Time Reverse Ray Tracing

Optical design programs are really fun to use and Time Reverse Ray Tracing is just about the most fun anyone could have with a computer. The object is to model an ideal HOE that works at a wavelength not possible to record at and then go back in time to see how it could have been made, but with a convenient wavelength. Some would call this reverse engineering but that would be a misnomer because the finished product only exists as a math model in your computer. Others would call it designing a null optic, because the object is to feed your ideal optic a completely wrong input wave and null out all the aberrations in the output wave. The null is a little closer except that some solutions require 5 or 6 elements in one leg and a few more in the other leg, and that would be an insanely complex null optic. A few others could probably work out an analytic solution that was close and maybe not even trace it. I typically model the HOE surface, launch a smooth reference wave of 488 nm light through it, look carefully at the mess the HOE makes out of it and then methodically insert real components in the path until the rays converge to a small common point. Obviously, that is the object point where the laser light must have come from to make the HOE that was originally modeled, thus Time Reverse Ray Tracing.

The first correction is usually for astigmatism because the original HOE is probably used off axis and a simple off the shelf cylindrical lens will get most of it. Sometimes taking liberties with the Brag condition by moving reference points around will also help reduce the astigmatism and the other aberrations, this can easily be overdone. The next step may be to insert a bent spherical lens and optimize allowing decenters and maybe some limited tilt and maybe some sliding of the cylinder lens. After that the game gets rough quickly, a few more spherical surfaces will gain a little more ground but improvement gets harder and harder to find. The overall object is to get a good focus so that a simple spatial filter can be used to illuminate the optical train you will be building.

My design experiences have been very rewarding sometimes and really awful at least once. My worst nightmare was a 1064 nm design that required a bilaterally symmetric binary optic to reduce the aberrations to about 1 wave. The design required help from another designer and the construction took the better part of 6 months just to align all the optics. The computer provided close positioning of the components but the final tweaks required an entire cycle of construction, optical test, computer modeling of the possible error, repositioning of suspected components and construction again. The cycle time was one or two days because the dichromated gelatin optic was 400 mm in diameter. Figure 1 is a scaled phase map of the binary optic we had to fabricate before a carrier was added to move the orders off axis. A metal binary mask was contact copied into several phase media to make it efficient enough to be usable.
Another recent design turned out to be a dream come true. It took about 1 day to complete, requiring only one cylindrical lens, one plano convex lens and a small adjustment of the construction points. Figure 2 shows the 488 nm construction layout for forming a well corrected off axis 100 mm diameter f# 2.3 lens to be used at 532 nm. The reference wave was nearly collimated and the object wave came from a pinhole and passed through only two real off the shelf lenses. It was straight forward to align the optics and easy to verify that the design worked. The fringe tilt error introduced during master construction was corrected in a simple contact copy made at a compensating angle. Rays were traced to just 1 wave of error and measured spots at 532 nm were about 50 microns, about the limit for the glass used. All the design work was done in ZEMAX-EE but could have been done as well in SE.

Figure 1.

Figure 2.
Time Reverse Tracing is limited at present by the inability to insert optics into the construction path of standard HOE surfaces in any current optical design program. When that becomes possible, many more ideal HOEs may be modeled and reverse traced at convenient wavelengths. A General Holographic Surface has been proposed for inclusion in a future version of ZEMAX and KDP optics. No telling when it will become worthwhile.

Primary References:


Other References:

- *Compensation of Aberrations Due to a Wavelength Shift in Holography.* J.M. Moran. *diags App Optics* 10:1909-13 Ag ’71