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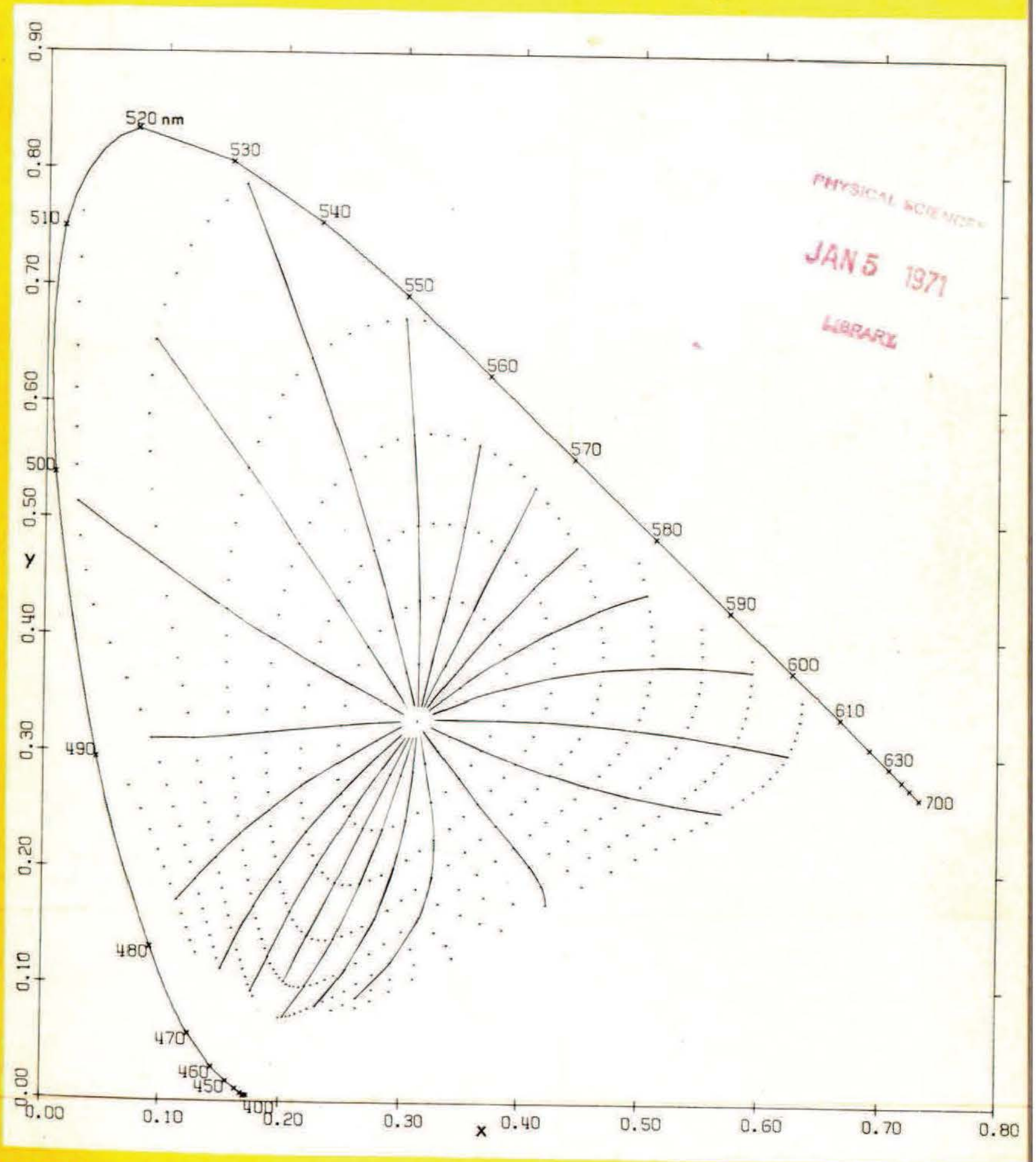

CHROMATICITY DIAGRAM

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Photoluminescent Conversion of Laser Light for Black and White and Multicolor Displays. 2: Systems

D. A. Pinnow, L. G. Van Uitert, and M. Feldman

Recent technological developments permit the modulation and scanning of laser beams at rates comparable with those of electron beams in television receivers. This accounts for much of the current interest in laser illuminated display systems which are not constrained in size, as is the cathode ray tube, by the necessity of a vacuum enclosure. The purpose of the present work is to show how photoluminescent materials can be used in conjunction with recently developed acoustooptic deflectors and modulators to achieve high quality laser display systems. The principal function of the photoluminescent materials is that of color conversion when coated onto a viewing screen. This allows an additional degree of freedom in laser display engineering by removing the spectral constraints imposed by the limited number of practical laser emissions. Various schemes for both black and white and multicolor displays are explored. Some of the concepts which evolved have been experimentally verified by the operation of a system which projected the video signal from a PICTUREPHONE set. The source was an argon ion laser which emitted a monochromatic blue (4880-Å) beam. After acoustooptic modulation and deflection, the blue beam was directed to a phosphor screen where it was converted into a brighter and speckle-free black and white display.

I. Introduction

In Part 1[1] we discussed the characteristics of a number of photoluminescent materials that can efficiently convert ultraviolet and visible light into light of a similar or longer wavelength spectral content. Here we will consider the application of these materials to white light and multicolor displays that use laser sources. A considerable effort in the field of laser scanned displays has been prompted by potential applications for which the cathode ray tube (CRT) is unsuited. One particularly important application of laser systems is that of large screen multicolor display. Such systems have been successfully developed in a number of laboratories[2] including Zenith, Texas Instruments, General Telephone and Electronics, and Hitachi. In general, they are complicated, expensive, and required a substantial and careful engineering effort. A major source of engineering complication has been the necessity of using three separately modulated laser beams of different colors to achieve the desired color gamut and the use in many cases of mechanical scanning motion. We have found that a greater freedom of action as well as possible simplifications could result by using photoluminescent screens to provide some switching action between colors. In this paper we will describe some schemes for color switching and the systems they make possible. We will also report experimental results of a particularly simple large screen black and white system which is speckle-free and provides PICTUREPHONE resolution.

In discussing laser display systems it is instructive to compare them with the conventional CRT systems. Recent technological advances in acoustooptics[3,4] and electrooptics[5] permit efficient and inertialess modulation and scanning of laser beams at rates approaching or comparable with those of electron beams in television CRT's. The principal difference between laser and CRT systems is not in resolution but in screen shape and size. Laser systems are inherently projection systems which can use flat screens; while the conventional CRT, which is most often directly viewed, has considerable volume. Generally, the size of a CRT screen is limited by mechanical considerations to at most 76 cm in diameter.[6] Even if the CRT image is projected, the viewing area is constrained by the light intensity that can be developed at the CRT screen. In order to provide a black and white picture with brightness comparable with that of a typical motion picture display the projection CRT screen size is limited to approximately 2 m^2 even with anode voltages on the order of 75,000 V, where x-ray radiation and heat dissipation become serious problems.[6] In contrast, screen heat dissipation is not a problem in laser displays since the beam is directly projected to as large an area as can be comfortably viewed with the available laser intensity. A rough estimate of the relation between light intensity and viewing area is that 1 W to 2 W of

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available laser light are required for each square meter of a diffusing screen to achieve typical television brightness levels,[7] while a factor of 3 less in intensity is satisfactory for theater viewing. For certain applications, directional screens can be used which reduce the required laser power by factors of up to several hundred.

The laser source is a limiting factor in many display system designs. By taking advantage of photoluminescent color conversion we can remove spectral constraints imposed by the limited number of practical laser emission wavelengths. Of the presently known laser types, the argon ion laser has already proven satisfactory for long term stable operation at a level of several watts,[8] and experimental units have demonstrated outputs up to 100 W.[9] Although this laser is satisfactory for a display system source in almost all respects, its efficiency is typically only on the order of several hundredths of 1%.[10] Thus an argon laser source adequate to illuminate a 1 m^2 screen would require several killowatts of electrical power. In comparison, only a few watts of electrical power are needed for modulation and scanning of the laser beam.[3] Because of this laser inefficiency the operating expense for a display system using an argon laser source will tend to limit its applications either to commercial uses involving large audiences or uses where very low light intensities are acceptable. However, it should be pointed out that low efficiency is certainly not fundamental to laser operation. For example, operation of an infrared (10600 Å) Nd:YAG laser at 2.4% efficiency has already been demonstrated,[11] and efficiencies of approximately 10% appear to be possible.[12]

For the present, however, the argon ion laser is the most suitable prototype for a display system source. It has prominent emission lines in the blue (4880 Å) and green (5145 Å). Because photoluminescent conversion can only produce light of a similar or longer wavelength, it is essential that the source have at least one blue or ultraviolet emission. The additional emission of a second color, such as the green line of the argon laser, can be used to advantage in certain systems that will be discussed in Sec. III. By using phosphors described in Part 1,[1] it is possible to convert a portion of the blue-green beam into red, which is the remaining component necessary for a multicolor display. This technique is substantially simpler than the alternate approach taken by others[2] of adding an additional red laser source to the display system and avoids the problem that presently available red lasers are even less suitable for a display system than the argon laser. The two principal choices are the He–Ne laser (6328 Å), which is inherently limited to low power operation for reasonable sizes by the low gain per unit length,[13] and the krypton ion laser (6471 Å), which is nearly an order of magnitude less efficient than the argon laser.[14] An additional advantage of photoluminescence is that the converted light is incoherent so that the unpleasant granular or speckled texture generally associated with viewing diffusely scattered coherent light is eliminated.[15]

The recently developed Cd–He laser which emits in the blue (4416 Å) should also serve as a useful prototype source, although its intensity is limited like that of the He–Ne laser.[16] In addition to the above lasers, it is possible to make multicolor laser hybrids by combining two or more gases into a single laser tube.[17] Experiments with mixed gas lasers which combine argon and krypton or He–Ne–Cd to achieve multicolor emission indicate that the over-all efficiency of the mixed systems are considerably less than optimized lasers having single components. For example, the red emission from a He–Ne–Cd laser has been observed to be only about one-fourth of that from an optimized He–Ne laser.[17] Thus, the present hybrids have a serious problem because of their inefficiency.

II. Color Control

There are many analogies between display systems that use electron beam sources and those that use laser beams. For example, both types of beam can be used to illuminate a phosphor which in turn produces a visible color. In the standard color CRT display three spatially separated electron guns are used to illuminate, respectively, three different colored phosphors through a shadow mask. A similar technique is also practical with laser displays. Thus, one method for achieving multicolor is by illuminating from different spatial directions.

An alternate method for achieving a multicolor effect with a CRT is the use of a single electron gun which excites a white phosphor screen located behind a rotating multicolor wheel.[18] Transparent red, blue, and green segments of the wheel sequentially appear in front of the CRT resulting in a repeating sequence of discrete color frames. The wheel rotates sufficiently fast so that an observer cannot distinguish the separate color frames but instead sees only the total effect. Variations on this approach can all be categorized as active (i.e., moving) screen methods. Similar methods are also possible with a laser system, although the screen may be substantially different from that used in the CRT system.

In addition to these well-known methods, which are applicable to both electron beam and laser beam illumination, there are several unique features of laser beams which can be used to advantage in achieving a multicolor system. First, the laser beam itself may provide at least one color, and in the important case of the argon ion laser there are two distinct colors. Next, a laser beam, or for that matter any light beam, has two orthogonal polarization states which can be used to transmit separate color information. And, finally, light beams can be brought to a focus in very short distances by passive elements such as plastic lenslets which can be made an integral part of a viewing screen.

The internationally accepted CIE chromaticity diagram[19] shown in Fig. 1 can be used as a guide in assessing the color quality of a display system. In this diagram the saturated (monochromatic) colors are located on the perimeter of the horseshoe shaped plot, while colors of decreasing saturation approach illuminant C which is

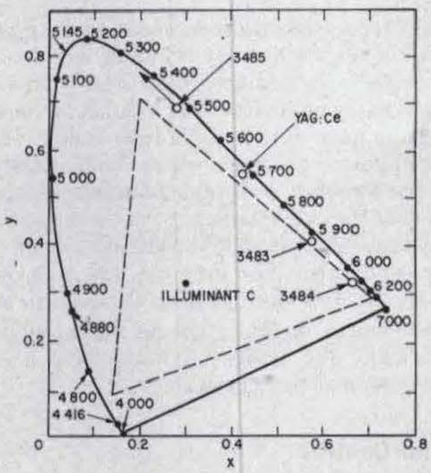

Fig. 1. The CIE chromaticity diagram. The dotted lines enclose the color gamut of a shadow mask color cathode ray tube.

a white color equivalent to average daylight illumination. Every real color, regardless of its spectral complexity, can be represented by a single point on or within this plot. A straight line connecting any two points (primaries) represents the locus of possible colors that can be achieved by blending the primaries in varying proportions. Similarly, the gamut of colors possible by the combination of more than two primaries are those that fall within the polygon determined by straight lines which connect adjacent primaries. As an example, the dotted triangle in Fig. 1 encloses the color gamut of a shadow mask color CRT. For comparison we have also shown the major cadmium and argon laser lines at 4416 Å, 4880 Å, and 5145 Å, as well as the emissions of the YAG:Ce phosphor and the three organic dye phosphors (types 3483, 3484, and 3485) which are discussed in Sec. III of Part 1.[1] The arrow on the type 3485 dye emission shows the effect of adding phthalocyanine, which is also discussed in Part 1. It can be seen that the combination of blue light (4416 Å or 4880 Å) from either of these laser sources and emission from the 3483 and 3485 phosphors results in a color gamut similar to that of the CRT.

III. Exploratory Systems

Various laser display systems are proposed and evaluated in this section. They are presented in such an order that the relative advantages and disadvantages become apparent. The first and simplest system concerns the conversion of a monochromatic display into black and white. The remaining systems are for multicolor displays.

A. Black and White

A black and white display can be achieved by scanning a monochromatic laser beam on a viewing screen that is coated with an appropriate blend of phosphors and direct scattering materials such as powdered MgO. For example, a combination of scattered light from a blue argon ion laser beam (4880 Å) and blue to red converted light from either Rhodamine dye phosphors, type 3483 or 3484, can produce a white appearance since a straight line connecting these primaries on the chromaticity diagram passes very near illuminant C. Similarly the combination of 4880-Å light and converted light from a YAG:Ce phosphor will produce a somewhat yellowish-white appearance since the line connecting these primaries passes above illuminant C. To achieve a truer white with this phosphor requires a shorter laser wavelength such as the less intense 4579-Å line of the argon laser or the 4416-Å line of the Cd–He laser.

A combination of more than two primaries can also be used to produce white. As an example, a Cd–He laser beam which illuminates a correctly proportioned mixture of MgO and dye phosphors 3483 and 3485 can be used to achieve a white appearance. Alternately, the MgO could be replaced by pyrelene (a blue to blue converting phosphor) to eliminate speckle completely.

Regardless of how many phosphors are used, it is apparent from the chromaticity diagram that a necessary condition for achieving a true white is that the illuminating laser beam have a wavelength of approximately 4950 Å or shorter. Otherwise it would be impossible to include illuminant C within a polygon whose primaries are the source and any combination of longer wavelengths that can be achieved by conversion. Fortunately, the argon ion laser can satisfy this necessary condition.

A factor which must be considered in the choice of photoluminescent materials is the relative sensitivity of the eye.[20] Figure 2 clearly demonstrates that there is an increasingly steep falloff in the eye's sensitivity as wavelength varies from the yellow-green portion of the spectrum at about 5550 Å. Thus, for a fixed laser power and a fixed phosphor conversion efficiency, the brightness of the screen depends critically upon the emission spectrum of the phosphor. In particular, the brightest screen will favor the yellow-green emitting

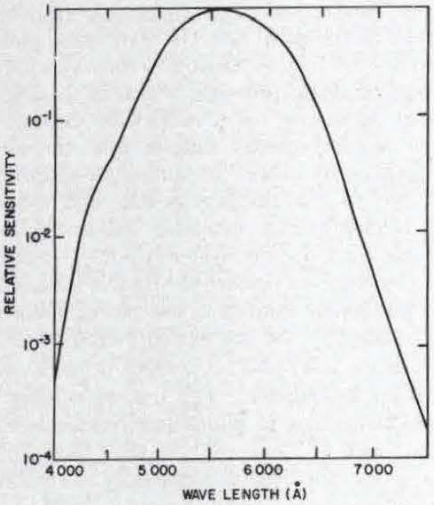

Fig. 2. The relative sensitivity of a standard normal eye to light of varying wavelength.

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