Technical note

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Phase spatial light modulators LCOS-SLM

Contents

The LCOS-SLM (liquid-crystal-on-silicon spatial light modulator) is an electrically addressed reflection type phase spatial light modulator based on liquid crystal on silicon (LCOS) technology in which liquid crystal (LC) is controlled by a direct and accurate voltage, and can modulate the wavefront of a light beam. The LCOS-SLMs are carefully designed to achieve high light utilization efficiency from various points of view, such as reflectivity, aperture ratio and diffraction noise due to the pixel structure.

The LCOS-SLM can be controlled via a PC using the digital video interface (DVI), which is a standard interface for PC displays.

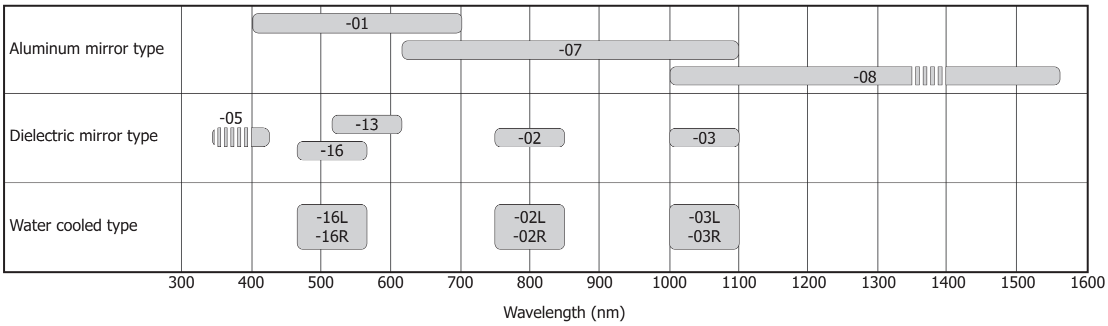
The distortions in the LCOS chip, such as wavefront distortion and non-linear response of the LC, are efficiently compensated by the controller.

Easy PC control and precise and linear phase modulation characteristics can be accomplished with the X15213 series. They can also provide high diffraction efficiency and high light utilization efficiency.

There are eight standard types of the X15213 series available. The X15213-01/-07/-08 have no dielectric mirror, but have higher diffraction efficiency and cover a wide range of the readout light spectrum. The X15213-02/-03/-05/-13/-16 have a dielectric mirror for a specified wavelength range, -02: titanium-sapphire laser (800 nm band), -03: YAG laser (1064 nm), -05: LD (405 nm), -13: second harmonic generation (SHG) of YAG laser (532 nm)/He-Ne laser (633 nm), and -16: second harmonic generation of YAG laser (532 nm). The enhanced reflectivity of the multilayered dielectric mirror also reduces the internal absorption, making operation with a high power laser possible.

Aluminum mirror types use reflection from the aluminum electrodes on the CMOS chip. The reflectivity is inferior to that of the former, but the reflection wavelength range is wider, covering a range of 400 nm to 1550 nm with just three types. The X15213-02L/-02R/-03L/-03R/-16L/-16R are types equipped with a water-cooled heatsink, which improves light resistance to high-intensity lasers.

Hamamatsu phase spatial light modulator LCOS-SLM



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1. Spatial light modulators

1 - 1 What is a spatial light modulator?

A spatial light modulator (SLM) is a key device for controlling light in two dimensions, consisting of an address part and a light modulation part. The optical characteristics of the light modulation part are changed by the information written into the address part, and the readout light is then modulated according to that change, producing an optical output that reflects the written information. The spatial distribution of light such as the phase, polarization state, intensity, and propagation direction can be modulated according to the written information. Among spatial light modulators, those specifically designed to modulate the phase of light are referred to as phase spatial light modulators.
The electronics industry has made rapid and remarkable progress along with the dramatic development pace of basic electronic components such as transistors, IC, LSI, and VLSI. In the optical industry, there are ever increasing demands for the development of spatial light modulators that are the basic components for optical control.

1 - 2 History of Hamamatsu spatial light modulators

In 1980, we started research and development of spatial light modulators. Since then, for more than 40 years we have manufactured various types of spatial light modulator products. Here is a brief look at our product development history.

Microchannel spatial light modulator (MSLM)

In 1985, we developed a product named MSLM. This device was an electron tube type using a photocathode as the optical addressing material and a lithium niobate nonlinear optical crystal ($LiNbO_3$) as the light modulating material. It had high input sensitivity and a number of internal arithmetic processing functions (binarization, accumulation, addition, subtraction, edge enhancement, contrast reversal, AND, OR, scaling, rotation, deflection, etc.), and has been used in a variety of optical research fields.

[Figure 1-1] Microchannel spatial light modulator (MSLM)

Parallel-aligned nematic liquid crystal - spatial light modulator (PAL-SLM)

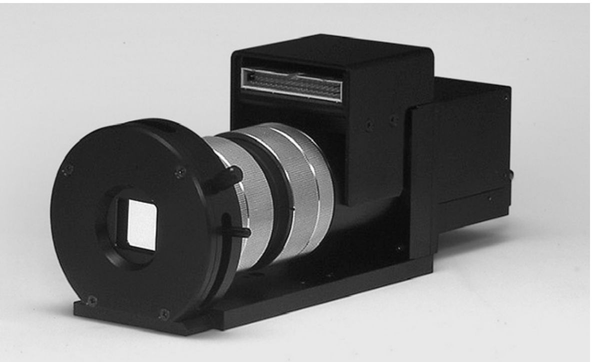
In 1992, we developed a PAL-SLM and placed it on the market. Compared to the MSLM, the PAL-SLM offered higher resolution, faster response time, smaller size, and lower voltage drive. It used an a-Si:H photoconductor as the optical addressing material and a liquid crystal as the light modulating material. The liquid crystal was parallel-aligned to allow pure phase modulation.

[Figure 1-2] Parallel-aligned nematic liquid crystal - spatial light modulator (PAL-SLM)

Programmable phase modulator (PPM)

To meet the need for connecting optical systems to a computer system, we developed a PPM (programmable phase modulator) as an electrically addressed spatial light modulator that can be controlled from a PC and placed it on the market in 1998. The PPM consisted of an electrically addressed liquid crystal panel and an optically addressed PAL-SLM, which were coupled by a relay lens. The PPM has been widely used in R&D work on industrial applications.

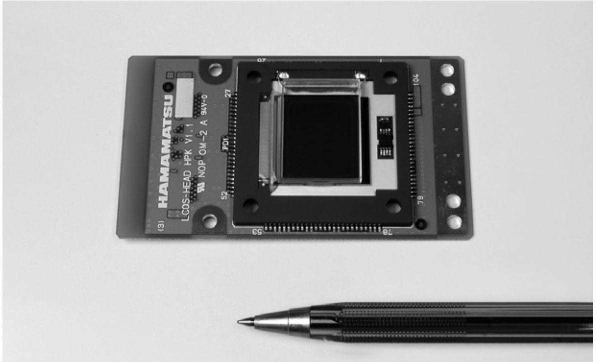
[Figure 1-3] Programmable phase modulator (PPM)



Phase spatial light modulator (LCOS-SLM)

To utilize phase spatial light modulation technology for industrial applications, we started in 2001 to develop the liquid-crystal-on-silicon spatial light modulator (LCOS-SLM), and placed the X10468 series on the market in 2007. In 2015, we started selling the X13138 series, with an increased number of pixels. In 2020, we commercialized the X15213 series, which is made even more compact. LCOS means a structure where a liquid crystal layer serving as the light modulating part is arranged on an electrically addressing part formed by CMOS technology.

[Figure 1-4] Phase spatial light modulator (LCOS-SLM) element



[Figure 1-5] LCOS-SLM X10468/X13138 series

[Figure 1-6] LCOS-SLM X15213 series

2. Wavefront control of light

2 - 1 Wavefront of light as a wave

Light is a stream of quanta having both the characteristics of a wave and a particle. When designing or analyzing an optical system, there is little need for taking the particle nature of light into account, so light can be treated as a wave (electromagnetic wave) in most cases. The theory that treats light as an electromagnetic wave is called electromagnetics. Actually, however, wave optics and geometrical optics (ray optics), which are approximate theories for electromagnetics, are used. The following describes light as a wave and also discusses the phase and wavefront of light.

Light is a transverse wave and so can be expressed by equation (2-1) using the wavelength λ, amplitude A, and phase ϕ when light travels in the z-axis direction and its electric field vibrates in the y-axis direction.

$$f(y) = A\cos(2\pi z/\lambda - \phi) \cdots\cdots (2\text{-}1)$$

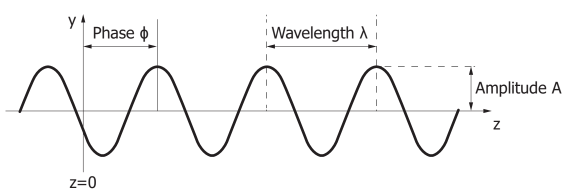
Wavelength is the distance between two successive wave peaks, and the frequency of light is the speed of light divided by its wavelength. The amplitude relates to the strength of a wave, or namely the square of the amplitude is equal to the strength (energy) of a wave. The phase indicates how far the wave peak shifts from the reference point (z=0). Since a wave vibrates over time, the time-dependent term is added to equation (2-1), but it is omitted to simplify the equation. When describing the constant behavior of an optical system that does not change with time, the time-dependent vibration term can be ignored as in equation (2-1).

Light waves can also be expressed by equation (2-2).

$$f(y) = Ae^{i(2\pi z/\lambda - \phi)} \cdots\cdots (2\text{-}2)$$

Equation (2-2) is physically the same as equation (2-1), but is more frequently used since the mathematical expression is easier to use. The expression in equation (2-2) is called the analytic signal.

[Figure 2-1] Physical quantity of waves



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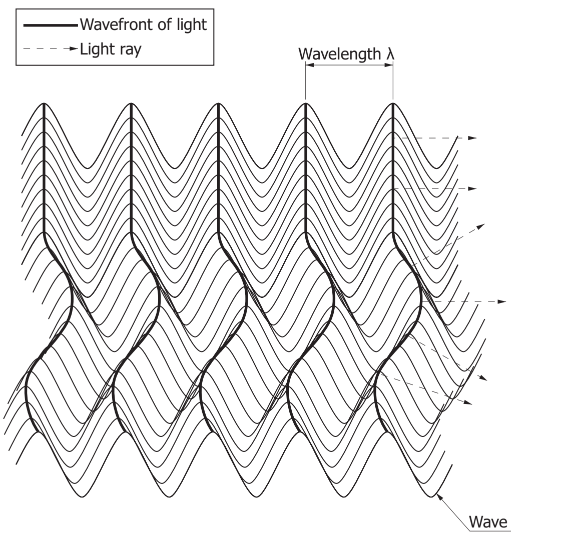
In fact, light waves vibrate not only along a one-dimensional axis but travel while spreading three-dimensionally. If there is a very small light source (point light source) in a vacuum and it lights up at a certain time, the light starts spreading at the speed of light in all directions (in a spherical pattern) from the moment that it is emitted. To describe such a three-dimensional spreading of light waves, the concept of "wavefront" is used. As shown in Figure 2-2, the wavefront of light represents an equal phase surface connecting the peak of each wave.

[Figure 2-2] Wavefront of light and light ray



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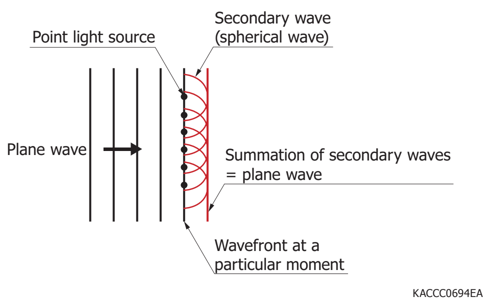
The wavefront of light emitted from a point light source is sphere-shaped (spherical wave). The wavefront of light emitted from a laser is generally flat-shaped (plane wave). If a light wave travels through a transparent object such as a glass, the speed of light is reduced by a factor of the refractive index of that object, causing the traveling wavefront to delay and change its shape. The wavefront shape in this way initially depends on the light source properties and then changes while propagating and interacting with a substance. The propagation of the deformed wavefront can be well understood by considering how light rays behave. Light rays are perpendicular to the wavefront and travel straight in a vacuum or in a medium with a constant refractive index. In an interface where the refractive index changes, such as when light rays enter glass or water from air, the traveling direction of the light rays bends according to Snell's law. At this point, part of the light reflects from the surface causing the traveling direction to change. As stated, light rays are perpendicular to the wavefront, so the changes in the wavefront that accompany the refraction and reflection can be understood by examining the behavior of light rays.

Next, let us discuss the behavior of a light wave when a light-blocking object is present in the traveling direction of the light wave. When a shadow of the light-blocking object is formed by irradiation of sunlight or laser beam, the shadow is dark and distinct near

the object but the shadow boundary is less distinct at positions away from the object. This phenomenon is caused by the light bending around the edge of the object (known as diffraction). (This phenomenon is also caused by the fact that the sun and laser light sources have a certain size.)
Besides the diffraction of light, its reflection and refraction can also be explained by using Huygens' principle. This principle states that if a point light source exists on a wavefront at a particular moment, the secondary waves are emitted from there, and after a certain time has elapsed, the secondary waves overlap and combine with each other to create a new wavefront [Figure 2-3 (a)].

[Figure 2-3] Huygens' principle

(a)



(b)

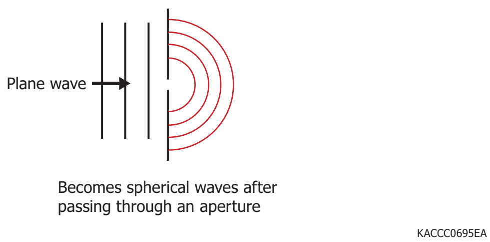


Figure 2-3 (b) shows a case where a light-blocking screen with a small aperture is irradiated by plane waves. The light passing through the aperture in the light-blocking screen spreads spherically as if wrapping around the light-blocking screen. This phenomenon cannot be explained by the behavior of light rays, but can be explained by Huygens' principle.
The propagation of light waves can be explained by using light rays and Huygens' principle. The theory using light rays is geometrical optics (ray optics), and the theory using Huygens' principle is wave optics. Geometrical optics is viewed as the theory approximate to electromagnetics in which light rays are considered as waves of zero wavelength. Wave optics is the intermediate theory ranked between both these theories. The number of phenomena that can be applied by each theory increases in the order of electromagnetics → wave optics → geometrical optics. In other words, the number of phenomena that can be applied by the theory of electromagnetics is most limited, so this theory is inconvenient for designing optical systems. In most cases of optical design and analysis of optical phenomena, geometrical optics is used to examine the general properties, and wave optics is applied to examine the phenomena in more detail.
Spatial light modulators can directly control the wavefront of light, so understanding wave optics makes it easier to handle them.

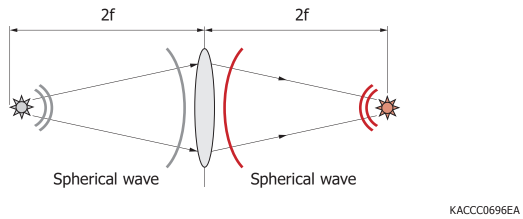
2 - 2 Controlling the wavefront of light using optical devices and techniques

Controlling the wavefront (or spatial distribution of phase) of light allows performing various functions. Many optical devices (lens, prism, etc.) and techniques are usually designed based on ray-tracing. In fact, however, those devices and techniques can be thought of as controlling the wavefront to achieve their particular function. Their functions can also be changed as needed and two or more functions performed simultaneously. The following sections describe typical optical devices and techniques for controlling the wavefront of light.

Lens

This section describes how a lens controls the wavefront of light when focusing an image. When a point light source is placed at a position of 2f from a lens with a focal length of f, a point image is formed on the opposite side of the lens at a position that is 2f from the lens. The wavefront of light emitted from the light source spreads spherically, creating a spherical surface with a curvature of -1/2f when the light enters the lens. Since the light coming out of the lens is focused onto one point, the wavefront immediately after coming out of the lens has a spherical surface with a curvature of 1/2f. The lens adds a spherical change to the wavefront by a curvature of 1/f that is the difference between the two curvatures. In geometrical optics, the lens is thought to bend light rays. In wave optics, however, the lens is considered to function by applying a spherical change to the wavefront as stated earlier.

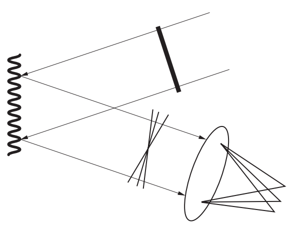
[Figure 2-4] Lens image focusing



Diffraction grating

This section describes how the wavefront of light is controlled by a diffraction grating used in spectrometers, etc. A diffraction grating is an optical component designed to separate light into wavelengths by utilizing the diffraction of light. Diffraction gratings have a periodic structure with a period nearly equal to the wavelength or several to a few dozen times longer than the wavelength. There are two types of diffraction gratings: reflection type and transmission type. The principle of a diffraction grating is briefly explained here using the reflection type as an example. Figure 2-5 shows the light being dispersed by a reflection type diffraction grating. Reflection type diffraction gratings are manufactured by forming a plane mirror or cylindrical mirror having a periodic concavo-convex structure or by engraving a pattern of very narrow, equally spaced grooves on a single plane mirror or cylindrical mirror. In either case, a number of narrow micromirrors are periodically arrayed. When the wavefront of light enters a diffraction grating, each of the periodic micromirrors reflects the light and serves as a secondary light source causing a spherical wave to spread from each mirror. If we apply Huygens' principle here, then the state of the reflected light from the diffraction grating can be explained by adding the spherical waves that are spread from the periodically arranged secondary light sources. An actual calculation shows that the light level increases and decreases according to the traveling direction (angle) of the light. It can also be seen that the light level increases in multiple specific directions. This means that the diffraction grating disperses light into multiple directions. In view of these facts, a diffraction grating is considered a device that creates periodic changes in one wavefront and splits it into multiple wavefronts of light in different directions. When the wavefronts of the split light pass through a lens, these are condensed to multiple positions as light spots (multifocal beam). The light level can also be made to increase only in a specific direction by adjusting the shape of the periodic structure for diffraction gratings (e.g., blazed diffraction grating).

[Figure 2-5] Light dispersed by reflection type diffraction grating



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Aberration compensation technique

This section describes an aberration compensation technique for controlling the wavefront of light. In an ideal focusing lens, light emitted from a point light source should focus onto one point. However, actual lenses have a deviation from the ideal focusing, and this deviation is called aberration. Aberration compensation is a technique for reducing the aberration to obtain good focusing.

In order for a lens to achieve the ideal focusing, the wavefront of the light must be spherical waves after passing through the lens. However, lens aberration causes a deviation in the wavefront shape. This deviation from the ideal wavefront is called wavefront aberration. Although all lenses have some aberrations, it may be possible to achieve virtually zero aberration under particular conditions. For example, parabolic mirrors used in reflecting telescopes have virtually no aberration when an image is focused on their optical axis. Wavefront aberration occurs when an image is focused on other positions. This means that only the center of the screen is nearly aberration-free and the image becomes blurry toward the periphery. Aberration is also caused by a glass plate interposed along the optical path or by the object being observed.

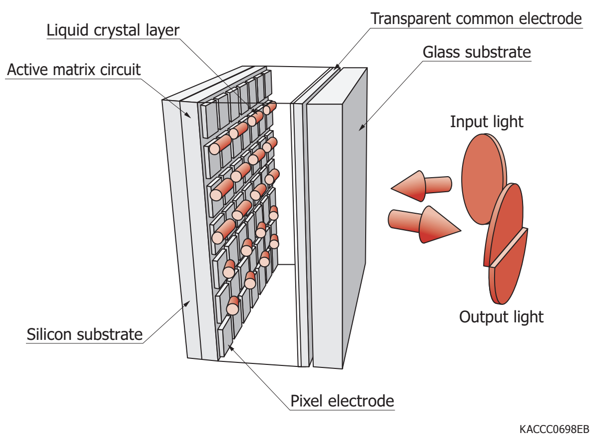
A good focal state can be obtained by compensating for aberration by reducing the deviation from the ideal wavefront. In Schmidt-Cassegrain telescopes, for example, aberration is compensated for by placing a compensating plate (glass plate whose surface is processed into a special shape) in front of the parabolic mirror. Light coming from a distant star is a plane wave when it enters a telescope. In Schmidt-Cassegrain telescopes, the plane wave is deformed by the compensating plate and then condensed by the parabolic mirror. This greatly reduces the aberration in the periphery of the field of view, which makes the image in the periphery very clear. This does meanwhile cause aberration in the center of the field of view, but the amount of aberration is held within an allowable range. The Schmidt-Cassegrain telescope in this way compensates for aberrations by intentionally deforming the wavefront of light coming from a star.

Besides the three items discussed above, a variety of other types of optical devices and techniques can also be understood by means of changes in wavefront. Achieving such changes in wavefront with a spatial light modulator would allow controlling the functions of those optical devices and techniques in whatever way needed.

3. Structure

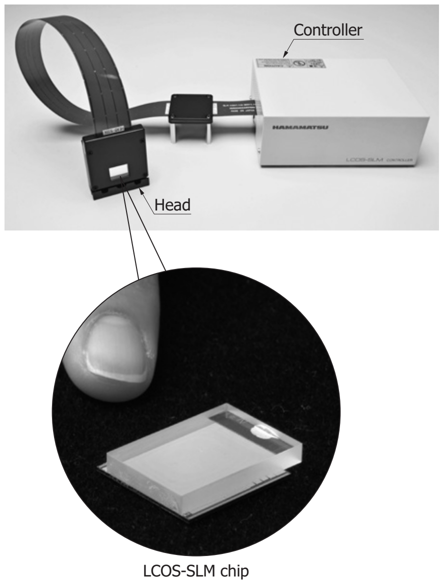
The LCOS-SLM is a spatial light modulator having a structure in which a liquid crystal layer is arranged on a silicon substrate. An addressing circuit is formed on the silicon substrate by semiconductor technology. The top layer contains pixels made by aluminum electrodes, each of which controls its electrical potential independently. A glass substrate is placed on the silicon substrate while keeping a constant gap, and the liquid crystal material is filled in that gap. The liquid crystal molecules are aligned in parallel by the alignment control technology provided on the silicon and glass substrates without being twisted between both substrates. The electric field across the liquid crystal layer can be controlled pixel by pixel. This causes the liquid crystal molecules to tilt according to the electric field so that the phase of light can be modulated. A difference in the liquid crystal refractive indexes occurs in different tilt angles. This changes the optical path length in the liquid crystal layer and so causes a phase difference. At this point, only the phase of the light can be modulated to align the polarization direction of the linearly polarized incident light to the alignment direction of the liquid crystal molecules. However, if the polarization direction of the linearly polarized light is not aligned parallel to the direction of the liquid crystal molecules or the incident light is not linearly polarized, the polarization state of the light changes and modulation of just that phase no longer occurs.

[Figure 3-1] LCOS-SLM chip structure



As shown in Figure 3-2, the LCOS-SLM X15213 series consists of a head and its controller, which are connected by two cables. The controller is connected to a PC via the DVI-D interface, and the phase modulation according to the phase image sent from the PC can be achieved. Generally, the second PC screen is assigned to the controller. The controller converts the 8-bit phase images sent from the PC by a look-up table (LUT) from 8-bit to 12-bit, compensating for the non-linear response of the refractive index changes in the liquid crystal material, and higher linearity as 256 gray levels can be accomplished.

[Figure 3-2] LCOS-SLM X15213 series



4. Characteristics

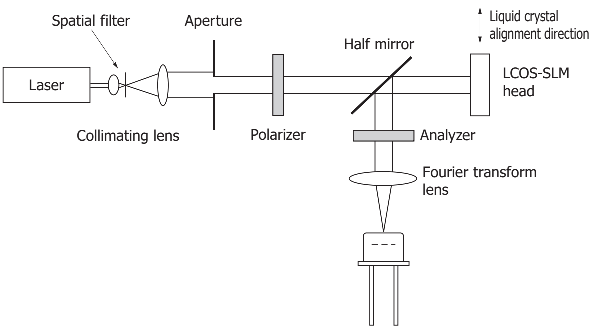
4 - 1 Phase modulation

Figure 4-1 shows a measurement setup using a crossed nicols optical system where the LCOS-SLM output can be obtained as an intensity modulation. This setup measures intensity changes that correspond to 8-bit pixel values (256 gray levels). The liquid crystal molecules in the LCOS-SLM are horizontally aligned, and then the polarization direction of the incident light is adjusted to 45 degrees to the alignment direction. The analyzer is set to be rotated 90 degrees to the polarization direction of the incident light. The aperture size is 10 mm in diameter. The phase value (ϕ) can be determined from equation (4-1), which is for calculating the output light level (I). The example in Figure 4-2 shows measurement results from the X15213-03 output light intensity and the result calculated for the phase modulation level.

$$I = (I_{max} - I_{min}) \sin^2(\phi/2) + I_{min} \quad \cdots\cdots \text{(4-1)}$$

Imax: maximum light level
Imin : minimum light level

[Figure 4-1] Measurement setup (crossed nicols optical system) for phase modulation characteristics



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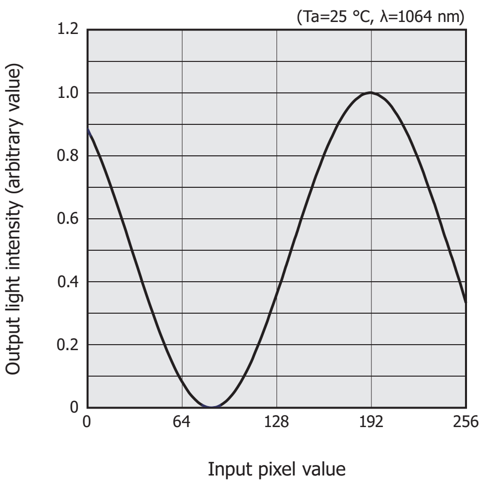
[Figure 4-2] Phase modulation characteristics (X15213-03, typical example)

(a) Output light intensity



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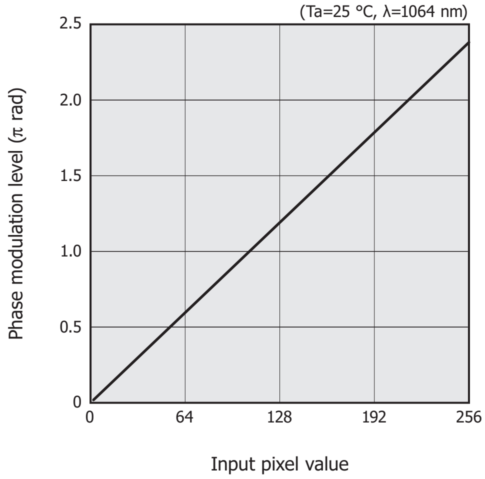
(b) Phase modulation level



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The phase modulation level of the LCOS-SLM will be shifted depending on the wavelength. The maximum phase modulation is adjusted to 2.28π rad for each type of X15213 series so that the phase resolution is 0.009π/digit.

4 - 2 Time response

Definition

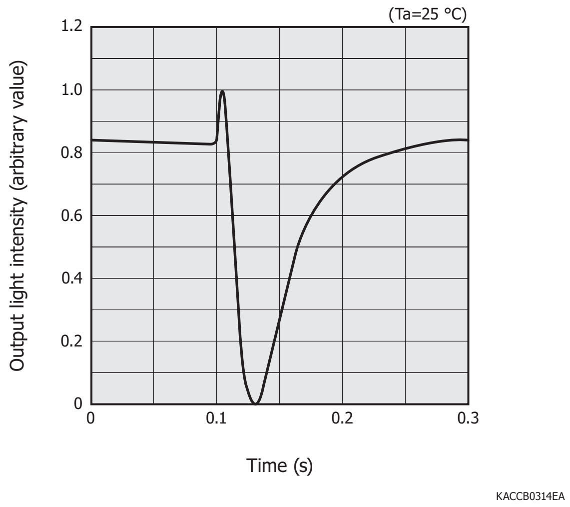
The response time is defined as a transition time (10% to 90%) at a 2π phase difference. The transition time when the pixel value changes from a larger value to a smaller value is defined as the rise time, and the transition time when the pixel value changes from a smaller value to a larger value is defined as the fall time. When the pixel gray level is represented by 8 bits, the voltage value is maximum when the pixel value is 0 (zero), and the controller is set so that the voltage value decreases as the pixel value increases.

Measurement method

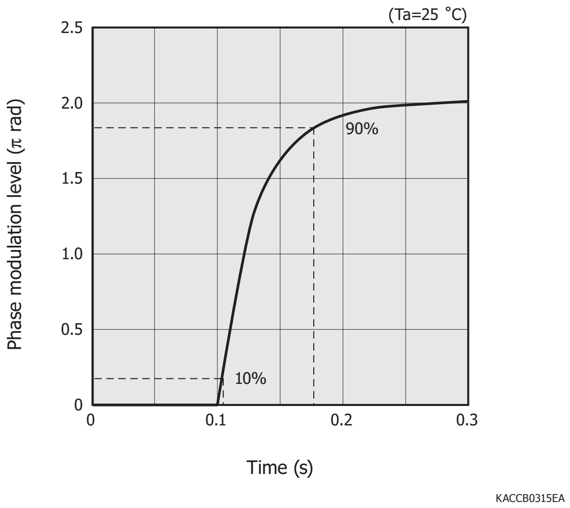
Time response characteristics are measured with a photodiode and an oscilloscope using the optical system shown in Figure 4-1 that is for observing phase modulation as intensity modulation. When the phase is switched between 0 and 2π, the change in the output light level is measured, and the light level change is then converted into a phase change to calculate the rise/fall times required for a transition from 10% to 90%. Examples of X15213-03 time response characteristics are shown in Figure 4-3.

[Figure 4-3] Time response characteristics (X15213-03, typical example)

(a) Output light intensity



(b) Phase modulation level



Measurement results

The average rise time and fall time of the X15213 series are shown in Table 4-1. The rise time tends to be faster than the fall time.

4 - 3 Light utilization efficiency

Definition

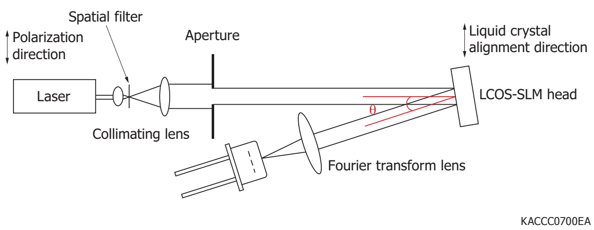
Light utilization efficiency is defined as the ratio of the average reflected light level (Iave) to the incident light level (Ipow) when the LCOS-SLM is operated with a supply voltage ranging from 1 V to the maximum voltage (Vhigh).

Light utilization efficiency = Iave/Ipow [%] ······ (4-2)

Measurement method

Light utilization efficiency is measured using the phase modulation optical system shown in Figure 4-4, where the polarization direction of the incident light is aligned with the direction the liquid crystal molecules are oriented. The reflected light level is measured at each supply voltage ranging from 1 V to the maximum voltage, which is divided into 128 points. The incident angle (θ) is within 10 degrees, and the aperture size is 6 mm in diameter.

[Figure 4-4] Measurement setup for light utilization efficiency



Measurement results

Average light utilization efficiencies of the X15213 series are shown in Table 4-2. Two or more light sources were used for measurement in the X15213-01/-07 aluminum mirror types with a wider wavelength range. Dielectric mirror types deliver more than 90% light utilization efficiency, and aluminum mirror types offer 70 to 83%. Loss of light level is mainly caused by generation of diffracted light resulting from the pixel structure, scattering in the liquid crystal layer, and absorption by the transparent electrode, etc.

[Table 4-1] Evaluation results of response speed (average values)

Type no.	X15213							
	-01	-02	-03	-05	-07	-08	-13	-16
Light source wavelength (nm)	633	785	1064	407	1064	1064	532	532
Rise time (ms)	5	30	25	10	10	12	10	11
Fall time (ms)	26	80	80	20	80	90	25	34

[Table 4-2] Light utilization efficiency evaluation results (average values)

Type no.	X15213							
	-01		-02	-03	-05	-07		
Light source wavelength (nm)	532	633	785	1064	407	532	633	1064
Light utilization efficiency (%)	71.8	74.6	97.6	97.8	97.7	74.0	72.0	85.7

Type no.	X15213			
	-08	-13		-16
Light source wavelength (nm)	1064	532	633	532
Light utilization efficiency (%)	86.0	96.2	96.9	97.5

[Table 4-3] Wavelengths of light sources for diffraction efficiency measurement

Type no.	X15213							
	-01	-02	-03	-05	-07	-08	-13	-16
Light source wavelength (nm)	633	785	1064	407	1064	1064	532	532

4 - 4 Diffraction efficiency

Definition

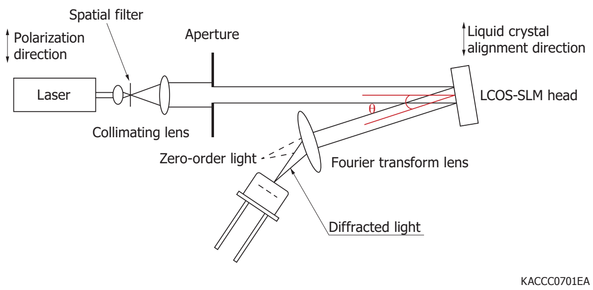
Diffraction efficiency is defined by equation (4-3) as the first-order diffraction light level (I1st) divided by the zero-order diffraction light level (Iave) when a phase pattern similar to a blazed diffraction grating is displayed on the LCOS-SLM. In the case of a 2-step diffraction grating however, the average value of plus/minus first-order light levels was used as the diffraction light level. The zero-order light level is the average value obtained by changing the input gray level from 0 to 255.

Diffraction efficiency = I_{1st}/I_{ave} [%] ······ (4-3)

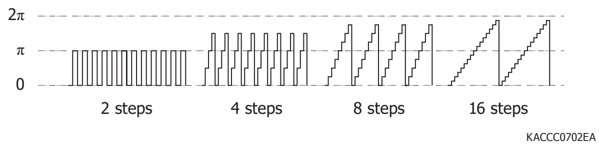
Measurement method

First-order diffraction light level is measured using the measurement setup shown in Figure 4-5, where the polarization direction of the incident light is aligned with the direction the liquid crystal molecules are oriented. The incident angle θ is set within 10 degrees, and the aperture size is ϕ10 mm. The four types of phase distributions shown in Figure 4-6 are used in the diffraction gratings.

[Figure 4-5] Measurement setup for diffraction efficiency



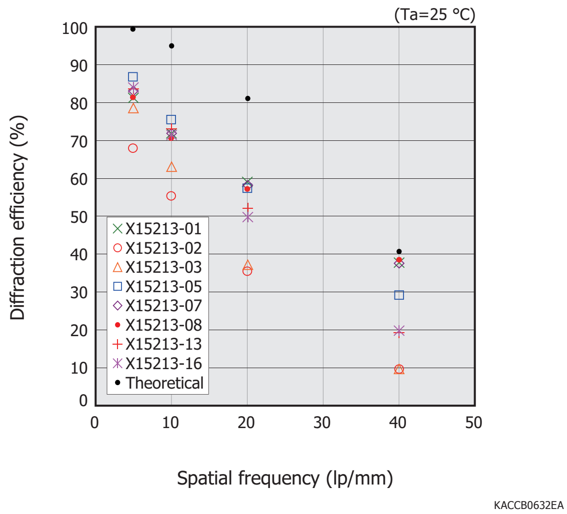
[Figure 4-6] Phase distribution of diffraction gratings



Measurement results

Figure 4-7 shows diffraction efficiency of the device and theoretical values. The wavelengths of the light sources used for the measurements are listed in Table 4-3. The spatial frequency of each diffraction grating shown in the figure is 40 lp/mm for 2 steps, 20 lp/mm for 4 steps, 10 lp/mm for 8 steps, and 5 lp/mm for 16 steps.

[Figure 4-7] Diffraction efficiency (typical example)



4 - 5 Device flatness

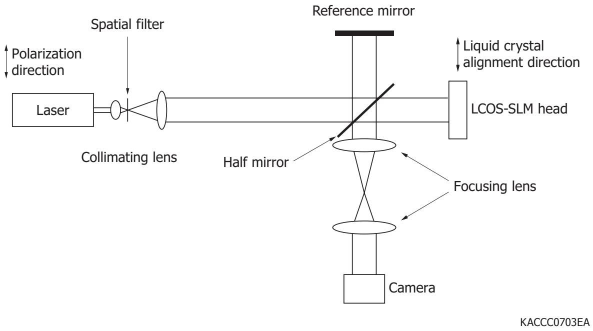
Definition

Flatness of the device is evaluated by the RMS variation of the PV (peak to valley) value that is the difference (maximum displacement) between the highest point and the lowest point in the effective pixel area (15.9 × 12.8 mm) of a LCOS-SLM.

Measurement method

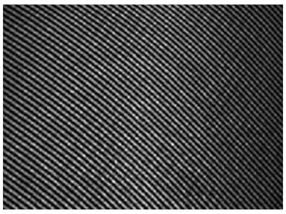
The fringe pattern interference between the LCOS-SLM and the reference mirror is captured on the optical system shown in Figure 4-8, where the polarization direction of the incident light is aligned to the direction of the liquid crystal molecules are oriented. The interference fringe is then Fourier-transformed to obtain the phase distribution, which indicates the flatness of the device. Figure 4-9 shows examples from measuring the interference fringe and the calculated device flatness. The surface shape at the reflection part in Figure 4-9 (b) shows the phase difference in 8-bit gray levels from 0 to 255 that correspond to one wavelength. The phase modulation level of the LCOS-SLM differs depending on wavelength, so the device flatness of each model of the X15213 series is evaluated by typical light source wavelengths.

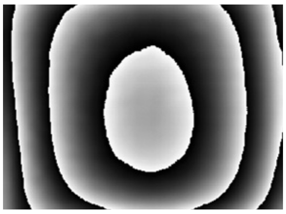
[Figure 4-8] Measurement setup for surface accuracy



[Figure 4-9] Measurement examples of device flatness

(a) Interference fringe (b) Surface accuracy shape





Measurement result

Table 4-4 shows the device flatness evaluation results of the X15213 series. The PV value and RMS value averaged over the calculated surface shape data are listed for each model. A software for LCOS-SLM control has function to correct the flatness and a flatness with correction is obtained λ/20 or less in PV value.

4 - 6 Resistance to light

When a high power laser beam is irradiated onto an LCOS-SLM, physical damage or irreversible changes in the characteristics may occur. To check whether such damage and irreversible changes in the characteristics will occur or not, a laser irradiation test is carried out on the LCOS-SLM and the test results are examined. Physical damage includes damage to the transparent electrodes, multilayered dielectric mirror and aluminum mirrors, and also thermal damage caused by boiling of the liquid crystal materials. Irreversible changes in the characteristics may occur in the constituent materials due to two-photon absorption when the LCOS-SLM is irradiated by an ultrashort pulsed laser or by an ultraviolet laser (400 nm or shorter wavelength). A reversible change in characteristics may arise due to the liquid crystal temperature characteristics accompanying a heat generation caused by light absorption in the LCOS-SLM.

After irradiation testing, the appearance of damage is checked and the output image and phase modulation characteristics are evaluated. If an abnormal condition is found when no voltage is applied to the LCOS-SLM, it is viewed as physical damage. If an abnormal condition is found when the voltage is applied, it is viewed as an irreversible change in the characteristics.

Table 4-5 shows data examples obtained after irradiation of light. The resistance to light depends on the averaged power of light (entire incident light) entering the LCOS-SLM and the peak power (light power density) incident per unit area.

The X15213-05 may be damaged if used with UV light at 400 nm or shorter wavelength. Please consult us when using the X15213-05 with UV light at 400 nm or shorter.

[Table 4-4] Evaluation results of device flatness (average values)

Type no.	X15213							
	-01	-02	-03	-05	-07	-08	-13	-16
Light source wavelength (nm)	633	785	1064	407	1064	1064	532	532
PV value	1.8λ	3.1λ	2.3λ	3.0λ	1.7λ	1.3λ	3.2λ	2.0λ
RMS value	0.4λ	0.6λ	0.5λ	0.5λ	0.4λ	0.3λ	0.7λ	0.4λ

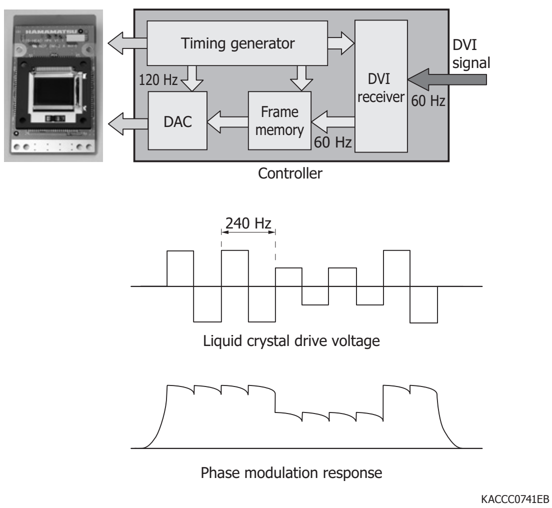
[Table 4-5] Light stability test (typical examples)

Light source: Type	Wavelength (nm)	Pulse width	Repetition frequency (kHz)	Beam diameter 1/e² (mm)	Incident time	Incident light level: Average power (W)	Average power per unit area (W/cm²)	Peak power	Peak power per unit area	Result: Damage	Change in characteristics
(a) X15213/X15223-02											
Ti:S laser (pulse)	800	50 fs	1	ϕ9	3 hours	2.7	4.3	108 GW	170 GW/cm²	None	Changed
				ϕ11	10 hours		2.9		114 GW/cm²		None
		30 fs	0.01	ϕ18	6 hours	0.05	0.02	333 GW	131 GW/cm²		
(b) X15213/X15223-03											
YAG laser (CW)	1064	-	-	ϕ2.5	1 hour	2.0	40.7	-	-	None	None
					Several minutes	3.5	71.3				Changed
YAG laser (pulse)		200 ns	80		1 hour	2.0	40.7	0.25 kW	5.1 kW/cm²		None
					Several minutes	3.5	71.3	0.44 kW	8.9 kW/cm²		Changed
Pulsed laser	1030	670 fs	1	ϕ4.5	10 hours	0.6	3.8	1.8 GW	11.3 GW/cm²		None
		1.37 ps	30	ϕ8.11	8 hours	5.2	10.1	0.25 GW	0.49 GW/cm²		
		11.4 ns	10	ϕ13	8 hours	17.4	13.1	0.31 MW	0.23 MW/cm²		
(c) X15213/X15223-16											
Pulsed laser	515	4 ps	25	ϕ3.7	27 hours	0.162	1.5	1.6 MW	30 MW/cm²	None	None
					60 hours	0.36	3.3	3.6 MW	67 MW/cm²	Yes	Changed

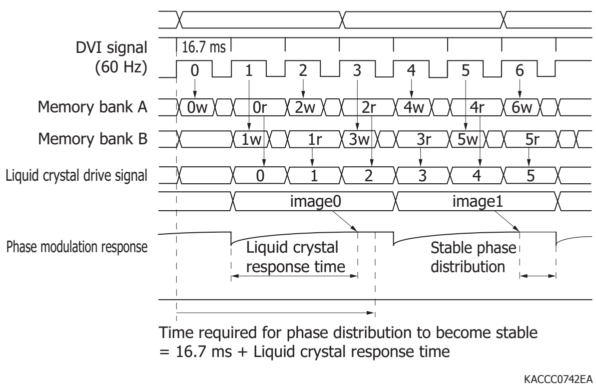
4 - 7 Drive timing

The LCOS-SLM controller contains a frame memory that stores phase images in synchronization with DVI signals at a frame rate of 60 Hz in the case of the X15213 series. The phase images are read out from the frame memory at a rate of 240 times per second and are then sent to the D/A converter (DAC) to produce analog signals that drive the LCOS-SLM. Generally, the liquid crystal has to be driven alternatively, so the liquid crystal drive cycle (refresh rate) is set to 120 Hz and the corresponding phase fluctuations are observed. Since the liquid crystal response time (see section 4-2, “Time response characteristics”) is slower than the refresh rate and DVI frame rate (60 Hz), the response time (phase image update cycle) for obtaining a phase distribution that corresponds to phase images is dependent on this liquid crystal response time and so ranges from about 10 to several dozen hertz.

[Figure 4-10] Block diagram



[Figure 4-11] Timing chart



4 - 8 Phase fluctuation

LCOS-SLM is subject to phase fluctuation according to the liquid crystal drive cycle of 120 Hz. The higher the drive voltage of the liquid crystal, the greater the phase fluctuation will be. The phase fluctuation can be reduced by lowering the drive voltage of the liquid crystal. The response speed of the liquid crystal will be slower if the drive voltage of the liquid crystal is lowered. There is a trade-off between response speed and phase fluctuation. With the X15213 series, the user can set the drive voltage of the liquid crystal to low voltage using a PC connected to the X15213 series via USB.

5. Application examples

5 - 1 Beam shaping

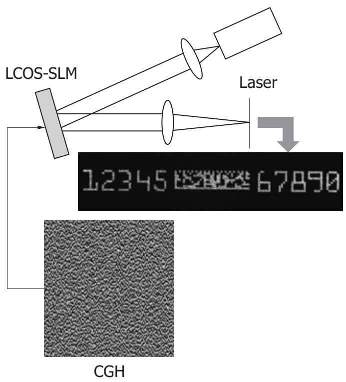
Any desired light intensity distribution can be generated with high efficiency by controlling the diffraction and interference phenomena of light using light phase modulation. A phase distribution that is calculated by a computer for generating the desired light intensity distribution is called a computer generated hologram (CGH), and the technique for creating the desired light intensity distribution using CGH technology is called beam shaping [Figure 5-1]. Projectors are a well-known common beam shaping method. These create a light intensity distribution by passing or blocking light as shown in Figure 5-2 (a), so that in a dark projection area there is a loss of light from the light source. The higher the percentage of the dark area, the lower the light utilization efficiency will be. In contrast, as shown in Figure 5-2 (b), the CGH-based projection method redistributes the light intensity distribution of the light source by utilizing light interference in order to create the desired light intensity distribution. This is an excellent beam shaping method in terms of light utilization efficiency. This CGH-based projection method will prove useful as structured illumination in laser processing/machining and microscopy applications.

[Table 4-6] Drive voltage vs. response speed, phase fluctuation

Type		-01		-02		-03		-05	
Drive voltage		Standard	Low voltage	Standard	Low voltage	Standard	Low voltage	Standard	Low voltage
Response speed	Rise time (ms)	5.6	33.0	28.8	83.0	24.0	126.0	6.0	27.0
	Fall time (ms)	22.8	61.0	75.0	134.0	79.0	256.0	14.8	43.0
Phase fluctuation	Peak to peak (πrad.)	0.0208	0.0124	0.0031	0.0023	0.0043	0.0013	0.0099	0.0073
	RMS (πrad.)	0.0061	0.0038	0.0008	0.0007	0.0013	0.0003	0.0030	0.0023

Type		-07		-08		-13		-16	
Drive voltage		Standard	Low voltage	Standard	Low voltage	Standard	Low voltage	Standard	Low voltage
Response speed	Rise time (ms)	7.6	59.0	9.2	100.0	9.2	68.0	11.6	54.0
	Fall time (ms)	55.0	118.0	65.0	170.0	18.8	126.0	37.0	110.0
Phase fluctuation	Peak to peak (πrad.)	0.0076	0.0047	0.0154	0.0022	0.0169	0.0034	0.0029	0.0017
	RMS (πrad.)	0.0021	0.0014	0.0042	0.0005	0.0056	0.0010	0.0008	0.0004

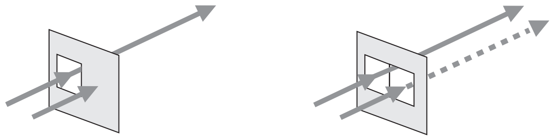
[Figure 5-1] Beam shaping



KACCC0704EA

[Figure 5-2] Difference between light intensity modulation and light phase modulation

(a) Light intensity modulation (b) Light phase modulation



Passes or blocks light

KACCC0705EA

Utilizes light interference

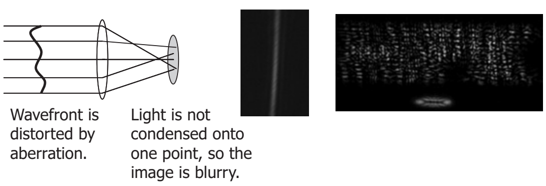
KACCC0706EA

5 - 2 Aberration correction

Optical systems always include some kind of nonuniformity which disturbs the phase of light. For example, if an aberration exists in an optical system as shown in Figure 5-3 (a), then the lens might not focus the light to a sharp point, or CGH-based projection might not reproduce sharply focused images. Correcting the optical aberration with a LCOS-SLM will focus the light to a nearly ideal point and also make the CGH-based projection images sharper and clearer [Figure 5-3 (b)]. When observing the inside of the human eye, this technique corrects the aberration caused by crystalline lens distortion which differs from person to person, allowing us to see sharper and clearer images [Figure 5-4]. When processing the inside of objects using a laser, the LCOS-SLM achieves high precision and high efficiency laser machining by correcting optical aberration in the object [Figure 5-5].

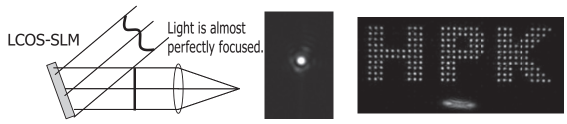
[Figure 5-3] Aberration correction of optical system

(a) Without aberration correction



KACCC0707EA

(b) With aberration correction

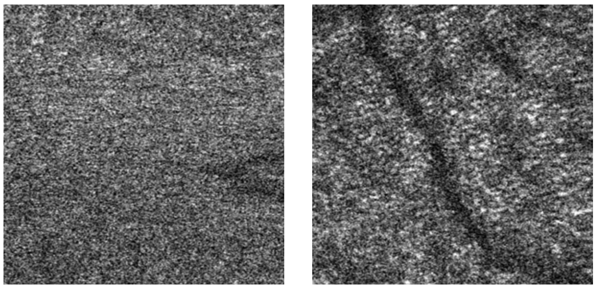


KACCC0708EA

[Figure 5-4] Phase correction for fundus camera

(a) Without aberration correction (fundus image before correction)

(b) With aberration correction (fundus image after correction)

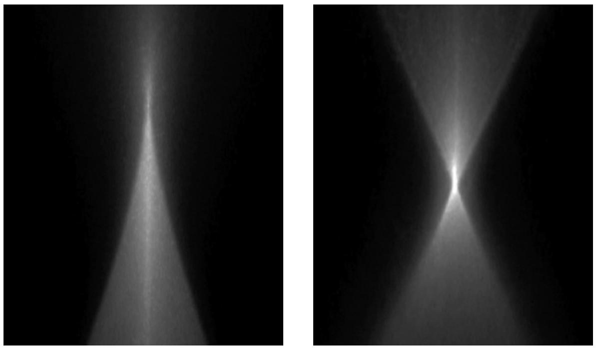


Cannot identify the structures

Can identify even visual cells

[Figure 5-5] Focused beam viewed from lateral side

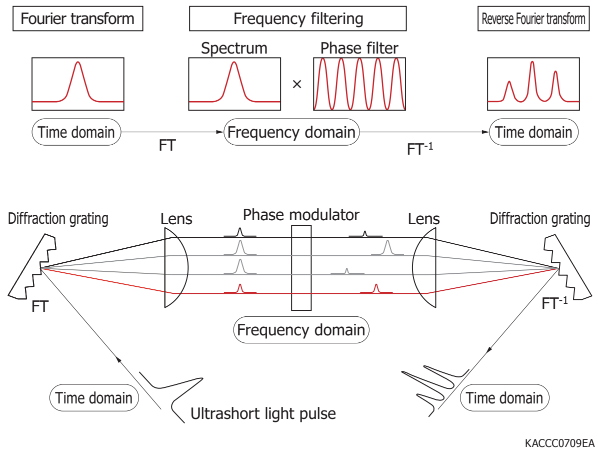
(a) Without aberration correction (b) With aberration correction



5 - 3 Optical pulse shaping

Ultrashort light pulses of a femtosecond laser cannot be directly controlled because there is no electronic device that exhibits a response within the femtosecond time domain. Optical pulse shaping is a technique for freely controlling the amplitude and phase of light pulses in such a time domain. To do this, ultrashort light pulses are optically transformed to the frequency domain by Fourier transform, frequency-filtered, and then inverse Fourier-transformed [Figure 5-6]. Although it is possible to obtain accurate control by individually controlling the amplitude and phase at the frequency domain, controlling the amplitude will lower the light utilization efficiency, so the commonly used technique generally controls only the phase, and shapes waveforms over time to an approximate degree. Optical pulse shaping using a LCOS-SLM allows controlling the light pulse width and generating multiple light pulse trains, and so will likely prove effective in applications including laser processing and chemical reaction control.

[Figure 5-6] Principle of optical pulse shaping



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