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New applications of modulated digital images in document security

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Abstract

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Keywords

digital, applications, security, document, modulated, images

Disciplines

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New applications of modulated digital images in document security

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ABSTRACT

In previous work we have demonstrated that selective masking, or modulation, of digital images can be used to create documents and transparent media containing covert or optically variable, overt images. In the present work we describe new applications and techniques of such “modulated digital images” (MDI’s) in document security. In particular, we demonstrate that multiple hidden images can be imperceptibly concealed within visible, host images by incorporating them as a new, half-tone, printing screen. Half-toned hidden images of this type may contain a variety of novel features that hinder unauthorized copying, including concealed multiple images, and microprinted-, color-, and various fade-effects. Black-and-white or full color images may be readily used in this respect. We also report a new technique for the embossing of multiple, covert- or optically variable, overt-images into transparent substrates. This method employs an embossing tool that is prepared using a combination of electron beam and greytone lithography. Two approaches may be used: (i) a double-sided “soft” emboss into curable, transparent, lacquer layers, and (ii) a single-sided “hot” emboss in which multiple, dithered images consisting of distinctly-sloped microprisms are impressed into the substrate. Technique (ii) requires a novel, electron-beam-originated master dye.

Keywords: security, document, branding, hidden image, half-tone, printing screen, optically variable, OVD, novelty

1. INTRODUCTION

The manipulation of light by selective masking forms the basis of several major industries, including, lithographic patterning in the silicon chip and certain printing industries. Selective masking has not, however, been widely used in the field of optical security devices (except, perhaps, in the form of Moiré patterns). The advent of digital image processing and high resolution reproduction techniques now allows selective masking to be conveniently and readily applied at the pixel level. This involves altering or modulating the properties of images, thereby rendering them Modulated Digital Images, or MDI’s. In previous reports and patent disclosures, we have described a range of methods to modulate digital images for the purposes of securitizing documents by concealment or novel optical effects.¹⁻⁷

The counterfeiting of financial and transaction documents has long been an active area of criminal activity. Counterfeiting of high-value software, pharmaceuticals, and brand name products has now also become problematic. According to the International Chamber of Commerce Counterfeiting Intelligence Bureau, over 5% of world trade consists of counterfeit product. The cost of this illegal activity amounts to over US\$350 billion annually and is growing.⁸ The personal and human cost of counterfeiting is also increasing rapidly. Identity theft, arising from poorly securitized identity documents, is particularly important because of the crucial role it plays in organized money laundering and terrorism. According to a 2004 UK Home Office report, over 30% of terrorist incidents have involved the use of false identities.

Optical security devices based on selective masking offer potentially useful ways to counteract these rapidly evolving threats. In this work we will describe new applications and techniques for “modulating digital images” in this respect. In particular, we will describe how MDI’s may be used to create printing screens incorporating covert images and the effects that are generated thereby. Techniques for the embossing of covert and overt images into transparent substrates, such as polymer identity and credit cards and polymer passport data pages, will also be discussed.

2. HALF-TONED HIDDEN IMAGES

2.1 Techniques for concealing images within printed representations and their use in document security

In order to print an image, professional printers use a variety of so-called “screening” methods to create the printing plate. In effect, the picture is broken up into a series of image elements, which are typically microscopically small dots or lines of various shapes and combinations. These are then printed in distinctive patterns known as “screens” or “half-tones” in order to create the overall image. Numerous half-tone patterns are used in the printing industry, including round-, line-, and elliptical-screens like those depicted in Figure 1.

Figure 1. Magnified views of the same image printed with: (a) round-, (b) line-, and (c) elliptical-printing screens

Images must be screened in this way because of physical limitations in printing technology which make it impossible to print, at the microscopic level, a truly continuous tone. Instead, the best that can be achieved is to break the print up into these very small dots or lines. The dots and lines are much smaller than the human eye can perceive, so that images printed using such screens appear to have a continuous tone or density.

A wide range of technologies have been created over the last 40 years to imperceptibly conceal images within printed materials.⁹ Such “hidden” or “scrambled images” are typically revealed by suitable means; for example, by overlaying them with a transparent, lens-type decoder or by applying a decoding algorithm to a photographic or video rendition of the image. “Hidden image” technologies of this type usually exploit the very tiny structure of the screening elements used in printing. For example, the lines or dots employed are often moved very slightly or their shape or orientation is changed. This is done in patterns corresponding to the hidden message. When a suitable lenticular lens is then, for example, overlaid upon the printed article, it selectively displays only the altered features, thereby revealing the hidden image. This method of hiding images is broadly known as “line-“ or “dot-modulation” and has been practiced in a very wide variety of guises.⁹

Hidden images of this type have important potential applications in document security. For example, they may be designed to disappear in an unauthorized copy of the printed article, thereby providing a means for testing the authenticity of the document. Alternatively, such hidden images may be made to become distinctly visible upon copying, thereby revealing a “void” or other message; such devices are known as “void pantographs” or “screen traps”. A third alternative is that the hidden image may be designed to imperceptibly carry over some concealed information to a copy, such as a serial number. This serial number may be used to identify the original of a sensitive document that was subjected to unauthorized copying.

Figure 2. Picture containing a line-modulated concealed image (left) with a magnified section shown on the right

2.2 Overcoming the visibility of line- and dot-modulated hidden images at high magnification

A key disadvantage of line- or dot-modulated hidden images is that they rely on the inability of the human eye to detect minor variations in extremely small printed features.⁹ This element is, of course, lost when such devices are

viewed at a higher resolution than that provided by the human eye. Thus, while a patterned hidden image like that shown on the right in Figure 2 may be well concealed to the human eye, it generally becomes clearly visible upon magnification. In effect, line- or dot-modulated hidden images therefore depend on the observer's naiveté to remain hidden.

In the last conference in this series, we described two new methods for hiding images within printed matter using modulation of digital images.¹⁻⁶ In the "Phasegram" technique, a computer-generated, incremental displacement of line screens is used to create a detailed hidden image in a range of grey- or color-scales. The other technique, known as "Binagram", employs a computer-controlled dithering algorithm to generate a hidden image in which each element is paired with a new element of complementary density.

In developing Phasegram and Binagram, we noticed a relationship between the complexity of a hidden image and the extent of its concealment under magnification. Thus, the encoding of very simple hidden images, such as a message containing only a word or text, typically generated a pattern that could be more easily recognized under magnification than that created by a complicated, multi-shade or multi-hue image, such as a photographic portrait. This finding suggested that the key to properly concealing an image is to maximize the amount of information it contains. In more general terms, it is to maximize the use of the available information space; that is, to make the greatest possible use of the information-bearing capacity of the printed indicia.

This deduction implies that the way to make hidden images truly invisible, even at high magnification, is to take the process of hiding the images back a step. Rather than manipulating individual structures within a particular printing screen as is presently done in line- or dot-modulation, one should manipulate the screen itself. That is, one should design an entirely new printing screen within which the hidden image is concealed and which makes full use of the information-bearing capacity of the printed indicia. To achieve this, the tiniest possible image elements available to the printer (namely, the "pixels") must be mathematically manipulated to turn the hidden image into a unique half-tone. This should be readily achievable by digital image modulation.

2.3 Methods for concealing hidden images within unique printing screens

We now report that new printing screens involving large-scale use of the available information space can be created by mathematically combining Phasegrams or Binagrams using novel and propriety algorithms. Such manipulations generate screens that entirely defy human observation of any hidden image(s) even at full magnification. Moreover, these procedures allow the rapid and routine development of unique, new printing screens for any image or

Figure 3. A pharmaceutical box printed with a half-tone containing a hidden image (magnified section shown on right)

Figure 4. The same pharmaceutical box overlaid with a suitable decoder to reveal the hidden image

images to be hidden. Figure 3 (right) depicts one such printing screen. As can be seen, this screen consists of complex, regularly repeated mixtures of lines and dots that reveal nothing of the hidden images that they contain. Indeed, they do not even suggest the presence of a hidden image, which can be revealed using a suitable decoder (Figure 4).

2.4 Novel effects in half-toned hidden images

Because of their ability to access so much of the information-carrying capacity of a printed representation, half-toned hidden images can incorporate a range of novel and unusual effects. Some of these effects include:

2.4.1 Multiple, Detailed, Overlapping, Hidden Images

A feature of this technology is that multiple hidden images of remarkable detail can be included within a printing screen. Figure 5 (left) depicts a mock passport data page which has been printed with a half-tone containing three distinct and very detailed hidden images. On the center and right of Figure 5, two of these images are revealed by overlaying with suitable decoders. As can be seen, they are highly detailed. The hidden portrait shown in the middle picture of Figure 5 contains seven shades of grey, so that it provides an accurate representation of the overt photograph of the passport holder on the left-hand side of the data page. A government official armed with a suitable decoder would easily be able to check such a document for fraudulent alteration of the bearer's photograph.

Figure 5. Passport (left) containing multiple, overlaid hidden images which are revealed by two different decoders (center and right)

2.4.2 Microscopic Hidden Images

Because half-toning allows a far more efficient use of the information bearing capacity of the printed indicia than has hitherto been available, it becomes possible to create hidden images that are microscopically small. An example of such a “microprinted” hidden image is depicted in Figure 6. Hidden images of this type can only be viewed through a decoder under high magnification. We have developed a small, pocket-sized device, somewhat like a slide viewer, that can be used to readily view such microscopic hidden images. The use of high magnification has the added advantage that it allows the observer to closely inspect the printing quality of the hidden image for copy-related defects.

Figure 6. Magnified view of an area containing a microprinted hidden image, without decoder (left), with decoder (right). Note: the scale bar on the far right.

2.4.3 Full-Colour Hidden Images

Hidden images have traditionally taken the form of black-and-white representations when they are revealed. However, the greater information content available using half-toning allows the incorporation of full- and true-color hidden images. The algorithms for including color are analogous to those used for black-and-white, but expanded to include a range of possible hues and saturations. Color in hidden images is discussed in greater detail in section 2.5.

2.4.4 Fade Effects (Vignettes) in Hidden Images

It has, in the past, generally been difficult to seamlessly incorporate hidden images into printed areas that fade strongly from one side to another. In some printing circles, such effects are known as “vignettes” or “fade-effects”. A potentially important advantage of half-toning hidden images is that the printing screen automatically takes into account such fade effects. That is, the intensity of the printing screen will decline consistently, in accordance with the fade-effect. Thus, if the printing screen contains a hidden image, this also fades in an entirely uniform and seamless manner.

Figure 7 depicts an example of a half-toned hidden image in a fade effect. As can be seen, the hidden image disappears smoothly from top-to-bottom, along with the intensity of the printing.

Figure 7. Magnified view of printing containing a half-toned hidden image in a fade-effect. Left: printed area without decoder. Right: printed area with an overlaid decoder. The hidden image portrait fades smoothly from top to bottom.

2.5 Incorporating hidden images within color printing screens (“Total Color Management” or “TCM”)¹⁰

When one is seeking to hide images within a visible and complicated color picture, a challenge is thrown up: how does one accurately incorporate hidden images as half-tones within color pictures? Color pictures are typically printed in a set of hues that, when combined, generate full color in a wide range of densities. For example, the Cyan-Yellow-Magenta-Black (CYMK) system is often used. A separate printing screen would typically be used for each of these colors, with the final, full color picture being an overlay of each of these screens, printed in their appropriate colors. How then does one incorporate a half-toned hidden image within such a color picture, especially a hidden image that is, itself, in full color?

To achieve this we have developed a set of algorithms that we call “Total Color Management” or TCM.¹⁰ In this technique, each hidden image is half-toned in each constituent color. Because of the need to precisely control the overall color balance, a set of equations must be applied, at the pixel level, in order to best match the density of the hidden image(s) with the density of each individual color. In a future publication we will describe the formal derivation and application of these equations.

When the TCM equations and algorithms are applied, one can readily hide multiple hidden images within visible, full-color, printed pictures. Figure 8 depicts an example of TCM (in black-and-white format, suitable for this present SPIE publication media). As can be seen, three hidden images have been incorporated in overlay upon each other throughout the picture. That is, the images are seamlessly hidden over, essentially, all of the color and contrast variations in the visible photograph.

Figure 8. Full-color printed photograph (shown here in a black-and-white format that is suitable for the present publication medium) (top) containing three hidden images, which are revealed by overlaying with suitable decoders (bottom left and right).

2.6 The “Precarious Internal Consistency” of half-toned hidden images makes them highly copy resistant

As noted earlier, the key advantage of concealing images within half-toned printing screens is that it potentially allows the greatest possible use of the available information space in a printed representation. That is, the printed indicia can be manipulated to yield the maximum information. This means that in a half-toned hidden image whose information content has been *fully* harnessed, *every single* individual printed feature is altered relative to the original. However, this is done in a way that leaves the overall, visible representation entirely unchanged. Thus, a tension is created between the appearance of the external, visible representation and the placement of the individual printing indicia. In effect, as increasing information is hidden within the external, visible picture, the positions and structures of the printing indicia become increasingly finely balanced in order to maintain an unchanged external appearance. When such an image is then subjected to unauthorized copying, even very minor errors in the placement or structure of the printing indicia will have a dramatic and greatly amplified effect on either the appearance of the overall, external representation or on the appearance of the hidden images when they are decoded.

Half-toned hidden images can therefore be considered to be “*Precariously Internally Consistent*”. That is, their external, visible appearance and their ability to properly render their hidden images are highly dependent on very accurate and finely balanced alterations in the position and structures of all of the individual printed indicia. Any errors in these alterations, as may occur during unauthorized copying, will, consequently, produce amplified and unpredictable changes in their external appearance or in their hidden images when decoded. This precarious and interdependent quality arguably makes half-toned hidden images substantially more copy resistant than previous hidden image technologies. For example, unauthorized copying leading to even minor dot-gain (that is, the bleeding of ink beyond the area actually printed) may be sufficient to throw the entire representation off balance, thereby providing an indication that the image is a copy.

The incorporation into half-toned hidden images of microprinted, color, or fade effects further amplify this precarious internal consistency and allow for improved detection of unauthorized copies. Indeed, the more information

included in a half-toned hidden image and the greater its complexity, the more difficult it will be to accurately copy. Moreover, the level of difficulty increases non-linearly with the information content; that is, it becomes progressively more difficult to copy as the information content is increased. This seems to be particularly true when color is thrown into the equation. In our experience, detailed color hidden images within complex, visible, color host pictures are extraordinarily difficult to copy accurately, even by the highest caliber professional printers. There are simply too many variables in such pictures, each of which are precisely balanced and each of which must be correct in order to achieve fidelity. Half-toned hidden images therefore truly have the property that they are easy to print, but difficult to accurately copy.

3. EMBOSSED COVERT IMAGES

A range of embossed covert images have been reported, since the mid-1990's. Most have been used in overt, diffractive Optically Variable Devices (OVD's), such as CSIRO's Exelgram technology,¹¹ where they provide an additional, covert, level of protection.

As previously noted,¹⁻⁷ the principle of selective masking involves adjusting an input digital image such that the light it generates, at the pixel level, creates various grey- or color tones that define the image. Thus, for black-and-white images, white is generated by allowing maximum transmission of light. Black is produced by blocking as much light as possible. Intermediate shades of grey are mixtures of these two extremes. The creation of embossed hidden images consequently involves manipulating, at the pixel level, the amount of light that is transmitted by a substrate.

Figure 9. Double hidden image embossed in polypropylene film, with magnified section shown on right.

Figure 10. Transparent decoder with magnified section shown on right.

Figure 11. Representation of the images made visible by overlaying the screen in Figure 9 with the decoder in Figure 10.

In recent studies, we have been able to emboss complex hidden images as grooved-well type structures in a series of transparent and non-transparent substrates. Figure 9 shows an example of a covert, double-portrait, hidden image embossed into a polypropylene film substrate. When overlaid with suitable, similarly grooved decoding masks having the line structure shown in Figure 10, the portraits depicted in Figure 11(a)-(b) become visible. As can be seen, this technique produces highly intricate, multi-shaded images having a unique, almost pallid quality that cannot be readily simulated using printing or other methods. Indeed, even photographing them is extraordinarily difficult. Devices of this type can therefore be accurately termed “covert watermarks”.

Such structures have potential utility in security applications: they are physically robust and can be unobtrusively incorporated within a wide range of possible products, from polymer banknotes to plastic wrapping and bottling materials, through to products that are traditionally embossed, such as high-quality leather garments. They are not easily simulated using photographic and printing techniques. Moreover, while printed hidden images of the types described in the previous sections are limited by the printing process – in particular the printing resolution available – embossing of this type can be carried out at very high resolutions, provided that an e-beam-originated embossing tool is used. For such high resolution applications, and in particular, for high-resolution applications on robustly-handled substrates where printing is easily rubbed off, the technique of embossing potentially improves upon the printing method.

While grooved-well type structures give interesting, if somewhat pallid, covert watermark-type effects when they are embossed, very much clearer effects can be achieved by changing the groove of the emboss into a lens-type structure. Figure 12 depicts in cross-section, a lenticular lens-type surface relief that was achieved by embossing a suitable structure into a polypropylene film. The fidelity of these lens arrays are excellent, as demonstrated by the remarkably clear Moire patterns that are generated when two such embossed polypropylene films are overlaid (Figure 13). Lens-type structures are clearly close to optimum for embossing hidden images that decode in a clearly apparent manner. To the best of our knowledge, this is the first example of so efficient a lenticular lens being embossed into standard polypropylene film. In future work we plan to drastically improve the visibility of the embossed covert image effect shown in Figures 9-11 by replacing the grooved-well-type pixels used in those cases with micro-lens pixels of the type shown in Figures 12-13.

Figure 12. Cross-section of a polypropylene film embossed with a cylindrical lenticular lens array comprised of lenses of 60 μm diameter.

Figure 13. Strong Moire interference patterns are produced by overlapping two polypropylene films embossed with a lenticular lens array of the type shown in Figure 12.

4. EMBOSSED, OPTICALLY-VARIABLE, OVERT IMAGES

As previously noted,¹⁻⁷ the techniques of modulated digital images can also be applied to the production of optically variable, overt images. Perhaps the best known optically variable devices (OVD's) are diffractive surface relief microstructures of the type used in, for example, CSIRO's Exelgram™ diffractive Optically Variable Device (OVD) technology.¹¹⁻¹³ OVDs of this type are typically mass produced by embossing the diffractive structure into hot stamping foil, followed by vacuum-coating of the embossed film with a thin layer of a reflective metal. The key security feature underpinning these OVD's and, indeed, all OVDs is, as the name implies, the variability of the image with changing angle of view or changing angle of illumination by a light source. This image variability means that such devices cannot be copied by the usual photographic, computer scanning or printing techniques. Therein lies their attractiveness to security printers.

The effectiveness of a particular OVD technology in counterfeit deterrence is, however, dependant upon the uniqueness of the optical effects produced by the device. Many diffractive OVD technologies have the disadvantage that the effects they produce can be simulated by simple dot matrix holographic technology. Dot matrix holograms are available off-the-shelf and are therefore readily accessible to unscrupulous operators.¹⁴ Another problem with foil based OVD technologies involves the costs associated with the production and subsequent incorporation onto the product, of the embossed hot stamping foil. If OVD microstructure could be print-embossed directly onto the substrate without any intermediate foil phase, this would reduce costs significantly.

In earlier papers we have described a possible solution to the above problems in the form of a directly printable or embossable OVD microstructure based on the use of micro-mirror arrays and highly reflective inks or lacquers.¹⁵⁻¹⁷ Besides being less costly, these ink or lacquer-embossed micro-mirror arrays also generate optically variable images by reflection rather than diffraction. Moreover, the images they produce are clearly different to standard OVDs, so that they are well differentiated in appearance from simulation by dot matrix holography. In the sections below, we will report that such micro-mirror arrays provide an effective counterfeiting deterrent even when directly embossed into transparent polymer substrates without the use of underlying reflective inks or lacquers.

In the following sub-sections, we will discuss the use of embossing techniques to create optically variable, overt images on transparent polymer substrates. In section 4.1, we describe the use of grooved-well type structures to create optically variable images when embossed in register on opposite sides of a transparent polymer film. In section 4.2, we describe how our previously reported micro-mirror technology may be used to create optically variable, overt images using a single-sided emboss.

4.1 Double-sided “soft” embossing (“Composite Optically Variable Watermark”)

One way to achieve novel effects using modulated digital image techniques is to physically attach the decoder to the encoded image with an intermediate, transparent layer between them. This can be done by coating both sides of a transparent polymer film with a suitably transparent, curable lacquer. The encoded image is then embossed, in register, on one side and the decoder is embossed on the other side, after which the lacquer is cured. Embosses of this type can be termed “soft” embosses, since they do not require high pressures or temperatures. Because the decoder and the encoded image are physically attached to each other, one may refer to such devices as “Composite Optically Variable Watermarks”)

Devices of this type can be made to display a range of optically variable effects. Figure 14 shows one such device which flicks from a positive portrait to its negative, upon tilting left and right. Animation and other effects¹ that can be created using MDI techniques may be similarly achieved.

Figure 14. Two views at different angles of a double-sided “watermark” emboss on a polypropylene film.

4.2 Single-sided “hot” embossing (Optically Variable Watermark; OVW)

Optically variable images may also be embossed in suitable substrates using a single-sided process; the resulting device is conveniently termed a true “optically variable watermark” (OVW).

The technology for this device is a spin-off from our earlier work on the development of direct-print micro-mirror, optically variable device technology. This direct-print OVD technology avoids the need for hot stamping foil as required for traditional diffractive OVDs by the simple expedient of replacing the miniature diffraction gratings of the device by miniature mirrors, which in this case can be over 30 μm deep. The miniature mirrors are created in two different orientations. One orientation is used to display the pixels of one image. The other orientation displays the pixels of another image. Because the two orientations are different, the two images can only be viewed at two different angles. The pixels are made highly reflective by embossing these OVD microstructures directly into substrates pre-coated with reflective inks. This technology also allows for much better encryption of the picture information and for this reason it has been given the generic descriptor of NanoCODES - meaning Nanofabrication of Cellular Optical Device Encryption Surfaces.

The optically variable watermark (OVW) version of NanoCODES is fabricated in the same manner as the micro-mirror arrays. However, these structures are then embossed directly into transparent polymer. The operable OVD mechanism then simply converts from one in which the pixels *reflect* incident light according to their orientation, to one in which the pixels *refract* light that is transmitted through the polymer, according to their orientation. In effect, arrays of micro-mirrors are converted into arrays of micro-prisms.

Figure 15 depicts two views of an OVW produced in this way on the surface of a polypropylene film. Figure 16 depicts a magnified view of the film surface showing the different structures that create the OVW.

Figure 15. Optically Variable Watermark (OVW) images in a polypropylene film observed at two different angles. The OVW was hot embossed. The vertical stripe on the \$/50 images (also present in Figure 17) is an error due to an instability in the electron beam current as the \$/50 mask was being written.

Figure 16. Magnified view of an embossed OVW microstructure

5. FABRICATION OF EMBOSSED COVERT AND OVERT IMAGES

5.1 Origination process for embossing optically variable watermarks (OVW's)

The optically variable images were designed with typical dimensions of $\sim 25 \times 25$ mm square. Each image consists of approximately 160,000 micro-mirror structures, each on a scale of 60×60 μm . The mirrors within the array are arranged at pre-determined angles according to the input picture information. The fabrication of this type of device

Figure 17. Images produced at two angles of view from nickel shims corresponding to the \$/50 switch and portrait/logo artwork. The \$/50 image is 20mm x 20mm while the second image is 13.5mm x 36mm. The depth of the microstructure is approximately 30 microns in each case.

involves, firstly, the production of an image-specific mask by electron beam lithography (EBL) and wet chemical etching. Finally, ultraviolet (UV) exposure through the mask onto a 30 μm thick optical resist layer, is employed to produce the intended relief structure within a layer of thick resist. The resulting image is then replicated by electroplating the surface of the resist layer to provide a hard nickel tool or printing die.¹⁸⁻¹⁹ In the present case, this nickel shim is directly embossed into polypropylene in order to convert the arrays of micro-mirrors into arrays of micro-prisms. Two angles of view of the reflection optically variable images produced by the nickel shims originated by this process are shown in figure 17.

Both of the sample microstructures shown in Figure 17 above were produced using the same microstructure palette – an enlarged section of which is shown for the portrait / logo image in the Figure 18 SEM image below. In Figure 18, the cellular units are each 60 μm x 60 μm in size and consist of micro-mirrors of opposite slope, corresponding to the portrait and logo channels respectively, together with a volcanic light trap microstructure which reduces shadowing between the two different channels of the image by a diffuse scattering effect.

Figure 18. A magnified section of the microstructure corresponding to the portrait / logo switch image of figure 17. Variable width micro-mirrors correspond to the portrait image while the fixed width micro-mirrors correspond to the logo channel. The micro-volcanoes create light absorbing and diffuse scattering effects which disguise the shadow of the alternate channel image when the other image is highly reflective. This image is taken at an angle of 45° to the vertical.

5.2. Embossing tests and results

Using the nickel shims produced according to the process described in the previous section, we have produced transparent polypropylene replicas of the microstructures by an embossing process using an embossing force of 100 kN

Figure 19. Observation geometry for the optically variable watermark (OVW) effect. The respective “\$” and “50” images are refracted through the micro-prism arrays and observed at the alternate eye positions E1 or E2 respectively.

over an area of 100 mm x 100 mm and a temperature of 130 °C for the embossing shim. The embossed polypropylene film was then observed in transmission mode with a small globe type light source located behind the film as shown in Figure 19 in the case of the \$/50 image. The optically variable watermark effect shown in Figure 15 was photographed with the camera looking vertically down on the embossed polypropylene film and a point light source behind the film moved to different positions to obtain the different image effects. This observation geometry is equivalent to the geometry shown in Figure 19 – but with the camera replacing the light source S and the light source moved to positions shown by E1 or E2 in order to obtain the different images. By the reciprocity theorem of optics this observation geometry is equivalent to Figure 19. The polypropylene film used for the experimental tests was provided by Note Printing Australia and is of the same formulation used in the production of Australia's polymer banknotes.

As can be seen from the sample results shown in Figure 15, the OVW technology produces highly visible images for both portrait and non-portrait images. The two-channel switch effect in both cases can be observed with a broad range of light sources with channel separation angles of more than 30°. The embossing process has been tested over a range of temperatures from 80 °C upwards. The embossing is most effective at 130 °C - with the OVW effect most visible at this temperature.

The microstructure corresponding to the portrait / logo image embossed under these temperature and pressure conditions is shown in Figure 16. Note that the microstructure is the inverse of the nickel shim microstructure shown in Figure 18 due to the mirror imaging nature of this replication process. In particular the micro volcanoes of Figure 18 now appear to be turned inside out. Figure 16 also shows that the fidelity of the embossing process is good with very little distortion across the micro-prism array and good reconstruction of individual micro-prisms.

6. CONCLUSIONS

In this paper we have described novel applications and refinements of modulated digital images (MDI's) as they relate to concealing images within other, printed images. We have shown that creating an entirely new printing screen containing the hidden image or images, provides significant advantages in document protection, such as dramatically improved concealment and copy resistance. Novel effects may, additionally, be achieved, including multiple-, micro-sized-, color-, or fade-effect hidden images. New techniques for seamlessly concealing multiple images within complex, full color photographs have also been described. We have further shown that MDI's can be readily embossed in transparent media as covert or overt watermarks. Micro-fabrication processes for the production of such embossed security features have been described, including processes for the production of a novel optically variable watermark (OVW) effect and a lenticular lens array effect; both features being highly suitable as anti-counterfeiting measures for polymer substrate applications.

All of the above technologies have prospective applications in the protection of valuable documents. Documents based on transparent substrates, like polymer films, may potentially also benefit from these developments. Where necessary, embossed microstructures can be overcoated with a clear ink of different refractive index to protect them from copying by electroplating.

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