Nano-Media: A Novel Multi-Channel Color Image Display with Embedded Covert Information

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Abstract

In this paper, a novel color image display with concurrent data storage is presented. We use a Nano-Media concept that consists of a nano-fabric based on sub-wavelength pixelated structures and an intensity control layer (ICL) deposited on top of a fabric. The ICL is used to tune the brightness of individual RGB sub-pixels and to obtain the desired pattern, data or image. Using this technology, any information can be stored and displayed as optical machine and/or human readable. The experimental work is presented to show the Nano-Media used for the multispectral layers of information storage and display. The fabrication results are discussed together with the practical examples for various applications.

Introduction

Visual information is a major channel for people to receive information. The visual information carrier probably has a history the same as the civilization: from text and picture printed on paper or plastics to a variety of the digital displays.

Metal nanostructures represent a class of materials made of metal with nanoscale features. Owing to the surface plasmons (conduction electrons on the metal surface) metal nanostructures can manipulate light at nanoscale and display intense colors and unique visual effects tunable with different periodicities over the entire visible/infrared spectrum [1][2][3][4][5]. Due to the excellent color properties, metal nanohole arrays (NHAs) have been applied as high quality color filters for cameras [6][12]. Nanostructures comprising nano-holes and nano-disks can function as bright color pixels smaller than a micrometer and can be used to produce a color image at a strikingly high resolution around 100,000 dots per inch (DPI) [7]. Metal nanostructures can be patterned into unique color images or optically variable graphics, which can be applied towards security and authentication applications [8]. Such a technology has been commercialized by Nanotech Security Corp. (nanosecurity.ca).

Producing a color image using nanostructures can be very time consuming and is currently a major challenge. At the existing systems, specific color pixels comprising sub-wavelength structures are positioned at the corresponding locations of the substrate, in accordance with the desired color image. The fabrication process usually requires lengthy procedures and costly techniques. Chuo and Kaminska et al. [9] have shown that nanostructures can be patterned onto one master stamp according to a customer-input image and large quantity of color images can be replicated from the same master stamp using a roll-to-roll process. The limitation is that each color image requires a completely new master stamp that may take many days to fabricate. Such a problem greatly hinders the applications of nanostructures in general visual media and a solution is in great demand.

In our previous works, a solution has been proposed that allows for rapid production of any color image using nanostructures [10]. In that method, fabrication of only one universal master stamp is needed and any given color image can be produced using the same master stamp. This method has recently been developed into a concept called Nano-Media, literally a media carrier made of nanostructures that can display any full-color images together with embedded covert information. A Nano-Media can be considered as a conventional media rebuilt with nanotechnology. Figure 1 shows the general flowchart of the Nano-Media creation.

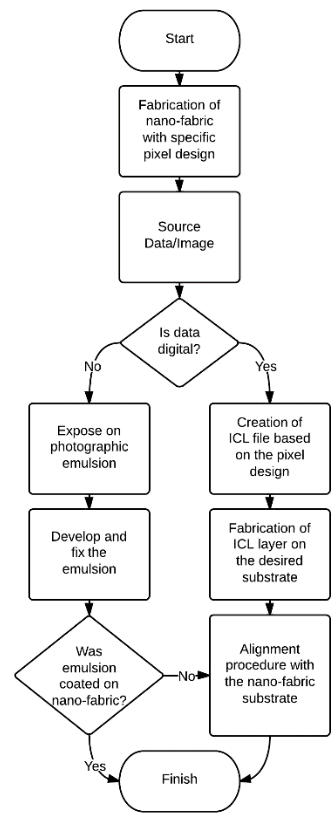

***Figure 1**. General flowchart for creation of the Nano-Media*

Fabrication of Nano Optical Structures

To create a Nano-Media, a layer of nano-substrate and an intensity control layer are required. Figure 2 shows the schematic of Nano-Media consisting of the above-mentioned layers. The nano-substrate is a pixelated layer composed of the sub-pixels from NHAs arranged into a mosaic of red (R), green (G) and blue

(B) for displaying visible colors. The mosaic pattern can also include other visible or non-visible pixels to achieve extra functionalities from the substrate. As it was mentioned before, by controlling the periodicity and the diameter of the NHAs, the color of each pixel is determined. Each NHA structure can be considered as a 2D grating, and the interference of light wave causes angle-dependent light reflection. As shown in Figure 2, white light is the incident at an angle θ from a medium of refractive index n, and the NHA has a periodicity P. The NHA reflects the m^{th} grating order into the normal direction for light of wavelength λ. The relation that links P with λ is given by Equation 1.

$$nPSin\theta = m\lambda \quad (1)$$

In our design, white light is incident at 60° (i.e., θ = 60°) and the red, green, blue sub-pixels reflects light with λ equal to 630nm, 530nm, and 470nm, respectively. We chose the 1^{st} grating order, i.e. (m = 1), in order to obtain solid colors and to minimize the rainbow effects that exist in many commercial holograms. The designed periodicities for red, green, and blue sub-pixels are 727nm, 612nm, and 542nm, respectively.

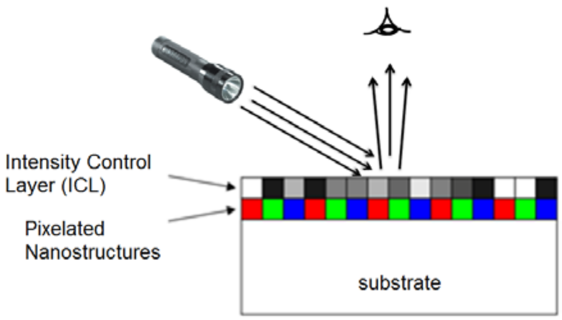

***Figure 2**. Schematic of Nano-Media*

The key to the fabrication of Nano-Media is the new implementation method of a 'universal' design for the nano-substrate so that the created master stamp can be used for producing any color image [9]. Figure 3 shows the layout of the pixelated NHAs with red, green, and blue sub-pixels. The fourth sub-pixel (shown in gray) is reserved for extra functionalities of the substrate. These sub-pixels are repeated periodically throughout the entire substrate and can be fabricated into large scale with one master stamp in a roll-to-roll process.

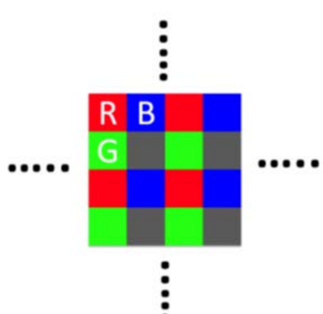

***Figure 3**. Schematic of a universal design layout of the pixelated NHAs*

After fabricating the universal substrate on the desired substrate, an Intensity Control Layer (ICL) is used to tune the intensities of the sub-pixels to create visual colors, similar to the liquid crystal in the color LCD screen. Figure 4 shows how a color image is produced from the nano-substrate fabricated from the universal master stamp. For the red circle, the ICL layer makes red sub-pixels transparent and blocks all the other sub-pixels to give red color. For the yellow crescent, the ICL layer makes red and green sub-pixels transparent and blocks blue sub-pixels to give yellow color.

Manufacturing ICL can be done in various forms depending on the nano-structure and the data type. The next subsection describes one of the methods ICL is created for this paper.

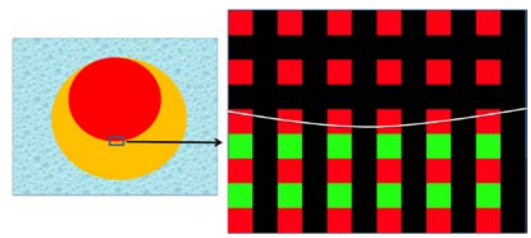

***Figure 4**. Schematic of how a color image is displayed on a Nano-Media*

Design and Fabrication of Intensity Control Layer

As seen in the flowchart of the Nano-Media in Figure 1, depending whether the image or data is digital or analog, different methods can be used to create ICL. In this paper, digital images are used to produce the Nano-Media. Hence, the ICL file is created using a computer software based on the sub-pixel arrangement on the nano-substrate. The nano-substrates used in this paper include R, G, and B pixels along with an Infra-Red (IR) pixel in the fourth reserved position (as seen in Figure 3). Using the IR sub-pixel, hidden information can be stored together with the visible color image on the Nano-Media. After creation of the file, the ICL is patterned into a continuous-tone gray-scale mask and is aligned with the nano-structure to produce the correct colors. Figure 5 illustrates the diagram of generating ICL from a digital file and how to achieve the final image by aligning the fabricated ICL on the nano-substrate.

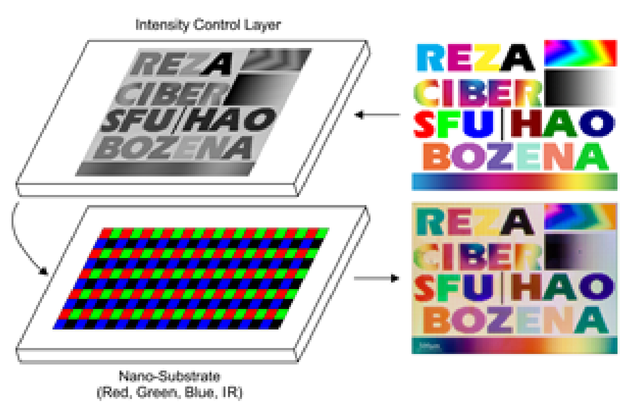

***Figure 5**. Diagram of ICL creation and alignment on nano-substrate to create a Nano-Media*

To estimate the stability of with the Nano-Media, stability of the nano-substrate and the ICLs should be analyzed. However, the nano-substrates are currently used for security applications by Nano-Tech Security Corp. and as one of the requirements of the application, the lifetime of the polymer or plastic substrate used is long. The ICL on the other hand is created using the silver halide black and white emulsion used in microfilms technology which can have more than 100 years of lifetime [11].

Full color images on the Nano-Media

Having a pixelated substrate with RGB color pixels, any information can be stored in the form of a visible image and can be displayed using simple optics such as magnifying lenses or projection systems. In the first experiment, ICL patterns have been designed in high resolution photomask according to the sub-pixel layouts on the fabricated nano-substrate using different color images including hidden information. By accurately aligning each ICL layer with the nano-substrate, the color images were successfully reproduced. Figure 6 illustrates experimental Nano-Media results created with 10x10µm^2 sub-pixels with the effective pixel size of 20x20µm^2. Using this pixel size, the resolution of the recorded images are 1270 pixels-per-inch (PPI).

(a) Color texts and color bars

(b) A yellow bee on a purple flower

***Figure 6**. Full color images displayed by a Nano-Media. The size of each image is 4 mm x 3 mm. Images were captured using a Canon 50D camera with 50 mm lens (F/22, ISO-400).*

The second experiment was performed using a lower resolution nano-substrate with 25x25µm^2 sub-pixels. The advantage of having larger sub-pixels is that the ICL can be created with conventional printing methods rather than using ultra-high resolution photomask technology. For this specific experiment, the ICL was created using an imagesetter with 3600dpi resolution printed on a light sensitive negative film. Figure 7 shows the color image created with the Nano-Media with only a rough alignment of the ICL with the nano-substrate.

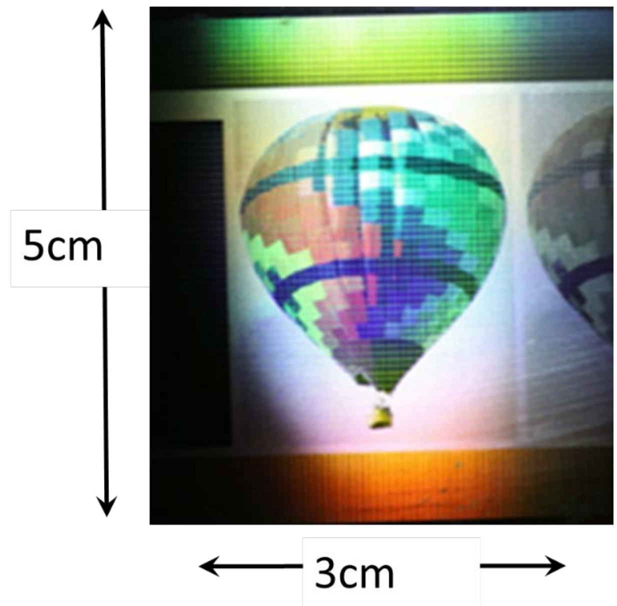

***Figure 7**. Color images displayed by a Nano-Media. Image was captured using a Canon 50D camera with 50 mm lens (F/22, ISO-400).*

Due to the limitation of the imagesetter print resolution, a group of 2 x 2 pixels were used as a single pixel in the image and each sub-pixel was defined to be either on or off. This combination allowed only 5 levels of color per channel which resulted in 125 distinct colors on this Nano-Media. To display the colors on the Nano-Media, a white light source is required. As it is seen in the image, an LED flash light was used for this purpose which caused the oval shape of lit area on the image. By using a better light source, the oval shaped light artefact will be eliminated.

As seen in the color image figures, especially in Figure 6, it can be seen that all color ranges can be displayed using Nano-Media. Beside the ability to store visible data/image on the Nano-Media, the fourth sub-pixel (IR) can be used to record hidden data/image within the overt data. Using the IR spectrum, additional information like metadata can be stored without interfering with the visible image. Figure 8 shows the additional data (a digital QR code in this case) and an image (a personal photograph in this case) stored along with the image shown in Figure 6. For this experiment, as there is only one IR sub-pixel available per pixel, separate designs of ICL were used to achieve each hidden data. To read or see the covert data on the Nano-Media, an edge-pass IR filter with a camera sensor sensitive to IR was used. The edge-pass filter only passes the IR wavelength while filtering out all visible part of the spectrum for the camera. As the human eye is not sensitive to IR, the hidden feature will not affect the quality of the visible image. To store extra covert data on the Nano-Media, extra IR sub-pixels with different wavelengths can be used. Using the right filter for each band, different information can be recovered on the substrate [12]. The multispectral display can be applied for higher density of storage or for different information formats or accessibility.

(a) Covert QR code recorded within the visible image on Nano-Media (Image is inverted)

(b) Covert personal photograph recorded within the visible image on Nano-Media (Image is inverted)

Figure 8*. Covert grayscale images/information stored in the Nano-Media. The images were captured using a sumix SMX-10M3C camera with an IR edge-pass filter using a telecentric lens.*

It should be noted that in the infrared image there are obvious disturbances that seemingly come from the pattern of the visible color image. However, after studying this effect, it has been found that the disturbances were actually caused by the scattering of light from the intensity control layer, not from the nano-substrate. The current experiments of the Nano-Media involves the integration of the nano-substrate and the ICL from the first step which reduces such disturbances so that the visible color image and infrared image should not have noticeable interferences on each other.

Applications of Nano-Media

Nano-Media can store high-resolution visual color images together with covert information. Because it is made of metal and plastic materials, Nano-Media is very long-lasting, immune to electromagnetic waves and resistant to oxidation. Therefore Nano-Media is an ideal candidate for archiving documents for a long period. The document stored in a Nano-Media can potentially be well preserved for longer than 100 years.

Color images produced using nanostructures are usually very difficult to duplicate, because each 1 mm^2 area of the image can contain more than 4 million of such nano-features. Therefore, color images produced from Nano-Media are very appealing for security document applications. Applications include passport with personal photos, personalized security cards, ID tags (e.g. driver license, medical cards), tickets, software licenses, DVDs/CDs, inspection tags drug detection and verification (pharma), court documents, wills and many others.

Nano-Media can also be used to produce general publishing media, such as newspapers, posters, book covers and magazines. By engineering the optical properties of sub-pixels, exotic visual effects can be achieved and can be used for artistic purposes.

In the scope of this work, we focused on using Nano-Media as an information carrier. In fact, we can also integrate an information receiver into the Nano-Media to explore many other possibilities. For example, by embedding pressure sensor arrays, the Nano-Media can function as an interactive display.

Conclusion

In this paper, we introduced the Nano-Media concept that uses sub-wavelength metallic structures allowing manipulation of light at nano-scale to produce primary colors of Red, Green, and Blue. The examples of our experimental work show high resolution overt images and embedded covert IR patterns created with the Nano-Media. By engineering the optical properties of nanostructures, many more novel functions from the sub-pixels can be explored. The Nano-Media technology can potentially change how visual information is presented in daily life.

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Author Biography

Reza Qarehbaghi received his MASc in MOEMS from Simon Fraser University (2013) focusing on improving the quality of bimetallic grayscale photomasks for creating 3D microstructures. He is currently pursuing his PhD in optics, nano-technology, and nano-fabrication at CiBER lab, Simon Fraser University with the focus on manufacturing of Nano-Media for security, publication, and data storage industries.

Hao Jiang received his Ph.D. from Western University (2011) studying nano-scale sensors based on plasmonic structures. He is currently working as a MITACS postdoctoral fellow at CiBER lab, Simon Fraser University. His research interests includes advanced nanofabrication technique, ultra-small nano-scale plasmonic structure physics and display technology based on nano-structures.

Bozena Kaminska, Ph.D., has 30 years of academic and corporate experience as a researcher, engineer, entrepreneur and educator. She is presently Professor and Canada Research Chair at Simon Fraser University, focusing on the research and development of new nano-devices and the manufacturing technologies. Kaminska is a prolific inventor, having authored multiple patents and more than 300 IEEE peer-reviewed publications in top scientific journals and conference proceedings.