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Parallel operation and crosstalk measurements in GaAs étalon optical logic devices

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We report the first parallel operation of GaAs optical logic elements and bistable devices. Arrays up to 2×4 in size were operated using a picosecond pump and probe technique, while in the bistable mode we achieved uniform response in two spots. Crosstalk due to carrier diffusion became noticeable at separations of typically $\sim$20–30 μm in the bistable devices. Pulsed operation at 82 MHz allowed separations down to $\sim 10\,\mu$m limited only by diffraction. Efficient heat sinking in the pulsed array resulted in negligible heating even when continually operated for many minutes. All experiments were performed at room temperature.

Nonlinear Fabry–Perot étalons using semiconductors to provide the optical nonlinearity are promising devices for performing logic operations in massively parallel architectures at rates extending into the GHz range.[1–5] Crosstalk due to diffraction and/or carrier diffusion will severely limit the packing density of such devices unless steps are taken in the fabrication (e.g., etching of pixel arrays[6]) to reduce it. Experimental results showing parallel operation in the most promising devices, however, have lagged far behind the theory and speculation. Crosstalk between pixels on (thermally driven) dye-filled étalons optical bistable devices (OBD's) was observed[7] and found to agree reasonably with theory.[8] Similar observations in ZnS and ZnSe interference filters yielded switching by crosstalk for distances $\leqslant 20\,\mu$m with 7.7-μm-diam spots.[9] Parallel operation of OBD's in other thermally driven ZnSe interference filters[10] and in InSb étalons[11] has been accomplished, but without any published account of crosstalk effects.

We report the first parallel operation of optical logic devices in GaAs. Two OBD's using $\sim 1\,\mu$s triangular-wave inputs[12] and arrays (up to 2×4) of optical logic étalons (OLE's) using picosecond pump and probe pulses[13] are described. In two-spot experiments crosstalk became noticeable at interpixel separations of about 30 and 10 μm, respectively. The difference is mainly due to the lack of any significant carrier diffusion during the $\sim$30 ps time of the OLE operation.

The construction of the OBD étalons was similar to that previously described.[14] The nonlinear material was 2.05 μm of bulk GaAs clad on each side by 6450 and 3500 Å $Al_{0.3}Ga_{0.7}As$ and having a 2000-Å $Al_{0.48}Ga_{0.52}As$ stop layer. This sample was sandwiched between $\sim$94% reflectivity dielectric coatings deposited on microscope coverslips. Lack of flatness limited operation to two spots aligned parallel to a transmission fringe.

The OLE multiple quantum well (MQW) device had 63 periods of 76-Å wells with 81-Å $Al_{0.37}Ga_{0.63}As$ barriers and was clad by 1047- and 1570-Å $Al_{0.37}Ga_{0.63}As$ layers. The mirror coatings were ten-layer interference filters having four-waves-thick spacers and transmitted 825 nm wavelength. The peak reflectivity was only $\sim$85%; thus finesse was quite limited and about 60 pJ input pulse energy was required to produce 5:1 contrast (compared to 3 pJ in a high finesse device[4]). The mirror substrates were sapphire disks 0.5 in. diameter × 0.08 in. thick (about 1 wave flat) and yielded nearly uniform response over $\sim 100\,\mu$m regions.

The OBD experimental setup used an argon-pumped LDS 821 dye laser. The beam was split, then recombined with polarizing beamsplitters (Fig. 1). This allowed continuous displacement of the two beams, and the orthogonal polarizations allowed us to split them again after the étalon and monitor the two outputs separately on a single detector. Equal input intensities were verified using a power meter with either beam blocked. The OLE experiment required two dye lasers mode locked in synchronism with each other. For this we used a single mode-locked 82 MHz Nd:YAG oscillator and two frequency doublers (Fig. 2). The second harmonic from the first ($\sim$10% efficient) doubler pumped the input dye laser while the leftover fundamental was fed into the second doubler. This doubler's output then pumped the probe laser. Input and probe wavelengths were about 825 and 875 nm, respectively. Uniform multiple spots were easily and efficiently obtained by inserting appropriately oriented Wollaston prisms in the combined beams. A single detector monitored the average performance and a CCD camera verified spot uniformity. Although the use of Wollaston

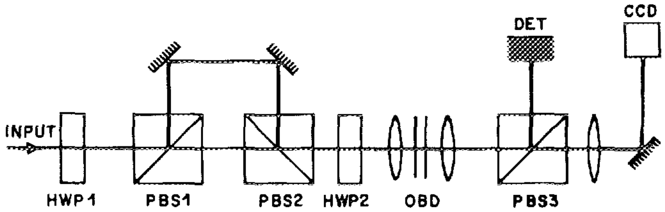

FIG. 1. Layout for two-spot optical bistability. HWP—halfwave plate; PBS—polarizing cube; DET—detector. CCD—camera. Displacement of the split-off beam was accomplished by tilting PBS2. Rotating HWP2 determined which beam reached the detector.

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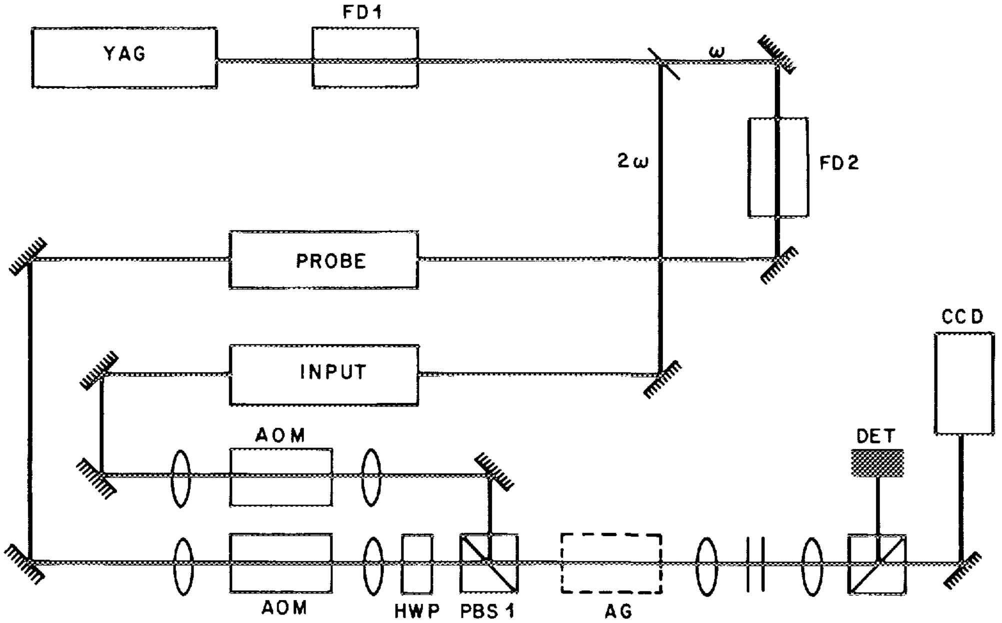

FIG. 2. Pump and probe OLE layout. FD—frequency doubler; AOM—acousto-optic modulator, AG—Wollaston prism array generator.

prisms is extremely convenient for generating small arrays, their expense would make them impractical for very large (e.g., 1000×1000) arrays. Such arrays should probably be generated by lenslet arrays[15] or by holographic techniques.

Figure 3 shows nearly identical responses of the bulk GaAs OBD's with 23 mW peak power at 884 nm incident on each ~6-μm-diam spot. Of chief interest are the switch-on intensities I_{on}. When a sufficient number of carriers generated by one spot diffuse into the other's illuminated region a decrease in its I_{on} is evident. In Fig. 4 we plot the average I_{on} of the two spots against their separation. For each data point here we verified that each spot had the same I_{on} as the other when only one beam was present. Crosstalk was evident out to ~30 μm when one beam switched on significantly before the other. This situation more closely resembles the condition of having one spot "on" and the other "off" with a bias beam present. The range of carrier diffusion apparent here is consistent with measurements by Olsson *et al.*[16]

A doubly exposed photograph of the TV monitor from the CCD camera shows a 2×2 array of NOR gates (Fig. 5). The four spots, fairly dim with the input beam present, became much brighter with the input blocked. The actual contrast measured on the oscilloscope was 5:1 and the spacing was ~16 μm. A 2×4 array was operated with similar performance; however, the illumination by the probe beam was slightly nonuniform. All spots did show similar changes in apparent brightness when the input was changed. Since both pump and probe beams were pulses on the order of 10 ps long and about 12 ns (approximately the carrier lifetime) elapsed between operations, diffusion did not play an important role. Two-spot crosstalk was most conveniently measured by us-

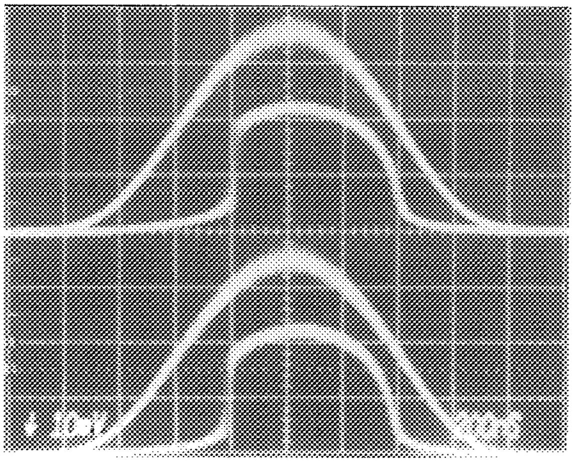

FIG. 3. Time traces for two OBD's separated by ~28 μm. Upper: "straight-through" beam; lower: "split-off" beam. The triangularly shaped traces are the input signals while the (renormalized) output traces showing switching in the "on" and "off" directions are displayed within the input traces. Switch-on intensity is ~19 mW for each beam.

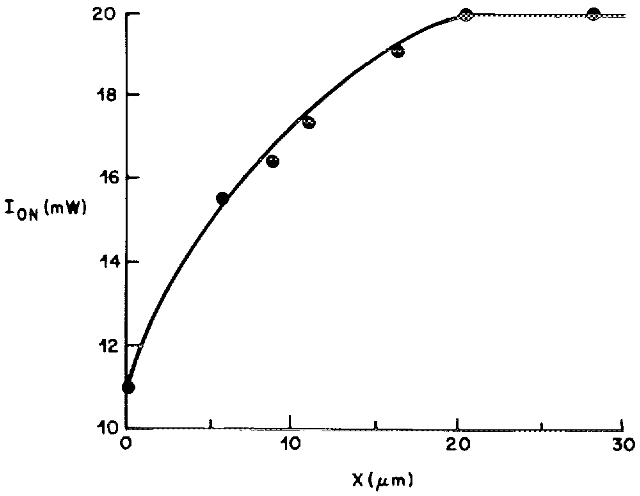

FIG. 4. I_{on} vs the separation X of two bistable spots. The infinite separation limit is reached at $X \approx 20\,\mu$m. For total overlap, I_{on} is 11 mW, reasonably close to the expected 10 mW.

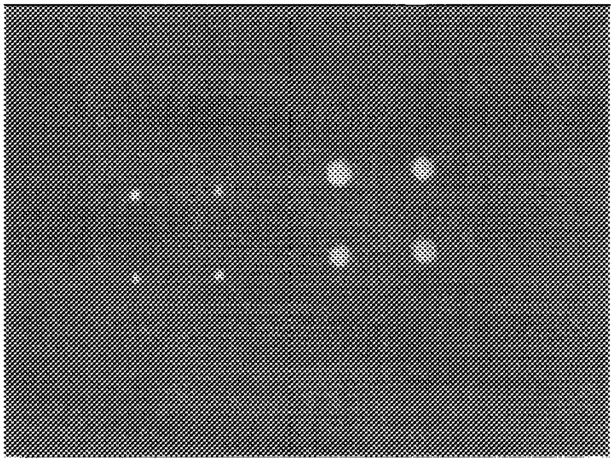

FIG. 5. 2×2 NOR gate array (double exposure). Left (darker): with input; right (brighter): no input. Contrast observed on the oscilloscope was 5:1; spot separation ~ 16 μm.

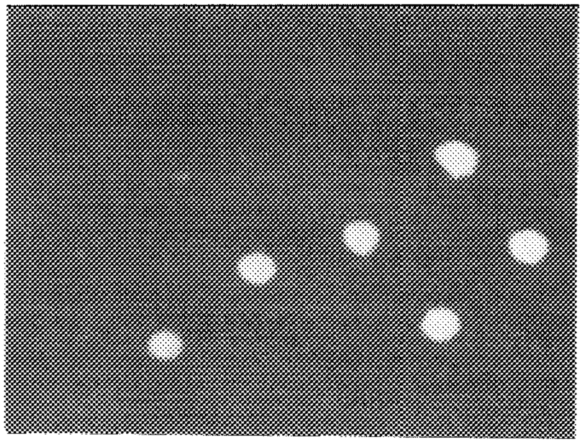

FIG. 6. Double exposure of 2×2 NOR array with input incident on only two spots (left) and with input blocked (right).

ing single pump and probe beams and measuring the distance (typically about 10 μm) at which the pump just barely affected the probe (when 5:1 contrast resulted from direct overlap). Figure 6 shows another 2×2 array of NOR gates with the input illuminating only two spots. The nonroundness of some of the spot images results from the birefringent sapphire substrates. Two-spot "crosstalk" measurements were also carried out with very similar results on ètalons with glass substrates and even on "windowless" bulk GaAs ètalons (which showed 150 ps recovery time due to surface recombination of the carriers[13]). Thus, we believe that neither the birefringent substrates nor carrier diffusion (during the 12 ns between operations) played any important roles in our results.

A final interesting feature of these NOR gate arrays is that when all spots were continually illuminated by both pump and probe beams for times ranging from 1 μs to many minutes, there was no noticeable change in the probe transmission. Thus, any temperature rise due to absorption was so small that the ètalon transmission peak shifted only a very small fraction of its width. This thermal stability undoubtedly resulted from efficient heat sinking provided by having optically contacted one or both sides of the sample to the mirrors. It is distinguished from a previously reported thermally stable NOR gate[4] in which it was necessary to increase the probe wavelength with increasing duty cycle to accommodate the rising temperature.

These first successful operations in room-temperature bulk GaAs and GaAs-AlGaAs MQW ètalons of as many as eight optical logic devices in parallel demonstrate the ease and straightforwardness of such operation. The use of inexpensive nonflat substrates and the poor performance of the dielectric coatings leave room for much improvement. The two-spot crosstalk measurements give approximate minimum pixel separations (in the absence of any crosstalk inhibiting techniques) for arrays. Obviously, the minimum separations would be somewhat larger for arrays since the effects will occur from several sides instead of only one. Hopefully in the future, pixels will be defined (e.g., by etching[6]), thus virtually eliminating both diffusive and diffractive crosstalk and allowing much closer pixel spacing and lower power operation. Finally, we have demonstrated that optical contacting of GaAs-AlGa-As material to mirrors can produce efficient heat sinking and thus thermal stability at 82-MHz operation frequency.

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