Wire Grid Polarizers: a New High Contrast Polarizer Technology for Liquid Crystal Displays

A White Paper by Agoura Technologies

1.0 Summary

Polarizers, which are essential components of all Liquid Crystal Displays (LCDs), are a key target for innovation. Polarizers which are typically adhesively attached to the front and back surfaces of the LCD panel are essential to the operation of an LCD; they provide basic contrast for the display. However, they are also a major cause of the poor brightness of LCDs; the rear polarizer absorbs approximately 60% of the light produced in the backlight. A new, fundamentally different polarizer technology, wire grid polarizers, is capable of decreasing the amount of light absorbed by the rear polarizer while simultaneously offering opportunities for increasing the contrast of LCDs. This document summarizes the principles of operation and design tradeoffs for wire grid polarizers, and concludes that this technology is capable of very high contrast levels, well in excess of 40,000. This is confirmed by published reports cited in this document of others that have evaluated wire grid polarizer technology.

2.0 LCD Introduction

Liquid Crystal Displays have emerged to become the dominant technology for displaying graphic and video content in a wire variety of applications over a wide range of form factors, from cell phones to very large TVs. Spurred by the unrelenting consumer demands for price reductions and performance improvements, the manufacturers of LCDs have been aggressively pursuing methods and technologies that improve both display performance and reduce costs. Polarizers, which are essential components of all LCDs, are key targets for innovation; currently they absorb ~60% of the backlight illumination and limit panel contrast to 3-5,000. The current dichroic polarizer technology produces polarized light by absorbing or eliminating one plane of polarization emitted from an unpolarized light source (CCFL or LED). This technology dates back to the late 1920's and has very little capacity for either further performance improvements or further cost reductions. An innovative new polarizer technology is needed that addresses both the lower cost and higher performance goals.

As illustrated in Figure 1, there are two major subassemblies of a LCD: the backlight unit (BLU) and the LCD panel. The BLU produces a constant source of white light illumination that is modulated on a pixel by pixel basis by the LCD panel.

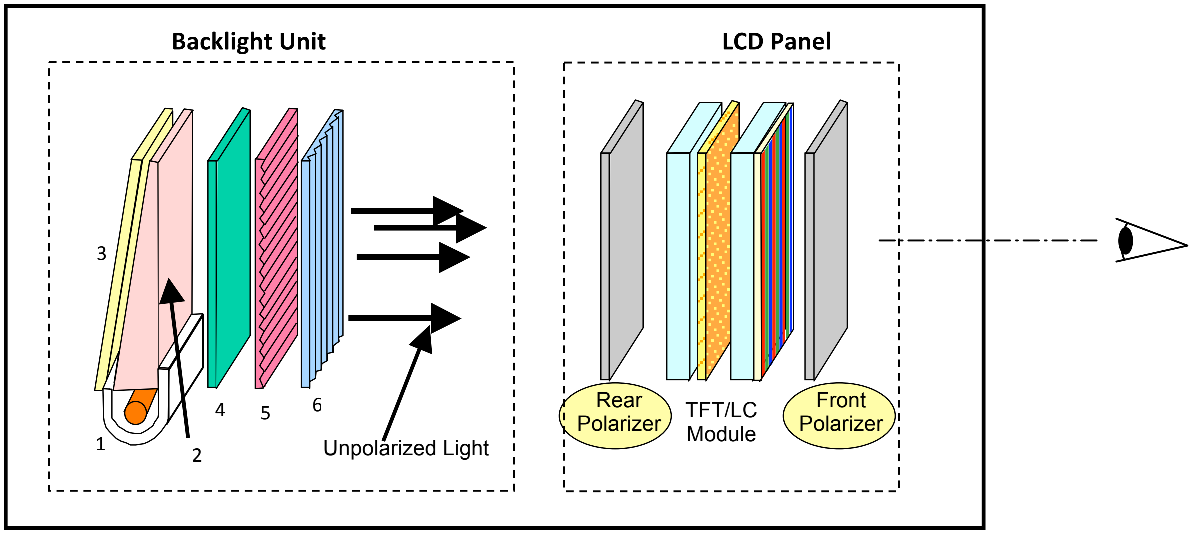

Figure 1. Cross-section of a typical Liquid Crystal Display. To produce an image, an LCD must have polarizers on both the front and back of the TFT/LC Panel.

<u>BLUs</u> typically consists of:

1. Light source (a cold cathode florescent tube is illustrated but LEDs are often used)
2. Light guide to distribute the illumination
3. Reflector to direct light emanating from the back towards the viewer
4. Diffuser film to homogenize the illumination
5. Horizontal prism film to redirect oblique rays into a narrow vertical cone aimed at the viewer
6. Vertical prism film to redirect oblique rays into a narrow horizontal cone aimed at the viewer

<u>LCD Panels</u> typically consists of:

1. Rear polarizer to produce polarized light from the unpolarized illumination from the Backlight Unit
2. TFT/LC Module that rotates the plane of polarization in proportion to the voltage applied to each pixel
3. Front polarizer that absorbs light that has had its plane of polarization rotated by the TFT/LC Panel

Since the liquid crystal material in a LCD is limited to rotating the plane of polarized light, a rear polarizer is essential to produce polarized light and a front polarizer is essential to absorb the rotated plane of polarization. Without these two polarizers, a LCD could not produce an image.

3.0 Current Absorptive Polarizer Technology

At present, LCDs exclusively use absorptive polarizer technology. It is the only polarizer technology that is capable of being made in large area and acceptable cost. With the current polarizer technology, the undesired plane of polarization is absorbed, while the desired plane of polarization it transmitted with minor loss. Absorptive polarizers, also know as dichroic polarizers, were developed in the late 1920's by Edwin Land, the founder of the Polaroid Corporation. A thin film of polyvinyl alcohol (PVA) is stretched to several times its initial length and then dyed with an iodine complex. The iodine complex binds to the linear backbones of the polymer chains that have been aligned parallel to each other by the stretching. To maintain the alignment of these dye molecules, the PVA, while it is still stretched, is sandwiched between two sheets of triacetate cellulose (TAC). The TAC films provide mechanical support to prevent relaxation of the stretched PVA and, hence, the dye molecules. The aligned dye molecules absorb one plane of polarization and transmit the orthogonal plane of polarization.

The most important performance metrics for any polarizer technology, including absorptive polarizers, are (1) Transmittance: the percentage of the incident unpolarized illumination that is converted into polarized light, and (2) Contrast Ratio: the ratio of the intensity of light in the desired plane of polarization to the intensity of the unwanted orthogonal plane of polarization.

4.0 Wire Grid Polarizer Background

A fundamentally different approach to producing polarized light uses a technology known as Wire Grid Polarizers. Wire grid polarizers reflect the unwanted plane of polarization rather than absorbing it.

Wire grid polarizers were first described by the eminent German scientist, Heinrich Hertz in 1888 (Macmillan & Company, Ltd., London, 1893). In the subsequent 120 years, the fabrication technology for wire grid polarizers has advanced from the original winding of thin metal wires on a mandrel to nanometer scale replication and metallization methods, such as those developed by Agoura Technologies.

The detailed physics and design parameters of wire grid polarizers have also undergone a similar evolution. Since Prof. Hertz's pioneering work, wire grid polarizers have been thoroughly analyzed and their physical principles have been detailed in a number of well known textbooks, such as M. Born and E. Wolf, "Principles of Optics", 6th ed., Pergamon, New York, 1980, and D. Goldstein, "Polarized Light", 2nd ed., CRC Press, New York, 2003.

In the following, we will briefly describe wire grid polarizers and then summarize several theoretical analyses that have been published in the technical literature by others. These published results by others in the field are completely consistent with all of the work done at Agoura.

5.0 Description of Wire Grid Polarizers

An illustration identifying the essential attributes of a wire grid polarizer is shown in Figure 2. A wire grid polarizer consists of parallel metal lines fabricated on a transparent substrate, typically glass or a clear plastic. Ideally the periodicity, or pitch, of the grid of parallel lines should be as small as possible, but to be efficient as a polarizer the pitch must be at least ~3x less than the wavelength of the light it is intended to polarize. Thus, for the visible spectrum of 400-800nm, this means the pitch must be less than 150nm. Gratings with a pitch less than the wavelength of light do now show any diffraction behavior. With the absence of diffraction orders, the wire grid polarizer can be treated theoretically as an anisotropic medium.

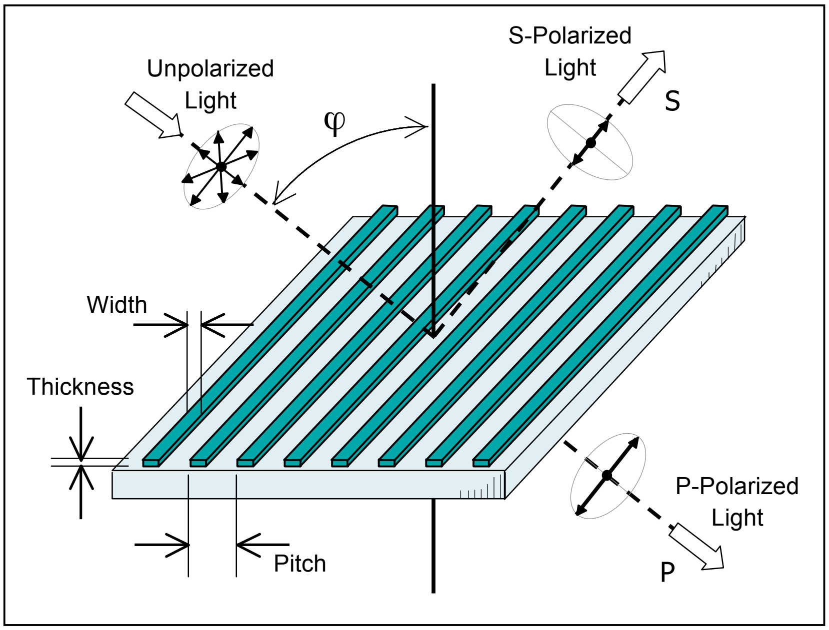

Figure 2. Wire Grid Polarizer. Modern wire grid polarizers are an array of thin parallel metal lines fabricated on a transparent substrate such as glass or a polymer film.

6.0 Theoretical Performance

Yariv and Yeh were the first to describe wire grid polarizers using the effective medium theory in the 1970s ("Electromagnetic propagation in periodic stratified media. I. General theory", J. Opt.

Soc. Am. **67**, pp 423, 1977). In their seminal analysis, they showed that a medium consisting of alternating layers behaves as a uniaxial birefringent medium. In the case of wire grid polarizers, one medium is metal (a near perfect conductor) and the other a dielectric. When unpolarized light is incident upon the wire grid polarizer, light polarized parallel to the metal lines (S polarization or TE mode) will interact with the medium that has a refractive index mostly determined by the metal lines. This S-polarization will "perceive" a continuous metal film and get reflected. Light polarized perpendicular to the metal lines (P polarization or TM mode) will be mostly transmitted, since the "perceived" refractive index will be closer to the dielectric (air, substrate).

Due to the difficulty of solving the electromagnetic equations of wire grid polarizers, several commercial software packages have been developed to assist in their design. Rigorous coupled-wave analysis provided by the commercial simulation software G-Solver (http://www.gsolver.com) has become the industry standard for simulation of wire grid polarizers. The G-Solver software allows the designer to vary all of the key physical parameters to examine their impact on the optical performance. All of the simulations reported in the technical literature and that are described in this document were done with G-Solver.

7.0 Wire Grid Polarizer Performance

7.1 Simulation Results

In LCDs, the transmission is a measure of how much of the incident backlight will reach the viewer, and thus determines the maximum brightness level for a given backlight. The contrast is a measure of how dark the darkest pixel will be for that same backlight. Polarizers are one of the key elements affecting display brightness and the elements that sets the upper limit for display contrast. Hence, contrast ratio and transmission are the two main performance parameters for any polarizer technology,.

In the following paragraphs, we will summarize the contrast and transmission simulation results that have been published in the technical literature by various groups. The dominant factor in determining the contrast of a wire grid polarizer is the pitch of the metal lines. Results from the wire grid polarizer simulations published by Seh-Won Ahn, et. al. of LG Electronics are shown in Figure 3 and illustrate the effect of pitch on contrast ratio: the contrast ratio increases exponentially with decreasing pitch. It is important to note that these simulations, as well as all other known simulations, indicate that contrast ratios of 50,000 can be obtained with 100nm pitch, and that the contrast rises to over 100,000 when the pitch is reduced to 90nm.

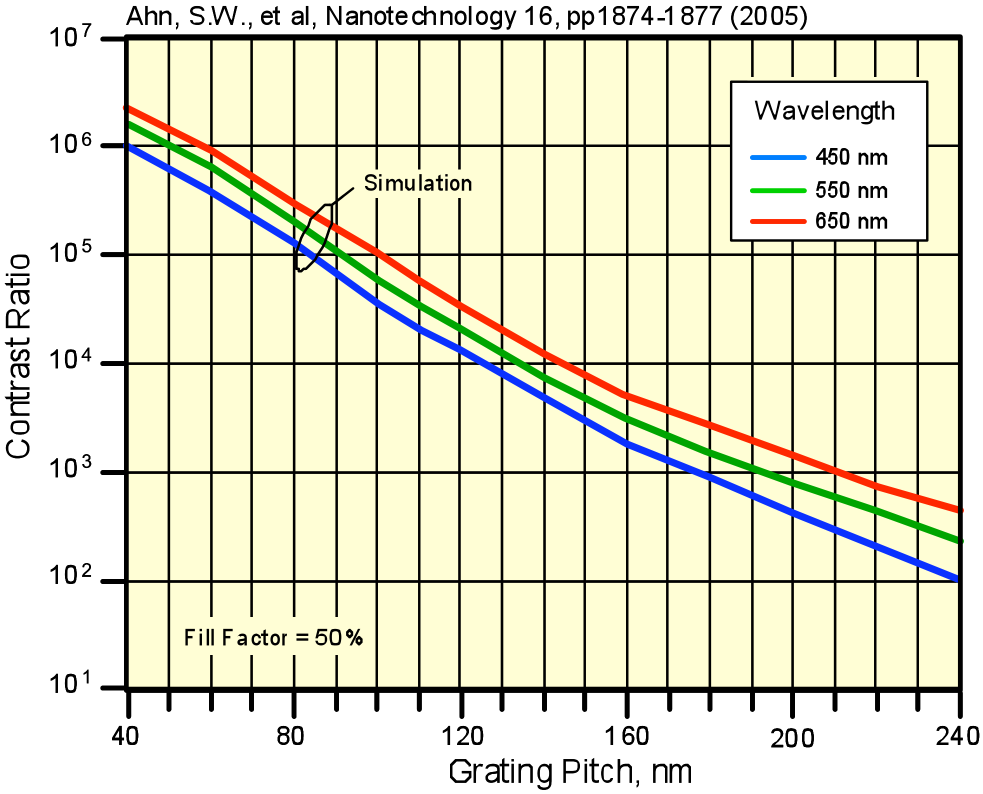

Figure 3. The wire grid polarizer contrast increases steeply as the pitch of the conductive lines is reduced. At 100nm pitch, the wire grid polarizer contrast exceeds 40,000 for green light which is at the center of the visible band.

According to theory, the contrast of a wire grid polarizer depends on the ratio of the wavelength of light to the pitch of the metal lines. Since the wavelength of blue light is nearly a factor of 2 shorter than that of red light, the contrast of a wire grid polarizer at any particular metal line pitch is not as high in the blue as it is in the red; this phenomena is also illustrated in Figure 3.

The detailed spectral characteristics of the improvement of optical contrast ratio with decreasing metal line pitch are shown in Figures 4 & 5. Jian-Jim Wang et al. of NanoOpto compared, via simulation, the contrast ratio (Figure 4) and the optical transmission (Figure 5) of two wire grid polarizer designs, one at 148 nm pitch and one at 118nm pitch. The point to be emphasized with these data is the steepness of the increase in optical contrast ratio when the pitch is reduced by a relatively small amount. In this case, a 20% reduction in the pitch of the metal lines improves the contrast ratio by about 6x.

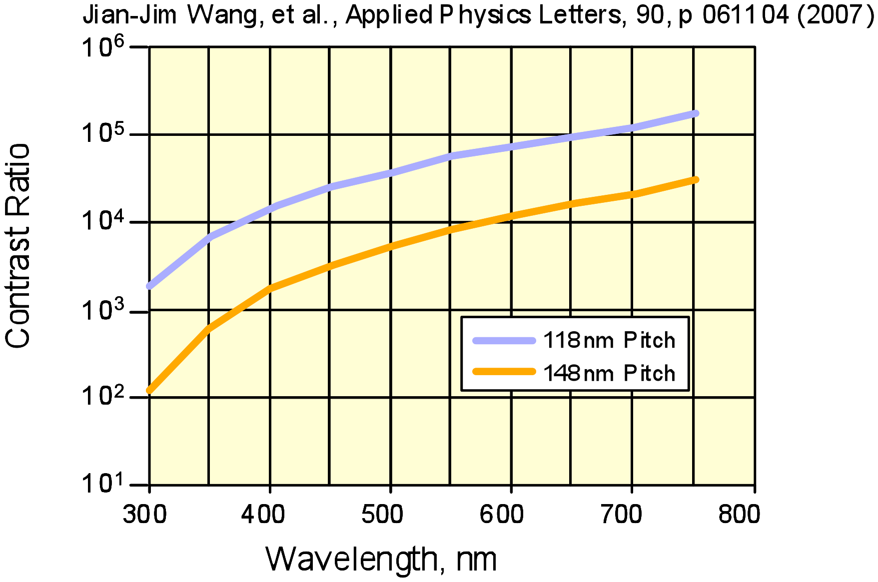

Figure 4. This simulation shows that the optical contrast of a wire grid polarizer improves by ~6x when the pitch of the metal lines is reduced by 20% (from 148nm pitch to 118nm).

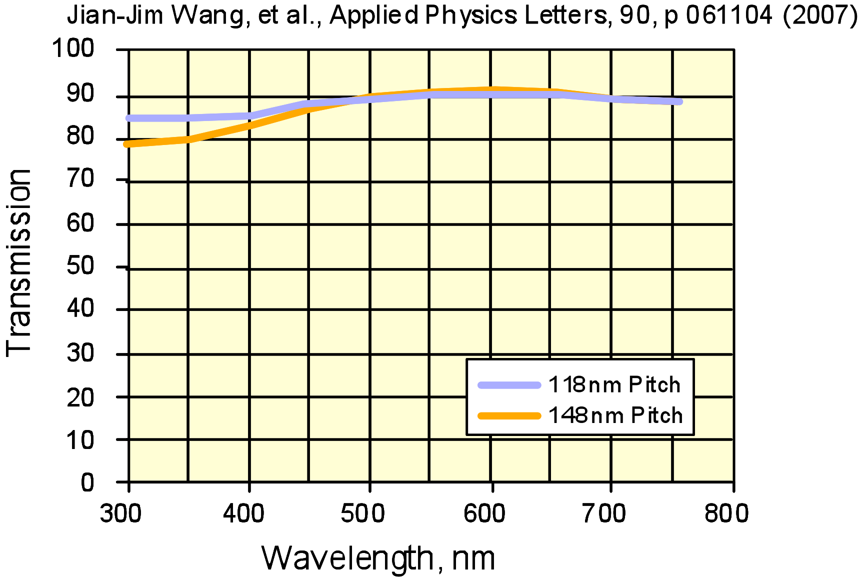

Figure 5. The same simulation as in Figure 4 shows that the optical transmission of a wire grid polarizer is improved somewhat, particularly in the blue, when the pitch of the metal lines is reduced.

In addition to the pitch of the metal lines, the other important design parameter of wire grid polarizers is the width of the metal lines. It is most convenient to describe the width of the metal lines in terms of the pitch, so the ratio of the width of the metal line to the pitch of the metal lines is commonly used, and is referred to as the “fill factor”. The effect of metal line width, or fill factor, on the contrast can be illustrated by another simulation published by Jian-Jim Wang et al. of NanoOpto, as shown in Figure 6. The simulation data shown is for a wire grid polarizer with a pitch of 146nm. At any specific pitch, very narrow metal line widths (low fill factor) have very low contrast. As the fill factor is increased, the contrast rises sharply as more and more metal is available to interact with the incident light. As this simulation demonstrates, at a pitch of 146nm, the optical contrast can vary from a few hundred for a small fill factor to over 3,000 for larger fill factors. Thus, while it was shown earlier that the pitch is the major determining factor of contrast, the fill factor at any particular pitch must be same for accurate comparisons of simulated or measured optical contrast levels.

Jian-Jim Wang, et al, Applied Physics Letters 89, p141105 (2006)

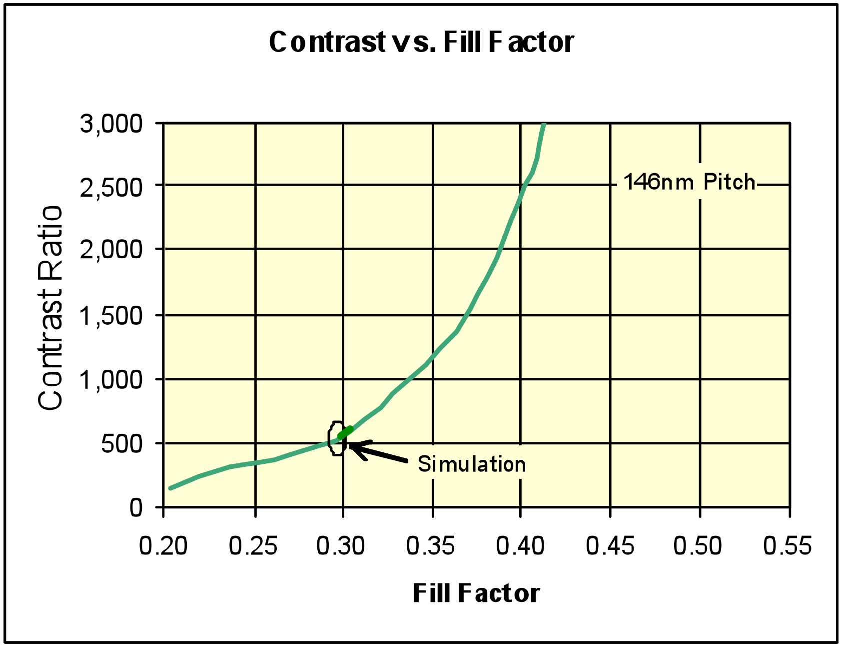

Figure 6. This simulation shows that at any particular metal line pitch, the optical contrast is a strong function of the width of the metal lines, more commonly known as the fill factor. At a pitch of 146nm, the optical contrast can vary from a few hundred for a small fill factor to over 3,000 for larger fill factors.

An undesirable consequence of increasing the fill factor of the metal lines of a wire grid polarizer is a reduction in its transmission. This effect was analyzed and presented in a paper published by Xiang-Dong Mi et al. of Kodak and is shown in Figure 7. While this simulation was for a wire grid polarizer with a pitch of 140nm, it illustrates the effect. At low fill factors, there is little metal to interact with the incident light and the transmission is very high. Recall, however, that the corresponding contrast will be very low, as was seen in Figure 6. As fill factor increases, transmission drops (Figure 7) and contrast rises (figure (6), until the fill factor gets to 100% (i.e., a solid metal film) and the transmission goes to zero as expected. This trade-off between transmission and contrast with changing fill factor must be kept in mind when comparing simulation or experimental results from different sources.

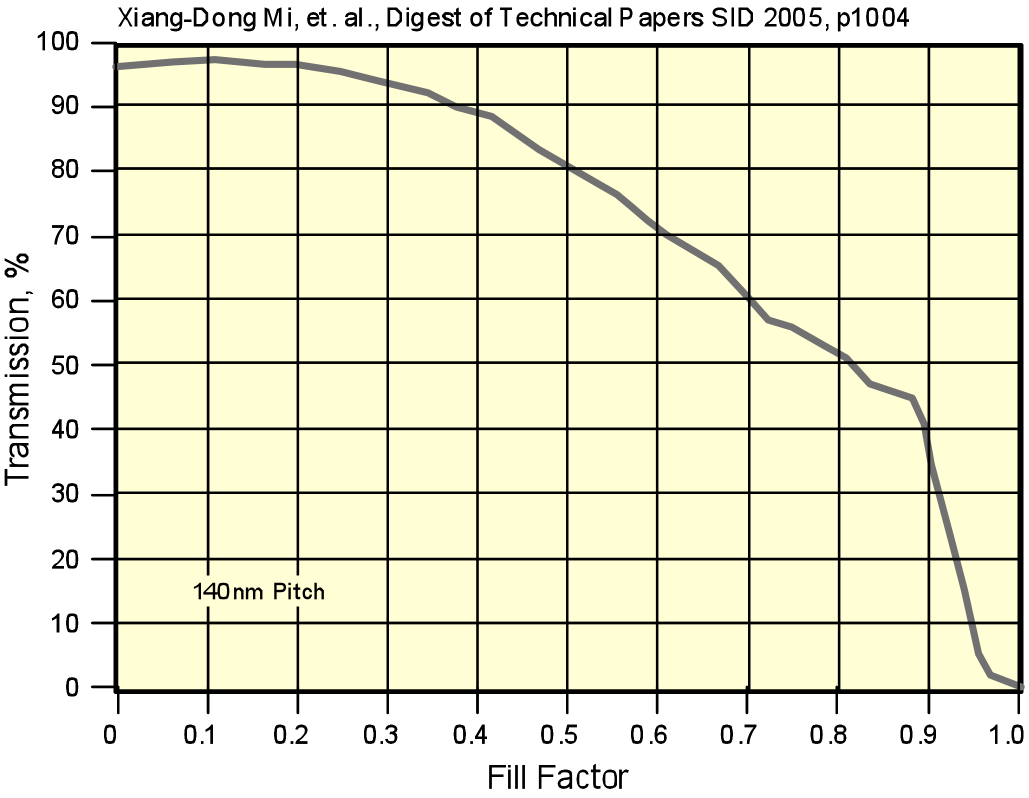

Figure 7. The optical transmission of a wire grid polarizer goes down as the width of the metal lines increases. Thus, while wider metal lines increase contrast ratio, they decrease the optical transmission.

7.2 Experiment

The above summarizes the published simulations that elucidate the important design considerations for a wire grid polarizer. An open question is always, “how well do the simulations correlate with actual device performance”? In the remaining portion of this document, we will focus on this comparison. Wherever there is an overlap in the physical measurements made on Agoura’s PolarBrite^{TM} samples with the published results, we have superimposed the Agoura measurements onto the published results.

As seen above, the key factors in determining the contrast and transmission of wire grid polarizers are the metal line pitch and fill factor. While simulation results have been published for a wide range of pitches and fill factors, there are only a few instances where the reported measurements were made on wire grid polarizers with pitch and fill factors that closely match the simulated geometry. It is these few instances we will summarize below.

In Figure 8, the contrast measurements published in 2005 by Jian-Jim Wang of NanoOpto for a 118nm pitch wire grid polarizer are superimposed on the corresponding Wang simulation from 2007. The simulation predicted a contrast of ~55,000 at a wavelength of 550nm, whereas the measured contrast was ~27,000. In his publication, Wang comments that he believes the ~2x shortfall to be due to the small irregularities and roughness inherent in actual metal lines, as

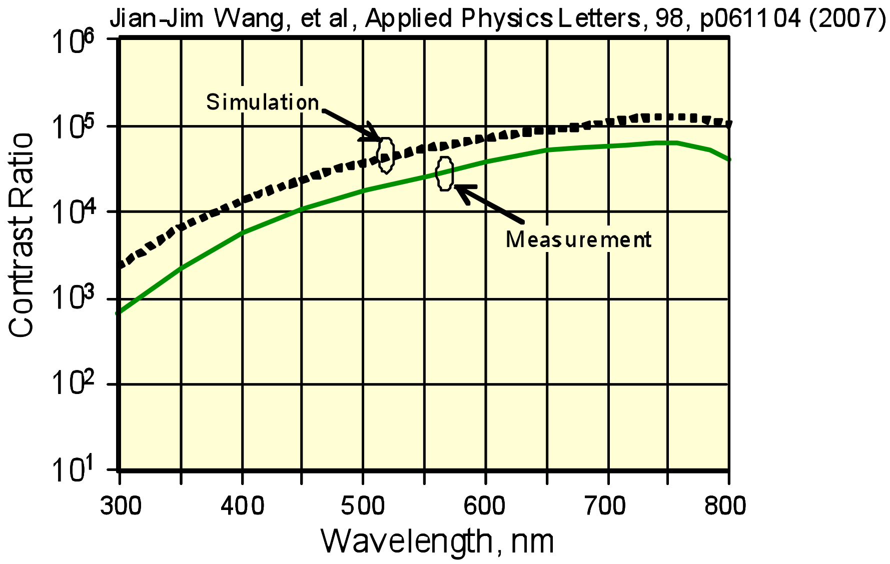
Jian-Jim Wang, et al, Applied Physics Letters, 98, p061104 (2007)

Figure 8. The optical contrast measurement is lower than that predicted by a simulation for 118nm pitch and the same fill factor. This ~2x delta was attributed by the authors to edge roughness of the metal lines.

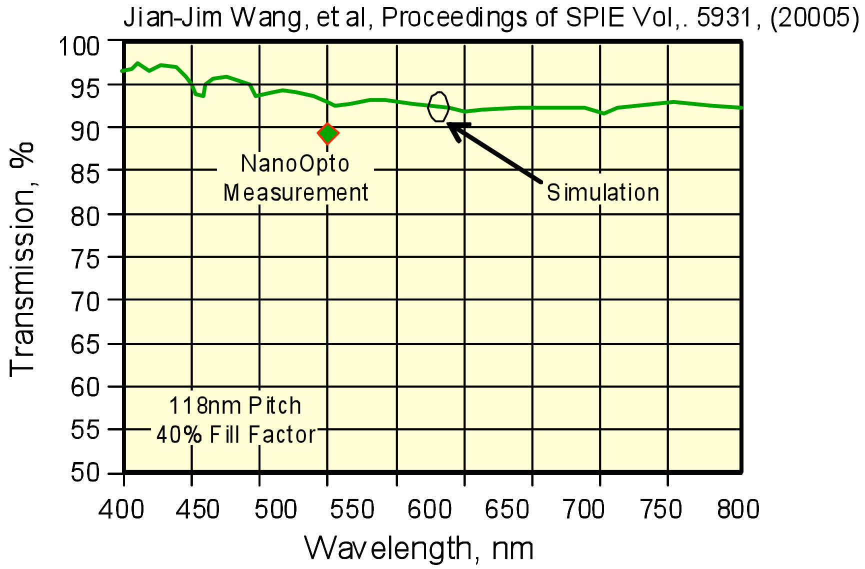
Jian-Jim Wang, et al, Proceedings of SPIE Vol,. 5931, (20005)

Figure 9. The measured optical transmission is in fairly close agreement with the simulated value; 93% transmission was predicted and 89% transmission measured at 550nm wavelength for a pitch of 118nm.

compared to the perfectly smooth metal lines assumed in the simulation.

Figure 9 compares the measured and simulated wire grid polarizer transmission from the same publications. The simulation predicts a transmission of 93% while the measurement produced a value of 89% at 550nm. These two values agree fairly closely; the minor shortfall was again attributed to the small roughness of the metal lines.

In Figure 10, we superimpose the measurements made by Moxtek, currently the world's leading supplier of wire grid polarizers, and by Agoura on the simulations for 550nm wavelength published by Ahn et al, of LG Electronics. Table 1 shows the approximate contrast values extracted for simulation and measurements, along with the ratio between the two. Note that Agoura's structures are rougher and less ideally rectangular than Moxtek's, and that this is reflected as a greater difference compared to simulation. Nevertheless, Agoura's measured performance tracks the trend predicted by simulation. Extrapolation of the experimental curve to 20,000 and 50,000 contrast indicates that 100nm and 85nm, respectively, will be required to achieve those levels. Both required pitch targets are within Agoura's technological reach.

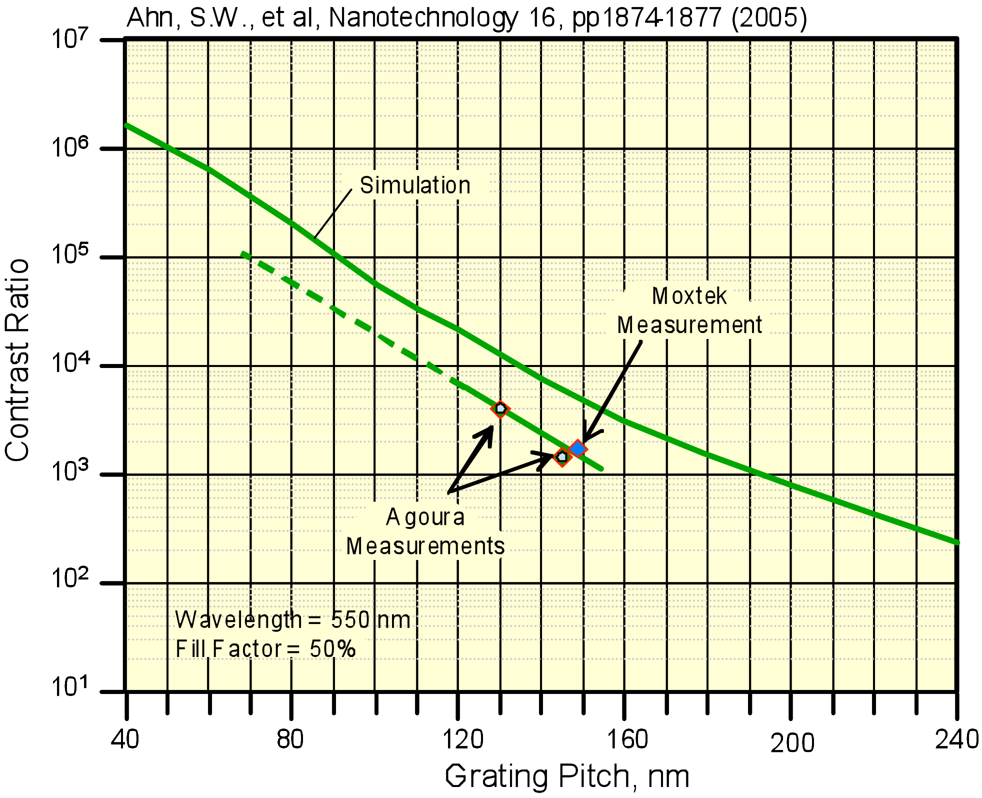

Figure 10. The shortfall in the optical contrast, measured by both Moxtek and Agoura, relative to the simulated performance is a systematic offset due to actual metal lines being rougher than the perfect lines assumed in the simulation. Nevertheless, the trend of exponential rise in contrast with decreasing pitch holds for Agoura's PolarBrite polarizers.

Data Source	Pitch (nm)	Simulation Contrast	Experimental Contrast	Simulation / Experimental
Moxtek	148	4800	1600	3.0
Agoura	145	5400	1300	4.2
Agoura	130	12000	4000	3.0

Table 1. Experimental and simulated values for contrast at several pitches. Experimental data tracks simulation with ~3x offset showing that exponential rise in contrast with decreasing pitch holds for Agoura's PolarBrite polarizers.

8.0 Conclusions

Wire grid polarizers are projected to be capable of extremely high contrast levels. Simulation predicts that an optical contrast ~100,000 can be achieved with metal line pitches of 90nm and a contrast of ~60,000 is expected of wire grid polarizers with a 100nm pitch. However, measurements performed by several groups indicate that the common software tool G-Solver that is used to project the performance of wire grid polarizers consistently over-estimates the optical contrast levels by ~2x. Agoura's data suggests that a factor of 3x may be a more conservative estimate. Taking this factor into account, it appears that a pitch of 85nm will realize the targeted optical contrast level of 50,000, and a pitch of 100nm will realize 20,000. The lower of these contrast levels will meet the vast majority of LCD requirements, and the higher will meet even the most demanding requirements forecast for LCDs.

For more information:

Agoura Technologies, Inc.
www.agouratech.com
info@agouratech.com