Progress in true color holography

Tung H. Jeong and Edward Wesly

Center for Photonics Studies
Department of Physics
Lake Forest College
Lake Forest, IL 60045 USA

## ABSTRACT

It has been a long and elusive goal of display holographers to produce true multicolored images closely matched to that of the objects. Much progress has been reported recently by K. Bazargan(1), T. Kubota(2), P. M. Hubel and A. A. Ward(3,4,5), and H. Owen and A. E. Hurst(6). However, most of the works reported require sandwiches of different materials independently exposed.

Herein we report our recent work in "true color" holography using single elements of silver halide, dichromated gelatin (as proposed by J. Blyth(7)), and the Du Pont photopolymer material. Also, new sandwich combinations are reported.

## 2. HEURISTIC DEFINITION OF "TRUE COLOR"

Since laser light is required to record holograms, the reconstructed image by an incandescent source will never recreate precisely the image of a multicolored object as it appears under natural lighting.

At least two major factors contribute to this problem: the object may fluoresce; and the reconstruction bandwidth will always be wider than laser lines, causing color desaturation. Furthermore, because color perception is subjective, there cannot ever be complete agreement among different observers as to the "truthfulness" of the reconstructed image.

We offer the following heuristic definition which is amenable to scientific verification:

> A hologram is said to have "true color" if it recreates an image which has the same combination of wavelengths and their relative intensities as those laser wavelengths detected from the object during recording.

Thus the optimal hologram has to be illuminated by the same combination of laser wavelengths that recorded it. The intensity ratios during recording must be readjusted for reconstruction due to the variation of spectral sensitivity of the medium versus wavelength. While this may be realizable in the future when tunable semiconductor lasers become available, we must live in the present with incandescent source and narrow-bandwidth holograms.

## 3. RECORDING SCHEMES

In general, we record the hologram using three primary wavelengths from three independent lasers. This is superior to using any single laser with multi-wavelength outputs because it allows us to control the intensities independently. Two argon lasers and a HeNe laser (krypton will be used in the future) together provide the three primary colors. By judicious adjustments, the combined beam can be white or any other color the additive primaries can produce.

There are many methods for combining the beams. Among them are the use of: (1) a prism, (2) a system of beamsplitters and mirrors, (3) optical fibers[8,9], and (4) a holographic optical element (HOE)[10]. We favor techniques (3) and (4), as shown in Figures 1 and 2 for Denisyuk recordings. (Note: A photograph represented by Figure 2 is the cover picture for the July 1989 issue of LASER FOCUS WORLD.)

When it is necessary to control the reference-to-object beam ratio, the configuration shown in Figure 3 is used. Since we are dealing with a polychromatic beam, half-wave plates can no longer be used for polarization rotation. Instead, we use "double Fresnel rhombs" as shown.

Figure 4 shows the detailed operation of a panchromatic polarization rotator in the form of a double Fresnel rhomb. The rhombs are made from glass with 1.51 index of refraction. Plane polarized light enters from the left. The s and p states undergo different phase shifts upon each internal reflection and become elliptically polarized. For a rhomb with the acute angle of $54.6^{\circ}$, the beam is circularly polarized emerging from the first rhomb. After passing through the second rhomb, the beam is plane polarized again, but rotated.

## 4. TRUE COLOR HOLOGRAMS

### 4.1. Agfa 8E75

It is generally assumed that the 8E56 emulsion is not intended for recording in the red and the 8E75 is not intended for recording in the green and blue. However, while the assumption for the 8E56 is correct, it is not the case for 8E75.

We have found that 8E75 records quite well in the three primary colors provided we use the 476 nm line for the blue. The main requirement is heavy exposures for the unintended wavelengths. The actual exposures are: 633 nm - 50 $mJ/cm^2$; 515 nm - 0.4 $mJ/cm^2$; and 476 nm - 0.8 $mJ/cm^2$.

Another necessary requirement is that the chemical processing must not result in the shrinking of the emulsion. For good results, we used what is now called the CWC2[11] developing procedure and the PBQ (parabenzoquinone) bleach[12]. Reference 12 is highly recommended for detailed studies before attempting these procedures.

The two-beam configuration shown in Figure 3 is used for these experiments when a quasi point source for the object is desired. Otherwise, the "light mixer," which is essentially a "light pipe," is substituted by a piece of ground glass placed behind the translucent object.

4.2. Dichromated gelatin

We have duplicated the procedure of red-sensitization by Blyth(7) and recorded on the same hologram with three primary wavelengths. All colors are reconstructed, albeit, due to our lack of experience in coating, the results were uneven.

Because alcohol is heavily used for processing, we are waiting for the installation of a fume hood before repeating this experiment.

4.3. Du Pont Photopolymers(13)

We have recently succeeded in recording true color Denisyuk holograms on the HRF-705 material using a single combined beam. Except for the relatively long exposures, similar to those used on DCG, the procedures are wonderfully simple.

The material consists of binders, monomers, a photoinitiation system, and sensitizing dyes, and is provided on 20 mm or thicker layers sandwiched between Mylar sheets. When the top sheet is peeled off, the tacky material can be attached to glass or plastic substrates. Exposures are made with the second Mylar intact.

The absorbed photons polymerize the monomers in the areas of interference maximum, causing an increase in local index. Furthermore, monomers migrate from surrounding regions until hardening occurs and the process stops. Exposure of the entire hologram to incoherent white light (such as sunlight) uniformly polymerizes any remaining monomers.

We used a common 15-watt UV, "black-light" lamp at 0.1 meter above the exposed hologram for one minute. Heating the finished hologram in an oven at 100$^{\circ}$C for one-half hour further increases the efficiency.

Because no wet processing is involved, the medium can be of arbitrary thickness. We had made transmission holograms on a 50 mm thick, older version of this material over twenty years ago. Not only does it show no degradation over time, but it can be viewed with an incandescent source.

4.4. Sandwiches

4.4a. Agfa-Bulgarian

We have a stock of six-year-old HP-490 plates made in Bulgaria and have been successful in producing good two-beam reflection holograms in green and blue. When processed in the same manner as the Agfa plates, the image qualities are comparable to those recorded in DCG, with no observable scattering.

When sandwiched with a red image recorded on Agfa 8E75, the resultant hologram is in excellent true color, with better saturation than any other similar recordings in silver halide.

The drawback of this material is that its sensitivity is similar to DCG, requiring over 30 mJ/cm$^2$ in exposure.

4.4b. Ilford-Ilford

This material had been somewhat successful in producing color holograms[2,3,4]. Our tests with the SP695 plates (green-blue) and the SP737T (red) film show that the developing procedure recommended by Phillips[14] works best. It contains pyrogallol as the developing agent to tan the gelatin to counteract the shrinkage caused by the built-in pre-swelling (bips) agent. It also uses restrainers sodium metaborate and potassium bromide to raise the contrast and minimize the fog in the dim fringe areas.

There is no developing activity for the first 30 seconds. But after five minutes, the density builds up to the proper level. For SP737T film, this developer is about one stop slower than the pyrogallol-ascorbic acid formula recommended by Ilford[15].

4.4c. Agfa-Agfa

Because of the relatively high scattering in the blue for 8E56, we decided not to pursue this material for sandwiching.

4.4d. Agfa-Du Pont

Because of the lack of sensitivity to the red in the Du Pont photopolymer (over 300 mJ/cm$^2$), the use of HeNe laser is practically ruled out for all but tiny holograms. Under this circumstance, a sandwich of 8E75 with the photopolymer should be considered.

We have successfully made 4" x 5" Denisyuk holograms using this technique, with the finished HRP-705 photopolymer film on top of a 8E75 plate. The exposures were 40 mJ/cm$^2$ for 515 nm, and 80 mJ/cm$^2$ for 458 nm.

## 5. CONCLUSION

Sandwiching is a stop-gap technique at best. The ultimate aim must be to record on a single material.

DCG is a hopeful prospect. Until better techniques are developed whereby plate and film are pre-coated with reasonable shelf life, quality control and convenience are sacrificed.

Although we are encouraged by the possibilities of recording all colors on silver halide, grain scatter, especially in the short wavelength region, remains a problem.

We conclude that the new Du Pont material represents the most significant advance to the state-of-the-art holographic recording. Its chief attributes are: good storage characteristics before and after exposure; freedom from wet processing; extremely low scattering; high diffraction efficiency; and true color reproduction. One remaining problem to be solved is its low spectral sensitivity, particularly in the red.

## 5. REFERENCES


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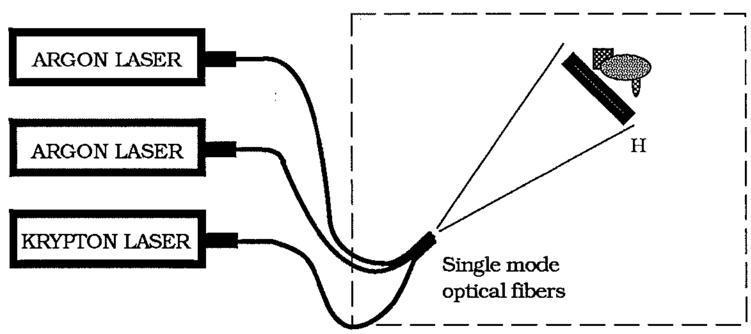


Figure 1

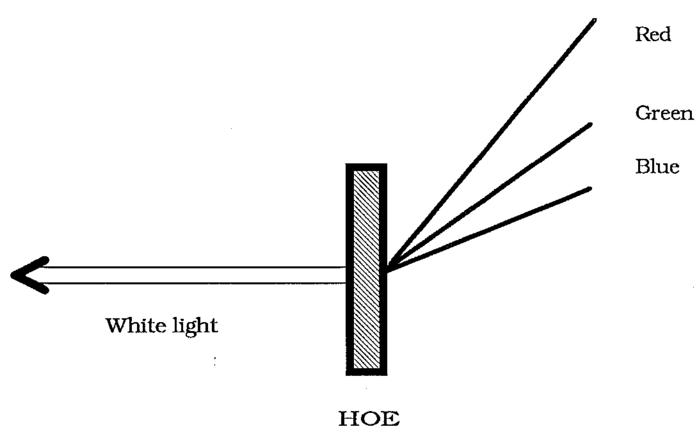


Figure 2

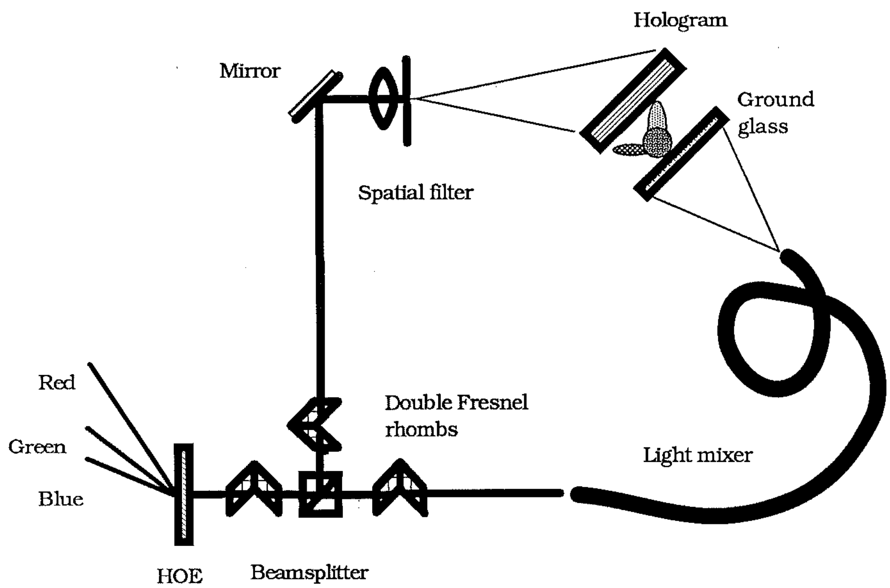


Figure 3

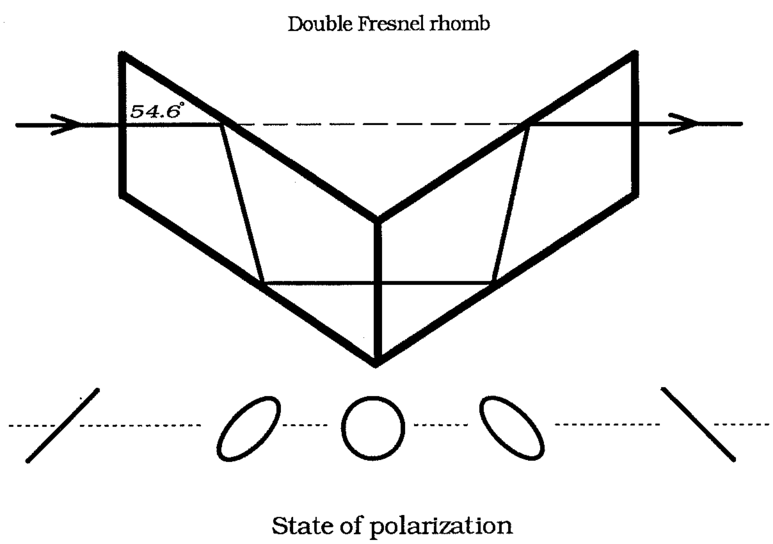


Figure 4