0. Introduction
This is the third paper in a series that describes a futuristic design for a 3D display device. The first paper introduced the subject and looked at invisibility technology. The second paper touched on some technology related to the millions of transmissions lines that thread the transparent cube.

This paper will look at the backplanes. The current design calls for three backplanes, one each for red, green, and blue. Each backplane contains an array of \((121 \times 11 = 1331)\) x 1331 micro-LEDs. The first part of this paper will look at current micro-LED technology.

The design decision has been made to allow the transparent cube to be removed from its cradle, and thus to be completely independent. This gives the cube a beautiful aesthetic quality, as well as an interesting tactile one, but this design also makes things technically complex. The second part of the paper will look at light enhancement of the LEDs, and waveguide coupling from the backplane into the cube.

1. Micro-LED Technology
The leader of the micro-LED revolution is the Japanese printer manufacturer Oki Data Corporation [1]. They’ve developed a thin-film bonding technique called Epitaxial Film Bonding (EPI). For 600 dots per inch (dpi) applications, the LED size is A4, with a light-emitting region 20 x 20 micrometers, and an LED array pitch of 42.3 \( \mu \text{m} \). A scanning electron microscope image of this setup is shown below.

![Micro-LED Technology Setup Image](courtesy [1])
The LEDs are manufactured on one substrate, and this is matched to a CMOS driver that’s manufactured separately. The two are mounted side by side and mated with gold wires as shown above. The micro-LED size is on par with the 76 micrometer array pitch of the display cube backplane. The EPI bonding process works on flexible films, glass, and diamond-like carbon (DLC), this latter acting as an effective heat sink for the LED array. A picture of a 24 x 24 array bonded to flexible film is shown below.

Oki manufactures a 1200 dpi printer that uses even smaller micro-LEDs with a 10 \( \mu \text{m} \times 10 \, \mu \text{m} \) light emitting region, e.g. A3 size. These have also been made using the EPI bonding process.

2. Micro-LED Technical Details
Lee and Tu have written a comprehensive survey of micro-LED technology [2]. Most of the LED light emission is frustrated by total internal reflection, or TIR. The light extraction efficiency from the surface of the active region of the LED is typically 4.6 percent. TIR is mostly due to the difference in refractive index between the LED surface and air, which causes light rays beyond a certain critical angle to be reflected back into the substrate or film medium. This is shown in the diagram below.
There are different ways to circumvent TIR, but in general the idea is to roughen the surface a little to increase the diffraction and to perturb the angles of the escaping light rays. Lithographic techniques can be used to add bumps that increase light emission.

At the nano-scale, or really the sub-micron level, there are some physics that are not very well measured and thus not well understood except by their effects. One such effect is plasmon resonance. A paper by Liu et al [3] describes a hole-array technique, whereby an array of holes etched on a thick aluminum film has the effect of increasing LED electroluminescence (EL) efficiency.

The author admits that some of the enhancement is due to electroluminescent transmission through the perforated aluminum cathode, as opposed to the solid aluminum through which there’s practically no transmission. But the basic enhancement via perforations is further enhanced by “anomalous” transmissions that are related to surface resonance due to the 2D hole array.

This is basically the same effect as described in the second paper of this series, revolving around the work of Ates et al. Here, however, the aperture effect has been moved to the substrate level and thus localized to the immediate area of the LED.

Not all LEDs have the same substrate design. For example, the Oki micro-arrays are based on silicon, not gallium nitride (GaN). Liu’s LED is “organic” and composed of a semiconductor polymer called PPV, combined with a metallo-dielectric photonic crystal (MDPC). Amazingly, this LED was made in a homemade glovebox at the University of Utah!

The image below shows the perforated aluminum film in the inset, and the layer structure at the top. The aluminum is labeled as MDPC-Al. The “A” and “G” lines indicate the emission enhancement at the “air” and “glass” interfaces respectively, due to resonances in so-called surface plasmon polaritons (SPPs).
Most blue micro-LEDs are made of gallium nitride grown on a sapphire substrate. However, red and green micro-LEDs have been manufactured using this technology by changing the layer thicknesses [4]. Thus all the colors for an RGB display are available. It should be possible to control the color luminosity via a CMOS driver interface.

3. Nano-Focusing
Plasmon resonance can be used to enhance luminescence out of the LED active region, but this may not be necessary for the Oki-like or GaN technologies, which may already be bright enough for display applications. Either way, getting that light into the cube is another matter altogether.

By drilling holes resonance provides an increased light emission, but in general the surface roughness also increases the refractive dispersion. A Fresnel lens at nano-scale, positioned directly in front of the LED, can refocus the light as a precursor to waveguide coupling. This technique was simulated by a team in Korea (Jung et al [5]).

A Fresnel lens is a lightweight version of a normal convex lens, with ribs that alternate with air spaces. The ribs follow the contours of the otherwise filled-out convex lens. It turns out that a 2D version of this lens can be etched on a metallic thin film, and placed in front of a planar light wave, with the effect of focusing that lightwave. The simulation is shown below.
The Fresnel lens has been flattened, but it has the same effect. The waveguide is the vertical column. Depending on parameters, the coupling takes place with 45 to 59 percent efficiency. Another researcher verified the focusing effect in actual experiments [6]. The agreement between theory and experiment diverged by no more than 3.5 percent, an extraordinary confirmation of the focusing technology.

4. Waveguide Coupling
So far then, a possibly enhanced LED output shines into a nano-Fresnel lens etched onto thin film, which in turn leads to some kind of coupling to a plastic fiber waveguide as described in the second paper in this series. Again we take a cue from Ates et al (see previous paper), but instead of placing a CSRR (connected split ring resonator) in an aperture, we thread it with the plastic fiber.

As described in [7], the requirements for a coupling are somewhat rigorous. The main concern is a polished even cut on the receiving surface of the waveguide. Chen and Chen [8] polished the ends of their 200 µm fishing line with sandpaper to enhance coupling efficiency. (I wonder if maybe this paper is a university joke?) Hopefully it was fine sandpaper!

Chen and Chen reported waveguide attenuation of less than 0.01/cm. The Fresnel lens would focus the LED light onto the polished plastic fiber end, which would conduct the light through not a metal plate (as in Ates), but a non-absorbing paper panel over plastic, since Chen and Chen report that paper shows a low absorption of terahertz radiation. To avoid light reflections the paper would be matte black. A low absorption sheath would surround the fiber to hold it firmly perpendicular to the backplane.

We take another idea from Chen and Chen, which is to terminate the light fiber on the exterior of the backplane (which makes contact with the display cube backface) with a parabolic concavity. The cube mates to this with a parabolic convexity.
Thus the cube is studded with low-profile “circular light contacts” as proposed in the first paper in this series. This is a risky design since the cube rests in the cradle by gravity, so the pressure will be light between the parabolic surfaces. This means there may be an air gap which will attenuate the light transfer. But Chen and Chen note that with increased terahertz frequency, the coupling efficiency is improved because of improved mode-field overlap.

The amount of fractional power (radiation) that flows outside of the polyethylene core decreases with an increase in transmission frequency. In other words, towards light frequencies the light tends to be captured by the core rather than the surrounding medium (air). The finely polished parabolic contacts should see the same behavior. A diagram of the entire setup is shown below.

5. Conclusion
This paper has explored futuristic technology for the backplane design of a 3D display device. The goal is to be able to fabricate features in monolithic form, at micron or nanoscales. We have shown that micro-LEDs are far enough advanced to be used in production. The coupling technology also seems doable, though more integration to reduce parts counts is needed. We are dealing with relative difficulties. Compared to the difficulty of full invisibility, the difficulty of the backplane coupling is minor.

References
[1] Ogihara et al. 1200 dpi Thin Film LED Array by Silicon Photonics Technology, Electronic Components and Technology Conference, 2008, online
Nanoimprint Lithography, in Recent Advances in Nanofabrication Techniques and Applications, Cui (Ed.), 2011, online
[5] Jung et al. Metal slit array Fresnel lens for wavelength-scale optical coupling to nanophotonic waveguides, Optics Express, v. 17 no. 21, 2009, online