Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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To cite this Article Gitin, A. V. and Tomilin, M. G.(1993) 'Controllable source-object light scattering imaging in optical systems', Liquid Crystals, 14: 6, 1953 — 1957
To link to this Article: DOI: 10.1080/02678299308027731
URL: http://dx.doi.org/10.1080/02678299308027731

LIQUID CRYSTALS, 1993, VOL. 14, NO. 6, 1953–1957

Controllable source-object light scattering imaging in optical systems

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The imaging process in an ideal optical system with an essentially inhomogeneous source-object, based on a liquid crystal, is discussed.

1. Introduction

In references [1–3], the quasihomogeneous source-object indicatrix effect on the imaging process in ideal and isoplanar optical systems has been described. In the present paper, for the first time, we make an attempt to describe the imaging process in an ideal optical system with an essentially inhomogeneous source-object, specifically with a source homogeneous in luminosity that is, however, controlled by the light scattering indicatrix.

This problem is of practical importance owing to the advent of display devices based on controllable light scattering effects, for example, liquid crystal (LC) displays [4] and vesicular films. The salient feature of these display devices is that the illuminance distribution over the retina of an observer's eye is formed not by the luminance variation (as is the case in conventional display devices), but by the variation of the light scattering indicatrix pattern; in fact, the luminance varies insignificantly. In this case the observer's eye can be considered as an example of an ideal optical system.

2. The imaging process in an ideal optical system with an inhomogeneous source-object

Let us examine the imaging process in an ideal optical system which is carried out by variation in the indicatrix pattern of a luminance-homogeneous source-object similarly to an LCD based on the electrically controlled light scattering effect. The technique, presented in [1–3], considered the effect of a source-object indicatrix pattern on the illuminance distribution over the image plane. In essence this technique suggests the use of the 'speed' in terms of hamiltonian optics

$$\dot{r}=\frac{dr}{dz}=(\tan\theta\sin\phi,\tan\theta\cos\phi)$$

to specify the direction of radiation propagation in real space with cartesian coordinates $(r,z)=(x,y,z)$, rather than the use of angles in spherical coordinates (θ,ϕ). The convenience of this description is due to the plane-parallel arrangement at the beam-limiting apertures, typical for the ideal optical system. This implies that the difference in angles $\Delta\theta=\theta_1-\theta_2$, at which the edge of the entrance pupil is seen from a point $r=(r,0)$ in the source-object plane, see figure 1, decreases with the source

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element offset $d\dot{r}$ from the optical axis

$$\lim_{|\dot{r}|\to 0} \Delta\theta = 0,$$

while the tangent difference of these angles $\Delta \tan\theta = \tan\theta_1 - \tan\theta_2$ is constant and does not depend on the offset $|r|$.

$$\Delta \tan\theta = \text{const.} \quad \text{by any } |r| \text{ (see figure 1).}$$

The distribution of the source-object light flux F over the surface plane and along the directions in space can be defined both by the specific light intensity $I(\theta,\phi,r)$

$$d^2F = I(\theta,\phi,r)\, d\Omega\, dr,$$

where $d\Omega = \sin\theta\, d\theta\, d\phi$ is the spatial angle element, and by the specific light-tan intensity $G(\dot{r},r)$

$$d^2F = G(\dot{r},r)\, d\dot{r}\, dr.$$

In the case of the axially symmetric source, its specific light tan-intensity and conventional specific light intensity are connected by a simple relation

$$G(|\dot{r}|,r) = I(\arctan|\dot{r}|,r)\cos^3\theta(|\dot{r}|),$$

where

$$\cos^2\theta(|\dot{r}|) = \frac{1}{1+|\dot{r}|^2}.$$

Let us consider an optical system with the entrance pupil as a screen with a hole whose shape is described by the flux transmission distribution function $\tau(r_z)$. Let z be the distance from the object plane $\{r\} = \{(r,0)\}$ to the entrance pupil plane. It was shown in [1-3] that the propagating illuminance distribution E forming in the image plane is described by the integral expression

$$E(r') = \frac{1}{m^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G\left(\frac{r'}{m},\dot{r}\right)\tau\left(\frac{r'}{m}+z\dot{r}\right) d\dot{r}, \tag{1}$$

where m is the linear magnification of the optical system.

In the case of the quasihomogeneous source [1-3], that is, a source whose luminance $M(r)$ and tan-indicatrix $g(\dot{r})$ ('source transfer function') [2] are independent

$$G(\dot{r},r) = M(r)g(\dot{r})$$

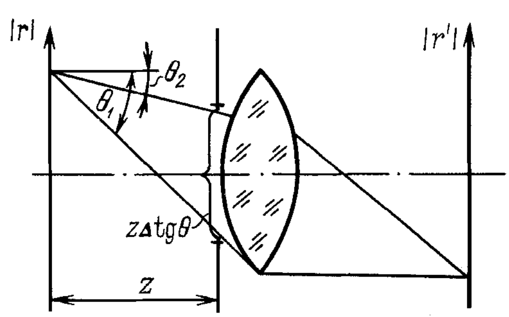

Figure 1. Optical system: entrance pupil light beam limiting function.

the general expression (1) takes the form of convolution

$$E(r') = \frac{1}{m^2} M\left(\frac{r'}{m}\right) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(\dot{r}) \tau\left(\frac{r'}{m} + z\dot{r}\right) d\dot{r}. \tag{2}$$

Provided that the size of the entrance pupil can be neglected, the pupil function $\tau(r_z)$ can be assumed to be proportional to the Dirac delta function

$$\tau(r_z) \sim \delta(r_z).$$

Then, in accordance with the delta function filtering property, expression (2) takes the form

$$E(r') = \left(\frac{1}{mz}\right)^2 M\left(\frac{r'}{m}\right) g\left(\frac{r'}{mz}\right). \tag{3}$$

Thus, in the case of the pinhole entrance pupil and the quasihomogeneous source, the illuminance distribution $E(r')$ over the image plane is related to the source tan-indicatrix by purely a scale transformation and, consequently, the indicatrix bordering causes less illuminance drop from the centre to the image edge (see figure 2).

It should be noted that the illuminance of a point in the image plane grows in at one place and falls at another place, with the tan-indicatrix changing from $g_1(r)$ to $g_2(r)$. This effect can be conveniently described by the contrast function $k(r')$

$$k(r') = \frac{E_1(r') - E_2(r')}{E_1(r') + E_2(r')}, \tag{4}$$

where $E_1(r')$ and $E_2(r')$ are the illuminance distributions formed by the quasihomogeneous source with tan-indicatrices $g_1(\dot{r})$ and $g_2(\dot{r})$, respectively (see figure 2).

Since the illuminance of the image plane element of an ideal optical system is supposed to depend only on the light flux emitted by the optically conjugated point of the source-object, one can make use of the 'superposition principle'. This implies the following procedure: speculatively break up the plane of the arbitrary source into zones wherein the quasihomogeneity condition is satisfied, then using equations (2) or (3) calculate the illuminance distribution in optically conjugated 'zones' of the image plane of the ideal optical system, and combine the results obtained.

An information display device based on a controllable light scattering effect can be treated as an essentially inhomogeneous source-object. We restrict our study to the case of a luminance-inhomogeneous source-object with only two indicatrix

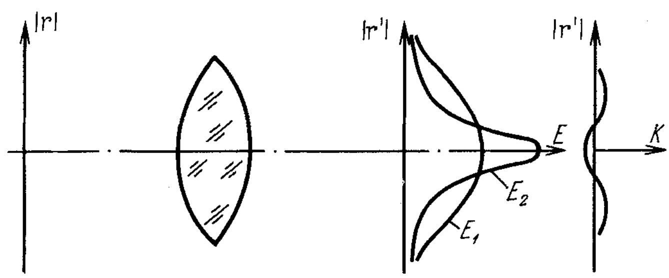

Figure 2. Contrast function.

grades. Then the source surface A can be speculatively broken up into the 'signal' zone A_1

$$A_1=\{(r):G(\dot{r},r)=g_1(\dot{r})\}$$

and the 'background' zone A_2

$$A_2=\{(r):G(\dot{r},r)=g_2(\dot{r})\}$$

(both zones correspond to homogeneous sources with the tan-indicatrices $g_1(\dot{r})$ and $g_2(\dot{r})$, respectively), the

$$A=A_1\cup A_2$$

condition being fulfilled. Using equation (1), let us calculate the illuminance distributions, as over the image plane, for each 'zone' and plot them in figure 3 with the dashed curves.

An arbitrary point r in the image plane may fall into two situations: if $r\in A_1$, or $r\in A_2$, the curve should be chosen corresponding to the first or to the second indicatrix, respectively. The illuminance drop in the zone boundaries that is equal to $k(r')$ [4] will characterize the 'contrast' of the 'signal' and 'background' image elements. It is clear that this contrast (see figure 2) depends both on 'signal' and 'background' indicatrix patterns (that are the features of the display itself) and on the displacement of the point to the image edge.

It should be noted that the use of the 'contrast' concept for estimating the display device efficiency is convenient, subject to contrast constancy over the observer's field of view. Since in the case under study this condition is not met, the conventional contrast concept is inapplicable to estimating the performance of displays based on controllable light scattering effects. One can use the envelope of the family of light scattering indicatrices, obtained at different control voltages, as an analogue of the voltage-contrast characteristic for the displays, based on the dynamic light scattering effect. This envelope describes the tan-indicatrix width as a function of voltage. A similar speculation can be applied to display devices with an arbitrary number of grades of the indicatrix pattern.

3. Conclusion

For the first time source-object indicatrix-variable imaging in an ideal optical system has been described. The description presented here should be treated as a

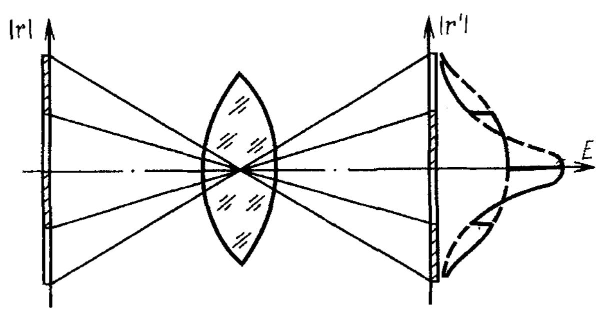

Figure 3. Picture-forming process by displays with a voltage controllable light scattering effect. Hatched portion = 'signal' area, and the unhatched portion = 'background' area.

model of a display operating on the controllable light scattering effect. The conventional contrast concept is shown to be inapplicable for estimating the efficiency of such displays. The envelope of the family of indicatrices is suggested for use as an analogue of the voltage–contrast characteristic for these displays.

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