# P-125: Personal Projection, or How to Put a Large Screen in a Small Device

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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 explore the engineering and perceptual suitability of arrays of surface-emitting lasers for this application, and discuss a prototype constructed in our research group.*

## 1. Introduction
The proliferation of increasingly sophisticated handheld computational devices such as pocket PCs, wireless phones with imaging capability, GPS units, small technical instruments, and the like has made very apparent the limitations that are imposed on these devices by the small displays required by their form factors. One possible solution would be to incorporate projection displays, but any such projector must take into account the main characteristics of typical handheld products:

- They're small
- They're inexpensive
- They're battery-powered

Accordingly, if we wish to create a projection display for such devices, we need to design it such that it doesn't add significantly to the size, the cost, or the power consumption of the product in which it's installed. As a practical matter, we can't set these variables to zero, but we can set reasonable design requirements for a *personal projector:*

- Very small (capable of fitting into a 2cm cube)
- Extremely inexpensive (ideally at most tens of dollars)
- 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 with usable brightness
- Not necessarily full-color or high-resolution (VGA or less)

## 2. Technological Background
Desktop video projectors based on light modulators such as liquid crystal or digital micromirror devices are dropping in price and size, but the above requirements do not suggest a direct extrapolation of these product designs. In particular, the low power consumption requirement is more appropriately served by electrical rather than optical modulation of a very efficient light source; combined with the focus-free requirement this suggests the use of a semiconductor laser.

Unlike the familiar semiconductor lasers used in laser pointers, vertical cavity surface emitting lasers, or VCSELs, emit from the top of the device rather than the side.[1] As a result, it is possible to create monolithic arrays of these devices by cutting groups of them from a wafer; also the round beam of a VCSEL is easier to collimate well with simple optics than the elliptical beam from an edge-emitting device. As of this writing, infrared VCSELs are commercially available in both discrete and array form, while discrete visible emitters (far-red) are coming onto the market.

We are exploring the application of linear visible VCSEL arrays to video projection purposes. The use of a single high-powered laser and a two-axis scanner for video projection has been investigated since the 1960s,[2] and Symbol Technologies has recently resurrected this idea in a small package aimed at the same sorts of applications as described above.[3] Zalevsky, *et al.* report the use of semiconductor lasers to illuminate a light modulator to enable small projectors.[4] If monolithic arrays of semiconductor lasers are available, they may offer desirable advantages for the building of a personal projector, as they avoid the need for a large-angle horizontal scanner operating at tens of kilohertz, and reduce the modulation speed needed to generate grayscale (albeit at the cost of modulating many lasers in parallel). The small size of such arrays may also reduce the cost of the optical design. Other researchers have described the application of arrays of lasers to projectors [5,6] and direct-view displays.[7]

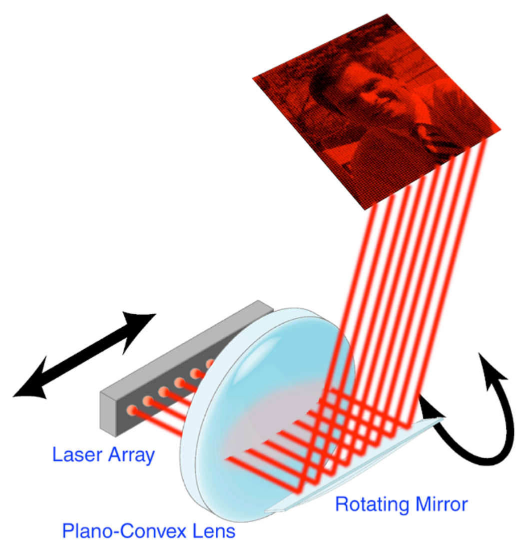


**Figure 1. Simplified diagram of prototype system.**


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## 3. System Design

Our proposed personal projector (Figure 1) combines a one-dimensional array of VCSELs with a simple arrangement of a lens and a rotating mirror. The laser array spans a single scan line, and the mirror moves the image of the line to create a raster. Driver circuitry both modulates the lasers and generates the signal for the scanning mechanism. In the following subsections we discuss some of the relevant engineering and perceptual considerations.

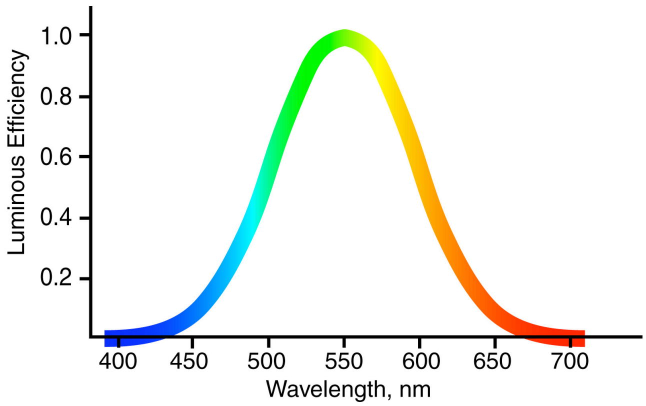


**Figure 2. CIE spectral luminous efficiency curve V($\lambda$) is used in conversion of watts to lumens.**

### 3.1 Perceptual Issues

To determine whether a typical VCSEL array can provide enough light for video projection use, we need to convert its radiated power in watts to photometric units such as lumens. Doing so requires quantifying the eye's differing sensitivity to different wavelengths of light, which is tabulated in the CIE eye response curve.[8] For a monochromatic source such as a single color of laser at wavelength $\lambda$, 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 is normalized to be 1.0 at its peak of $\lambda$ = 555 nm (perceived as yellow-green). The red VCSELs available to us as of this writing operate at a wavelength of 670 nm, at which point V($\lambda$) is 0.032, while it rises by a factor of three by 650 nm and almost another factor of three by 630 nm. If an individual element is capable of radiating approximately 2 milliwatts, an array of 160[1] of them would be able to produce 218 lumens if they were at the peak of the luminance curve.[2] Unfortunately, because 670 nm light is near the tail of the curve, the output for such lasers is approximately 7 lumens. When green VCSELs are readily available, the visual efficiency of displays like those proposed here will increase significantly, and even red lasers at slightly shorter wavelengths than those we now have would appear dramatically brighter. Semiconductor laser development in laboratories extends to the blue end of the visible spectrum.[9]

Assuming current typical efficiencies, those 160 lasers would be consuming about 7 milliamps each, at 2.5 volts, so the total power requirement would be 2.8 watts. This is not much more power than a flashlight bulb, and if the personal projector is not the primary display, but rather accompanies a small LCD or OLED screen, it should be acceptable – particularly when we take into account the fact that this is the peak consumption (all pixels at full brightness) and will rarely if ever be reached. It's also perhaps not unreasonable to expect that the power efficiency of visible VCSELs will improve as the technology matures.

### 3.2 Stationary Optics

The beams from raw semiconductor laser devices diverge, but can be collimated to eliminate the divergence. In the case of a VCSEL, this task is particularly easy, as the emitted beam is circular in cross-section. Because we're trying to produce an image that increases in size with distance, we don't want just to collimate the beams but also to magnify the image overall. One way to do this is to place a collimating microlens array on the laser array and then use an additional lens to image the whole array. The method we've adopted is to use a single short-focal length plano-convex lens to provide both the collimation and the magnification for the entire array. The lens is fixed in place during assembly and does not need to be adjusted for screen distance.

The horizontal divergence, the vertical scan angle, and the screen aspect ratio are interrelated. If we assume the common 4:3 aspect ratio, and denote the vertical angle through which the vertical scanning arrangement scans as $\theta_v$, we then need the display to diverge horizontally through an angle $\theta_h$ such that

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

### 3.3 Scanning Optics

Given the size of the laser array (100 micron spacing of the lasers is typical), it's practical to reflect the entire array from a small rotating single mirror or mirrored polygon in order to create a raster image. Galvanometers have been a popular scanning method since the first laser displays,[2] though they may consume too much power for our target application (as much as an ampere of current to reach the needed angular deflection). Other possibly-appropriate technologies include motors synchronized to the video signal, piezoelectric devices, or Micro-Electro-Mechanical Systems (MEMS).[10] The latter two of these may require special mechanical arrangements in order to provide a sufficiently large angle.

The devices in VCSEL arrays commonly are spaced much farther apart than the diameters of their apertures. The arrays we are using are typical, with a 10 micron aperture and a 100 micron spacing. Given such a device, the optical arrangement described in the preceding section would leave objectionable dark spaces between the pixels in a line. We can both correct this effect and increase the resolution of the display if we use each laser to generate several adjacent pixels by applying a fast but small

[1] The choice of the number 160 is not arbitrary, but (as discussed in section 3.3 below) would be sufficient to produce 640 by 480 image resolution given a horizontal interlace factor of 4.

[2] In comparison, a typical portable video projector produces around 1000 lumens, but spreads it over a much larger area.

horizontal scan (tens of kHz, tens of microns peak-to-peak displacement) to either the array itself or an appropriate optical element in front of it. This approach will increase the modulation speed by the horizontal "interlace" factor: for example if each laser produces four pixels then 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. MEMS or piezoelectric devices might be used for this horizontal scan.

## 3.4 Drive Electronics

The overall task of driving a display as described is of similar complexity to driving other display technologies (*e.g.* an LCD panel) at the same resolution; a difference of note is the requirement for buffers with enough current drive capacity for the lasers and the scanners. Such a drive circuit must:

- Accept a video signal in analog or digital form (and in the former case, digitize it), converting 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

## 4. Prototype

We have constructed several prototypes along the lines of Figure 1, including an early one based upon then-available infrared VCSEL arrays which had to be viewed against a phosphor screen. More recent designs employ 25-laser 670 nm array prototypes provided by Honeywell's VCSEL Products Division.

Our most recent projector uses two of these arrays, with each laser creating four adjacent pixels, for an image resolution of 200 pixels by 150 lines.

A single plano-convex lens provides collimation of the beams and magnification of the image. In order to reduce cost, size, and power consumption, we have replaced the sawtooth-driven scanning galvanometer and single mirror of our earlier systems with an inexpensive plastic miniature brushless motor of the sort used to power microprocessor cooling fans, continuously rotating a very small mirrored polygon. The most inexpensive of these motors are not intended for synchronous operation but we have developed a drive circuit capable of producing acceptably stable synchronization to the vertical timing of the video. The current consumption of this motor is approximately 20 milliamperes at 5 volts.

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.

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.

## 5. Conclusions

Overall, the design requirements enumerated in the Introduction are within reach, provided that shorter-wavelength VCSEL arrays become available, and that the per-laser cost of an array drops significantly below $1.00 as required. The latter isn't yet the case for infrared arrays, but the prices are declining rapidly.

When green and blue arrays reach the market, an obvious improvement is the creation of a full-color display. A less-obvious improvement available before that takes advantage of the fact that we can control the timing of the modulated light signal from each laser, and thus can perform fast time-of-flight rangefinding. Doing so requires that we add a phototransistor that images the entire screen and circuitry that can compare the phase of the reflected light with that of the emitted signal to compute distance. Applications of rangefinding in this case are not limited to the usual purposes of distance measuring or 3D modeling, but also include detecting the position of occluding objects on the projected image such that the user can interact by pointing with a finger or a pen,[11] and determining relative screen orientation for automatic keystone correction of the projected image.

## 6. Acknowledgements

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