Personal Projection

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Abstract

We introduce the technology and applications of *personal projectors,* small and inexpensive video projection devices intended for use in battery-powered handheld or wearable products. We then discuss a prototype constructed in our research group, based on an array of semiconductor lasers.

Introduction

Sharing of soft-copy visual information is increasingly important in business and will likely become equally so for consumers.[1] It's often desirable for this sharing to take place in a physical space, and advances in light-modulation technology such as liquid-crystal devices and digital micromirror devices have enabled bright, high-resolution video projection to be packaged into products approaching the size of a hardcover book.

In the design of hand-held or wearable communication and computation devices, significant attention has been given to small personal visual displays. But as mobile or wearable computation and communication devices grow ever smaller and more ubiquitous, we should consider adding projection capabilities to such products, both so that the user can share visual information with others in the room who might not have similar devices, and to get around the screen size and resolution limits imposed by the form factors of the devices. Consider the following scenarios:

- Downloading a map onto a mobile phone, and projecting it onto a wall or desk so as to see details
- Giving an impromptu slide presentation from a pocket PC or a digital camera
- Hand-held test equipment which can provide a detailed page-sized display
- A laser pointer that is also a dynamic information presentation device

The characteristics of such *personal projectors* are quite different from those of typical conference-room or consumer-electronics video projection devices:

- Very small (let's say capable of fitting into a 2cm cube)
- Efficient (needs to operate on battery power)
- Shock-resistant and possibly waterproof
- Minimal, focus-free optics
- Capable of projecting up to about one meter diagonal images
- Extremely inexpensive (at least two orders of magnitude less than typical tabletop projectors)
- Not necessarily full-color or high-resolution

Other applications such as automotive heads-up displays might also be well served by devices that meet these requirements.

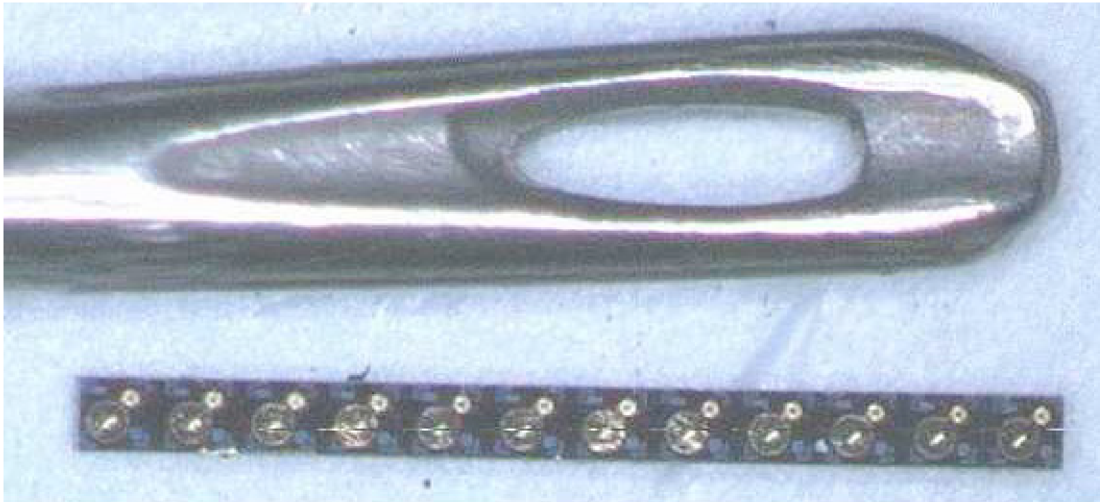

Figure 1: An array of VCSEL devices compared in size with the eye of a needle. (Courtesy Honeywell VCSEL Products Division)

VCSELs

The light-modulation technologies behind the current small video projectors don't necessarily extrapolate into the requirements of the miniature personal projector. Considerations of efficiency, cost, and optical simplicity suggest using semiconductor lasers as the light source, and modulating the light electronically rather than optically. Conventional semiconductor lasers of the sort used in optical storage devices or laser pointers emit light from the side of the device, but in recent years a new component called a vertical cavity surface emitting laser, or VCSEL, has emerged.[2] Because these emit from the top surface, it is possible to test them before cutting a wafer into individual devices, leading to cost savings; also it is feasible to fabricate 1D or 2D arrays of emitters simply by cutting a corresponding section from a wafer. As of this writing, infrared VCSELs are becoming commonplace, while visible emitters (far-red) are just beginning to arrive in commercial quanitities.

Our research explores the use of a visible VCSEL array for video projection purposes. The idea of using a single high-powered laser for video projection has been investigated since the late 1960s,[3] and Symbol Technologies has this year resurrected this idea in a small package aimed at the same sorts of applications as described in the preceding section.[4] Over the past several years, researchers have described the application of laser arrays to projectors [5][6] and direct-view displays.[7] The use of arrays relaxes a number of engineering problems that might arise when a single laser is used in a raster display:

- Cost and safety issues of a single multiwatt laser
- Flicker – unlike a CRT display, the screen has no persistence, so the eye must provide the integration function
- Need to modulate the laser's brightness at extremely high speed

- Difficulty of providing fast enough optomechanical scanning for the horizontal axis – it's relatively easy to make a scanner (*e.g.* a galvanometer-driven mirror) that runs at the vertical scan rate but not so easy at the horizontal rate
- Difficulty of compactly packaging a two-axis mechanical scanner

Our proposal is to employ a single scan line of lasers, one per pixel, and scan only in the vertical direction. Because a whole line of lasers will be illuminated simultaneously, flicker won't be an issue, the modulation speed can be reduced by a factor of N (where N is the total number of lasers), the scanning need take place only in the "slow" direction so the scanner can be inexpensive, and the radiant power will be distributed over a group of lasers so safety issues associated with a single bright spot will be lessened. An additional cost associated with this approach is the need to do simultaneous modulation of tens or hundreds of emitters, which will be discussed below.

System Design Overview

A complete projector system needs several parts: the lasers themselves, the stationary optics, the scanning mechanism, and the drive electronics (which accepts a video signal input, modulates the lasers, and drives the scanner). We shall examine each of these in a separate section to follow.

Lasers and Visibility

When considering the output of a device such as a semiconductor laser, it's appropriate to use *radiometric* units such as radiated power in watts. When considering a display, however, we want to use *photometric* units such as lumens. Converting between these requires knowing something about the eye's differing sensitivity to different wavelengths of light. For a monochromatic light source of wavelength λ the conversion from radiometric flux P in watts to photometric flux F in lumens can be expressed very simply as

$$F = 680\ P\ V(\lambda)$$

where $V(\lambda)$ is the CIE eye response curve (Figure 2), which gives the relative sensitivity of the eye as a function of wavelength. This curve is normalized to be 1.0 at its peak of λ = 555 nm (which is perceived as yellow-green) and drops to essentially zero at 400 and 700 nm. See for example [8].

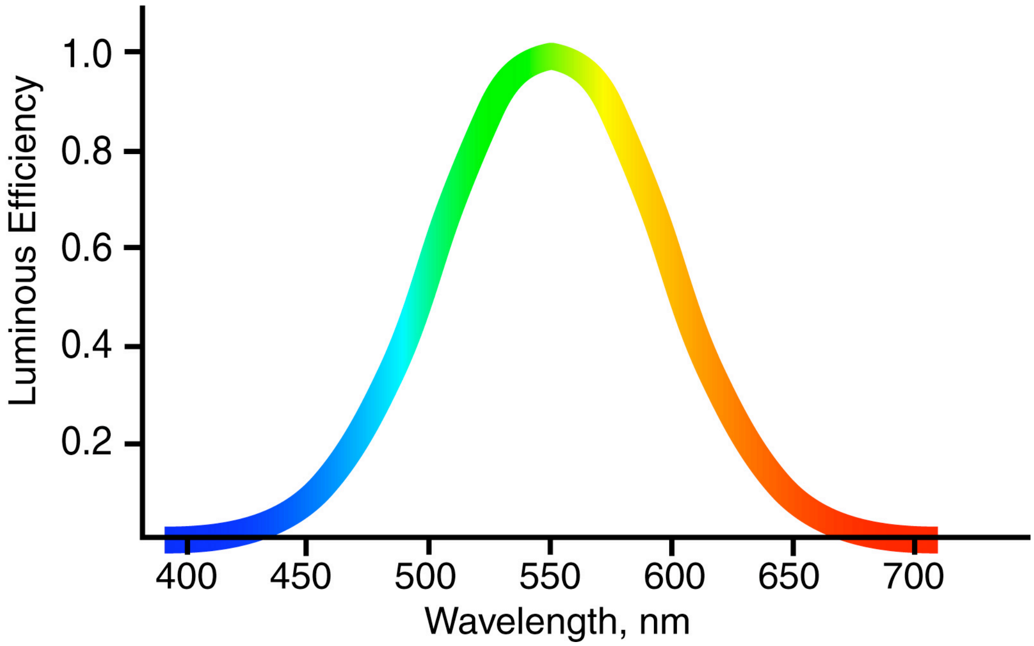

Figure 2: CIE eye response curve gives relative sensitivity of the eye to various wavelengths of light.

The red VCSELs coming onto the market as of this writing are capable of radiating approximately 2 milliwatts at a wavelength of 670 nm, and thus an array of 100 of them would be able to produce a respectable 136 lumens if they were at the peak of the luminance curve (for reference, a typical portable video projector produces around 1000 lumens, but that's displayed on a screen of much more area than will be our personal projector). Unfortunately, at 670 nm the V(λ) curve is less than 0.1. Certainly when green VCSELs are readily available, the visual efficiency of displays like those proposed here will increase significantly. Even red lasers at 620 or 630 nm would appear noticeably brighter. Current semiconductor laser development in laboratories extends to the blue end of the visible spectrum.[9]

Those 100 lasers, incidentally, would be consuming about 7 milliamps each, at 2.5 volts, so the total power consumption would be 1.75 watts. This is not unreasonable for a battery-powered device, and indeed it is similar to the power consumption of a flashlight bulb.

VCSEL arrays are generally not closely-packed, but instead have interelement spacing much greater than apertures of the laser devices. The arrays we are using in our prototype are typical, their lasers having a 10 micron aperture, and a 100 micron spacing. The image produced by such a laser array would have significant dark spaces between the pixels in a line, and we somehow must compensate for that effect. We shall return to this issue in a later section.

Stationary Optics

Raw semiconductor laser devices produce diverging beams, but because their beams are coherent they can be collimated to eliminate the divergence. This is the idea behind a laser pointer. However, if we perfectly collimate a small laser array, we end up with an image that is the same size as the array (small!) irrespective of distance to the screen. So what we need is for the beams to be imperfectly collimated to give both a small degree of divergence in each beam and a corresponding horizontal divergence across the array. This could be done by placing collimating microlenses on the individual lasers on the array and then a single external lens, or (since the arrays are so small) by using a single small plano-convex lens to provide collimation and divergence for the whole array.

The amount of horizontal divergence required is a function of the aspect ratio and the vertical scan angle. If we assume a 4:3 aspect ratio, and denote the vertical angle through which the vertical scanning arrangement scans as θ_v , we then need the display to diverge horizontally through an angle θ_h such that

$$\tan(\theta_h/2)= (4/3)\tan(\theta_v/2)$$

We might also further imperfectly collimate the beams such that the gaps between them are filled in. However, in a later section we propose to solve the interelement spacing issue in a different fashion.

Scanner

An advantage of the small size of the laser arrays is that it's practical to use a single mirror or prism mounted on a mechanical scanner in order to provide vertical deflection. Various technologies are available, ranging from the scanning galvanometers that have been used since the earliest days of laser displays [3] to Micro-Electro-Mechanical Systems (MEMS) [10]; the important point to remember is that the scanning is relatively slow (less than 100 Hz).

As noted above, typical VCSEL arrays have significant interelement spacings. We propose to solve this problem by using each VCSEL to generate several adjacent image pixels, by means of very small, high-frequency lateral motion (tens of kHz, but only tens to hundreds of microns peak-to-peak displacement) of either the array itself or an appropriate optical element between the array and the vertical scanner. This could be accomplished by one of several methods, including MEMS or piezoelectric devices. As a side effect, we will have to increase the modulation speed by the interlace factor: if every laser generates four adjacent pixels, we must intensity modulate the lasers such that we generate a full gray scale in one-fourth the line duration instead of the entire line duration.

Hardware Driver

The drive circuitry for a system as described here must perform several tasks:

- Accept a video signal in analog or digital form (and in the former case, digitize it), convert resolution as needed
- Generate drive signals for the vertical scanner, as well as the horizontal scanner if used
- Buffer at least one scan line of pixels
- Pulse-width modulate (PWM) the lasers to create gray scale

Consider a VGA-resolution (640x480, 60Hz) display. Let's assume a linear array of 160 lasers (so each laser is responsible for four adjoining pixels on a line), and also assume that the drive electronics has only a few line buffers rather than a full frame store – so we can drive lasers during the horizontal retrace time of the input but we'll lose a little potential brightness during vertical retrace (say 10% of the frame time). Then a given laser has to render a pixel in

1/60 second / 480 lines / 4 = 8.68 microseconds

and 256 intensity levels via pulse-width modulation requires a PWM clock of 29.5 MHz, which is really quite modest these days. The only really significant hardware design issue is the need for as many outputs on the drive chip as lasers in the array; as a practical matter the drive chip and the array should be mounted in close proximity to each other on the same printed-circuit board.

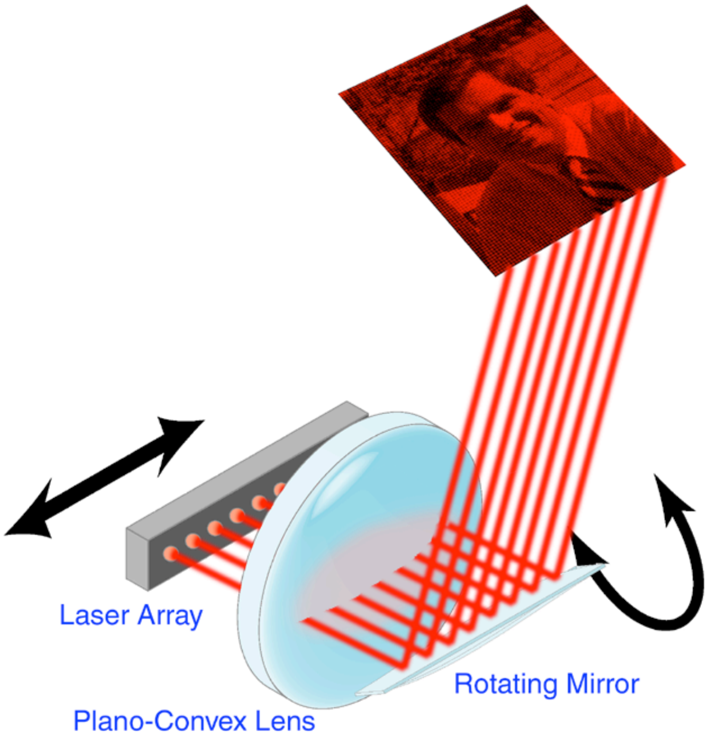

Figure 3: Simplified diagram of prototype system.

Our Prototype

In order to demonstrate the feasibility of a VCSEL-array projector, we've constructed a prototype along the lines of the above discussion. A very early version used an infrared array, and had to be viewed against a phosphor screen; we're now using 670 nm far-red array prototypes provided by Honeywell's VCSEL Products Division. 50 lasers each creating four pixels results in an image of 200 pixels by 150 lines.

A drive circuit based upon a Xilinx Spartan-II field-programmable gate array (FPGA) accepts a VGA-resolution video input, and downscales it for the projector, as well as generating the PWM and scanner-drive signals.

A single plano-convex lens provides collimation and divergence, and a small front-surface mirror driven by a scanning galvanometer provides vertical scanning (Figure 3). As of this writing we are investigating several methods of horizontal movement to provide the horizontal pixel interlace, both by moving the array with a piezoelectric device and by moving an optical element in front of the array.

Conclusions

While the red laser arrays available as of this writing operate at too long a wavelength to be optimally visible, and while green and blue VCSELs are at least a few years from commercialization, it is clear to the authors that inexpensive and durable small projectors are within reach. While wavelength, efficiency, and power limitations of VCSELs will probably be resolved relatively quickly, other issues remain to be worked out, most particularly building a smaller, cheaper, and more efficient vertical deflection mechanism – the galvanometer we are currently using not only is larger than the rest of the projector, but it consumes as much power as the laser array.

A projector of this sort also has other potentially useful properties. For example, if a phototransistor and some computational circuitry are incorporated, the system can provide fast time-of-flight rangefinding at the spatial resolution of its raster. The basic principle here is that of modulating the lasers with a regular waveform and comparing the phase of the reflected light with that of the emitted signal to compute distance. Applications of rangefinding in this case extend beyond the obvious cases of distance measuring or 3D modeling, and include enabling the user to interact with the screen using his/her hands,[11] and automatic keystone correction by detecting the orientation of the screen plane.

Acknowledgments

The authors thank Emily Cooper and Daniel Adams for their lead-bonding and packaging assistance, and Juan Rivas and Christopher McEniry for their work on early prototypes. Particular thanks to Honeywell's VCSEL Products Division for providing laser devices. This work has been sponsored in part by the Digital Life Consortium and Telmex.

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Author Biographies

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