A Nanotechnology-based Platform for Next-generation Optically Variable Devices

Abstract

This paper introduces Nanotech’s optically variable device (OVD) platform technologies, based on sub-wavelength nano-scale structures and their novel processing for high throughput manufacturing. The origination of nano-scale master shims for embossing and casting has been optimized for precision and throughput of large-scale shims. This new technique for originating OVDs creates distinctive, highly visible colours that are much more discernable than current holographic micro-scale grating-based structures, even in low-light environments. Nanotech has demonstrated that sub-wavelength periodic nano-hole arrays can produce high efficiency diffractive colours, extraordinary optical transmission, and surface plasmonic resonance for absorption and reflection of specific wavelengths of light. These properties can be exploited to produce visible features in both reflection and transmission modes in thin films commonly used in security OVD industries. The micro and nano-scale structures introduced here have many advantages over traditional grating and lens-based optics, including low aspect ratios leading to more mechanically robust structures, thinner material layers, as well as unique spectral signatures that can provide a medium for high density encoding of data.

Introduction & Background

Recognizing that hologram technology was largely antiquated and did not offer sufficient differentiation to the observer or authenticator, Nanotech saw the need to develop a new advanced OVD platform. This platform would deliver TV-like display animations on printed documents and serve as a paradigm shift in the technological advancement of visual security features and all forms of document authentication. Nanotech’s research was inspired by nano-scale structures found on the wings of Blue Morpho butterflies. Nanotech envisioned creating stunning structural colours through the interaction and manipulation of natural light with an array of nano-structures. In 2015, Nanotech’s original master patent was granted which demonstrated the company’s ability to produce unique images, but also laid the foundation for many future technology avenues including using nano-structures for energy generation and storage, next-gen medical sensors, and flexible electronic displays.

The ideal security OVD possesses multifaceted features that require complex processing to manufacture and yet produce an intuitive and simple message to the authenticator. Incorporating multiple effects into a single OVD is desirable as it greatly increases the complexity to deter counterfeiters. Despite a large number of recent emerging technologies, superimposing multiple advanced features typically extends the thickness of the OVD and/or increases the number of materials required, leading to greater manufacturing complexity, lower yields, and higher cost.

Nanotech’s nanotechnology platform transcends these issues by imposing a number of novel combinatory features beyond typical single-function designs. At the most fundamental level, the sub-wavelength dimension of nano-scale structures leads to high-intensity diffractive colours that can be complemented and enhanced by plasmonic absorption. The nano-scale structures result in a pattern resolution of 254,000 dpi (100nm “dots”) or higher, while
yielding potential perceivable image resolutions as high as 25,400 ppi (1 pixel per micron). Collections of tailored nano-structure arrays, each exhibiting an independently unique structural colour, are adjacently placed to form striking effects. In such manner, a single thin layer of arrays can be arranged to produce multiple overt features such as animations, fluid motion, “ON/OFF” colour transitions, and high definition artwork, as well as covert, forensic, and machine-readable features.

Core to supporting the design and layout of Nanotech’s nanotechnology-based OVDs, a proprietary software suite that utilizes optical modeling for rapid simulation was developed. The tools allow Nanotech’s designers to anticipate the perceived optical phenomena under a number of lighting conditions, based on far-field wave propagation resulting from sub-wavelength geometric structures, considering parameters such as nano-structure size and array configurations. Nanotech’s OVD images showcase intense high-definition artwork, capturing deep colours including skin tones via RGB-based colour mixing, fluid motion effects containing up to 8-frames of overlaid animation, and easy-to-verify high-resolution plasmonic colour images.

The current state-of-the-art overt security features found on high-end security documents, such as banknotes, passports, and bankcards rely on diffraction based OVDs, which are largely holographic in nature. OVDs are traditionally considered to be difficult to forge because they are replicated from a master holographic shim that requires expensive, technologically advanced equipment. Mainstream consumer use of holograms has lowered the cost of these specialized tools compromising the security of these features. Diffraction gratings in the micrometer scale, which form holographic features, are limited by small viewing angles and poor colour definition, as the grating will diffract all wavelengths of light within a few degrees of viewing. Volume holograms offer a partial solution to this problem by providing high optical efficiency and good definition of single colours; however, they are more costly to produce, require thicker materials to be effective, and are limited to very small viewing angles making large images difficult to see.

Nano-scale diffraction gratings can provide much larger viewing angles and therefore better colour definition for OVD features. More advanced nano-structures such as nano-hole arrays can be used to absorb or couple with specific wavelengths of light and are responsible for the brilliant iridescence of the Blue Morpho butterfly and many other insects. The study of these sub-wavelength or nano-scale optics addresses the specific interaction of light and matter at geometries smaller than wavelengths of visible light. Standard optics theory states that such geometries should not transmit significant quanta of light1, however the discovery of surface plasmons (SPs) and their aid in the transmission of light through sub-wavelength holes2 has yielded a plethora of research in this area ranging from biosensors3 to photovoltaic cells4. The fabrication of such small geometries poses many challenges, as the diffraction limit of light restricts standard photolithography to sizes larger than the wavelengths in the visible spectrum. Deep-UV systems face many barriers to produce the 100nm to 200nm geometries required, with projection and immersion lithography being too costly and unpractical for security OVD applications. A new-class of direct-write based lithographic systems, including electron-beam lithography (EBL) and focused-ion beam lithography (FIB), provide a

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method for constructing structures well below the diffraction limit, as small as 8nm or less. For OVD applications, these systems can be used to create originations or master shims for reproduction of nickel shim tooling and recombination necessary to manufacture these nano-structures at high volumes in the same manner as traditional surface relief holograms. Proper handling, substrate preparation, and subsequent processing of materials in the EBL or FIB require specialized clean-room facilities and supporting equipment. The fact that the manufacturing of a master shim requires expensive, highly advanced technologies in Class-100 clean rooms is attractive for security OVD industries where accessibility to such equipment is not predicted to reach consumer levels in the foreseeable future.

**Nanotechnology Platform**

To date, Nanotech has invested over $20 million to develop this revolutionary nanotechnology platform. Nanotech’s OVD devices are constructed using proprietary software coupled with electron beam lithography to embed billions of engineered nano-structures to create beautiful vibrant images. The platform provides unprecedented design options including true colour and motion exhibiting a high resilience against counterfeiting. The future for this platform has no bounds and can have as dramatic an impact on the print world as when colour printing replaced black and white printing in 1845. The Nanotech platform is not a fixed set of technologies, but rather an ever-evolving system which adds and subtracts technologies as required to achieve a particular goal. Currently the platform consists of three categories of optical structures: micro-structures, sub-wavelength nano-scale diffractive structures, and deep sub-wavelength nano-scale plasmonic structures. The power of the platform is that these three categories can be combined, or “mixed and matched” as needed. The following sub-sections provide a high-level look at each category as well as motivations for combining them.

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Broad Spectrum Control of Light using Micro-structures

Micro-structures come in many shapes and sizes. They are physically much larger than the light waves they interact with, but smaller than what one can see with the naked eye. Micro-structures are common in many high-end security OVDs today and can be seen as micro-lenses, micro-mirrors and diffraction gratings. Nanotech’s micro-structures are generally smaller than these, but still at the micro-scale. Their primary optical characteristic is to deflect and/or reflect all waves of light equally. They can be used to control how light behaves on a macro-scale i.e. specifying a particular viewing angle that light will be generally reflected towards. Some specific applications are diffusing light hitting the surface of a reflective material (e.g. aluminum) such that the surface appears a matte white; or creating a mirror-reflection point so that all the light is reflected at a specific desired viewing angle.

High Efficiency Diffraction Realized using Sub-wavelength Nano-structures

Nano-scale diffractive structures are separated by a distance (the periodicity, or pitch) roughly on the same scale as a wavelength of light (~400nm to 700nm). These nano-structures split (diffract) different light waves into specific
directions depending on the periodic spacing. The intensity of the light waves reflected is related to the density and shape of these diffractive structures. Generally, the smaller the periodicity (the denser) the structures are, the higher the intensity of light. The relationship of diffractive structure size and periodicity to intensity is proportional to the square of the amplitude – the more slits per area, the greater the intensity.

In reference to Nanotech’s definition of micro-optic structures controlling light at a macro-scale, one can think of these diffractive nano-structures as controlling light at a micro-scale. Diffractive structures can be blazed or non-blazed. Blazed structures provide the highest theoretical diffraction intensity for a given wavelength of light at a specific angle of diffraction; however, these are difficult to produce, particularly at the nano-scale. Combining blazed structures with nano-scale density produces a kind of ultimate diffractive platform. Nanotech’s current blazed diffractive structures provide density for red, green, and blue sub-pixels resulting in true RGB colours for hyper-photorealistic image reproduction. The true RGB means a wider and more flexible colour triangle in the CIE 1931 colour space diagram compared to active displays and other known diffractive technologies (see below). While this capability provides unprecedented image reproduction, it introduces design challenges as images designed on current computer display technologies may appear different than the final OVD output. For example, a slight over saturation in Photoshop may translate into a gross over saturation in the Nanotech OVD image.

![Nanotech's diffractive RGB CIE colour triangle vs. HDTV capability (left). Example of an actual Nanotech OVD demonstrating true colour (right)](image)

**Plasmonic Colour Generation using Deep Sub-wavelength Nano-structures**

When both the nano-structure and the periodicity is well below the wavelength of light it interacts with, new and exciting optical phenomenon can appear. Surface plasmonic resonance is a specific phenomenon that occurs in such structures when combined with conductive metal films sandwiched between dielectric materials. The structures can change the colour of the metal surface through selective light wave absorption and reflection. The colour effect is closer in look to metallic colour pigments than diffractive “holographic” effects.
Absorption and reflection occur due to an interaction of photons and metal electrons, caused by the specific nano-structures engineered in the metal’s surface. Surface plasmons (SPs) are collections of surface oscillations of electrons in sub-wavelength nano-structures at the interface of a metal and dielectric capable of trapping optical waves near their surface leading to extraordinary optical transmission (EOT) [Ebbesen et al. 1998]. When a metal film with a thickness that transmits little radiation, i.e. “optically thick”, is perforated with an array of nano-holes the transmission of light can be observed at very high efficiencies. The same is true in reflection modes; a thick metal film with hole-shaped divots will resonate at specific wavelengths of light absorbing some and reflecting others. Recently, studies have investigated the dependence of EOT on a variety of parameters to improve nano-hole array performance\(^7\),\(^8\).

The excitation of SP modes depends highly on the spacing between adjacent holes (periodicity) and dielectric constants of the metal and dielectric. Ebbesen [1998], was first to derive an equation describing the dependence of the SP resonance modes (the EOTs) on the arrangement of nano-holes for a square lattice when the incident light is normal to the plane of the nano-hole array:

\[
SP(i, j) = p \frac{\sqrt{d_m}}{\sqrt{i^2 + j^2 \sqrt{d + m}}}
\]

Where \(p\) is the array periodicity, \(\varepsilon_d\) and \(\varepsilon_m\) are the dielectric constants of the metal-dielectric interface and the metal respectively; \(i\) and \(j\) are integers expressing the scattering mode indices. Metals such as gold, silver, aluminum and copper are known to have stronger optical resonant transmission peaks compared to other metals such as tungsten and chromium which exhibit smaller resonance due to their absorption properties\(^9\). Moreover, variations in the nano-hole shape and size, pitch (or periodicity), hole depth, and relative locations of hole arrays, as well as the


thickness of the metal and dielectric films affect the surface plasmon properties, allowing for a large scope in design parameters to consider. The optical transmission efficiency of the nano-hole array reaches an asymptotic upper value with a precise finite number of holes in the array\textsuperscript{10}.

Furthermore, the optical resonant transmission of a nano-hole array may be adjusted by varying the dielectric constant on the back and front surface of the array effectively altering the SP energy on each side. The adjustment of dielectric constants on the surface translates into an effective “red” or “blue” shift of the first and second order peaks. Simply changing the dielectric and/or metal combination even with the same nano-structures can shift the colour of the transmitted or reflected light. The above equation is used as a first order approximation of SP modes and does not consider the specific geometries\textsuperscript{11}. However, it provides an easy to understand sense of how plasmonic colours are impacted by modifying the material parameters and the periodicity of the nano-structures.

**Combining Micro and Nano-structures**

Taken individually, the various technologies currently available in Nanotech’s platform provide a gamut of state-of-the-art optical effects which can be leveraged to produce many OVD types on the market today and many others not currently offered. For example, Nanotech’s diffractive effects include not only full RGB true colour images or multi-channel image switches, but full colour multi-channel image switches (i.e. one RGB image switching to another RGB image), which is currently only offered through Nanotech’s products.

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<tr>
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<th>Micro-structures macro effects</th>
<th>Diffractive effects</th>
<th>Plasmonic effects</th>
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Nanotech’s platform summary of capabilities


Another advantage of the platform is its modularity. Different technologies, and their respective effects, may be treated as different modules and combined to cover a wider range of desired effects. Even more ambitiously, the technologies may be combined to realize all together new optical effects, such as full parallax multi-axis 3D images and animations.

Nano-structures (either plasmonic or diffractive) can be formed along the 3D contour of a given micro-structure. Combining micro-structures and nano-structures augments both the micro-structure and nano-structure effects by controlling the light at different scales: macro, micro and nano. In doing so, Nanotech can create many unique effects where the sum is greater than the parts.

Origination of such exotic hybrid structures is extremely difficult and complex and is beyond the scope of this paper. Suffice to say, Nanotech has invested years into developing a multi-stage EBL process which has enabled the company to produce these theoretical structures and manufacture them in what is likely true world-first.

Combing the power of nano-scale plasmonic coloration and macro-scale light diffusion or angular viewing of micro-structures opens pathways to a variety of effects. Effects from static full colour imagery, to simple colour shifting films, to complex 3D images and movement can be realized from a single layer of embossed aluminum-coated structures.

Conclusion

Nanotech’s next-generation OVD platform of nanotechnologies, based on sub-wavelength nano-scale structures can be exploited to produce highly unique visible features in both reflection and transmission modes in thin films commonly used in security OVD industries. The micro and nano-scale structures introduced here have been shown to have many advantages over traditional grating and lens-based optics, including low aspect ratios leading to more mechanically robust structures, thinner material layers, as well as unique spectral signatures that can provide a medium for high density encoding of data.