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Invited

Ultrafast Optoelectronic Devices

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One of the important problems in high speed optoelectronic devices is how to achieve simultaneously high-efficiecy and high operating speed which are usually alternative.

Here, we describe three kinds of ultrafast optoelectronic devices which suggest certain solutions of above problem; 1) OE or EO devices with optically long or resonant structure and electrically short structure, 2) EO devices with electrically narrowband but optically wideband, 3) optical switch using lifetime-free resonant excitation.

In addition, several practical examples of such devices are demonstrated.

1. Introduction.

There are various kinds of speed limiting factors in optoelectronic or electrooptic devices as shown in Table 1. It is seen from the table that the optical devices are superior in operating speed to the ordinary electric devices. Accordingly, it seems that the optical devices operate more speedily than the purely electronic devices at first sight. However, since the electrooptic(E-O) or opto-optic(O-O) interaction is relatively weak, the optical devices require relatively long interaction length. Consequently, the effective operating speed of the optical devices is not always faster than that of the electric devices which function for the case of the small ($\sim\mu$m) size.
(If we limit the function to high-speed signal transmission, an optical transmission line is much better than an electric one including even a high-Tc superconductive line.)

The short optical devices can not operate with high-efficiecy while the long electric devices can not operate at high speed. Then, how can I drive the optoelectronic device, which are partially optical and partially electrical, with high efficiency at high-speed?

Here, we propose a couple of methods to bring high-speed together with high-efficiency.

Table.1 Speed limiting Factors in OE devices.

1. signal propagation delay
   propagation delay of EM/light wave
   length of device/group velocity : ℓ/v_g
   where v_g=group velocity of EM or light
   $=(\partial k/\partial\omega)^{-1}$
   $k=\omega\sqrt{\varepsilon\mu}=n\omega/c$
   carrier transport delay : ℓ/v_d
   v_d:drift velocity of carrier$\sim 10^{-5\sim 6}c$

2. frequency bandwidth
   optical:transparent and linear-group-delay dispersion range
   electrical:low loss(related to skin depth) and dispersion-less range
   optical bandwidth >> electrical one
   even using high Tc super conductor
   RC time constant
   also related to E-bandwidth

3. time response of active interaction
   lifetime of upper level T_1 and
   relaxation time of polarization T_2
   response time of photoelectric and electrooptic effects

4. velocity mismatching
   between E and O signals

2. Practical examples of the optoelectronic (OE and EO) devices with high-speed and low driving power (high efficiency).

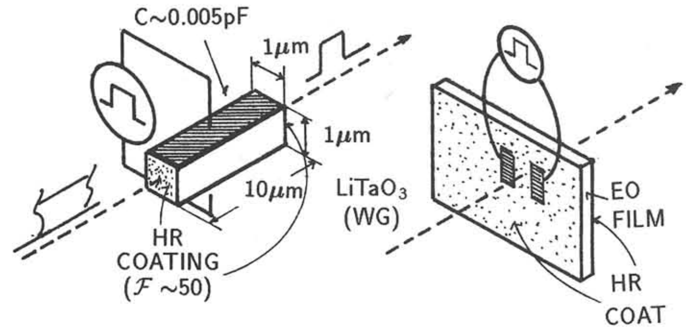
1) OE or EO devices with optically long or resonant structures and electrically short structures.

Considering RC time-constants and transmission loss of the electric signal in EO/OE devices, the length of the electrode must be shorter than 100μm in order to get picosecond response. This is, however, not enough length for optical signal to interact well with the electric signal through the electrooptic or the inverse electro-optic effect. On the other hand, the optical bandwidth is wide enough to treat picosecond pulse signals even in mm-cm devices. Therefore, to get picosecond time-response together with sufficient EO/OE-interaction length, the device having two kinds of lengths, namely, mm optical length and <100 μm electrical length is required. Such optoelectronic devices are materialized by employing optically multipath / multi-reflection structure for small size EO devices. Figure 1 shows a typical example of them. This is known as a Fabry-Perot electrooptic modulator[1-3]. Roughly speaking, the effective optical length of the device is longer than its geometrical (electrical) length by a factor of the finesse of a Fabry-Perot optical cavity. For the case of Fig.1(a), the switching time and the switching voltage is estimated to be 4ps(>>RC) and 3.4V at 600nm, respectively, although no experimental work has been done in such high speed range.

For the case of OE devices, since the optical power is enhanced in the optical resonator, nonlinear effect is also enhanced.

2) Electrooptic(E-O) devices with electrically narrowband but optically wideband.

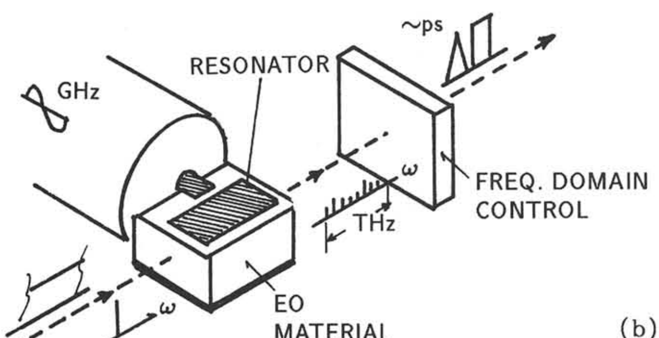
To generate ultrafast electric signals in the picosecond to femtosecond range is very difficult with the present technical



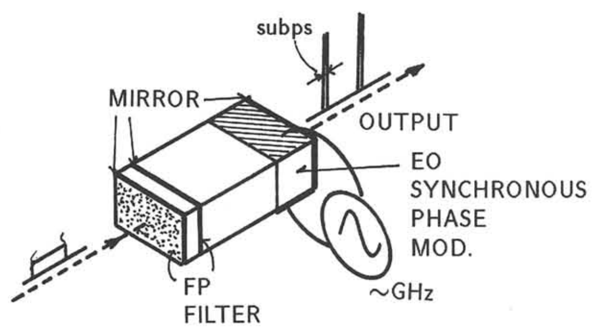
(a) Tiny FPM
(V_{on}~3.4V, τ~4ps)

(b) Film FPM

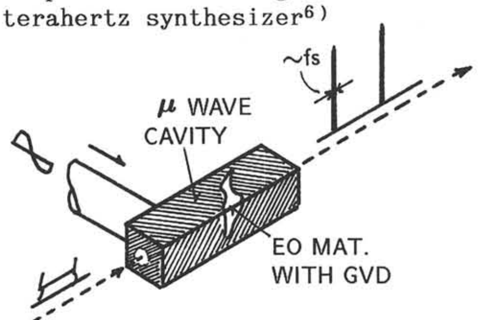
Fig.1 Fabry-Perot EO modulator



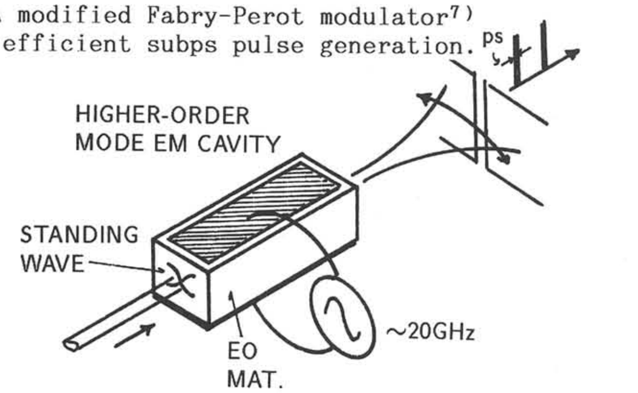
(a) Wide optical sideband generation and a terahertz synthesizer[6]



(b) A modified Fabry-Perot modulator[7] for efficient subps pulse generation.



(c) A dispersive EO modulator for femtosecond pulse generation[4]



(d) An EO deflector/lens[4,5]

Fig.2 Examples of electrooptic devices with optically wideband but electrically narrowband.

level. If we require only high-speed optical output but not electrical one as in the case of generation of periodical ultrafast optical pulse signals, an EO device with electrically narrowband but optically wideband is effective. Using the electrical resonator or waveguide structure for the case of electrically narrowband or single frequency, we can enhance the driving electric power and control the phase velocity of the electric signal. Then, we can increase the driving efficiency and stretch the interaction length by realization of velocity matching[4,5]. Consequently, deep optical modulation with very high modulation index can be achieved and extremely wide optical sidebands as wide as THz are produced. Controlling such wide optical sidebands, various types of ultrafast optical pulse signals including femtosecond optical pulses can be generated/ synthesized [7]. Several examples are shown in Fig.2.

3) Ultrafast optical switching using lifetime-free resonant excitation

In the optoelectronic(O-O, O-E) switches driven by optical gate pulses with nonlinear optical effects, the switching efficiency is incompatible with the switching speed. For example, the optical switch using resonant excitation operates with high efficiency (low switching power) but at slow switching speed due to the long lifetime of the excited state. On the other hand, the optical switch using off-resonant (virtual) excitation operates at high-speed but with low efficiency.

Here we propose new type of ultrafast optical switching compatible with low driving power utilizing 0-degree pulse excitation[8]. This kind of excitation is well known as coherent transient process without absorption [9], but never been used for the optical switching. Figure 3 shows the basic configuration of this kind of optical switch. The experimental work have not been done yet but it may be promising device with high speed and high efficiency. The 0-degree (0π pulse) pulse causes resonant transition efficiently but has no resonant frequency components and hence no absorption. The switching time is free from the relaxation times of the nonlinear material, namely, T_1 and T_2. In addition, the excitation power required for switching is very low as compared with 2π-pulse which is also resonant absorption-free excitation.

3. Discussions.

The ultrafast optoelectronic devices described here are useful in the picosecond to subpicosecond range. For the device to work at its own operating speed in such high-speed range, it is essential to shorten the electrical wires, if exist, which connect the device and a driving source or a load. Accordingly, integration of the total system including the optoelectronic devices should be required for the actual application.

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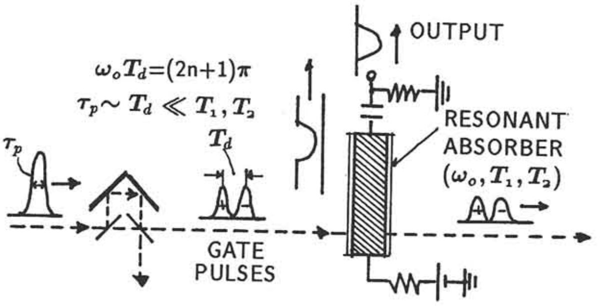
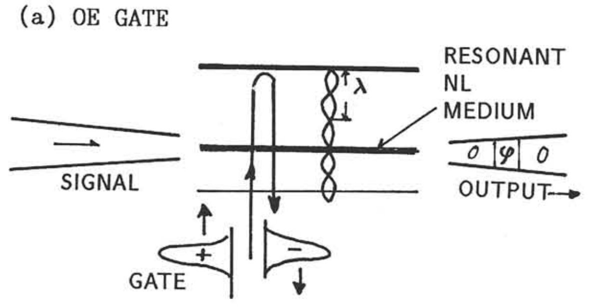
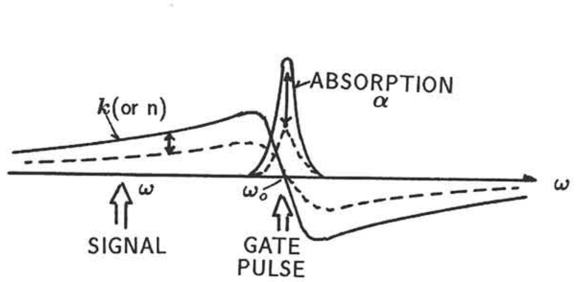


(a) OE GATE



(b) OO phase switching



(c) Principle of phase modulation

Fig.3 Ultrafast optical switching using 0-degree pulse excitation[8].