Numerical Analysis of the Transient Response of the Excited Photocurrent Inside the Optoelectronic Integrated Device (OEID)

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ABSTRACT

In this paper, the transient response of the excited photocurrent inside an Optoelectronic Integrated Device (OEID) is analyzed. The device is composed of a Heterojunction Phototransistor (HPT) and a Laser Diode (LD). The expressions describing the transient response of the output, the rise time, and the output derivative are derived. The effect of the various device parameters on the transient response is outlined. The results show that the transient response of these types of devices is strongly depend on the optical feedback inside the device and it is found that the device works in two different modes, which are: amplification, for small optical feedback coefficient, switching, for high optical feedback coefficient. This type of model can be exploited as an optical amplifier, optical switching device and other applications.

I. INTRODUCTION

A tremendous effort has been focused on fabrication, modeling, and analysis of the performance of optoelectronic Integrated Devices (OEID) [1-5]. One type of OEIDs consists of a Heterojunction Phototransistor (HPT) that is vertically integrated with a laser diode (LD). The input light is shined on the phototransistor, and it is converted into current that passes through the LD. When the current in the LD is greater than the threshold current, the LD will emit light. Part of this light is fed back to the phototransistor. This feedback is referred to as optical feedback.

Zhu et al. [6], focused on the transient behavior of the optical output and showed that, based on the value of the optical feedback, the device can operate in one of two modes. For a small optical feedback coefficient the device operates in an amplification mode, where the output light varies linearly with the input light. While for large values of the feedback coefficient, the device operates in a switching mode. In this mode the light jumps abruptly from a low state to a high one when the input light exceeds a specific threshold value. In their
work they assumed constant optical feedback that is independent from frequency and currents.

S. Noda et al [3] focused on the fabrication and the analysis of the static device performance. However, they did not analyze the transient behavior of the excited photocurrent inside the device. Therefore, there is a genuine need to showing the transient response of the photocurrent inside the device. In this paper, the same method used by Zhu et al. [6] is used to analyze transient behavior of the photocurrent inside the device.

II. THEORETICAL ANALYSIS

II. 1. Transient Behavior

The excited photocurrent inside the Optoelectronic Integrated Device (OEID) has two components; the first is due to the light incident on the Hetrojunction Phototransistor (HPT) from the external source, the second component is due to the light back inside the device from the Laser Diode to the Hetrojunction Phototransistor (HPT). The Block of the optoelectronic integrated device with optical feedback is shown in Fig. 1. From the block diagram, the excited photocurrent inside the device can be expressed as [3]:

$$i(\omega) = \frac{\left(\frac{q}{h\nu}\right)g(\omega)p_{in}}{1 - k(\omega)g(\omega)\eta(\omega)},$$

where $g(\omega)$ denotes the conversion gain of HPT, $\eta(\omega)$ is the external quantum efficiency of the LD, and $k(\omega)$, the ratio of the photons which reach the HPT to those emitted by the LD and assumed to be constant. $k(\omega) = k_0$.

![Fig. 1 Block diagram of OEID with optical feedback](image-url)

By using the same method used by Zhu et al. [6], the frequency response of the excited photocurrent inside the optoelectronic integrated device can thus be expressed as:
\[
i(\omega) = \left( \frac{q}{h\nu} \right) \frac{g_0}{(1 + j\omega/\omega_\beta)} P_m \left( 1 - \frac{k_0 g_0 \eta_0}{(1 + j\omega/\omega_\beta)(1 + j\omega/\omega) \beta} \right),
\]

where \( g_0 = \beta_0 \eta_0 \) denotes the conversion gain of the HPT at low frequency regime, and \( \beta_0 \) and \( \eta_0 \) are the current gain and the quantum efficiency of the HPT in the low frequency regime, and \( \omega_\beta \) is the beta cutoff frequency. While \( \eta_0 \), the quantum efficiency for the spontaneous emission in the low frequency regime, \( \omega_1 \) is the cutoff frequency of the LD where \( \omega_1^{-1} = \tau_0 \) is the minority carrier lifetime.

When the input light is assumed as a step function in time, the Laplace transform of the photocurrent can be obtained as

\[
i(s) = \frac{qg_0 \omega_\beta P_m}{h\nu (s + \omega_\beta) s (1 - \frac{g_0 \omega_\beta \eta_0 w_1 k_0}{(s + \omega_\beta)(s + \omega_1)})}.
\]

The output response of the electrical current of the optoelectronic integrated devices can be obtained from the inverse Laplace of Eq. (3) as

\[
i(t) = L^{-1} \left\{ \frac{qg_0 \omega_\beta P_m}{h\nu (s + \omega_\beta) (s + \omega_1)} \right\}
\]

The output response of the electrical current of the optoelectronic integrated devices can be obtained as

\[
i(t) = \left( \frac{q}{h\nu} \right) g_0 P_m \left\{ \frac{\omega_\beta \omega_1}{\lambda_1 \lambda_2} + \frac{\omega_\beta (\lambda_1 + \omega_1)}{\lambda_1 (\lambda_1 - \lambda_2)} e^{\lambda t} + \frac{\omega_\beta (\lambda_2 + \omega_1)}{\lambda_2 (\lambda_2 - \lambda_1)} e^{\lambda t} \right\}
\]

where

\[
\lambda_1 = \frac{-\left( \omega_\beta + \omega_1 \right) + \sqrt{\left( \omega_\beta + \omega_1 \right)^2 - 4(1 - k_0 g_0 \eta_0) \omega_\beta \omega_1}}{2}, \quad \text{and}
\]

\[
\lambda_2 = \frac{-\left( \omega_\beta + \omega_1 \right) - \sqrt{\left( \omega_\beta + \omega_1 \right)^2 - 4(1 - k_0 g_0 \eta_0) \omega_\beta \omega_1}}{2},
\]
II. 2. Derivative of Output Photocurrent

The derivative of the output photocurrent inside the OEID with respect to time is expressed by

$$\frac{di(t)}{dt} = \left(\frac{q}{h\nu} g_0 P_{in} \right) \left\{ \frac{\omega_\beta (\lambda_1 + \omega_\epsilon)}{\lambda_1 - \lambda_2} e^{\lambda_2 t} + \frac{\omega_\beta (\lambda_2 + \omega_\epsilon)}{\lambda_2 - \lambda_1} e^{\lambda_1 t} \right\}$$

which describes how fast the output photocurrent inside the OEID changes with time. By using the approximation where, $\lambda_1 \lambda_2 = \omega_\epsilon \omega_\beta (1 - g_0 \eta_0 k_0)$ and $\lambda_2 = -\omega_\epsilon$. For $k_0 g_0 \eta_0 = 1$

$$\frac{di(t)}{dt} = \left(\frac{q}{h\nu} g_0 P_{in} \right) \omega_\beta$$

II. 3. Rise Time Characteristics

The rise time of the photocurrent inside the optoelectronic integrated devices is defined as the time required for $i(t)$ to rise to 0.9 of its final value, by solving Eq. (5). The rise time can be given as

$$T_A = \frac{1}{\lambda_1} \ln \left[ \frac{(q/h\nu) g_0 P_{in} - 0.9(1 - k_0 g_0 \eta_0) i_u}{(q/h\nu) g_0 P_{in}} \right]$$

where

$$i_u = \frac{(q/h\nu) g_0 P_{in}}{1 - g_0 \eta_0 k_0}$$

In the switching mode, the rise time can be obtained by setting $i_u = i_s$, which can further be simplified as

$$T_s = \frac{1}{\lambda_1} \ln \left[ \frac{(q/h\nu) g_0 P_{in} + 0.9(k_0 g_0 \eta_0 - 1)i_s}{(q/h\nu) g_0 P_{in}} \right]$$

III. RESULTS AND DISCUSSION

The device parameters used in the following calculations are the same as those used by Zhu et al. [6], where $\omega_\beta = 10^8$ Hz, $\omega_\epsilon = 10^{10}$ Hz, and $g_0 \eta_0 = 100$. The input light is assumed as a step function in time. The transient response of the excited photocurrent inside the OEID in the amplification mode is shown in Fig. 2. It can be seen that the photocurrent inside the device approaches a definite and is stable in this mode, while the transient response of the photocurrent inside the device is shown in Fig. 3. In this mode the output photocurrent increases exponentially with time, which corresponds to the jump in the switching mode.
Figure 4 shows the output photocurrent versus the HPT conversion gain at the amplification mode. It can be seen that the photocurrent inside the device increases as the gain of the phototransistor and the optical feedback increase, while Fig. 5 shows the time dependence of the derivative of the output photocurrent (which describes how fast the output photocurrent inside the OEID changes with time) in the amplification mode, it can be seen that the output photocurrent inside the OEID changes with decreasing derivative and thus will approach a definite value, also the derivative increases with increasing optical feedback at any time. In the switching mode, as shown in Fig. 6, the output photocurrent inside the OEID changes with an increasing derivative, and thus will not approach a definite value unless there is an external limitation. It can be seen that at any time, the derivative increases with increasing the optical feedback inside the device.

The dependence of the rise time of photocurrent inside the OEID on the optical feedback coefficient in the amplification mode is shown in Fig. 7. It is clear that by increasing the optical feedback, there is an increase in the rise time due to the increase of the difference between the output photocurrent at the initial and the final state. The optical feedback is usually weakened in the amplification mode by inserting an absorption layer between the HPT and LD, and thus the rise time in this mode is equal in magnitude as that of the HPT with optical feedback.

Different from the amplification, the rise time in the switching mode decreases with increasing the optical feedback as shown in Fig. 8. By increasing the optical feedback, the decrease in the rise time in the switching mode is due the increase of the derivative of the output

IV. CONCLUSIONS

The transient response of the excited photocurrent inside an Optoelectronic Integrated Device (OEID) composed of a Hetrojunction Phototransistor (HPT) and Laser Diode (LD) is analyzed. The analytical expressions describing the transient response of the excited photocurrent inside the device are derived; the effect of the various device parameters on the transient response is outlined. The photocurrent inside the device is in the amplification (stable) mode for lower optical feedback, and in the switching (unstable) mode for higher optical feedback. The rise time in both amplification and switching modes have been calculated. In the amplification mode, the rise time increase with increasing the optical feedback inside the device, while in the switching mode, it decreases with increasing the optical feedback inside the device. This type of model can be exploited as optical amplifier, optical switching device and other applications.

REFERENCES


![Diagram showing the transient response of photocurrent inside OEID at different values of \(k_0\).](image-url)
Fig. 3. Transient response of the photocurrent in the switching mode

Fig. 4. Photocurrent versus the conversion gain of the phototransistor at different values of $k_0$. 

- at $k_0=0.04$
- at $k_0=0.06$
- at $k_0=0.08$

- at $k_0=0.0001$
- at $k_0=0.0005$
- at $k_0=0.0008$
Fig. 5 Derivative of Photocurrent inside OEID in the amplification mode

Fig. 6 Output Derivative of the output photocurrent in the switching mode
Fig. 7. Dependence of the Rise Time on optical feedback coefficient in the amplification mode

Fig. 8. Dependence of the Rise Time on Optical Feedback Coefficient in the switching mode