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Recovery Dynamics Analysis of Saturable Absorber Optical Gates by Optical Sampling

Masayuki Shirane, Yoichi Hashimoto, Hirohito Yamada, and Hiroyuki Yokoyama

Optoelectronics and High Frequency Device Research Laboratories, NEC Corporation
34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
Tel: +81-298-50-2625, Fax: +81-298-56-6140, E-mail: shirane@obl.cl.nec.co.jp

1. Introduction

All-optical signal processing is a key technology for future ultra-high-speed (>100 Gb/s) optical communications. Optical gate switching devices are one of the essential elements. Among them, semiconductor waveguide saturable absorber (SWSA) optical gates are promising because they are expected to have a fast response time. The SWSA optical gates operate under reverse bias voltage, which sweeps the photo-generated carriers out from the active layer. Thus understanding the dynamics in the SWSA is very important for optimizing the device operating performance.

In this paper, we investigate absorption recovery dynamics of an SWSA optical gate by pump-probe measurements using optical sampling. We found that the absorption recovery in the SWSA is mainly composed of two processes with different time contants. Theoretical analysis well explains these features: the slow recovery process is due to the slow photo-carrier extraction process from the device. This result indicates that device design as well as precise electrical package design is important for ultra-high-speed switching of the SWSA from the viewpoint of electrical response.

2. Experiment

The basic structure of the measured SWSA was a strained InGaAsP quantum-well (QW) active layer with a bandgap wavelength of 1550 nm and a double-channeled planar buried heterostructure. The device length was 300 μm and both end-facets were anti-reflection coated. The SWSA was operated under reverse bias voltage, and this scheme could rapidly remove photo-generated carriers from the active layer. Recovery measurements of the SWSA were carried out by the pump-probe method combined with optical sampling.

Figure 1 shows the block diagram of the experimental setup. Optical pump and probe pulses were generated from wavelength-tunable mode-locked laser diodes (MLLDs). The advantage of the present optical sampling is that the time delay between the pulses is achieved electrically, so quasi real-time measurements are possible. Optical pulse widths of both MLLDs were about 2 ps and their repetition rates were f_1 = 10.00 GHz and f_2 = 999.9 MHz, respectively. The slight difference in their repetition rates causes a delay δt in the probe pulse relative to the pump pulse in every probe pulse period, and δt corresponds to the equivalent sampling time. The sampling time is written as

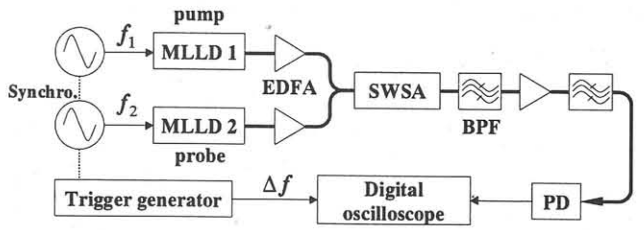

Fig. 1: Block diagram of the pump-probe measurement setup with optical sampling.

$$\delta t = \frac{1}{f_2} - \frac{m}{f_1} \quad (m: \text{integer}) \qquad (1)$$

In the present case, m is set to be 10, then δt is equal to 0.1 ps. The timing jitter of the entire measurement system was less than 1 ps and the entire temporal resolution was estimated to be 2.2 ps. The wavelengths of the pump and probe were respectively fixed to 1550 nm and 1555 nm. The absorption recovery process was measured by monitoring the intensity change of the transmitted probe pulse.

Figure 2 shows the transmittance of the probe pulse through the SWSA as a function of time under various reverse bias voltages. The optical pump and probe pulse energies were 2.5 pJ and 0.3 pJ, respectively. These values were determined to operate above saturation level of the SWSA for the pump pulse and below saturation level for the probe pulse. The absorption recovery of the SWSA results in a decrease in the transmittance as a function of time. It should be noted that there are two time-constant components in the recovery curve at reverse bias of 2 V. The fast component rapidly decreases with increasing reverse bias, which means that thermo-ionic emission dominates the carrier sweep-out process from the QW under an applied electric field [1]. The observed recovery time at reverse bias of 2 V was 8 ps. This value was also confirmed by the previous nonlinear cross-correlation measurement [2]. However, we also observed the long time-constant component, which limited the entire recovery speed. This slow recovery speed will cause the pattern effect in actual device operation. The slow electrical response might cause the slow component, thus we also prepared another device in which a fast electrical response for the entire device system was achieved. Figure 3 (A) shows the recovery process for the latter device. The slow component was improved compared with the former one (B). Furthermore no pattern effects was observed in this device under 10 Gb/s random optical pulse excitation [3].

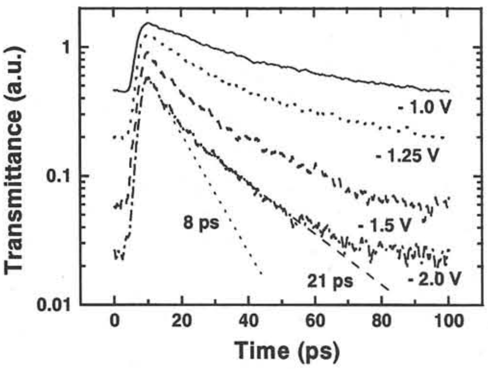

Fig. 2: Change in transmittance of the probe pulse through the SWSA as a parameter of reverse bias voltages.

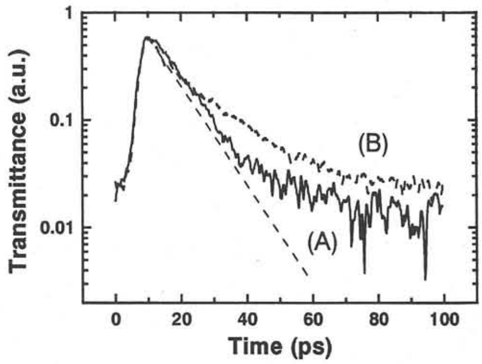

Fig. 3: Measured transmittance recovery curves for different SWSA devices (A) with and (B) without improved of electrical response.

3. Analytical Results

In order to make clear the essential factor limiting the speed of the device, we performed calculations using a set of rate equations translated from the equivalent elecrtical circuit of the actual SWSA including the parasitic components. We introduced the time constants of carriers as follows: τ_{12} is from the active layer of the SWSA to the stray capacitance, τ_{21} is from the stray capacitance to the active layer, and τ_{23} is from the stray capacitance to outside of the device.

Figures 4 (a) and (b) show the calculated results of recovery dynamics excited by random optical pulses of 5-ps temporal duration. The data rate is set at 10 Gb/s in order to compare with the experimental results. The parameters used in the simulation were τ_{12} = 10 ps, τ_{21} = 50 ps, τ_{23} = 100 ps for (a), and τ_{12} = 10 ps, τ_{21} = 50 ps, τ_{23} = 20 ps for (b). Only τ_{23} is different. We can see two components with different time constants in the calculated result of (a); this feature qualitatively agrees well with the experimental results. The apparent pattern effect is also seen, and this pattern effect is not desirable for actual signal processing. In the calculated result of (b), on the other hand, recovery dynamics looks like a single exponential decay process and the pattern effect is almost completely suppressed. This is only due to the differnce in time contant τ_{23}. These results indicate that a slow carrier extraction process to the outside circuit becomes the bottleneck of the recovery speed, and it is important for high-speed response of the SWSA to improve the entire electrical response of the system even though we utilize nonlinear-optic effects in the device operation.

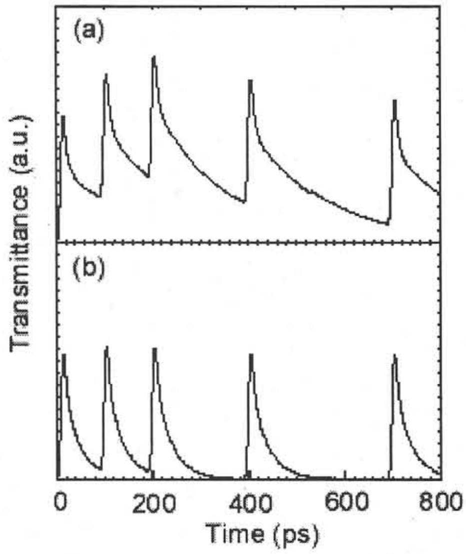

Fig. 4: Calculated transmittance excited by random RZ data pulses for different time constants: (a) τ_{23} = 100 ps and (b) τ_{23} = 20 ps.

4. Summary

In summary, we investigated absorption recovery dynamics of an SWSA optical gate by pump-probe measurements using optical sampling. We found that the absorption recovery in the SWSA was mainly composed of two processes with different time contants. Theoretical analysis well explained these features, the slow recovery process was due to the slow photo-carrier extraction process from the device. The results indicate that device design as well as precise electrical package design is important for the ultra-high-speed switching of the SWSA from the viewpoint of electrical response.

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