Investigation on multiple-port microcylinder lasers based on coupled modes

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Abstract
Microcylinder resonators with multiple ports connected to waveguides are investigated by 2D finite-difference time-domain (FDTD) simulation for realizing microlasers with multiple outputs. For a 10 μm radius microcylinder with a refractive index of 3.2 and three 2 μm wide waveguides, confined mode at the wavelength of 1542.3 nm can have a mode Q factor of $6.7 \times 10^4$ and an output coupling efficiency of 0.76. AlGaInAs/InP microcylinder lasers with a radius of 10 μm and a 2 μm wide output waveguide are fabricated by planar processing techniques. Continuous-wave electrically injected operation is realized with a threshold current of 4 mA at room temperature, and the jumps of output power are observed accompanying a lasing mode transformation.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Microcavity lasers with multiple ports are suitable for applications such as light sources and optical signal processing in photonic integrated circuits. Microdisk lasers have attracted a great deal of attention in the past two decades owing to their small cavity volume and low threshold current. However, circular symmetry limits the directional emission from perfect microdisk lasers. To obtain directional emission and high power output, various schemes of deformed circular cavities were proposed, such as quadrupolar-shaped cylinder laser [1], spiral-shaped micropillars [2], elliptical microdisks [3], stadium-shaped polymer microlasers [4], microdisks vertically coupled to a bus waveguide [5, 6] and limaçon-shaped chaotic microcavity [7–9]. Directly connecting an output waveguide is a simple method to realize directional emission microlasers, if the confined modes still have high Q factors. We have fabricated directional emission triangle and square microlasers connected with an output waveguide [10–12].

A microcircular resonator can have high Q confined modes in a much smaller cavity size than the triangle and square resonators. However the mode Q factors are expected to drop greatly for microcircular resonators connected with an output waveguide, because mode light rays will reach the output waveguide over a period of the perimeter of the circular resonator. However, mode coupling between two whispering-gallery modes (WGMs) with near wavelengths will result in high Q coupled modes in a microcircular resonator connected with an output waveguide [13]. Furthermore, AlGaInAs/InP microcylinder lasers connected with an output waveguide were fabricated by planar technology, and continuous-wave (cw) operation with a threshold current of 8 mA was realized at room temperature [14].

In this paper, microcircular resonators with multiple ports connected with output waveguides are investigated by a finite-difference time-domain (FDTD) technique. The numerical results show that circular microresonators with three or four ports connected to output waveguides can still have high Q confined modes, which are suitable for fabricating microlasers with multiple output ports. Finally, the output characteristics are reported for an AlGaInAs/InP microcylinder laser with an output waveguide.
2. Mode coupling simulation

In this section, coupled mode characteristics are simulated for a 2D circular resonator with the radius of 10 μm and multiple ports by the FDTD technique [15]. The refractive index of the resonator and the output waveguide is taken to be 3.2, and the resonator is surrounded by air. The following cosine impulse modulated by a Gaussian function is applied as the exciting source

\[ P(x_0, y_0, t) = \exp \left[ -\left( t - t_0 \right)^2 / t_w^2 \right] \cos(2\pi f_0 t), \]

where \( t_0 \) and \( t_w \) are the times of the pulse center and the pulse half width, respectively, and \( f_0 \) is the center frequency of the pulse. A 50-cell perfectly matched layer (PML) absorbing boundary is used as the boundaries to terminate the FDTD computing window. The mesh cell size of 20 nm and the time step of \( \Delta t = 4.67 \times 10^{-17} \) s satisfying the Courant limit are used in the FDTD simulation. 1.5 \times 10^6-step FDTD simulation is performed with the impulse (1) at \( f_0 = 195 \) THz, \( t_w = 6 \times 10^3 \Delta t \) and \( t_0 = 3t_w \). The time variation of a field component is recorded at one point inside the resonator over the last 2 \times 10^5-step FDTD simulation and is transformed from the time domain to the frequency domain by the Padé approximation [16].

The obtained intensity spectrum is plotted in figure 1 for TE modes in the microcircular resonator with the radius of 10 μm and a 2 μm wide output waveguide. The mode wavelength and the \( Q \) factor are calculated from the peak position of the spectrum and the ratio of the mode wavelength to the full width at half maximum of the peak. The mode \( Q \) factors 1.5 \times 10^4, 1.1 \times 10^5, 6.5 \times 10^4, 2.3 \times 10^5, 2.2 \times 10^5, 1.3 \times 10^4 and 7.5 \times 10^4 are obtained for the modes at the wavelengths of 1542.3, 1546.6, 1550.3, 1552.9, 1556.7, 1557.2 and 1558.9 nm, respectively. Choosing the exciting source (1) with \( t_w = 1.2 \times 10^5 \Delta t \) and \( t_0 = 3t_w \) as a narrow-band pulse centered at a resonant frequency, we simulate mode field patterns for the high \( Q \) confined modes by 1 \times 10^6-step FDTD simulation. The obtained mode field patterns are plotted in figure 2 for modes at the wavelengths of (a) 1542.3, (b) 1546.6, (c) 1550.3 and (d) 1552.9 nm, respectively. The field distributions have the polygonal patterns with the side numbers of 3, 7, 5 and 4 in figures 2(a), (b), (c) and (d), where the field in the output waveguide is magnified ten times to be clearly visible. The corresponding output coupling efficiencies, defined as the ratio...
of output power confined in the output waveguide to the total
radiation power from the resonator, are 0.89, 0.77, 0.92 and
0.79 based on the field patterns. The field pattern of the
coupled mode can be obtained by the superposition of two
WGs with near mode wavelengths [13]. In the following
part, we search the original WGS involved in the mode
coupling.

For a 2D microcircular resonator with the radius of \( R \)
surrounded by air, the field distribution of the WGS can be
expressed as [17]

\[
F_z(r, \theta) = AJ_v(nk_0 r) \exp(i\nu \theta) \quad r < R
\]

\[
F_z(r, \theta) = \frac{A}{R} J_v(nk_0 R) H_{11}^{(1)}(k_0 r) \exp(i\nu \theta) \quad r > R, \tag{2}
\]

where the time dependence \( \exp(-i\omega t) \) is omitted, \( A \)
is the amplitude, \( F_z \) is the electric field \( E_z \) for the TM mode or the
magnetic field \( H_z \) for the TE mode, \( n \) is the refractive index of the
circular resonator, \( k_0 \) is the wave number in air, and \( J_v(x) \) and
\( H_{11}^{(1)}(x) \) are the Bessel function and the first-kind Hankel
function of order \( v \), respectively. The mode wavelengths and
\( Q \) factors of the WGS can be calculated from the following
eigenvalue equation [17]:

\[
J_v(nk_0 R) H_{11}^{(1)}(k_0 R) = \eta J_v'(nk_0 R) H_{11}^{(1)}(k_0 R), \tag{3}
\]

where \( \eta \) equals to \( n \) and \( 1/n \) for TM \( v,m \) and TE \( v,m \) WGSs,
respectively, and \( v \) and \( m \) are the angular and the radial mode
numbers. The mode wavelengths of the TE WGSs in the 10 \( \mu \text{m} \) radius circular resonator versus the radial
mode numbers are plotted in figure 3 as the open circles for the modes with mode \( Q \) factors larger than \( 10^5 \) from
1538 to 1552 nm. The numbers within the parentheses in
figures 2 are the corresponding angular mode numbers.

The side number of the field pattern in figure 2 is
\( F_{\text{amplitude}} \), where the time dependence \( \exp(-\nu t) \) function of order
mode wavelength obtained from (3) is about 3 nm less than
the difference of the angular mode numbers of the
WGSs with near wavelengths.

As shown in figure 2, the coupled modes have polygonal mode
field patterns. We can expect that the confined modes in figures 2(a) and (d) can still have high \( Q \) factors, if introducing
symmetric three and four ports to the microcircular resonator,
respectively. The field intensity spectra obtained by the FDTD
simulation are plotted in figure 4 as solid and dashed lines for
TE modes in the 10 \( \mu \text{m} \) radius microcircular resonator with three and four 2 \( \mu \text{m} \) wide ports, respectively. The \( Q \) factor of the coupled mode at the wavelength of 1552.9 nm reduces from
2.3 \( \times \) \( 10^4 \) to 5.4 \( \times \) \( 10^3 \) as the number of the ports increases from
one to four. The decrease of the mode \( Q \) factor is reasonable
with the increase of the output ports. However the mode \( Q \)
factor of the coupled mode at the wavelength of 1542.3 nm
increases from 1.5 \( \times \) \( 10^4 \) to 6.7 \( \times \) \( 10^4 \) as the number of the
ports increases from one to three.

To examine the reason for increasing the mode \( Q \) factor, the
mode field patterns are simulated under the impulse (1)
with \( \tau_w = 2 \times 10^5 \Delta t \) and \( 1.2 \times 10^5 \Delta t \), for the coupled modes
at the wavelengths of 1542.3 and 1552.9 nm over 1.5 \( \times \) \( 10^6 \)-
and 1 \( \times \) \( 10^6 \)-step FDTD simulation, respectively. Because of
the existence of two high \( Q \) modes with near wavelengths,
we need to perform FDTD simulation over a longer time
to get the field pattern for the microcircular resonator with
three ports. The obtained field patterns are plotted in
figure 5(a) for the coupled modes at (a) 1542.3 nm and
(b) 1552.9 nm in the microcircular resonators with three and
four ports, respectively. The corresponding output coupling
efficiencies are 0.76 and 0.78 based on the field patterns in
figures 5(a) and (b). The coupled mode field distribution in
figure 5(b) has almost the same pattern as in figure 2(d), so the
(corresponding mode \( Q \) factor decreases with the increase of
the port number normally. However, the \( Q \) factor of 5.4 \( \times \) \( 10^3 \)
is still larger than that in a 300 \( \mu \text{m} \) Fabry–Pérot resonator with
cleaved mirrors. A slight variation of the mode field patterns
between figures 2(a) and 5(a) may explain the increase of the
mode \( Q \) factor in the resonator with three ports. The other
high \( Q \) mode in figure 4 has a hexagonal field pattern in the
resonator with three ports.
4. Characteristics of microcylinder lasers

Finally, we report the output characteristics of an AlGaInAs microcylinder laser connected with an output waveguide [14], which is fabricated from an IQE laser wafer. The active region of the laser wafer is five compressively strained Al_{0.24}Ga_{0.71}In_{0.54}As/Al_{0.44}Ga_{0.56}As quantum wells between 60 nm undoped graded AlGaInAs and 60 nm doped AlGaInAs cladding layers, and the thicknesses of the quantum wells and barrier layers are 6 and 10 nm, respectively. The upper layers are p-InP and p’-InGaAs contacting layers with the total thickness of 1920 nm. The techniques for fabricating the microlasers are simply described as follows. Firstly, an 800 nm SiO₂ was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the laser wafer as a hard mask for dry etching. Then, the circular resonator patterns are transferred onto the SiO₂ layer using standard photolithography and inductively coupled-plasma (ICP) etching techniques, and the laser wafer is etched by about 5 μm using the ICP technique with the patterned SiO₂ as hard masks. After the ICP etching process, a chemically etching process is used to improve the smooth of the side walls of the microcylinders, and then the residual SiO₂ hard masks on the microcylinders are removed using a diluted HF solution. Finally, a 450 nm SiO₂ insulating layer is deposited on the laser wafer and a contact window is opened on the top of each circular resonator using the ICP etching process again. A top Ti–Au p-contact is formed using the standard metal deposition process, and Au–Ge–Ni metallization is used as n-type contact metal after lapping down the laser wafer to a thickness of about 100 μm. The scanning electron microscope (SEM) image of a microcylinder laser with the radius of 5 μm and a 1 μm wide output waveguide is plotted in figure 6, which shows that the uppermost part of the etched sidewalls is only covered by p-electrode without the SiO₂ insulator layer.

After cleaving over the output waveguide of the microcylinder lasers, we test the fabricated lasers by directly placing them on a Cu heat sink and injecting cw current at room temperature. The output power coupled into an optical fiber and the applied voltage versus the cw injection current are plotted in figure 7 for a microcylinder laser with the radius of 10 μm and a 2 μm wide output waveguide. The output power versus injection current indicates a very soft increase at the current of about 4 mA, and then output power suddenly increases as the injection current becomes larger than 7.4 mA. The jump of the output power may be partly explained by the mode transition from the mode with low output coupling efficiency to that with high output efficiency. The mode competition between modes with different output coupling efficiencies can result in the optical bistability under certain conditions [18].
The applied voltage in figure 7 shows that the laser has a large resistor of 150 Ω as the ratio of the voltage difference to the current difference around 4 mA. The laser spectra measured by an optical spectrum analyzer at the resolution of 0.1 nm are plotted in figure 8 at the injection currents of (a) 4 mA and (b) 6 and 7 mA. Two main peaks appear at the wavelengths of 1546 and 1557 nm with the intensity 2 dB larger than those of the other peaks at the injection current of 4 mA. Fitting the peak around the wavelength of 1557 nm by a Lorentzian function, we get the 3 dB full width of 0.286 nm and the mode Q factor of 5.4 × 10^5 as the ratio of the peak wavelength to the 3 dB width. The intensity of the main peak at 1547 nm is 8 dB larger than that at 1558 nm at 6 mA, but the main peak transfers to 1558 nm with the intensity 16 dB larger than that at 1547 nm at 7 mA. The peak wavelength increases from 1546.7 to 1547.0 nm as the current increases from 6 to 7 mA, and the increase of mode wavelength 0.3 nm indicates the temperature increase of 3 K if mode wavelength varies with temperature at 0.1 nm K⁻¹. In addition, we find that the microcircular lasers are easier to realize lasing than the triangle and square microlasers in the same wafer fabricated by the same technique processes.

5. Conclusion

In conclusion, the multiple-port microcylinder resonators are analyzed by the FDTD technique. The numerical results indicate that the microcylinder resonators with multiple ports can have high Q coupled modes, which are suitable to realize microlasers with multiple-port output. AlGaInAs/InP microcylinder lasers with an output waveguide are fabricated by planar processing techniques. The room-temperature continuous-wave threshold current of 4 mA is obtained for a microcylinder laser with the radius of 10 μm and a 2 μm wide output waveguide. We can expect that the microresonators with multiple ports can have versatile applications in 2D photonic integrated circuits and optical signal processing.

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