Lensless Vanderlugt optical correlator using two phase-only spatial light modulators

Invited Paper

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A lensless Vanderlugt optical correlator using two phase-only spatial light modulators (SLMs) is proposed. The SLMs are used for displaying input and filter patterns respectively. The SLMs are also used as programmable lenses in order to realize the lensless construction. This lensless system is simple and its alignment adjustment is easy. The performance of the SLMs as programmable lenses is also described.

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Pattern recognition based on optical correlation has been studied widely[1,2]. There are two main processing architectures used for optical correlators: the Vanderlugt-type correlator (VC) and the joint transform correlator (JTC). JTC is robust against misalignment; however, its detection efficiency is low, particularly for multi-target recognition[3]. VC has higher detection efficiency, but it is sensitive to optical misalignment. Furthermore, its optical path tends to be long because it requires two Fourier transform lenses which are set in a $4f$ configuration. To simplify the design of optical correlators, a few lensless systems have been proposed[4,5]. To eliminate the Fourier-transform lens, those systems use a hologram on which a filter pattern is recorded with convergent beams. Those systems, however, cannot change the reference patterns flexibly, and recording with convergent beams is, in general, more difficult than that with plane waves.

In this letter, we propose a Vanderlugt-type optical correlator in which two phase-only spatial light modulators (SLMs) are used and no lens is employed. By using SLMs, the input patterns and correlation filter are changeable. In addition, the proposed system has a simple construction, and it is easy to achieve true alignment.

The optical setup of the proposed lensless optical correlator is shown in Fig. 1(a). While most phase-only SLMs are of the reflection-type, we chose an oblique readout configuration. An input image, consisting of one or more input patterns, and a correlation filter created from a reference pattern are displayed on SLM1 and SLM2, respectively. The input patterns are coded in phase-only forms, and the filter is the phase component of the Fourier transform of the reference pattern. In the setup, a collimated laser beam is outputted from a light source. The beam is then reflected at the two SLMs and is finally detected by a charge-coupled device (CCD) camera.

In order to realize a lensless construction, the two SLMs are used not only as information representation devices but also as programmable lenses. The programmable lens function can be realized by adding Fresnel lens patterns (FLPs) to the input phase image and the phase filter. The FLPs are spherical phase patterns whose phase is wrapped within a range of 2π rad[6]. Since the input image and phase filter are coded in a phase range of 2π rad, the phase range after adding the FLPs may exceed 2π rad. Therefore, the additional patterns should be re-wrapped so that their phase ranges are within 2π rad. The focal length of the FLP for SLM1 is set to be identical to the distance from SLM1 to SLM2. The focal length of the FLP for SLM2 is set so as to make the planes of SLM1 and the CCD optically conjugate. Under this focus condition, a Fourier transform of the input pattern (FTIP) is formed on SLM2, and correlation signals, corresponding to the input patterns, are imaged onto CCD. An example of a FLP is shown in Fig. 1(b).

This setup acts as a VC so that the focus condition mentioned above should be accurately realized and the center position of the FTIP on SLM2 should be coincident with that of the filter. If some misalignment exists in the alignment of the center positions or in the focus condition, the correlation peaks weaken rapidly. In the proposed system, the focus condition can be realized by controlling the focal lengths of the FLPs represented on SLM1 and SLM2. The center position of the FTIP can be adjusted by controlling the center position of the FLP represented on SLM1. Because this control of the focal length and center position of the FLP can be performed electrically, the adjustment is very easy in the proposed system.

We constructed an experimental system using a 633-nm He-Ne laser as a light source and conducted pattern recognition experiments using Japanese characters. The

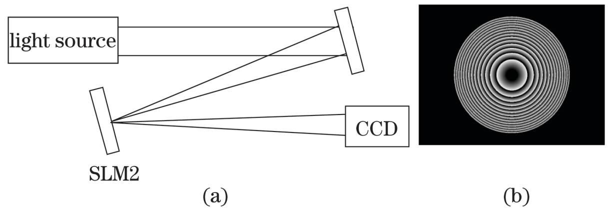

Fig. 1. Principle of lensless VC with phase-only SLMs. (a) Optical setup of correlator and (b) example of a Fresnel lens pattern.

incident angles to the SLMs were approximately 8°. Before conducting the pattern-recognition experiments, we adjusted the center positions and focal lengths of the FLPs.

We used two sets of SLMs (X10468-06, Hamamatsu Photonics, K. K.)[7,8]. These SLMs are based on liquid crystal on silicon (LCOS) technology and are suitable for a lensless optical correlator because they can realize pure phase modulation. The structure of the devices is shown in Fig. 2(a). The liquid crystal in the device was of the homogeneously-aligned nematic type. The SLM consisted of 792×600 pixels. The pitch and fill factor of the pixel electrodes were 20 μm and 95%, respectively. To enhance light-utilization efficiency, a multilayered dielectric mirror (MDM) with a reflectivity of approximately 100% at 633 nm was employed. The light-utilization efficiency, which is the intensity ratio of the 0th diffraction order to the input light when the tested SLM is controlled to output a uniform wavefront, is approximately 90%.

The SLMs were controlled by 8-bit digital signals transmitted from a personal computer (PC) via a digital visual interface (DVI). This allowed us to drive the SLMs as a secondary monitor of the PC, making them easy to use. The 8-bit digital signals from the PC were converted to analog signals with 12-bit digital-to-analog converters (DACs) in the controller. When these signals were analog-converted, a look-up-table (LUT) was applied in the controller of each SLM to compensate for the nonlinear response of the liquid crystal. The measured phase modulation characteristic is shown in Fig. 2(b). The phase modulation was precise and quite linear up to the 8-bit input signal level.

In the experiments, the focal lengths of the FLPs used for SLM1 and SLM2 were 1296 and 648 mm, respectively. Under this condition, the size of the FTIP calculated from the pixel pitch of SLM1 was 40.96 mm, which was larger than the active area of SLM2. Therefore, in order to reduce the size of the FTIP, we treated 4 × 4 pixels as one pixel when representing the input patterns on SLM1.

An example of the experimental results is shown in Fig. 3. The correlation filter was calculated from a reference pattern shown in Fig. 3(a). The input image used is shown in Fig. 3(b). It contains fifteen Japanese characters, and three of them are the same character as the reference pattern. The phase of the characters was set to π, and the phase of the background was set to zero. The image taken at the output correlation plane is shown in Fig. 3(c). Three strong correlation peaks were observed and their locations were coincident with the positions of the three characters identical to the reference pattern. We conducted the same experiment with other input and reference patterns and confirmed that the proposed system acted as a VC. Although binary phase images were used as the input images in these experiments, multi-level phase images can also be applied in this lensless optical correlator.

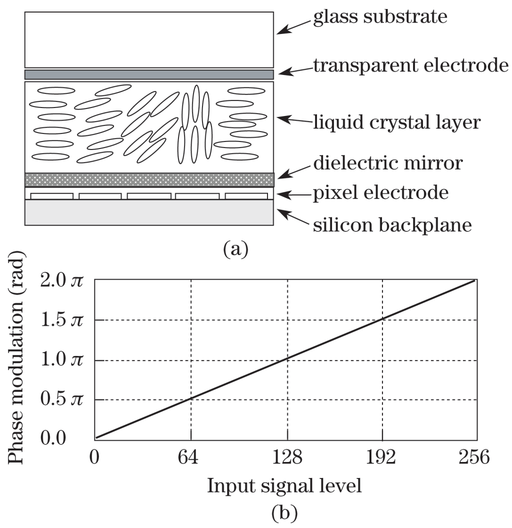

Fig. 2. (a) Structure and (b) phase modulation characteristics of the LCOS-SLM used in the experiments.

The most important factor that affects the recognition performance of the proposed system is the performance of the SLMs as programmable lenses. To investigate this performance, we measured the diameters of the focal spots made by FLPs. We also measured the focus efficiency η, which is defined as $\eta = I_f/I_{\mathrm{T}}$, where I_f is the intensity of focal spot, I_{T} is the total intensity of modulated light with SLM. I_{T} also means the intensity of the 0th diffraction order when the SLM is controlled to output a uniform wavefront. In the measurements, a collimated beam of the same He-Ne laser used in the pattern recognition experiments illuminated an X10468-06 SLM in an oblique incident arrangement, and FLPs of various focal lengths were displayed. The focus spot generated with each of the FLPs was observed with a CCD camera, and its diameter and focus efficiency were calculated.

The measured spot diameters are shown in Fig. 4. The measured diameters were very close to the diameters of diffraction-limit spots, and it can be concluded that near diffraction-limited spots were obtained at focal lengths more than 300 mm.

The measured focus efficiencies are also shown in Fig. 4. Though the focus efficiency was high at focal lengths more than 800 mm, it decreased as the focal length decreased from 800 mm. This decrease in focus efficiency is due to the low diffraction efficiency (DE) of the SLM at high spatial frequencies. As shown in Fig. 1 (b), a FLP can be recognized as a concentric-circle grating whose spatial frequency gradually increases from its center to its outer periphery. Furthermore, the shorter the focal length of the FLP is, the higher the spatial frequency in the outer periphery becomes. As a result, the focus efficiency for short focal length FLPs is small compared with that for long focal length FLPs.

The measured relative DEs of the SLM are shown in

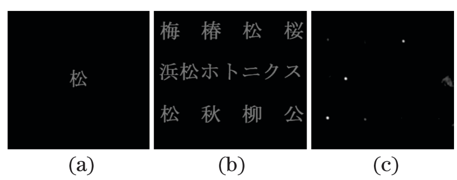

Fig. 3. An example of pattern recognition. (a) Reference pattern, (b) input image including fifteen Japanese characters, and (c) image of correlation signals.

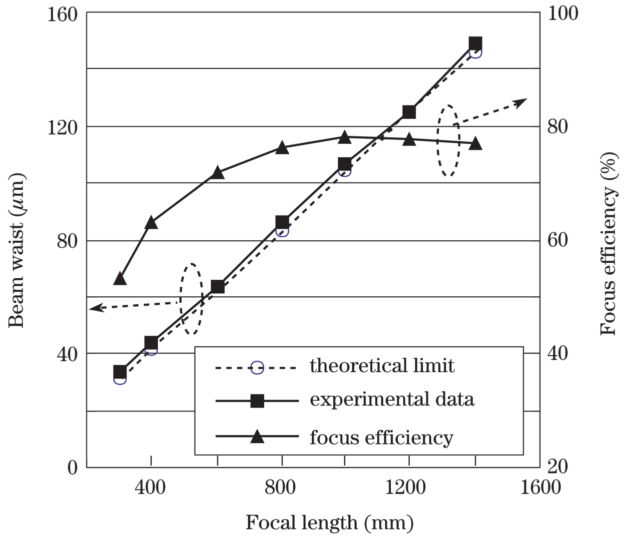

Fig. 4. Diameter and focus efficiency of the focal spots generated with FLPs displayed on the SLM.

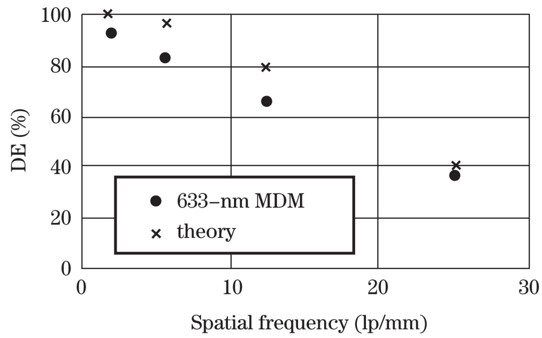

Fig. 5. Relative diffraction efficiency of the SLM.

Fig. 5, with theoretical limits. We displayed blazed grating patterns (BGPs) on the SLM and measured the DEs. The relative DE is the intensity ratio of the 1st diffraction order when the BGP is applied to the 0th diffraction order when no pattern is applied. DEs of more than 80% of the theoretical limits were obtained at all spatial frequencies. The theoretical limits are quite low in the higher frequency region. This is the origin of the decreasing focus efficiency at short focal lengths.

In conclusion, we have proposed a lensless Vanderlugt optical correlator that uses two phase-only SLMs as both information presentation devices and programmable lenses. The proposed system enables easy adjustment of the lateral and axial optical alignments. We experimentally confirmed the effectiveness of the proposed correlator. We also investigated the performance of the SLMs used in the experiments as programmable lenses. The results show that the focus efficiency decreases when the focal length of the FLPs becomes short, but near diffraction-limited focus spots can be obtained even with FLPs of short focal lengths.

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