White-light schlieren optics using bacteriorhodopsin as an adaptive image grid

R. E. Peale, A. B. Ruffin, and J. E. Donahue

A schlieren apparatus using a bacteriorhodopsin film as an adaptive image grid with white-light illumination is demonstrated for the first time to our knowledge. Relevant spectral properties of the film are characterized. Potential applications include a single-ended schlieren system for gas-leak detection.

Key words: Schlieren, bacteriorhodopsin, photochromic, imaging.

1. Introduction

Remote imaging of leaks is needed at large industrial complexes including the space shuttle launch facilities at Kennedy Space Center. Backscatter–absorption gas imaging[1] is useless for gases that lack strong IR absorption, such as O_2, H_2, He, and N_2. Backscatter–absorption gas imaging and other laser techniques, e.g., Raman imaging, may be dangerous for personnel and equipment. A system using white light, ideally ambient light, is preferred.

The schlieren method is well established for imaging gas plumes.[2] The test region is sandwiched between a source grid and its negative, onto which the source grid is imaged with appropriate optics. Only rays deflected by a plume in the test region may pass the image grid. These rays are used to image the plume. With the uninteresting background thus eliminated, the signal-to-noise ratio is greatly enhanced, and otherwise invisible plumes appear in high-contrast detail.

All usual schlieren setups sandwich the test region between optics, and this limits the field of view to industrially uninteresting scales. Peale and Summers[3] showed that the optics on one side can be replaced by a high-contrast pattern on flexible reflecting cloth. Here a zoom lens images the pattern onto its negative. This scheme can be scaled to large fields of view with only modest cost increases, in principle. An obvious extension of this idea is to substitute a naturally occurring high-contrast scene for the pattern–cloth combination, thereby creating an essentially single-ended schlieren system. The negative can be photographic, but exposure, development, reinsertion, and realignment are time-consuming operations, during which the scene and its illumination may change.

Erasable photochromic films offer an attractive alternative to photographic creation of the image grid. Films made with bacteriorhodopsin (BR) from the purple membrane of halobacterium halobium are promising because larger absorbance changes and more optical cycles (10^6) can be realized than with manmade photochromic chemicals.[4] The BR ground state (*bR* state) has a strong absorption in the yellow–green. In the simplest model, absorption by this band pumps BR into its long-lived excited M state, which absorbs in the blue. Thus a negative of a scene in blue light can be created in a BR film by using yellow–green light.

Downie demonstrated a BR schlieren apparatus using blue and green laser light, but an attempt with white light and color filters was unsuccessful.[5] We demonstrate in this paper successful white-light BR schlieren with performance a factor of only two times less than a traditional schlieren apparatus. The BR system is still sufficiently sensitive to observe heat waves generated by the human body. This result is a first step toward realizing a truly single-ended remote-imaging system for leaks by means of ambient light. A variety of laboratory applications can also be envisioned.

Although the general spectral properties of BR films are well established, a presentation of relevant

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optical behavior with the common low-cost sources and filters used here is of value, since a previous effort using different optics reported failure.[5] A brief summary of the apparatus used is given in Section 2. Section 3 gives the relevant spectral properties of the BR film and, finally, schlieren results.

2. Experiment

The BR film was obtained from Bend Research and had a nominal optical density of 2.8 at 570 nm (absorbance of 6.5). The wild-type BR was encased in polyvinyl alcohol to form a ~100-μm film. The nominal M-state lifetime was 1–5 s; a half-life of 10 s was observed for the recovery of the ground-state absorption in the dark.

Transmission spectra were collected with a diverging incandescent source, a 400–700-nm variable interference filter having 20-nm bandwidth, and a large-area photovoltaic detector. Low-intensity measurements were performed with this setup with the BR film placed just in front of the detector, where the beam spot size is ~2 cm. Here no time dependence is observed in the transmission. Higher-intensity measurements were performed with the film placed just after the interference filter, where the spot size is still just a few millimeters and strong time dependence is observed. Data were recorded on a strip-chart recorder.

Time-dependent transmission data were also recorded with a variety of long-pass filters, blue–violet bandpass filters, and a common flood lamp. This source and the optimum filter pair were used subsequently for schlieren experiments. A large-area Si detector was used in photovoltaic mode with a variety of low-impedance load resistors to maintain linear response. The output was recorded on a strip chart. Neutral-density filters were moved from front to back of the BR film to provide a range of incident intensities at the BR film while keeping the average intensity at the detector constant.

Standard schlieren optics in the configuration shown in Fig. 1 collected images of a variety of phase objects for comparison with BR schlieren. The optics were located at the center of curvature of the mirror on either side of its symmetry axis. The 19-in, 6-ft-focal-length spherical mirror imaged the source grid onto the image grid. The grids were Ronchi rulings having 50 lines/in from Edmund Scientific. A 5-V incandescent lamp diffused by thin Teflon illuminated the source grid. A Javelin JE2062IR black-and-white video camera monitored the test region, which was located just in front of the spherical mirror. A zoom lens optimally filled the camera image plane with the test region.

The BR schlieren setup is shown schematically in Fig. 2. A ground-glass plate diffused the flood-lamp illumination and reduced UV emissions. The heat-absorbing filter was Schott KG2. The long-pass filter was Schott OG550. The blue–violet bandpass was Schott BG12, which was combined with a neutral-density filter having an optical density of 1.

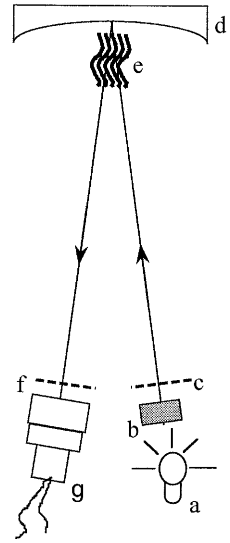

Fig. 1. Schematic of standard schlieren optics: a, incandescent lamp; b, Teflon diffuser; c, source grid; d, spherical mirror; e, phase object; f, image grid; g, camera with zoom lens.

3. Results

The basic spectral properties of the BR film were measured first with monochromatic light to help select bandpass filters for schlieren experiments. Figure 3 presents absorbance spectra. The open circles represent measurements that were taken at an intensity sufficiently low that no time dependence of the transmission was observed. The crosses in Fig. 3 give the absorbance spectrum immediately after completion of a higher-intensity bleach transient with 525-nm light. Since BR has no absorption at 1 μm, the experimental absorbance at 1 μm was subtracted to eliminate contributions of reflection and scattering. After the bleach, the absorbance is lower

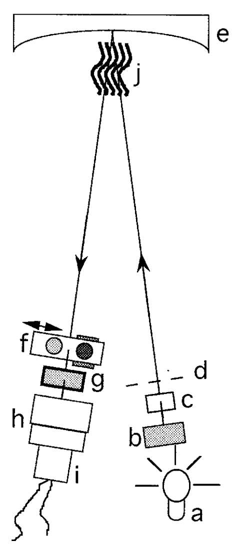

Fig. 2. Schematic of the BR-schlieren setup: a, flood lamp; b, ground glass diffuser; c, heat-absorbing filter; d, source grid; e, spherical mirror; f, filter holder with two interchangeable filters; g, BR film; h, zoom lens; i, camera; j, phase object.

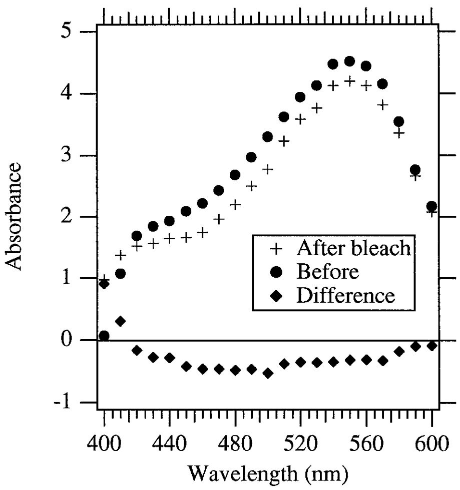

Fig. 3. Absorbance spectra before and after creation of M-state population in the BR film with 525-nm light and their difference.

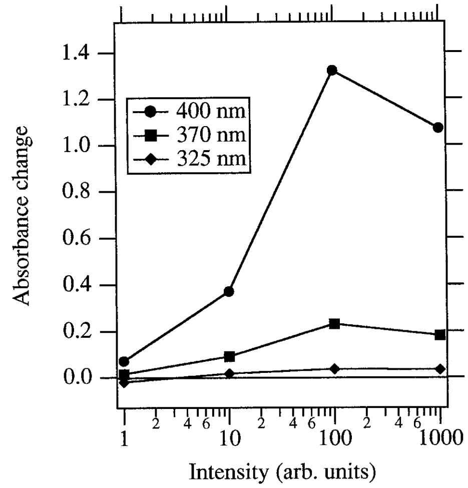

Fig. 5. Absorbance changes measured with various bandpass filters as a function of write intensity with a 550-nm long pass used as the write filter. Wavelengths given are bandpass centers.

everywhere except near 400 nm. The solid diamonds in Fig. 3 represent the difference in the two curves, which reveal the decreased absorbance in the yellow–green region and the increased absorption in the blue–violet. These changes result from the light-induced population of the BR metastable M state.

A suitable long-pass filter for writing the image grid in the BR film was determined as follows. Figure 4 plots the absorbance change at 400 nm versus write intensity for different long-pass filters. A 400-nm bandpass filter was used for reading. The 550-nm long-pass filter (Schott OG550) produced a larger absorbance change than the 475-nm long-pass filter.

Next the optimum bandpass read filter was determined. Figure 3 suggests that the largest absorbance increase occurs at or below 400 nm. Published results indicate that wavelengths below 400 nm should give only smaller changes.[4] This was tested with the 550-nm long-pass filter used to bleach the ground state and a number of blue–violet bandpass filters to read the effect. Figure 5 presents the results, where the center wavelength of the read filter is given for each solid symbol. The largest absorbance increases are confirmed to occur near 400 nm, where the bandpass filter used was Schott BG12.

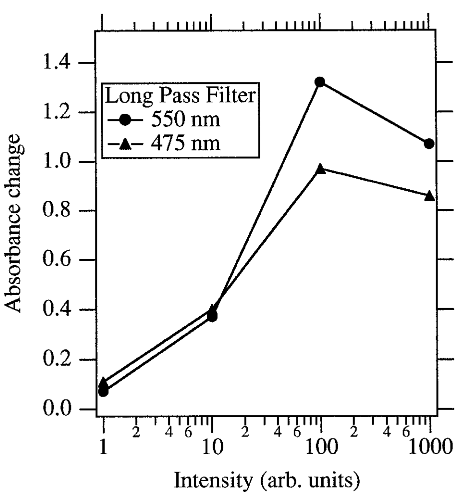

Fig. 4. Absorbance change at 400 nm as a function of write intensity for different long-pass write filters. The wavelengths given are the pass edges.

Figures 4 and 5 reveal that the best filter combination for the schlieren experiments is the 550-nm long-pass filter for writing the image grid and the 400-nm bandpass filter for reading it. The largest expected absorbance change at the read wavelength is ~1.3. An additional observation is the appearance of an optimum write intensity well below the damage threshold of the film. This phenomenon is unexplained by the simple two-state model but is consistently observed. Illumination with wavelengths coincident with M-state absorption is known to accelerate ground-state recovery.[4] To allow for adequately long schlieren read times, attenuation of the 400-nm read light by a factor of 10 was found to be adequate.

Next, schlieren images of two different gas plumes are presented. For reprographic purposes the images have been processed with a ramp filter to enhance the contrast. This procedure consisted of multiplying the image histogram by 0 for pixels in the 1–64 grey scale range, by a linear 0 to 1 ramp for pixels in the 65–192 grey scale range, and by 1 for pixels in the 193–256 grey scale range. (Raw digital data can be obtained from the authors.) In these experiments, a 1:1 image of the source grid was bleached into the BR film at an intensity sufficient to cause an absorbance change of 0.8 at 400 nm. The bleaching time was 10 s in each case. The gas plumes were absent from the test region while writing the image grid. Then the read filter was inserted, the gas plumes activated, and an image of the test region recorded. Real-time images of the test region were observed on a video monitor. After

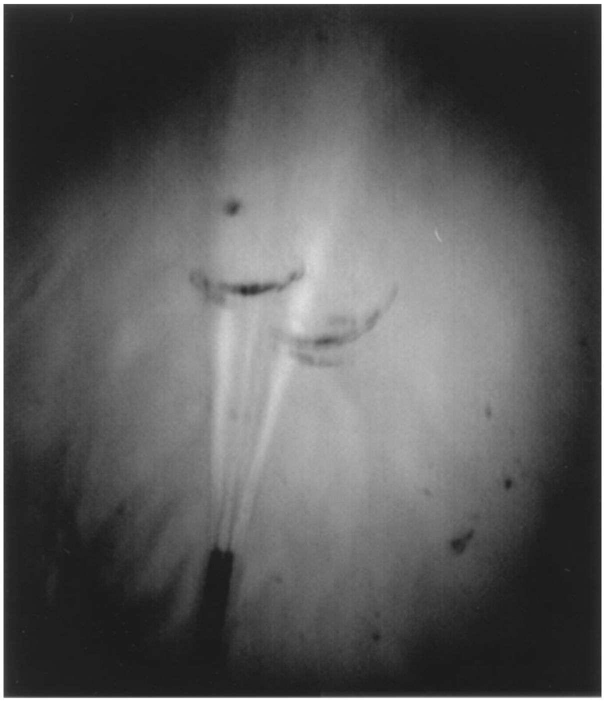

Fig. 6. BR-schlieren image of the spray from a compressed-gas duster. The vertically oriented light and dark bands form the image of the jet. The black crescents are scratches on the mirror.

Fig. 7. BR-schlieren image of a low-velocity He gas plume.

switching to the 400-nm read light, the picture gradually brightened, and the contrast of the schlieren images gradually faded to invisibility after several minutes. An image was then collected of this scene as a reference to obtain information about the fading of the schlieren effect with time.

Figure 6 is a BR-schlieren image of a high-velocity jet from an inert-gas duster. The gas is 1,1,1,2-tetrafluoroethane. Each distinct section of the jet appears darker on its left side and lighter on its right. This is because schlieren detects index gradients,[2] which change sign when crossing a phase object. (The dark crescents are scratches in the mirror's coating.)

Figure 7 presents BR-schlieren results for a low-velocity flow of He gas. Turbulence is observed. Again, identifiable regions are darker on the left side and lighter on the right.

In Figs. 8 and 9 we present intensity profiles across portions of the unprocessed images. The heavy curves are BR-schlieren data. The lower heavy curve, taken immediately after writing the image grid, shows intensity variations of $\sim$10% with spatial frequencies of a few tens of profile points. The upper heavy curve, taken after several minutes of read-light illumination (reference image), shows an overall transmission increase and a near disappearance of the intensity variations.

The light curves in Figs. 8 and 9 are profiles of images taken with the standard schlieren setup. An attempt was made to locate high-contrast regions in these images with spatial frequencies similar to those plotted for BR schlieren. Since these regions can occur at different locations in front of the nonuniformly illuminated mirror, the slope of the baseline can differ from their BR-schlieren counterpart (heavy curves). Additionally, a smaller range of profile points happened to be collected from the standard-schlieren images than from the BR-schlieren images. Despite these unimportant differences, it is clearly observed that the intensity variations having spatial frequencies of tens of points are only about two times larger than the BR results. This suggests that BR schlieren can be as sensitive as standard schlieren

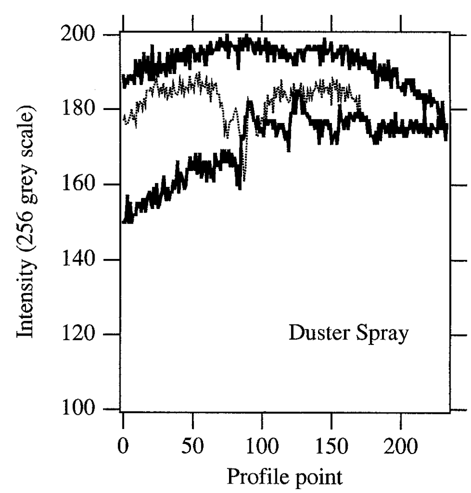

Fig. 8. Image profiles for the compressed-gas duster spray. The thin curve is from standard-schlieren results. Thick curves are from BR schlieren immediately after the write procedure (lower) and several minutes later (upper).

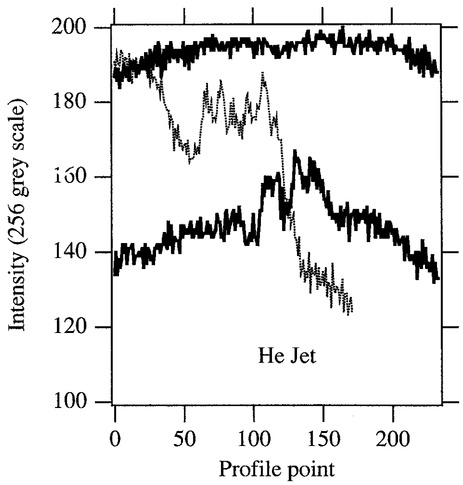

Fig. 9. Image profiles for the low-velocity He plume. The thin curve is from standard-schlieren results. Thick curves are from BR-schlieren immediately after the write procedure (lower) and several minutes later (upper).

but with the advantages of adaptability and automatic image-grid alignment.

A variety of other phase objects were also imaged with both standard- and BR-schlieren setups. Heat waves were clearly observed from a soldering iron and even weakly from hands waved in the test region. Static-phase objects such as glass plates revealed streaks or wood-grain patterns. Such static-phase objects needed to be inserted in the BR-schlieren test region immediately after writing the image grid. If they rested in the test region during the writing, their index gradients were invisible during the read cycle. This is because distortions in the image of the source grid cause a similarly distorted BR image grid, which remains distorted for the read cycle. In contrast, we observe turbulent jets and heat waves during the read cycle even when they are present during the write step.

4. Summary

An adaptive schlieren apparatus using a bacteriorhodopsin film as a photochromic medium for writing image grids has been demonstrated by using white light as the illumination source for the first time to our knowledge. Images of phase objects reveal only two times less sensitivity than that found with a standard schlieren apparatus. The potential for laboratory applications, where intensity and scene contrast can be controlled at will, seems clear. It also seems feasible to the authors, from a qualitative inspection of the intensities used in the present experiments, that enough reflected sunlight from a suitably high-contrast scene could be collected and concentrated on a BR film to realize an adaptive single-ended schlieren system for industrial leak detection. This remains to be tested, however, and it is impossible to predict the limits of sensitivity of such a system without further experiments.

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