Published in Optics Letters 19, issue 1, 1-3, 1994
which should be used for any reference to this work


# Electrically switchable diffractive optical element for image processing

**M. Stalder**

*Paul Scherrer Institute Zürich, Badenerstrasse 569, 8048 Zürich, Switzerland*

**P. Ehbets**

*Laboratoire de Microtechnique, Université de Neuchâtel, 2000 Neuchâtel, Switzerland*

An electrically switchable diffractive optical element has been built based on a computer-generated phase hologram and a liquid-crystal layer. The design of the diffractive optical element and the fabrication and performance of the device are discussed. The application of the device in a machine vision system for optical surface inspection is shown.

In machine vision applications often a substantial amount of image data has to be processed quickly. There exist vision problems in which the image processing can be performed with optical components, resulting in an instantaneous parallel processing of the image data. A nontrivial example of such a device is presented in this Letter.

The motivation for this research is image processing for textured surface inspection. It was found that fractal analysis is an adequate mathematical tool for extracting valuable roughness information from gray value images.[1] Optical image processing has recently been applied to this task.[2] A focused image and an image convolved with a Gaussian function are needed for the analysis. Using the switchable diffractive optical element (DOE) described below, one can deliver the two required images onto the image sensor within a fraction of a second.

In coherent optical system the complex amplitude of the output image is given by the convolution of the complex input object with the coherent impulse response $h(x)$ of the imaging system,[3] with $x$ describing the one- or two-dimensional spatial coordinates. For incoherent light, the intensity of the output image is given by a convolution of the input intensity object with the incoherent impulse response or point- spread function (PSF) $H(x)$, where $H(x) = |h(x)|^2$. In our case incoherent illumination is chosen, because a convolution with the input intensity image is needed. Incoherent light is also preferred, because of reduced speckle noise compared with that of systems that use coherent light.

The DOE responsible for the desired convolution is placed preferably into the exit pupil plane or between the focusing optics and the image sensor. To obtain the best signal-to-noise ratio, we chose a phase DOE, described by $\Phi(x)$, with a continuous surface profile leading to a high diffraction efficiency. The modified PSF is then given by the convolution of the imaging system's PSF with the Fourier transform of the additional phase DOE.

To obtain a simple beam path for our imaging system, we use liquid crystals (LC's) with their electrically adjustable index of refraction on top of the computer-generated DOE, resulting in a device that permits switching between the normal system PSF and the desired Gaussian PSF.

The nematic LC molecules used in our experiments are rod shaped and ~2 nm long. LC molecules have a strong tendency to be aligned parallel to one another on a microscopic scale.[4] For the macroscopic alignment, thin uniformly rubbed polyimide layers are used. The chosen LC's align parallel to the rubbing direction. If the LC's are confined between two uniaxially rubbed substrates, a uniaxial birefringent plate results, with the optical axis parallel to the rubbing direction. The ordinary and extraordinary indices of refraction of the LC are given by $n_o$ and $n_e$, respectively. If a uniaxially oriented device is equipped with transparent electrodes, it is possible to control the index of refraction of the LC from $n_e$ to $n_o$ for linearly polarized light oriented parallel to the rubbing direction by application of an electric field. This is because the chosen nematic LC molecules align parallel to the electric field. By replacement of one of the alignment layers in such a device with a thin surface profile phase DOE, it is possible to control the optical influence of the DOE in one polarization direction by applying an electric field. If the index of refraction of the DOE is equal to the index of refraction of the LC, the device acts as a plane-parallel plate. For a certain index-of-refraction difference between the LC and the DOE, adjustable by the applied voltage, the desired influence of the DOE appears. A cross section through the fabricated device is shown in Fig. 1.

Because of the Fourier relation between the coherent impulse response and the phase profile of the DOE in the imaging system, one has to find a phase function $\exp[i\Phi(x)]$, whose Fourier transform leads to the desired PSF.[3] For a periodic DOE with multiple periods illuminated, a discretized PSF ap-

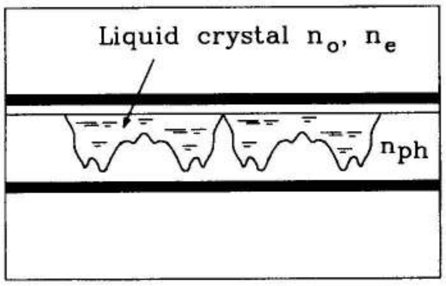


Fig. 1. Cross section of the switchable DOE device. ITO, indium tin oxide.

pears, which would result in unwanted aliasing in the image sensor. We therefore choose to illuminate a single period of the DOE, which should result in a continuous PSF. Various methods have been described to solve such problems, for instance, the iterative error reduction algorithm by Gerchberg and Saxton[5] and its popular modifications introduced by Fienup[6] and by Wyrowski and Bryngdahl.[7] The PSF of interest for our application is a two-dimensional Gaussian function. In this case the convolution is separable, and therefore only one coordinate will be considered for the iteration.

Now a short description of the two-step algorithm for determining the phase profile $\Phi(x)$ of the DOE is given. First Fienup's input–output algorithm is utilized. Because of the high sensitivity of the algorithm to the start phases, which are superimposed upon the target amplitude function, many different random start phases are generated. For each start value 30 iteration loops are performed. The maximum of the local mismatch $\Delta R$ between the Gaussian PSF and the PSF resulting from the iterated DOE is determined. To obtain a fast response from the used LC layer, which will cover the DOE, we must produce a surface profile with a shallow profile depth. The maximum phase modulation depth $\Phi_{max}$ is therefore calculated simultaneously in each run. Figure 2 shows the result from 2000 runs, where the $\Phi_{max}$ is plotted against the $\Delta R$. It is seen from Fig. 2 that solutions with a broad variety of maximum errors and phase modulation depths result for the chosen iteration algorithm. Solutions with a $\Delta R$ of less than 10% and a $\Phi_{max}$ of less than 6 rad can be found. In the second step a Gerchberg–Saxton algorithm is applied to the best solutions found in the previous step. During this process, only the large-deviation points in the PSF domain are corrected. This results in a significant drop of the $\Delta R$ within the next tens of iteration loops. The $\Phi_{max}$ is only very weakly influenced by this last procedure. Solutions with a $\Delta R$ of a less than 1% are typically obtained.

The calculated DOE is designed for a single-period square-shaped illumination. Any practical imaging system, however, has a circular aperture, and therefore errors in the resulting PSF are expected. Another source of high-frequency intensity fluctuations is the permitted phase freedom in the image plane used in the calculation. A possibility for reducing these intensity fluctuations is to use the oversampling concept.[7] Because of the large pixel size of the used image sensor, these fluctuations are essentially averaged out. The iterative algorithm proposed by Wyrowski leads to an unwanted deeper surface profile depth and is therefore not pursued any further.

A good solution, leading to the fabricated DOE, with a $\Phi_{max}$ of 5.3 rad is converted into a two-dimensional surface profile, with a maximum profile depth of $S_{max} = \Phi_{max}\lambda/(\pi\Delta n)$. $\lambda$ is the wavelength of the light used, and $\Delta n$ is the index-of-refraction difference between the DOE and the LC. For $\lambda = 0.63\ \mu m$ and $\Delta n = 0.14$ (see below) an $S_{max}$ of 7.6 $\mu m$ results. Because of the adjustable index of refraction of the LC, which covers the DOE, the same DOE is also useful for incoherent light at 0.59 $\mu m$ from a sodium-vapor lamp.

The material that carries the DOE is a photoresist (Shipley S1650) with an index of refraction of $n_{ph}$ = 1.64 and that is spin coated onto a glass substrate. The top of the glass substrate is covered with a transparent conductive layer of indium tin oxide. The calculated DOE is written into the photoresist with a HeCd laser-beam writer with a beam diameter of 7.7 $\mu m$. This laser-beam writing system is described in more detail by Gale *et al.*[8] The fabricated DOE has a profile depth of 7.6 $\mu m$, and the photoresist layer is 10 $\mu m$ thick. The period of the fabricated device is 1.6 mm. The surface profile of the DOE is modulated smoothly, with a steepest slope of ~3°. For our application a LC has been chosen (Hoffmann-LaRoche 3010) for which the $n_e = 1.64$ is equal to the index of refraction of the photoresist. Hence, with linear polarized light parallel to the rubbing direction and no electric field applied to the device, the influence of the DOE is switched off. For a sufficiently high applied voltage and the same polarization direction, an index of refraction $n_o = 1.5$ of the LC results, leading to a usable index-of-refraction difference $\Delta n = 0.14$ between the DOE and the LC. As a consequence the influence of the DOE is switched on.

LC's with a high birefringence $(n_e - n_o)$ are preferred, because they require shallow phase profiles and result in fast response times, as the response time of the LC layer is proportional to the square of the layer thickness. It is interesting to note that our iterative algorithm is able to produce phase profiles

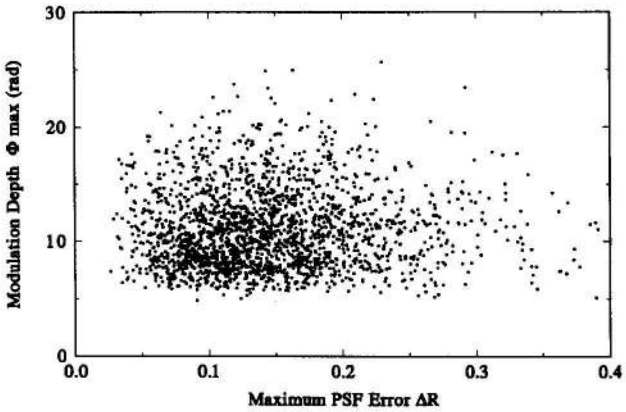


Fig. 2. Maximum PSF errors $\Delta R$ and phase profile depths $\Phi_{max}$ resulting from 2000 runs with the iterative algorithm.

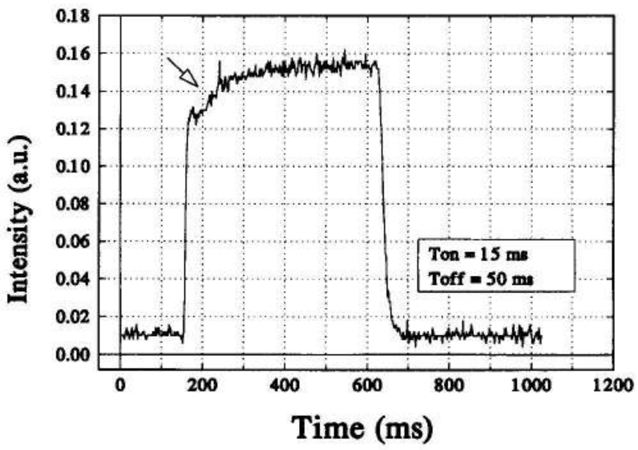


Fig. 3. Switching behavior of the switchable DOE.

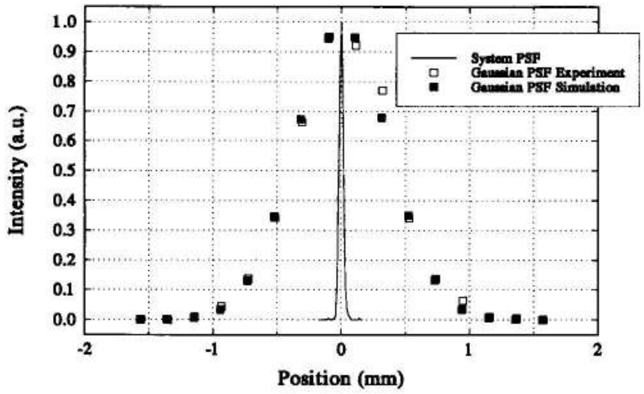


Fig. 4. Measured and simulated Gaussian PSF; the PSF of the imaging system is also given.

with a depth of less than $2\pi$ rad (see Fig. 2). Phase profiles with a depth of greater than $2\pi$ rad could be cut down to $2\pi$ rad. This is not practical since discrete phase jumps cannot be fabricated and steep surface profiles disturb the parallel alignment of the LC molecules. The calculated DOE with a profile depth of 5.3 rad is shallower than any modulo $2\pi$ element, and, because of the reduced depth, the LC response times are 40% shorter.

The measured response times of the switchable DOE are shown in Fig. 3. The device exhibits a short rise time of ~15 ms for an applied rms voltage of 20 V. The switching-off time is ~50 ms. The slower rise, indicated by the arrow in Fig. 3, is due to unwanted formation of transient LC defects, called disclination lines,[4] which act as scattering centers. The disclination lines occur because of the nonplanar surface profile of the DOE. Most of the defects disappear again within more than 100 ms.

Using a He–Ne laser, we measured the influence of the switchable DOE on the PSF, and the results are displayed in Fig. 4. In the first step the PSF of the system is measured in the absence of the device (Fig. 4, solid curve). Then the DOE is inserted in the switched-off state. Slight distortions are visible. The additional background noise is less than 2.5% of the peak intensity. These distortions are not crucial, because in the final imaging system the relative size of the sensor pixels will be much larger and the additional noise will be averaged out. Finally the DOE is switched on. High-frequency intensity modulations are observed in the PSF, as expected and described above. The resulting PSF is shown in Fig. 4. Here the image taken with the camera is averaged over many pixels to simulate the detector geometries for our ultimate imaging system, which was not available when the measurements were made. A simulation of the detector response to the theoretical Gaussian PSF is also given in Fig. 4. A good match is obtained.

It has been shown that the combination of a DOE and LC's leads to a switchable device with interesting properties and applications. Such devices are especially appropriate in cases in which the flexibility of expensive spatial light modulators is not needed. Compared with the use of spatial light modulators, significantly smaller pixel sizes can be obtained, and switching speeds of the order of milliseconds are possible. The device described works only in one polarization direction, but, by a combination of two of them, a polarization-independent optical component results. For the mass production of such devices, the DOE would be embossed or cast in a polymer.[8]

The device described can also be used as a static optical component, having two different PSF's depending on the chosen polarization direction. When the device is combined with a fast LC polarization rotator, considerably higher switching speed can be obtained.

This research was supported in part by the Swiss foundation Kommission zur Förderung der wissenschaftlichen Forschung (project 2139.1) and the Board of the Swiss Federal Institutes of Technology.

## References

1. U. Müssigmann, in *Fractals in the Fundamental and Applied Sciences,* H. O. Peitgen, ed. (North-Holland, Amsterdam, 1991), p. 269.
2. P. Seitz, M. Stalder, J. M. Raynor, G. K. Lang, C. Claeys, I. Debusschere, N. Ricquir, G. Gilia, C. Cavanna, U. Muessigmann, and A. Abele, Proc. Soc. Photo-Opt. Instrum. Eng. (to be published).
3. J. W. Goodman, *Introduction to Fourier Optics* (McGraw-Hill, New York, 1969), Chap. 5-2, pp. 83ff; Chap. 6-2, pp. 110ff; Chap. 6-3, pp. 113ff.
4. S. Chandrasekhar, *Liquid Crystals,* 2nd ed. (Cambridge U. Press, Cambridge, 1992), Chap. 1.1.1, p.1; Chap. 5.3, pp. 117ff.
5. R. W. Gerchberg and W. O. Saxton, Optik **35,** 237 (1972).
6. J. R. Fienup, Opt. Eng. **19,** 297 (1980).
7. F. Wyrowski and O. Bryngdahl, J. Opt. Soc. Am. A **5,** 1058 (1988).
8. M. T. Gale, M. Rossi, H. Schütz, P. Ehbets, H. P. Herzig, and D. Prongué, Appl. Opt. **32,** 2526 (1993).