q factors for the microcylinder cavity [9]. Furthermore, the laser needs two second-order gratings that will increase the fabrication difficulty. It was demonstrated that a transverse-magnetic (TM) WGM laser can keep high Q even when the radius of the microcylinder cavity is reduced down to micron range [10]. From this perspective, a surface-emitting laser based on the TM WGM can have the cavity volume greatly reduced, which will potentially increase the direct modulation bandwidth and decrease the threshold of the laser.

In this paper, we investigate a new radially polarized surface-emitting laser based on the TM WGMs. We find that through shallowly etching a second-order grating on top of the cavity, a WGM with the azimuthal mode number equal to the number of periods of the grating will be selected as the lasing mode. Meanwhile, the grating will scatter the selected mode vertically to form surface emission. The emission has the major electric field aligning along the radial direction. The laser only needs a shallowly-etched grating and is regrowth free, therefore it will be rather easy to fabricate. In this paper, we use the three-dimensional finite-difference time-domain (3D-FDTD) method [11] to simulate the TM-mode microcylinder cavity etched with the second-order grating. The laser structure used in the simulation is presented and the laser is analyzed theoretically and numerically in detail.

2. Theoretical analysis and modelling

The TM WGM of the microcylinder cavity has two major magnetic field components \( H_r \) and \( H_\theta \) along the radial and tangential direction, respectively; a major electric field component \( E_z \) in the vertical direction. They can be expressed under the effective index approximation as:

\[
H_{r,m} = F(r) h(z) \exp(\pm im \phi) \\
H_{\theta,m} = -i G(r) h(z) \exp(\pm im \phi)
\]

where \( F \) and \( G \) are the effective index functions that can be analytically calculated for any given grating array.
where \( m \) is the azimuthal mode number; \( h(z) \) is the field distribution in the vertical direction; the common factor \( \exp(\pm im\varphi) \) represents the dependence on \( \varphi \); WGMs are doubly degenerate and \( \pm \) corresponds to anti-clockwise and clockwise propagating fields, respectively; \( F(r), G(r) \) and \( f(r) \) describe the dependence of the major field components on \( r \) in the radial direction; the dependence on \( r \) is very different, and typical distributions as calculated by the 3D-FDTD method are shown in Fig. 1. In the simulation, radius of the cavity is assumed to be 2 \( \mu \)m. The cavity consists of three layers vertically: the upper cladding layer, the active region and the lower cladding layer. The resonant wavelength of the WGM is around 1.2905 \( \mu \)m. In the following, only modes with wavelengths around 1.31 \( \mu \)m are considered.

From Fig. 1, it is seen that \( E_z \) is the major electric field component while the major magnetic field components are \( H_r \) and \( H_\phi \). In order to efficiently scatter the beam vertically out of the microcavity, the upper cladding layer is made thin enough so that the modes can be perturbed by the shallowly etched grating effectively. \( H_r \) and \( H_\phi \) have similar distributions in the vertical direction as shown in Fig. 1, so they will interact with the grating similarly. It is expected that the scattered magnetic field by the grating will be mainly from \( H_r \) because \( H_r \) is larger than \( H_\phi \).

The schematic structure of the RPSEL device with an NIP structure is shown in Fig. 2, which is a microcylinder cavity with a thin upper cladding layer and a second-order grating etched on the top. The active region consists of five tensile-strained InGaAlAs quantum wells sandwiched by two 100-nm-thick InGaAlAs optical confinement layers. The thickness of the active region is about 0.34 \( \mu \)m. Proton (H\(^+\)) is implanted into the p-doped lower cladding layer right below the active region, but keeps away from the area of the WGMs as shown in Fig. 3(b). The proton implanted region ensures that carriers will be mainly injected into the edge area of the active region so as to overlap with the mode area of WGMs. Through this way the injection efficiency of the laser can be greatly improved.

The number of periods of the grating is assumed to be \( M \). The grating will scatter the WGMs both upwardly and downwardly. In the following only the upward emission is considered and the downward emission is similar. Actually adding a reflective mirror upside or downside can make the laser emit in a single direction. The magnetic field components of the upward emission above the grating can be expressed approximately as:

\[
E_{z,m} = f(r)h(z)\exp(\pm im\varphi) \tag{3}
\]

where \( h(r) \) is the field distribution in the vertical direction; the common factor \( \exp(\pm im\varphi) \) represents the dependence on \( \varphi \); WGMs are doubly degenerate and \( \pm \) corresponds to anti-clockwise and clockwise propagating fields, respectively; \( F(r), G(r) \) and \( f(r) \) describe the dependence of the major field components on \( r \) in the radial direction; the dependence on \( r \) is very different, and typical distributions as calculated by the 3D-FDTD method are shown in Fig. 1. In the simulation, radius of the cavity is assumed to be 2 \( \mu \)m. The cavity consists of three layers vertically: the upper cladding layer, the active region and the lower cladding layer. The resonant wavelength of the WGM is around 1.2905 \( \mu \)m. In the following, only modes with wavelengths around 1.31 \( \mu \)m are considered.

![Fig. 1. Distributions of the electric and magnetic field components of a fundamental WGM of the microcylinder cavity with radius of 2 \( \mu \)m.](image)

![Fig. 2. Schematic structure of the RPSEL device.](image)
WGMs of the cavity will reorganize so as to have definite parties relative to this symmetry plane [12]. The magnetic field of the upward emission can be re-organized into the following form:

\[
h_{r}^{e,o} = -AF(r)\begin{pmatrix} \cos[(m-M)\varphi] \\ \sin[(m-M)\varphi] \end{pmatrix}
\]

(6)

\[
h_{\varphi}^{e,o} = BG(r)\begin{pmatrix} \sin[(m-M)\varphi] \\ -\cos[(m-M)\varphi] \end{pmatrix}
\]

(7)

where e, o denotes symmetrical or anti-symmetrical relative to the symmetry plane. Here, symmetrical or anti-symmetrical are defined for the magnetic field vector.

It is seen that if \( m \) equals to \( M \), the emission from the symmetrical mode is \(-AF(r)\) while is \(-BG(r)\) from the anti-symmetrical mode. From previous analysis, it is known that \( H_{r} \) is larger than \( H_{\varphi} \), therefore the emission from the symmetrical mode \((-AF(r))\) is stronger than the anti-symmetrical mode \((-BG(r))\). This means that the anti-symmetrical mode will have a higher Q factor than the symmetrical mode, therefore the two originally degenerate WGMs will split if \( m = M \). If \( m \) is not equal to \( M \), the two WGMs will still be degenerate. The scattered field will be mainly from \( H_{\varphi} \) as \(-AF(r)\cos[(m-M)\varphi]\), which in average will be smaller than \(-AF(r)\) but still larger than \(-BG(r)\). So if \( m \) is not equal to \( M \), the Q factors of the WGMs are expected to be between the two split modes. The anti-symmetrical mode with \( m = M \) will have the highest Q factor and therefore becomes the lasing mode. The magnetic field of the mode emission will mainly come from \( H_{\varphi} \), i.e. being tangentially polarized.

To simulate the microcylinder cavity with the grating, we used the 3-D FDTD method [9]. A uniform Yee’s cell with 20 nm side length has been used and the corresponding time step used is 0.0381 fs. Perfectly matched absorption layers are used to circumvent the simulation window. Several broadband Gaussian pulse sources with pulse length about 10 fs in the time domain are added to the electric field component \( E_{z} \) close to the periphery of the microcylinder cavity to excite TM modes as many as possible. The variation of a specific field component with time is recorded as the FDTD output, which is transformed into the frequency domain through the Padé approximation transform method [13]. Then the mode resonant frequency and Q factor can be calculated by a Lorentzian fitting. To find the mode distribution, we excite only one mode by elongating the excitation pulse with a pulse length about 1000 fs in the time domain so as to compress the pulse spectrum to cover just the mode of interest. This however cannot separate the degenerate modes because they are supposed to have the same resonant frequency. By selecting a symmetry plane as shown in Fig. 3(a) and applying the symmetric or anti-symmetric boundary condition in the FDTD simulation, we can then select just one mode from the degenerate mode family to excite. Details of the cross section of the simulated RPSEL device structure is shown in Fig. 3(b). The radius of the \( N \) ohmic contact (1 µm) is smaller than the cylindrical cavity radius (2 µm) to avoid causing extra loss to the WGMs. Below the center of the active region, a cylindrical area is made to have high resistance through proton implantation. As depicted in Fig. 3(b), the material index, length and thickness of each part of the structure has been listed. The number of periods of the grating \( M \) is set to be 26 because the WGMs with \( m \) close to 26 will have wavelengths around 1.31 µm. The normalized spectral distribution of the modes in the vicinity of 1.31µm are shown in Fig. 4. Here both the symmetrical and anti-symmetrical modes with \( m \) around 26 are excited as many as possible. The fundamental modes with different azimuthal mode numbers existed in the microcavity are designated.
3. Simulation results

The grating duty cycle is set to be 0.5 firstly. To get the emitted mode distribution, we excite the symmetrical mode and the anti-symmetrical mode with azimuthal mode number $m = M = 26$ separately. The scattered magnetic field distributions above the grating for the modes are shown in Fig. 5(a). The upper row is for the symmetrical mode while the lower row is for the anti-symmetrical mode. Fig. 5(b) shows the corresponding electric field distributions. As can be seen, the magnetic field of the lasing mode (anti-symmetrical mode in the lower row) is tangentially polarized and has no dependence on $\phi$ ($H_x \propto \sin(\phi)$, $H_y \propto \cos(\phi)$). While its corresponding electric field is radially polarized ($E_x \propto \cos(\phi)$, $E_y \propto \sin(\phi)$). On the opposite, the symmetrical mode has the magnetic field radially polarized while the electric field being...
tangentially polarized. Therefore, to get the radially polarized electric field emission, the anti-symmetrical mode will be suitable to be the lasing mode.

Fig. 6 (a) Q factors of WGMs versus the azimuthal mode number \( m \) with duty cycle of the grating equal to 0.5; (b) dependence of Q factors on the duty cycle of the top grating.

Q factors of different WGMs with \( m \) close to \( M = 26 \) are shown in Fig. 6(a). Both symmetrical and anti-symmetrical modes are shown. Mode splitting is obvious when \( m \) equals 26. The Q factor of the anti-symmetrical mode is the highest, while its symmetrical counterpart is the lowest. As can be seen, the second-order grating will cause scattering for all azimuthal modes. When \( m \) equals \( M \), the anti-symmetrical mode has a perfect cancellation of the scattering from \( H_r \), while for the symmetrical mode, the scattering from \( H_r \) is the highest (in equation (6)). The situation is on the opposite for the scattering from \( H_{t77} \) (in equation (7)). As mentioned in section 2, the scattering from \( H_r \) is expected to be larger than from \( H_{t77} \). Therefore, it is expected that the anti-symmetrical mode will have a much higher Q factor than the symmetrical mode. This is why the previously degenerate WGMs will split in this case. As shown in Fig. 6(a), the WGMs with \( m \) unequal to \( M \) are still degenerate. Their Q factors are between the two split modes because they cannot perfectly cancel the scattering from \( H_r \). From Fig. 6(a), we can see that the anti-symmetrical mode with \( m = M = 26 \) has the highest Q factor and is more than twice the other modes, therefore the laser will work with the anti-symmetrical mode with \( m = 26 \) and show a good single mode performance.

The Q factors of the WGMs versus duty cycle of the grating is shown in Fig. 6(b). Similar to the laser working with TE modes [4], duty cycle (defined as the ratio of the un-etched part to the period) of the grating will affect the proportion of the radial and tangential magnetic field components within the total scattered field (the \( A \) and \( B \) coupling coefficients in equations (4) and (5)). The anti-symmetrical mode with \( m = 26 \) has its Q factor increased dramatically when the duty cycle is increased as shown in Fig. 6(b). This is due to the reason that when the duty cycle is increased, the radial magnetic field from \( H_r \) is scattered more while the tangential magnetic field from \( H_{t77} \) is scattered less. Because the anti-symmetrical mode prevents its radial magnetic field being scattered through destructive interference, its total scattering loss becomes less and its Q factor increases thereafter. However when the duty cycle decreases and becomes smaller than 0.3, the anti-symmetrical mode with \( m = M \) will not have the highest Q factor any more. In this case, all modes have their Q factors increased slightly due to the fact that the scattering from the grating is weakened. So it is seen that the mode quality factors can be adjusted by varying the grating duty cycle.

As seen from Fig. 6(b), as far as the grating duty cycle is larger than 0.3, the anti-symmetrical mode with \( m = M \) has the highest Q factor and will be the lasing mode. Its vertically scattered magnetic field will be mainly the tangential field \( h_{t77} = -BG(r) \). It would be comfortable to choose the duty cycle of the grating to be around 0.5.

Fig. 7. Q factors of WGMs versus the thickness of the upper cladding layer with duty cycle of the grating being 0.5.

All above analysis is based on the fact that the thickness of the upper cladding layer is 0.2 \( \mu \)m. The Q factors of the laser can also be adjusted by varying the thickness of the upper cladding layer. As seen from Fig. 7, the Q factors of the
factors of all modes increase exponentially with the thickness of the upper cladding layer similarly. This means that we can adjust the Q factor of the lasing mode so as to change the output efficiency of the laser by adjusting the thickness of the upper cladding layer, without sacrificing the single mode performance of the laser.

4. Conclusion

We have investigated the characteristics of a radially polarized surface-emitting laser based on TM modes both theoretically and numerically. From the analysis, it is seen that the laser has a good single mode performance and its circular output spot can couple with the $TM_{01}$ mode of a few-mode fiber. The laser can be rather easily fabricated by etching a shallow second-order grating onto a cylinder cavity.

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