Semiconductor Physics, Quantum Electronics & Optoelectronics, 2023. V. 26, No 3. P. 315-320.

Transient response analysis of a resonant cavity enhanced light emitting diode

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Abstract. This article is devoted to a theoretical evaluation of the transient behavior of a light emitting diode with a resonant cavity called the resonant cavity enhanced light emitting diode (RCELED). The used analytical model is based on applying the convolution theorem for a step input signal and the transfer function of RCELED in the presence of photon recycling. Influence of the efficiency of extraction due to photon recycling on the output optical power is analyzed. The target parameters characterizing the transient behavior are investigated. A traditional light emitting diode with no photon recycling is compared to a diode with photon recycling. The obtained results show the improvement of the output optical power and the rise time with the increase of extraction efficiency and in the presence of photon recycling in the light emitting diodes. The light emitting diode considered here reaches the highest steady state output power within 2 ns. Therefore this diode model may be used for fast speed and high optical gain applications such as in thermal imaging systems and short reach optical interconnects.

Keywords: transient response, RCELED, distributed Bragg reflector (DBR), extraction efficiency, internal quantum efficiency.

https://doi.org/10.15407/spqeo26.03.315
PACS 85.30.De, 85.60.Jb

Manuscript received 26.04.23; revised version received 16.07.23; accepted for publication 13.09.23; published online 20.09.23.

1. Introduction

Light emitted by an active region can be reabsorbed within this region again. The generated charge carriers can then recombine emitting new photons. This process enhances the internal quantum efficiency and is called photon recycling. By photon recycling, the overall external quantum efficiency of a device is enhanced since the carriers have a higher opportunity to produce photons that escape from the cavity. The photon recycling effect takes place in thick active regions. The increase of internal quantum efficiency is defined by the number of generated photons in the guided mode and the characteristic absorption length of this mode, which depends on the absorption coefficient of the active layer [1].

Presence of resonant cavity in the LED structure increases the emission efficiency due to the constructive interference of light inside the cavity, by which light generation towards the surface enhances. Moreover, the cavity improves the propagation characteristics of the optical modes matching with the cavity length, while the other modes are suppressed. Up to now, photon recycling has been observed in devices with the active layers of direct band gap III-V semiconducting materials. The photon recycling phenomenon has received a great attention because of its role in controlling the carrier lifetime as well as its prevalence in some semiconductors having large optical absorption coefficients [2].

According to the concept and theory of the photon recycling effect, there is no little doubt that this effect is able to enhance absorption and improve the quality of semiconductor devices. Photon recycling within light emitters is achieved by using thick active layers, bottom mirrors with higher and top mirrors with lower reflectivity [3].

Resonant cavity enhanced light emitting diodes (RCELEDs) have been proposed to solve the problem of wide divergence angles in conventional LEDs. The main idea of RCELEDs is to confine the generated spontaneous light within a resonant cavity to improve the wavelength selectivity and the divergence angle. RCELED can be integrated at the bottom side of a photodiode for single fiber bi-directional transmission in plastic optical fiber link applications [4]. Compared to LEDs, RCELEDs have several advantages including narrow spectral widths, stable peak wavelengths at different current injections, superior directionality, high extraction efficiency, and better output coupling efficiency due to relatively coherent output light. RCELEDs have improved characteristics as compared to those of conventional LEDs, while preserving the inherent LED advantages [5]. The reflectivity of RCELED reflectors is lower as compared to that of Vertical Cavity Surface Emitting Laser (VCSEL), which means lower manufacturing cost and operation below lasing mode [6].

Optical confinement characteristics of an InGaN RCELED structure was analyzed by adding the top dielectric distributed Bragg reflector (DBR) and the bottom DBR structure [7]. Spectral windows at 510 and 570 nm resulted from III–V nitride semiconductors with reduced temperature sensitivity are more suitable for automotive environments. Directional emission pattern and narrow spectral width were obtained for the structure consisting of an InGaN active layer with porous bottom DBR and dielectric top DBR, having the optimum layer spacing to match the cavity configuration [6–8]. Such observation offers a different view on conventional III-V semiconductor LEDs and lasers [9–12]. The cladding layer cavity can improve the conversion quantum efficiency and the spectral stability in a wide range of injected current values [7, 8, 13].

In this paper, transient behavior of RCELED is analyzed. The article goal is to evaluate the speed and the rise time of this device upon receiving an incoming signal. Furthermore, the effect of the resonant cavity on the device speed is addressed. The study is based on the transfer characteristic function in application to RCELED. The output power, output derivative and rise time are calculated using the forward and backward light components. The paper is organized as follows. Section 2 presents a transient response analysis using the convolution theorem. The obtained results are explained and analyzed in Section 3. The conclusion and references are presented in Sections 4 and 5, respectively.

Fig. 1 shows a schematic view of RCELED. The RCELED consists of a single cavity sandwiched between two DBRs. The top and bottom DBR mirrors comprising 4 pairs of *p*-doped layers are grown to finalize the resonant cavity structure. The total thickness of the RCELED structure is about 13 μm. If the period of the alternating layers is of sufficient value, most of the incident light will be reflected and the layers will act as a high-quality reflector. Alternatively, the light reflected from the layers can superimpose and form constructive interference.

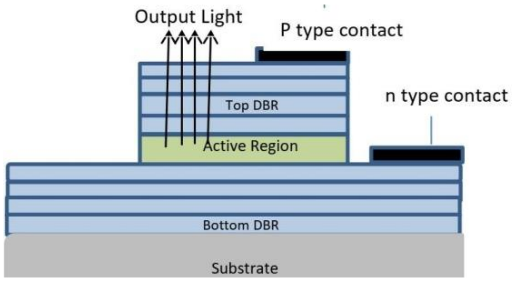

Fig. 1. Schematic structure of RCELED.

2. Theoretical analysis

There are two components of light extracted by the device under consideration. The first component is the light emitted from the active region through the layers in the forward direction. The second component is the light, which is reabsorbed and re-emitted again in the forward direction. The latter process is called photon recycling. The external quantum efficiency of RCELED as a function of frequency *f* is calculated as follows [14, 15]:

$$\eta^{\mathrm{RCELED}}(f)=\eta_f^{\mathrm{RCELED}}(f)+\eta_r^{\mathrm{RCELED}}(f), \qquad (1)$$

where $\eta_f^{\mathrm{RCELED}}(f)$ is the external quantum efficiency due to the first light component and $\eta_r^{\mathrm{RCELED}}(f)$ is the external quantum efficiency caused by the second light component, respectively. These characteristics can be evaluated as

$$\eta_f^{\mathrm{RCELED}}(f)=\frac{R\eta_{int}}{1-4\pi^2 l_d^2 f^2}, \qquad (2)$$

$$\eta_r^{\mathrm{RCELED}}(f)=\eta^{\mathrm{RCELED}}(f)(1-R)\eta_{int}\frac{\alpha_1\alpha_2}{\alpha_2^2+4\pi^2 f^2}. \qquad (3)$$

Then

$$\eta^{\mathrm{RCELED}}(f)=\frac{R\eta_{int}}{1-4\pi^2 l_d^2 f^2}+\eta_r^{\mathrm{RCELED}}(f), \qquad (4)$$

where

$$\eta^{\mathrm{RCELED}}(f)=\frac{R\eta_{int}}{1-4\pi^2 l_d^2 f^2-(1-R)\eta_{int}\dfrac{\alpha_1\alpha_2}{\alpha_2^2+4\pi^2 f^2}}, \qquad (5)$$

η_{int} is the internal quantum efficiency, l_d is the diffusion length, R is the extraction efficiency, α_1 is the absorption coefficient of a *p*-type confinement layer in the RCELED, and α_2 is the absorption coefficient of a *n*-type confinement layer in the RCELED, respectively.

In the case of $\alpha_1 < \alpha_2$, the expression above can be reduced to

$$\eta^{\mathrm{RCELED}}(f)=\frac{R\eta_{int}}{1-4\pi^2 l_d^2 f^2-(1-R)\eta_{int}}. \qquad (6)$$

Applying the convolution theorem described in [16, 17] to a step input current with the amplitude I_{in} and a time domain of the transfer function of external quantum efficiency, the time domain of optical output power is obtained as follows:

$$P(t)=\int_0^t \eta^{\mathrm{RCELED}}(\lambda)I_{in}(t-\lambda)d\lambda, \qquad (7)$$

where $\eta^{\mathrm{RCELED}}(\lambda)$ is the external quantum efficiency at a time λ that can be expressed as

$$\eta^{\mathrm{RCELED}}(\lambda)=\frac{R\eta_{int}}{l_d^2}e^{-\left(\frac{1-\eta_{int}+R\eta_{int}}{l_d^2}\right)\lambda}, \tag{8}$$

$$I_{in}(t-\lambda)=\begin{cases} I_{in} & t\geq\lambda \\ 0 & t<\lambda \end{cases} \tag{9}$$

Applying convolution to $\eta^{\mathrm{RCELED}}(\lambda)$ and $I_{in}(t-\lambda)$ the optical output power is obtained as

$$P(t)=\frac{\eta_{int}\,I_{in}}{1-\eta_{int}+R\eta_{int}}\left\{1-e^{\frac{-(1-\eta_{int}+R\eta_{int})t}{l_d^2}}\right\}. \tag{10}$$

To estimate the output derivative of the optical output power in order to determine the device speed, we differentiate Eq. (10) with respect to time obtaining the following expression:

$$\frac{d}{dt}P(t)=\frac{R\eta_{int}}{l_d^2}I_{in}e^{\frac{-(1-\eta_{int}-R\eta_{int})}{l_d^2}t}. \tag{11}$$

The time to reach 0.9 of the final output optical power is calculated as follows:

$$T=$$

$$=\ln\left\{\frac{R\eta_{int}\,I_{in}}{\eta^{\mathrm{RCELED}}+R\eta_{int}-\eta_{int}\eta^{\mathrm{RCELED}}-R\eta_{int}\eta^{\mathrm{RCELED}}}\right\}\times\mathbf{k}, \tag{12}$$

where

$$\mathbf{k}=\frac{l_d^2}{1-\eta_{int}+R\eta_{int}}. \tag{13}$$

We consider excitation of RCELED by a rectangular pulse **Π(*t*)** of the width *b* described by the following function:

$$\Pi(t)=\begin{cases} 1 & 0\leq t\leq b \\ 0 & \text{else} \end{cases}=U(t)-U(t-b). \tag{14}$$

In this case, the output power takes the following form:

$$P(t)=\int_0^t\eta^{\mathrm{RCELED}}(t-\lambda)\Pi(t)I_{in}\,d\lambda=$$

$$=\frac{\eta_{int}R\left[1-e^{\frac{-(1-\eta_{int}+\eta_{int}R)}{l_d^2}t}-U(t-b)\left(1-e^{\frac{(t-b)(1-\eta_{int}+\eta_{int}R)}{l_d^2}}\right)\right]}{1-\eta_{int}+\eta_{int}R} \tag{15}$$

and the output derivative is calculated as

$$S(t)=\frac{d}{dt}P(t)=\frac{\eta_{int}R}{1-\eta_{int}-\eta_{int}R}\times$$

$$\times\left[\frac{(1-\eta_{int}+\eta_{int}R)e^{-\frac{(1-\eta_{int}+\eta_{int}R)}{l_d^2}t}}{l_d^2}-\delta(t-b)\left(1-e^{-\frac{(1-\eta_{int}+\eta_{int}R)(t-b)}{l_d^2}}\right)-\frac{U(t-b)(1-\eta_{int}+\eta_{int}R)e^{-\frac{(t-b)(1-\eta_{int}+\eta_{int}R)}{l_d^2}}}{l_d^2}\right], \tag{16}$$

where

$$\delta(t-b)=\begin{cases} 1 & t=b \\ 0 & \text{else}, \end{cases}\quad U(t)=\begin{cases} 1 & t\geq 0 \\ 0 & \text{else}, \end{cases}\ \text{and}$$

$$U(t-b)=\begin{cases} 1 & t\geq b \\ 0 & \text{else}. \end{cases} \tag{17}$$

3. Results and discussion

The device parameters used in the calculations are as follows: $\eta_{int}=1$, $I_{in}=10$ mA, $l_d=4$ µm, and *R*, being the ratio of the quantities of extracted photons and photons inside the LED, ranges from 0 to 1. Increase of the extraction efficiency of RCELED leads to a few steps of photon transformation before emission. The transient behavior of the optical output power of a conventional LED at different values of the extraction efficiency *R* is shown in Fig. 2. It can be seen from this figure that the output power increases with time until reaching a steady state value. This value increases with the extraction efficiency *R* and internal quantum efficiency η_{int}. The plots in Fig. 1 are obtained in the absence of photon recycling. Therefore, the output optical power is small as compared to that in the presence of photon recycling. To increase the light extraction efficiency, the reflectivity on the bottom side of the LED structure must be improved.

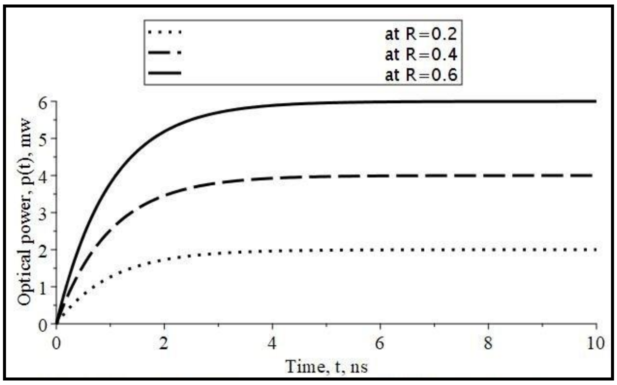

Fig. 2. Transient behavior of conventional LED at different values of *R*.

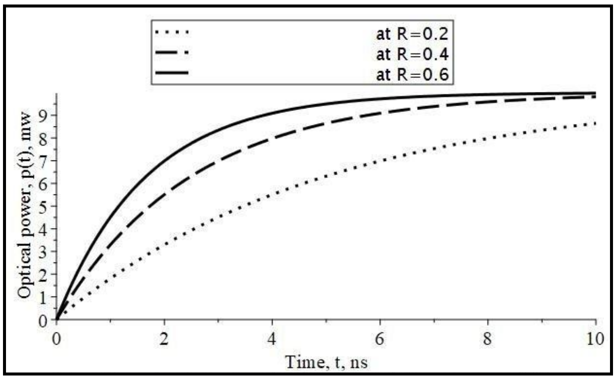

Fig. 3. Transient behavior of RCELED at different values of *R*.

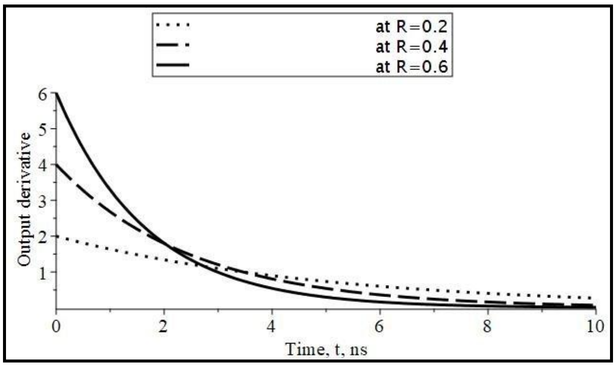

Fig. 4. Output derivative *versus* time at different values of *R*.

At the same time, the reflectivity of the emission side has to be reduced. This built-in reflector serves to prevent photons from being emitted through the bottom side and to redirect them to the emission side.

Fig. 3 shows the transient response for RCELED at different values of *R*. The output power response grows with the increase of *R*. To increase the extraction efficiency *R*, DBR should be located at a small distance under the quantum well (QW) active region. Semiconductor materials may be used to form such DBR structure. GaAs/AlGaAs system is the most effective and well-developed for creating semiconductor DBRs. The generated photons are reflected to enhance the extraction efficiency in the forward direction and achieve better coupling efficiency with the coupled optical waveguide or photonic integrated circuit.

The sensitivity of RCELED at any instant is defined as the slope of the output characteristic curve at this instant. The derivative of the output optical power sets the variation of output sensitivity with time. Moreover, this derivative is considered as the device speed characterizing the rate of the change of the device output optical power with time. The output derivative with respect to time at different values of *R* is shown in Fig. 4. It can be seen from this figure that this derivative decreases with time. At higher extraction efficiency, more time is required than at lower extraction efficiency due to the increased output which needs higher arrival time.

The rise time *versus* the output power at different values of *R* is shown in Fig. 5. It can be seen from this figure that increase of the extraction efficiency *R* reduces the rise time and, hence, the device speed. Presence of photon recycling increases the output optical power and at the same time reduces the rise time, which reaches the steady state response value. Moreover, combination of the DBR materials plays a major role in controlling the rise time. At very small lattice mismatch between the used materials, growth on the substrate can be done directly without inducing any cracks or dislocations. Furthermore, this combination can provide excellent reflectivity when contrast in the refractive indices between the DBR materials is large enough.

Fig. 6 shows the variation of output optical power *versus* extraction efficiency *R* at different values of internal quantum efficiency. The internal quantum efficiency is a measure of conversion efficiency of injected electrons into emitted photons. The extraction efficiency is zero when the light generated inside the structure is entirely recycled without exiting from the RCELED structure. At this, *R* is the total light intensity having exited the RCELED structure without recycling. Increase of *R* means more light emission and less photon recycling inside the structure and *vice versa*. In RCELED, DBR can be well integrated within the semiconductor layers, mainly being composed of alternating semiconductor

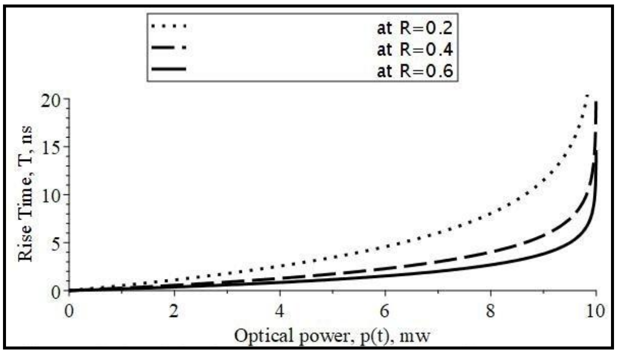

Fig. 5. Variation of rise time *versus* output power in the final state at different values of *R*.

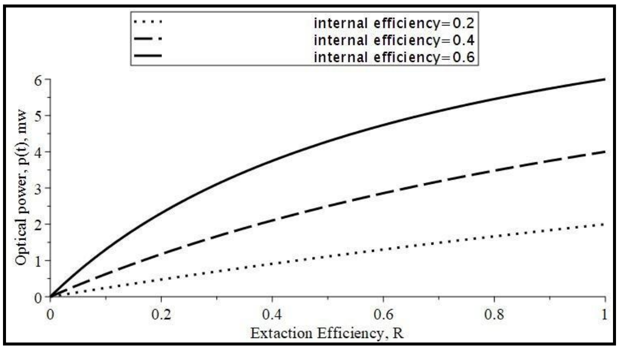

Fig. 6. Variation of optical output power *versus* extraction efficiency caused by photon recycling.

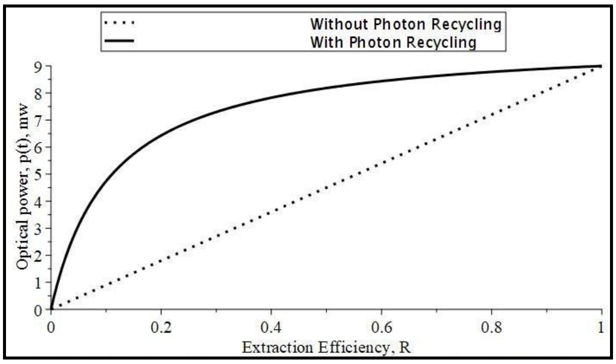

Fig. 7. Variation of optical output power *versus* extraction efficiency with and without photon recycling.

layers. The refractive index of each subsequent layer is different. Light incident on these layers is partially reflected and refracted. If the period of layer alternation is sufficient, most of the incident light will be reflected. In this case, the layers act as a high-quality reflector.

A comparison between a conventional LED and LED with photon recycling is shown in Fig. 7. It is clear from this figure that the photon recycling LED exhibits higher improvement of the output power than the conventional LED. Moreover, photon recycling causes nonlinear dependence of the output power on the extraction efficiency *R*, which is different from the respective linear dependence for conventional LEDs. For RCELED, the improvement of the output power is caused by the reflectivity, which is dominated by the difference in refractive indices between two different materials and the number of periods in DBR. Hence, the output optical power can be enhanced by increasing the number of pairs in DBR or by carefully choosing the materials with higher difference in their refractive indices. In general, such materials would provide high optical power at only a few pairs in DBR.

4. Conclusion

In this article, transient behavior of a light emitting diode with a resonant cavity is theoretically evaluated. The device considered here is called the resonant cavity enhanced light emitting diode (RCELED). Increase of the extraction efficiency *R* improves the output optical power and reduces the rise time and, hence, the device speed. A comparison between a traditional light emitting diode without photon recycling and the one with photon recycling is also presented. The obtained results show that the photon recycling LED exhibits higher improvement of the output power and rise time as compared to the conventional LED. Photon recycling causes the nonlinear LED characteristic, different from the linear one for conventional LEDs. The light emitting diodes considered here are very useful for the applications implying fast speed and high conversion efficiency, such as in thermal imaging systems and intra-chip optical interconnects.

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Authors’ contributions

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Аналіз перехідних характеристик світловипромінюючого діода з підсилюючим об’ємним резонатором

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Анотація. Ця стаття присвячена теоретичній оцінці перехідної поведінки світловипромінюючого діода з об’ємним резонатором, який називається світловипромінюючий діод з підсилюючим об’ємним резонатором. Використана аналітична модель ґрунтується на застосуванні теореми згортки для ступінчастого вхідного сигналу та передавальної функції такого діода за наявності рециркуляції фотонів. Проаналізовано вплив ефективності екстракції за допомогою рециркуляції фотонів на вихідну оптичну потужність. Досліджено цільові параметри, що характеризують перехідну поведінку. Представлено порівняння між звичайним світловипромінюючим діодом без рециркуляції фотонів та діодом з рециркуляцією фотонів. Отримані результати свідчать про поліпшення вихідної оптичної потужності та часу наростання зі збільшенням ефективності екстракції та за наявності рециркуляції фотонів у світловипромінюючих діодах. Вихідна потужність розглянутого світловипромінюючого діода досягає максимального стаціонарного значення протягом 2 нс. Отже, діоди такої моделі можна застосовувати за необхідності отримання високої швидкості та оптичного підсилення, наприклад у тепловізійних системах та оптичних з’єднаннях з малим радіусом дії.

Ключові слова: перехідна характеристика, світловипромінюючий діод з підсилюючим об’ємним резонатором, розподілений бреггівський відбивач, ефективність екстракції, внутрішній квантовий вихід.