

Advances in holographic replication with the Aztec structure

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Abstract

Holograms that are predominantly in use today as replicable devices for display, security, or packaging can generally be divided into two categories: either surface relief rainbow holograms, which include three dimensional images and intricate grating patterns, or reflection type volume holograms. The Aztec structure is a special surface relief device that combines aspects of both of these types. Its fabrication by holographic means requires techniques of both surface and volume holograms, and thus it is technically more difficult to make than either separately. The structure is deeper than the standard surface relief hologram, and its profile has the characteristic of several well defined steps, such that, when viewed on edge, resemble a stepped pyramid. Thus, replication of the Aztec structure requires special high resolution techniques to faithfully record the submicron features of the stepped profile, and thus is more difficult to manufacture. The visual characteristics of the Aztec structure are similar to the volume hologram, in that single colors, rather than rainbow colors, can be viewed. Also, a combination of single colors can be encoded into a single master, yielding unique visual effects.

Keywords: Holography; Gratings; Replication; Security devices

1. Introduction — conventional techniques

1.1. Surface relief structures

Replicable holographic type devices today can generally be divided into two categories: either surface-relief structures or volume reflection structures. The surface relief type is the most predominant, and its recording is derived from the basic Leith–Upathieks [1], or off-axis, configuration, in which light from an object (the “object” beam) interferes with light from a reference (the “reference” beam), both beams being incident from the same side of the recording medium. The basic interference fringe structure consists of planes that are predominantly perpendicular to the recording surface. Photoresist is always used as the recording medium, because intensity variations are translated into varying relief depths that resemble a sine wave, upon exposure and development. A hard replica in nickel can then be made by conventional electroplating techniques and installed onto a cylindrical drum of a roller-type replication machine. By use of heat and pressure, or by ultraviolet casting, the surface relief pattern can be replicated, literally into thousands of feet, onto a plastic substrate. The resulting replicated plastic base is then coated with an evaporated layer of aluminum to enhance the brightness of the observed image.

1.2. Volume reflective structures

The other major type of replicable holographic structure is the volume reflection, or “Denisyuk” hologram [2]. With this configuration the reference and object beams are brought in from opposite sides of the recording medium,

and the interference planes, instead of being perpendicular to the recording surface, are parallel to it. The recording medium, instead of being photoresist, usually consists of a silver halide photographic emulsion, dichromated gelatin, or photopolymer. Upon exposure and development many parallel layers are recorded throughout the depth and they are spaced a half-wavelength of the recording light apart. Upon illumination with the reference beam, light will be reflected from each of these semi-transparent layers and will coherently interfere to produce a bright reconstructed image. The unique characteristic of this type of hologram is that even when illuminated with broadband white light, the hologram will reconstruct at the wavelength with which it was recorded. The replication of this type of hologram requires making a master volume hologram on a flexible substrate that can be wrapped around a cylindrical drum, as with the surface-relief case. But replication depends on copying directly into the recording medium using laser light. The reference light is the incident unmodulated scanning light, and the object beam is the image light reflected from the master back through the recording medium. The recording medium could be photopolymer, for example, that is unwound from a cylindrical drum that passes over the master cylinder, where the scan light sweeps over it. This technique is effective, but it is inherently a more expensive process than surface-relief replication.

2. Nature’s surface relief volume hologram: The *Morpho* butterfly

A strong hint of an improved surface relief structure is provided by nature, in the form of the *Morpho* species of

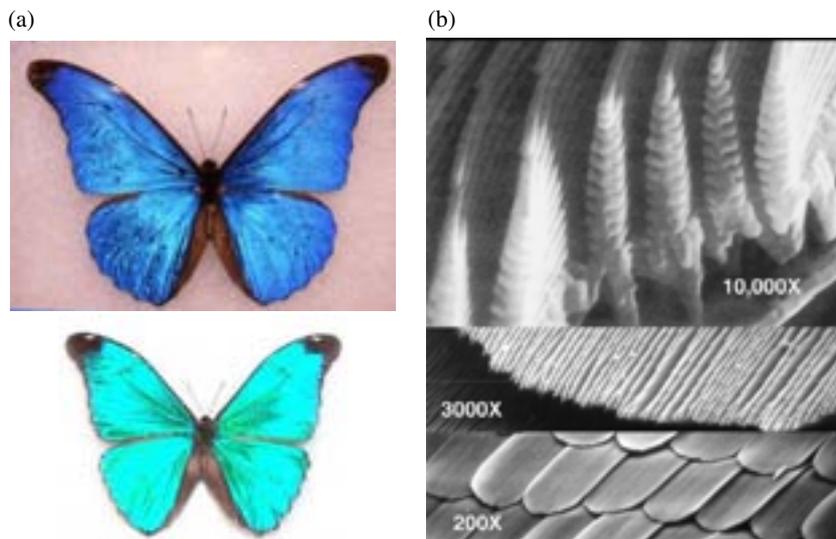


Fig. 1. (a) *Morpho rhetenor*, top, *Morpho absoloni*, bottom. (b) Wing structure of *Morpho rhetenor* butterfly.

butterfly (Fig. 1(a)), from the South American rain forest, and which is characterized by the brilliant, iridescent color of the wings. This iridescence does not arise from any pigment, but solely from the structure of the wing. This wing structure is displayed in Fig. 1(b), which shows scanning electron micrographs at varying degrees of magnification. The wing consists of what from the top surface resembles a linear grating, but which when seen from the side, is more complex, resembling a series of closely separated Christmas-tree like structures. The tree “branches” are separated by a half wavelength of the iridescent blue color that is seen when the wing is illuminated by white light. The remaining colors other than blue are absorbed by the material of the wing structure itself (chitin). The significant feature of this structure is that it is entirely surface relief, as the space between the “Christmas trees” consists of air.

3. The Aztec grating

Replication of the desired structure into photoresist can be done, provided the following modifications are made (1) where the wing structure is heavily undercut, make a structure that is not undercut, but is stepped instead, and (2) where the wing structure achieves brightness by virtue of the fact that it is undercut, instead make a single, but stepped layer, that achieves brightness by overcoating it with a highly reflecting metal, such as Al.

The Aztec grating described here is a combination of both an off-axis and a volume holographic grating, as shown in Fig. 2(a). A holographic grating is first recorded as an off-axis pattern, with the interference planes perpendicular to the surface. Etching by photoresist developer yields a conventional sine-wave profile grating, as described earlier. If now the plate is not developed, but a second recording made, this time with the two beams incident from opposite sides of the plate, then another set of interference planes will be formed that are parallel to the surface. Thus, there

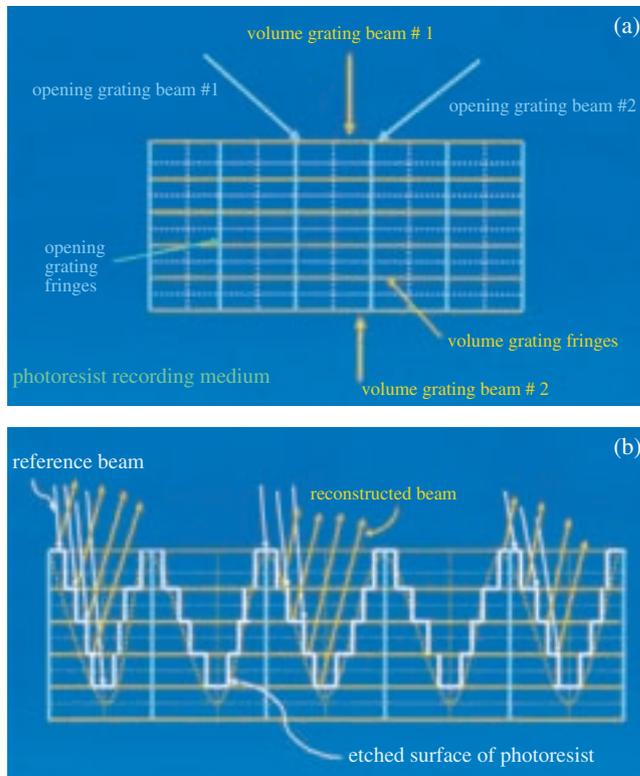


Fig. 2. (a). Construction of Aztec grating. (b) Reconstruction of Aztec grating.

are two sets of interference planes perpendicular to each other. When the plate is developed, the etching of the sine wave proceeds as before, except that the sine wave becomes modified into a stepped profile, as shown in Fig. 2(b). Thus, the information that was originally recorded in the volume can now be accessed. The off-axis hologram can be regarded as providing an “opening” structure to access the low-lying levels. Whereas a normal volume structure would have many

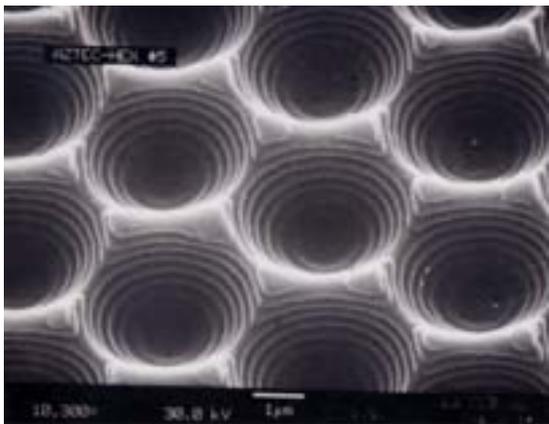


Fig. 3. Aztec honeycomb grating (10,300 \times).

semi-transparent parallel layers, the Aztec grating has only a single, but stepped layer. When overcoated with a highly reflecting metal, it will display a single color characteristic of the step height. The name “Aztec” is an acronym for diazo photoresist *technology*, after the chemical composition of photoresist, but it also refers to the pyramidal stepped structure of the etched surface [3–5].

A particular type of useful “opening” structure is the Aztec Honeycomb grating, made in the following way: (1) record a honeycomb grating with three coherent beams incident onto the photoresist surface at azimuthal angles 120° apart, and (2) record the step structure with beams incident from opposite sides of the plate. Fig. 3 shows the resultant profile, which can be regarded as a type of “single-color photonic crystal”. A typical step height is around 150 nm, which if embossed into plastic with an index of refraction of around 1.5 would yield an observable single color of $150 \times 2 \times 1.5 = 450$ nm. The bandwidth is approximately equal to the reciprocal of the number of steps; so, for example, for 10 steps, we would achieve a bandwidth of 45 nm, which to the eye appears relatively monochromatic. Ten steps at a spacing of 150 nm yields a total depth of 1.5 μ m, which is approximately an order of magnitude greater than the typical embossed hologram, but is also about an order of magnitude smaller than the typical volume hologram. Colors at longer wavelengths can be achieved by recording the oppositely propagating beams at large angles of incidence, which would lead to larger step heights. Another way of achieving other colors is by embossing into materials having different indexes of refraction. For example, if in the previous example, the plastic had an index of 1.7, the observed color, for the identical step height of 150 nm, would be $150 \times 2 \times 1.7 = 510$ nm. Color variation can also be achieved by sandwiching the grating structure with a liquid crystal overcoat between electrodes and varying the index electrically [6].

Fig. 4 shows an embossed “colorstripe” Aztec honeycomb grating, where different colors have been recorded in centimeter-wide strips into a single nickel master, pressed into plastic, and overcoated with aluminum. These colors are observed in the zero-order direct reflected light. Measured

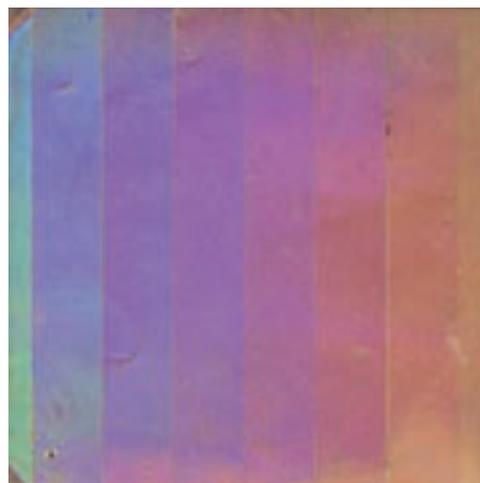


Fig. 4. Aztec colorstripe grating embossed in plastic, showing center wavelengths of each stripe.

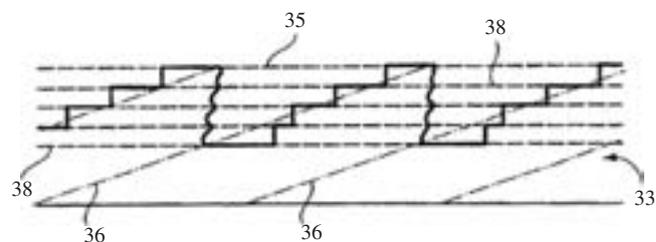


Fig. 5. Aztec asymmetric profile. Photoresist recording medium, 33; top surface, 35; volume fringes, 38; tilted off-axis opening fringes, 36.

center wavelengths in nanometers are shown beneath each stripe. Viewing is through the plastic base, which has an index of refraction, $n = 1.5$.

4. The Aztec hologram

The previous case describing the Aztec grating provides single colors, due to the step structure, in combination with rainbow colors, due to the “opening” hologram. These two separate optical effects arise because they are due to two separate recordings with two separate and distinct sets of interference fringes. Even although there is one rather complicated surface relief structure, each separate fringe structure provides its own “exit channels” for diffracted light. For those cases where one desires only single colors without the rainbow colors, this configuration has to be changed in such a way as to open up the information encoded in the lower levels of the photoresist surface while at the same time suppressing the diffractive rainbow spectra associated with the opening hologram.

This result can be accomplished by a configuration that combines a single object beam with two separate reference beams. One of these reference beams enters the recording surface from the same side as the object beam, and the second reference beam enters from the opposite side. The desired

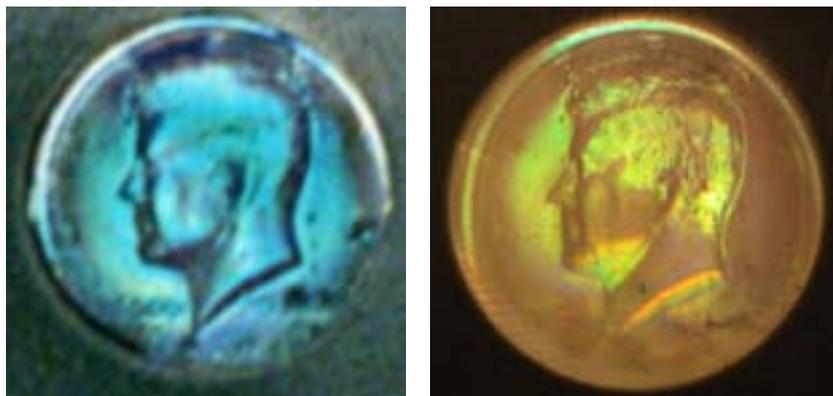


Fig. 6. Aztec single-color holograms. Left image, step height = 121 nm; right image, step height = 182 nm.

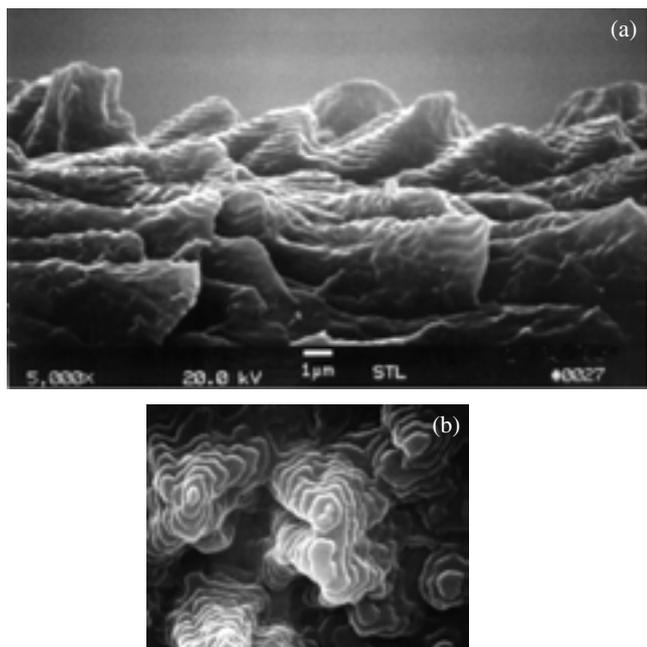


Fig. 7. (a) Asymmetric (blazed) embossed Aztec hologram, side view at 5000 \times . (b) Asymmetric (blazed) embossed Aztec hologram, top view at 10,000 \times .

result can then be achieved by relying upon the fortuitous circumstance of the varying diffraction efficiencies of an off-axis hologram, in the first case, and of a volume reflection hologram, in the second case, as a function of the total etch depth. The off-axis efficiency peaks at a certain depth and then decreases again to zero at a larger depth. The diffraction efficiency of the volume hologram, on the other hand, starts at zero at zero etch depth, then rises slowly to a maximum value at a certain larger depth, but then stays at this maximum value as the depth increases. Thus for a certain large etch depth value, the off-axis spectral efficiency essentially becomes zero, while the volume reflection efficiency maximizes.

A particularly advantageous type of Aztec hologram results when the opening fringes are tilted at a large angle

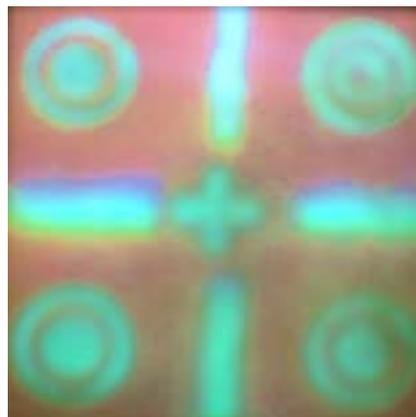


Fig. 8. Hologram from which micrographs in Fig. 7 were made.

with respect to the recording medium, with the result being an asymmetric stepped profile, as shown in Fig. 5 [7].

The advantages to an asymmetric (blazed) construction are the high diffraction efficiencies that can be obtained at many adjacent wavelengths, all of which fall under an envelope that is peaked at the design center wavelength. Fig. 6 shows two single color holograms recorded with two distinctive step heights, d , the blue image with $d = 121$ nm, and the greenish-yellow image, with $d = 182$ nm, and where the overcoating dielectric had an index of refraction of 1.65. There was an average of about ten steps for each image.

Fig. 7 shows micrographs of the surface of an embossed blazed hologram with many steps [8]. In this case the object appears relatively monochromatic but exhibits at the same time a diffuse quality. The micrograph clearly shows this result, in that the step heights are uniform and distinct, while the overall pattern appears random, which would be expected for a diffuse image. Fig. 8 shows the hologram from which the micrographs in Fig. 7 were made. The small cross and circles are focused in the recording plane, but the large cross in the background is focused a full 2 in behind it. This demonstrates the monochromatic quality of a deep Aztec hologram. Furthermore, this color is maintained throughout a full parallax movement of the hologram.

5. Conclusions

The Aztec structure is an attempt to improve upon both forms of conventional holographic replication and to provide some unique additional effects. Embossed holograms at the present time are limited by the shallow depths of the surface profiles which only allow for rainbow color effects and no discrimination for single colors. By recording at deeper depths into photoresist with structured, stepped profiles, single color discrimination can be achieved, and, in the case of display holograms, full parallax viewing. Furthermore, it is possible to make multiple color images on the same recording surface. A favorable comparison can also be made with conventional volume hologram replication, primarily in terms of cost, but also because replicating from a single master that already has multiple colors encoded into it is much more straightforward than having to record multiple colors on the production line.

While there are many obvious advantages to the use of Aztec structures in replication, there are many challenges in the manufacturing process. The brightness of the images depends strongly on the fidelity with which the fine, submicron steps are replicated. Very high efficiencies can be obtained for distinct, well-defined step heights in the profile. If we now assume that in replicating these steps from the photoresist master to some plastic substrate, some rounding of these steps occurs, or even more so, if the steps disappear completely, the efficiency reverts to that of simply a deep sinusoidal profile. As has been described earlier the efficiency of such a deep profile has already passed its maximum and has achieved a value close to zero. Observation of such a surface would show not only no color, but it would also

appear quite dark, and this would be true even if overcoated with aluminum. Obviously great care has to be taken in the replication process, and many conventional techniques, such as heat and pressure, are not effective. It has been found that ultraviolet casting does indeed work on a production line, but even with this, care must be taken to ensure that curing is complete for the intricate profiles that are encoded in the master plate. While these considerations mean that manufacturing of the Aztec profiles is much more difficult than conventional embossing, this is exactly what makes it desirable for several applications, one in particular being the security hologram.

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