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Optical logic on a single etalon

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A simple technique for performing all-optical logic (NOR etc.) on a single etalon is described. Computer simulation and experiments with dye-filled and GaAs etalons verify its validity.

OPERATION

We report a technique for operating a single nonlinear Fabry–Perot etalon that yields the decisions NOR, NAND, XOR, OR and AND, simultaneously if desired, and with minimum time and energy per cycle. The transmission–time characteristics obtained from experiments with dye-filled (Jewell *et al.* 1984) and GaAs etalons qualitatively verify a computer simulation.

Consider two inputs and a probe to be pulses of short duration in comparison to the medium relaxation time τ_R. The nonlinear medium must be such that absorption of one input pulse changes the refractive index enough to shift the Fabry–Perot transmission peak by about one f.w.h.m. To obtain all possible gates, two inputs should produce about twice the phase shift for one input. The peak will, of course, return to its original wavelength in a few τ_R, but if the probe pulse is incident much less than τ_R after the input(s) only this instantaneous transmission determines the output. With appropriate initial detunings of the probe, the various gates are obtained. This is shown graphically in figure 1, from which the approximate transmissions are found for five 'standard' probe detunings with 0, 1, or 2 inputs. Fine adjustment of the detuning and input strength can improve contrast, reliability, etc.

The pulsed operation minimizes both the time and energy per cycle because it *does not require the medium to be kept excited*. So, no extra energy is spent holding the device on and it *relaxes in the dark*, resulting in minimum relaxation time. The logical decision can be made in less than a picosecond for some materials (for example GaAs) (Shank *et al.* 1982; Shank *et al.* 1979), and the gate *self-resets* in a few τ_R.

The transmission against time was calculated and plotted (figure 2) by using the standard Fabry–Perot formula and a refractive index that suddenly changes (as from an imput pulse), then exponentially relaxes to its original value. Two inputs produce twice the phase shift as one in this simulation.

LOGIC GATES

In the dye-etalon experiment two inputs were formed by splitting a continuous wave (c.w.) argon laser beam, passing them through a mechanical chopper and focusing onto the etalon (figure 3). A c.w. probe from a dye laser at lower intensity was focused onto the same spot

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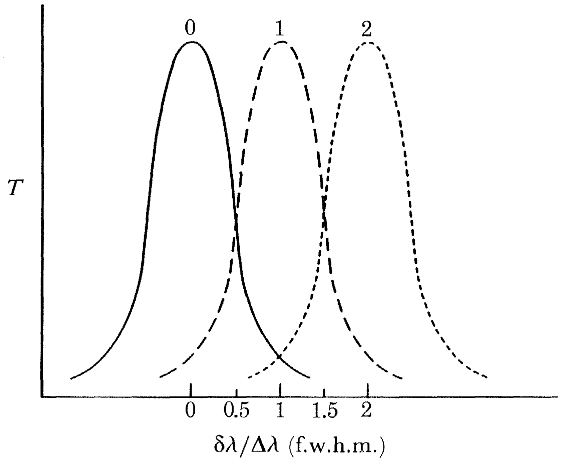

FIGURE 1. Position of the transmission peak with 0, 1, or 2 inputs. With the probe wavelength at one of the five labelled values (expressed by the initial detuning in f.w.h.m.s of the transmission peak) the gates in the table are obtained. The fractional values in the columns below 0, 1, and 2 (number of inputs) are the approximate transmissions when each input shifts the peak by one f.w.h.m. In reflection AND and NOR have poor contrast.

initial detuning	0	1	2	T	R
0	1	0.2	0	NOR	OR
0.5	0.5	0.5	0	NAND	(AND)
1	0.2	1	0.2	XOR	$\overline{\text{XOR}}$
1.5	0.1	0.5	0.5	OR	(NOR)
2	0	0.2	1	AND	NAND

and transmission against time was recorded. The dye in the etalon absorbed much more strongly at the input than the probe wavelength. Waveforms resembling those in figure 2 were easily obtained (figure 4) for all but the OR gate. An OR waveform was achieved that did not resemble the simulation. Although the relaxation time was milliseconds this technique is applicable for any dispersive nonlinearity. Recently we have observed NOR and OR gating in a GaAs etalon at room temperature (figures 5 and 6) by using mode-locked argon laser pulses as inputs. The 2.05 μm bulk GaAs layer clad by *ca.* 0.6 μm thick AlGaAs windows was sandwiched between *ca.* 90% reflecting mirrors. This construction is far from optimized. The phase shift was not linear with respect to input energy, so this other gates were not observed. Most of the energy in the *ca.* 1 nJ mode-locked argon laser pulses was absorbed by the AlGaAs window, thus increasing the energy requirements as well as accumulative heating. The high optical density of GaAs (and AlGaAs) at 514 nm prevented the input pulses from penetrating very far into any of our 3–5 μm thick samples. We believe the reason our bulk GaAs sample showed superior performance over our multiple quantum well structure (m.q.w.s.) devices is that carrier diffusion spreads the index change across the entire GaAs layer in the former, whereas in the latter, the AlGaAs barriers prevent diffusion between the GaAs layers. Despite its inefficiency, the device operated at 82 MHz with 5–10 ns recovery times. The *ca.* 150 mW probe beam (detuned sufficiently far from the band edge to have low absorption, but close enough to see a change in refractive index from the argon pulses) was c.w. to show the relaxation characteristics. Simple theoretical calculations indicate that an optimized GaAs gate may be able to work with input energies below picojoule levels. Previous work (Gibbs *et al.* 1979) with bulk GaAs at 80 K showed saturation energy densities of 10 μJ cm^{-2} (0.1 pJ $\mu\mathrm{m}^{-2}$).

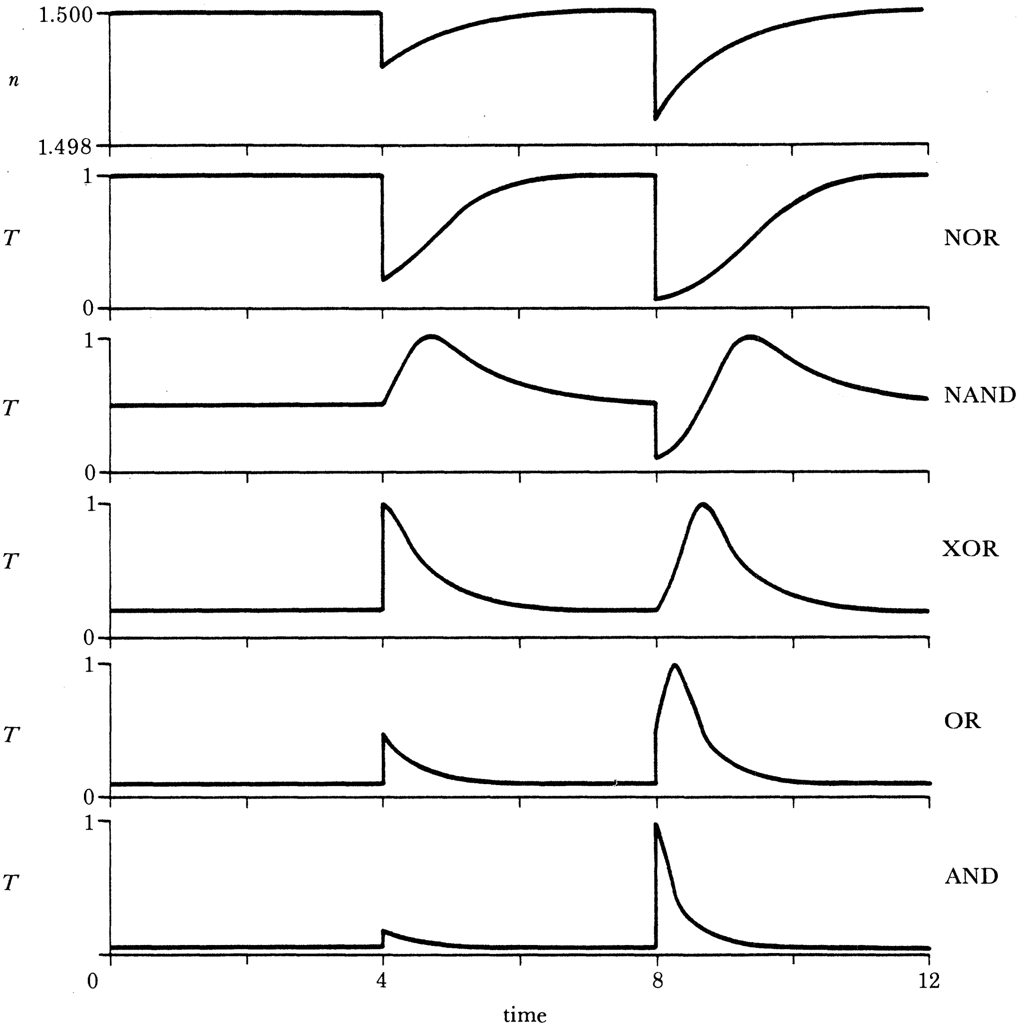

FIGURE 2. Computer-calculated transmission against time for five initial detunings with 0, 1, and 2 input pulses incident at times 0, 4, and 8. Time units are $(1/e)$ recovery times for the refractive index. The top trace is refractive index against time. Mirror reflectivities are 90 % with 10 μm spacing, wavelength 500 nm, and losses are zero.

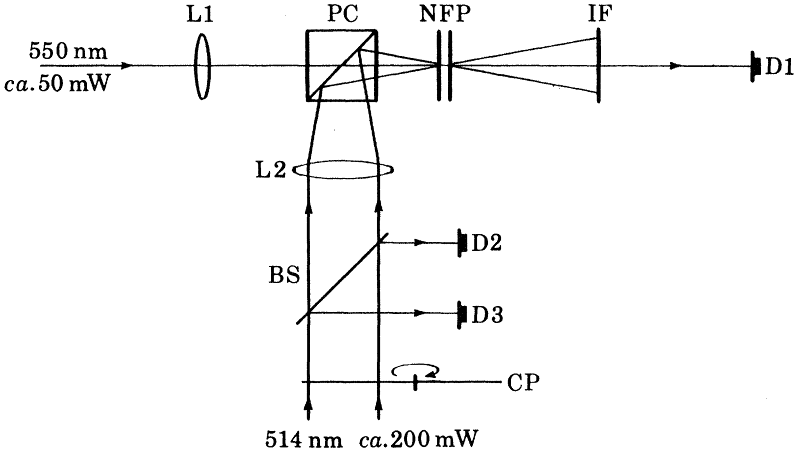

FIGURE 3. Experimental layout for monitoring dye-etalon gate transmission. Components: L1, L2, lenses; D1, D2, D3, detectors; PC, polarizing cube; NFP, nonlinear Fabry–Perot; IF, interference filter; CP, chopper; BS, beamsplitter.

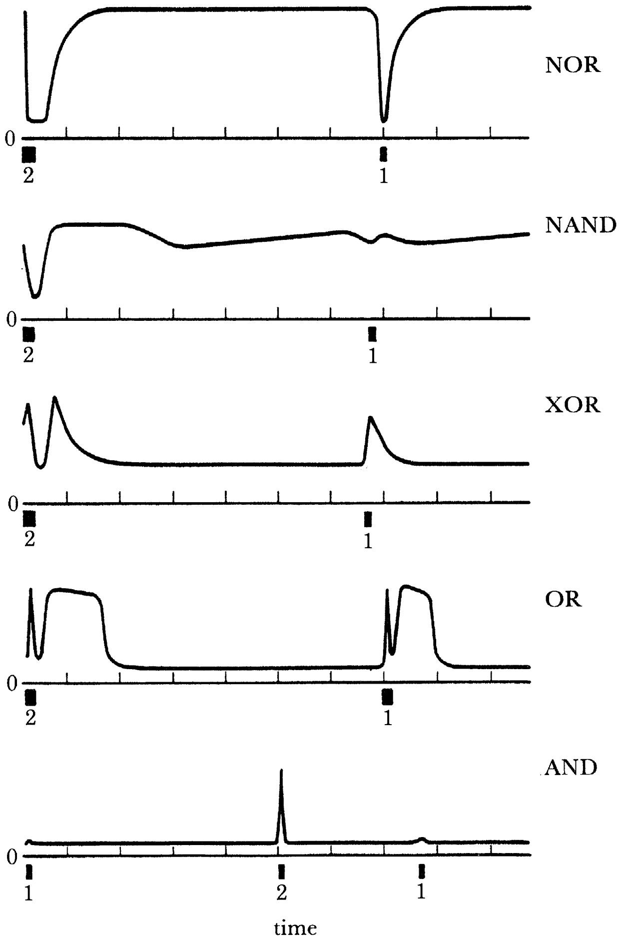

Figure 4. Transmission against time for the dye-filled etalon. The marks below the time axis indicate the time and duration of the input(s) with the number directly below indicating how many inputs are present. Time per division: NOR, NAND, XOR, 2 ms; OR, AND, 5 ms. OR does not agree with predictions.

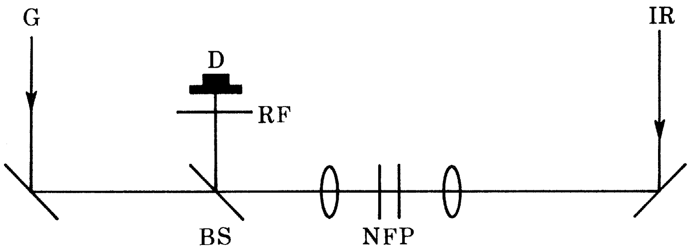

Figure 5. Layout for GaAs gatings: G, mode-locked Ar pulses, 514 nm; IR, c.w. infrared dye-laser beam; NFP, GaAs nonlinear Fabry–Perot; BS, beamsplitter; RF, deep-red filter blocks for any Ar light; D, photodiode.

Flip-flop

These gates can also work in a c.w. or mixed mode (c.w. inputs, pulse train probe), although accumulative heating would increase. The etalon could then be considered to be a kind of flip-flop. Another flip-flop that was conceived and tested at Arizona (Jewell *et al.* 1983; Rushford *et al.* 1983) employs two etalons in series in a c.w. beam (figure 7*a*). The first etalon

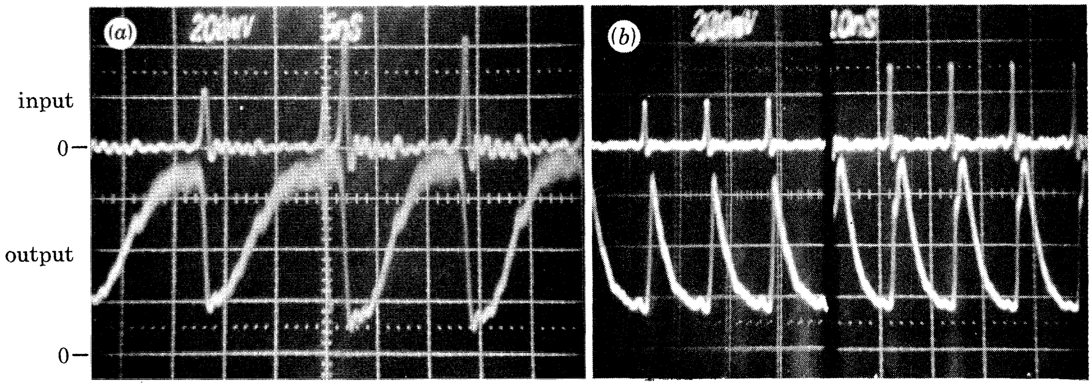

Figure 6. Split oscilloscope traces with one input on the left side and two inputs on the right show (*a*) NOR, and (*b*) OR capability. Top traces are the inputs; bottom traces are etalon transmissions.

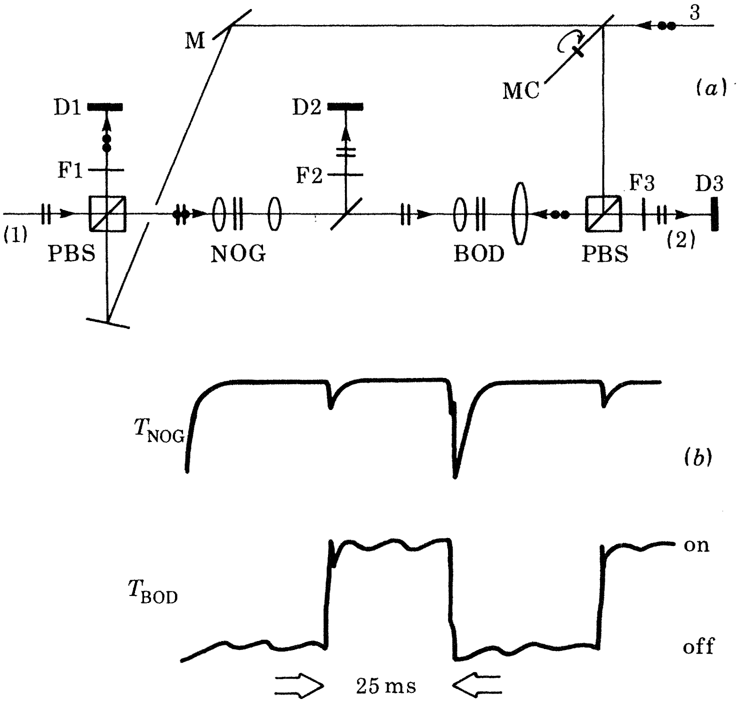

Figure 7. (*a*) Optical flip-flop. (1) Continuous-wave dye-laser bias beam (*ca.* 550 nm). (2) Transmission of bias beam through bistable optical device (BOD) switched on or off by 514 nm control beam directed by rotating mirror–chopper MC. D1 uses 'off' pulses to trigger the oscilloscope; D2 monitors negative optical gate (NOG) transmissions; D3 shows total flip-flop output. Filters F1, F2, F3 pass the appropriate wavelengths. Beams are combined by polarization beamsplitters (PBS). (*b*) Response of optical flip-flop; top trace from D2, bottom trace from D3. Large (negative) pulse switches the BOD off; the small pulse is a timing reference from mirror–chopper transmission and BOD transmission affecting the NOG. Bottom trace is on–off intensity monitored by D3. The on–off intensity ratio is *ca.* 10. The ripple is due to room lights.

is tuned for maximum transmission and the second uses the throughput to operate as a bistable optical device (Gibbs *et al.* 1980; Miller 1982) in the usual sense. The second etalon alone can be switched on by an optical pulse (Tarng *et al.* 1982), but switch-off requires a second nonlinearity of a drop in the incident intensity. The first etalon accomplishes such a drop if it is hit by a switch-off pulse that detunes its transmission peak away from the incident wavelength. This process is identical to that of the NOR gate except that there is only one input pulse and the probe is c.w. This flip-flop was tested with dye-filled etalons yielding light-by-light control (figure 7*b*). An optical memory or pulse–c.w. conversion are two possible applications for the flip-flop. Another application is to generate short rectangular-shaped optical pulses of precisely controllable length. Since switching on and off are both accomplished by *excitation* of the nonlinear media, the rise and fall times can be extremely short. The relative time separation between the 'on' and 'off' pulses gives the length of the transmitted pulse.

A technique for making logic operations on a single etalon has been presented. Some other optical logic gates have been proposed (Fork 1982) or tested (Seaton *et al.* 1983; Collins *et al.* 1980; Soffer *et al.* 1980), but those presented here are simple, use the high-speed capability of optics with low power requirements, and represent a new mode of operation for existing devices.

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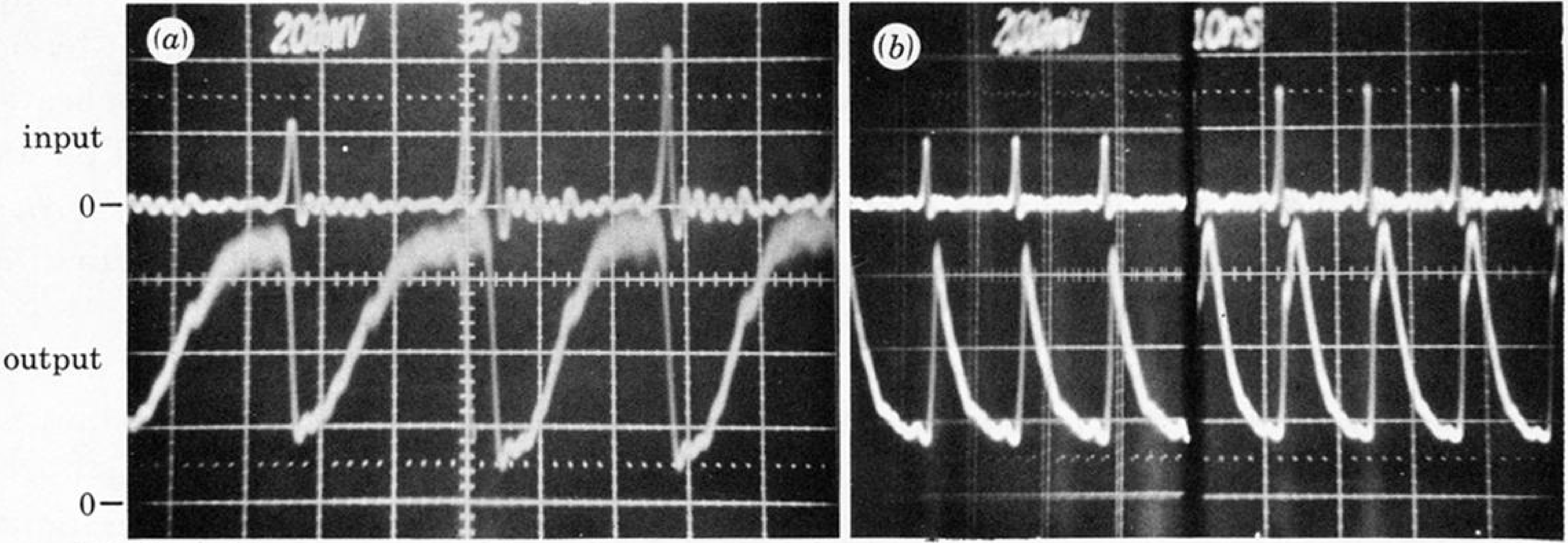
Note added in proof (1 *August* 1984). Very recently we have observed, in a m.q.w.s. device, all five gates of figure 2 with only 8 pJ per input pulse (0.1 pJ μm^{-2}) incident on the device producing 6:1 contrast in the NOR gate. This low energy was made possible by a high-finesse etalon whose mirrors were designed to transmit at the input wavelength.



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