Applied research using two-dimensional control of the optical phase is making rapid advances in areas such as optical communications, optical measurement and optical computing that rely on optical information processing. This kind of research involves optical phase control on the Fourier plane and compensation of the phase distortion that accompanies optical information transmission. The PAL-SLM was developed for this optical research work as a two-dimensional phase modulator for control solely of the optical phase.

PAL-SLM

Parallel Aligned Nematic Liquid Crystal Spatial Light Modulator

Two-dimensional phase modulator for control exclusively of the optical phase

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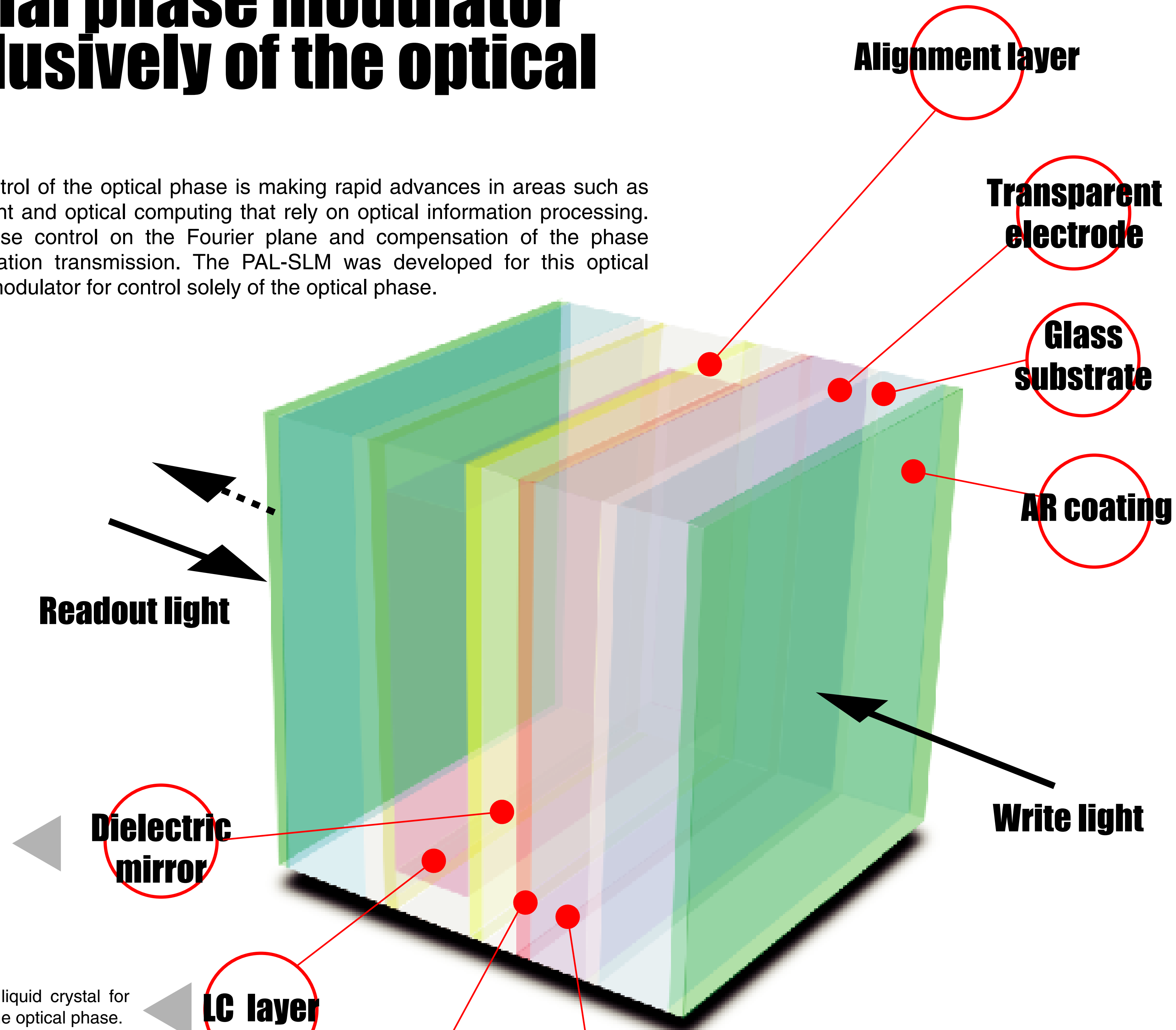
Structure

The PAL-SLM has a sandwich structure in which amorphous silicon (α-Si:H), a dielectric mirror, and liquid crystal are enclosed by two glass substrates with transparent electrodes.
A write light is irradiated on the amorphous silicon side, and a readout light is irradiated on the liquid crystal side. The impedance of the amorphous silicon layer becomes extremely high when in a state with no write light. When a write light is applied, the impedance of the amorphous silicon lowers and the voltage applied across the liquid crystal rises according to the intensity of the write light so that the readout light is modulated by movement of the liquid crystal molecules.

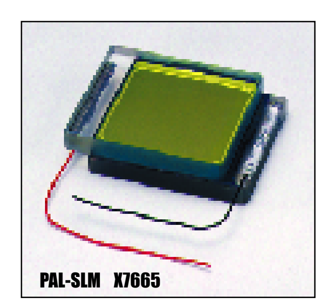


Reflects the readout light with high efficiency using a high reflectivity multi-layer mirror.

Employs a parallel-aligned nematic liquid crystal for high-efficiency modulation solely of the optical phase.

Light-blocking layer is added for high-intensity light readout.

An amorphous silicon (α-Si-H) layer with high sensitivity and uniform distribution is formed.



Features

■Uses parallel-aligned nematic liquid crystal delivering ideal phase modulation

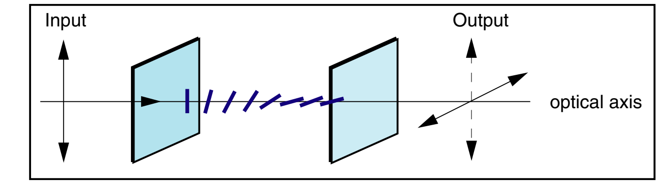


Figure 1: a) Twisted nematic

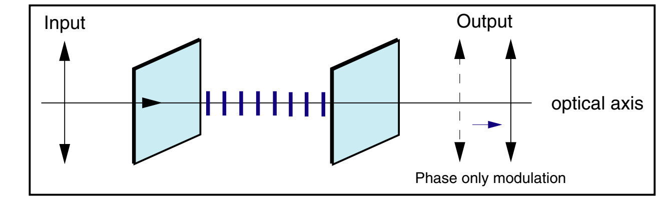


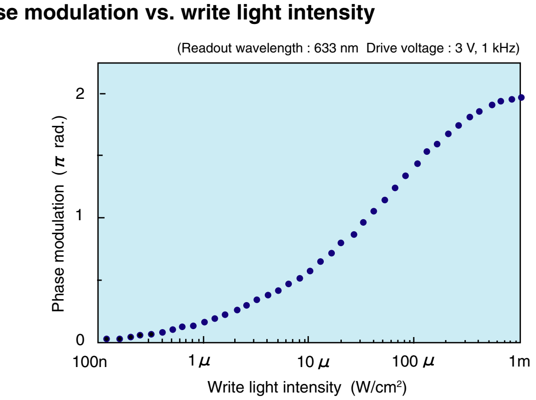
Figure 1: b) Parallel aligned nematic (PAL-SLM)

In liquid crystal devices such as used in projectors, the liquid crystal molecules are usually arranged as shown in Figure 1 a) in a twisted array from the front to the rear of the liquid crystal layer. This device varies the polarization plane of the light by applying a voltage to effectively function as a light intensity modulator. This device can of course also modulate the phase of the light but this causes unwanted rotation of the plane of polarization. This leads to a drop in phase modulation efficiency. In the PAL-SLM device, however, the liquid crystal molecules are aligned in parallel and not in a twisted state as shown in Fig. 1 b). Applying a voltage to this device causes the liquid crystal molecules to align horizontally along the optical axis, inducing a phase change on the light which has polarized along the molecular axis. On the other hand, the light which polarized in a direction perpendicular to the molecule axis is in principle, totally unaffected by the applied voltage.

■A phase shift of 2 π radians or more can be obtained

Figure 2 shows phase modulation characteristics when the readout light is polarized parallel to the liquid crystal molecules. A phase shift of 2 π radians or more can be obtained. However, no phase change occurs when the readout light is polarized in a direction perpendicular to the liquid crystal molecules.

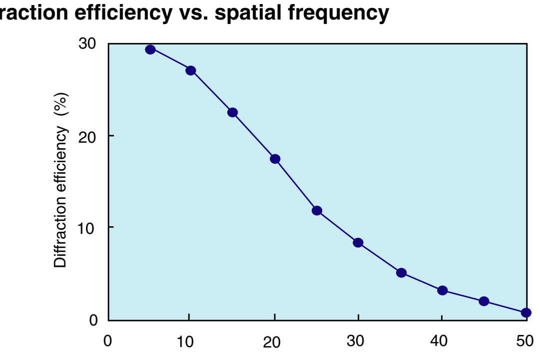
Figure 2: Phase modulation vs. write light intensity



■Diffraction efficiency higher than 30 %

Figure 3 shows the diffraction efficiency (defined as I1/I0) for 1st order diffraction light readout when changing the spatial frequency of write interference fringes, which is a sinusoidal wave grating image, into the PAL-SLM. Here, I1 is the 1st order diffraction light intensity and I0 is the readout light intensity when no interference fringes are written.
These results show the PAL-SLM delivers a diffraction efficiency of 30 %, which closely approaches the theoretical maximum value of 33.9 %.
The maximum spatial resolution reades approximately 50 Lp/mm.

Figure 3: Diffraction efficiency vs. spatial frequency



PPM

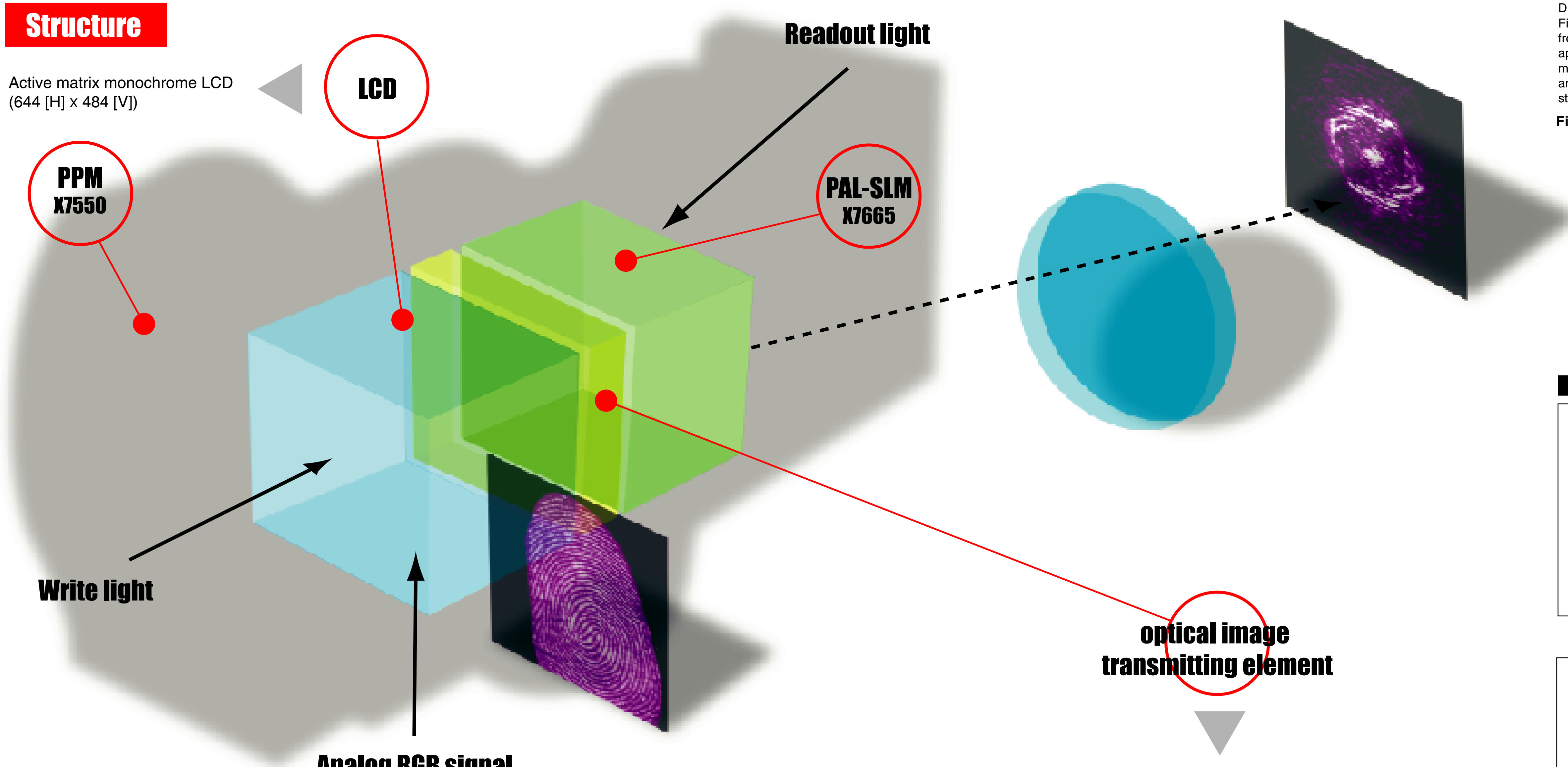
Programmable Phase Modulator

Easy computer control

The PPM is an electrically-addressable phase/intensity spatial light modulator capable of handling VGA signal inputs. The PPM consists of an X7665 series PAL-SLM and an electrically addressable liquid crystal display (LCD) which are coupled together by a optical image transmitting element.
Conventional LCD devices of electrical signal input type have problems with low aperture ratio and adverse effects from surplus diffraction light coused by the pixel structure of the LCD. The PPM, in contrast, has an optimized coupling optics design and a non-pixel structure of the PAL-SLM that does not transfer the pixel structure of the LCD into the PAL-SLM. This all comes together in a compact PPM ideal for optical information processing utilizing diffraction phenomenon such as spatial Fourier transforms.

Structure

Active matrix monochrome LCD (644 [H] x 484 [V])



The PPM, in contrast, has an optimized coupling optics and a non-pixel structure of the PAL-SLM that does not transfer the pixel structure of the LCD into the PAL-SLM.

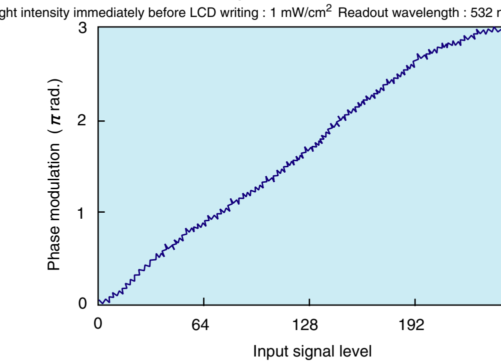
Features

Delivers linear input/output characteristics

The PAL-SLM has nonlinear input/output characteristics as shown in Figure 2 (horizontal axis: logarithmic scale). However, linear input/output characteristics have been needed to achieve multiple phase levels easily. In the PPM X7550, a linear output is achieved by compensating and adjusting the transmission light intensity on the LCD input device to match the PAL-SLM input/output characteristics as shown in Figure 4 (horizontal axis: signal level input to LCD, vertical axis: phase modulation level obtained).

Figure 4: Phase modulation vs. input signal level

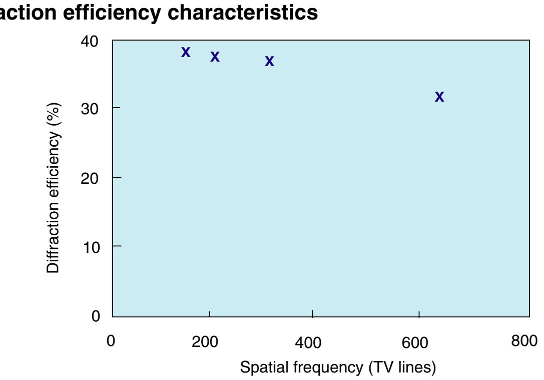
(Light intensity immediately before LCD writing : 1 mW/cm^2 Readout wavelength : 532 nm)



A 30 % of diffraction efficiency at maximum spatial frequency of 640 TV lines

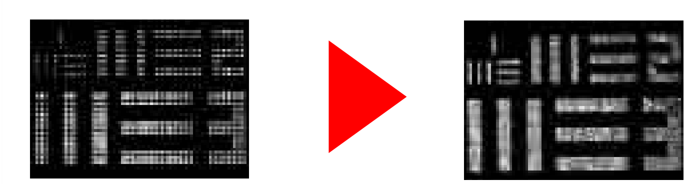
Diffraction characteristics for the PPM X7550 measured in phase modulation mode are shown below. Figure 5 shows the 1st order diffraction efficiency during π radian phase modulation for the spatial frequency of an input square wave grating image displayed on the LCD. A diffraction efficiency closely approaching the ideal theoretical value of 40.5 % was obtained. Some cross-talk occurred in the maximum spatial frequency (640 TV lines, approx. 12 Lp/mm) due to the coupling lens characteristics and the OTF characteristics of the SLM. However, a high diffraction efficiency greater than 30 % was still obtained.

Figure 5: Diffraction efficiency characteristics



Non-pixel structure

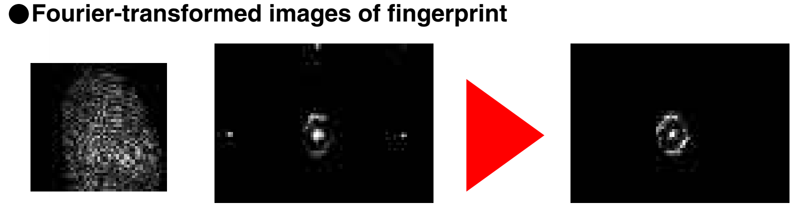
●LCD output vs. PPM output



▲ LCD output

▲ PPM output (π modulation)
Pixel structure is fading away.

●Fourier-transformed images of fingerprint



▲ Fingerprint input image

▲ Fourier-transformed image of LCD output

▲ Fourier transform image of PPM output
No unwanted diffraction light appears.

APPlication Example

Laser Applications
Laser Machining / Laser Printing / Laser Chemistry / Laser Nuclear Fusion

■ Optical temporal waveform shaping

In short pulsed light with a pulse width of about 10 femtoseconds (10^{-15} seconds), the spectrum distribution spreads out into a white colored light. By performing phase modulation on each spectrum, an output waveform with a double pulse can be formed versus an input waveform with the single waveform, as shown in Figure 6. Forming waveforms in this way allows for instance cutting a molecular chain in a short time with a double pulse that would otherwise be impossible to cut with a single pulse.

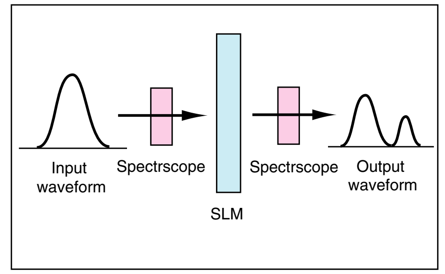


Figure 6: Waveform shaping

■ Optical spatial waveform shaping

The variable hologram written on the PAL-SLM forms the beam in the shape needed. Unlike beam shapes that form notched patterns in the optical path, all of the light can be used effectively thanks to a variable hologram written on the PAL-SLM by a phase pattern.

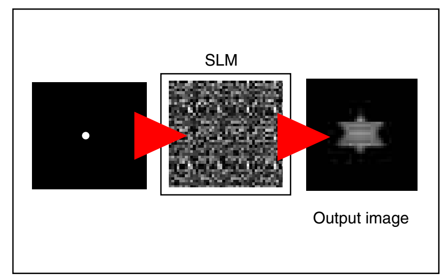


Figure 7: Waveform shaping

■ Wavefront compensation

In applications utilizing the energy from focusing laser beams with high efficiency such as in laser machining or laser nuclear fusion, and also in measurements made through a medium such as the atmosphere that acts to disturb the phase, it is necessary to perform wave shaping according to the particular application by compensating for the disturbed wavefront. The example in Figure 8 shows wavefront compensation to align the phase of the input light having phase disturbances and achieve a smooth, flat wave shape. This allows focusing the laser beam on one point with high efficiency so that a large amount of energy can be obtained.

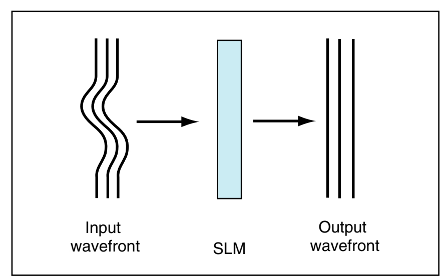


Figure 8: Wavefront compensation

Computing and Optical Measurement

■ Optical interconnections

Figure 9 is the concept view of optical interconnections utilizing light diffraction phenomenon while writing a variable hologram on the SLM. By changing a hologram written onto a PAL-SLM, focusing lines can be freely controlled by light. PAL-SLM performs 2-dimensional phase-only modulation so that connections utilizing light diffraction phenomenon in this way allow making interconnections that utilize the light with extremely high efficiency.

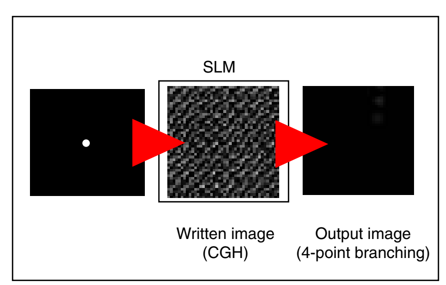


Figure 9: Concept view of optical interconnection

Factory Automation and Security
Machine Vision / Fefect Inspection

■ Optical analog processing (optical correlator)

This is one type of optical computer for processing vast amounts of information similar to image information by parallel processing of spatial Fourier transforms and holography. This device holds great potential as a tool for making practical optical computers a reality.
Both Fourier transforms and holography utilize the phenomenon of light diffraction, so using a device with a high diffraction efficiency such as the PAL-SLM will prove vital in building up an efficient system.

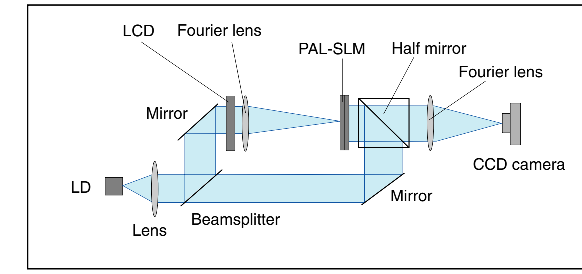


Figure 10: Analog optical computer structure

■ Image recognition and retrieval
(Fingerprint, Face and Medical Image, etc.)

Figure 11 shows a fingerprint recognition device using an optical correlator. As shown in the figure, a code number is entered in and the fingerprint pattern (reference image) of the person registered beforehand in the memory is called up. The actual fingerprint to be matched with the reference image in the memory is captured by a CCD camera by way of a fiber optic plate (FOP). This pattern (fingerprint to be checked) and the reference pattern (from the memory) are sent simultaneously to an LCD in the optical analog computer described earlier. The sample fingerprint image, Fourier-transformed image and correlated output image are shown in Figure 11.

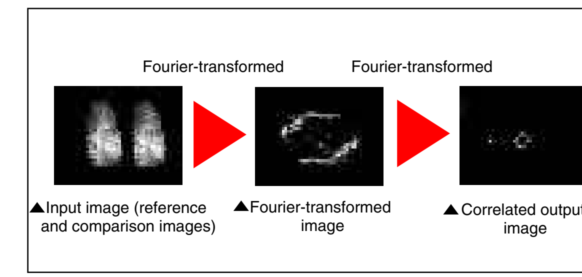


Figure 11: Information processing during fingerprint matching

■ Displacement and velocity measurement system
(particles, blood flow, speckle patterns, etc.)

This is an example of displacement and velocity measurement (utilizing an ultra-high-speed shutter camera consisting of an image intensifier (I. I.) and a CCD camera. The images before and after displacement (or movement) of a target object to be measured are captured within a short time period and set on each other to obtain the superimposed image as shown in Figure 12. This image is sent to the LCD inside an optical analog computer where correlation process ing is carried out, and the results obtained (correlated output shown in Figure 12 allow finding the displacement of the target object. The displacement of the target object corresponds to the distance between the light spots of the correlation image, while the displacement direction is shown by a line joining the light spots.

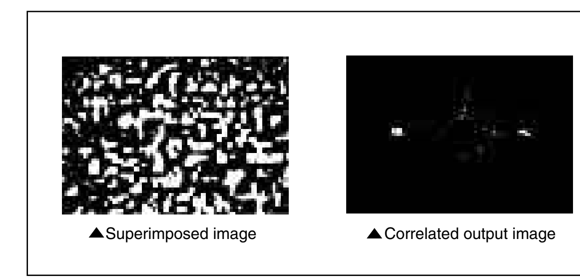
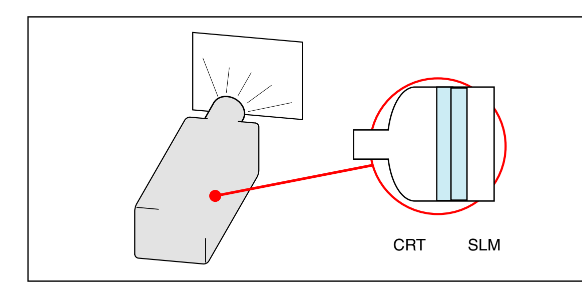


Figure 12: Status of information processing during displacement measurement

Display Equipment

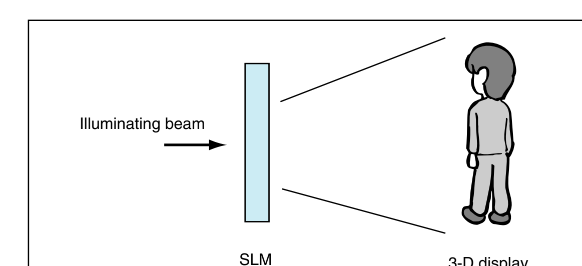
■ Projectors

A high resolution, high brightness projection of a good quality CRT image can be made by using the image from a CRT as an input image and amplifying the light output from a reflective type SLM. A color image can be output with one element by utilizing a high-speed SLM to make compact, adjustment-free projectors a reality.



■ Holography

The SLM also produces rewritable holograms that require no photo-film developing process. Phase-only modulation of the readout light is the terrific feature allowing the hologram record medium to use light with great efficiency.



Specifications

PAL-SLM X7665

Effective area	20 mm x 20 mm (Four corners rounded)
Response speed① Typ. (rise time / fall time) (10 to 90% modulation during π radian phase change)	30 ms / 50 ms
Resolution Typ.	50 Lp/mm
Phase modulation level (readout light wavelength 400 nm to 850nm)	2π radians or more
Phase modulation input sensitivity per 2π radians Typ.	1 mW/cm^2
Write light wavelength	600 nm to 700 nm
Readout light wavelength	400 nm or 1550 nm
Dimensions (W x H x D) ②	60.2 mm x 66.2 mm x 12.2 mm

PPM X7550

Body	
Effective area	20 mm x 20 mm (Four corners rounded)
Maximum display spatial resolution	12 Lp/mm
Effective number of pixels	230 400 (480 x 480)
Phase modulation level	2π radians or more
Readout light wavelength	400 nm to 1550 nm
Optical image transmitting element	Telecentric type on both sides
LCD	Active matrix monochrome LCD
Dimensions (W x H x D) ②	80 mm x 93 mm x 90.3 mm
X7550 driver power supply (supplied)	
Input voltage (AC)	100 V to 240 V (50 Hz /60 Hz)
Input signal	Analog RGB Signal (VGA)
Dimensions (W x H x D) ②	230 mm x 110 mm x 250 mm

Laser Diode Module L8279 (Option : sold separately)

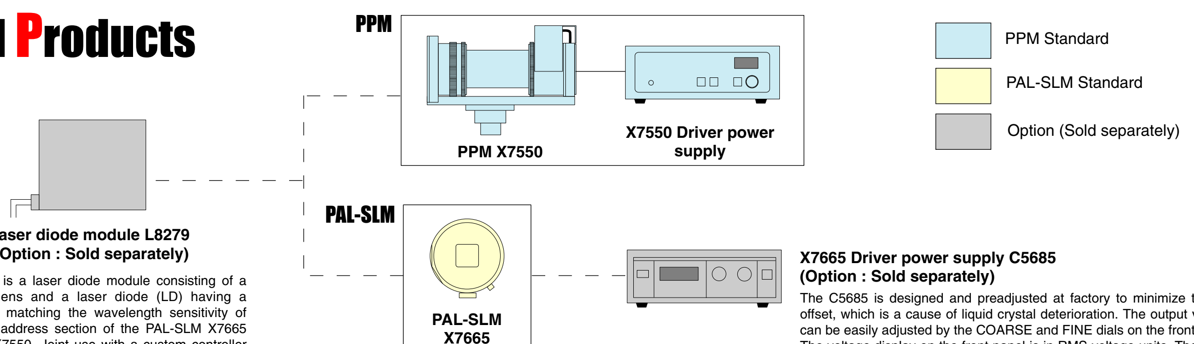
Output wavelength	690 nm
Light output size	30 mm dia.
Maximum radiant output power Typ.	1.5 mW/cm^2
Light output	Collimated
Operating mode	CW
Dimensions (W x H x D) ②	40 mm x 55 mm x 65 mm

X7665 Driver Power Supply C5685 (Option : sold separately)

Input voltage (AC)	85 V to 132 V (50 Hz / 60 Hz)
Output voltage	$\pm$0 V to $\pm$5 V
Output frequency	Selectable in range from 50 Hz to 100 kHz by DIP switch
Output waveform	Rectangular waveform
External gate	Output ON / OFF switching by TTL signal
Dimensions (W x H x D) ②	250 mm x 90 mm x 160 mm

①Data of the PAL-SLM for 633 nm. The corresponding wavelength becomes longer, the speed becomes slower.
②Excluding projections

Related Products



Laser diode module L8279
(Option : Sold separately)

The L8279 is a laser diode module consisting of a collimator lens and a laser diode (LD) having a wavelength matching the wavelength sensitivity of the optical address section of the PAL-SLM X7665 and PPM X7550. Joint use with a custom controller allows a stable optical output to be obtained.

X7665 Driver power supply C5685
(Option : Sold separately)

The C5685 is designed and preadjusted at factory to minimize the DC offset, which is a cause of liquid crystal deterioration. The output voltage can be easily adjusted by the COARSE and FINE dials on the front panel. The voltage display on the front panel is in RMS voltage units. The driver output is turned on and off by pressing the OUTPUT switch.

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