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Robert A. Lee, "Micromirror array nanostructures for anticounterfeiting applications," Proc. SPIE 5310, Optical Security and Counterfeit Deterrence Techniques V, (3 June 2004); doi: 10.1117/12.523919

SPIE.

Event: Electronic Imaging 2004, 2004, San Jose, California, United States

Micro mirror array nanostructures for anti-counterfeiting applications

Robert Lee

CSIRO Manufacturing & Infrastructure Technology, Gate 4, Normanby Road, Clayton, Victoria
3168, Australia.

ABSTRACT

The optical characteristics of pixellated passive micro mirror arrays are derived and applied in the context of their use as reflective optically variable device (OVD) nanostructures for the protection of documents from counterfeiting. The traditional design variables of foil based diffractive OVDs are shown to be able to be mapped to a corresponding set of design parameters for reflective optical micro mirror array (OMMA) devices. The greatly increased depth characteristics of micro mirror array OVDs provides an opportunity for directly printing the OVD microstructure onto the security document in-line with the normal printing process. The micro mirror array OVD architecture therefore eliminates the need for hot stamping foil as the carrier of the OVD information, thereby reducing costs. The origination of micro mirror array devices via a palette based data format and a combination electron beam lithography and photolithography techniques is discussed via an artwork example and experimental tests. Finally the application of the technology to the design of a generic class of devices which have the interesting property of allowing for both application and customer specific OVD image encoding and data encoding at the end user stage of production is described. Because of the end user nature of the image and data encoding process these devices are particularly well suited to ID document applications and for this reason we refer this new OVD concept as biometric OVD technology.

1. Introduction

The purpose of this paper is to describe a new approach to the design of optically variable devices (OVDs) for anti-counterfeiting applications. In particular we shall address the triad of problems related to improving the security of OVD optical effects, in-line replication of the resultant image and lowering the cost of originations. As an example of the application of the new design scenario we shall describe a new approach to the design of customized OVDs for identification document (ID) applications.

The most important step change underpinning the new OVD approach is the replacement of micro diffraction grating elements within the OVD architecture by arrays of micro mirror elements. Optical Micro-Mirror Array (OMMA) devices will be shown to offer the best hope of creating OVDs with sufficient microstructure depth to allow for direct printing onto the document substrate via the use of specialized reflective inks. The objective here is to do away with the current practice involving the costly intermediate step of producing an embossed hot stamping foil as the carrier of the OVD microstructure.

In the diffractive case the diffraction grating groove spacings must be of the order of the wavelength of light in order for diffraction effects to take place. The depth of the grooves is related to the spacing by nature of the origination process, whether by electron beam lithography or laser interference techniques, and this limited groove depth capability (usually much less than 1 micron) is the main reason diffractive OVD microstructures are unable to be printed by normal printing techniques. The roughness of the substrate surface is normally of much greater depth than the surface relief of the diffractive microstructure. Micro mirror devices on the other hand are not so limited in their microstructure depth characteristics. For example a micro mirror array of 60 micron square micro mirror pixels inclined at an average angle of 30 degrees to the horizontal would have an average microstructure depth of $60 \times \sin(30) = 30$ microns. It is this greatly increased depth characteristic that holds out the promise of being able to directly print the OVD microstructure.

The concept of direct print OMMA devices was first proposed several years ago^{1,2,3} by the present writer in the

context of a new micro-technology lithography process called “Colourtone Lithography”. The characteristics of the fabrication process for such optical arrays have been further discussed in the context of greytone lithography by Leech and Zeidler⁴. Here we first describe the optical characteristics of these OMMA devices by way of an isomorphic relationship to the well known optical characteristics of diffractive OVDs. We then discuss the optical security and design aspects of the two types of technologies and show how the devices may be originated using a combination of palette based electron beam lithography and photolithography techniques. It will then be shown how particular classes of generic OMMA devices can be used as recordable substrates for custom-specific OVDs for ID document applications. During the course of these discussions we shall also briefly describe the embossing of OMMA microstructures into transparent polymer substrates to produce counterpart Optical micro prism arrays for authentication of transparent security substrates.

2. Optical properties of pixellated micro mirror arrays

Consider the pixellated surface relief microstructure array shown in figure 1. This array is comprised of a multiplicity of 30 micron X 30 micron pixels, where each pixel is drawn from a palette of a finite number of different types of surface relief microstructures. We will first analyse the optical properties of the pixels in the case where each pixel acts upon the incoming light wave in a purely reflecting manner. We will then consider the alternative case where each pixel is a miniature diffraction grating consisting of an array of regularly spaced grooves of curvilinear form and in this way show how the two OVD scenarios are isomorphic in their optical properties. We will then analyse the structural stability and imaging properties of micro mirror arrays and in this way demonstrate how micro mirror arrays can be designed with predetermined optical properties best suited to security applications on flexible substrates.

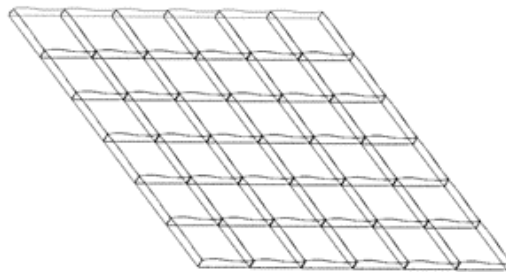


Figure 1. Pixellated surface relief microstructure array

2.1 Ray equations

Figure 2 shows a single reflecting pixel element of arbitrary surface form illuminated by a point light source at “A”, a distance R_{00} from a point “P” on the pixel surface and producing a reflected optical field. Point “B” is a point in the reflected optical field, a distance R_{10} from the point P. “O” is the origin of the coordinate system and X_0, Y_0, Z_0 represents the coordinates of the source point “A”, while X_1, Y_1, Z_1 are the coordinates of the point “B”. X, Y, Z are the coordinates of point P on the surface of the pixel.

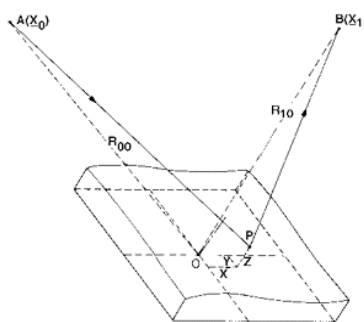


Figure 2. Pixel optical geometry

In the analysis of the optical properties of the reflecting pixel we shall apply scalar wave optics as represented by the Kirchoff integral and Huygen's principle, where each point on an optical wavefront propagates by acting as a secondary source of spherical waves. In figure 2 the surface relief characteristics of the pixel in the reflecting case may be described by the function $Z = Z(X, Y)$, where Z is the height of the surface above the X, Y plane. Therefore the components of unit normal vector $\underline{n}$ at the point X, Y is given by:

$$\hat{n}_x = \frac{\partial Z}{\partial X} \left[\frac{1}{\sqrt{1 + (\nabla Z)^2}} \right] \text{-----(1)}$$

$$\hat{n}_y = \frac{\partial Z}{\partial Y} \left[\frac{1}{\sqrt{1 + (\nabla Z)^2}} \right] \text{-----(2)}$$

$$\hat{n}_z = \left[\frac{1}{\sqrt{1 + (\nabla Z)^2}} \right] \text{-----(3)}$$

where ∇Z is the two component grad function in X, Y coordinates. The square root factor multiplied by the Cartesian differentials determines an element of area on the pixel surface. In terms of the Kirchoff integral the optical field at point B is given by:

$$F(X_1, Y_1, Z_1) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} A(\underline{X}; \underline{X}_0, \underline{X}_1) \exp[ik\Phi(\underline{X}; \underline{X}_0, \underline{X}_1)] dX dY \text{-----(4)}$$

where the amplitude function $A(\underline{X}; \underline{X}_0, \underline{X}_1)$ is given by;

$$A(\underline{X}; \underline{X}_0, \underline{X}_1) = -(i/2\lambda) [(\underline{AP} + \underline{BP}) \cdot \underline{n} / (<AP> + <BP>)] (1 + (\nabla Z)^2)^{1/2} \text{-----(5)}$$

and the optical path length function or phase function $\Phi(\underline{X}; \underline{X}_0, \underline{X}_1)$ is given by;

$$\Phi(\underline{X}; \underline{X}_0, \underline{X}_1) = <AP> + <BP> \text{-----(6)}$$

The magnitudes of the vectors $\underline{AP}$ and $\underline{BP}$ are given by:

$$<AP> = [(X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2]^{1/2} \text{ and } <BP> = [(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2]^{1/2} \text{ and}$$

$\underline{n}$ is the three component unit vector with components given by (1), (2) and (3) above. In the above expressions the underlined type denotes the three dimensional vector nature of the symbol.

Now a geometric optics approximation to the optical field function $F(\underline{X}_1)$ can be obtained by employing the method of stationary phase.

According to this method, the dominant contribution to the integral in the short wavelength limit arises from those points where the phase of the integrand is stationary.

$$\nabla_{\underline{X}} \Phi(\underline{X}; \underline{X}_0, \underline{X}_1) = 0 \text{-----(7)}$$

The classical intensity distribution, which follows from the stationary phase approximation, is given by:

$$I(\underline{X}_0, \underline{X}_1) = \sum_{\underline{X}_\alpha} \left[\frac{|A(\underline{X}_\alpha, \underline{X}_0, \underline{X}_1)|^2}{|J(\Phi)|} \right] \text{-----(8)}$$

where $J(\Phi)$ is the Jacobian of the transformation from the $\underline{X}$ space to $\underline{X}_1$ space and is given by the hessian of second derivatives of the phase function;

$$J(\Phi) = \frac{\partial^2 \Phi}{\partial X^2} \frac{\partial^2 \Phi}{\partial Y^2} - \left[\frac{\partial^2 \Phi}{\partial X \partial Y} \right]^2 \text{-----(9)}$$

Now, according to equation 8, the reflected light intensity from the micro mirror pixel will be infinite whenever the Jacobian vanishes. This obviously non-physical result is due to the fact that the stationary phase method is not valid for stationary points which cause the Jacobian to vanish. A more detailed analysis⁵ of integrals of the form shown in equation 4 using a uniform approximation⁶ shows that the amplitude is not infinite when the Jacobian vanishes, just very large in comparison to regions where $J(\Phi)$ does not vanish. The set of points in $\underline{X}_0, \underline{X}_1$ space corresponding to the points in $\underline{X}$ space where the Jacobian vanishes is referred to as the caustic line pattern of the micro mirror pixel. From a security device design point of view, it is important, for easy visibility of the images, to maximize the optical brightness of the reflected light from the micro mirror pixels. It is also important from a durability point of view, that the reflected light patterns, and therefore the pixel optical effects, from each micro mirror pixel should be relatively stable with respect to bending or flexing perturbations of the micro mirror pixels due to crinkling or bending of the security document surface as a result of normal wear and tear. Finally, it is also preferable that the optical effects generated by the pixel reflections should have some unique characteristics so that the optical properties of the device are much more difficult to simulate by other means. An understanding of these three key attributes; optical brightness, image stability and uniqueness, for particular surface profiles $Z(X,Y)$ is most easily obtained through a study of the Jacobian function described above. The calculation of the imaging properties of the OMMA device requires the further calculation of a set of micro mirror ray equations. Exact expressions for these generalized pixel ray equations can be obtained by substituting the expressions for the vectors $\underline{AP}$ and $\underline{BP}$ into equation 6 and the result into equation 7. The ray equations are then given by;

$$(N_0 + N_1) \frac{\partial Z}{\partial X} + L_0 + L_1 = 0 \text{-----(10)}$$

$$(N_0 + N_1) \frac{\partial Z}{\partial Y} + M_0 + M_1 = 0 \text{-----(11)}$$

where the direction cosines of the incident and reflected rays are given by;

$$L_0 = (X - X_0)/\langle AP \rangle \text{-----(12a)}, \quad L_1 = (X - X_1)/\langle BP \rangle \text{-----(12b)},$$

$$M_0 = (Y - Y_0)/\langle AP \rangle \text{-----(12c)}, \quad M_1 = (Y - Y_1)/\langle BP \rangle \text{-----(12d)},$$

$$N_0 = (Z - Z_0)/\langle AP \rangle \text{-----(12e)}, \quad N_1 = (Z - Z_1)/\langle BP \rangle \text{-----(12f)},$$

In the case where the source point and observation point are at relatively large distances from the micro mirror surface (compared to characteristic micro mirror pixel dimensions) the light path functions may be approximated to the following much simpler forms;

$$\langle AP \rangle \approx R_{00} + \left[\frac{X^2 + Y^2 + Z^2}{2R_{00}} \right] - (XU_0 + YV_0 + ZW_0) \text{-----(13a)}$$

$$\langle BP \rangle \approx R_{10} + \left[\frac{X^2 + Y^2 + Z^2}{2R_{10}} \right] - (XU_1 + YV_1 + ZW_1) \text{-----(13b)}$$

where,

$$R_{00} = [X_0^2 + Y_0^2 + Z_0^2]^{1/2} \text{-----(14a)}, \quad R_{10} = [X_1^2 + Y_1^2 + Z_1^2]^{1/2} \text{-----(14b)}$$

and the incident and reflected angle functions are given by; $U_0 = X_0/R_{00}$, $V_0 = Y_0/R_{00}$, $W_0 = Z_0/R_{00}$, $U_1 = X_1/R_{10}$, $V_1 = Y_1/R_{10}$ and $W_1 = Z_1/R_{10}$. The micro mirror pixel ray equations are now obtained by substituting the expressions for $\langle AP \rangle$ and $\langle BP \rangle$ in equations 13 into equation 6 and the result into equation 7 to give:

$$U_0 + U_1 = \frac{X}{R} + \left(\frac{Z}{R} - W_0 - W_1 \right) \frac{\partial Z}{\partial X} \text{-----(15a)}$$

$$V_0 + V_1 = \frac{Y}{R} + \left(\frac{Z}{R} - W_0 - W_1\right) \frac{\partial Z}{\partial Y} \text{-----(15b)}$$

where $(1/R) = (1/R_{00}) + (1/R_{10})$. Therefore, in the case of relatively distant illumination sources and human eye observation of the micro mirror pixel image, the ray equations reduce to the following far field reflection ray equations (obtained by letting R approach infinity);

$$U_0 + U_1 = -(W_0 + W_1) \frac{\partial Z}{\partial X} \text{-----(16a)}$$

$$V_0 + V_1 = -(W_0 + W_1) \frac{\partial Z}{\partial Y} \text{-----(16b)}$$

Now W_0 and W_1 satisfy the identities, $W_0 = [1 - U_0^2 - V_0^2]^{1/2}$ and $W_1 = [1 - U_1^2 - V_1^2]^{1/2}$ and therefore in the case where the micro mirror is being illuminated from directly above the device $U_0 = V_0 = 0$ and therefore the pixel ray equations become;

$$U_1 = -\{1 + \sqrt{(1 - U_1^2 - V_1^2)}\} \frac{\partial Z}{\partial X} \text{-----(17a)}$$

$$V_1 = -\{1 + \sqrt{(1 - U_1^2 - V_1^2)}\} \frac{\partial Z}{\partial Y} \text{-----(17b)}$$

Upon simplification these expressions may be written in the more convenient form;

$$U_1 = -2 \frac{\partial Z}{\partial X} [1 + (\nabla Z)^2]^{-1} \text{-----(18a)}, \quad V_1 = -2 \frac{\partial Z}{\partial Y} [1 + (\nabla Z)^2]^{-1} \text{-----(18b)}$$

Therefore for normally illuminated micro mirror pixels of relatively small surface slope (e.g. gradients of less than 1 in 3) we obtain the even simpler set of pixel ray equations describing the paths of the reflected light beams;

$$U_1 = -2 \frac{\partial Z}{\partial X} \text{-----(19a)}, \quad V_1 = -2 \frac{\partial Z}{\partial Y} \text{-----(19b)}$$

Via a very similar analysis to the above⁷ it can be shown that a planar pixellated diffraction grating generates a set of generalized diffraction grating ray equations of similar form to the pixellated micro mirror reflected ray equations. The generalized pixel diffraction ray equations⁷ are given by:

$$U_0 + U_1 = -\lambda h \frac{\partial \Omega}{\partial X} \text{-----(20a)}, \quad V_0 + V_1 = -\lambda h \frac{\partial \Omega}{\partial Y} \text{-----(20b)}$$

where $\Omega(XY)$ is the generalized diffraction grating pixel grating function and the groove pattern of the grating is given by $\Omega(XY) = n$ where n is an integer describing the groove index number. λ is the wavelength of the incident light and "h" is the diffraction order number. Note that for the case of normal illumination of the pixel grating U_0 and V_0 reduce to zero, as in the case of pixel reflection.

From equations 19 and 20 it can be seen that the ray equations for diffraction from a generalized grating pixel are isomorphic to the ray equations for reflection from a generalized micro mirror pixel. The defining ray equations for both systems have the form of gradient mapping relationships between the plane of the OVD and the space of the reflected or diffracted optical field. However the presence of the wavelength and order number parameters in the diffraction grating case means of course that pixellated micro grating arrays generate colour effects as well as multiple versions of the same diffraction image. The redistribution of the scattered light into a set of multiple propagating diffraction orders (including the optically invariable zero order) can be a disadvantage in terms of image brightness compared to the micro mirror case where only a single reflected achromatic image is allowed to propagate.

Since the ray equations of micro mirror pixel reflection are isomorphic to the ray equations of micro grating diffraction, we have a method for designing micro mirror pixels that generate achromatic versions of all the optical

effects generated by diffractive optically variable devices. Secondly we can construct similar methods for analysing the structural stability properties of micro mirror pixels. Thirdly we can construct analogous versions of the imaging equations for micro mirror pixel arrays and compare the relative effectiveness of different optical effects within the two OVD scenarios. In all of this analysis we are driven by the key advantage offered by micro mirror arrays over their corresponding diffraction grating equivalents; - the promise of being able to construct OVD microstructures of much greater physical depth than any diffractive optical effect equivalent. This of course suggests that micro mirror OVDs may not require the use of hot stamping foil as the means of attaching the OVD to the security document. Instead, there is the possibility of directly printing the micro mirror OVD directly onto the document in-line with the intaglio printing process, thereby reducing costs and possibly also increasing the security of the manufacturing process.

2.2 Micro mirror array pixel image patterns

As shown above, the defining ray equations of a micro mirror pixel have the form of gradient mapping relationships. It therefore follows that the imaging equation resulting from illuminating a micro mirror pixel by an extended light source can be arrived at through a similar analysis to the case of micro diffraction grating pixels where, as shown previously, the operative ray equations are also of the form of gradient mapping relationships. The derivation of the imaging equation for the generalized diffraction grating case has been discussed in an earlier paper⁸ and the result, applied to the variables of the present case, is given by:

$$S(U_0 + U_1, V_0 + V_1) = 0 \text{ -----(21)}$$

where U_0 , U_1 , V_0 and V_1 are functionally related to the spatial coordinates of the OVD pixel according to equations 20a and 20b above. In the micro mirror pixel case the corresponding relationships for U and V are given by equations 19a and 19b in the case of normal illumination and micro mirror pixels of small slope. In equation 21, S is the function describing the geometric shape of the light source. For document security applications it is more often the case that the OVD is observed with the line of sight located at normal angles (90 degrees) to the OVD surface and the angles of illumination being much less than 90 degrees. In this case the micro mirror pixel ray equations are given by equations 18a and 18b, but with subscript "1" on the U and V coordinates replaced by "0" to signify that it is the light source angle that is operative angle variable. The pixel imaging equation is then given by;

$$S \left\{ -2 \frac{\partial Z}{\partial X} (1 + (\nabla Z)^2)^{-1}, -2 \frac{\partial Z}{\partial Y} (1 + (\nabla Z)^2)^{-1} \right\} = 0 \text{ -----(22)}$$

As discussed previously, for small mirror slopes we can, to a good approximation, neglect the terms quadratic in the gradient. As a simple application of equation 22, consider a reflective OVD illuminated by a thin line source, such as fluorescent tube orientated parallel to the X axis and at an angle corresponding to the direction cosine value of α with respect to the Y axis; that is $V_0 = \alpha$. In this case equation 22 becomes;

$$-2 \frac{\partial Z}{\partial Y} (1 + (\nabla Z)^2)^{-1} = \alpha \text{ -----(23)}$$

In the simplest case of a micro mirror pixel of fixed slope β we have $Z = \beta Y$ and therefore, after substituting into equation 23, the imaging equation becomes

$$\alpha = -2\beta/(1+\beta)^2 \text{ -----(24)}$$

Therefore the micro mirror pixel of constant mirror slope will only reflect light into the observer's eye when the light source is at an angle corresponding to almost twice the slope angle of the micro mirror. Any deviation from this angle will cause the micro mirror pixel to "switch off". In this sense micro mirrors pixels of constant fixed slope may be regarded as being "structurally unstable" in the sense that any perturbation of the OVD surface (e.g. caused by crinkling) will cause pixels to suddenly "switch off" when compared uncrinkled micro mirror surfaces observed at the same angle. This example demonstrates the close relationship between image brightness and structural stability. Ideally we would like to have both maximum brightness and maximum structural stability with respect to angular perturbations. However this is not possible, and there must always be some trade off between the two in practical situations, where increasing the degree of image point stability always comes with a reduction in brightness due to the

to expand the cone of reflected light in order to reduce the angular sensitivity of the beam to surface perturbations.

A typical micro mirror OVD image may be comprised of up to a million micro mirror pixels selected from a palette of a limited number of pixel types and distributed across the OVD surface according to the required picture information. As discussed above it is desirable (particularly for applications requiring easy recognisability under rough handling conditions) that the shape of the micro mirror pixel surfaces be designed to reduce the sensitivity of the image to crinkling perturbations. At the same time, as discussed above, it is important to ensure that such pixel surface modifications are of limited scope in order to not detract too much from the brightness of the resultant image. However, as will be discussed later, there are situations where the relationship between image brightness and micro mirror topology can be used to create new types of highly secure optical effects based on the idea of using angular modulation of the reflected beam to spatially modulate the intensity of a reflected OVD image.

2.3 Image brightness and structural stability

The issue of structural stability of diffraction grating images has been discussed by the present writer in previous papers⁹. The theory has also been successfully applied to the design particular classes of diffractive OVDs^{10,11,12} and has been applied to particular security document projects¹³, including as an essential part of the design of the first OVD used on a currency note; the Australian \$10 polymer banknote issued in January 1988. Here we will apply similar considerations to the design of pixellated micro mirror array OVDs.

As shown by equations 8 and 9 the reflected light intensity of a micro mirror pixel is at a maximum whenever the hessian of second derivatives of the optical phase function vanishes. As shown in the general diffractive case earlier⁷, this hessian condition, when applied to the reflective case, can be written in a form which makes clear the connection with pixel surface shape function $Z(X,Y)$.

The resulting Jacobian of the mapping transformation corresponding to optical rays reflected from a micro mirror pixel may be written in the form:

$$J(X,Y) = \Gamma_L \Gamma_M - \Gamma_{LM}^2 \text{-----}(25)$$

$$\Gamma_L = L_{0X} + L_{1X} + [N_{0X} + N_{1X}] \frac{\partial Z}{\partial X} + [N_0 + N_1] \frac{\partial^2 Z}{\partial X^2} \text{-----}(26a)$$

$$\Gamma_M = M_{0Y} + M_{1Y} + [N_{0Y} + N_{1Y}] \frac{\partial Z}{\partial Y} + [N_0 + N_1] \frac{\partial^2 Z}{\partial Y^2} \text{-----}(26b)$$

$$\Gamma_{LM} = L_{0Y} + L_{1Y} + [N_{0Y} + N_{1Y}] \frac{\partial Z}{\partial X} + [N_0 + N_1] \frac{\partial^2 Z}{\partial X \partial Y} \text{-----}(26c)$$

and the functional dependences on source and observation distances is described by the relationships;

$$L_{0X} = \frac{1}{R_0} \left[1 - L_0^2 - L_0 N_0 \frac{\partial Z}{\partial X} \right] \text{-----}(27a), \quad L_{1X} = \frac{1}{R_1} \left[1 - L_1^2 - L_1 N_1 \frac{\partial Z}{\partial X} \right] \text{-----}(27b)$$

$$L_{0Y} = -\frac{L_0}{R_0} \left[M_0 + N_0 \frac{\partial Z}{\partial Y} \right] \text{-----}(27c), \quad L_{1Y} = -\frac{L_1}{R_1} \left[M_1 + N_1 \frac{\partial Z}{\partial Y} \right] \text{-----}(27d)$$

$$M_{0X} = -\frac{M_0}{R_0} \left[L_0 + N_0 \frac{\partial Z}{\partial X} \right] \text{-----}(27e), \quad M_{1X} = -\frac{M_1}{R_1} \left[L_1 + N_1 \frac{\partial Z}{\partial X} \right] \text{-----}(27f)$$

$$M_{0Y} = \frac{1}{R_0} \left[1 - M_0^2 - M_0 N_0 \frac{\partial Z}{\partial Y} \right] \text{-----} (27g), \quad M_{1Y} = \frac{1}{R_1} \left[1 - M_1^2 - M_1 N_1 \frac{\partial Z}{\partial Y} \right] \text{-----} (27h)$$

$$N_{0X} = \frac{1}{R_0} \left[-L_0 N_0 + (L_0^2 + M_0^2) \frac{\partial Z}{\partial X} \right] \text{-----} (27i), \quad N_{1X} = \frac{1}{R_1} \left[-L_1 N_1 + (L_1^2 + M_1^2) \frac{\partial Z}{\partial X} \right] \text{-----} (27j)$$

$$N_{0Y} = \frac{1}{R_0} \left[-M_0 N_0 + (L_0^2 + M_0^2) \frac{\partial Z}{\partial Y} \right] \text{-----} (27k), \quad N_{1Y} = \frac{1}{R_1} \left[-M_1 N_1 + (L_1^2 + M_1^2) \frac{\partial Z}{\partial Y} \right] \text{-----} (27l)$$

where R_0 and R_1 are the source and observation distances given by $R_0 = \langle AP \rangle$ and $R_1 = \langle BP \rangle$.

In the case of relatively far field sources and observation distances, the usual case of observation of security OVDs in actual practice, equations 26a, 26b and 26c reduce to a much simpler form given by;

$$\Gamma_L = [N_0 + N_1] \frac{\partial^2 Z}{\partial X^2} \text{----} (28a), \quad \Gamma_M = [N_0 + N_1] \frac{\partial^2 Z}{\partial Y^2} \text{----} (28b), \quad \Gamma_{LM} = [N_0 + N_1] \frac{\partial^2 Z}{\partial X \partial Y} \text{-----} (28c)$$

and therefore the resulting hessian or Jacobian function reduces to the much simpler form;

$$J(X,Y) = \frac{\partial^2 Z}{\partial X^2} \frac{\partial^2 Z}{\partial Y^2} - \left[\frac{\partial^2 Z}{\partial X \partial Y} \right]^2 \text{-----} (29)$$

While the above equation has been derived from purely optical field considerations starting from the Kirchoff integral of equation 4, the resulting expression is intimately connected to the surface geometry of a micro mirror pixel. The geometrical properties of a micro mirror pixel are best understood in terms of a function describing the general curvature properties of the pixel surface, and the most appropriate function here is the Gaussian curvature function. This function is derived by considering a small element of distance on the pixel surface and constructing a metric tensor from which the general curvature tensor can be derived. The elemental distance interval on the surface of a micro mirror pixel in X, Y, Z coordinates is given by the relation $dS^2 = dX^2 + dY^2 + dZ^2$. This can be written in the more generalized form;

$$dS^2 = \sum_{i,j=1}^2 g_{ij} dX^i dX^j \text{-----} (30)$$

where $dX^1 = dX$ and $dX^2 = dY$ and the components of the metric tensor are given by;

$$g_{11} = 1 + \left[\frac{\partial Z}{\partial X} \right]^2, g_{22} = 1 + \left[\frac{\partial Z}{\partial Y} \right]^2, g_{12} = g_{21} = \frac{\partial Z}{\partial X} \frac{\partial Z}{\partial Y} \text{-----} (31)$$

The contravariant components of the metric tensor are given by $g^{ij} = G_{ij}/g$, where g is the determinant of the metric tensor, $g = g_{11} g_{22} - g_{12} g_{21}$ and G_{ij} is the cofactor of g_{ij} in the determinant g and has the components; $G_{11} = g_{22}$, $G_{12} = -g_{12} = G_{21}$ and $G_{22} = g_{11}$. According to the techniques of Riemannian geometry¹⁴ the Gaussian curvature of the surface is given by $K = R_{1212}/g$, where R_{1212} is an element of the Riemannian Christoffel curvature tensor;

$$R_{ijkl} = \frac{1}{2} \left[\frac{\partial^2 g_{il}}{\partial X^j \partial X^k} + \frac{\partial^2 g_{jk}}{\partial X^i \partial X^l} - \frac{\partial^2 g_{jl}}{\partial X^i \partial X^k} - \frac{\partial^2 g_{ik}}{\partial X^j \partial X^l} \right] + \sum_{s,p=1}^2 g^{sp} \{ [jk,p][il,s] - [jl,p][ik,s] \}$$

where the Christoffel symbols are defined by the following first order sum of derivatives of the components of the metric tensor;

$$[ij,k] = \frac{1}{2} \left[\frac{\partial g_{ij}}{\partial X^k} + \frac{\partial g_{kj}}{\partial X^i} - \frac{\partial g_{ji}}{\partial X^k} \right] \text{-----} (32)$$

The expression for the Gaussian curvature obtained from equations 30 to 32 is given by;

$$K(X,Y) = \frac{\frac{\partial^2 Z}{\partial X^2} \frac{\partial^2 Z}{\partial Y^2} - \left[\frac{\partial^2 Z}{\partial X \partial Y} \right]^2}{|1 + (\nabla Z)^2|^2} \text{-----(33)}$$

The numerator of equation 33 is of exactly the same form as the Jacobian of the reflected micro mirror pixel optical field given in equation 29. Maximum brightness of the reflected field is achieved when the Jacobian vanishes. From equation 33 this means that micro mirror pixels of zero Gaussian curvature give the brightest reflected image. However, as discussed previously, these brightness aspects of the micro mirror design problem need to be considered in the context of the associated structural stability problem if an effective OVD design is to be obtained. The ray equations given by equations 18 or 19 and the corresponding imaging equation 21 can be used to determine the overall optical stability of the micro mirror pixel in response to bending or crinkling perturbations of the OVD surface. The form of the Jacobian function given by 29 and the mapping of those points on the micro mirror surface that cause the Jacobian to vanish (points of zero Gaussian curvature according to equation 33) into the space of reflections also contribute to an understanding of the stability of the pixel with changing angle of illumination. The vanishing of the Gaussian curvature function may occur either locally or globally. Local vanishing defines a line (or lines) on the micro mirror surface according to equation 29 or 33. This line or lines maps to a line image in the space of reflections according to the ray equations 18 or 19. The equation of this focusing or caustic line in reflection space is obtained by eliminating the X and Y coordinates between equations 29 (with J=0) and the ray equations 18 or 19. For the case of micro mirror pixels which cause global vanishing of the Gaussian curvature J=0 everywhere on the pixel surface, the ray equations define a purely singular line pattern (caustic lines) in the space of reflections.

Figure 3 shows two examples of caustic patterns produced by generalized diffraction grating contour map representations of micro mirror pixels of particular slope and surface modulation. The left hand image (A) in figure 3 shows the diffraction grating contour map representation (greatly enlarged) of a micro mirror pixel of largely fixed slope, but with a slight hump in the middle of the slope. It is this deviation from flatness that generates a degree of expansion in the reflected beam and the corresponding increased stability with respect to crinkling perturbations of the micro mirror surface, albeit with a slight reduction in brightness of the reflected beam. The middle image (B) in figure 3 is the first order diffraction pattern generated by the grating contour map representation of this slightly humped micro mirror surface. The geometric properties of this pattern may be calculated from an application of the ray equations and Jacobian condition to the grating function shown in (A) above. Note that a micro mirror surface of perfect flatness and fixed slope would be represented by a fixed periodicity straight line grating pattern. The use of a generalized diffraction grating representation to study the optical properties of generalized curved surfaces has been discussed in an earlier paper⁹ and the validity of the process is due to the isomorphic equivalence of the two optical systems as demonstrated by equations 19 and 20. A specific example of this process is given by the function $Z = \alpha Y + \beta \cos(Q\pi X) \cos(Q\pi Y)$ which represents the micro mirror slope function corresponding to the grating pattern shown in figure 3 (A) and the diffraction pattern shown in (B). In this example the modulation parameter β is very small when compared to the slope parameter α . That the caustic pattern is very sensitive to the form of the modulation function is shown by the right hand side image in figure 3.

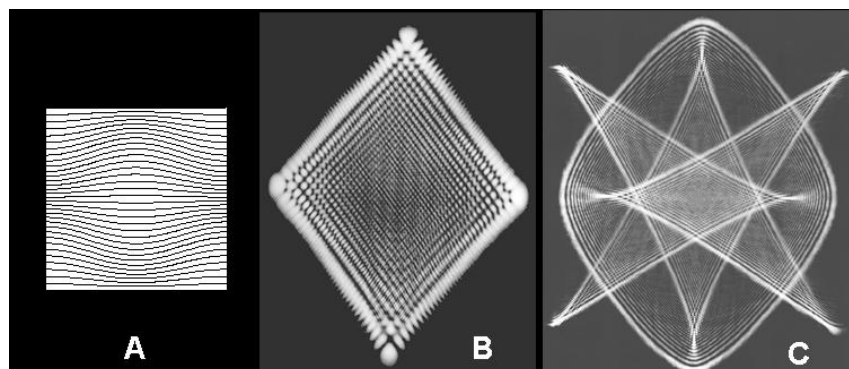


Figure 3. Examples of structurally stable optical field patterns generated by diffraction grating contour map representations of micro mirror pixel surfaces

The Z function in this case is given by $Z = \alpha Y + \beta [\cos(Q\pi X)\cos(Q\pi Y) - (1/3)(\cos(Q\pi X) + \cos(Q\pi Y))]$. The grating function for this optical field pattern is not shown. In both of the examples shown in figure 3 the slope functions $Z(X,Y)$ correspond to surface profiles where the Gaussian curvature only vanishes in a local manner and it is the mapping of these lines of zero Gaussian curvature into reflection space via the ray equations which generates the caustic lines or strongly focusing regions of the optical field functions shown in figure 3.

2.4 Optical effects.

The isomorphic relationship between diffraction and reflection effects generated by diffractive and reflective OVDs respectively is well demonstrated by the fact that in both cases the diffracted or reflected optical fields are described by gradient mapping equations. This is shown by the form of the ray equations 19 and 20. The main differences between the two systems relates to the presence of the wavelength and order number parameters in the diffractive case. Diffractive OVDs differ from reflective OVDs through the presence of colour effects and multiple diffraction orders. Except for these differences we can map all of the usual optical effects associated with diffractive OVDs into an equivalent set of optical effects produced by reflective OVDs. The table below compares the different mechanisms for achieving particular optical effects within the two OVD scenarios.

OPTICAL PROPERTY	DIFFRACTIVE PIXEL OVD	REFLECTIVE PIXEL OVD
Resolution dependence.	Determined by diffractive pixel dimensions	Determined by micro mirror pixel dimensions
Palette structure	Comprised of a finite set of diffractive pixels of different grating groove spacings, modulations, curvature and groove orientations.	Comprised of a finite set of micro mirror pixels of different mirror angles, curvatures and orientations..
Multi-channel image switching	Produced by using adjacent diffractive pixels of different spatial frequency	Produced by using adjacent micro mirrors of different mirror slope angles.
Microtext	Produced by constructing letters out of diffractive pixels of the same type	Produced by constructing letters out of micro mirror pixels of the same angle slope and orientation.
Right angle effects	Produced by using adjacent diffractive pixels with grooves orientated at 90 degrees to each other.	Produced by using adjacent micro mirror pixels with mirror slopes orientated at 90 degrees to each other.
Covert image effects	Produced by interlacing a positive and negative version of the same image, where the positive image diffractive pixels have different groove curvature to the negative image diffractive pixels.	Produced by interlacing a positive and negative version of the same image, where the positive image micro mirror pixels have different mirror curvature to the negative image micro mirror pixels.
Movement effects	Produced by filling adjacent areas of the OVD with diffractive pixels of different special frequency.	Produced by filling adjacent areas of the OVD with micro mirror pixels of different micro mirror angle.
Positive image to negative image switching greyscale portraiture	Produced by constructing the portrait out of a palette of diffractive pixels of different groove curvature.	Produced by constructing the portrait out of a palette of micro mirror pixels of different mirror surface curvature.

The last item in the table above shows how the structural stability properties of micro mirror pixels can be used to create a special type of optical effect based on using a palette of micro mirror pixels with different Gaussian curvature properties arranged in such a way that the greyscale properties of a portrait image can be mapped to micro mirror pixels of different degrees of surface curvature. This type of microstructure generates an image where the variations in optical intensity of the reflected micro mirror beams is due to the different degrees of expansion of the beams from pixels of different degrees of curvature. In effect, image intensity modulation results from micro mirror curvature modulation. An example of a micro mirror pixel surface curvature function which can be used for this purpose is the function $Z = \alpha Y + \beta \cos(Q\pi X) \cos(Q\pi Y)$ corresponding to the contour map and reflection pattern shown in figures 3A and 3B. In this case image intensity modulation is achieved by varying the modulation parameter β over a set of 16 values of increasing magnitude in order to obtain a set of micro mirror pixels of increasing curvature, and therefore generating reflected beams of decreasing intensity at a particular angle of view.

3. Design and origination techniques for a pixellated micro mirror OVD.

The design process for an Optical Micro Mirror Array (OMMA) device is very similar to the design process for a palette based diffractive OVD such as Exelgram¹². In this case we create a piece of artwork which uses colour effects to map the regions corresponding to different diffractive pixel types. In a similar way the input artwork for a micro mirror OVD consists of coloured regions representing regions of different micro mirror pixel types.

Figure 4 shows an example of a piece of input artwork used for the design of a micro mirror OVD. The regions of different colour shades represent micro mirror pixel regions of different pixel type. For example the euro symbol region might correspond to micro mirror pixels with slopes pointing towards the top of figure 4 and at right angles to the micro mirrors filling the region of the “50” symbol, while the background areas might correspond to micro mirror pixels reflecting randomly to create a diffuse scattering background. Using these three types of micro mirror pixels we could expect to produce an OVD which displayed the euro symbol switching on and off as the OVD was rotated about an axis parallel to the horizontal strokes of the euro symbol and also produced an image of the “50” symbol switching on and off when the OVD was rotated by 90 degrees about an axis perpendicular to the plane of the OVD and then rotated about an axis in the plane of the OVD perpendicular to the strokes of the euro symbol.

The process for converting the artwork of figure 4 into a micro mirror OVD involves firstly designing a palette of micro mirror pixels which generate the required optical effects, secondly determining a corresponding set of mask pixel elements, thirdly producing a greytone mask pixel version of the required artwork by electron beam lithography techniques and finally using this colourtone mask³ in a photolithography exposure arrangement to create a surface relief structure corresponding to the desired pixellated micro mirror array version of the input artwork.

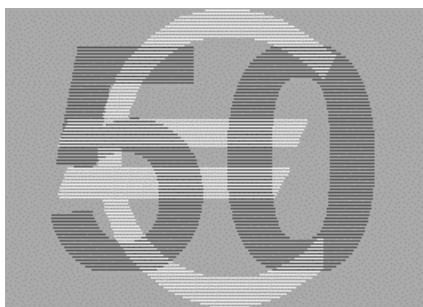


Figure 4. Micro mirror artwork example.

3.1 Micro mirror pixel and mask pixel design.

Figure 5 below shows a graphical calculation of a micro mirror pixel with a slightly curved slope designed to increase the structural stability of the reflected beam over what might be expected of a beam reflected from a pixel of perfectly flat mirror slope. In figure 5 the equation of the mirror slope is given by $Z = \alpha Y + \beta (X^2 + \gamma Y^2)$ where α , β and γ have the values 0.75, 0.4 and 0.2 respectively and we have exaggerated the values of β and γ in order to

make the slope curvature visible in figure 5. The range of X and Y values used is given by $-1.3 < X < +1.3$ and $-1.3 < Y < +1.3$.

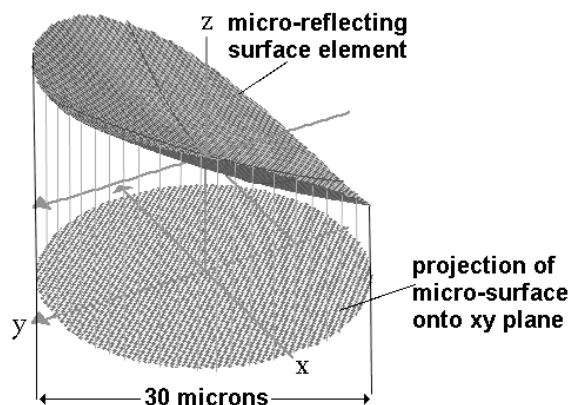


Figure 5. Example of micro –mirror pixel geometry

A palette of pixels of the type shown in figure 5 can be constructed by varying the values of α , β and γ and interchanging the positions of the X and Y variables to obtain micro mirror palette elements corresponding to pixels rotated by 90 degrees. Once the pixel surface geometry and palette variables have been defined it is then necessary to work backwards to find the corresponding variable transparency mask pixel elements which can be used to form the required surface relief by photolithography exposure techniques. This process also normally requires a knowledge of both the geometry and exposure characteristics of the optical lithography system and the exposure and development characteristics of the photoresist which is being exposed. In effect we need a knowledge of the complete optical transfer function of the optical system so that when convoluted with an unknown mask function, an ideal mask function corresponding to the surface relief function of figure 5 is obtained. The convolution relationship is then inverted to obtain the unknown mask function in terms of the ideal mask element and the optical transfer function of the photolithography system. However for the purposes of the present discussion we shall ignore these system dependent factors and calculate the mask pixel function corresponding to figure 5 on the assumption that the optical transfer function is unity and there is a linear relationship between mask element transparency and micro mirror exposure depth. In this way we obtain the greytone mask pixel transparency distribution shown in figure 6 below

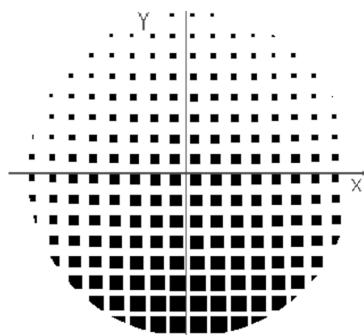


Figure 6. Micro –mirror mask pixel structure corresponding to figure 5.

The aperture sizes in figure 6 are described by a square aperture edge length function of the form;

$$D(X,Y) = \delta \left[\frac{\alpha(Y_m - Y) + \gamma(X_m^2 - X^2) + \beta\gamma(Y_m^2 - Y^2)}{\alpha Y_m + \gamma(X_m^2 + \beta Y_m^2)} \right] \text{-----(34)}$$

In the above equation $\delta = 40$, $X_m = Y_m = 1.3$ and the exel coordinates X_e , Y_e , which uses an address grid of 1024 X 1024 exels to define the mask pixel area, are related to the X and Y coordinates by the relations $X_e = 512(X_m +$

$X)/X_m$ and $Y_e = 512(Y_m + Y)/Y_m$. In this example there are 16 X 16 apertures within each mask pixel palette element and the pixel has dimensions of 30 X 30 microns.

3.2 Fabrication tests.

For the fabrication tests a simpler greytone mask palette set was used than the structurally stable versions described in the previous section. These mask elements were designed to produce flat micro mirrors of constant slope. Since these tests were designed to test basic concepts no correction was applied to take account of the optical transfer characteristics of the photolithography system. The mask elements therefore used aperture functions with linearly increasing edge dimensions as a way of modelling a linearly varying mask pixel transparency. It was assumed here that the optical exposure process would create a linearly varying resist exposure and a post development resist profile of corresponding linearity. Mask pixel palette elements of linear transparency distribution at three angles of orientation are shown in figure 7 below.

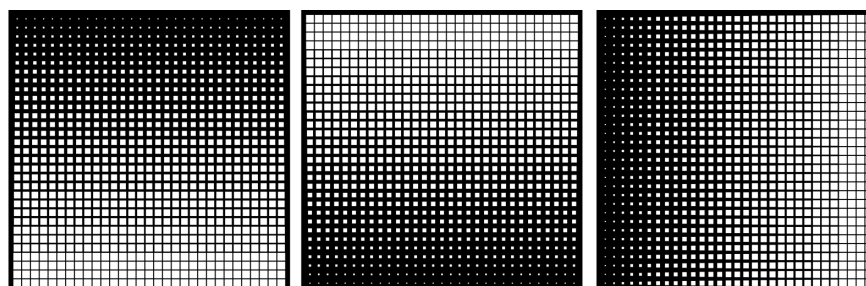


Figure 7. Calculated mask pixel palette elements of linear transparency distribution

In the figure 7 the calculated linear transparency distributions relate to mask pixel dimensions of 30 microns X 30 microns with an address grid of 1024 X 1024 definable points within each pixel area. The variable sized apertures used to define the transparency in a particular region of the mask were each centered on a 16 X 16 aperture grid and this grid, when combined with the 1024 X 1024 address grid, caused some striation type effects on the experimental mask pixel palette elements as shown in figure 8 below.

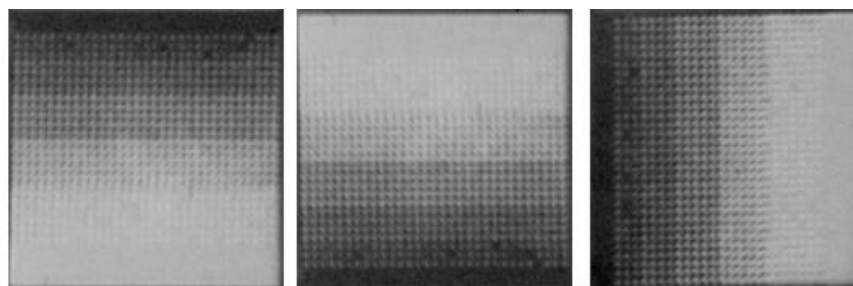


Figure 8. Photomicrographs of three mask pixel palette elements of linear transparency distribution.

The mask pixel element striation effects resulting from the use of digitized pixel address grids (an unavoidable consequence of the use of electron beam lithography for the fabrication of the pixellated mask) has an effect on the quality of the resulting pixellated micro mirror surfaces produced after optical exposure through the mask onto a thick photoresist layer. This is shown in figure 9, which shows a micrograph of a small part of an experimental micro mirror device. In this case the micro mirror device consists of alternating rows of micro mirrors of opposite slope.

In order to test the replication, printing and optically variable properties of the micro mirror concept a new device was constructed using larger 60 micron X 60 micron pixels and based on the sample artwork shown in figure 4 with pixel transparency distributions of similar linearity to those shown in figure 7. The purpose here was to construct a device where the image switched from the “50” symbol to the euro symbol as the device was rotated by 90 degrees about an axis perpendicular to the plane of the OVD

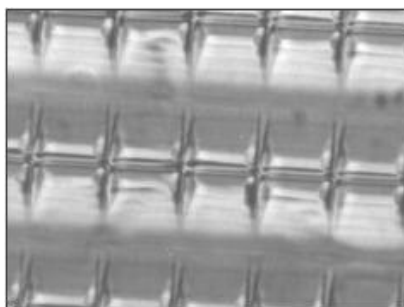


Figure 9. Photomicrograph of a small section of an experimental micro mirror OVD. The micro mirror pixels here are of size 30 microns X 30 microns and the length of the figure is therefore approx. 27 microns.

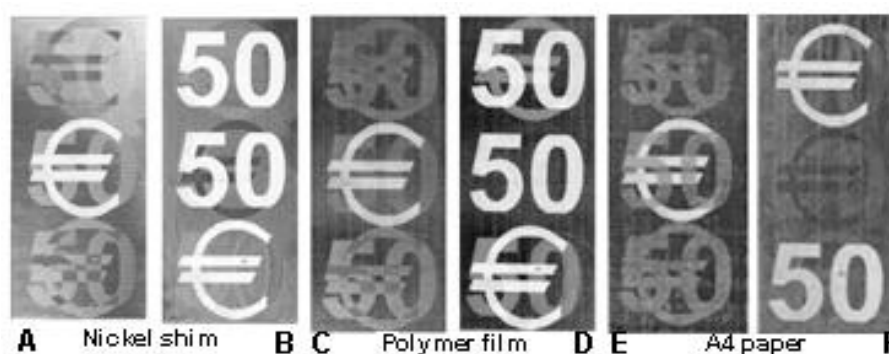


Figure 10. Photographs of OVD effects produced by a pixellated micro mirror device.

Figure 10 shows the results of this test. In figure 10 A and B show photographs of the image produced by the master nickel shim, while C and D show the corresponding optically variable effect after the microstructure has been printed on a polymer substrate via the use of a specially developed nanophase ink (particle sizes of less than 10 nanometres). Figures 10E and 10F show the corresponding results for printing on an A4 paper substrate. In the paper substrate test the OVD images were photographed at a different light source angle to the polymer film test. As discussed previously³ the printing of micro mirror OVDs involves first applying a highly reflecting printing ink to a substrate and then embossing the micro mirror structure into this coated substrate. This was the technique employed in the present case. The depth of the micro mirrors in the present case was determined to be about 20 microns

The results shown in figure 10 confirm the workability of the concept of a pixellated micro mirror OVD and the optically variable effects produced in the above test are clearly visible to the observer. However much further work needs to be carried out, both to improve the quality of the observed images; by reducing the amount of diffuse scatter from the micro mirrors due to surface striation effects, and to increase the range of optical effects; by creating micro mirror surfaces elements of variable surface angle and curvature so that the full range of optical effects discussed in the section 2 can be realized.

4. Reducing costs – subtractive image encoding of micro mirror OVDs.

While the micro mirror OVD concepts discussed in previous sections hold promise to reduce OVD production costs by eliminating the need for an intermediate hot stamping foil phase as required by diffractive OVDs, the cost of micro mirror originations will still be a significant factor determining the suitability of the technology for particular applications. In fact the OMMA origination costs are likely to be higher than for diffractive OVD originations because of the additional photolithography step required in the micro mirror case. These costs are not likely to be a significant barrier for very high volume applications because the origination

cost can be amortized over many millions of printed images and their associated documents. However, for small volume run applications the micro mirror technology is not such a competitive proposition. For these application areas there is an alternative origination strategy which closely parallels a subtractive image origination technique previously proposed for diffractive OVDs^{15,16}. We shall illustrate the principles of this new origination technique by applying it to the most extreme case of a low volume application; - the single unit ID card or document application.

4.1 Biometric OVD technology

In the current climate of uncertainty created by threats associated with terrorist activity there is a need for improved levels of security for documents related to the legitimate identification of individuals for travel, access control and other purposes¹⁸. Current ID document protective technologies include the traditional features of intaglio printing, watermarked paper, screen angle modulation printing as well as some relatively recent technologies such as the use of optically variable devices in the form of hot stamping foil patches or transparent overlays. While the use of OVDs in these two forms has certainly improved the security of ID documents, there is still a risk associated with altering the identity information without changing the other security features (e.g. by temporarily peeling away the transparent ovd overlay and replacing the photograph of the ID document holder with that of another individual). The linking personal biological information associated with the id document holder (e.g. iris scan information) to the document in a much more secure fashion is of course possible using electronic data storage methods such as chip cards. However this method requires machine authentication of the document and this requirement limits the utility of this method for protecting the document (e.g. on the spot visual authentication by field personnel is not possible without field portable equipment). As well as issues associated with expensive authentication infrastructure and equipment, there are also issues here related to individual privacy and the safeguarding of the document holder's biometric information and ensuring that this information is not made available for other purposes outside of its intended id document use.

With the above background in mind, it can be seen that there would be considerable advantages in having an id document protection solution which linked the visual image of the document holder to an ovd solution which was unique to that individual. While this is possible using current OVD technologies such as Exelgram¹², the cost of such an application would be prohibitive in the extreme because an OVD origination would need to be produced for each document holder. However there is now an alternative and much lower cost method of achieving a similar result. This method can be implemented by means of a diffractive OVD approach or an even lower expected cost micro mirror OVD strategy. It is this latter approach which we will now describe.

In its simplest form the micro mirror biometric OVD¹⁷ concept involves firstly originating a generic pixellated micro mirror array of only two different micro mirror angles. This is illustrated in figure 11 for the case of a track based generic micro mirror OVD. In this case every even numbered track contains only micro mirrors at one fixed micro mirror surface slope, while every odd numbered track contains micro mirrors angled at a different angle or orientation to the micro mirrors in the even numbered tracks. This generic micro mirror array forms the blank OVD canvas.

After production of the corresponding metal printing or embossing die and the coating of the id document portrait image area with reflective ink, the blank ovd die is pressed into this area to transfer the blank OVD canvas image into the document. In this way all id documents can be prepared prior to the inclusion of the id information.

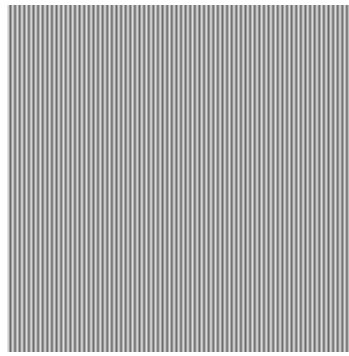


Figure 11. Schematic view of a two channel blank micro mirror OVD canvas.

The encoding of the image data into the blank OVD canvas to produce a two channel OVD now takes place via the following procedure. First, a photograph of the ID document holder is scanned and converted into a gridded and binary dithered image as shown by the example in figure 12A. Then a similar procedure is used to prepare the image chosen for the second channel of the OVD as shown by way of example in figure 12B.

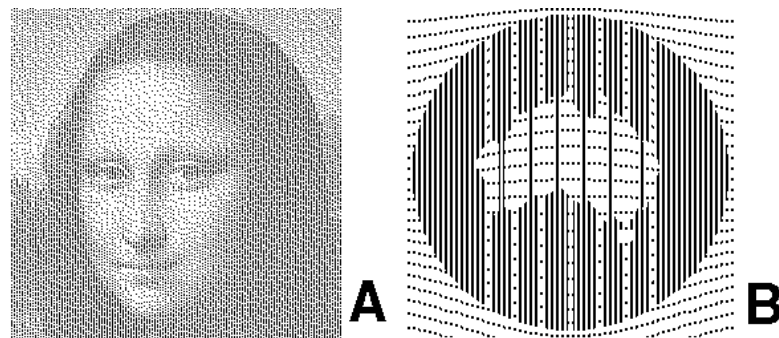


Figure 12. Channel 1(A) and channel 2 (B) input data for a biometric OVD.

Finally the two binary dithered images are interlaced into a set of tracks where the even numbered tracks contain the dithered image of the document holder and the odd numbered tracks contain the image data of the second channel image. The resultant image pattern is shown in figure 13. The preparation of this two channel image data is carried out by special software and is effectively instantaneous following the image capture of the id document holder's face.

The encoded two channel image data file is now used to control the operation of a laser exposure or ink jet printing system which scans the blank canvas micro mirror area on the id document and modifies the reflectivity of the micro mirror pixels at selected locations according to the form of the image data file. The resultant OVD now produces an image of the id document holder at one angle of view and also replays the second channel image at a different angle of view corresponding to the reflection of the second set of micro mirror pixels. These images are shown in figure 14.

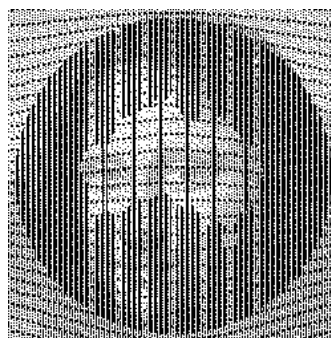


Figure 13. Combined channels input data file for biometric OVD.

Note that the method described above for producing a reflective biometric OVD structure involves an in-register modification of the reflectivity of pre-selected micro mirror pixels aligned in parallel tracks so that the interlaced double image information is initially scrambled by the data encoding process and then decoded or unscrambled by the two angle micro mirror array structure. The method can therefore be regarded as a subtractive OVD origination method in contrast to current diffractive origination methods where both the OVD microstructure and the project specific artwork or image information is required to be originated within a single process.

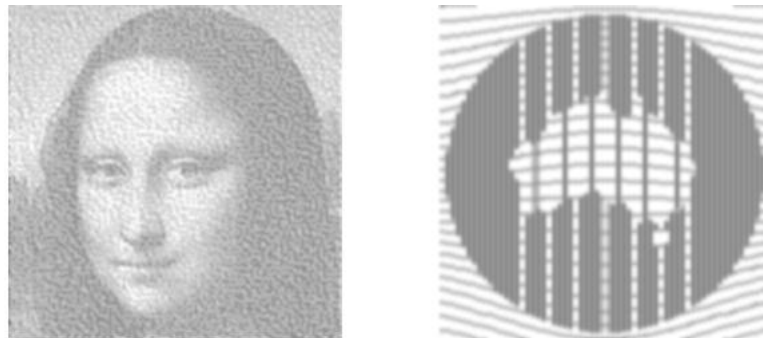


Figure 14. Biometric OVD image at two different angles of view.

By separating the optically variable microstructure information from the project specific artwork information into two processes involving a generic microstructure origination step and a low cost data encoding step we have uncovered a method for personalizing the OVD imaging process at relatively very low cost for the individual ID document. Personalizing the microstructure by subtractive modification of individual micro mirror pixels by laser ablation or ink jet printing is the low cost per unit part of this process. While we have focussed on the micro mirror ovd application of this biometric ovd idea, it is clear from the above discussion that a diffractive version of the same idea can be produced by replacing the generic micro mirror ovd canvas with a generic diffractive ovd canvas comprised of alternating Exelgram tracks of two different and well separated spatial frequencies^{15,16}.

There is another aspect of the above process which is inherently attractive from a document security applications point of view. This relates to the ability of the process to be tailored into specific classes of microstructures and corresponding data encoding algorithms for different groups of customers within the same application area. For example, it is highly likely that two passport issuing authorities in different parts of the world will require their documents to be not only secure from being copied by well known criminal groups, but should also be secure from other users of the biometric ovd technology process. This is allowed for in the process by arranging for different types of generic microstructures and corresponding data encoding software protocols to be produced. For example, instead of arranging for the two channel OVD microstructure to be based on an “odds” and “evens” basis, we could arrange for the channel 1 image to be coded into the micro mirror track sequence ‘1’ ‘2’ ‘4’ ‘7’ ‘9’ ‘12’ and then the channel 2 image would be coded into the track sequence ‘3’ ‘5’ ‘6’ ‘8’ ‘10’ ‘11’ This would prevent the data encoding algorithm from one customer group being able to be used for personalizing the generic OVD microstructure of another customer group. This class based security characteristic also applies to the novel high security data storing process described in the next section.

4.2 Personalized OVD bar code.

It can be seen from the example described in the previous section that the biometric OVD concept can be applied to the storing of bar code data in a very secure manner. Since a bar code is simply a picture of black and white bars of different widths organized into a particular sequence, we can imagine using two different bar code images as channel 1 and channel 2 images encoded into an interlaced sequence according to the method described in section 5.1. The bar code reader is then presented with two bar codes to read at two different angles of view and modified software within the reader correlates the two pieces of bar code data to determine the authenticity of the object carrying the two channel bar code. For example, an ID card or passport could include both a biometric OVD image of the document

holder for visual authentication and an OVD bar code containing other data pertaining to that individual. In both cases the data is written onto the document at the time of issue using the subtractive data encoding method described in the previous section.

In concluding this section it should be mentioned that, while we have focused the discussion on the use of a generic micro mirror array as the underlying OVD microstructure, similar biometric OVD and personalized data encoding techniques can be applied when the underlying generic OVD microstructure takes the form of a diffractive foil canvas comprised of alternating diffracting tracks or diffracting pixels of two different spatial frequencies. This version of the biometric OVD technology is discussed in another publication. Finally it should also be mentioned here that a transparent film version of the biometric OVD technology can be constructed by using the generic micro mirror surface relief structure as an embossing tool applied to a transparent polymer film in order to create arrays of micro prisms corresponding to different angles of refraction. In this case the images would be viewable in transmission at two different angles of view. In this case of course no reflective ink need to be applied to the substrate to view the images. It can be seen that the encoding of the data onto this film substrate can be carried out using similar in-register laser ablation techniques in order to modify the refractive properties of individual prism pixels. In fact, in this case of course, the laser ablation process would change the individual micro prism pixels into diffusely transmitting pixels.

5 Conclusions

In this paper we have described a new approach to the design of optically variable devices for anti-counterfeiting applications. Using arrays of micro-mirror pixels of very small size instead of arrays of miniature diffraction gratings we have shown how the embossed hot stamping foil transfer step may be replaced by a much simpler transfer process involving only the use of reflective nanophase inks and an embossed printing process. This simpler step provides a means for reducing the OVD replication costs as well as providing for a more integrated process in producing the security document and is a result of the greatly increased microstructure depth characteristics of micro mirror array devices. By replacing hot stamping foil with nanophase ink technology and a printing step there is no need for an off-site foil production plant and the OVD microstructure can be incorporated into the document in-line with the normal printing process.

We have analysed the optical physics associated with micro mirror devices and demonstrated that the reflective pixel ray equations are in isomorphic correspondence with the ray equations associated with diffractive devices. This mathematical analysis shows how the optical effects generated by diffractive devices can be mapped into a corresponding set of reflective optical effects. With the exception of colour effects all other characteristics of a diffractive OVD carry over into the reflective case.

The origination process for micro mirror array devices has also been discussed in this paper, and while more complex than the process used for diffractive devices (because of the extra photolithography step) the test results confirm the viability of the process. These tests also confirm that much further research needs to be carried out before the micro mirror surfaces reach the required degree of nanometer smoothness and the full range of micro mirror optical effects is realized.

Finally the application of the technology to the design of a generic classes of micro mirror OVD devices tuned to end user data encoding for ID applications was also discussed. This biometric OVD technology is currently the prime focus of OVD research in CSIRO at the present time.

Acknowledgements.

The author would like to thank Dr Tim Davis for preparing the test shim used for the production of the images shown in figure 10 and Dr Lech Wiczorek of CSIRO Telecommunications and Industrial Physics for using this shim to produce the reflective nanophase ink images shown in figure 10.

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