INK-JET PRINTING OF COLOR OPTICAL FILTERS FOR LCD APPLICATIONS

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Abstract

At the age of multi-media, portable electronic devices such as mobile phones, personal digital assistant and handheld gaming systems have increased the demand for high performance displays with low cost production. Inkjet printing color optical filters (COF) for LCD applications seem to be an interesting alternative to decrease the production costs. The advantage of inkjet printing technology is to be fast, accurate, easy to run and cheaper than other technologies. In this master thesis work, we used various disciplines such as optical microscopy, rheology, inkjet printing, profilometry and colorimetry. The specific aim of the thesis was to investigate the feasibility of using company-A pigment formulation in inkjet production of COF for active matrix LCD applications. Ideal viscosity parameters were determined from 10 to 20mPa·s for easy inkjet printing at room temperature. The red pigments used are fully dispersed into the solvent and present an excellent homogenous repartition after printing. Thickness investigations revealed that the printed COF were equal or slightly thicker than typically manufactured ones. The colorimetry investigations demonstrated color coordinates very close to the NTSC red standard. LED backlighting seems to be a valuable solution to combine with the printed COF regarding to the spectrum and color analysis. The results on this thesis will increase the understanding of inkjet printing company-A pigments to produce COF for LCD applications.
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1. Introduction

Today, the liquid crystal display technology is said to be a major technique for flat panel display systems. The growth of such systems has been supported by strong demand for portable flat color displays. The applications are various from the cheap simplest calculator to the most advanced vertically aligned (VA) and in-plane switching (IPS), high definition 55” LCD-TVs or LED backlight 22” graphic monitor. Small outline dimension, thin, lightweight, high resolution and low power consumption has been strongly demanded.

Color filter (CF) is one of the most important elements for colored liquid crystal displays because it directly defines the color image quality of the display. Color filters are also used in scanning devices to convert colored graphics or text into digital information. In digital cameras and camcorders, they are directly applied on the sensor to generate full colored pictures. However, the most visible and attractive application of color filters is in displays.

At the age of multi-media, portable electronic devices such as mobile phones, personal digital assistant and handheld gaming systems have increased the demand for high performance displays with low cost production. Inkjet printing color optical filters (COF) for LCD applications seems to be an interesting alternative to decrease these production costs. The main advantage of Inkjet printing technology is to be fast, accurate and cheap.

Since LCDs are considered as high-integrated systems and require knowledge in various scientific domains, we dedicated the first following chapters of our theoretical study on liquid crystal displays, color optical filters, inkjet technology and color.

2. Aim

The specific focus of this work is to investigate the feasibility of using company-A pigments and pigment formulations in inkjet production of color optical filters (COF) for active matrix LCD applications. To realize inkjet printed COFs and study their properties, we used several disciplines like optical microscopy, rheology, inkjet printing, profilometry and colorimetry. It is now expected that new research such as printing into back matrix will increase the possibility to use company-A pigments to produce COF for LCD applications.
3. Liquid Crystal Displays

3.1 What are liquid crystals?

3.1.1 Liquid crystal phases

We all learned during our childhood the fact that most of substances exist in different state of matter. Solids, liquids and gases are the most common. Water is definitely the most familiar example, which is a solid below 0°C, a liquid between 0°C and 100°C and a gas above 100°C. However, most of people forget that temperature is not the only factor in the states of matter changes. In fact, pressure is also an interesting one.

The three common states of matter are different from each other because the molecules in each state possess different amounts of order. In the crystalline state, all the molecules are more or less occupying a fix place in a certain positional order and keep this position. These molecules are also known to possess orientational order in a way that they orient themselves with the respect to another one. Because of this special arrangement of the molecules, it takes quite large external forces to change the structure. It is a reason why solids are hard and difficult to deform [1].

The liquid state is quite different because when a solid melts to a liquid, both orientational and positional orders are completely lost. Then the molecules neither occupy a specific average position nor remain oriented in a particular way.

However, it exists an intermediate phase between the solid and the liquid phases. This phase is called the liquid crystal phase (figure 3.1) and is characterized by the fact that some materials do not exhibit any positional order but they possess a certain degree of orientation order.

![Figure 3.1: Schematic illustration of the solid, liquid crystal, and liquid phases. Each shape represents a molecule.](image-url)
Since the year 1888 where the Austrian botanist F. Reinitzer discovered “a substance with two melting points” and later the German scientist Otto Lehman who was the first to use the term liquid crystals; it is at present, about 100,000 of different organic substances that have been observed in liquid crystalline phases. However, these substances have proved to form only a few different types of liquid crystalline order (or different phases).

The simplest liquid crystal phase is the nematic phase characterized by its orientational order (figure 3.2). The average of the molecules is given as a unit vector \( \hat{n} \), called the director. However, each of the molecules is free to move in a liquid while keeping oriented in a certain direction.

It exists both orientational order and some degree of positional order in some layered liquid crystal phases. These phases are known as smectic phases.

![Nematic, Smectic A, Smectic C](image)

*Figure 3.2: Nematic, smectic A and smectic C layered liquid crystal phases.*

### 3.1.2 Properties of liquid crystals

Liquid crystals are interesting phases of matter, probably in reason of the many properties that are involved in them. These properties are mainly: dielectric constants, elastic constants, viscosity and birefringence.

We saw that nematic liquid crystals are characterized by an orientational order. This implies a uniaxial symmetry, which will lead to different dielectric constants parallel and perpendicular to the director. The dielectric anisotropy is a result of these constants. In display applications of liquid crystals, an electric field is used to control the molecules orientation. The dielectric anisotropy is important, in fact that it will determine if the molecules will align perpendicular or parallel to the electric field.

One of the most important properties of liquid crystals concerns the elasticity of the molecules. Basically, elastic constants \( K \) depends on molecular structure and the nematic order parameter (\( S \)).

It’s possible to define 3 different elastic constants:
- \( K_1 \), which is a SPLAY deformation
- \( K_2 \), which is a TWIST deformation
- \( K_3 \), which is a BEND deformation

It is generally admitted that \( K_2 < K_1 < K_3 \). [2]
In all fluids, there are frictional forces between the molecules and, therefore, they display a certain flow resistance, which can be measured as viscosity. Viscosity is also an important property as a consequence that it has a direct impact on the switching times of a liquid crystal display (LCD).

The birefringence is the decomposition of a ray of lights into two rays when it passes through certain types of material, depending on the polarization of the light. This effect can occur if the structure of the material is anisotropic. Liquid crystals, because of the uniaxial symmetry present a birefringence with two refractive indices. The refractive index of a material is the factor by which the phase velocity of electromagnetic radiation is slowed in that material, relative to its velocity in vacuum.

### 3.2 Properties of LCD

#### 3.2.1 Types of LCD

The liquid crystal display technology, by its dominating position on the current market, provides plenty of different flat panel displays.

Today, simple twisted nematic (TN) LCDs are mainly used in low cost applications and are generally direct driven or low passive multiplexing devices. Less expensive to produce than every other LCD technology, they generally present a director $\hat{n}$, which undergoes a uniform 90° twist.

Super twisted nematic (STN) LCDs are still used in such devices like scientific calculators, inexpensive mobile phones and informational screens of some digital products. They use passive matrix addressing where each pixel in a display needs to be controlled electrically to allow switching between the on- and off-state. A pixel is formed by the overlap of a row and a column electrode. STN present a director $\hat{n}$, which undergoes a 180° to 270° twist. As opposed to TN-LCD, STN displays provide higher passive multiplexing ratio but worse optical properties than TN. STN-LCDs also suffer from response time, gray-scale ability, severe color dispersion, and its optical angular properties are worse compared to ordinary TN-LCDs.

Regarding to the actual market and especially desktop monitors, TFT-LCDs became the most popular type of flat panels. They present the property to be active matrix LCDs, which are usually ordinary 90° TN-LCD with a matrix of circuits to provide the electrical addressing of each pixels. In order to address each pixel individually, TFT incorporate a transistor and a capacitor. TFT TN-LCDs permitted to increase contrast ration, response time, viewing angles and color properties. However, TFT TN-LCDs still suffered from narrow optical angular properties compared to the old cathode ray tube (CRT) technology.

In order to solve the critical viewing angle problem related to large panel LCDs, various external and internal methods have been proposed. An external method is to use thin birefringent film into the LCD. In the other hand, internal method modifies the LCD structure internally. For less than ten years, two major internal technologies have been released.
These are in-plane switching (IPS) and vertical aligned (VA) that represent the state of the art for high definition wide (>42”) LCD-TVs and professional applications.

### 3.2.2 Light modes

LCDs are typically non-emissive devices. This means an impossibility to generate any light. However, it transmits or absorbs part of the light that passes trough it. It exists two different operating modes and a combination that can be used with LCDs. These modes, always combined with external light source are: transmissive, reflective and transflective (figure 3.3).

A transmissive LCD is illuminated from the back by a backlight and viewed from the opposite side. This type of LCD is used in applications requiring high luminance levels such as desktop monitors and televisions. The illumination device used to illuminate the LCD in such a product is usually cold cathode fluorescent lamp (CCFL). Such backlight consumes much more power than the LCD itself. However, light-emitting diodes (LED) might soon replace CCFLs as far as they consume much less power.

Reflective LCDs are often found in digital watches, calculators and some information displays. They are illuminated by external light reflected by a diffusing reflector placed behind the display. Daylight readability is one of the best solutions to significantly reduce power consumption.

Tansflective LCDs works either as transmissive or reflective LCDs by using a special optical film that both transmits and reflects light. This solution tends to be the major technology for high portable devices such as personal digital assistant (PDA), mobile phones and soon available on camcorders and digital cameras.

![Figure 3.3: Transmissive, reflective and transflective operating mode.](image)
3.2.3 Contrast and Brightness

Contrast and brightness are two of the most important characteristics used to describe electro-optical devices such as LCDs. Basically; contrast is the ratio between the luminance of the bright areas on the dark areas. Contrast is a sensitive notion since there is no specific definition in order to compare different devices. Most of displays companies do not use the same test configuration. It appears now necessary for future tests to measure and compute in a definite procedure in order to make further comparisons.

Contrast ratio will then be expressed as the following equation: [4]

\[
C_R = \frac{L_{\text{bright}}}{L_{\text{dark}}} \tag{3.2}
\]

Contrast in luminance will also be expressed as:

\[
C = \frac{L_{\text{bright}} - L_{\text{dark}}}{L_{\text{dark}}} \tag{3.3}
\]

Brightness is usually considered as the luminance of the bright state.

3.2.4 Polarization

In electrodynamics, polarization is a property of waves, such as light and other electromagnetic radiation. So far, polarization is a very important concept in understanding the optical behavior of liquid crystals.

Like in figure 3.4, light can be represented as a transverse electromagnetic wave made up of mutually perpendicular, fluctuating electric and magnetic fields with respect to the direction of propagation [1, 5].

![Figure 3.4: Light passing through crossed polarizers. [6]](image)

When the electric field vectors are restricted to a single plane then the light is said to be polarized with respect to the direction of propagation and all waves vibrate in the same plane.
3.3 Structure, principle and operation

3.3.1 Structure

Today, a TFT-LCD consists of a complex multilayer structure (figure 3.5). However, the LCD panel structure remained almost the same for many years. It consists of two substrate plates that are glued together along the edge and filled with the liquid crystal material. One of the two-substrate plates receives the TFT layer, which is almost transparent to visible light while the other substrate, generally receives the color filter layer.

Figure 3.5: Structure of a TFT-LCD. [7]
3.3.2 Principle and operation

As represented on figure 3.6, the liquid crystal molecules present a relaxed state in the white (TFT Off) mode. In a 90° TN cell the liquid crystal molecules on the top substrate are aligned perpendicular to those on the lower substrate. In TFT Off mode, the director \( \hat{n} \) of the liquid crystal molecules undergoes a 90° helical structure or twisted structure. The polarization state of light passing through one polarizer is rotated as it passes through the liquid crystal, allowing it to pass through the second polarizer.

When an electrical charge is applied to the electrodes (TFT On), the liquid crystal’s molecules align themselves parallel to the electric field and thus limiting the rotation of incoming polarized light. Light will be then polarized perpendicular to the second polarizer (also called analyzer) and then ideally be totally absorbed.

Thus, by controlling the orientation of the liquid crystal molecules, light can be allowed to pass through each pixel in varying amounts and then allow LCDs to display any information such as pictures.

Figure 3.6: Operating system of a TFT-LCD. [8]
4. Color optical filters for LCD application

4.1 Structure
An LCD panel has two glass substrates, which are aligned to each other. One is color filter (CF) substrate and other is driving substrate. A pixel, coming from “picture element” is the smallest unit to indicate a picture image. Each pixel is formed by three sub-pixels respectively red, green, and blue. The number of effective pixels gives the resolution of the TFT-LCD. Color filter’s pixel has R, G, B color elements and the black matrix is located between the colors to avoid leakage of light and photoelectrical conversion in TFT.
The filter surfaces must be as smooth as possible for maximum color purity and minimum dispersion. The fundamental structure of LCD color filters is magnified in Fig. 4.1. A color filter consists of clear substrate, black matrix, color filter layer (RGB colors), overcoat layer and ITO film. The black matrix material is deposited on clear substrate in the optically inactive areas to prevent light leakage and provide a light shield for the amorphous silicon transistors. After the color layer is formed, protection overcoat layer is deposited. Indium tin oxide (ITO) is finally deposited at low temperature. The color filter layer, which contains red, green and blue colors, is fabricated from either dyes or pigments. It exists several technology of manufacturing color filters. These technologies are the dyeing, pigment dispersed, electro-deposition and printing methods.

Figure 4.1: Fundamental structures of LCD color filters. [9]
## 4.2 Requirements

In table 4.2, is presented an attributes comparison of actual display technologies such as cathode ray tube (CRT), plasma, STN-LCD and TFT TN-LCD.

Table 4.2. Overall technology attributes of CRTs and common flat panels. [9]

<table>
<thead>
<tr>
<th>Display Attributes</th>
<th>CRT</th>
<th>PLASMA DC/AC</th>
<th>STN-LCD</th>
<th>TFT TN-LCD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DISPLAY VISUAL PARAMETERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixel density</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Screen Resolution</td>
<td>High</td>
<td>Med/High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Raster Distortion</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Flicker Propensity</td>
<td>Yes</td>
<td>Yes/No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Luminance</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Dimming Range</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Contrast</td>
<td>Medium</td>
<td>Med/High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Gray Shades (intrinsic)</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Viewing Angle</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Med/High</td>
</tr>
<tr>
<td>Number of Colors</td>
<td>High</td>
<td>Med/High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Screen Update Time</td>
<td>Fast</td>
<td>Fast</td>
<td>Slow</td>
<td>Fast</td>
</tr>
<tr>
<td><strong>DISPLAY SYSTEM PARAMETERS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>Wide</td>
<td>Med/Wide</td>
<td>Narrow</td>
<td>Narrow</td>
</tr>
<tr>
<td>Vibration Endurance</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Volume</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Weight</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
4.2.1 High contrast, low reflection

Contrast is defined as the ratio of transmittance of the bright state to that of the dark state. High contrast characteristic is necessary for high color purity and good legibility. Reflectance of TFT-LCD module is mainly determined by black matrix material on CF. Chromium, chrome oxide or black resins have been widely used for STN-LCD and TFT-LCD because of light shielding ability and low reflection. High resistance, high optical density, high light shielding, high resolution, low disturbing reflectance and low cost black matrix are preferred for LCD applications.

4.2.2 High color purity, high transmittance

In order to have both high quality color picture and portability features in notebook PCs and monitors, the TFT-LCD panel is required to have high color purity and high transmittance. The selection of the pigments should be based on sharp spectrum eliminating unnecessary wavelengths. By using such pigments, both the color purity and transmittance of color filters can be improved so that light does not attenuate as it passes through the filter. A color filter must also possess a high degree of color purity with good reproducibility for the colors that are produced by combinations of red (R), green (G), and blue (B). The rule of thumb is a color purity that approximates the primary color chromaticity coordinates for the color TV system defined by the National Television System Committee (NTSC). The colors produced by a color filter are matched to the emission spectra of the fluorescent backlight (figure 4.2). A critical requirement is the absence of an overlapping of light transmittance spectra between filters of different colors. The figure below shows the emission spectra and the spectral properties of color filter elements and backlight.

![Figure 4.2. Color filter spectral properties](image-url)
4.2.3 **High stability against heat, light and chemicals**

High thermal stability requirement relates to the color LCD fabrication process. As a consequence, CF should be resistant to heat so that there are no color-tone changes and no separation of color material when the orientation film on the color filter is baked (e.g., at 180°C for one hour) or when a low-resistance ITO film is formed. The CF must exhibit high heat resistance without thermal flow and chromatic changes during the alignment layer formation step. The chromatic changes should be minimal after heating at 250°C for 1 h. The light stability of the pixels is important because these pixels are illuminated with back light of LCDs. Color filters should not undergo discoloration or fading due to the effects of backlight or when exposed to outdoor lighting conditions. Organic color materials are especially susceptible to discoloration. When used as a projection unit, a color LCD is subjected to a high luminous flux (on the order of a million lux at the color filter). This requires color filters that have superior thermal stability and resistance to bleaching. The CFs are exposed to a mercury-xenon lamp with ultraviolet (UV) filter for more than two million lux hours. The chromatic changes after exposure should be minimal. The chemical stability is a key factor since CFs are exposed to solvents, acids and bases during the LCD fabrication process. The cured film must be resistant towards alignment layer solvents such as NMP and y-butyrolactone, acids during etching of the ITO, and bases used in the development system. Although a protective film is deposited in most cases, a CF should not deteriorate due to the effects of solvents or cleaning liquids in the ITO electrode formation process or in the orientation film-coating process. In addition, there should not be any leaking of impurities from the CF to the liquid crystal.

4.2.4 **Flatness and dimensional precision**

A color filter should not contain any foreign objects or surface bumps. This is a critical requirement because in STN the cell gap can significantly affect display quality. For attachment to a TFT array substrate, a CF should have accurate physical dimensions. To meet stringent alignment precision requirements and larger aperture requirements, a CF should be free of any pitch misalignment.

4.2.5 **High degree of assembly reliability**

Color filters should possess a high degree of bonding to sealant. Even when the liquid crystal cell is used under high temperature or high thermal impact conditions, the CF should not change in physical appearance or disturb the liquid crystal cell performances.
4.2.6 Comparison of Color Filter Types

In table 4.3, we presented characteristics comparison of the different technology used to produce color filters.

Table 4.3. Characteristics of color filters. [9]

<table>
<thead>
<tr>
<th>Property</th>
<th>Dyeing</th>
<th>Printing</th>
<th>Pigment Diffusion</th>
<th>Electro Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colored-layer resin</td>
<td>Casein, gelatin, polyimide</td>
<td>Epoxy</td>
<td>Acryl</td>
<td>Epoxy, acryl</td>
</tr>
<tr>
<td>Color material</td>
<td>Dye</td>
<td>Pigment</td>
<td>Pigment</td>
<td>Pigment</td>
</tr>
<tr>
<td>Color filter thickness (µm)</td>
<td>1 ~ 2.5</td>
<td>1 ~ 3.5</td>
<td>0.8 ~ 2</td>
<td>1.5 ~ 2.5</td>
</tr>
<tr>
<td>Spectral property</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Resolution (µm)</td>
<td>10 ~ 20</td>
<td>50 ~ 70</td>
<td>10 ~ 20</td>
<td>10 ~ 20</td>
</tr>
<tr>
<td>Surface flatness</td>
<td>Fair</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Thermal stability</td>
<td>180°Cx1hr</td>
<td>250°Cx1hr</td>
<td>260°Cx1hr</td>
<td>250°Cx1hr</td>
</tr>
<tr>
<td>Resistance to bleaching</td>
<td>Poor</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Resistance to chemicals</td>
<td>Poor</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
</tr>
</tbody>
</table>

Although the dyeing method excels in spectral properties, the pigment diffusion and electro-deposition methods produce superior thermal stability and resistance to bleaching. The dyeing and pigment diffusion methods are preferred from a density standpoint. The electro-deposition method is favored in terms of surface flatness. The printing method is the most economical method. Cost and properties remain the principal criteria by which these methods are judged.
4.3 Manufacturing process

The dyeing method has been used for fabrication of CF for imagers. The most commonly used water soluble polymeric materials for dyed CF are natural products such as gelatin, caesin and synthetic products such as polyvinyl alcohol (PVA), polyvinyl pyrrolidone. Figure 4.3 illustrates the dyeing method.

A dyeable photopolymer such as gelatin is coated on glass substrate, exposed through a photomask, developed by water to form transparent pattern, which is dyed with an acid or a reactive dye. The dyed pattern is treated with a hardening agent for protecting each color migration, one color is thus formed. This entire process is repeated three times for Red, Green and Blue colors. In an etching method, polyimide is used so the binder and dyes are dispersed in it.

*Figure 4.3: Typical manufacturing process of the dyeing method. [10]*

CF fabricated by this method are characterized by high transmittance and good color purity, high color contrast and shows excellent dimensional accuracy and film thickness accuracy. The process generates CF with fine resolution, good chromaticity and excellent dyeing properties. However, such process is more expensive, use more steps, more chemicals and has to be repeated three times compare to the single pass of an inkjet printing process.
4.4 **Black matrix**

As opposed to the color filters, the black matrix’s role is to stop the light. It increases the contrast ratio by reducing the photo leakage of a non-display area. That specification makes black matrix, one of the key technology integrated on TFT-LCD systems.

By increasing the aperture ratio of the display, it is possible to obtain higher transmittance and then reduce the power level of the backlight. Then, it decreases the total power consumption of the display (figure 4.4).

![Diagram of conventional black matrix and BCB using TFT array]

*Figure 4.4: Reduce the black matrix by using benzocyclobutene (BCB). [11]*

Developed by LG-Philips, BCB is an organic insulation material, which provides more prominent higher aperture ratio.


5. Color

5.1 Light

Until Isaac Newton was the first who realized that white light is composed of the whole spectrum (figure 5.1), only a few were known about the physical nature of light.

Visible light is an electromagnetic radiation with a wavelength range that is detectable by the human eye (visible light). However, the electromagnetic spectrum extends from very low frequency radio waves, through microwaves, infrared, visible and ultraviolet light to x-rays and gamma rays. In a technical or scientific context, electromagnetic radiations of wavelengths are studied in the field of optics.

The three basic dimensions of light are:

- Intensity (or amplitude)
- Frequency (or wavelength)
- Polarization (or angle of vibration)

Figure 5.1: The visible spectrum.

Our eyes respond to the visible light. If we want to detect the rest of the electromagnetic spectrum, special instruments ranging from radio receivers to scintillation counters are required. The visible spectrum is considered to have the wavelengths between 380 and 770 nm. It means if electromagnetic radiation of such wavelength hits our eye, we will see it. The perceived color depends on the wavelength of the radiation (figure 5.2).
5.2 Color Generation

During our childhood, we all have experimented mixing colors with paint or colored pencils using a basic color wheel for understanding (figure 5.3). In fact, most of our color display systems result from an additive mixture. To achieve this addition and thus recreate the visible spectrum, we need 3 primary colors: red, green and blue.
However, it exists another system called subtractive mixture using yellow, magenta and cyan. This system is used by the photographic industry in color films, papers and some digital cameras (concerning the sensor color filters).

5.3 Colorimetry

Colorimetry is the science of measuring colors. However, each of us can perceive colors differently. For example, most of human people have 3 photo-receivers whereas recent studies showed some women with 4 photo-receivers. Independently of these recent researches, more than 70 years ago, the CIE has defined a standard observer by performing color-measuring experiments. [12]

A number of color matching experiments have been performed under these standardized conditions. Color matching experiments consists of choosing three particular light sources that emit light on the white screen, where three projections overlap and form an additive mixture. On the other side of the screen a target color is projected, and an observer tries to match the target light by altering the intensities of the three light sources.

After many experiments using light sources of the wavelengths red= 700nm, green= 546.1 nm and blue= 435.8 nm, color matching curves as shown in figure 5.4 were proposed by CIE.

Figure 5.4: The $\bar{x}$, $\bar{y}$ and $\bar{z}$ standard observer trichromatic functions
In 1931, the CIE researchers purposed the first chromaticity diagram following the equations:

\[
X = k \int_{380}^{780} \bar{x}(\lambda).T(\lambda).S(\lambda).d\lambda \\
Y = k \int_{380}^{780} \bar{y}(\lambda).T(\lambda).S(\lambda).d\lambda \\
Z = k \int_{380}^{780} \bar{z}(\lambda).T(\lambda).S(\lambda).d\lambda
\]  

(5.3)

Where:

- \( S(\lambda) \): spectral distribution of the light
- \( T(\lambda) \): spectral transmittance (or reflectance) of the sample
- \( \bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda) \): standard observer trichromatic functions.
- \( k \): Calibration coefficient

The weights, X, Y and Z define a color in the CIE XYZ space. The CIE XYZ is a 3D linear color space, and it is quite impossible to work in it directly. It is common to project this space to the X+Y+Z=1 plane. The result is a 2D space known as the CIE xy 1931 chromaticity diagram (figure-5.5). The coordinates in this space are usually called x and y and they are derived from XYZ using the following equations:

\[
x = \frac{X}{X + Y + Z} \\
y = \frac{Y}{X + Y + Z}
\]  

(5.4) (5.5)
Chromaticity diagrams can give us a lot of useful information on a particular color but it also takes count of the human eye chromatic adaptation. The inside area of the diagram represents the whole spectrum. The straight line connecting the lowest wavelength (400nm) to the highest (780nm) represents the “magenta line” and do not represent any spectral colors. The white points are represented by the inside curved line, depending on the light source used.

In theory, by pointing two colors, all possible mixture of colors are given by connecting these two points and so on for three points which represent a triangle.

Gamut or color gamut is a certain complete subset of colors, which can be accurately represented in a given circumstance, such as within a given color space or by a certain output device. We can now understand that the color gamut of any display device using three primaries (like an LCD monitor) is only a part of all visible colors.

Due to non-uniformity problems on the CIE 1931 Diagram (mainly known as Mc Adams rings), the CIE developed several other diagram by mathematical conversions.
In 1976, CIE proposed two alternatives as improvements compared with CIE xy 1931 chromaticity diagram. These are CIE LUV and CIE LAB. These diagrams can almost be considered as perceptually uniform color spaces. However, the major difference between these two color spaces consists of their spatial representation. The CIE u’v’ 1976 (figure 5.6), based on the CIE xy 1931 predecessor, is a 2D space resulting of the 3D CIE LUV linear color space. In the other and, the CIE LAB 1976 is a full 3D color space.

The CIE u’v’ 1976 chromaticity diagram is given by the following equations:

\[
u' = \frac{4X}{X + 15Y + 3Z}
\]  

(5.6)

\[
u' = \frac{9Y}{X + 15X + 3Z}
\]  

(5.7)

![Figure 5.6: CIE LUV 1976 Chromaticity Diagram](image-url)
6. **Ink-jet technology**

6.1 **History of inkjet technologies**

Inkjet technology could be more than 128 years old. So far that by 1878, Lord Rayleigh described the mechanism by which a liquid stream breaks up into droplets [13]. However, in Sweden by 1948, Siemens Elema patented the first practical inkjet device based on Rayleigh’s researches. R.G. Sweet demonstrated the first continuous inkjet system in the early 1960’s. In fact, Sweet deflected droplets by using an electric field and was able to fly them directly onto the media to form an image.

The major drawback of continuous printing was its incredible waste of ink. It was then necessary to develop a device, which will eject ink droplets only when they are needed. Then, by the late 1970s, the first Drop-on-Demand (DOD) inkjet methods appeared [14]. During the late 70s and upcoming 80s, many DOD systems were invented. However, most of them ejected ink drops by a pressure wave created by mechanical motions of piezoelectric ceramic actuators. Today, this system allows a drop volume close to 1 pl and is still the major technology used by major manufacturers such as Epson.

In 1979, Canon released his Bubble-Jet technology. This method allows drops to be ejected from the nozzle by the growth and collapse of a water vapor bubble on the top surface of a small heater located near the nozzle. Independently at the same time, Hewlett Packard developed its ThinkJet (thermal inkjet).

Because of their low cost, small size, quietness, and color capability, thermal inkjet and bubble-jet have become the major printing technologies for home and office use.
6.2 Continuous inkjet

Continuous inkjet was the first operating system, which allowed very high-rate drop generation. However, this technology is expensive to manufacture and to operate mainly because of the waste of ink. Today, continuous inkjet is still used in high-speed industrial printers but was totally replaced by DOD inkjet systems for small office and home office (SOHO) applications.

Figure 6.2 shows the typical continuous jet printing process. A pump makes ink under pressure that will be delivered from an ink tank to the printhead. A piezoelectric driver plate mounted on the printhead react to an electric field and produces a mechanical resonance frequency. By then, ink stream breaks into many individual drops. The charging plates apply electrical charges to the drops that will be deflected by passing between the deflection plates and finally fly to the media. At the same time, non-used drops are deflected to a recirculation ink system in order to lower the waste of ink.

Figure 6.2: Functional principle of a continuous inkjet system
6.3 Drop on demand inkjet

Drop on demand systems permit by electronic driving, to generate drops only when needed. However, two different DOD methods are actually dominating the current market. These methods are thermal inkjet (used by e.g. Hewlett Packard and Canon) and piezoelectric inkjet (used by e.g. Xaar, Epson and others). [14]

6.3.1 Thermal inkjet

Today, most consumer inkjet printers’ work by using electrically heated chambers mount in cartridge. Thermal inkjet (ThinkJet by Hewlett Packard) and BubbleJet (Canon) in order to produce an image, run a pulse of current through the heating elements. A steam explosion in the chamber forms a bubble, which propels a droplet of ink out of the nozzle and then onto the media. The ink’s surface tension pumps another charge of ink by capillary into the chamber through the ink channel attached to a reservoir (figure 6.4).

Thermal inkjet is the dominating technology for office and consumer markets. It presents a low product cost and large development and investment. However, due to its thermal technology, thermal inkjet is incompatible with a large panel of inks and then is mainly restricted to low duty cycles.

Figure 6.3: Roof-shooter and side-shooter thermal ink-jet system. [16]

Figure 6.4: Drop formation process of a thermal ink-jet system. [16]
6.3.2 Piezoelectric inkjet

Piezoelectric inkjet is a system used by a lot of commercial and industrial inkjet printers. Piezo materials exhibit the piezoelectric effect; they undergo distortion when an electric field is applied. Most common material is PZT ceramic. PZT is poled by applying a poling field, analogous to magnetizing a magnet [17]. Piezoelectric gives more freedom for ink development and allows a wider variety of inks than thermal or continuous inkjet. It permits more controlled drop production than thermal, higher drop production rates. Piezo inkjet has a long head life, which is important for high duty cycles such as industrial printing. However, this technology presents higher cost for printhead than thermal and a lower nozzle density.

Depending on the piezoelectric ceramics’ deformation mode, the technology can be classified into four main types: bend, squeeze, push, and shear mode (Figure 6.5).

![Figure 6.5: Various deformation modes of piezoelectric actuator for inkjet printing technology. [15]](image-url)
7. Optical microscopy

In order to investigate actual color optical filter (COF) properties, we first proceed to a microscopic investigation of several portable devices. These are notebooks, PDAs, PSP, mobile phones and digital cameras. Therefore, we focused on different properties such as:

- COFs’ width, height and surface.
- Black matrix’ width and height
- Displays’ size and resolution
- Year of production

All results are presented in a table of comparison page 35.

7.1 Notebooks

We began our investigations on two recent notebooks from Sony and Apple.

7.1.1 Sony - Vaio VGN-FS215E

![Microscopic picture of a SONY - Vaio VGN-FS215E display]

The SONY - Vaio VGN-FS215E display is very interesting for optical microscopy since it does not have any effective anti-glare / anti-reflection film. As a consequence, the display’s structure is easily observable. In figure 7.1, we can clearly notice the red, green, blue filters, black matrix, capacitors and some spacers. Furthermore, we measured the size of the display’s color filters, which are conceivably 72 µm width by 240 µm height (0.173mm²).
7.1.2 Apple - PowerBook G4 15”

As showed on figure 7.2, the APPLE - PowerBook G4 15” presents a strong un-sharp effect mainly due to a particularly effective anti-glare / anti-reflection film. This anti-glare / anti-reflection film allows Apple- PowerBook G4 15” users to run their notebook in various lightening conditions without major light disturbances. However, we were still able to measure color filters’ size. According to our measurements, PowerBook G4 15” COFs’ are 57 µm width and 212 µm height (0.121 mm$^2$).

7.2 PDAs

7.2.1 Mio - Digi Walker Mio 168

According to our measurements and by observing figure 7.3, MIO Digi Walker Mio 168 COFs’ are 58 µm width and 148 µm height (0.086 mm$^2$).
7.2.2 Sony – PSP

According to our measurements, SONY- PSP COFs’ are 56 µm width and 70 µm height (0.039 mm²).

7.3 Mobile phones

7.3.1 Sony-Ericsson – T630

According to our measurements, SONY-ERICSSON – T630 COFs’ are 55 µm width and 145 µm height (0.079 mm²).
7.3.2 T-Mobile MDA

![Microscopic picture of a MDA display](image)

*Figure 7.6: Microscopic picture of a MDA - display*

According to our measurements, COFs’ are 42 µm width and 82 µm height (0.034 mm²).

7.4 Digital Camera

7.4.1 Konica-Minolta – Dimage X60

![Microscopic picture of a KONICA MINOLTA Dimage X60 display](image)

*Figure 7.7: Microscopic picture of a KONICA MINOLTA Dimage X60 display*

According to our measurements, KONICA-MINOLTA Dimage X60 COFs’ are 85 µm width and 120 µm height (0.102 mm²).
7.4.2 SONY – Cyber-shot DSC-P200

Figure 7.8: Microscopic picture of a SONY – Cybershot DSC-P200 display

According to our measurements, COFs’ are 64 \( \mu \text{m} \) width and 88 \( \mu \text{m} \) height (0.056 mm\(^2\)).

7.5 Interpretation

As we can notice on the different pictures and on table 7.6 below, it seems that there is no standard concerning the shape of COFs and even with the same dates of release. When looking at the 2 digital cameras, even 3months older and 0.5” smaller, the SONY-Cybershot DSC-P200 display present one of the most advanced COFs’ layer (including the back matrix).
### 7.6 Table of comparison

#### Table 7.6: Comparison of the inspected devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Year of prod°</th>
<th>Size</th>
<th>Resolution</th>
<th>Width</th>
<th>Height</th>
<th>Surface</th>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Notebook</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APPLE PowerBook G4</td>
<td>2005/07</td>
<td>15”</td>
<td>1280 x 854</td>
<td>57µm</td>
<td>212µm</td>
<td>0.121mm²</td>
<td>20µm</td>
<td>40µm</td>
</tr>
<tr>
<td>SONY Vaio VGN-FS215E</td>
<td>2005/07</td>
<td>15.4”</td>
<td>1280 x 800</td>
<td>72µm</td>
<td>240µm</td>
<td>0.173mm²</td>
<td>15µm</td>
<td>17µm</td>
</tr>
<tr>
<td><strong>PDA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIO Digi Walker Mio 168</td>
<td>2005/02</td>
<td>3.5”</td>
<td>240 x 320</td>
<td>58µm</td>
<td>148µm</td>
<td>0.086mm²</td>
<td>15µm</td>
<td>77µm</td>
</tr>
<tr>
<td>SONY PSP</td>
<td>2005/05</td>
<td>4.3”</td>
<td>480 x 272</td>
<td>56µm</td>
<td>70µm</td>
<td>0.039mm²</td>
<td>10µm</td>
<td>40µm</td>
</tr>
<tr>
<td><strong>Mobile phone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SONY-ERICSSON T630</td>
<td>2004/03</td>
<td>1.8”</td>
<td>128 x 160</td>
<td>55µm</td>
<td>145µm</td>
<td>0.079mm²</td>
<td>19µm</td>
<td>75µm</td>
</tr>
<tr>
<td>T-Mobile MDA</td>
<td>2004/11</td>
<td>2.8”</td>
<td>320 x 240</td>
<td>42µm</td>
<td>82µm</td>
<td>0.034mm²</td>
<td>18µm</td>
<td>98µm</td>
</tr>
<tr>
<td><strong>Digital camera</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KONICA-MINOLTA Dimage X60</td>
<td>2005/05</td>
<td>2.5”</td>
<td>115.000 pixels</td>
<td>85µm</td>
<td>120µm</td>
<td>0.102mm²</td>
<td>16µm</td>
<td>35µm</td>
</tr>
<tr>
<td>SONY Cybershot DSC-P200</td>
<td>2005/02</td>
<td>2.0”</td>
<td>134.000 pixels</td>
<td>64µm</td>
<td>88µm</td>
<td>0.056mm²</td>
<td>8µm</td>
<td>30µm</td>
</tr>
</tbody>
</table>
8. Viscosity

Controlling droplet formation and in particular, the break up and corresponding tail or ligament formation is dependent on the rheology of ink as it flows through the nozzle. One important part of inkjet printing technology is the ink and its physical properties such as viscosity, viscoelasticity and surface tension [19].

Viscosity is a measure of resistance of a fluid to deform under shear stress. Viscosity describes a fluid’s internal resistance to flow and may be thought of as a measure of fluid friction [18].

For ideal viscous fluids at a constant temperature, the value of the ratio of the shear stress \( \tau \) to the corresponding shear rate \( \dot{\gamma} \) is a material constant. \( \tau \) is the shear stress and is given by:

\[
\tau = \frac{F}{A}
\]  

(9.1)

\( F \) [N] is the (shear) force and \( A \) [m\(^2\)] the (shear) area.

The unit of the shear stress is [Pa] (“Pascal”)

\( \dot{\gamma} \) is the shear rate and is given by:

\[
\dot{\gamma} = \frac{v}{h}
\]

(9.2)

\( v \) [m/s] is the velocity and \( h \) [m] is the gap between the plates of the measuring device.

The unit of shear rate is [1/s] (or [s\(^{-1}\]), called “reciprocal second”)

The definition of the shear viscosity is given by the following equation: [22]

\[
\eta = \frac{\tau}{\dot{\gamma}}
\]

(9.3)

The unit of the shear viscosity is [Pa·s] (“Pascal-seconds”)

8.1 Standard procedure

8.1.1 Requirements

In order to investigate if Company-A pigments and pigment formulations are feasible to use in LCDs, we focused part of our research on ink viscosity. The specific aim of this part was to collect enough viscosity information on our ink to afterwards inkjet it by using Xaar printhead.
8.1.2 Components

- Ink: Red ink, Company A
  - Pigment: R (red)
  - Solvent: Cyclohexanone/n-butylacetate 2:3
- Pigment concentration: 1.5%, 2.25%, 3%, 3.75%, 4.5%, 7%, 9%, 11%, 13%, 14% and 15%.
- Viscosity increaser: Vinyl VYHD

8.1.3 Preparation

In order to simplify our manipulations, Company-A provided us a 1kg pot of 15% diluted pigment-A. Then we prepared 10 different pigment concentrations so that we could have an overall aspect of our pigment’s viscosity.

8.1.4 Rheometer settings

All tests were proceeded with Anton Paar PHYSICA MCR 301 Rheometer. We followed the same standard procedure as below for all of our measurements.

- Temperature: 20°C
- Sample density: $1\text{g/cm}^3$
- Compliance Rheometer: 0.59$\mu$m/N
- Shear rate: 20 to 300 s$^{-1}$.

8.2 Measurements

![Figure 8.2: Viscosity of the red ink A for 20 different shear rates as a function of 11 different pigment concentration.](image)

In figure 8.2, we can notice the exponential aspect of our viscosity measurements.
Figure 8.3: Viscosity of the red ink A for 11 different pigment concentration as a function of shear rate.

In figure 8.3, the decrease of viscosity is mainly due to the shear rate effect. This satisfy Newton’s criterion, which explained that Newton fluids decrease in viscosity while increasing in shear rate. The phenomenon observed in figure 8.3 is also called a shear-thinning flow behavior. For samples that display shear-thinning behavior, the shear viscosity is dependent on the degree of shear load. The flow curve shows a decreasing curve slope, $\eta$ decreases with increasing $\dot{\gamma}$.

Figure 8.4: Viscosity of the red ink A for 20 different shear rates as a function of 8 different pigment concentrations.
In figure 8.4 and 8.5, we have limited the pigment concentration scale so that is easier to notice our measurements in the range of our requirements (10-20mPa·s).

Furthermore, it is admitted that modern inkjet printing implies that ink experienced very high shear rate, close to thousands of s⁻¹. Under such circumstances and regarding to figure 8.5, we would have only used a pigment concentration from 8.8% to 10.8%, in order to proceed to our inkjet printing tests. In the other hand, we decided to test more concentrations, even the lowest one. As a consequence, we used vinyl as a viscosity increaser to reach our requirements.

On figure 8.6, we can notice the small effect of shear rate on lower pigment concentration. This rejoins what we observed on figure 8.3.
9. Ink-jet printing

9.1 Test procedure

9.1.1 System

Our hardware printing system consists of:

- MELLES GRIOT high quality optical table.
- Windows 2000/NT workstation to control the system.
- Printing table with vacuum holes to maintain the samples.
- MITSUBISHI ELECTRIC MR-J2S-□ CL servo controller system
- Xaar XJ126/200 printhead

Our software printing system consists of:

- Xaar PH Commander (printhead commander)
- PCI Plus (image loader)
- Servo Controller system

Figure 9.1: Photograph of our printing system inside Swedish LCD Center’s cleanroom.
9.1.2 Xaar printhead

The printhead we used from Xaar, belongs to the shear mode piezoelectric technology. The structure and principle of operation of this printhead are described in the two following pictures.

Figure 9.2: Schematic of Xaar printhead structure. [20]

Figure 9.3: Printhead datum locations.

Figure 9.4: Principle of operation of Xaar type actuator showing wall displacement and drop generation due to applied electric field. [21]
The specification table 9.1 details the performance of the printhead we used for our investigations. Xaar has tested this printhead under standard operational conditions. However, these specifications can vary according to printhead integration and system set-up.

**Table 9.1 Xaar printhead product specifications**

<table>
<thead>
<tr>
<th>Description</th>
<th>XJ126/200 printhead</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active nozzles</td>
<td>126</td>
<td>-</td>
</tr>
<tr>
<td>Nozzle pitch</td>
<td>0.137</td>
<td>mm</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>50</td>
<td>µm</td>
</tr>
<tr>
<td>Typical drop volume</td>
<td>80</td>
<td>Pl</td>
</tr>
<tr>
<td>Typical drop velocity</td>
<td>6.0</td>
<td>m/s</td>
</tr>
<tr>
<td>Max drop deviation</td>
<td>1.0</td>
<td>Degrees</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>15 to 35</td>
<td>°C</td>
</tr>
<tr>
<td>Ambient humidity (non condensing)</td>
<td>10 to 90 RH</td>
<td>%</td>
</tr>
<tr>
<td>Max frequency</td>
<td>5.2</td>
<td>kHz</td>
</tr>
<tr>
<td>Max linear speed (single pass)</td>
<td>660</td>
<td>mm/s</td>
</tr>
<tr>
<td>Pixel resolution, swathe x traverse</td>
<td>200 x 200</td>
<td>dpi</td>
</tr>
<tr>
<td>Print width at given resolution</td>
<td>15.9</td>
<td>mm</td>
</tr>
<tr>
<td>Weight (dry)</td>
<td>35</td>
<td>g</td>
</tr>
<tr>
<td>Dimensions (WxHxL)</td>
<td>43x11.8x45</td>
<td>mm</td>
</tr>
<tr>
<td>Recommended printing distance</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum printhead acceleration</td>
<td>9.81</td>
<td>m/s</td>
</tr>
</tbody>
</table>
9.1.3 Printing procedure

As shown on figure 8.6, we used vinyl in order to get a 14.5 mPa·s viscosity for lower 1.5%, 2.25%, 3%, 3.75%, 4.5% and 7% pigment concentration samples. We did not use any vinyl to print 9% pigment concentration.

Preparation:
Clean the printhead by following the procedure in appendix 16.1.

Load the printer head with ink by connecting it to the polypropylene conical tube containing the wanted fluid to print with and flush it using a 60 ml syringe to the tube. “Peck” carefully on the colored side of the printer head, “holes” to the top, this to eliminate air bobbles inside the head. Flush again with syringe and repeat until no bobbles appear when flushing.

Mount the printhead into the system, colored side facing the inside and the “PCB-copper” side facing the substrate table. Set the printing distance between the media or substrate surface. In our tests, we used a 1 mm printing gap. A maintained constant print distance ensures optimal print quality. Connect the transmission cable to the printer head with the flexible cable pointing to the colored side of head.

Turn on hardware:
Computer, electronic locker of the servo controller and Xaar PCI Plus.

Software:
- Xaar PH Commander, to connect to printer head.
- PCI Plus, to choose picture bitmap file to be printed and load it to system.
- Mitsubishi Servo Controller System, to program the stepmotors.
  - Xaar PH Commander:
    Here you can change the Efficiency Factor for the printer head, found in the datasheet.
  - PCI Plus:
    Here you open the picture to be printed and rotate it with Angle 126 Image, to be used with 200/300 dpi (71.56° alt. 36.87°).
  - Servo controller system:
    Here you have the programs for each step motor. Station 00 and Port 1 in System menu for movement in Y-direction (table), and Station 01 and Port 2 for movement in X-direction (printer head).

Printing:
By respecting the viscosity parameters, the printing is quite easy. The system just needs to be flushed if not used continuously in order to prevent internal curing.

Curing:
After printing, all of our filters have been cured on a hotplate at 60°C for 20 minutes so that all solvent has been evaporated.
9.1.4 Continuous printing

Most of our printing tests were achieved by using the following continuous pattern (figure 10.4). Continuous printing was the easiest way to investigate the different properties of inkjet printed COFs such as thickness and optical properties (figure 9.5).

Figure 9.4: Continuous bitmap 126/252 pixels pattern

Figure 9.5: Scan of one of our 9% pigment concentration inkjet printed COF on the ITO side of a 24/30 mm glass plate.
We used photo-microscopy in order to notice if Company-A pigments were fully dispersed into the solvent. As you can observe on figure 9.6, all pigments are homogeneously spread on the glass substrate. In addition, all our microscopic pictures from different pigment concentration present the same encouraging results.

### 9.1.5 Individual printing

Individual printing into a black matrix is the final step to produce inkjet printed COF. For this reason, we prepared a square pattern (figure 9.7) so that it will be possible to valid our results by manufacturing an LCD prototype with back matrix pattern.
10 Thickness

10.1 Test procedure

10.1.1 Requirements
The thickness of COFs partly determines the transmission characteristics of a display. Unfortunately, it was impossible for us to measure the COF’s thickness of the different devices tested during our optical microscopy investigations. In the other hand, we have found some typical values from the literature and interviewed people of $1\mu$m to $3.5\mu$m thicknesses for printed COFs. However, because optical properties mostly determine if the inkjet printed COFs can be used in LCD applications, it is not necessary valuable to achieve thicknesses close to the values we found from literature. It is then possible for us to print thicker COF if they fulfill our optical properties requirements.

10.1.2 Components
Our components are the 8 different, 1.5%, 2.25%, 3%, 3.75%, 4.5%, 7%, 9% and $x2#9\%$ inkjet printed COFs.

In order to determine the filter thickness and thickness uniformity of the filters, 4 analysis locations (m1, m2, m3 and m4) were defined (figure 10.1). On the 8 different filters, the printed ink was removed around 1mm width and ‘mm long at the defined locations, by means of a needle. The thickness was then determined by profilometrying (Veeco DEKTAK Profilometer) at two different positions for each analysis location.

10.1.3 Profilometer settings
- Scan length: 1500 $\mu$m
- Scan speed: Medium (9 seconds)
- Data resolution: Medium / High
- Data points: 750
- Scan resolution: 2.000 $\mu$m/s
- M range: 655 KA
- Stylus force: 2 mg
10.2 Measurements

In figure 10.2, we can observe one of our thickness measurements over an analysis location of a 9% pigment concentration inkjet printed COF.
Figure 10.3: Thickness of inkjet printed red COF at the different locations defined in Figure 10.1, as function of concentration of Company A pigment. Measurements were made with Veeco DEKTAK Profilometer. (Note: graph has been linearized.)

The results, shown in Fig. 10.3, indicate a quasi-linear increase of the thickness as a function of the pigment concentration, with fluctuations of around 5%. However, small fluctuations should not be noticed because of the size of our inkjet printed COF compared to a real COF integrated to a black matrix.

An interesting phenomenon can be noticed while observing the quasi-linear aspect of our curves. Our Company-A red pigments are floating in a Cyclohexanone/n-butylacetate 2:3 solvent. Furthermore, our cured inkjet printed COF should only be constituted of Company-A red pigment, which means that all the solvent should disappeared during the curing step. By extending linearly the curves, 0% of pigment concentration would give filters with a thickness from 0.5 to 0.8µm. This phenomenon might be due to the viscosity increaser (vinyl) added to the first 5 low pigment concentration, which still remain in the COF even after curing. However, the vinyl showed no impact on the color properties.

The observed thickness range is between 1.2µm (1.5%) and 4µm (9%). These observations are close to the actual thickness for COFs that we found in the literature. It is also observed a slight reduction of the thickness closer to the filter edge (m1 and m4), compared to the filter central region (m2, m3). This implies strong surface tension interactions on such a wide surface (1.04cm x 2.07cm, 21.53mm²) compare to actual COF used in electronic devices (Table 7.6: from 0.056 to 0.173 mm²).
After printing up to 9% of company-A pigments concentration, we decided to try a multi-layer printing system. The procedure consisted of printing one layer then another in the shortest time possible between the prints. We noticed an interval around 18 seconds in our case.

As observed on figure 10.4, the increasing in thickness between a 9% COF and x2#9% COF is between 55% and 65%, which corresponds to a COFs’ thickness from 6.27µm to 6.8µm. Such thickness is slightly higher than typically but of course still valuable to allow the manufacturing of a LCD prototype with black matrix.
11 Optical properties

11.1 Test procedure

11.1.1 Requirements

Color LCDs have red, green and blue COFs. Consequently, video signals are universally based on RGB color components. However, there is no universal, objective definition of what colors constitute “red”, “green” and “blue”. For RGB data that indicates saturated red – 100% red, 0% green, 0% blue (like in our project) – is the red intended to be pink, scarlet, reddish-purple, or reddish-orange? In practice, the color reproduced depends upon the interpretations given to each of the primaries by a particular device. In a LCD, the colors produced by the COFs’ used in the manufacture of LCD determine the colors of red, green and blue. But LCDs are also transmissive or reflective devices, which implies that an external light source is needed and then will interfere with the COFs to generate the colors. Backlight, COF and even polarizer are parameters that are different for each LCDs, and color reproduction is not predictable without control of these parameters.

Now, we will investigate the optical properties of our inkjet printed COFs and particularly the transmission and colorimetric properties. We will compare our results to the NTSC system, which is one of the most used standard in the display industry.

11.1.2 Components

Our components are the 8 different, 1.5%, 2.25%, 3%, 3.75%, 4.5%, 7%, 9% and x2# 9% inkjet printed COFs.

In order to determine our COFs’ spectral properties between 380 and 780nm, we used the Perkin-Elmer Lambda 900 Spectrometer with an integrating sphere. Each spectrum was measured in the central region of every COFs.

The transmittance results were then computed by using the different CIE equations in Microsoft “Excel” and in the scientific graphing and analysis “Origin” software.

11.1.3 Spectrophotometer settings

- Scan range: 380nm to 780nm
- Data interval: 1nm
- Integration time UV/Vis: 0.36sec
11.2 Measurements

![Transmittance values of the 7 different inkjet printed red COF using company-A pigments. Measurements were made with Perkin-Elmer Lambda 900 Spectrometer.](image)

In figure 11.1 we can observe the different transmittance spectrums of our inkjet printed red COFs. The first visible and interesting consequence in increasing the pigment concentration is the decrease of the UV/Blue transmission part from 380nm to 480nm but we will discuss more about it in the next two figures. The second consequence is the little loose of general transmittance while increasing the pigment concentration, which is also related to thickness. We can notice that these results are very close to typical transmittance spectrum of other COF technologies.
Figure 11.2: Transmission spectrum of a 4.5% pigment concentration inkjet printed COF compared to the $\bar{x}$, $\bar{y}$, and $\bar{z}$ color-matching functions

Figure 11.3: Transmission spectrum of a 9% double layer pigment concentration inkjet printed COF compared to the $\bar{x}$, $\bar{y}$, and $\bar{z}$ color-matching functions
In figure 11.2 and 11.3, we can compare the transmittance spectrum of our 4.5% and x2#9% inkjet printed COF to the $\bar{x}$, $\bar{y}$, and $\bar{z}$ color-matching functions. As you can notice, the x2#9% inkjet printed COF transmittance in the UV/Blue is almost negligible. This will directly affect the color coordinates of our COFs by moving them to the red part of the chromaticity diagrams.

We also compared our x2#9% inkjet printed COF transmission to a RGB LED backlight emission spectrum, commonly used in very portable devices such as PDA and mobile phones. We noticed that our filter was matching to the emission spectrum of the red LED emitter.

Figure 11.4 is a comparison between LED and CCFL gamut in the CIE xy 1931 chromaticity diagram. As you will notice later in figure 11.5, our x2#9% inkjet printed COF xy coordinates are very close to the red emitter xy coordinates of a LED backlight.

![Comparison of CCFL and LED backlight gamut in the CIE xy 1931 chromaticity diagram.](image)

*Figure 11.4: Comparison of CCFL and LED backlight gamut in the CIE xy 1931 chromaticity diagram.*
In 1953, the USA Federal Communications Commission (FCC) adopted the NTSC color television standards, which defined the intensity and hue of red, green, and blue in terms of x-y coordinates in the CIE1931 chromaticity diagram. They are labeled NTSC red, NTSC blue, and NTSC green. In addition, NTSC red is defined as Red 0.674(x) 0.326(y).

Table 11.2: Color coordinates of NTSC red and our inkjet printed COFs in the CIE xy1931 and CIEu’v’1976 chromaticity diagram.

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>u'</th>
<th>v'</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25%</td>
<td>0.405</td>
<td>0.247</td>
<td>0.314</td>
<td>0.431</td>
</tr>
<tr>
<td>3%</td>
<td>0.415</td>
<td>0.241</td>
<td>0.328</td>
<td>0.428</td>
</tr>
<tr>
<td>3.75%</td>
<td>0.450</td>
<td>0.235</td>
<td>0.365</td>
<td>0.430</td>
</tr>
<tr>
<td>4.50%</td>
<td>0.450</td>
<td>0.228</td>
<td>0.371</td>
<td>0.425</td>
</tr>
<tr>
<td>7%</td>
<td>0.530</td>
<td>0.247</td>
<td>0.431</td>
<td>0.454</td>
</tr>
<tr>
<td>9%</td>
<td>0.587</td>
<td>0.270</td>
<td>0.463</td>
<td>0.480</td>
</tr>
<tr>
<td>x2#9%</td>
<td>0.665</td>
<td>0.297</td>
<td>0.507</td>
<td>0.511</td>
</tr>
<tr>
<td>NTSC red</td>
<td>0.674</td>
<td>0.326</td>
<td>0.484</td>
<td>0.527</td>
</tr>
</tbody>
</table>

Figure 11.5: Company-A red pigment concentration inkjet printed COF in the CIE xy 1931 diagram. x, y color coordinates of the 2.25%, 3%, 3.75%, 4.5%, 7%, 9%, double 9% layer pigment concentration filters and red NTSC.
Figure 11.6: Company-A red pigment concentration inkjet printed COF in the CIE u'v' 1976 diagram. u' and v' color coordinates of, from left to right 2.25%, 3%, 3.75%, 4.5%, 7%, 9%, double 9% layer pigment concentration filters and red NTSC.

In figure 11.5 and 11.6, we can notice the progression of our inkjet printed COF to the red area of the two CIE chromaticity diagrams. We understand now the high transmission’s impact of our 2.25% to 4.5% COFs in the blue/UV region of the spectrum. However, the most interesting part of these two figures is the location comparison between NTSC red and our 9% double layer inkjet printed COF. We can notice that even if our filter is a little less saturated than NTSC red, it is otherwise redder.
12 Conclusions

The work of this thesis consisted of the correlation between literature researches and experimental studies. LCDs are considered as high-integrated systems and require knowledge in various scientific domains. As a consequence, we focused our first literature researches on liquid crystal displays, color optical filters, color and inkjet technology. Then, our specific objective was the investigation of the feasibility of using Company-A pigment formulation in inkjet production of color optical filters (COF) for active matrix LCD applications by using disciplines such as optical microscopy, rheology, inkjet printing, profilometrying and colorimetry.

Regarding to our results, the following conclusions are proposed:

- Typical values of COF area can vary from 0.034mm$^2$ to 0.173mm$^2$. Such range is mainly due to the nature of the electronic device. Very high-resolution portable devices will need small COF in order to increase their resolution. Inkjet printing, by its high resolution and low typical drop volume should be then an interesting alternative in production of COF.

- The viscosity investigations on company-A pigments dispersed in the proper solvent allowed us to determine ideal viscosity parameters from 10 to 20mPa·s for inkjet printing.

- The inkjet printing process confirmed our viscosity parameters and allowed us to print COF with various pigment concentrations from 1.5% to 9%. However, vinyl has been used for lower concentrations (1.5% to 7%), in order to achieve our parameters. By using optical microscopy, we also noticed a very good repartition of all pigments, which were fully dispersed into the solvent.

- By our thickness investigations we noticed that single COFs layer printing was close to typical CFs thickness values. Double layer printing was also an interesting alternative with a thickness slightly higher than typically but of course still valuable to allow the manufacturing of a LCD prototype with black matrix.

- The colorimetry investigations showed us that 9% pigment concentration double layer COFs color coordinates were very close to the NTSC red standard. This increases the possibilities to use company-A red pigment to the inkjet printing of color optical filters for LCD applications.

- By studying different backlight emission spectrums, we noticed that it should be possible to find the proper backlight technology, matching our inkjet printed COF. The use of LED backlighting seems to be a valuable solution regarding to its emission spectrum and gamut.
The results on this thesis will increase the understanding of inkjet printing company-A pigments to produce COF for LCD applications. Inkjet printing COF is a promising technology because it is fast, accurate, easy to run and cheaper than other technologies. It is now expected that new research results in the same fields such as printing into back matrix will increase the possibility to use company-A pigments to produce COF for LCD applications.

Table 12: Summary of the results.

<table>
<thead>
<tr>
<th>#</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ink Viscosity</td>
<td>10-20 mPa·s</td>
</tr>
<tr>
<td>2</td>
<td>Ink Surface tension</td>
<td>30-50 mN/m</td>
</tr>
<tr>
<td>3</td>
<td>Inkjet head solvent compatibility</td>
<td>Acetone</td>
</tr>
<tr>
<td>4</td>
<td>Size of color filter pixel (only color area)</td>
<td>0,034 mm² to 0,173 mm²</td>
</tr>
<tr>
<td>5</td>
<td>Black matrix</td>
<td>Width: 8 µm to 20 µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Height: 30 µm to 98 µm</td>
</tr>
<tr>
<td>6</td>
<td>Thickness of color filter</td>
<td>4 µm to 6,3 µm</td>
</tr>
<tr>
<td>7</td>
<td>Color R Inkjet material (Depending on application)</td>
<td>x2#9% red COF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,665(x) and 0,297(y)</td>
</tr>
<tr>
<td>8</td>
<td>Transmittance</td>
<td>x2#9% COF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>58.6% at 650 nm</td>
</tr>
</tbody>
</table>
13 Acknowledgements

This master thesis is the summary of the investigation of inkjet printing of color optical filters for LCD applications by using company-A red pigments, performed at Swedish LCD Center, Borlänge, Sweden, in 2006. This work was a part of our Master of Display Technology at Högskolan Dalarna.

During my master thesis work, the following people have contributed to the completion of this project and I would like to express them my sincere thanks:

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My parents, for always supporting me through years.

And last but not least, thank you Britta!

Borlänge, June 2006

Maxime Compagnon
References


