DOI: https://doi.org/10.4038/sljp.v24i2.8140

INSTITUTE OF PHYSICS – SRI LANKA

Research Article

Estimation of power output and conversion efficiency for quantum dot lasers

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Abstract

Interest in Quantum Dot Lasers stem mainly from the low threshold current which can result due to quantization of energy levels and change in density of state function. In the most used lasers, separate confinement heterostructures, the nanoscale active region is 'built into' the waveguide region (optical confinement layer, OCL) based on a wide gap semiconductor material.

The most important characteristic of quantum dot laser is the amount of light it emits as current is injected into the device. The dependence of laser power output on current, cavity length, and various other parameters has been estimated based on the rate equations model. Linear relation has been obtained between power and current and as the cavity length increases, the slope of the power–current characteristic decreases.

The external quantum efficiency indicates the efficiency of a laser device in converting the injected electron–hole pairs (input electric charges) to the photons emitted from the device (output light). External differential quantum efficiency decreases linearly with increasing cavity length. As the internal loss increases, the slope of external differential quantum efficiency versus cavity length increases. The internal quantum efficiency is independent of the geometrical properties of the laser device, such as the cavity length or the stripe width. Internal quantum efficiency is one of the main figures of merit that should be used in assessing the quality of the semiconductor wafer from which the quantum dot laser is manufactured.

One of the most important device characteristics of a laser diode is the efficiency of conversion of the input electric power into output optical power. Power conversion efficiency is found to increase with increasing drive current, gets its maximum value and after that it decreases slightly with increasing drive current. Power conversion efficiency also depends on different parameters like cavity length, internal efficiency, and threshold current.
Keywords: Quantum Dot Lasers, Threshold Current, Rate Equations, Output Power, Conversion Efficiency.

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1. INTRODUCTION

Semiconductor quantum dots (QDs) with three–dimensional carrier confinement offer potential advantages to optoelectronic devices in terms of high modulation bandwidth, low threshold current density, temperature insensitivity, reduced saturation fluency, and wavelength flexibility. A QD laser is a semiconductor laser that uses QDs as the active laser material in its light emitting region. The discovery of self–organized epitaxial QDs resulted in multiple breakthroughs in the field of physics of zero–dimensional heterostructures and allowed the development of QD lasers [1]. The significant progress in the understanding of basic lasing properties is also achieved for QDs made of II–VI materials. QD lasers enable substantial performance improvements over quantum well devices due to their unique atom–like energy level structure properties that can be finely tuned by changing growth conditions. The discrete density of states and inhomogeneously broadened gain lead to lasers with low threshold, high continuous wave operating temperature, ultrahigh stability against optical feedback, and ultrafast gain recovery. These concepts have been experimentally demonstrated by Norman et al. [2].

Andrea Fiore and Alexander Markus have derived analytical expressions for the differential gain and K–factor of QD lasers, which relate the bandwidth limitations to the underlying carrier dynamics, and investigated the role of inhomogeneous broadening and independent e–h dynamics [3]. The current for which the gain satisfies the lasing condition is the threshold current for the laser. The lowering of the threshold current and enhancement of the output power is the central problem in quantum electronics. Threshold current can be reduced by decreasing the active layer thickness in double heterostructure (DH) lasers. Interest in QD lasers stem mainly from the very low threshold current that can result due to quantization of energy levels and change in density of state function. There has been much effort to use QDs as an active region in diode lasers. In the most used lasers, separate confinement heterostructure, the nanoscale active region is ‘built into’ the waveguide region or the optical confinement layer (OCL) based on a wide gap semiconductor material. The OCL in such a structure performs two main functions– first, optical emission is confined mostly within this layer; second, the OCL is a reservoir from which carriers are ‘delivered’ to the active region.

Figure 1 shows the energy band diagram of a conventional QD laser and the main processes. Due to bipolar population in the reservoir, a certain fraction of the injection current goes into the electron–hole recombination there. Carrier capture from the OCL by the active region occurs not instantaneously, but at a finite rate. This results in accumulation of carriers and an increase in their concentration in the waveguide region as the pump current increases under conditions of stimulated emission. The increase in the carrier concentration in the OCL, in turn, leads to amplification of parasitic spontaneous recombination in the OCL [4–5]. As a result, the internal quantum efficiency of stimulated emission decreases with the injection current; therefore, the power–current $(P-I)$ characteristic of the laser with a quantum confined active region becomes sub–linear [6]. Thus, the carrier accumulation in the waveguide region, which occurs due to the finite rate of their capture by the active region, can be one of the causes limiting the achievement of a high output power in a laser with a quantum confined active region.

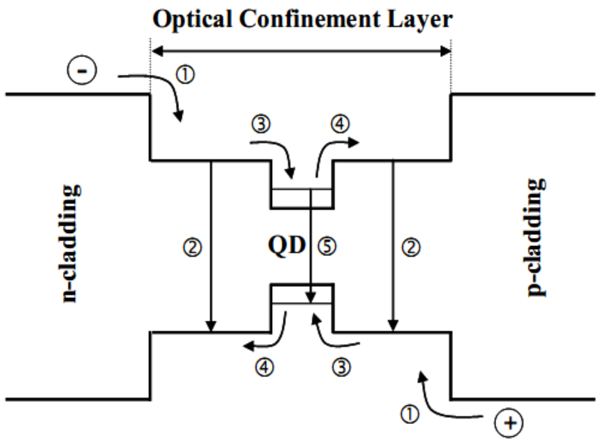

Figure 1: Energy band diagram of a conventional QD laser and the main processes: (1) Injection from the cladding layers to the OCL, (2) Spontaneous recombination in the OCL, (3) Carrier capture from the OCL into a QD, (4) Carrier thermal escape from a QD to the OCL, and (5) Spontaneous and stimulated recombination in a QD.

2. RATE EQUATIONS MODEL

The popular and useful way to deal with carrier and photon dynamics in lasers is to solve rate equations for carriers and photons. The relaxation means the process that both an electron and a hole relax into the ground state simultaneously to form an exciton. If a single discrete electron and hole ground state is assumed to be formed inside the QD and the charge neutrality always holds in each QD, the rate equation for carriers confined in a QD (assuming $f_n = f_p$) has been reported as [7],

$$\frac{\partial f_n}{\partial t} = \sigma_n v_n n(1 - f_n) - \sigma_n v_n n_1 f_n - \frac{f_n^2}{\tau_{QD}} - \frac{c}{\sqrt{\epsilon_g}} \frac{g^{max}}{N_s S}(2f_n - 1)N$$

… (1)

For free carriers in OCL (assuming $n = p$),

$$\frac{\partial n}{\partial t} = \sigma_n v_n n_1 \frac{N_s}{b} f_n - \sigma_n v_n n \frac{N_s}{b}(1 - f_n) - Bn^2 + \frac{j}{eb}$$

… (2)

For photons,

$$\frac{\partial N}{\partial t} = \frac{c}{\sqrt{\epsilon_g}} g^{max}(2f_n - 1)N - \frac{c}{\sqrt{\epsilon_g}}(\beta + \alpha_i)N$$

… (3)

where, σ_n is the cross section of carrier capture into a QD, v_n is the carrier thermal velocity, n is the number of free electrons, τ_{QD} is the life time in QD, N_s is the surface density of QDs, c is the light velocity in vacuum, $\sqrt{\epsilon_g}$ is the group index of the dispersive OCL material, f_n is the electron level occupancy and f_p is the hole level occupancy in QDs, $S = WL$ is the QD layer area (the cross section of the junction), W is the QD layer width (the lateral size of the device) and L is the cavity length (the QD layer length), N is the number of photons in the lasing mode, j is the current density, e is the electronic charge, b is the thickness of OCL, and α_i is the internal loss.

Under steady state conditions,

$$\frac{\partial f_n}{\partial t} = 0, \frac{\partial n}{\partial t} = 0, and\ \frac{\partial N}{\partial t} = 0$$

… (4)

The solution of Eq. (3) in steady state gives,

$$g^{max} = \frac{(\beta + \alpha_i)}{(2f_n - 1)}$$

… (5)

Similarly, under steady state conditions, solving Eq. (1) and Eq. (2) simultaneously, the injection current density is obtained as,

$$j = ebBn^2 + \frac{eN_s}{\tau_{QD}} f_n^2 + \frac{e}{S}\frac{c}{\sqrt{\epsilon_g}} g^{max}(2f_n - 1)N$$

… (6)

Eq. (6) stretches the expression for injection current density.

3. THE POWER–CURRENT CHARACTERISTICS

The most important characteristic of QD laser to be measured is the amount of light it emits as current is injected into the device. As the injected current is increased, the laser first demonstrates spontaneous emission which increases very gradually until it begins to emit stimulated radiation, which is the onset of laser action. The first parameter of interest is the exact current at which this phenomenon takes place. This is typically referred to as the threshold current. It is generally desirable that the threshold current should be as low as possible, resulting in a more efficient device. The photon life time in the cavity is written as [8],

$$\tau_{ph} = \frac{\sqrt{\epsilon_g}}{c}\frac{1}{\beta} \qquad \dots (7)$$

If we ignore the internal loss, α_i in Eq. (5) and put it along with Eq. (7) into Eq. (6), the expression for current density, j becomes,

$$j = ebBn^2 + \frac{eN_s}{\tau_{QD}} f_n^2 + \frac{e}{S}\frac{N}{\tau_{ph}} \qquad \dots (8)$$

Rearranging the above equation,

$$\frac{N}{\tau_{ph}} = \frac{S}{e}\left(j - ebBn^2 - \frac{eN_s}{\tau_{QD}} f_n^2\right) \qquad \dots (9)$$

The output power can be expressed now as,

$$P = h\nu\frac{N}{\tau_{ph}} = h\frac{c}{\lambda}\frac{S}{e}\left(j - ebBn^2 - \frac{eN_s}{\tau_{QD}} f_n^2\right)$$

or,

$$P = h\frac{c}{\lambda e}\left(I - SebBn^2 - S\frac{eN_s}{\tau_{QD}} f_n^2\right) \qquad \dots (10)$$

The above expression shows the relation between power and injection current, where h is plank constant, B is the radiative constant for the OCL, and I is the injection current.

The variation of power with current has been calculated as per Eq. (10) and the parameters for this calculation are specified in Table 1. Figure 2 displays the power–current $(P - I)$ characteristic curve for QD laser, which is almost linear and the output power increases with the injection current.

Parameter	***Value Used***	***Unit***
$\boldsymbol{h}$	6.6×10^{-34}	J–S
$\boldsymbol{e}$	1.6×10^{-19}	C
$\boldsymbol{\lambda}$	1.3	µm
$\boldsymbol{b}$	0.28	µm
$\boldsymbol{B}$	1.8×10^{-14}	m^3/s
$\boldsymbol{N_s}$	6.11×10^{10}	cm^{-2}
$\boldsymbol{\tau_{QD}}$	1	ns
$\boldsymbol{S}$	3.2×10^{3}	$µm^2$

Table 1: The value of parameters used in the calculation for Eq. (10).

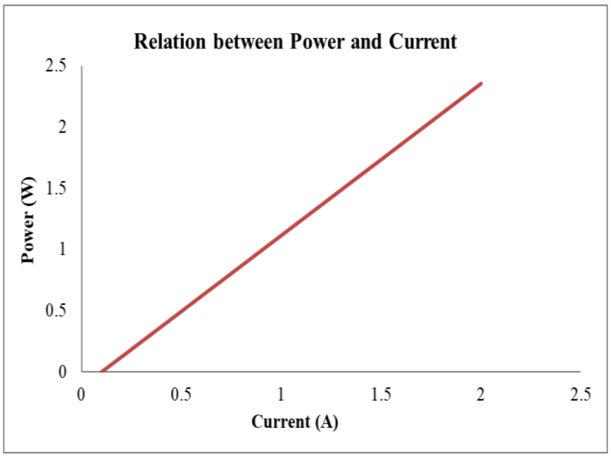

Figure 2: The power–current characteristic curve of QD lasers.

4. THE QUANTUM EFFICIENCY

The external quantum efficiency, measured in percentage, indicates the efficiency of a laser device in converting the injected electron–hole pairs (input electric charges) to the photons emitted from the device (output light). In an ideal perfect laser, the recombination of each electron–hole pair results in the generation of one photon, which survives its travel through the laser waveguide structure and is finally emitted from the device to contribute to the output light power. In a real laser, not all the photons generated inside the laser are emitted from the device; some of them are reabsorbed by the structure of the laser.

In an ideal perfect laser, a current of e coulombs per second (amps) results in a light power of $h\nu$ (hc/λ) joules per second (watts). Thus, the P/I ratio of an ideal perfect laser emitting at a wavelength of λ would theoretically be $(hc/\lambda e)$. Accordingly, the efficiency of a real laser is the ratio of its associated (P/I) parameter to $(hc/\lambda e)$, which is referred to as the external differential quantum efficiency, η_{diff} written as,

$$\eta_{diff} = \frac{P/(I - I_{th})}{hc/\lambda e} \quad \ldots (11)$$

where, $E = hc/\lambda$ is the photon energy, and I_{th} is the threshold current.

At room temperature, the power–current characteristics can be closely approximated by a well–known linear dependence of output power, P on injection current, I as given below,

$$P = \frac{hc}{\lambda e}\eta_{diff}(I - I_{th}) \quad \ldots (12)$$

The differential quantum efficiency is also defined in terms of the internal quantum efficiency of the stimulated radiation, η_i and the cavity loss as [9],

$$\eta_{diff} = \eta_i \frac{\alpha_m}{\alpha_m + \alpha_i} \quad \ldots (13)$$

where, α_m and α_i are the radiation output loss and the internal loss of the laser cavity, respectively.

The radiation output loss, α_m is also expressed in terms of the cavity length, L and the reflectivity of the cavity faces, R as,

$$\alpha_m = (1/L)\ln(1/R) \quad \ldots (14)$$

Putting Eq. (14) into Eq. (13) results in,

$$\eta_{diff} = \eta_i \frac{(1/L)\ln(1/R)}{(1/L)\ln(1/R) + \alpha_i} \quad \ldots (15)$$

and solving the above equation,

$$\eta_{diff} = \eta_i \left[1 - \frac{\alpha_i}{\ln(1/R)} L\right]$$

… (16)

Eq. (16) relates external differential quantum efficiency, η_{diff} with cavity length, L. The dependence of η_{diff} on L for different values of internal loss, α_i has been shown in Figure 3. For a given cavity length, the value of η_{diff} decreases with increase in α_i.

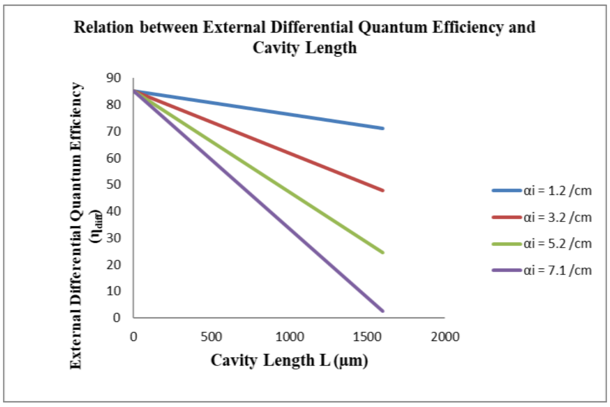

Figure 3: The variation in external differential quantum efficiency with cavity length for different values of internal loss at $\eta_i = 85\%$ and $R = 0.31$.

The plot in Figure 3 can be used to find out the value of internal quantum efficiency (η_i), which is independent of the geometrical properties of laser device, such as the cavity length or the stripe width. Internal quantum efficiency is one of the main figures of merit that should be used in assessing the quality of the semiconductor wafer from which the QD laser is manufactured.

Eq. (15) is placed into Eq. (12) to obtain, along with other factors, the dependence of output power on cavity length,

$$P = \frac{hc}{\lambda e}(I - I_{th})\eta_i \frac{(1/L)\ln(1/R)}{(1/L)\ln(1/R) + \alpha_i}$$

… (17)

It is clear from the above equation that, apart from other parameters, the power depends on cavity length of QD laser. The variation of power with current has been calculated as per Eq. (17) and the parameters used in this calculation are documented in Table 2. The power–current plot for different cavity lengths has been shown in Figure 4. It is seen that for given injection current, the output power decreases with increase in cavity length.

Parameter	***Value Used***	***Unit***
$\boldsymbol{h}$	6.6×10^{-34}	J–S
$\boldsymbol{e}$	1.6×10^{-19}	C
$\boldsymbol{\lambda}$	800	nm
$\boldsymbol{c}$	3×10^{8}	m/s
$\boldsymbol{I_{th}}$	0.1	A
$\boldsymbol{\eta_i}$	80	%
$\boldsymbol{L}$	900	μm
$\boldsymbol{R}$	0.32	–
$\boldsymbol{\alpha_i}$	2.3	cm^{-1}

Table 2: The value of parameters used in the calculation for Eq. (17).

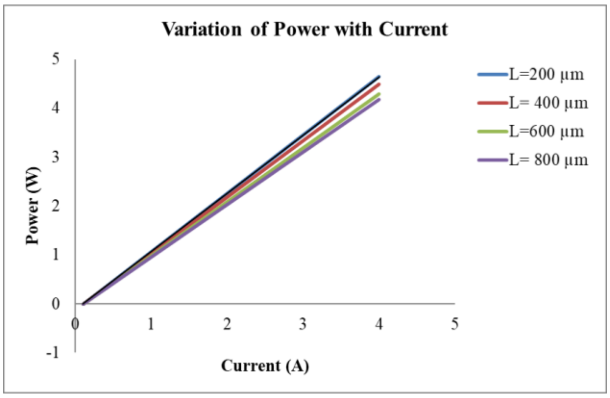

Figure 4: The variation of power with current for different cavity lengths.

The variation of power with current at different values of the internal loss of QD laser is shown in Figure 5. The parameters used for this calculation are same as outlined in Table 2 with $L = 900\ \mu m$. It is seen that at fixed current, if the internal loss of QD laser increases, the output power decreases.

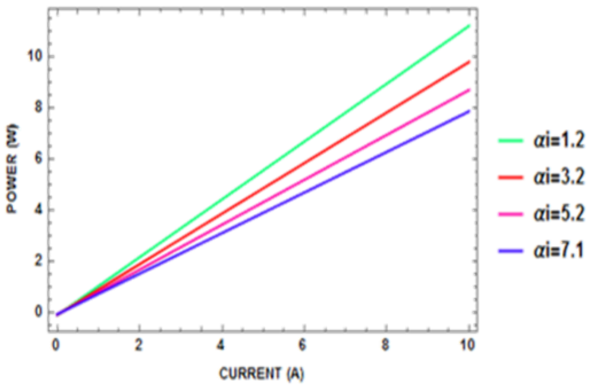

Figure 5: The variation of power with current at different values of internal loss.

5. THE POWER CONVERSION EFFICIENCY

One of the most important device characteristics of a laser diode is the efficiency of conversion (η_c) of the input electric power into output optical power P. The power conversion efficiency is of critical importance to many commercial applications. It is defined as a ratio of the total output optical power, P to the input electric power and can be approximated as [10],

$$\eta_c(P,L) = \frac{P_{out}}{P_{in}} = \frac{P}{VI} = \frac{P}{(V_0 + IR_s)I} = \frac{P}{V_0 I + I^2 R_s} \quad \dots (18)$$

where, I is the drive current which is necessary to apply for achieving the designed output power, V_0 is the diode turn–on voltage, $R_s = \rho_s/WL$ is the series resistance of the diode with width, W. Putting the expression for P from Eq. (12) into Eq. (18), the expression for η_c becomes,

$$\eta_c = \frac{hc\eta_{diff}(I - I_{th})}{\lambda e(V_0 I + I^2 R_s)} \quad \dots (19)$$

Furthermore, substituting the value of η_{diff} from Eq. (16), we get,

$$\eta_c = \frac{hc\eta_i}{\lambda e(V_0 I + I^2 R_s)}\left[1 - \frac{\alpha_i}{\ln(1/R)}L\right](I - I_{th}) \quad \dots (20)$$

Rearranging the terms,

$$\eta_c = \frac{hc\eta_i}{\lambda e(V_0 + IR_s)}\left[1 - \frac{\alpha_i L}{\ln(1/R)}\right]\left[1 - \frac{I_{th}}{I}\right]$$

… (21)

The above equation shows the relation between power conversion efficiency and drive current. The power conversion efficiency also depends on cavity length and other parameters like internal quantum efficiency, threshold current etc. The variation of η_c with I has been calculated as per Eq. (21) using the parameters listed in Table 3. The plot of η_c with I for different cavity lengths is shown in Figure 6.

Parameter	***Value Used***	***Unit***
$\boldsymbol{h}$	6.6×10^{-34}	J–S
$\boldsymbol{e}$	1.6×10^{-19}	C
$\boldsymbol{\lambda}$	800	nm
$\boldsymbol{c}$	3×10^{8}	m/s
$\boldsymbol{I_{th}}$	0.1	A
$\boldsymbol{\eta_i}$	99	%
$\boldsymbol{V_0}$	1.37	V
$\boldsymbol{R}$	0.32	–
$\boldsymbol{\alpha_i}$	1	cm^{-1}
$\boldsymbol{R_s}$	70.7	mΩ

Table 3: The value of parameters used in the calculation for Eq. (21).

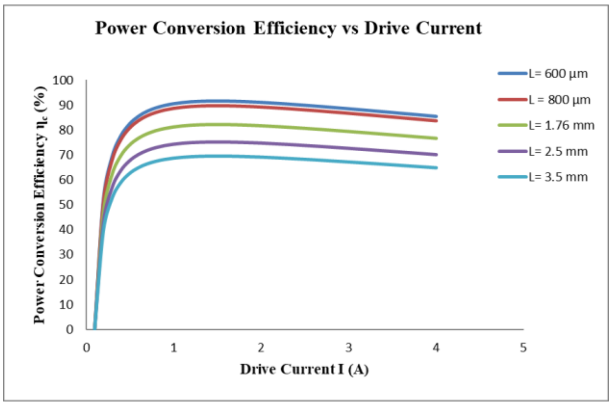

Figure 6: The variation of power conversion efficiency with drive current for different cavity lengths.

To improve the power conversion efficiency of a QD laser, extra voltage drop across the laser heterostructure should be reduced, the laser internal loss, α_i should be very small, the laser internal quantum efficiency, η_i should be high, and the threshold current, I_{th} should be low. A maximum power conversion efficiency of 91.6% is achieved at $L = 600\ \mu m$.

Power conversion (wall–plug) efficiency is one of the most important characteristics of laser diodes. It is possible to reach an extremely low threshold current density, high temperature stability, and low level of internal loss by using self–assembled arrays of InAs/InGaAs QDs in the active region of lasers operating in the 1.2–1.3 μm wavelength range [11–13]. These conditions make such QD structures a promising basis of creating effective laser diodes for various applications including optical communication systems, frequency doubling, and medicine. However, the choice of optimum design for QD lasers is not as simple due to complicated dependence of threshold current density on the level of optical loss. The maximum wall–plug efficiency of 56% has been reported for QD lasers operating in the 1.3 μm range [14].

6. RESULTS AND DISCUSSION

The simulation has been done throughout the study for a self–assembled QD laser diode, using rate equations model with nonlinearity being ignored, if any. The expressions for power output and conversion efficiency of a QD laser, as a function of different parameters, have been well estimated in Eq. (17) and Eq. (21) respectively. The external differential quantum efficiency has been estimated in Eq. (16).

The $P\!-I$ characteristic of QD laser is shown in Figure 2, where the threshold current for the ground state transition is found to be 0.1 A. Furthermore, the $P\!-I$ characteristics as a function of cavity length and internal loss are shown in Figure 4 and 5 respectively. It is seen that the output power decreases with increase in cavity length as well as increase in internal loss.

The dependence of external differential quantum efficiency on cavity length, for different values of internal loss, is depicted in Figure 3. The external differential quantum efficiency decreases linearly with increasing cavity length; the slope being higher for higher internal loss. The internal quantum efficiency can be determined from the plot; the intercept point of linear fit line of the set of data points with the vertical axis is the internal quantum efficiency.

The power conversion efficiency increases with increase in drive current as shown in Figure 6, gets its maximum value and after that it decreases slightly with further increase in drive current. The power conversion efficiency also depends on other parameters like cavity length, internal quantum efficiency, threshold current etc. The maximum value of power conversion efficiency decreases with increasing cavity length.

Several experimental results reported by different researchers agree with our theoretical predictions. Klopf et al. [15] have investigated the influence of waveguide design on basic device properties of a QD laser with a single active layer. Using a large vertical cavity, a significant reduction in threshold current density could be achieved. Slope efficiencies of more than 1 W/A and absorption levels as low as 2.6 cm^{-1} could be realized. Their results agree with the theoretical estimates expressed by Eq. (17).

Kovsh et al. [16] reported the high power output of diode laser in continuous or constant wave (CW) operation regime. Specially designed QD laser was grown with improved doping profile to check high current operation of QD devices. Laser structure contained 5 layers of QDs. The conversion efficiency reaches 30% at 2A and remains higher than 20% at high drive current. Their outcomes agree with the estimates of Eq. (17) and Eq. (21).

In addition to size–tunable emission wavelengths, QDs offer other benefits for lasing applications, including low optical–gain thresholds and high temperature stability of lasing characteristics. Recent progress in understanding and practical control of processes impeding light amplification in QDs has resulted in several breakthroughs, including the demonstration of optically pumped CW lasing, the realization of optical gain with direct current electrical injection and the development of dual–function electroluminescent devices that also operate as optically pumped lasers [17]. Chen et al. have discussed the recent developments and research progress of perovskite based QD lasers. The advantage of perovskite QDs as lasing gain materials and the method to achieve low–threshold lasing have been summarized [18]. Shang et al. have presented the most recent advances in monolithically integrated QD devices on a Si photonic platform, with a focus on breakthroughs in a long life time at elevated temperatures. Several technological breakthroughs in high temperature CW operation at the device and platform levels have been described [19]. Yao et al. have exposed that the QD lasers could operate without cooling and optical isolators. A new (novel) structure is introduced into the III–V QD structures, such as the hybrid saturable absorber with van der Waals heterostructures combining graphene or other two–dimensional materials with III–V semiconductors, which offers superior performance of optoelectronic devices [20].

7. CONCLUSIONS

QD lasers are the ideal devices to address the issues of low threshold current, high output power, and improved conversion efficiency. The power–current curve as a function of cavity length is linear. The external differential quantum efficiency decreases linearly with increasing cavity length and the internal quantum efficiency is independent of the geometrical properties of the laser device. The power conversion efficiency increases with drive current, becomes maximum and decreases slightly thereafter. QD lasers, therefore, find commercial applications in medicine, display technologies, spectroscopy, and telecommunications. Being insensitive to temperature fluctuations, they are ideal for use in optical data communications and networks.

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