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Performance analysis and stability testing of a new structure of optoelectronic integrated device

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Abstract

This paper is devoted to the evaluation of the transient performance as well as testing the stability of a new version of optoelectronic integrated devices. This version is composed of a resonant cavity enhanced heterojunction phototransistor and a light-emitting diode. It will be called as a resonant cavity enhanced optoelectronic integrated device. The evaluation of its transient response is based on the frequency response of the constituent elements and the optical feedback inside the device. Analytical expressions describing the transient behavior are derived. The numerical results show that the transient performance of the version under consideration strongly depends on the optical feedback inside the device and it has a very high optical gain in comparison with the conventional types. In addition, the possibility of operating the new device in two distinct modes is also available as similar to conventional types. Moreover, testing the stability of the new version demonstrates that its optical gain is stable as long as the value of the optical feedback is maintained below threshold value, while exhibits instability for values of optical feedback, which is greater or equal to this threshold value.

Keywords: Optoelectronic integrated device; Optical feedback coefficient; Optical amplification mode; Optical switching mode

1. Introduction

There has been much interest in optoelectronic integrated devices (OEIDs) [1,2], which are important for optical information processing and optical computing. A vertical and direct integration of light detecting and light-emitting devices, such as heterojunction phototransistor (HPT) and laser diode (LD), respectively is an effective method to obtain optical functional devices. One type of such devices is shown in Fig. 1, where a resonant cavity enhanced heterojunction phototransistor (RCE-HPT) and a light-emitting diode (LED) or an LD are directly integrated. The RCE-HPT converts the input light to amplified current after making a round trip between two separate mirrors and the LED or LD driven by current, and emits an intensified output light [3].

In addition to the input light, the RCE-HPT also responds to the light emitted from the LED or LD, which is called as an optical feedback inside the device. This optical feedback plays an important role in realizing various optical functions such as light amplification, optical switching and other applications [4–6]. In the amplification mode, the output light changes linearly with input light, while in the switching mode, the output light jumps abruptly from the low-current state to the high-current state.

Stability is the most important system specification and can be tested with the method called the Routh-Hurwitz. This method requires two steps [7]: The first is to generate a data table called a Routh table, and the second is to interpret the Routh table. Fig. 1 shows the schematic layer structure of a proposed model, the entire structure is grown on a 10 period AlAs/GaAs quarter wave stack used as a high reflectivity mirror ($R_2 = 0.9$, center wavelength $\lambda = 950$ nm). The optical output can be extracted through the quarter wave stack mirror as the GaAs substrate, if such a configuration is desirable. The resonant cavity of length, L and the refractive index, $n = 3$, $\alpha d = 0.1$ is formed between the buried AlAs/GaAs quarter wave stack mirror and the native GaAs surface, $R_1 = 0.3$. Fig. 2 shows the block diagram of the device with optical feedback.

In this paper, a theoretical analysis of the transient behavior of the OEIDs consisting of RCE-HPT and LED is done by the use of the same method as that indicated in

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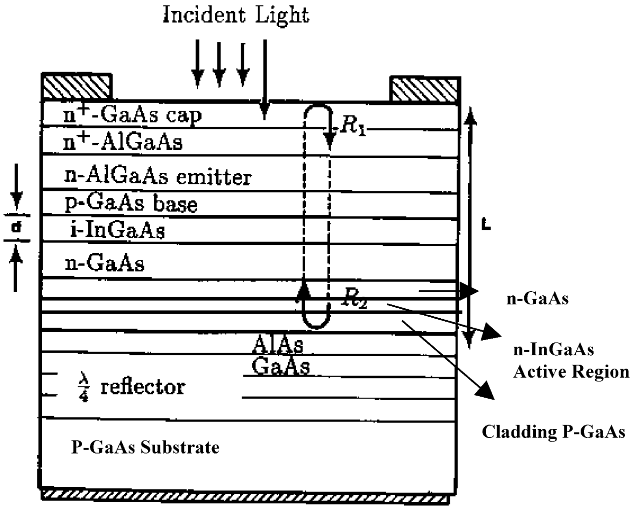

Fig. 1. Schematic drawing of integration of RCE-HPT and LED to form RCE-OEID.

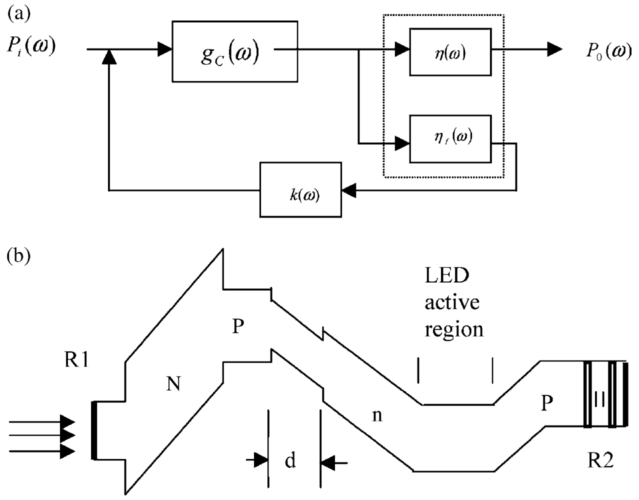

Fig. 2. (a) Block diagram of RCE-OEID with optical feedback. (b) Energy band diagram of the RCE-OEID.

Ref. [3]. The method of Routh-Hurwitz for stability is applied on this model for different values of optical feedback. The obtained results are compared with those of conventional types composed of HPT and LED; the comparison shows that the resonant cavity enhanced optoelectronic integrated device (RCE-OEID) has a very high optical gain and large speed because RCE-HPT, which acts as light-detector in OEID, has high optical conversion gain and high cutoff frequency than that of HPT.

2. Transient response of resonant cavity enhanced optoelectronic integrated device

2.1. Frequency response characteristics

Characteristics of an optoelectronic device depend both on the frequency (wavelength) and the modulation signal frequency of an input light. The former is called the spectral response, and the latter is the frequency response. The block of the RCE-OEID with optical feedback is shown in Fig. 1, and the frequency response of the optical gain $G(\omega)$ of this device can be expressed as [3]:

$$G(\omega) = \frac{g_{\mathrm{C}}(\omega)\eta(\omega)}{1 - k(\omega)g_{\mathrm{C}}(\omega)\eta_{\mathrm{f}}(\omega)} \tag{1}$$

where $g_{\mathrm{C}}(\omega)$ is the conversion gain of the RCE-HPT, $\eta(\omega)$ the external quantum efficiency of the LED, $\eta_{\mathrm{f}}(\omega)$ the internal quantum efficiency of the LED for the feedback light and $k(\omega)$ the ratio of the photons, which reach the RCE-HPT, to those emitted by the LED.

The frequency response of the conversion gain of the RCE-HPT is expressed as [3]

$$g(\omega) = \frac{g_{\mathrm{C0}}}{1 + \dfrac{j\omega}{\omega_\beta}} \tag{2}$$

where $g_{\mathrm{C0}} = \beta_0 \eta h_0$ is the conversion gain of the RCE-HPT at low frequency regime and β_0 and ηh_0 the current gain and the quantum efficiency of the RCE-HPT in the low frequency regime, respectively and ω_β is the beta cutoff frequency. The conversion gain of RCE-HPT is derived as [8].

$$\begin{aligned} g_{\mathrm{C0}} &= \left\{ \frac{1 + R_2 \mathrm{e}^{-\alpha d}}{1 - 2\sqrt{R_1 R_2}\mathrm{e}^{-\alpha d}\cos(2\beta L) + R_1 R_2 \mathrm{e}^{-2\alpha d}} \right\} \\ &\quad \times \beta_0 (1 - R_1)(1 - \mathrm{e}^{-\alpha d}) \\ &= \{\mathrm{CEF}\} g_0 \end{aligned} \tag{3}$$

where CEF is the cavity enhanced factor,

$$\begin{aligned} \mathrm{CEF} &= \left\{ \frac{1 + R_2 \mathrm{e}^{-\alpha d}}{1 - 2\sqrt{R_1 R_2}\mathrm{e}^{-\alpha d}\cos(2\beta L) + R_1 R_2 \mathrm{e}^{-2\alpha d}} \right\}, \\ g_0 &= \beta_0 (1 - R_1)(1 - \mathrm{e}^{-\alpha d}) \end{aligned} \tag{4}$$

In the above expressions, g_0 is the conversion gain of the conventional HPT, R_1, R_2 the reflection coefficient of the upper and bottom mirrors, respectively, α is the absorption coefficient of the active layer of thickness d, β the propagation constant of the light waves, $\beta = 2n\pi/\lambda_0$, where, λ_0 is the vacuum wavelength and n is the refractive index of the medium. The frequency response of an LED can be expressed as

$$\eta_{\mathrm{sp}}(\omega) = \frac{\eta_{\mathrm{sp0}}}{1 + \dfrac{j\omega}{\omega_1}} \tag{5}$$

where η_{sp0} is the quantum efficiency of the spontaneous emission in the low frequency regime, ω_1 the cutoff frequency of the LED where $\omega_1^{-1} = \tau_0$ is the minority carrier lifetime. The frequency response of the OEID can