The Memoirs of Faculty of Engineering
Fukuyama University
The 8th issue, March 1986

Preliminary Experiments of Light-Pulse Waveform Synthesizer Implementing Optical Bistability Circuit

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ABSTRACTS

This paper proposes an application of the optical bistability to an optical-waveform synthesizer. This device is featured with a sub-nanosecond speed achieved with employing both GaAs- and Si-optoelectronic switches as photo detector. A result of experiment for an optical pulse shaping is also given.

1. Introduction

Recently much efforts have been devoted to develop devices for optical signal processing.$^{1)}$ Among those, optical bistable devices (OBD's) are classified into two groups by a type of an incorporated feedback. One is all-optical or "intrinsic" type of OBD's, and the other, "hybrid" type. Intrinsic devices generally employ a Fabry-Perot resonator containing a nonlinear medium inside, and optical feedback is applied to the medium. Hybrid-type devices are based on the principle that electric signals to optical ones are fed back to an electrooptic crystal which shows nonlinear refraction. In either cases, a feedback is necessary for optical bistability. Hybrid OBD's are expected to be useful in an optoelectronic system where optical signals co-operate with electric ones. Intrinsic types of small sized semiconductor devices are appreciated in a pure-optical signal processing where an ultra-fast switching capability is prerequisite.$^{2)}$

In this paper, a new hybrid device is proposed. This device performs an optical waveform synthesis with a subnanosecond resolution. This device employs optoelectronic switch of GaAs and another, of Si as photodetectors, which enable the device to work faster than conventional hybrid devices with photodiode detectors. As a preliminary experiment, optical-pulse shaping for a dye laser pulse (pulse width 3ns) and Si OE switches only without GaAs ones are used.

2. Optical-waveform synthesizer

Figure 1 shows a schematic of the waveform synthesizer. This device employs two electro-optic modulators controlled by a Si optoelectronic (OE) switch and a GaAs OE switch, respectively. The modulator controlled by the Si OE switch, called MOD. 1, produces a stepwise optical pulse Pi (t) with a rise-time on the order of picosecond and a pulse width of approximately 100

A part of this paper deals with common contents with the references (7), (8).

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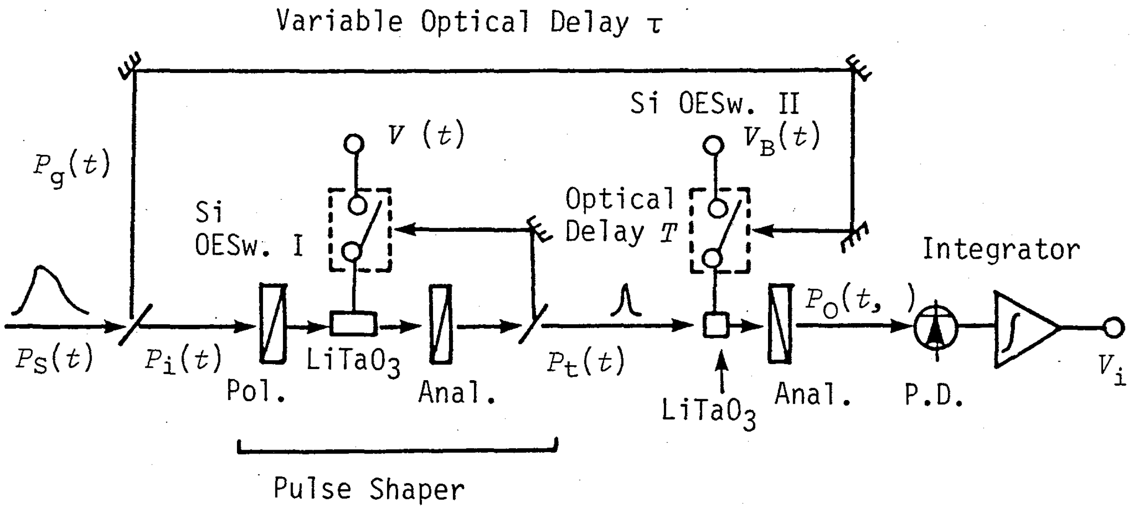


OESw.: Optoelectronic Switch; Pol.: Polarizer; Ana.: Analizer; P.D.: Photodiode

Fig. 1 Optical-waveform synthesizer with GaAs and Si-optoelectronic switches

nanosecond limited by a carrier life time in Si.[3] The optical pulse $P_i(t)$ passes through the modulator controlled by the GaAs OE switch, Mod. 2. The GaAs OE switch is triggered by the transmitted optical pulse, $P_t(t-T)$, delayed by the optical fiber. The delay time T is taken enough longer than the lifetime of GaAs carriers. Suppose that a picosecond optical pulse triggers the Si OE switch at time $t = 0$. Then, Pi (t) can be written as

$$P_i(t) = P \cdot U(t) \qquad (1)$$

where U (t) stands for a unit step function. In the following time interval $0 < t < T$, MOD. 2 is in a transparent state since the GaAs OE switch is off, and $P_i(t)$ is in the "high" state. At $t = T$ in turn, $P_t(t-T)$ triggers the GaAs OE-switch, that makes the MOD. 2 opaque, and $P_t(t)$ falls down to the "low" state. At $t = 2T$, when the feed-back optical signal $P_t(t-T)$ distinguishes, the GaAs OE switch quickly responds to fall since its carrier lifetime is shorter (~ 100 ps)[4] than T. Thus, $P_t(t)$ comes up to the "high" state again, and those switching actions go on successively. The transmitted optical power $P_t(t)$ is roughly expressed as

$$P_t(t) = P \cdot \{ U(t) - U(t-T) + U(t-2T) \ldots \} \qquad (2)$$

which is synthesized of the incident optical power $P_i(t)$.

Numerical simulation of the device in Fig. 1 are executed as follows. A trigger by a picosecond optical pulse to the Si OW switch at $t = 0$ produces a step-wise optical signal $P_i(t)$ with a

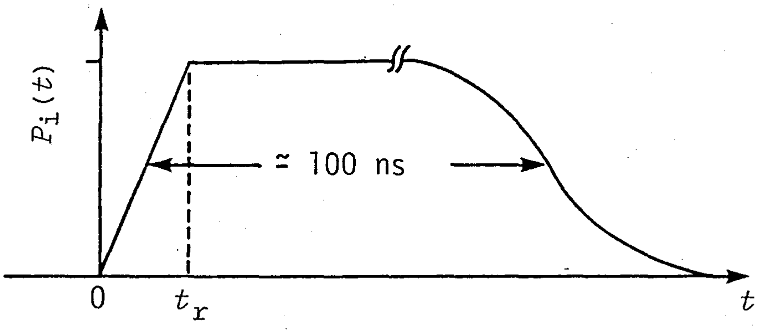


Fig. 2 Supposed waveform of the incident pulse P (t)

risetime of t_r determined by the MOD. 1 as illustrated in Fig. 2. The transmitted optical power $P_t(t)$ is given by the following three equations:

$$P_t(t) = 1/4\,P_i(t)\ \ [1 + \cos\{\pi(\alpha + V(t)/V\pi)\}] \qquad (3)$$

$$V(t) \doteq z_o\,G(t)\,V_B/\{1 + 2\,z_o\,G(t)\} \qquad (4)$$

$$G(t) = en/h\mu\,(\mu_e + \mu_h)\,1/r \int_0^t P_t(t-T)e^{(\tau-t)}\tau_0\,dt \qquad (5)$$

where α is a bias retardation factor, $V\pi$, a half-wave voltage of the electro-optic gate, V_B, a bias voltage, Z_o, a characteristic impedance of the transmission line (50 ohms), G (t), a conductance across the gap of the GaAs OE switch, $\mu_e + \mu_h$, a sum of electron and hole mobilities in GaAs (~ 10 cm/v.s), r, a gap width, and τ_o, a carrier lifetime in GaAs (~ 100 ps). Results of numerical simulations are given in Fig. 3 for various parameters with r = 10 μm and wavelength of optical source 0.5 μm, The pulse height of incident optical power P_i, the optical bias retardation factor α, the are taken as parameters.

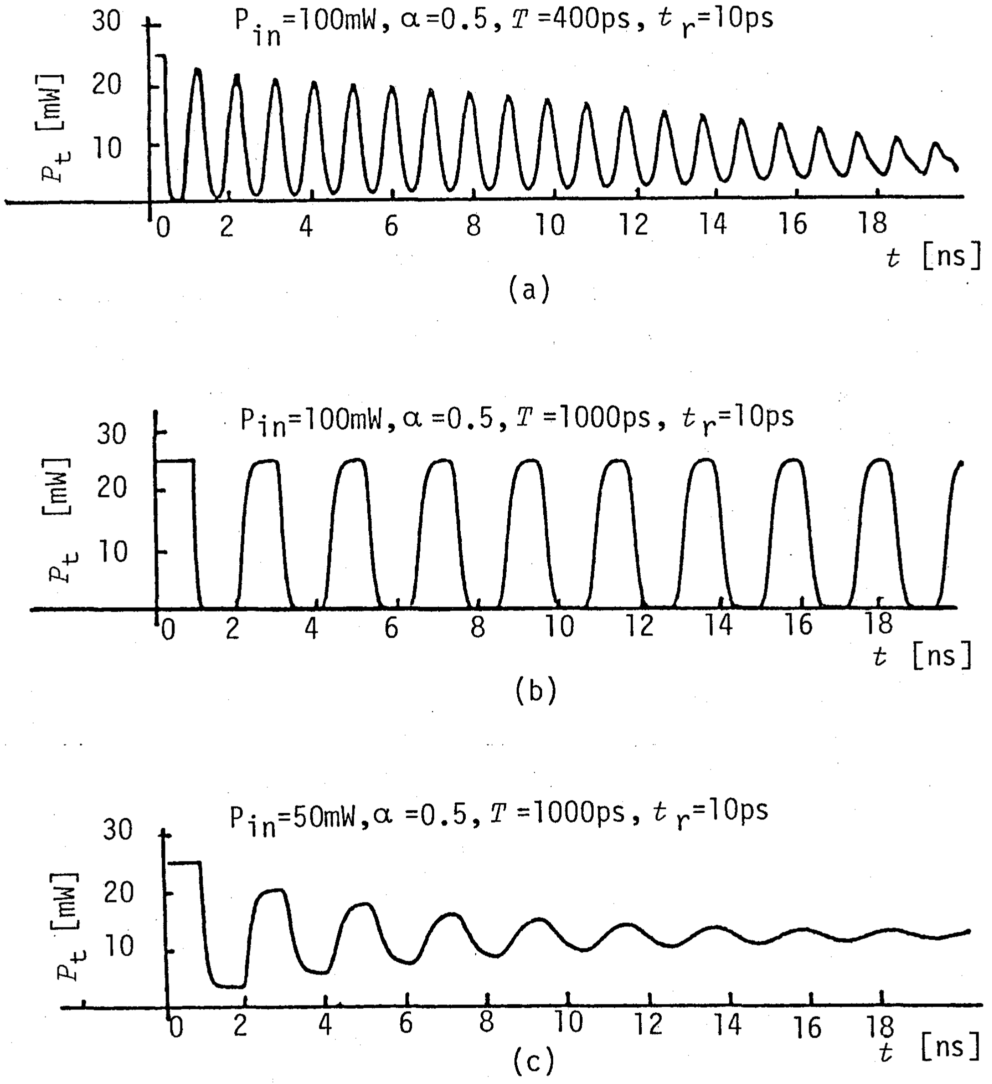


Fig. 3 Calculated response of the opticalwaveform synthesizer

In the following, explanations are given for optoelectronic switches, since they are basic elements to compose the optical-waveform synthesizer. An optoelectronic switch was first investigated by Auston, and an OE switch in Fig. 4 is sometimes called an "Auston"[5] -type OE switch. A high-power electric pulse can be supplied to a 50 Ohm line with the OE switch in a rise-time of less than 10 ps[5] triggered by a picosecond optical pulse. Therefore, these switches are useful for picosecond applications.

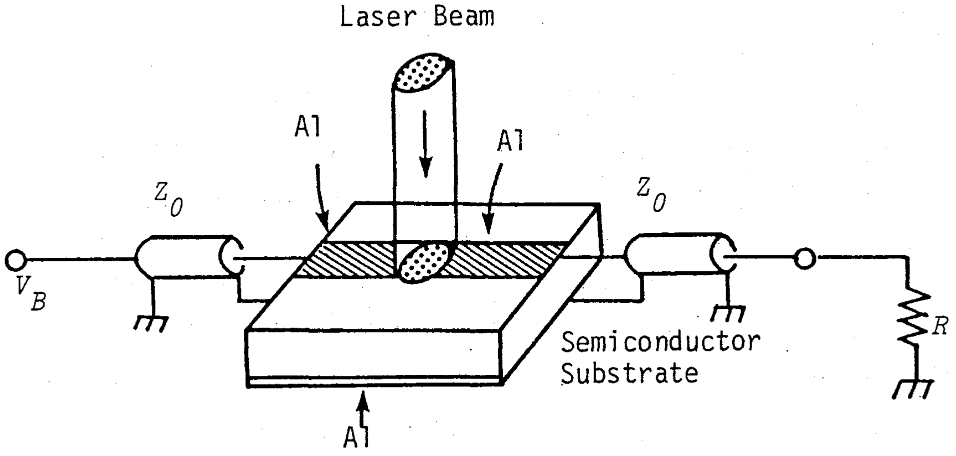


Fig. 4 "Auston" type Si optoelectronic switch

A schematic of an OE switch is depicted in Fig. 4. On one side of a Si substrate, two Al electrodes are evaporated or sputtered, and they are opposed across a small gap. The back side is covered by evaporated Al to work as the ground plane. When the gap is irradiated with intense visible-laser pulse, electron-hole pairs are generated near the surface of the substate, giving an ultra-fast switching action. The schematic for GaAs OE switch is the same as one in Fig. 4: a turn-on speed is also on the same order as that of the laser pulse.[6] But a turn-off characteristic of GaAs switch is shorter than that of Si due to the difference of carrier lifetimes. Figure 5 gives oscillograms of the response of Si OE switch triggered by a dye laser light (estimated pulse

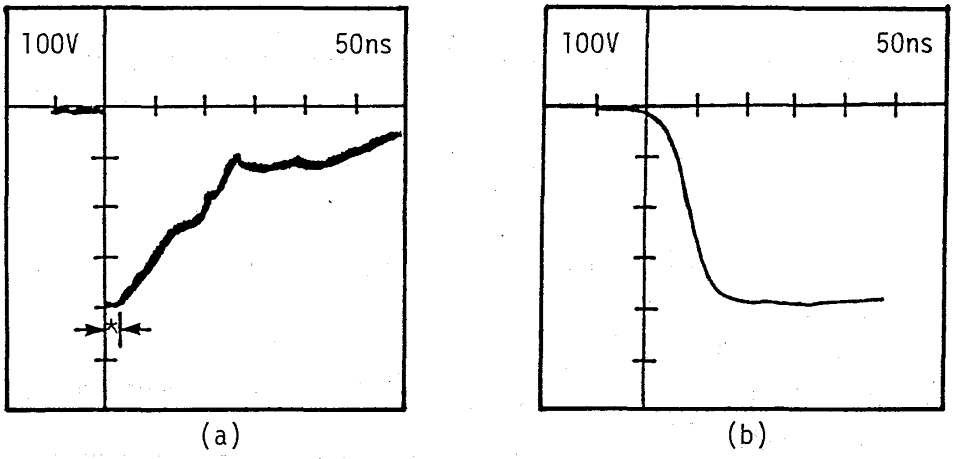
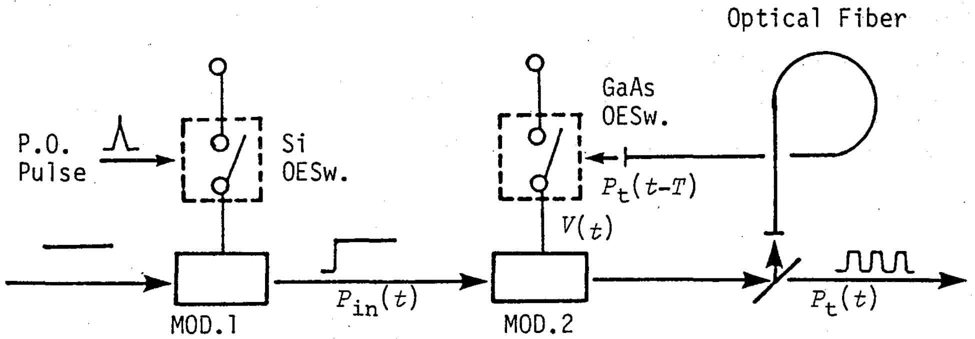


Fig. 5 Response of the Si optoelectronic switch. Gap width is 0.8 mm and a laser pulse energy is about 20 J. A pulsed bias of 640 V is applied. The trace (b) is a part of the trace (a) designated with (*) magnified in the temporal axis.

width ~ 3 ns) pumped by a N_2 laser. In those oscillograms, the rise-time is limited by the bandwidth of the oscilloscope used (100 MHz). The true-time is estimated as less than 330 ps from experiments mentioned later.

3. Experiments of optical pulse shaping

Figure 6 shows the experimental setup for optical-pulse shaping whose configuration is similar to that of the device in Fig. 1. In this setup, only a Si OE switch is used in a different manner. This system includes an optical-pulse waveform monitor composed of the same elements as those in the pulse shaper. A principle of this monitor is described later. A detailed sketch of the optical-pulse shaper is given in Fig. 7. A half-wave voltage of the modulator in the pulse shaper is about 200 V for $\lambda = 0.46\ \mu m$. Electrooptic modulators used are a $LiTaO_3$ Pockel's cell, controlled by the Si OE switch.



P.O. Pulse: Picosecond Optical Pulse;
MOD.: Modulator;
OEsw.: Optoelectronic switch.

Fig. 6 Experimental setup for optical-pulse shaping

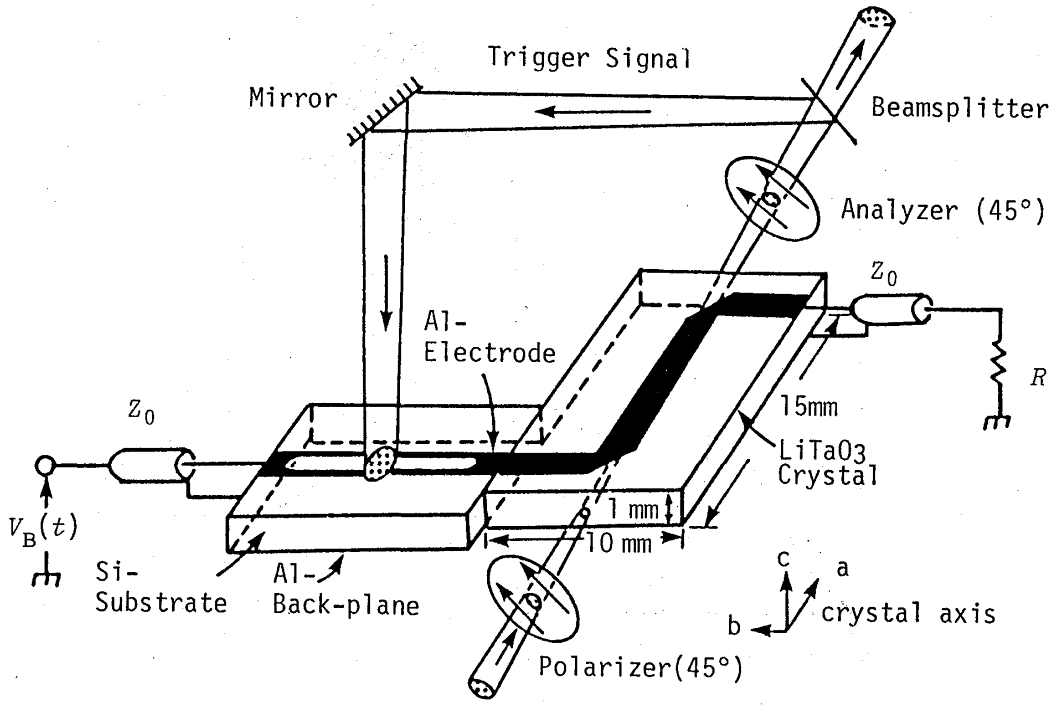


Fig. 7 Detailed illustration of the pulse shaper

As a light source, a dye laser pumped by the N_2 laser was employed. Let $P_t(t)$ be a laser pulse from the dye laser. The beamsplitter divides $P_s(t)$ into the incident pulse shaper and the trigger pulse $P_g(t)$ to the waveform monitor. The delayed transmitted pulse $P_t(t-T)$ turns the Si OE switch I on, that makes the modulator opaque. The "on" state of the Si OE switch continues longafter $P_i(t)$ goes through the modulator, since the carrier lifetime is much longer than the pulse width involved here (width of the pulse from the dye laser ~ 3 ns $\ll 100$ ns). The incident optical pulse $P_i(t)$ is shaped into the pulse $P_t(t)$ with the pulse width of approximately T. The use of a GaAs instead of the Si can make a pulse train with an width T for each pulse because of much shorter carrier lifetime.

The shaped optical pulse $P_t(t)$ has the pulse duration on the order of subnanosecond. Hence, a special equipment is required to monitor the waveform of $P_t(t)$. An *ad hoc* system was built

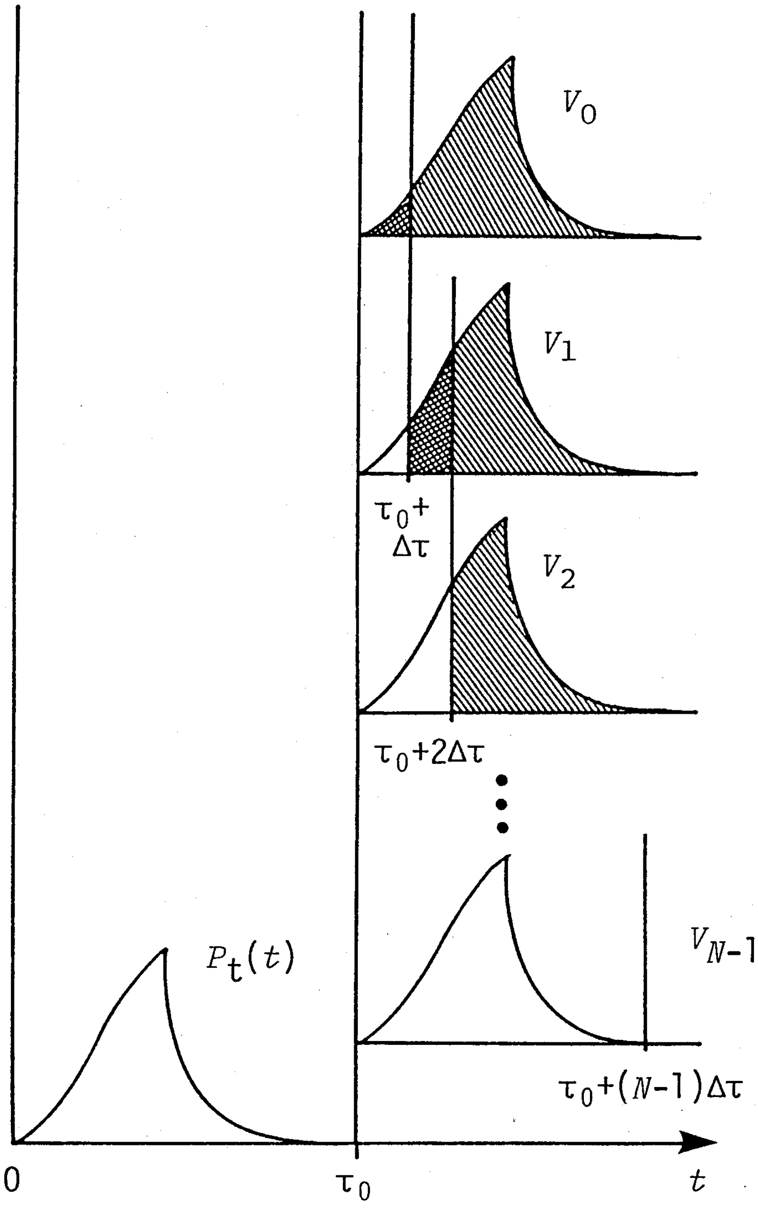


Fig. 8 Principle of waveform monitoring

comprising the LiTaO3 Pockels' cell and the Si OE switch. A principle of the monitor is given in the following. The pulse the Si OE switch, after going through the optical delay τ that gives the gated pulse $P_t(t)U(t-\tau)$ as the output pulse $P_o(t,\tau)$, where $U(t)$ is the unit step function. Changing the value of τ from τ_o to $\tau_o+(N-1)\Delta\tau$ by the increment of $\Delta\tau$ gives a train of N pulses $P_o(t,\tau_o+i\Delta\tau)$, $(i=0,1,.....N-1)$. The pulses $P_o(t,\tau_o+i\Delta\tau)$ are caught by a photodiode yielding output electric charges q_i which is proportional to energy of $P_o(t,\tau_o+i\Delta\tau)$, or

$$q_i = q(\tau_o+i\Delta\tau) \propto \int_{-\infty}^{\infty} P_t(t-\tau_o)\,U(t-\tau_o+i\Delta\tau)\,dt \tag{6}$$

In Fig. 8, hatched areas correspond to q_i's and cross-hatched areas to (q_i-q_{i+1}). Hence, $(q_i-q_{i+1})/\Delta\tau$ is approximately to the sampled value of $P_t(t-\tau_o)$ at $t=\tau_o+(i+1/2)\Delta\tau$ if the condition

$$\frac{d}{dt}P_t(t-\tau_o)\Big|_{t=\tau_o+(i+\frac{1}{2})\Delta\tau} \cong \frac{P_t(i+1)\Delta\tau-P_t(i\Delta\tau)}{\Delta\tau} \tag{7}$$

holds, where $i=0,1,2,.....N-2$.

Figure 9 gives experimental results: (a) and (b) are the sampled waveform of the shaped optical pulse $P_t(t)$; (a)' and (b)' are those of pre-shaped optical pulse $P_i(t)$. The optical delay time T is taken as about 930 ps for (a), and 600 ps for (b). The time resolution in the pulse monitoring, or $\Delta\tau$, is 330 ps. The Si OE switch is off when $t<T$, and the OE switch turns on at $t=T$. A value of 100 ns of the carrier life-time of Si results in a similar time duration of the

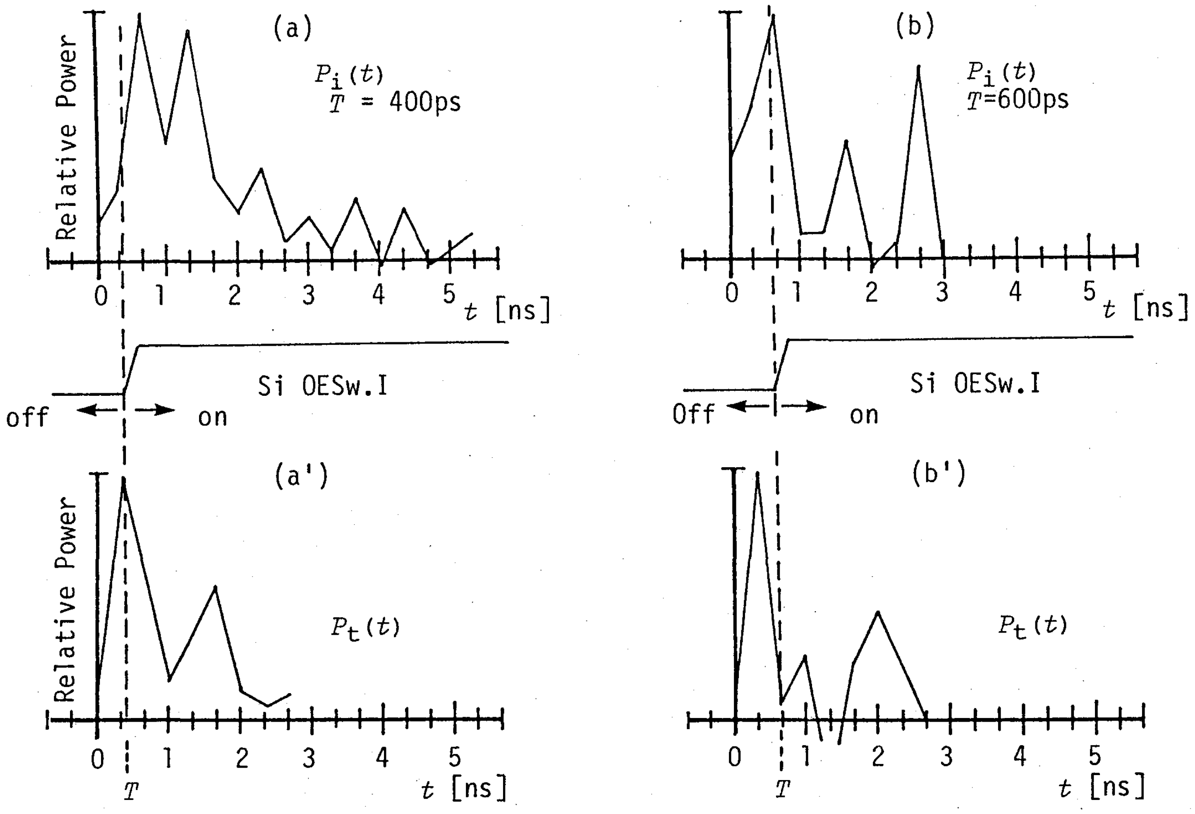


Fig. 9 Experimental results

"on" state. Since the width of the optical pulse involved here is approximately 3 ns which is far shorter than the life time, the Pockels' cell controlled by the Si OE switch works as if it is an analog switch for the optical signal. Otherwise a relation between the incident and the transmitted optical signals is nonlinear. In Fig. 9 (a) and (a)', the Si OE switch I turns on at a time when the majority of energy of $P_i(t)$ passes through the pulse shaper. Hence, it is difficult to see whether $P_i(t)$ is shaped or not. In Fig. 9 (b) and (b)', however, the incident optical pulse P_i (t) has enough power before and after the turn-on time of the Si OE switch I, or T: a performance of the optical pulse is clearly found. In Fig. 5, the response of the Si OE switch monitored with an storage oscilloscope (100 MHz bandwidth) is given. Since the rise-time of the trace is limited by the bandwidth of the oscilloscope, actual rise-time attained can not be known from Fig. 5, but is estimated from the last results. In Fig. 9 (a)' and (b)', the negative-slope portion with heavy solid line is determined by the turn-on speed of the Pockels' cell in the pulse shaper controlled by the Si OE switch I. Therefore, the rising-up speed of the Si OE switch I determines an inclination of the negative slope in Fig. 9 (b). The rise-time of the switch can be evaluated by this negative slope. In Fig. 9 (b), a fall-down time in the region with heavy solid line is found to be 330 ps which coincide with the time resolution of the monitor. Hence, the rise-time of the Si OE switch is estimated to be less than 330 ps at least.

4. Conclusion

The optical waveform synthesizer with utilizing both GaAs- and Si-optoelectronic switches has been described. The characteristic prospect of this device is a fast operation of subnanosecond time resolution. As preliminary experiment, optical-pulse shaping with Si OE switches was performed, and the rise-time of the Si OE switches was performed, and the rise-time of the Si OE switches was evaluated to be less than 330 ps from the results in the case of illumination of a laser pulse from the dye laser on the gap of the switches. It is expected that a use of narrow gap optoelectronic switches and low half-wave-voltage modulator enables us to demonstrate the optical-waveform synthesizer with the use of a cw laser.

An attempt to examine the whole function of the system proposed here is under preparation.

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