Computer-controlled two-color laser-based optical stimulator for vision research

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A two-color laser-based stimulator is described. This device produces high intensity uniform field illumination with temporal control over a wide range of temporal frequencies. In addition it can be used to produce wide field flicker (40°). Key words: Vision, speckle, temporal vision.

We find that visible lasers share many of the advantages of light emitting diodes (LED's) for vision research and have several important advantages that outweigh the increased cost of a laser-based stimulator. Light-emitting diodes have been widely used as light sources for studying the visual system in recent years. The principal advantage of LEDs for vision research is their low cost, ease with which they can be controlled, and their stability. However, the light output of a LED is spectrally broad (20–40-nm half-widths), and the pattern of illumination from a LED can be quite uneven. These properties of LED's are disadvantageous in a number of uses. The spatial inhomogeneity causes most investigators to modify the LED or to diffuse the light, thereby reducing the maximum luminance available. Lasers have not been so widely used in vision research, mainly because of speckle (spatial inhomogeneities that arise from the coherent nature of the light). Thus lasers have been used as light sources relatively little in vision, except in cases where the coherence is important, such as interferometry, or where their high intrinsic luminance is critical, such as in scanning displays. The exception is a three-color mixture device that took advantage of the high illuminance and spectral purity of lasers and avoided speckle by the use of a suspension of plastic beads that was described by Krauskopf et al. In recent years a number of visible wavelength (543 nm and longer) He–Ne and semiconductor lasers have become available at prices that are competitive with other traditional light sources for vision research, such as arc lamps and high-quality video monitors. In addition, the necessary components for precise control of laser light have started to appear on the used equipment market, primarily because of the increased use of lasers in page printers and fax machines.

The principal disadvantage of using lasers as light sources is the speckle that is generated by interference. There are three main approaches to eliminating speckle: spatial filtering, raster scanning, and speckle blurring. In spatial filtering, the laser is brought to focus at a pinhole, and the central area of the far-field diffraction pattern is used to generate the visual stimulus. Spatial filtering works but has two disadvantages for most vision work. First, the small size of the image of the pinhole in the plane of the eye's pupil provides a great depth of field. Thus one can see imperfections anywhere in the optical system including the lens and cornea of the eye. The second problem is that any dust on the optics produces interference patterns on the retina; thus optics must be kept clean. Scanning systems solve this problem by raster scanning a diffraction-limited spot of light across the retina. These systems work well but have disadvantages for some types of visual research, e.g., the temporal modulation is limited by the frame rate of the scanning system. We describe a relatively simple apparatus that uses speckle blurring to produce a visual uniform, spectrally pure stimulus. The apparatus is similar in principle to Krauskopf's with the exception that we avoid the use of a liquid diffuser.

The light sources used are two He–Ne lasers, 543 and 633 nm, respectively (Fig. 1). Each laser beam is passed through a separate acoustooptic modulator (AOM). The AOM acts as a diffraction grating that can be turned on and off at high rates (1 MHz) by the application of a digital control signal. When turned on, the AOM divides the laser beam into a series of beams (zero order, first order, etc.). When turned off, all the light from the laser goes into the zero-order beam. Thus the AOM acts as a very fast shutter. The first-order laser beam is selected by an aperture, then expanded, combined by a dichroic beam splitter, and finally brought to focus on a MgO white reflectance coating. The MgO is then used as the light source for a conventional Maxwellian view optical system. As described the system would produce a large bright field with a great deal of speckle. Speckle is reduced in two ways. First, the MgO is moved continuously. Thus the scattering centers that create the speckle are in constant motion. We first attempted to move the diffuser by spinning a wheel so that the laser beam impinged on the wheel, and the motion of the wheel caused the rapid modulation of the speckle pattern. This system had the problem that any wobble in the wheel caused a wobble of the system's entrance pupil in the plane of the eye's pupil and thus a very...
slight temporal modulation of the brightness of the field. In addition, any variation in the spatial distribution of the diffuser caused temporal modulation of the field. To minimize this we coated the end of the shaft of a small surplus DC motor with Kodak White. The shaft itself does not wobble, and the spinning diffuser, therefore, smears the speckle. Alone, this system reduces the speckle almost totally, but there is a slight tendency for the speckle to form a concentric pattern (since the velocity of the diffusing elements varies radially from the center of the shaft). The pattern can be minimized by using a small laser spot and displacing the spot slightly from the center of the motor shaft.

For many applications this approach alone is acceptable, but we chose a somewhat more complex approach to ensure that all visually significant speckle was eliminated. We reflected the lasers prior to the diffuser from a pair of galvanometer-mounted mirrors. The galvanometers are used to move the laser beam, the first horizontally and the second vertically. Lenses are arranged so that the first galvanometer is imaged on the second, and the second galvanometer is imaged on the moving diffuser. This arrangement creates a system where the beam itself is moving but the laser spot is motionless on the diffuser. This blurs the speckle considerably without causing modulation of the intensity of the laser spot on the diffuser. In addition, since the nature of the scan is not critical, inexpensive galvanometers can be used. We used surplus pen motors that were driven by simple function generators. The addition of the deflector system eliminates the concentric pattern described above.

The size of the laser beam on the diffuser controls the pupil size of the Maxwellian view system. This can be easily varied by the use of an inexpensive positive lens, such as a trial lens (Fig. 1). By placing the lens in the expanded beam, one focal length before the first galvanometer, the size of the spot on the galvanometer is controlled. A high-power lens will reduce the spot size while a low-power lens will produce a fairly larger spot size. Using this system we can vary the spot size from ~50 μm to 2 mm.

AOM's can be controlled in either an analog or digital fashion, although specific AOM/driver combinations are typically optimized for one type of control or the other. Analog AOM's vary the output of the first-order beam with the voltage of a control signal, but the input/output relation is sinusoidal. This makes them less desirable for our purpose since we would need to linearize them. We use digital AOM's driven using a pulse frequency generator that has been previously described. 8 This system accepts three voltage inputs. The first controls the temporal nature of the waveform, the second controls the modulation, and the third controls the mean luminance of the waveform. These three voltages are combined at a precision multiplier, and the output of the multiplier is fed to a voltage to frequency converter that controls the repetition rate of identical 2-µs pulses. Since the AOM's are sufficiently fast to follow the 2-µs pulses, the density of pulses controls the average luminosity of the light. Simple alternatives to this somewhat complex system would be to use only the voltage to frequency converter chip (Burr-Brown) or to use pulse width modulation, which is available from many computer timer chips. The calibrations shown below (Fig. 2) were made using only the voltage to frequency converter and thus give an indication of the system behavior possible with readily available parts.

We calibrated the linearity and spatial inhomogeneity of the apparatus. An EG&G model 550 radiometer/photometer was placed at the exit pupil of the apparatus. For the linearity measurements a voltage from the 12-bit digital-to-analog converter was applied directly to the input of the voltage to frequency converter, bypassing the multiplier, and the voltage was varied from minimum to maximum. We have independently measured the linearity of the system including the multiplier chip with similar results. For the spatial homogeneity measurements an 8-mm aperture was scanned across the field stop of the Maxwellian lens, and the intensity of light at the pupil plane was measured.

Figure 2 shows the calibration for the 543-nm He–Ne control system. Note that the output of the AOM is linear over three log units (r = 1.000). The maximum luminance of the apparatus for a 15° field was 35,000 Td for the 543-nm He–Ne and 25,000 Td for the 633-nm He–Ne. The fields are much more uniform than those that we have been able to obtain using LED's in standard configurations (Fig. 3). Both the red and the green fields follow the same spatial variation in luminance. The variation obtained is symmetric and can most likely be attributed to the optics of the lens that collects light from the diffuser. The variations we have obtained using LED systems are much less predictable. The uniformity of LED produced fields can be improved using diffusers, but this lowers the maximum luminance that can be obtained. The intrinsically high luminance of the laser makes the use of a diffuser acceptable.
Most of the components used in this system can be obtained for a reasonably low cost. We were able to purchase surplus laser printer internals for $500 (Timeline, Inc). This included the 632.8-nm He–Ne (10 mW), AOM and power supply, laser focusing lens, and beam expander. Thus a complete 632.8-nm system using this platform requires only a voltage to frequency converter, relatively simple optics, and the motor and galvanometers. The 543-nm He–Ne laser is still fairly expensive (~$950), but we were able to mount the green laser into another printer platform and combine the beams using a stock dichroic beam splitter. The extreme collimation of lasers makes the alignment of the system easy. The use of semiconductor lasers, which can be directly modulated without the use of AOM's, could reduce the cost further. We have now worked with a 670-nm diode laser that can be controlled with TTL logic. The diode laser avoids the need for an AOM, and the cost for a 10-mW diode is currently about $300 (Applied Laser Systems).

We have used this apparatus for temporal modulation of the luminance and chromaticity of a uniform field for both psychophysical and electrophysiological studies. By driving it from an arbitrary waveform generator (Qua-Tech, Inc.) we can program in complex temporal waveforms (ramps, sum-of-sins, noise, etc.). By adding the modulated fields to auxiliary fields, a wide range of stimuli is possible. For example, we have designed a three-laser system, which can be used as an anomaloscope with a 594-nm He-Ne laser as the standard. Gains by operating the radiometer at liquid helium temperatures are significant below 0.001%,5 the designers of the next generation of cryogenic radiometers is simple. Thermal (or other) radiant power from a source, in this case a blackbody R at a temperature of radiant power were measured which showed a stability and reproducibility over a period of 6 yr of ~0.001%. It was during these measurements that the problem of H2 condensation was encountered. Although the effects, at worst, amounted to only ~55 nW, or 0.015% of the measured radiant power, this was ten times the standard deviation of the measurements and was therefore important. In view of the potential of cryogenic radiometry for uncertainties significantly below 0.001%,6 the designers of the next generation of such instruments should be aware of the problem.

Cryogenic radiometers employing a detector at liquid helium temperatures have demonstrated a much improved accuracy over those operating at room temperature. It is recommended that detectors be operated at temperatures below 3 K.

The recent article by Foukal et al.1 is evidence of the growing interest in cryogenic radiometry for a wide range of earth and spaceborne applications. In their paper Foukal et al. quite rightly emphasized the many advantages to be gained by operating the radiometer at liquid helium temperatures and these need not be repeated here. They suggested, however, that an operating temperature for the receiver of 2 K is to be preferred to one at 4.2 K, the temperature used in their cryogenic radiometer. While from most points of view we would agree with this, we wish to point out that in certain conditions a radiometer operating at temperatures below 4 K can be less stable and less reproducible than one at 4 K due to the effects of condensation of the residual hydrogen gas in the system.

Using lasers as light sources allows us to produce spatially homogeneous, spectrally pure fields of large angular extent and high retinal illuminance. This type of system is more expensive than one using LED's as light sources, but for many purposes it is far superior. Rapid changes in the availability of semiconductor lasers should further reduce the cost of using lasers as light sources for vision research.

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References