We often witness the beauty of nature, but fail to see the beauty of science and technology. A contest held this past summer in Hawaii demonstrates that the two are not mutually exclusive.

DIFFRACTIVE BEAUTY

By Joseph N. Mait

A beauty contest in Hawaii is perhaps not unusual, unless of course the sponsor is OSA. But a beauty contest is what was indeed held at the 1998 summer topical meeting, Diffractive Optics and Micro-Optics, in Kailua-Kona. The event raised more than a few eyebrows when it appeared in the scheduled program, however, the beauty of interest to the organizers was neither tawdry nor titillating, but based solidly in science and technology. Despite amusing references to "swimsuit and talent competitions," The Miss America Pageant has little to fear from OSA; artists and engineers, however, may be intrigued by the aesthetic possibilities of diffractive optical technology.

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The intent of the conference organizers was to uniquely demonstrate advances in the state of diffractive optical technology through the production of visually complex images. As stated in the contest announcement, its purpose was "to promote the development of diffractive optical technology in a light-hearted competitive manner by challenging the community to be creatively artistic."

Twelve entries were received in response to the contest announcement, primarily from "professional diffractikers"—individuals well known within the diffractive optics community; however, a single entry was received from a self-proclaimed amateur. All entries were judged in terms of artistic interpretation and technical implementation, *i.e.*, the effects used to create the reconstructed image. The top three winners in both categories, selected by a jury of conference committee members, are presented here. In a true display of ingenuity and science, the winner in the artistic interpretation category also placed third in technical implementation, so only five entries are discussed.

The top three winners in each category are showcased on pages 23–24. Per the contest rules, all elements were designed for 632.8 nm and their element size was restricted to 1×1 cm^2.

Background

Diffractive optical technology is rooted in the work of Adolf Lohmann. Lohmann's ideas on grating modulation, which later became known as the Detour Phase Technique, were first presented at a 1956 German Optical Society meeting in Berlin, and later published in 1958.[1] While at IBM in the early 1960s, Lohmann and summer student, Byron Brown, combined the developing field of holography with the similarly nascent computer technology of the time to develop what has become known as computer-generated holography.[2, 3] Fabrication technology was also in its infancy, and the first computer-generated hologram (CGH) was fabricated through a combination of primitive plotting, hand drawing, and photography.

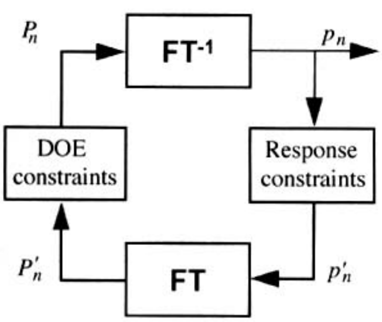

Figure 1. Iterative Fourier transform algorithm (IFTA) used to design diffractive optical elements.

Aided by advances in both computing and fabrication technology, the complexity of functions that CGHs, or what are more commonly referred to now as diffractive optical elements (DOEs), has increased considerably. Diffractive lenses, deflectors, and array generators (elements capable of splitting a single- input beam into multiple-output beams) are now offered commercially by several vendors.[4–7] The size of elements is typically on the order of centimeters and the elements can contain up to 10,000 $\times$ 10,000 1-μm features.

In spite of the numerous technical applications, to the lay populace the most eye-catching characteristic of diffractive optical technology remains its ability to produce arbitrary images. In fact, the winner of the artistic interpretation category is being used in an animated display of marine life at the National Aquarium in Baltimore, Md.

Design

A significant difference between natural and computer-generated holography is that a physical object is not required to create a CGH. Rather, one only needs to represent the object in some fashion on a computer. Yet, despite advances in computer and fabrication technology, objects that can be optically reconstructed with high fidelity are typically planar, for example, pictures or graphic images.

To design a diffractive element, one essentially inverse-propagates a complex-wave amplitude description of the desired image from the image plane to the plane containing the element. The distances and feature sizes of state-of-the-art diffractive elements is such that scalar diffraction theory is valid. Thus, inverse propagation can be achieved using either an inverse Fourier or Fresnel transform.

If that was all that needed to be designed, the optics community would have little need for a series of conferences to address diffractive technology. The difficulty is that since the object representation is complex, the resulting wavefield is also complex, but due to limitations imposed by fabrication, the diffractive element itself has limited transmission. For example, the first CGHs were generated by photoreducing black and white drawings produced by paper plotters. Restricted to binary amplitude structures, Lohmann modulated the area and location of binary rectangular cells to encode complex values. Most of the methods and algorithms used in diffractive optic designs have been developed to address the encoding of a complex wavefield into a format that represents the limited transmission of the element.[8]

Today, photolithography can be used to create multilevel surface relief structures, which are known as phase-only elements. One advantage of phase-only elements over amplitude elements is that, being transparent, they provide greater throughput. However, because the phase of a Fourier representation contains approximately twice as much information as the amplitude,[9] reconstruction errors using phase-only elements are also lower than those using amplitude elements. Thus, phase-only elements can generate simultaneously high signal-to-noise ratios and high-diffraction efficiencies (the percentage of input energy that is used to form the desired image).

Nonetheless, designing a phase-only DOE that generates little error with high-diffraction efficiency is a balancing act. Although other design algorithms exist (*e.g.*, direct binary search and genetic algorithms), the iterative Fourier transform algorithm (IFTA) is perhaps the simplest for managing this balancing act, especially when designing DOEs to reconstruct large objects ($> 256 \times 256$ pixels).[10–15] In the IFTA represented in Figure 1, the designer imposes fabrication constraints on the DOE (*i.e.*, it has only a finite number of phase levels) and simulates propagation of the wavefield to the image plane using either an inverse Fourier or inverse Fresnel transform. The image is modified in amplitude, and sometimes in phase, to ensure that the desired response is created. The modified image is inverse-propagated to the DOE plane. However, due

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to the modifications, the DOE no longer satisfies the fabrication constraints, which must be reimposed, thus initiating a new cycle.

If the constraints and modifications are imposed with care, the changes required to meet the constraints in both the image and element domains are reduced in magnitude with each iteration. The result is an element that satisfies the constraints in both domains with high fidelity. Most of the beauty contest contestants used the IFTA to design their elements.

(The IFTA is also referred to by some as the Gerchberg-Saxton algorithm.[11, 12] However, Gerchberg and Saxton were crystallographers interested in solving an inverse problem of object reconstruction from Fourier magnitude information. Independently, but contemporaneously, Gallagher and Liu developed a similar algorithm for computer-generated holography.[13] Upon publication of Gallagher and Liu's work, it was revealed that the algorithm was actually first discovered by Lesem, Hirsch, and Jordan[10] for designing kinoforms, the name they gave to the first phase-only diffractive element. Thus, the honor of naming the algorithm rightly belongs to Lesem, Hirsch, and Jordan.)

To ensure high-fidelity reconstruction of the desired object, the pattern designed using the IFTA is typically replicated several times. Replication ensures that the reconstruction consists of discrete points and accurately reflects the sampled representation of the object used in the computer-generated design.[16] Further, the larger the number of replications, the greater the reduction in reconstruction errors.[17] A typical representation of a phase-only element is presented in Figure 2a.

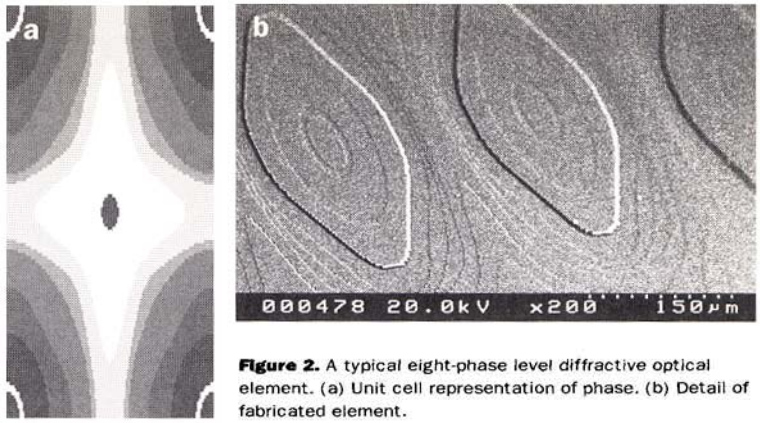

Figure 2. A typical eight-phase level diffractive optical element. (a) Unit cell representation of phase. (b) Detail of fabricated element.

Fabrication

Many methods for fabricating DOEs have been proposed, including contact printing, diamond turning, ion-diffusion, and mass transport. However, by virtue of its ubiquity, the most common method relies on the photolithographic technology of the microelectronics industry. A layer of photoresist is spun onto a substrate and exposed to UV-illumination using a mask. The photoresist is developed and etched using, for example, reactive ion etching or chemically assisted ion-beam etching. The depth h of the etch corresponds to an optical phase ϕ related to the wavelength λ and substrate index of refraction n_s, so $\phi = 2\pi h(n_s - 1)/\lambda$.

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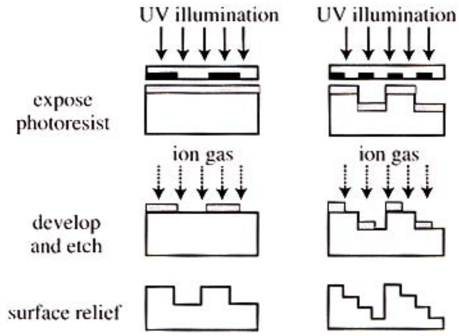

Figure 3. The multi-step photolithographic process used to fabricate diffractive optical elements.

The Congeniality Award

Rick Morrison (Lucent Technologies and the Univ. of Illinois) entered an element that produced different images at two different spatial planes. One was a reconstruction of the Chicago Bulls team logo and the other was the words "Illinois U." Although not selected as a winner in either category, Rick made his presentation in the spirit of good-natured fun, and therefore was recognized by the contest judges as "Mr. Congeniality." The full text of his remarks are presented below. The words in italics relate to the field of diffractive optics, most of which are defined in the main article.

Introduction

Rick: This beauty contest turned out to be a lot more fuss than I had anticipated. I just moved my lab to the University of Illinois, so I was instructing a graduate student and only able to work part-time on this project from a distance. I would like to share with you some of the phone conversations that I had with my graduate student, Colin Byrne, who is responsible for our entry.

Rick: Well Colin, have you given much thought to the project?
Colin: Yes, Prof. Morrison, and I am sorry to inform you that it can't be done.
Rick: Why do you say that?
Colin: I checked at the university administrative offices and they have no forms for kinos.
Rick: Colin, they're called ***kinoforms*** and you'll be in charge of fabricating them! Now, have you obtained approval from the department head?
Colin: Again, I'm sorry. He says that you are too obsessed with skin care.
Rick: What???
Colin: He asserts that the topic of ***surface relief*** is best handled by the medical school.
Rick: Colin, get a grip on reality! We are trying to create a phase encoded ***hologram*** that replays when it is correctly aligned with its conjugate pattern, just like a ***correlator.***
Colin: Whoa, boss! If you arrange conjugal activities between close relatives in this part of the country, you'll be doing jail time.
Rick: I'm beginning to regret this project. Colin, have you been able to garner support from anyone at the University of Illinois?
Colin: Yes, Rick. I'm happy to say that you have the full support of the department faculty. They all agree that you will never win a beauty contest unless we make a ***mask*** for you.
Rick: Thanks, Colin. I'll call back when I feel better.

A week later.
Rick: Hello, Colin. What's the status?
Colin: Well, Professor Morrison, I've been expelled.
Rick: What happened?
Colin: I made the mistake one evening of inviting the women's swim team up to my lab to see my ***etchings.***
Rick: Colin, you're ***incoherent.***
Colin: Sorry, it's a ***phase*** I'm going through.
Rick: How often do you work on the grating?
Colin: ***Periodically.***
Rick: Colin, get back to work!
Colin: Alright boss. You ***Dammann!***

A last minute conversation.
Rick: Colin, we need a title for this diffractive optic entry immediately.
Colin: How about "Half the Lone Ranger"?
Rick: Please explain.
Colin: See, you have a mask, but you'll need a silver bullet to get this diffractive done on time.
Rick: Ouch. Any other suggestions?
Colin: How about "Doubles"?
Rick: Doubles? I don't get it.
Colin: Doubles! Doubles! You know, that basketball team that Michael Jordan plays for–Duh Bulls.
Rick: Please, no more! All of your jabbering is making me sick.
Colin: So Rick, are you telling me that being ill annoys you (Illinois U.)?
Rick: That's it! I've come up with my own title. We're going to use the Yale motto.
Colin: You've got me Professor. What's the Yale motto?
Rick: Come on, Colin, you've heard it. "For God, for country, and ***Fourier!***"