

Four-color laser white illuminant demonstrating high color-rendering quality

A. Neumann,¹ J. J. Wierer, Jr.,^{2,*} W. Davis,³ Y. Ohno,³ S. R. J. Brueck,¹ and J.Y. Tsao²

¹Center for High Technology Materials, University of New Mexico,
Albuquerque, NM 87106, USA

²Sandia National Laboratories, 1515 Eubank Blvd SE,
Albuquerque, NM USA 87185, USA

³National Institute of Standards and Technology, 100 Bureau Dr # 1000,
Gaithersburg, MD 20899, USA

*email jwierer@sandia.gov

Abstract: Solid-state lighting is currently based on light-emitting diodes (LEDs) and phosphors. Solid-state lighting based on lasers would offer significant advantages including high potential efficiencies at high current densities. Light emitted from lasers, however, has a much narrower spectral linewidth than light emitted from LEDs or phosphors. Therefore it is a common belief that white light produced by a set of lasers of different colors would not be of high enough quality for general illumination. We tested this belief experimentally, and found the opposite to be true. This result paves the way for the use of lasers in solid-state lighting.

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References and links

1. J. Y. Tsao, H. D. Saunders, J. R. Creighton, M. E. Coltrin, and J. A. Simmons, "Solid-state lighting: an energy-economics perspective," *J. Phys.* **D43**, 354001 (2010).
2. Y. Narukawa, M. Ichikawa, D. Sanga, M. Sano, and T. Mukai, "White light emitting diodes with super-high luminous efficacy," *J. Phys.* **D43**, 354002 (2010).
3. M. H. Crawford, "LEDs for solid-state lighting: performance challenges and recent advances," *IEEE J. Sel. Top. Quantum Electron.* **15**(4), 1028–1040 (2009).
4. J. Y. Tsao, "Solid-state lighting: lamps, chips, and materials for tomorrow," *IEEE Circuits Dev. Mag.* **20**(3), 28–37 (2004).
5. M. Peters, V. Rossin, M. Everett, and E. Zucker, "High Power, High Efficiency Laser Diodes at JDSU," *High-Power Diode Laser Technology and Applications V*, edited by Zediker, Proc. of SPIE 6456, 64560G (2007).
6. R. Poprawe, "High-Power Diode Lasers: The ultimate source for economic photons in the next decade," Keynote talk, SPIE Photonics West (Jan 2011).
7. J. M. Phillips, M. E. Coltrin, M. H. Crawford, A. J. Fischer, M. R. Krames, R. Mueller-Mach, G. O. Mueller, Y. Ohno, L. E. S. Rohwer, J. A. Simmons, and J. Y. Tsao, "Research challenges to ultra-efficient inorganic solid-state lighting," *Laser Photon. Rev.* **1**(4), 307–333 (2007).
8. T. Kozaki, S. Nagahama, and T. Mukai, "Recent progress of high-power GaN-based laser diodes," *Proc. SPIE* **6485**, 648503, 648503–648508 (2007).
9. H.-Y. Ryu and D.-H. Kim, "High-brightness phosphor-conversion white light source using InGaN blue laser diode," *J. Opt. Soc. Korea* **14**(4), 415–419 (2010).
10. A. Michiue, T. Miyoshi, T. Kozaki, T. Yanamoto, S. Nagahama, and T. Mukai, "High-power pure blue InGaN laser diodes," *IEICE Trans. Electronics*, **E 92C**, 194–197 (2009).
11. S. Grzanka, P. Perlin, R. Czernecki, L. Marona, M. Bockowski, B. Lucznik, M. Leszczynski, and T. Suski, "Effect of efficiency 'droop' in violet and blue InGaN laser diodes," *Appl. Phys. Lett.* **95**(7), 071108 (2009).
12. N. Narendran, Y. Gu, J. P. Freyssinier-Nova, and Y. Zhu, "Extracting phosphor-scattered photons to improve white LED efficiency," *Phys. Status Solidi., A Appl. Mater. Sci.* **202**(6), R60–R62 (2005).
13. J. K. Kim, H. Luo, E. F. Schubert, J. H. Cho, C. S. Sone, and Y. J. Park, "Strongly enhanced phosphor efficiency in GaInN white light-emitting diodes using remote phosphor configuration and diffuse reflector cup," *Jpn. J. Appl. Phys.* **44**(21), L649–L651 (2005).
14. H. T. Huang, Y. P. Huang, and C. C. Tsai, "Planar lighting system using array of blue LEDs to excite yellow remote phosphor film," *J. Display Tech.* **7**(1), 44–51 (2011).

15. C. Lok, "Vision science: Seeing without seeing," *Nature* **469**(7330), 284–285 (2011).
16. J. M. P. J. Versteegen, D. Radielovic, and L. E. Vrenken, "A new generation of "deluxe" fluorescent lamps, combining an efficacy of 80 lumens/W or more with a color rendering index of approximately 85," *J. Electrochem. Soc.* **121**(12), 1627–1631 (1974).
17. J. J. Opstelten, D. Radielovic, and J. M. P. J. Versteegen, "Optimum spectra of light sources," *Philips Tech. Rev.* **35**, 361–370 (1975).
18. L.J. Sandahl, T.L. Gilbride, M.R. Ledbetter, H.E. Steward, and C. Calwell, "Compact fluorescent lighting in America: lessons learned on the way to market," Pacific Northwest National Laboratory Technical Report (May, 2006).
19. Energy Independence and Security Act of 2007.
20. S. Tonzani, "Lighting technology: Time to change the bulb," *Nature* **459**(7245), 312–314 (2009).
21. H. M. Brandston, "Summary of CFL Concerns" website and references therein.
<http://www.concerninglight.com/commentary.html>.
22. G. Giladi, "Phasing-out' the Incandescents – Is the Public Misinformed or Disinformed" Professional Lighting Designers' Association white paper. http://www.pld-a.org/fileadmin/download/Gad_s_report_on_GLS___CFL.pdf.
23. S. Nakamura, "The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes," *Science* **281**(5379), 956–961 (1998).
24. S. Shionoya, W. H. Yen, and H. Yamamoto, eds., *Phosphor Handbook*, 2nd Edition. (CRC Press, 2006).
25. W. Davis and Y. Ohno, "Color quality scale," *Opt. Eng.* **49**(3), 033602 (2010).
26. Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
27. IESNA RP-11–1995, "Design criteria for lighting interior living spaces," The Illuminating Engineering Society of North America (1995).
28. Y. Ohno, "Spectral Design Considerations for Color Rendering of White LED Light Sources," *Opt. Eng.* **44**(11), 111302 (2005).
29. W. J. Conover, (1980). *Practical Nonparametric Statistics* (3rd Ed.).
30. P. Moon and D. E. Spencer, "Polynomial representation of reflectance curves," *J. Opt. Soc. Am.* **35**(9), 597–598 (1945).
31. L. T. Maloney, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters," *J. Opt. Soc. Am. A* **3**(10), 1673–1683 (1986).
32. W. A. Rushton, "Pigments and signals in colour vision," *J. Physiol.* **220**, 1–31 (1972).

1. Introduction

Solid-state lighting is poised to become the dominant technology for general illumination, with enormous worldwide ramifications for human productivity and energy consumption [1]. As a consequence, huge efforts worldwide are aimed at continuing to increase its efficiency and decrease its cost.

At this point in time, solid-state lighting based on blue-emitting InGaN light-emitting diodes (LEDs) and phosphors has demonstrated the highest luminous efficacy of any white light source: 265 lm/W (about triple the 70-90 lm/W of fluorescent lamps) [2]. This high luminous efficacy, however, can only be achieved at relatively low (2.5 A/cm^2) current densities. At higher current densities, the LEDs exhibit a decrease in efficiency with drive current – the so-called "efficiency droop" problem universally exhibited by InGaN LEDs [3]. Efficiency droop limits drive currents, leading to a higher initial cost per lumen of the solid-state light source, and is in a direction contrary to that needed for economical solid-state lighting [4].

The need for high efficiency at high current densities suggests the use of lasers. At high current densities ($\sim \text{kA/cm}^2$), lasers are the most efficient converters of electrical to optical energy, with today's best being 76% wall-plug efficiency for edge-emitting InGaAs/GaAs lasers emitting in the infrared at 940 nm [5]. At these infrared wavelengths, lasers are thus emerging as economical sources of photons [6]. If similarly efficient lasers could be developed at visible wavelengths, economical solid-state lighting could enter the "ultra-efficient" >70%-efficiency domain [7].

In the short run, the simplest use of a laser in solid-state lighting would be as a replacement for the blue LED as an excitation source for the phosphor [8,9]. Blue laser efficiencies as high as 24.3% have already been demonstrated [10], suggesting the potential

for ultra-high (>70%) efficiencies. Through stimulated emission, carrier density clamping may enable blue lasers to avoid efficiency droop [11]. In addition, blue-laser-pumped-phosphor approaches to white light would have advantages beyond high efficiency and low cost (per lumen of light produced), including facile spatial controllability of the blue light accompanied by more options for placement of remote phosphors [12–14].

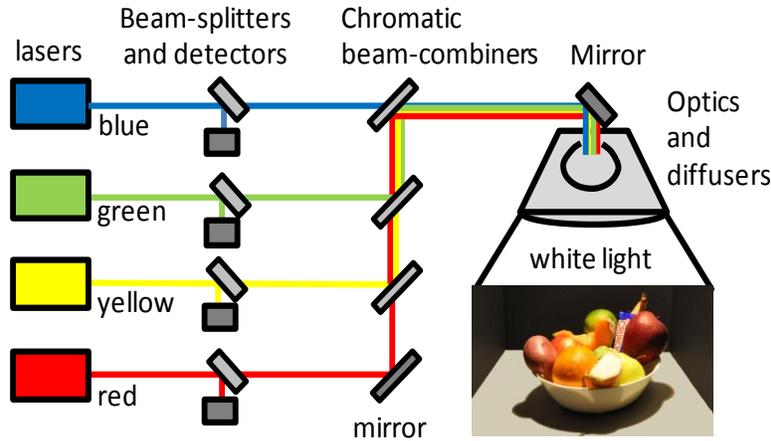


Fig. 1. Schematic of four-color laser white illuminant. Light from four lasers is combined using chromatic beam splitters, then passes through multiple ground-glass diffusers to reduce speckle before illuminating the test objects.

In the long run, as lasers at visible wavelengths mature and improve, the use of multiple lasers of differing emission wavelength for solid-state lighting could become a possibility. The absence of phosphors would eliminate significant inefficiencies (including Stokes deficits associated with downconversion from the blue to the green and red). The use of low-divergence light from lasers, markedly easier to control (focus, steer and mix) than Lambertian light from LEDs, would enable new systems-level lighting architectures. The use of color-mixed laser light would enable in situ tailoring to human or economic preferences of chromaticity, color rendering quality, or health [15]. Other properties of lasers might also be useful, including: high modulation bandwidth for communication purposes, and polarization control for minimizing glare from reflective surfaces.

Lasers suffer, however, from some potential drawbacks, the most obvious being their narrow linewidths. An RGB (red-green-blue) or RYGB (red-yellow-green-blue) white light source composed of three or four discrete laser lines far from fills the visible spectrum, and it has not been demonstrated that either would properly render the colors of objects in typical environments.

Although early simulations of fluorescent lamps based on rare-earth phosphors with spiky spectra indicated good color rendering could be achieved [16,17], subsequent subjective human experience with such lamps has been mixed, and has in part been responsible for widespread prejudices against fluorescent lamps [18]. In response to recent legislation that would effectively ban incandescent light bulbs [19,20], criticisms of the color quality of alternative technologies are often attributed to “spectral deficiencies” of those technologies [21,22].

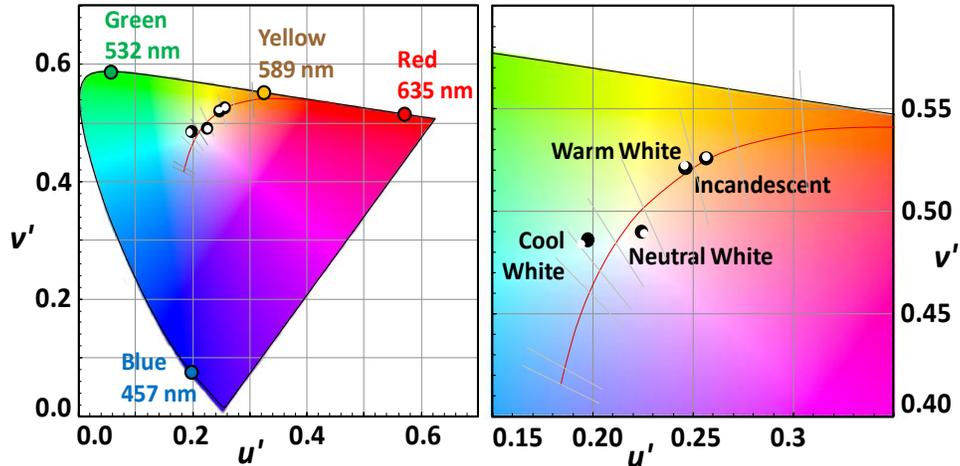


Fig. 2. Chromaticities of the laser and reference illuminants. CIE (Commission Internationale de l'Éclairage) 1976 (u',v') diagrams showing the chromaticities of the RYGB laser (black circles) and reference (white circles) white light illuminants, and of the four lasers themselves (colored black-outlined circles).

Moreover, a laser illuminant would take spectral spikiness to an unprecedented extreme; semiconductor laser linewidths can easily be <0.1 nm [23], while rare-earth phosphor linewidths are typically >1 nm [24]. Thus, the question of the suitability of narrow-linewidth laser light for general illumination is an open one, indeed one whose intuitive answer would seem negative. With so much of the spectrum missing, how could colors of objects possibly be rendered well?

In this Letter, we answer this question experimentally. We constructed an RYGB four-color laser white illuminant (Fig. 1), and compared its color rendering ability with those of high-quality reference illuminants using human test subjects and two side-by-side viewing booths. Each viewing booth had installed in it one illuminant from each of four near-identical pairs of reference illuminants (an incandescent lamp, and warm-, neutral- and cool-white phosphor-converted white light-emitting diodes). Additionally, one viewing booth was equipped with the four-color laser illuminant. Laser power levels were adjusted (see Fig. 2 and Table 1) so that the resulting white light: (a) matched the chromaticity and illuminance of the reference illuminant to which it was being compared; and (b) had a maximal color rendering quality as measured by the so-called color quality scale (Q_a) [25].

2. Experimental

2.1 Laser illuminant

All four lasers were purchased from Opto Engine LLC [26], with the following specifications:

Red: 635nm, 800mW maximum power, Model MRL-III-FS-635, FWHM < 2 nm, multi-quantum well AlGaInP laser diode.

Yellow: 589 nm, 500 mW maximum power, Model MGL-N-589, FWHM < 0.2 nm, sum frequency generation of 1064 nm and 1319 nm from 808 nm laser-diode (LD) pumped Nd:YAG.

Green: 532 nm, 300 mW maximum power, Model MGL-III-532, FWHM < 0.2 nm, frequency doubled 1064 nm from 808 nm LD pumped Nd:YVO₄.

Blue: 457 nm, 300 mW maximum power, Model MBL-F-457, FWHM < 0.2 nm, frequency doubled 914 nm from 808 nm LD pumped Nd:YVO₄.

The laser output powers were controlled by sending pulse-width modulated (PWM) signals to the transistor-transistor-logic power control inputs of the lasers. For reliability and timing reasons, the PWM signals were generated by an 8-bit digital comparator whose inputs were the output of a repeatedly up-running counter and the binary code supplied by power controlling software over a National Instruments IO interface. The base frequency of the PWM was chosen to be fairly high (781 Hz) to eliminate flickering and strobe effects. Laser powers were controlled to 0.5% via measurements from individual laser beam pick-off detectors. The four beams were combined with chromatic beam-combiners. The resulting white beam was then diffused so as to reduce speckle. The diffuser had two parts: the first consisted of the powder-coated wall of a soft-white incandescent bulb while the second consisted of the mirrored cone and grounded bottom glass housing of a commercial heat lamp.

We note that eliminating speckle was very important. Speckle detracted from the visual appearance of the test objects, especially for younger test subjects. For expediency in this work, a brute-force diffusive approach was taken, resulting in a beam attenuation of 75%. For a practical laser illuminant, a more elegant (and less lossy) solution would be necessary.

2.2 Reference illuminants

The four reference illuminants were: an incandescent lamp, and warm-white, neutral-white, and cool-white phosphor-converted white LEDs. They were chosen to span a wide (2,800-6,000K) range of correlated color temperatures (CCTs) from warm to cool white. The incandescent sources were 75 Watt bulbs made by General Electric. The warm-white phosphor-converted white LED sources were manufactured by Lighting Science Corporation (EccoSmart brand) and were A19 8.6 Watt (40 Watt equivalent) LED retrofit light bulbs. The neutral and cool white sources consisted of three Philips-Lumileds Rebel LEDs mounted on a metal core printed circuit board. The illuminances, chromaticities, and color rendering indices were measured at the bottom of the viewing booths and are listed in Table 1. Illuminances were in a range (125-200 lx) appropriate for dining environments [27].

Table 1. Properties of Illuminants and Results of Comparisons between Illuminants^a

Illuminant Type or Illuminant Type Mimicked	Laser Illuminant Properties													Reference Illuminant Properties					Comparisons between Illuminants							
	E_B (lx)	E_G (lx)	E_B (lx)	E_G (lx)	E_B (lx)	E_G (lx)	R/Y (W/W)	CCT (K)	D_{uv}	u'	v'	CR_i (R_a)	CR_i (R_g)	QOS (Q_a)	E (lx)	CCT (K)	D_{uv}	u'	v'	CR_i (R_a)	CR_i (R_g)	QOS (Q_a)	Mean _R	Mean _g	Mean _R - Mean _g	p-value
Incandescent	1.9	81	82	31	197	1.35	2,838	0.0009	0.256	0.526	91	96	85	196	2,838	0.0013	0.256	0.527	100	100	98	0.15	-0.08	0.23	0.060	Ref
LED Neutral White	3.3	69	51	18	141	1.23	4,256	-0.0058	0.224	0.490	85	75	84	140	4,217	-0.0069	0.226	0.489	90	53	85	-0.07	0.02	-0.08	0.160	Laser
LED Cool White	3.3	74	41	12	130	1.03	5,665	0.0110	0.197	0.486	83	82	82	128	5,923	0.0125	0.194	0.484	71	-30	72	-0.24	0.01	-0.25	0.001	Laser
LED Warm White	2.3	85	79	28	194	1.28	3,111	0.0015	0.246	0.521	90	95	86	192	3,113	0.0023	0.246	0.522	87	53	86	-0.29	-0.04	-0.26	0.016	Laser

^aAs discussed in the text, slight drifts in laser illuminant properties during the course of a test run were periodically checked and eliminated; the properties listed here (and plotted in Fig. 2) are considered representative.

2.3 Chromaticity and illuminance matching

All chromaticities and illuminances, for both the laser and reference illuminants, were measured at the bottom of the viewing booths using a Konica Minolta CL-200A Chroma Meter. Color rendering quality (R_a , R_g , Q_a) for the laser illuminants were determined by simulation, and for the reference illuminants were inferred from power spectral distributions measured using an Ocean Optics USB2000 spectrometer with ~1.5nm resolution.

The laser powers were tuned to match the (u',v') chromaticities and illuminances (E) of the reference illuminants to which they were being compared [28]. Since chromaticity and illuminance represent three constraints but our laser illuminant has four independent component powers, a fourth additional constraint, that the color quality scale (Q_a) be maximized, was imposed. After tuning the output powers of the lasers to the values determined by the above procedure, we found that there were slight but visually noticeable residual chromaticity mismatches. To eliminate these, the powers were given slight (<5%) manual adjustments using our own visual matching. Slight drifts during the course of experimental test runs were similarly eliminated.

2.4 Participants

For all but the incandescent lamp tests, participants consisted of 41 volunteers (25 males and 16 females). The numbers of subjects within specific age ranges were: 1 (11-20 years), 9 (21-30 years), 15 (31-40 years), 5 (41-50 years), 4 (51-60 years), and 7 (61-75 years). A color deficiency evaluation was done during a pre-test interview; data from the five test subjects who were found to be color deficient were not used.

For the incandescent lamp tests, the participants consisted of 19 volunteers (10 males and 9 females). The numbers of subjects within specific age ranges were: 2 (21-30 years), 6 (31-40 years), 5 (41-50 years), 1 (51-60 years), and 5 (61-75 years). Data from the four test subjects found to be color deficient were not used.

2.5 Testing procedure

Side-by-side viewing booths were equipped with identical reference illuminants. The left booth was additionally equipped with the four-color laser white illuminant. Two identical bowls consisting of natural fruit and wrapped candy were placed at the bottom center of each of the viewing booths.

To avoid any researcher-induced bias, the test procedure was “double-blind,” controlled by software which presented a sequence of 80 comparisons drawn randomly from eight possible comparisons: four laser-to-reference and four reference-to-reference. The software created a log file with test identifications and questionnaire number for later data decoding and evaluation. Subjects were asked to mark a 7-point scale with the values: $-3 =$ strongly prefer left, $-2 =$ moderately prefer left, $-1 =$ slightly prefer left, $0 =$ neutral, $+1 =$ slightly prefer right, $+2 =$ moderately prefer right, $+3 =$ strongly prefer right.

2.6 Statistics

The 7-point scale described above was used to calculate the means (Mean_{LR} and Mean_{RR}) and differences between means ($\text{Mean}_{\text{LR}} - \text{Mean}_{\text{RR}}$) of the preference distributions listed in Table 1. However, because the degrees of preference in such so-called Likert scales are not considered linear, the statistical significances of the results were calculated making use only of the ranking, not the values, of the preferences. In particular, the non-parametric Mann-Whitney-Wilcoxon (MWW) rank sum test [29] was used to obtain p -values characterizing the probability that the data are consistent with the null hypothesis. We took the null hypothesis to be that the laser-reference preference distribution is the same as the reference-reference preference distribution. Lower (<0.05) p -values thus indicate a statistically significant, while higher (>0.05) p -values indicate a statistically insignificant, preference for one illuminant over another.

3. Results and discussion

The results of the comparisons between illuminants are summarized on the right side of Fig. 3. The control comparisons between identical reference illuminants (white curves) show single peaks centered (dashed vertical white lines) at neutral, indicating that the pairs of

reference illuminants of the same type were well matched to each other, *and* there was no significant bias towards the left or right viewing booths themselves.

The comparisons between the laser and reference illuminants (black curves) are also centered (dashed vertical black lines) at neutral, but with double peaks. Post-test interviews revealed two classes of participants: those who preferred more, and those who preferred less, saturation in object colors. Because the colors of objects illuminated by the laser illuminants appeared slightly but noticeably more saturated, the laser illuminants were preferred by the first, while the reference illuminants were preferred by the second, class of participants. Note, though, that the degree of saturation, while fixed for the reference illuminants, can be tuned for the laser illuminants. As discussed above, the laser powers were tuned to optimize Q_a [25], a metric which is neutral with respect to color saturation. Other metrics, which either favor or disfavor color saturation, could have been used.

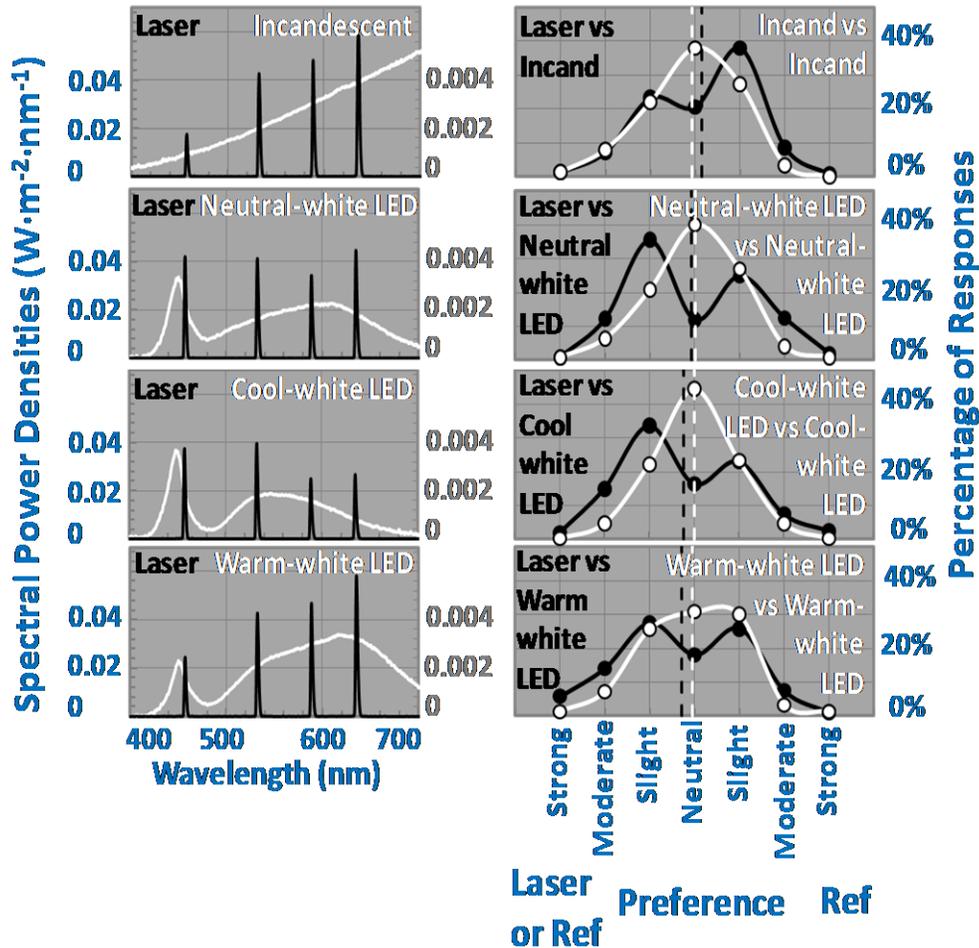


Fig. 3. (Left) Power spectral densities of the various illuminants: laser illuminants in black (with scale on left-axis); reference illuminants in white (with scale on right-axis). (Right) Summary of preferences: between the laser and reference illuminants in black; and between the reference illuminants in white. Vertical dashed black and white lines are the means of the preference distributions, where the degree preferences were assigned numerical values of $-3, -2, -1, 0, 1, 2, 3$.

In addition, the comparisons between the laser and reference illuminants were not as centered at neutral as the control comparisons, with: slight preferences for the laser illuminants over the warm-white and cool-white LEDs; an extremely slight preference for the

laser illuminant over the neutral-white LED; and a slight preference for the incandescent illuminant over the laser illuminant. The comparisons are consistent with the relative ordering of the Q_a 's of the various illuminants, though only the first two comparisons mentioned above are considered statistically significant.

We conclude that, in terms of color rendering quality, the laser illuminant is nearly indistinguishable from high-quality reference illuminants. That this can be so is, as mentioned above, contrary to intuition. However, it can be understood by considering the sequence of events, shown in Fig. 4, involved in the perception of color.

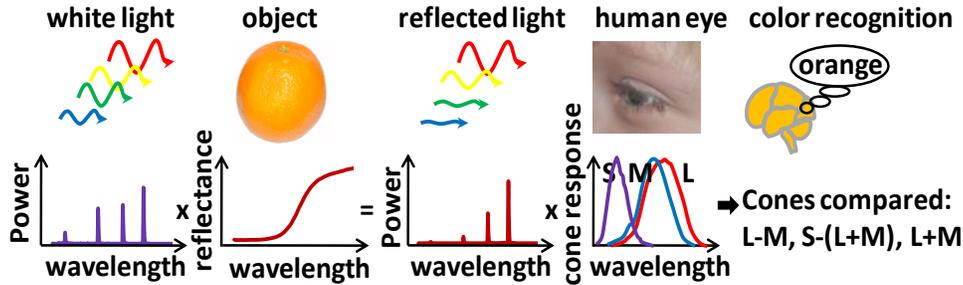


Fig. 4. White light (left), shown composed of four narrow spectral lines, reflects off an orange. The orange preferentially reflects red and yellow and hence the L and M cones of the eye are preferentially stimulated. The brain compares the cone responses and interprets the color of the object to be a particular shade of orange.

After being emitted from a source, light reflects off the surface of objects. If objects reflected only narrow spectral bands of light, spiky sources would risk not emitting any light that could be reflected. That is not the case, however: the reflectance spectra of virtually all objects, natural or man-made, are broad, smooth, and continuous [30,31]. Therefore, *some* light, provided the narrow band light sources are not too widely spaced in wavelength, will be differentially reflected off object surfaces with such spectrally broad reflectances.

Then, the light travels to, and is absorbed by the three cone photopigments in, the human eye. The visual system does not “know” the wavelength of light based on cone excitation and is unable to distinguish between changes in wavelength based on the response of just one cone type [32]. Only by combining and comparing the excitation of all three cone types does the visual system construct percepts of light color. It does not matter whether the light is evenly distributed over all, or concentrated in a narrow set of, wavelengths within a cone’s photopigment range. Thus, spectrally continuous and discontinuous light sources can, and (as demonstrated here) do, have the same effect on the visual system.

4. Conclusion

In conclusion, a four-color laser white illuminant has been shown experimentally to be virtually indistinguishable from high quality state-of-the-art white reference illuminants. This result paves the way for serious consideration of the use of lasers in solid-state lighting. Importantly, our experiment represents the most extreme configuration for lasers in solid-state lighting, in which each source of light is a laser. These results would presumably apply as well to less extreme configurations, in which some of the light is laser light but some is from phosphors.

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