Diffractive Nano-Structures as
Optical Visual and Machine Readable Features

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B.Sc., Aachen University of Applied Sciences, 2007

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of the Requirements for the Degree of
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Abstract

With the help of nano-fabrication and nano-optical structures a method for data storage is presented. The information in this method is encoded and represented in a multi-state system where colors or wavelengths are used as variables. The high resolving power of nano-scale diffraction grating has enabled the detection of distinguishable colors (or wavelengths) and that in turn is used to improve the storage capability of the presented system as well as achieving a natural physical compression. The data in this method are represented physically.

This method offers a good data density and creates a secure system for authentication. It has both color change effect, which can be used for the first level of authentication and machine readability.

In addition, by using nano-diffractive features, type of diffraction grating is designed which is capable of holding the same color for a large viewing angle. By using materials with a high refractive index a system is introduced in which images can be recorded and perceived in a 3D like manner similar to what is found in holograms recorded on film.

**Keywords:** Diffraction; Diffraction Grating; Refractive Index, Data Storage; Nano-Fabrication
I am dedicating this work to my father for his constant encouragement and never ending support, to my mother for the sacrifices she has made for me and helped me get to where I am, to my lovely sister for giving me the strength and to my brother for being a friend, a brother and an incentive in my life.
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<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>NOF</td>
<td>Nano Optical Feature</td>
</tr>
<tr>
<td>LoCo</td>
<td>Low Coercivity</td>
</tr>
<tr>
<td>HiCo</td>
<td>High Coercivity</td>
</tr>
<tr>
<td>UPC</td>
<td>Universal Product Code</td>
</tr>
<tr>
<td>EAN</td>
<td>International Article Number</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>HIBCC</td>
<td>Health Industry Business communications Council</td>
</tr>
<tr>
<td>UCC</td>
<td>Uniform Code Council</td>
</tr>
<tr>
<td>QR</td>
<td>Quick response</td>
</tr>
<tr>
<td>CCD</td>
<td>Charged Couple Device</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor Sensor</td>
</tr>
<tr>
<td>HCCB</td>
<td>High Capacity Color Barcode</td>
</tr>
<tr>
<td>ISAN-IA</td>
<td>International Standard Audiovisual Number-International Agency</td>
</tr>
<tr>
<td>BAP</td>
<td>Battery Assisted Passive</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-High-Frequency</td>
</tr>
<tr>
<td>EPC</td>
<td>Electronic Product Code</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Electrically Erasable Programmable Read Only Memory</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>MROM</td>
<td>Mask Read-Only Memory</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>OS</td>
<td>Operating System</td>
</tr>
<tr>
<td>WORM</td>
<td>Write Once Read Many</td>
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<tr>
<td>BEST</td>
<td>Burst Error for Satellite Transmission</td>
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<tr>
<td>PET</td>
<td>Polyethylene Terephthalate</td>
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<tr>
<td>IPA</td>
<td>2-Propanol</td>
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<td>DI</td>
<td>Deionized</td>
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<td>Focused Ion Beam</td>
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<td>Physical Vapour Deposition</td>
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<tr>
<td>NA</td>
<td>Numerical Aperture</td>
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<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>RCA</td>
<td>Radio Corporation of America</td>
</tr>
<tr>
<td>HSQ</td>
<td>Hydrogen Silsesquioxane</td>
</tr>
<tr>
<td>HF</td>
<td>Hydrofluoric acid</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
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<tr>
<td>NOF</td>
<td>Nano Optical Feature</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>DPI</td>
<td>Dots Per Inch</td>
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<tr>
<td>JPEG</td>
<td>Joint Photographic Experts Group</td>
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<tr>
<td>HTML</td>
<td>Hyper Text Markup Language</td>
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<tr>
<td>MOS</td>
<td>Multilayer Optical System</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>OPV</td>
<td>Organic Photovoltaic</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium-Tin Oxide</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>WMRM</td>
<td>Write Many Read Many</td>
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1. Chapter I: Introduction

In the field of security and authentication, developments are moving towards technologies that can provide a maximum level of security for data and personal information with minimal complexity of use. The need for storing and protecting information in a secure environment has been a strong motivation for the evolution of technologies used for security and authentication purposes. Some common examples of current state-of-the-art in this field are magnetic stripes, radio frequency identification (RFID) tags, barcodes, holograms, microchips and optical memory features found on credit and bank cards, driver’s licenses, passports and store goods. Despite the major differences that these technologies might have in the recording/storing of information, they share one common factor, “data encoding”. Although the technological advancement has led to more complicated data recording/encoding systems (such as RFID tags or smart cards) the simplicity in the implementation of these devices has allowed them to become a part of our daily lives.

Even though these technologies have managed to provide a moderate level of security for documents, they still have failed to eliminate the threat of identity theft and counterfeits and that is due to the advancement of technology and wide range of accessibility to the fabricating machineries and sites as well as the internet where the required information can be easily found. This issue has become even more critical since these technologies are being used as a measure of identification by storing personal data. Despite the improvement in data encoding techniques, these technologies are still used together as a combination of different security features serving different purposes on a document or a card.

In general, there are two levels of securities which are used to authenticate the originality of a document and they can be categorised as:
1. Visual features

2. Machine readable features

The visual features are mostly serving the first level of security for authentication. These features in fact play a very important role since they simply prove the originality of the document. The majority of the users and handlers might not be familiar with the type or quality of the original document therefore the visual features are designed in a way that they can be easily noticed and recognized by inexperienced eyes. Holograms are the most common technologies used as visual features. Holograms can be found on the back of credit cards, brand stickers, passports, etc. and that shows the importance of visual features for authentication. On the other hand the machine readable features store certain information related to the application they are used for. The recoded/stored data can be encrypted depending on the importance of the information, but in either case a reading device is required in order for the recorded information to be read. The machine readable features are the second level of security where the extraction of data for authentication is needed. The stored data can only be read and interpreted by the designated reading device. In most cases a high security document would carry both types of features.

By making a quick overview on the commonly used authenticating technologies on documents (such as banknotes, bank cards, etc.), it can simply be noticed that the visual and machine readable features are placed individually on the document to serve their own purposes but there is not yet a feature which has the recoding capability along with a brilliant optical/visual effect. The absence of such technology became a great motivation to create features which could carry out both levels of securities. Apart from having a good optical effect and a recording capability which could match the common state-of-the-art in field of security and authentication, the new features should also be hard to duplicate.

The motivation of this work was to create a new system which is capable of storing data as well as performing color change effect. Such a system can satisfy both machine readability and visual effect for a technology used for authentication. The technologies which are used commonly as machine readable features for security and
authentication do not offer a high data storage density (except optical memory cards) and the security provided by these technologies for personal information is limited. The high costs of manufacturing, and sensitivity of these technologies to the operating environment, add to their disadvantages. The majority of the visual features, which are used for the first level of authentication, are incapable of exhibiting a strong color change effect and in many cases these features were counterfeited with the help of a high precision laser printer.

The challenge of creating features which could satisfy both good visual effect and machine readability purposes has been solved by the advancement of nano-technology and the improvement of the equipment and techniques used in this fairly new field. The machineries used in nano-fabrication have the capability of fabricating nano-size structures with high precision. Since the fabrication of the nano-structures requires a specialized environment (cleanroom) and fabricating machines, the duplication of such features will be very difficult.

Here a new technology which creates a more secure environment for storing and reading data using nano-optical features (NOF) is being presented. By using arrays of NOF, a new technique for encoding data is created that is hard to replicate and also inexpensive to fabricate. The nano-scale nature of the NOF permits a large number of characters to be stored in a very small space. The diffractive characteristic of the NOF is used to filter the light through transmission or reflection and the optical signals were acquired to encode information. The encoded information can be read and decoded into words or pictures with a designed optical reading device. The absence of physical contact for reading the data adds to the life time of the material used for recording data. These diffractive nano-structured arrays can be used in 1D, 2D or even 3D patterns and since standard optical wavelengths can be used to store information there are at least 1100 different characters (300 nm-1400 nm) in the UV, visible and NIR spectrums to encode with. An improved and enhanced diffraction grating is also designed which exhibits a better visual effect than holograms.
2. Chapter II: Background

In this chapter some of the most common features and technologies used for storing data and creating an optical effect will be reviewed. Diffraction as the physical phenomena behind the optical effect of many visual features will be briefly discussed.

2.1. Magnetic Stripe

Magnetic stripes that are being used widely for security and authentication are in practice a method to store data by the modification of the magnetism of iron-based magnetic particles (Halliday 1997). Although the magnetic stripes look the same on a card but still significant differences can be found. There are factors, such as materials used for coating and the method by which the magnetic materials are made, that can affect the performance of the magnetic stripes (Halliday 1997) and therefore there exists different types of magnetic stripes. The manufacturing process used for fabricating the magnetic stripes can control:

- The signal strength
- The stripe’s coercivity
- The stripe’s resistance against erasure
- The wave shape of recorded data

These parameters can influence the performance of the stripes greatly (Halliday 1997).

Coercivity is the key factor in magnetic stripe technology for reading stored information. The magnetic materials used in the stripe show a resistance once they are exposed to a magnetic field which is called coercivity (Garcia 2007). In other words, coercivity could be explained as the required magnetic intensity of an applied field which is to be used to change information (Garcia 2007). The unit used for coercivity is called an oersted. The information will be stored based on the resistance that the material shows at different sections of the stripe against the magnetic field of the reading device.
In general there are two different types of materials used as the magnetic stripes medium:

- Low Coercivity (LoCo)
- High Coercivity (HiCo)

The LoCo material which is used mostly for credit cards is about 300 oersteds and the HiCo material has a range of 2500-400 oersteds. The information stored on LoCo material is easy to erase once the material is exposed to a relatively strong magnetic field (household magnets) while data in HiCo material is much harder to remove therefore HiCo materials are usually used in security credential applications.

To standardize the use of magnetic stripes, there are two segments which have been developed by magnetic stripe standards:

- Physical Standards
- Application Standards

The physical standards generally define the density of recorded data, location of recording tracks, encoding methods, and quality of the magnetic recording, while content and format of the stored data for different market usage is categorized under application standards.

Based on magnetic stripe standards, there are three tracks in total (Figure 1) being used on a common credit card. Tracks 1 and 3 both have a data density of 8.27 bits/mm² where track 2 has only 2.95 bits/mm². Tracks 1 and 2 are commonly specified to read-only tracks, track 3 might be used to write to. The storage capacity of the magnetic stripes is small (1000 bits) and therefore limited information can be recorded using this technology. The types of data which can be stored on a magnetic stripe are either alphanumerical characters (7-bit) or numerical characters (5-bit).
Figure 1: A typical magnetic stripe on a card contains three tracks where data stored within these tracks. Track 3 in most cases stays unused.

2.2. Barcode

Barcodes, in practice, are features with which information is represented physically. In this method, digits, letters and symbols will be encoded in the features and the encoded information will be placed on a document (Questex Media Group 1996) (Mashud Rana 2011). The stored encoded text data can then be retrieved by the designated readers. The typical one-dimensional barcodes which are amongst the early barcode systems contain parallel vertical lines which have been separated by a series of white lines. The combination of these black and white lines represents data which is encoded within these features (Mashud Rana 2011).

The simplicity of the use of barcodes has made them a dominant technology for tracking, inventory control, shipping and receiving, and security. The popularity and the inexpensiveness of the barcodes have made them a global technology and therefore a standard symbology method for global use was required. Barcodes could be listed under two major categories:

- One-Dimensional Barcodes (1D)
- Two-Dimensional Barcodes (2D)

1D barcodes, as it was mentioned earlier, are the earliest types of barcodes used for data representation and up to this day they are still being used for various purposes.
Based on the required application there are different standard codes developed around 1D barcodes. The Universal Product Code (UPC) and the International Article Number (EAN) are widely accepted codes used in retail and can only represent numbers (all-numeric symbology) (Questex Media Group 1996). Figure 2 illustrates a UPC barcode representing numbers 1 to 8.

![UPC Barcode](image)

*Figure 2: Demonstration of a U. P. C. barcode. The barcode represents numbers 1 to 8. A U. P. C. barcode can represent up to 12 digits.*

Code 39 is another type of barcode widely used in government and medical applications (Questex Media Group 1996). These linear barcodes use an alphanumeric symbology and provide a good security level due to its self–checking properties (Questex Media Group 1996). There is no fixed variable length for representing information with code 39 barcodes. The upper-case alphabetic characters, numbers and a series of punctuation are supported by code 39 (Figure 3) (Questex Media Group 1996).

![Code 39 Barcode](image)

*Figure 3: Code 39 barcode supports alphabetic characters, numbers and punctuations. Here "SASAN$29" has been presented by code 39 barcode.*
The barcode system which is used to represent the entire American Standard Code for Information Interchange (ASCII) characters is called code 128. This barcode system has enabled relatively a high density for data representation and fairly high security which is why it is being used majorly by the Health Industry Business communications Council (HIBCC) and the Uniform Code Council (UCC) for container marking (Questex Media Group 1996). Figure 4 demonstrates code 128 barcode system.

![Barcode Example](image)

*Figure 4: Demonstration of the ability of code 128 in representation of ASCII characters. Here "Sasan V. Grayli 1983" is encoded by this barcode system.*

The typical 1D barcode readers use visible (or infrared) light or laser beam sources to illuminate the symbols. The dark area absorbs and the white portion reflects the illuminated light. A photo sensor records this light fluctuation and transforms it into electrical signals. These electrical impulses mimic the entire bar and space pattern of the barcode which then with the help of mathematical algorithms the information will be decoded (Questex Media Group 1996).

2D barcodes were invented in the early 1990s. This generation of barcodes provides a much larger capacity to store data per unit area than 1D barcodes, and thus has introduced more security against counterfeiting of the encoded information (Kan, Teng and Chen 2011) (Questex Media Group 1996). There are two major groups of 2D barcodes which are categorized based on the way these barcodes represent information (Questex Media Group 1996) (Mashud Rana 2011):

- Stacked barcode
- Matrix barcode
In 2D stacked barcodes, the encoded data is stacked on top of each other as rows in a two-dimensional manner as smaller size bars and space patterns (Mashud Rana 2011). Some of the famous 2D stacked barcodes are PDF417, Codablock, Code 16K, Code 49, and SuperCode. In Figure 5 two common 2D stacked barcodes are shown. These two barcodes both have encoded “Sasan V. Grayli 1983”.

![Figure 5: Representation of "Sasan V, Grayli 1983" with a) PDF417, b) Codablock, which are two common stacked barcodes.](image)

The 2D matrix barcode however, provides more data-density storage within a fixed predefined area where the information is encoded (Questex Media Group 1996). The data in these barcodes is printed as a matrix with a cell which is not edge-dependant (Questex Media Group 1996) (Kan, Teng and Chen 2011). QR, Data Matrix, Aztec and MaxiCode are some common examples of 2D matrix barcodes (Figure 6).

![Figure 6: Demonstration of a) QR, b) MaxiCode, c) Aztec and d) Data Matrix 2D matrix barcodes. These four barcodes have all encoded "Sasan V. Grayli 1983".](image)
The quick response (QR) barcode has the largest data storage capacity and data type among the rest of the 2D matrix barcodes (numeric: 7089, Alphanumeric: 4926, Binary: 2953 and Kanji: 1817) within a small printout size and high scan speed (Kan, Teng and Chen 2011).

Unlike 1D barcodes, a simple laser barcode reader cannot be used for decoding the information stored in 2D barcodes. Whether it is a stacked barcode or matrix type barcode, since the information is not presented in one row a more complex system is required for reading the data (Questex Media Group 1996). The scanner types used for reading 2D barcodes are based on image capturing sensors such as charged couple devices (CCD) or complementary metal oxide semiconductor sensors (CMOS). In order to read the stored data, the whole symbol should be read at once therefore the 2D barcode scanners, by taking an image and using image processing algorithms, decode the stored data (Questex Media Group 1996).

The high capacity color barcode (HCCB) (also known as Microsoft Tag) is the newest generation of 2D barcodes which was introduced by Microsoft Corp. and has been licensed by the International Standard Audiovisual Number-International Agency (ISAN-IA) (Mashud Rana 2011). The innovative factor used in the Microsoft Tag is the way that the data is being represented along with the geometry and shape of the features. The HCCB uses a series of colors to represent a cluster of data rather than only 1 or 0 per bars and spaces used in conventional barcodes (Jancke 2004). The geometrical shape used in HCCB is an equilateral triangle, in four different colors (black, red, green and yellow), placed in rows (Figure 7) (Grillo, et al. 2010)(Mashud Rana 2011).

Figure 7: Demonstration of a Microsoft Tag encoding "Sasan V. Grayli 1983".
The adjacent triangles are separated from each other by white lines which help in better recognition of the features by the reading device (Grillo, et al. 2010). The reason that the triangular shape was chosen rather than other shapes is due to the existence of less number of the edges which in turns it helps the features to be recognized even if the captured image is of low quality (Jancke 2004). The HCCB is mostly used for marking commercial media products such as video games, broadcasts.

In general the limitations of barcode technology arise from the amount of data they can store and the fragility of these devices when wrinkled, damaged or exposed to dust, which creates problems for the reader to scan the label (White, et al. 2007).

2.3. Radio Frequency Identification

Radio frequency identification (RFID) tags are a fairly old technology developed during World War II to differentiate friendly aircrafts from enemy aircraft. Improvements in micro-fabrication and micro-electronics and advancements in wireless communications have made this technology a popular candidate for many applications especially in the field of security where RFID systems have been introduced for cards that carry personal information (Lozano-Nieto 2011).

The method of transmitting media is one of the main factors which differentiate between different automatic identification systems. RFID systems use electromagnetic waves in the range of radio frequencies for transmitting data and that allows them to communicate with the reader from a distance wirelessly. A transponder or a tag is the device that carries the data which, with the use of radio waves, will be transmitted to a receiver (reading device). The RFID readers are mostly a fixed device which captures and transfers information. The reader (also known as interrogator) creates an electromagnetic field within a defined range and this is the distance from which the transponder can communicate with the reader (Lozano-Nieto 2011)(White, et al. 2007). Transponders, in order to transmit media, require a source of power and that has been achieved by a power harvesting circuitry integrated in the transponders to convert the electromagnetic field generated by the interrogator (reader) into electricity (Lozano-Nieto 2011).
In practice there are three types of RFID tags which are used broadly with their own specific application in the market. These three types are:

- Passive
- Active
- Battery assisted passive (BAP)

The passive RFID tags are probably the smallest and cheapest transponders. These transponders do not use any onboard power source; however the required energy is being harvested by the internal circuitry of the transponder from the electromagnetic field which is generated by the reader (Lozano-Nieto 2011). The interrogator (reader) of the passive RFID tags has a short range.

The active RFID tags use an internal source of energy which allows them to broadcast actively to the reading device (Lozano-Nieto 2011). The presence of an onboard energy source has extended the reading range of these types of RFID systems but that in turn has increased the cost and the size of the transponder. The active tags commonly broadcast in the ultra-high-frequency (UHF) and microwave range therefore the distance of communication between the reader and transponder can reach to several hundred feet (Lozano-Nieto 2011). The major differences between passive and active tags are listed in Table 1.

The battery assisted passive (also called semipassive) tags are the third types of RFID transponders. These tags also have an onboard battery but unlike active transponders the battery is not used to broadcast signals to the reader. The onboard battery is mostly to enable secondary functions such as data logging from different sensors. There is also a power harvesting part included in these transponders which is used for powering up the internal circuits from the electromagnetic field generated by the reader (Lozano-Nieto 2011).

Although active and passive tags operate differently and use different ranges of radio waves to transmit information, they still carry the same type of data. This data type, known as the Electronic Product Code (EPC), is also a means of classification for RFID tags (Lozano-Nieto 2011)(White, et al. 2007). EPC defines the functional classification of
RFID tags within the consumer packaged goods industry (Lozano-Nieto 2011). Table 2 lists the common frequency bands used for RFID systems.

**Table 1: A comparison between passive and active transponders\(^1\).**

<table>
<thead>
<tr>
<th>Active Transponder</th>
<th>Passive Transponder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powered by battery (finite lifespan)</td>
<td>Powered by internal energy harvesting circuitry (infinite lifespan)</td>
</tr>
<tr>
<td>Less sensitive to environmental interferences</td>
<td>Sensitive to environmental interferences</td>
</tr>
<tr>
<td>High data transmission rates</td>
<td>Low data transmission rates</td>
</tr>
<tr>
<td>Capable of reading many tags at once</td>
<td>Capable of reading few tags at once</td>
</tr>
<tr>
<td>Precise aiming is not required for reading the tags</td>
<td>Reader needs to be aimed at the tag</td>
</tr>
<tr>
<td>Long range</td>
<td>Short range</td>
</tr>
</tbody>
</table>

\(^1\) The content of the table is adopted from (White, et al. 2007)
Table 2: List of the common frequency band used in RFID technology.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Frequency Range</th>
<th>Frequency Used in RFID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Frequency</td>
<td>100 kHz-500 kHz</td>
<td>125 kHz, 134.2 kHz</td>
</tr>
<tr>
<td>High Frequency</td>
<td>10 MHz-15 MHz</td>
<td>13.56 MHz</td>
</tr>
<tr>
<td>UHF</td>
<td>400 MHz-950 MHz</td>
<td>866 MHz Europe, 915 MHz US</td>
</tr>
<tr>
<td>Microwaves</td>
<td>2.4 GHz-6.8 GHz</td>
<td>2.45 GHz, 3.0 GHz</td>
</tr>
</tbody>
</table>

Easy scanning and implementation of barcodes had made them the front runner for the applications they were being used for but now barcodes are facing a serious challenge from RFID systems. The speed of scanning of RFID tags is the greatest advantage of this technology where thousands of items can be scanned at the same time while only one barcode at a time can be scanned (White, et al. 2007). But the high cost of RFID tag manufacturing has still allowed barcodes to be the most favourable technology in the industry (Lozano-Nieto 2011).

Despite the numerous advantages that RFID technology has over other card technologies, this system shows a liability in exposing personal information to identity thieves (Leyden 2006). The information within the a card with RFID technology can be accessed by an inexpensive off-the-shelf radio and card reader system and it has been reported that, even though the manufacturing companies claim that the data stored in RFID-based cards is encrypted, the majority of cards do not use any algorithm or encryption technique for data protection (Leyden 2006).

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2 The content of the table is adopted from (Lozano-Nieto 2011).
2.4. Smart Card

Smart cards, which recently have started to become more popular in the North American banking system, are in fact plastic cards with an integrated microchip (Vossos 2011). These cards are probably considered the newest technology introduced to the family of identification cards and have the capability of transmitting, storing and processing data. The data transmission is enabled through the contacts on the surface of the chip or it could be contactless (RFID) (Rankl W. 2002). The embedded microchips in the smart cards can be programmed and mostly contain a microprocessor chip along with a large memory capacity (Questex Media Group 1996). The onboard microprocessor has the role of controlling and the security of the entry of the database. Based on their functionality and the cost of manufacturing, the smart cards are divided into two groups (Rankl W. 2002):

- Memory cards
- Microprocessor cards

The memory cards are mostly Electrically Erasable Programmable Read Only Memory (EEPROM) in which the memory is being controlled and accessed by security logic. The data to and from the memory card are transferred via the I/O port. The implementation of these types of chips is fairly inexpensive due to the special synchronous transfer protocol which is defined in part 3 of the ISO 7816 standards (Rankl W. 2002). Memory cards mostly can be found in prepaid telephone cards and health insurance cards.

The microprocessor cards have an embedded processor within the integrated chip which typically consists of four functional blocks (Rankl W. 2002):

- Mask read-only memory (MROM)
- EEPROM
- Random access memory (RAM)
- I/O port

The operating system (OS) of the chip is located in the MROM. Since the OS is burned in MROM when the chip is manufactured, all the chips of a production run will have identical ROM content and therefore it cannot be changed during the chip’s lifetime.
The data can be written to and read from the EEPROM while it is being controlled by the OS. The RAM is the working memory portion of the processor and the information and stored data in this section will be lost once the chip’s power goes off. The data will be transferred bit by bit via I/O port which has only a single register (Rankl W. 2002).

As was mentioned earlier, data transmission from the smart cards occur via direct surface contact with the chip or without any physical contact (contactless). One of the major disadvantages that the contacts smart cards have is the risk of the chip being damaged by electrostatic discharge (Rankl W. 2002). The other problem with contact cards is the abruption of electrical connection between the contacts and the reader caused by contamination (Rankl W. 2002). These potential issues have been removed by the introduction of the contactless technology to smart cards. This has been achieved by adding an RF interface to the microcontroller. These types of contactless smart cards offer a visual advantage so that there would be no visible parts of the chip on the surface of the card (Rankl W. 2002). Smart cards can also be dual interfaced having both RF interface and the contacts together in one chip. Such smart cards are mostly used for electronic purse systems and are typically called dual-interfaced cards or combicards (Figure 8).

![Illustration of a dual-interface card](https://www.smartcardsource.com/)

**Figure 8: Illustration of a dual-interface card³.**

Despite the enhanced security level of smart cards, information on a card can be accessed through a pin code, and once this password has been exposed, the card can

³ The figure is adopted from “www.smartcardsource.com/”
easily be misused by identity thieves (Vossos 2011). The high cost of smart cards and the reading software (Chadwick 1999) make them less attractive for a large scale deployment in daily life as the ultimate security feature. Another down side is the lack of compatibility between the wide variety of available smart cards and microchips as each card possess its own software interface which decreases the mobility of the user of the card (Chadwick 1999).

2.5. Optical Memory Card

Optical memory cards are another generation of identification cards which provide a high level of security. The technology used in these cards is very similar to a compact disc (CD) where the features are a series of tracks which can be read by a laser beam (Questex Media Group 1996). In other words the optical memory cards can be interpreted as a piece of CD glued to the surface of an ID card but unlike a CD, it can be carried in a wallet without being damaged and an image or text can be included on the digital data portion (Dyball and Lichtenstein 2001). The images or text are usually carved by a laser used for optical memory cards (Figure 9).

![Image of an optical memory card](image)

*Figure 9: Illustration of an optical memory card with laser carved image and texts*.  

4 The figure is courtesy of “www.secureidnews.com”
The tracks on a CD are read as the disc spins however for the optical memory cards a rectilinear format is used to read the recorded tracks. These tracks are placed in an arrayed format in a linear manner where each one is numbered (Dyball and Lichtenstein 2001). By far the optical memory cards offer the largest memory storage (4-6.6 MB) with which image files such as biometrics, photographs, logos, are enabled (Halliday 1997).

The material which is used for recoding the media on the optical memory cards is silver halide based which can be also found in photographic films (Dyball and Lichtenstein 2001). A photographic formatting process is applied for the creation of high resolution laser carved images (12000 dpi) on the media to add an extra security feature to the ID card (Dyball and Lichtenstein 2001). Although the principle of recording and reading the data in and from the optical memory cards are similar to CDs but due to creation of physical pits in the recording medium, the card will become a write once read many (WORM) type technology (Dyball and Lichtenstein 2001)(Questex Media Group 1996).

An optical memory card generally is made of three different layers (Figure 10).

![Figure 10: Illustration of layers of an optical memory card](www.laserfocusworld.com)

The figure is adopted from “www.laserfocusworld.com”.

Figure 10: Illustration of layers of an optical memory card

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5 The figure is adopted from “www.laserfocusworld.com”.
The top layer acts as an encapsulator which protects the crust layer underneath. The crust layer contains silver particles which are dispersed in an organic colloid. The underlayer, which is beneath the crust, is made of the same organic colloid but lacks the silver particles (Dyball and Lichtenstein 2001).

The information is recorded in the layers of an optical memory cards using a 780 nm semiconductor laser. The laser creates 2.5 μm pits in the crust and the surface of the underlayer of the card. The track size in an optical memory card is about 12 μm. The track and pit sizes in these cards are large compared to a CD and that gives the card a better robustness and a longer lifetime since they are meant to be carried around in pockets or wallets over long periods of time (Dyball and Lichtenstein 2001).

The readability of the optical cards is enabled by an optical drive with a higher durability than the typical CD drives. The optical card drive has a powerful error-correction code, called a burst error for satellite transmission (BEST) code, which takes up a good portion of the raw memory of the optical card capacity so that a card with 4.1 MB raw capacity will only offer a 2.9 MB user data capacity, however this large overhead allows the card to be read even after it has been damaged due to long use (Dyball and Lichtenstein 2001).

The optical memory cards are used mostly in applications where a large amount of personal record is required to be stored on one card such as with healthcare, government cards (such as Canadian permanent resident cards), auto maintenance records, cargo manifests, and retail purchase cards (Halliday 1997) (Questex Media Group 1996).

2.6. Diffraction

Diffraction is part of the characteristic of any material which can propagate in a wave form such as electromagnetic waves, acoustic waves and mechanical surface waves (Chartier 2005). This phenomenon was first discovered by Francesco Maria Grimaldi (Meyer 1934). Diffraction occurs when a wave front encounters an obstacle on its trajectory path which causes the wave to deviates from the straight line path (Chartier 2005). This divergence of waves can be observed as dark and bright fringes on a screen.
when a single wavelength light is the source of wave propagation. In general, small openings, obstacles, and sharp edges can create diffraction once a wave passes through them (Chartier 2005) (Serway and Jewett 2004). These dark and bright fringes are known as a diffraction pattern. The brightest spot can be observed in the middle and this is due to constructive interferences and the dark spots are where the destructive interferences occurs (Serway and Jewett 2004). Figure 11 illustrates a diffraction pattern created by an opaque object as an obstacle.

![Light Source](image)

**Figure 11: Illustration of diffraction pattern caused by opaque obstacles on a screen.**

Such a pattern can be observed if the illumination is from a small light source passing the edge of an opaque obstacle (Serway and Jewett 2004).

Placing a penny between a light source and a screen can also create a diffraction pattern and this is another common way of experiencing diffraction. The patterns made this way are rings with a dark section in the middle (Serway and Jewett 2004)(Chartier 2005). Figure 12 demonstrates the ring pattern created by a penny once it is located half way between the light source and the screen.
In Figure 12 a tiny bright spot can be observed in the middle of the dark area. This is explained by Huygens-Fresnel wave theory in which Huygens explains that any point disturbance the light reaches becomes a secondary source which propagates in a circular manner and the final wave form is created from the sum of these secondary waves and Fresnel later explained this interaction of the secondary waves by his interference principle (Smith and King 2000) (Serway and Jewett 2004).

The aforementioned diffraction patterns are recorded mostly when the screen is close to the source of illumination (Al-Azzawi 2007)(Smith and King 2000). Similar diffraction patterns can be observed if the light passes through a slit. But if the screen is far from the slit there will be a change in the created pattern which is explained by Fraunhofer’s diffraction principle. Fraunhofer’s diffraction considers that the rays which

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Figure 12: The ring shape diffraction pattern around a penny is shown.6

6 The figure is courtesy of (Serway and Jewett 2004).
pass through the narrow slit travel almost parallel to one another (Chartier 2005)(Serway and Jewett 2004) (Al-Azzawi 2007). Such a pattern can also be made by using a convex at the point where the rays pass through the slit (Serway and Jewett 2004) (Poon 2007). At the center of the diffraction pattern the brightest fringe is made and alternating dark and bright fringes will occur at either side of the central fringe (Figure 13).

![Diagram of diffraction patterns](image)

**Figure 13:** Fraunhofer diffraction: a) illustration of Fraunhofer diffraction when the screen is far from the slit, b) illustration of Fraunhofer diffraction when a convex lens is used to focus the rays, c) the image of Fraunhofer diffraction pattern on a screen.

In general Fraunhofer’s diffraction is considered as far-field diffraction and Fresnel's diffraction is known as near-field diffraction (Lipson 2011). Fraunhofer’s and Fresnel's diffraction can be explained mathematically as a condition of \(\frac{\rho^2 k_0}{z}\) when it is less or greater than \(\frac{\pi}{2}\) where \(\rho\) is the diameter of the aperture, \(k_0\) is the wave vector and \(z\) is the distance of the aperture from the screen (Lipson 2011). This could be also explained with respect to the wavelength (Lipson 2011):

- Fresnel diffraction: \(\rho^2 \geq \lambda z\)
- Fraunhofer diffraction: \(\rho^2 \ll \lambda z\)

Another well-known experiment to observe diffraction patterns is using double slits. This experiment was first performed by Young and it is also known as Young’s double slit experiment. Based on Huygens’ principle, the two slits will act as a point source once the light passes through and at the presence of a screen the waves will overlap with each other creating a diffraction pattern consisting of constructive (bright fringes) and destructive (dark fringes) interferences (Wilcox 1984)(Lipson 2011). The
created pattern is dependent on the distance of these slits from each other and that can also be predicted by (Cowley 1995)(Serway and Jewett 2004):

\[ d \sin \theta = m \lambda \]  

(1)

for constructive interferences (bright spots) and

\[ d \sin \theta = \left( m + \frac{1}{2} \right) \lambda \]

(2)

for destructive interferences (dark spots) where \( d \) is the distance between the slits.

The diffraction pattern is observed as dark and bright spots if the source of illumination is monochromatic (laser) but in the case of having a polychromatic light source (white light) the diffraction pattern consists of the light spectrum. Such patterns can be observed in both single and double slit demonstrations (Brooker 2003)(Hutley 1982). Figure 14 demonstrates the diffraction pattern created by single and double slits for both monochromatic and polychromatic light sources.

\[ Figure 14: \text{Single and double slit wave propagation, a) light passes through single slit, b) diffraction pattern of monochromatic light (top) and polychromatic light (bottom) created by a single slit, c) propagation of wave through double slit, d) diffraction pattern of monochromatic light (top) and polychromatic light (bottom) created by double slit.}^7 \]

\[ ^7 \text{The figure is courtesy of "www.skepticsplay.blogspot.ca" and "www.itp.uni-hannover.de"} \]
Adding more slits, the same distance from each other, will create a narrower maximum which is located at the center of the diffraction pattern and the repeated orders will be less bright (Serway and Jewett 2004).

2.7. Diffraction Grating

In the previous section it was explained how optical diffraction will occur when light passes through a slit. It was also shown how a double slit can create diffraction and how the diffraction pattern is different from the one which is created by a single slit. Increasing the number of slits will lead to the creation of a dispersion element which is different than a prism and has the capability of diffracting light; such an element is known as a diffraction grating. A diffraction grating in fact is a system consisting of grooves or slits which are spaced periodically from each other (Optical Society of America 2010). A diffraction pattern can be created through the reflection of the surface of a diffraction grating where the grating structures are highly reflective and such a dispersion element is called a reflection grating (Palmer 2002) (V. Grayli, et al. 2011). A diffraction grating might diffract the light through transmission. In this case it is called a transmission grating and it consists of a grating superimposed on a transparent surface as opposed to a reflection grating where a reflective surface is what the grating is superimposed on (Palmer 2002). Figure 15 illustrates both types of gratings.

![Figure 15: Schematic of two types of diffraction gratings: a) reflective grating, b) transmission grating. α is angle of incident light, β is the dispersion angle, m is the diffraction order, and d is the period of the grating.](image-url)
It should be noted that the angle of incident light and dispersion angle are measured from the grating normal (a line perpendicular to the surface of the grating) to the beam by convention and depending on whether the light is diffracted on the same side as the incident light or the opposite side of it the sign convention is defined (Palmer 2002). The angles are measured counter clockwise with respect to the grating normal and therefore on the right side of the grating normal the diffraction will be in negative orders and on the left side, the positive orders (Palmer 2002).

The pitch of the periodic structures which is known as the period of the grating affects inversely the dispersion angle, as the periodicity of the gratings becomes smaller; the angle of dispersion becomes larger which correlates with a greater separation of the diffracted wavelengths (Optical Society of America 2010) (Figure 16).

![Figure 16: Diffraction of polychromatic light where $\alpha_i$ is angle of incident and $\beta_d$ is angle of dispersion. By decreasing the periodicity of the grating from a) to b), the dispersion angle ($\beta_d$) will increase.](image)

A diffraction pattern and the orders of diffraction and the angle in which the wavelength are being dispersed can be predicted by (Lipson 2011):

$$m\lambda = d(\sin \alpha_i + \sin \beta_d)$$

where $\alpha$, $m$, $d$ and $\beta$ are respectively the incident angle, the diffraction order, the grating periodicity and the dispersion angle. At $m = 0$, the reflective diffraction grating acts as a mirror while the transmission diffraction grating behaves as a transparent substrate. This
order is referred to as zero order mode and corresponds to $\beta = \alpha$ (V. Grayli, et al. 2011). If diffraction occurs in the same direction from which the beam of light reaches the surface of the grating it will be a Littrow configuration and the grating equation will be (Palmer 2002):

$$m\lambda = 2d \sin \alpha$$

An advantage that a diffraction grating has over a prism is its capability to select the dispersion angle by changing the spacing between the grooves. A grating will diffract the light in multiple orders. The energy of the diffracted orders can be enhanced by altering the profile of the grooves (Optical Society of America 2010).

In gratings with a triangular groove profile and smooth surface maximum efficiency can be achieved (Palmer 2002). To obtain the highest efficiency the angle of the triangular grooves is designed so that the specular reflection angle for the angle of incidence becomes equal to the angle of diffraction in magnitude but opposite in sign (Palmer 2002).

Sinusoidal-groove diffraction gratings are another type of diffraction grating in which the behaviour of diffracted efficiency is different than triangular-groove gratings. In these types of grating there are five domains (very low, low, medium, high, very high) considered where the modulation $\mu$ is progressively increasing (Palmer 2002). The modulation can be expressed by (Palmer 2002):

$$\mu = \frac{h}{d}$$

where $h$ is the height of the grooves and $d$ is the periodicity (spacing) of the grooves.

Another important parameter of diffraction gratings is their power in distinguishing the small differences between wavelengths. This parameter is called the resolving power ($R$) of the grating and it can be defined as (Serway and Jewett 2004):

$$R = \frac{\lambda}{\lambda_2 - \lambda_1} = \frac{\lambda}{\Delta \lambda}$$
where $\lambda = (\lambda_1 + \lambda_2)/2$ and $\lambda_1$ and $\lambda_2$ are two wavelengths which are very close to each other and a diffraction grating can hardly distinguish between them.

2.8. Holography

Holography is a technique based on the interference patterns created by directly transmitted monochromatic coherent light and the light scattered by an object to record an image on a film. This can be achieved by using a basic setup comprising of a laser, a beam splitter, mirrors, a holographic film and the object which is being recorded on the film. In this setup, the laser beam is split after passing through the beam splitter. Under a polychromatic light illumination, the result is a 3D-like image commonly referred to as hologram (P. Hariharan 2002) (Ackermann and Eichler 2007). One portion of the beam is directed towards the object and then scattered onto the holographic film, while the other portion becomes the directly transmitted light beam. This scattered beam contains information which is in the form of amplitude and phase creating a pattern in the holographic film. Depending on the angle at which these two beams converge on the surface of the film, an interference pattern is created. This recorded pattern can be observed at the correct angle under a polychromatic light (i.e. white light).

The advantage of holography on films is its ability to store various interference patterns on the same plane at different angles. Consequently, multiple images can be observed on the same surface area by tilting the film at different angles and/or directions (P. Hariharan 2002) (Ackermann and Eichler 2007) (Figure 17).

Usually, holograms are categorized under transmission or reflection types, and this depends on the way the recorded interference patterns are observed (P. Hariharan 2002) (Bjelkhagen 2005) (Yu and Jutamulia 2007).
Another method of creating a hologram is by using photoresist (PR). This technique is widely used for mass replication of rainbow holograms by embossing. More precisely, the original features are made on a PR layer and subsequently a master mould is fabricated from which the holograms are directly embossed on polymer-based materials (P. Hariharan 2002)(Bjelkhagen 2005). These types of holograms are widely used in security applications, and credit cards (Bjelkhagen 2005)(P. Hariharan 1996).

Holography techniques can be used to create high quality diffraction gratings where the interference pattern is recorded in a layer of a PR coated substrate (P. Hariharan 2002). This type of grating is known as a holographic grating and they are capable of producing low levels of scattered light due to an absence of periodic and random errors (P. Hariharan 2002).

Holographic gratings are produced through interference fringes and patterns created from the intersection of double or single laser beam interference (P. Hariharan 2002)(Palmer 2002). The result is a sinusoidal pattern on the resist based on the

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8 The figure is courtesy of "© 1996-2007 Holophile, Inc".
intensity of the exposed areas. After processing the resist, these gratings can be transferred onto a rigid substrate which will be subsequently used as a stamper for the replication of the features (Palmer 2002). These types of grating can be coated with reflective materials, such as a metal, in order to enhance their brightness (P. Hariharan 2002)(Palmer 2002), however the finite conductivity of the metal can affect the efficiency of the grating. The diffracted wavelengths above 4 μm are not that influenced by this factor but the dielectric constant and the refractive index have a noticeable effect on the wavelengths below 1 μm (Palmer 2002). The finite conductivity of the metal becomes more visible as the wavelengths get smaller (Palmer 2002). The effect of finite conductivity on the P-plane is a reduction in efficiency but on the S-plane this effect plays a more complicated role as the wavelengths become shorter and the depth of the grooves increases (Palmer 2002). The holographic gratings are mostly used for wide wavelength regions and the near infrared ranges.

In the event of having sawtooth grooves, the grating is called a blazed holographic grating. These types of gratings are capable of concentrating a large portion of energy of the incident light in a certain diffraction order once the wavelength and the angle of incident light have an appropriate value (Miler 1991). The sawtooth profile of the blazed holographic grating is made by recording the interference field of a sinusoidal distribution. The blazed holographic gratings are used in spectroscopy for UV and visible light. Figure 18 demonstrates both holographic and blazed holographic gratings.
A volume hologram (also known as thick hologram) is another type of hologram which is made on a substrate where its thickness is much more than the interference patterns' spacing. The amplitude of diffracted light by the volume holograms is in accordance with the Bragg condition (Solymar and Cooke 1981) (P. Hariharan 2002). The reconstruction and the color of perceived image depends on the index of refraction of substrate materials, the wavelength of light, and the angle, known as the Bragg angle, at which the incident light illuminates the pattern (P. Hariharan 2002) (Yu and Jutamulia 2007). The wavelength illuminating the features at the Bragg angle defines the color of the hologram (P. Hariharan 2002)(Yu and Jutamulia 2007) (Figure 19). Due to the ability of the volume hologram in selecting the color, they are widely used as color filters.
The volume holograms usually offer a high angular and wavelength selectivity due to the substrate thickness and that property is used in holographic memory devices where multiple holograms can be recorded in a small volume of crystals (Yu and Jutamulia 2007). Volume holograms can also be formed and stored in a single-crystal fibre. The Laser-heated pedestal growth technique is used to grow these single-crystal fibres.

2.9. Chapter Summery

Maintaining a secure environment to protect personal information is one of the challenges of our century. To succeed in this critical task, many technologies have been proposed from which a few have remained as the first pick for the companies which provide security and authentication for cards and documents that hold personal identification data.

The figure is courtesy of “Dai Nippon Printing Co., Ltd.”
Magnetic stripes which can be found on almost every bank or ID card, store data by the modification of the magnetism of iron-based magnetic particles. The magnetic stripes contain three tracks and each track can either contain 7-bits alphanumeric characters or 5-bit numeric characters which shows the limit of this technology in storing data. The method of reading the magnetic stripe is through physical contact with a magnetic reading device. This reader has a magnetic reading head which works similarly to the tape head used in a tape recorder. This physical contact over time damages the magnetic layers which in turn shortens the life of the magnetic stripes. The data can also be damaged if the card is exposed to an external magnetic field.

Barcodes, on the other hand, are optical representations of data, which shows data about the object to which it is attached. The barcodes represent data one dimensionally by having parallel lines which are printed with different spacing and widths. Their limitations arise from the amount of data they can store and the fragility of these devices when wrinkled, damaged or exposed to dust, which creates problems for the reader to scan the label.

RFIDs have shown a great potential to replace bar codes since it allows scans of thousands at a time while barcodes scanning is one at a time. RFIDs can be either passive (without a battery) or active (on-board battery). But even the fast scanning capability of RFIDs cannot overcome their liability in exposing personal information to identity thefts. RFIDs, despite many advantages such as the scanning speed, are relatively expensive and have been shown to offer a low level of security, particularly on credit and personal identification cards. Since RFIDs transmit signal in radio frequency from a distance, a simple receiver in the vicinity can intercept the signal and record the transmitted information. RFID is ideal for use on items which do not require a high level of security, such as low cost store goods, however this technology is currently too expensive for this kind of application.

Smart cards contain an integrated microchip capable of storing data. Even with an enhanced level of security, data on smart cards can be accessed through a pin code, and once this password has been exposed, the card can easily be misused by identity thieves. The high cost of smart cards and the reading software make them less attractive for large scale deployment in daily life as the ultimate security feature. Another down
side is the lack of compatibility between the wide variety of available smart cards and microchips as each card possess its own software interface which decreases the mobility of the user of the card.

Optical memory card technology offers a large data storage capability. This is a useful technology for applications in which there is a need for personal records to be accessible for further authentication such as immigration cards or health cards. The base of this technology is similar to what has been used in the CD industry with a slight modification in its reading method. The large capacity of these cards has enabled a better encryption algorithm for data protection. The optical cards are WORM technology and therefore the information cannot be modified once it has been recorded. The high cost of the optical cards is probably one of the major reasons for this technology not to be as popular in card industry.

Diffraction occurs when materials, which are capable of propagating in wave forms, encounter an obstacle in their path. The result is the propagation of circular secondary wavelets as new sources. These secondary waves will form interference patterns on a screen which can be observed as a series of constructive and destructive interactions resulting in dark and bright fringes. The formed fringes caused by constructive and destructive interference of waves is known as a diffraction pattern. Diffraction is in fact a divergence of wave regimes. For a polychromatic light (white light) this phenomenon can be seen as colors (wavelengths) of which the light beam consists of. If the diffraction occurs when the screen is very close to the source then it would be considered near-field or a Fresnel diffraction. In a Fraunhofer or far-field diffraction, the interference pattern occurs on a screen which is far from the source. This could also be simulated by placing a converging lens between the source and the screen when the screen is located close to the light source.

Diffraction gratings consist of periodic structures which cause the incident light to diffract. Diffraction can occur both in transmission (e.g. prism) or reflection (e.g. CDs and DVDs) modes, and it is due to the transparency or reflectance nature of the substrate which contains the period structure. The pitch of the periodic structures, which is known as the period of the grating, affects inversely the dispersion angle. As the periodicity of the gratings becomes smaller, the angle of dispersion becomes larger which correlates
with a greater separation of the diffracted wavelengths. Gratings with a triangular groove profile tend to have the highest efficiency and by choosing the right angle for the grooves, the grating can be tuned to have the maximum efficiency for a certain wavelength. The angle of the grooves in this case should match the specular reflection angle of the incident light. To reduce the scattering effect, the sharp edges of the facets should be smoothed out as much as possible.

Holograms, in practice, are the recorded interference pattern on a holographic film. This interference pattern is made by illuminating an object by a coherent monochromatic light (laser). Prior to the recording, the laser beam is split into two where one would reach the film without interacting with any obstacle on its path and is called the reference beam. The other beam will be guided towards an object and the scattered light off the object which is different in phase and amplitude will expose the film. The interaction of the reference beam and the modulated beam will create an interference pattern on the film which can be seen as a 3D image at the presence of white light. By using PR, this interference pattern can be made and then transferred onto a substrate which results in the fabrication of a holographic grating. There are three types of groove profiles used commonly in holographic gratings:

- Sawtooth grooves (triangular)
- Sinusoidal grooves
- Rectangular grooves
3. Chapter III: Overview of the Conducted Research

In the previous chapter, some of the technologies which are commonly used in authentication applications were introduced and briefly analyzed. Diffraction and diffraction grating on which this work is based were also reviewed. Chapters IV, V and VI are dedicated to present the work and the contribution of the author of this thesis as well as the possible application for the proposed technologies. In this chapter a brief overview of the proposed technologies will be presented and that includes introducing visual and machine readable features and the enhancements which are made to improve their optical performance as well as the systems used for fabrication.

3.1. Introduction to Optical Visual Features

The main factor for the visual features is their ability to exhibit a bright and noticeable color change effect by diffracting light. Holograms, which are the leading technology in this field, usually do not perform a strong diffraction effect due to their method of fabrication.

The nano-scale diffraction grating and their capability in diffracting light will be introduced in Chapter IV. The perceived diffracted wavelengths from a nano-scale diffraction grating have large dispersion angles and thus rays can be detected more distinguishably. Such gratings have a much higher resolving power due to the spacing of the grooves. Efficiency of these gratings can be controlled by altering the grooves’ profile.

At first, the capability of the nano-scale diffraction grating in diffracting light will be investigated. This investigation is conducted by creating a setup in which the diffracted wavelengths were detected at a fixed angle with respect to the plane of the grating. For the simplicity of the work the angle was chosen to be normal to the plane of the grating.
therefore the diffracted wavelength which disperse with 0° angle (normal to the surface) are detected. This setup was designed so that the light source can rotate and by that the angle of incident light was used as a variable to analyze the resolving power of the gratings for the first order of diffraction. The detailed description of this experiment is presented in Chapter IV.

The investigation of the nano-scale diffraction grating was conducted once numerically (simulation) and once experimentally. The Matlab was used to simulate the effect of nano-size gratings with circular profiles. To explore the accuracy of the obtained simulated results, arrays of nano-scale diffraction gratings with circular profiles were fabricated using a focused-ion beam (FIB, Strata DB 235) (Figure 20) on a polymer based substrate.

\[ \text{Figure 20: The FIB system model Strata DB 235 manufactured by FEI is shown in this figure}^{10}. \]

The high resolving power and efficiency which have been achieved by the nano-scale grating have made this technology a possible candidate for applications where the

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\(^{10}\) The figure is courtesy of “www.4dlabs.ca/facilities/nanoimagin”. 
visual features for the first level of authentication are used. In addition, a nano-scale grating with an enhanced optical effect was fabricated that offers a wide angle of view for specific colors for which the grating is tuned. These gratings with such capability can be simply used as a visual feature on documents for authentication. The nano-nature of these diffraction gratings and their exhibiting color effects allow them to be less susceptible to forgery and duplication. These gratings were fabricated with the help of an electron-beam lithography (EBL, e_LiNE) system (Figure 21).

![Figure 21: The e_LiNE EBL system manufactured by Raith is shown in this figure](image)

Furthermore, a reactive-ion etching (RIE) (Figure 22) system was used to transfer the pattern onto a quartz based substrate. The fabrication of these arrays was done in a cleanroom.

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11 The figure is courtesy of “www.nanofabrication.4dlabs.ca”.

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Figure 22: A RIE system model Etchlab 200 manufactured by Sentech is demonstrated\textsuperscript{12}.

One of the important characteristics of transparent material, which was noticed and explained early in the development of optics, is the index of refraction of the medium (Chartier 2005). Snell’s law of refraction introduces refractive index $n$ which is a normalized value of propagation speed $V$ of light with respect to the speed of propagation in transparent materials (Chartier 2005). $V$ is normalized with respect to the speed of propagation of electromagnetic waves in a vacuum (Chartier 2005). This property of material affects the speed of propagation of light at the interface of two mediums and this leads to the deviation of the light from its path. This phenomenon mathematically is explained by Snell’s law (Chartier 2005):

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$  \hspace{1cm} (7)

\textsuperscript{12} The figure is courtesy of “www.nanofabrication.4dlabs.ca”.
where \( n_1 \) and \( n_2 \) are the refractive indices of medium 1 and medium 2 respectively and \( \theta_1 \) and \( \theta_2 \) are the angles between the beam of light and the normal line to the plane of the interface of medium 1 and medium 2 respectively. Figure 23 illustrates the refraction between two mediums with different refractive indices.

In the fundamental overview, the refractive index \( n \) defines the wavelength and its velocity by which it reduces with respect to their values in a vacuum (Chartier 2005)(Al-Azzawi 2007). This is expressed by:

\[
v = \frac{c}{n}
\]

(8)

where \( v \) is speed of light in the medium, \( c \) is speed of light in vacuum and \( n \) is the refractive index of the material. The Refractive index of material also causes dispersion which can lead to diffraction and this can be observed in diffraction by a prism (Al-Azzawi 2007)(Chartier 2005).

\[\text{Figure 23: Illustration of refraction phenomenon}^{13}.\]

\[\text{Figure 13: Illustration of refraction phenomenon}^{13}.\]

\[13 \text{ The figure is courtesy of "http://skullsinthestars.com"}\]
By using materials with different refractive indices a new optical system, for improvement of visual effects and a better dynamical experience, is proposed where it enhances the field of view for the nano-scale gratings as well as creating a 3D-like effect for the recorded images.

In this technique, diffraction gratings can be stored in different layers of a multilayer optical system (MOS). Materials with different refractive indexes are proposed to be used in the MOS and that allows the physical gratings to be perceived in 3D and by changing the angle of view different recorded features can be visualized. The MOS can be considered as an enhancement to the optical visual features.

### 3.2. Introduction to Machine Readable Features

A new technology has been introduced in which both visual effect and machine readability are incorporated. In this method arrays of nano-scale diffraction gratings are used to store information. This system uses a multi-state variable for data representation which allows more information to be stored as well as offering a natural physical compression for a given bit size. These features are capable of diffracting light which can be used as the first level of authentication and since this is a method for data storage, the proposed system directly becomes a machine readable technology.

The nano-optical features (NOF) can satisfy both machine readability and visual effect for authentication of documents. The NOF is capable of storing more information than other conventional systems. It offers 625 bit/mm² (for a four bit NOF system) with respect to its minimum feature size which is higher than magnetic stripes (11 bit/mm²). It should be noted that the NOF is a multi-state variable system, as opposed to common data storage technologies which are based on binary, and that increases the represented characters for the same number of bit/mm² in the binary system.

Here, two different types of NOF based on the method with which the stored data is read will be explained. There are also methods proposed for additional states of variation and data storage density.
The NOF is read only by a reader device which makes the system difficult to decrypt without the designated reading device. There is no physical contact between the reader and the NOF which will add to the life of the features. Since these features can be fabricated on polymer based substrate, they are a good candidate to replace the machine readable card technologies.

The fabrication of the NOF is enabled with EBL or FIB, but for high volume and automated fabrication, stamping is the ideal method of transferring the patterns onto a polymer based substrate. For that, a master mould for each of the arrays is required and the mould can be fabricated by EBL or other nano-fabrication techniques.

The MOS can also be used for enhancing the data density in storage. The optical bit system introduced in Chapter V can be stacked on top of each other but due to the refraction of light they will be perceived in slightly different positions and that would be interpreted as if they are on one surface rather than multiple layers.

The integrated features used for 3D effects are fabricated individually on each layer and that can be done by conventional nano-fabrication techniques as it will be explained in Chapter IV Section 4.3.1. The materials however are to be transparent with different refractive indexes and thickness. Features with different groove profiles can be used to control the dispersed rays which are to be perceived.
4. Chapter IV: Optical Visual Features

In Section 2.7, the relationship between the dispersion angle and the periodicity of the diffraction grating was explained. It was also noted that as the frequency of the grating increases (the space between the grooves decreases) the diffracted wavelengths of a polychromatic light becomes larger. In this chapter an explanation of how arrays of nano-hole on any type of substrate can act as a nano-scale diffraction grating will be presented (V. Grayli, et al. 2011). Furthermore it will be shown how a grating consisting of nano-structures is capable of increasing the angle of view for a specific range of wavelengths. These diffractive structures exhibit a noticeable color change effect and thus this effect can be used as an optical visual feature for the first level of authentication.

4.1. Nano-Scale Diffraction Grating

An array of nano-holes with the periodicity as small as a wavelength in the visible range (400 nm- 700 nm) is capable of diffracting light. The diffracted wavelengths are finely separated due to the high frequency of the grooves in the grating. The large dispersion angle of the diffracted light leads to a decrease in the orders of diffraction. For the gratings with periodicities from 700 nm down to 500 nm, up to two orders of diffraction are detectable (depending on the angle of incident light) but as the periodicity of the grating becomes smaller than 500 nm, only the first order of diffraction can be observed. By using numerical calculations (the simulation is programmed in Matlab), the diffraction orders and the dispersion angle of diffracted light can be predicted with respect to the angle of incident light. Figure 24 demonstrates the diffraction for two diffraction gratings with periodicities of 700 nm (top) and 450 nm (bottom) at 60° incidence angle of light, numerically calculated up to the third orders.
Figure 24: Demonstration of a) and d) first order, b) and e) second order, c) and f) third order of diffraction for gratings with 700 nm (top) and 450 nm (bottom) in periodicity. The incidence angle of light is 60°.

In this numerical calculation the grooves are considered holes with circular profiles on a transparent substrate without taking into account the refractive index of the material from which the substrate is made. Figure 25 illustrates the structure of the grating used for this simulation.

Figure 25: schematic of the structure of the grating used for the simulation of diffraction through arrays of nano-holes; diameter of the holes $D=200$ nm and period of the grating is $d=\lambda$ where $\lambda$ is a wavelength of light.
4.1.1. **Experimental Investigation**

In order to confirm the results obtained by numerical calculations, diffraction through nano-scale grating should be investigated. Therefore arrays of nano-scale grating with circular profiles with different periodicity were fabricated.

4.1.1.1. **Fabrication of the Nano-Scale Grating**

Nano-hole arrays were fabricated on polyethylene terephthalate (PET) substrates. It should be noted that these nano-structures can be made on, but not limited to, any transparent and flexible material such as glass or transparent polymers. The PET substrate was washed thoroughly with acetone, 2-propanol (IPA), deionized (DI) water and dried with a N$_2$ gun. Subsequently, a thin layer of 5 nm of chromium (Cr) was sputtered on one side of the PET substrate to create a thin conductive surface for the milling. The nano-holes were milled into the PET using a FIB (Strata DB235). Thereafter, the conductive Cr layer was etched using the wet etching technique. The fabrication steps are depicted in Figure 26.

![Figure 26: Schematic of the fabrication steps: a) clean substrate and b) deposition of a thin conductive layer via physical vapour deposition (PVD), c) milling of the nanostructures using a FIB, and d) etching of the thin metallic layer.](image)

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Figure 26: Schematic of the fabrication steps: a) clean substrate and b) deposition of a thin conductive layer via physical vapour deposition (PVD), c) milling of the nanostructures using a FIB, and d) etching of the thin metallic layer.
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The fabricated arrays of nano-holes on the PET substrate are shown in Figure 27. The arrays are 400 nm, 550 nm and 650 nm in periodicity. The picture is taken in a way that the glow on each array represents the periodicity of the corresponded array.
4.1.1.2. Experimental Setup

A polychromatic tungsten halogen light source was used as the lighting component. The light was being directed through a fibre optic cable. A collimator lens was placed at the end of the fibre optic to create a collimated light source. The collimator head was mounted to an 8 cm long rod. The end of the rod was placed in the center of a protractor with which reading of the incidence angle of light for each measurement was enabled. An array of nano-holes was attached to a condense lens (0.22 NA) via which the transmitted spectrum was being collected. The condense lens was connected to a Mightex HRS-VIS-025 spectrometer through a fibre optic cable. The condense lens was fixed in a way that the array of nano-holes was located at the center of the protractor. The light source had the capability of rotating 180° around the array of nano-holes. The setup was designed to only measure the diffracted wavelengths which leave the plane of substrate with an angle normal to the surface therefore the separation of the diffracted wavelengths and the relationship between the detected wavelengths and the angle of incident light could be visually observed. The aforementioned experimental setup used to measure the angle dependency of diffracted wavelengths is shown in Figure 28.
4.1.1.3. Experimental Results

Three 3 mm x 3 mm arrays of nano-holes and one 4 mm x 5 mm array of nano-holes fabricated on a transparent sheet of PET were used to measure the diffraction capability of these structures using the aforementioned method. Starting from the angle normal to the surface of the nano-holes array ($\alpha = 0^\circ$), after the detection of the 1st wavelength, as the angle of incidence light changes, the detected wavelength for a 650 nm periodic nano-hole gratings shifts from 400 nm (blue) towards 600 nm (red). The angle at which the first detection occurred was different for arrays with different periodicities. The array with smaller periodicities had a larger separation for diffracted wavelengths and the detected spectrum had a narrower bandwidth which indicates the large angle for dispersed wavelengths. Figure 29 shows the experimental measurement on the 4 mm x 5 mm array with 650 nm in periodicity and the simulated results on an array with the same periodicity for the 35° angle of incident light at which the first wavelength was detected. It is noticeable that the numerical results and the experimental
results show the same range of diffracted wavelengths leaving the array with a normal angle at 35° angle of incidence. See appendix A for the complete comparison.

Figure 29: a) The simulation on array with 650 nm periodicity for 35° angle of incident light, b) the spectral measurement on the 4 mm x 5 mm array of nano-holes; plot legend indicates the wavelengths and the corresponded incident angle of light. The dash lines indicate the calculated wavelengths for the specified angle of incidence for array with 650 nm in periodicity.

The spectrometry and simulated results for 70° of incident light on the array with 450 nm in periodicity are shown in Figure 30. Once again the simulated results and experimental results confirm that at 70° angle of incidence, the diffracted wavelength which is normal to the surface is in the same range. However the wavelength which is calculated with the equation (3) shows that there is a difference between the experimentally detected peak and the predicted wavelengths. The difference can be due to the error on fixing the exact angle of incident light during the measurement or a change in the position of the condenser lens which in turn could have led to collecting the wavelengths at different angles rather than normal to the surface of the grating. Similar difference can be noticed in Figure 29 where the peak of detected wavelengths does not match the calculated wavelengths for the corresponded angle of incident light.
4.2. Diffraction Grating with Large Angle of View

A diffraction grating which is capable of holding one color across its surface for a large angle of view can be very beneficial especially in the field of security and authentication. The designing of such a grating can be very challenging since the perceived color (wavelength) at a specific angle has a direct dependency on the angle at which the grating is illuminated. Any small changes to the angle incident light leads to the change of the color to the eyes of an observer at the primary viewing position. Such a problem was resolved by using a grating which consists of three alternating periodicities. The grooves for each line of the grating are spaced so that the same wavelength is dispersed in three different angles for a fixed angle of incident light. For instance, at the angle of incidence $\alpha$, the periodicity $P_1$ diffracts wavelength $\lambda$ at the $0^\circ$ angle (normal to the grating), periodicity $P_2$ diffracts wavelength $\lambda$ at the angle $\beta$ and periodicity $P_3$ diffracts wavelength $\lambda$ at angle $-\beta$. Selectivity of wavelength in human eyes is limited therefore to a close range of wavelengths that can be perceived as one color while the same range consists of multiple wavelengths once it is measured by a spectrometer. This limitation of the human eye was used as an advantage to create a diffraction grating which is capable of maintaining the same color. The angle of view for
one color will be the sum of $\beta$ and $-\beta$ which is around $20^\circ$-$30^\circ$. Figure 31 illustrates the cross section of a numerically calculated diffraction pattern of three lines of a color holding grating.

![Figure 31: Numerical calculation of a color holding grating at the cross section. $\theta$ is the angle of view for color a) blue, b) green and c) red.](image)

The diffracted wavelength for each line of grating was predicted by:

$$\beta(\lambda) = \arcsin\left(\frac{n\lambda}{d} - \sin \alpha\right)$$

which is derived from equation (1).

### 4.2.1. Fabrication Method

Three arrays of color holding grating were fabricated on quartz (fused silica) using EBL. The quartz substrate was first cleaned using the Radio Corporation of America (RCA) recipe for removing organic materials. This recipe is also known as RCA1 in which ammonium hydroxide ($\text{NH}_4\text{OH}$) and hydrogen peroxide ($\text{H}_2\text{O}_2$) are mixed with DI water in a ratio of 1:1:5. The solution must be at the temperature of $75^\circ$-$80^\circ$ before the process begins. The quartz substrate was kept in the RCA1 solution for 10 minutes and then it was rinsed in water for 2 minutes and finally it was blow dried by $\text{N}_2$ gun. A thin layer of Cr was deposited using PVD system as the conductive layer on the quartz. Depending on the type of PR (positive or negative) different technique can be
used to fabricate the color holding grating. In the event of using negative resist, such as maN-2403 or hydrogen silsesquioxane (HSQ), the lift-off process will be used in order to obtain the final grating pattern. In this process the pattern will be written on the PR using EBL and after development, the surface of the substrate will be filled with the PR nano-pillars which are the remaining of the resist. The desired metal then is deposited using PVD. It should be noted that the height of the deposited metal should be less that the height of the PR pillars. Finally the PR will be dipped in acetone (for maN-2403 and HF for HSQ) to remove the PR and that leads to creation of nano-holes. The metallic layer can be used as a mask in order to transfer the pattern onto the quartz substrate. That is enabled by a proper RIE recipe. Figure 32 illustrates the fabrication steps using maN-2403.

**Figure 32**: Schematic of fabrication steps of color holding nano-grating by EBL. a) EBL pattern after deposition of Cr and maN-2403, b) development of PR, c) Deposition of Cr, d) lift-off process, e) transferring the pattern onto the quartz by RIE, f) Cr etch and finished grating.
By using the explained fabrication method three 5 mm x 10 mm arrays of nano-scale diffraction grating were fabricated. These arrays were designed to maintain colors blue, green and red across the surface of the grating (Figure 33).

![Demonstration of three 5 mm x 10 mm arrays of nano-diffraction grating with color holding capability.](image)

**Figure 33:** Demonstration of three 5 mm x 10 mm arrays of nano-diffraction grating with color holding capability.

It should be noted that these types of arrays can only hold color once the incident beam of light reaches the grating from a certain direction. Figure 34 demonstrates the direction at which these grating are capable of diffracting the light so that a large angle of view for a specific color is enabled.

![Schematic of a color holding diffraction grating.](image)

**Figure 34:** Schematic of a color holding diffraction grating. At the demonstrated configuration the array is capable of maintaining a color once the beam of light reaches the grating along x-axis as it is shown in the figure. d is the spacing between each line and \( P_1, P_2 \) and \( P_3 \) are periodicities of each line.
The difference of in the periodicity between each two adjacent grating should be 25 nm, for instance, in Figure 34 $P_2 = P_1 + 25$ nm and $P_3 = P_2 + 25$ nm.

### 4.3. Enhancement of Optical Visual Features with a Multilayer Optical System

A multilayer optical system (MOS) consists of optical components making use of the spatial depth of the device (i.e. different levels). This configuration allows the optical components to be located on different layers at different depth, thus creating a 3-dimensional-like device where the optical features are stored and displayed using several layers. The advantage of this system is in its physical density of the features populating not only in one plane but in several planes. A holographic storage device is a perfect example of a 3D multilayered optical system. In holographic technology, the data is being stored in different layers and consequently the storage capacity is enhanced (Hunter, et al. 1990).

In the MOS, the third dimension is added to the configuration of an optical system which reduces surface area required for similar system in a 2D configuration setup. The MOS uses the optical property of the materials used at each layer as well as the diffraction capability of the grating incorporated in its structure.

The holograms, holographic gratings and the nano-structural diffraction grating use diffraction phenomena to create a colourful image under white light illumination. The representation of 3D patterns in only one plane is limited by the physical proximity which leads to the cross talk between the fabricated features thus reduction in clarity of the observed image. Consequently, a limited number of features can be recorded in a small area.

As it was explained in section 2.8, the created interference pattern of a hologram can be transferred onto a rigid substrate to create a holographic grating. The advantage that holography on a film has is the ability of storing various interference pattern on the same plane in different angles therefore multiple image can be observed on the same surface area in a hologram only by tilting the film in different directions (Figure 17),
however this is not the case for holographic gratings since they are physical periodic patterns fabricated on a substrate.

By using the nano-structures, artworks with unique brilliance and colour pattern can be made through simple diffraction, and similar to holographic gratings only one pattern can be fabricated on one plane. The MOS presented here enables storing of several images/patterns in different planes (c.f. Figure 35); mimics a holographic effect, and through lighting-up different images at various angles a 3D-like moving objects can be observed.

![Figure 35: Schematic of a multilayered optical system with several images fabricated in different layers: a) different features can be fabricated on different layers, b) the layers stacked together.](image)

The advantage of using the third dimensional axis (i.e. depth) to store multiple gratings in a confined surface area, allows the system to have similar behaviour as holographic devices. The effect perceived by the naked eye has a great dependency on the profile of the grating, refractive index and the thickness of the materials. Figure 36 shows two views of the MOS depicted in Figure 35 under two different viewing angles.
Figure 36: This figure illustrates how the fabricated patterns in different layers can be perceived at different viewing angles.

Figure 37 Demonstrates a MOS fabricated on two layers of Polydimethylsiloxane (PDMS). It should be noted that refractive index of PDMS is 1.4 which is fairly higher than air.

Figure 37: A MOS fabricated on PDMS; the image is scanned with 300 dpi resolution.
4.3.1. Fabrication of the MOS

The nano-structural features can be fabricated in or on the different MOS layers using various techniques, mentioned in the previous chapters. The key factor in MOS is the index of refraction of the material and their thickness which can be tuned to selectively define the angle and the position of the features at each viewing angle. The choice of materials can differ based on the requirement of the application. A combination of transparent, semi-transparent (transparency to certain wavelength only), translucent materials can be used at different MOS layers to achieve the desired optical effect. It should be noted that the adjacent MOS layers needs to have different refractive index and/or thickness in order to maintain the optimal 3D optical effect. The difference in refractive index of the materials needs to be carefully chosen to optimize the desired visual effect.

Casting and NIL are two techniques which have shown a great potential for large-scale fabrication. The nano-features used in MOS can simply be casted or embossed on the different layers, and then the layers can be stacked and capsulated using a flexible and transparent polymer or elastomer. In some cases, a very thin adhesive layer can be used in between the layers. The profile and the position of the grating dictate the angle at which the light is diffracted thus defining at which viewing angle the color will be observed. Figure 38 illustrates an example of a possible scenario of nano-features fabricated in different layers of a MOS.

Figure 38: The nano-structural grating can be placed in variety of positions in a MOS in different layers.
4.4. Chapter Summery

An array of nano-holes with periodicity in the visible spectrum (λ) and hole diameters smaller than λ/2 acts as a diffraction grating. The depth, profile and width of the nano-features define the intensity of the diffracted wavelengths which is substantially higher than conventional micro-scale gratings. The fabrication of nano-scale diffraction gratings can be performed, but not limited to, using focused ion-beam (FIB), electron-beam lithography (EBL), laser interferometry, nano-imprint lithography (NIL), etc.

The periodic nano-hole arrays fabricated on a transparent polymer based substrate can create diffraction pattern and act as a transmission grating. Since the periodicity of the grating is in nano-scale, there is a large separation between the diffracted wavelengths and this is due to the larger angle of dispersion. The narrow bandwidth of the detected wavelengths also confirms the capability of fabricated structures in creating a diffraction pattern with a great dispersion. The detection of diffracted wavelengths was done through far-field spectroscopy under illumination of a polychromatic collimated light source.

Due to the nano-scale nature of the array, the order of diffraction is limited to the second mode for the 500 nm and 600 nm and to the first mode for the 400 nm. The detected wavelength is directly dependent on the angle of the incident light. Using far-field spectroscopy it is shown that these nano-hole arrays can act as a good transmission diffraction grating with a wide separation between adjacent wavelengths. Considering the numerical aperture of the detector (0.22 NA) and the condense lens (4 mm in diameter) it is concluded that for every 5° change, there is a 50 nm shift in the detected wavelength. This is translated to 10 nm shift for every degree in change of the angle of the incident light. By decreasing the diameter of condense lens and the numerical aperture, a better resolution can be achieved.

It is known that a diffraction pattern is dependent on the shape and profile of the gratings and. Consequently, a periodic array of sub-wavelength apertures of ~100 nm in diameter is expected to generate diffraction patterns in both x and y directions with a pattern consisting of circular spots.
By using nano-scale diffraction grating and placing them in an alternating order, creating a grating which is capable of maintaining color across the surface of the grating has been enabled. A grating with three lines, where each line has a different periodicity, can increase the angle of view for a specific color once the beam of incident light illuminates the grating from a certain direction. The angle of view for such grating for a tuned color is 20° to 30°.

The refractive index of material is used to create an optical system in which depth is added to its existing dimensions enabling 3D representation of images. This has been achieved by stacking materials with different refractive index. By choosing transparent materials with relatively high and low refractive index as different layers a MOS can be made. Thickness of the layers also plays an important role in observation of the features recorded in the layers.

Features in a MOS are in fact diffraction gratings which are fabricated and placed within the layers. The profile of the grooves can be used to define the angle of dispersion and therefore an illusion of moving object can be perceived. Such illusion can be seen in holograms where different interference patterns are recorded on a holographic film in different angles but this cannot be made using diffraction grating since there are physical features fabricated on the surface; however this has been enabled with a MOS.

The MOS layers are made of flexible transparent materials differing in thickness and refractive index. The features used in the MOS layers are diffraction gratings with different groove profiles and periodicities. The gratings can simply be fabricated by NIL or via casting.
5. Chapter V: Machine Readable Features

A novel method of physically representing information is being proposed using NOF with which data can be stored and encoded. The NOFs consist of arrays of nano-scale diffraction gratings differing in periodicities. The nano-scale nature of the features allows for a better color separation which in turns adds to the number of distinct colors being perceived by the reading device. Information can simply be represented by combining different features differing in shapes/orientations/colors (Figure 39), orientation/colors (Figure 40) or only combination of different colors (Figure 41). Just like diffraction grating, NOF can also be categorized under transmission NOF (transmitted wavelengths will be detected) and reflection NOF (reflected color will be detected).

![Figure 39: Color, shape and position can be used to represent information with NOF a) combination of triangles differing in colors and orientation can be used to encode information, and b), c), d) combination of features differing in color and shape can be used to encode information.](image)

a)  

b)  

c)  

d)  

*Figure 39: Color, shape and position can be used to represent information with NOF a) combination of triangles differing in colors and orientation can be used to encode information, and b), c), d) combination of features differing in color and shape can be used to encode information.*
Figure 40: One geometrical shape can be used to encode information by alternating both the color and the orientation.

Figure 41: Illustration of the simple representation of data by using only combination of different colors.

Adding more variables (such as different positions, angles, geometries, colors, etc.) to the presented coding scheme will increase the capability of the system to represent data which in turns allows NOF to encode more characters.

5.1. Transmission NOF

The readability of NOF depends on the application and the reading device. NOF can be read through transmission in which the transmitted wavelength is detected and used for the data encoding. To read the desired signal, the sensor is designed to detect diffracted light normal to the plane of the substrate. Consequently using a fixed angle of incident light with a combination of multiple arrays differing in periodicities, information can be encoded and represented in terms of light spectrum. Figure 42 illustrates a
schematic of a system in which authentication occurs through detection of optical signal created by transmission NOF. The colors of the features represent the detected wavelengths.

Figure 42: Schematic of a transmission NOF-based system in which the authentication of the card will be through the optical signals.

Depending on the reading system, the detection of the signals can be simultaneous (Figure 43) or sequential (Figure 44).

Figure 43: Combination of three different optical signals through transmission NOF detected simultaneously.
Figure 44: Sequential detection representation: a) and b) after the detection of the first signal, letter “N” will be printed on the screen, c) and d) second signal at 500 nm decodes into letter “T”, and e) and f) letter “S” appears on the screen after the third at 400 nm gets detected.

Figure 45 illustrates an example of a card made using transmission NOF. The detections depicted in Figure 44 are the optical signals read from the card shown in Figure 45.

Figure 45: Illustration of transmission NOF on a card which was used to encode the three letters shown in Figure 44.

5.2. Reflection NOF

The NOF can be read in reflective mode as well. The diffracted light can be simply detected and the assortments of colors will be used to represent data. The data density depends on the feature size. The detected color also depends on the angle of the incident illuminating the features. A color sensor (e.g. CMOS or CCD) is required in order to capture a full color image of the features. The size of the features depends on
the resolution of the reading device; larger NOF can be read by low resolution systems such as camera phones, while smaller features require high resolution systems such as optical scanners with at least 2400 dpi in resolution. Figure 46 depicts a 9600 dpi scanned image of 20 x 20 μm² arrays of NOF spaced by 20 μm.

![Figure 46: Three colors can be distinguished in a 9600 dpi scanned image of 20 x 20 μm² arrays of NOF.](image)

The minimum feature size defined for reflection NOF is 20 μm² while the features are spaced 20 μm apart from one another (Figure 46). This the maximum power with which a scanner like optical sensor can detect. Even with 20 μm spacing the cross talk between the features is inevitable and that shows how the separation between features is critical for color detection once the pattern is read.

The minimum feature sizes were defined by choosing four array sizes of 2 μm², 5 μm², 10 μm² and 20 μm². These arrays were fabricated in three different periodicities placed next to each other to investigate the color distribution of the arrays with respect to their grating frequencies and the angle of incident light. In order to scrutinize the cross talk effect and the minimum spacing between the arrays, for each array size four different spacing was designed so that nine arrays of the same dimension but different in periodicity (three of each color in one column) were spaced by 2 μm, 5 μm, 10 μm and 20 μm. Furthermore, the sample was scanned by an HP Scanjet G400 optical scanner with 9600 dpi resolution. Figure 47 demonstrates the fabricated features on a quartz substrate.
Figure 47: Demonstration of fabricated NOF for defining the minimum feature size. The smallest cross talk can only be observed in arrays of 20 μm² with 20 μm separation.

In Figure 47, three colors of red, green and blue can be easily detected for 20 μm² arrays which are spaced by 20 μm.

5.3. Data Storage Capability

In this work a new method for storing as well as encoding data is being presented in which information will be physically represented as sequence of nano-scale diffraction gratings on a document. Colors in the NOF system are in fact the base which will be used in order to represent one single value. This gives a major advantage to the NOF against other technologies where binary system is used for data representation. In the next section a brief comparison will be done between the binary as a based 2 system and the multi-dimensional system on which the NOF is based where colors are used to increase the number of the base used for data representation.

Barcodes as a method for physically representation of data are the closest technology to the NOF. However due to the reasons mentioned in section 2.2 barcode cannot be considered a technology with a high level of security. In theory there is no data storage limitation for barcodes since their capacity depends on the physical space
but it is very impractical to store kilo bytes of data, an image for instance, with barcodes where a large area is required for the whole information to be represented.

The NOF, as a technology for physically representation of information, is capable of storing any type of data (image, text, numerical, etc.) in a very small area. To demonstrate the data storage capability of the NOF, as a first attempt, arrays of 200 μm x 200 μm of NOF were fabricated to record a 300 bit image. The minimum defined base for NOF is 4; therefore three colors and one empty space were used to represent this image. In total an area of 6 mm² was needed for storing 300 bits of data using 200 μm² features. Figure 48 demonstrates the encoded image as well as the NOF used for data storage.

![Figure 48: 300 bit image stored with 200 x 200 μm² features in an area of 6 x 1 mm². In this sample combination of colors and positions are used for representing the information.](image)

This pattern was scanned by an HP Scanjet G400 optical scanner at 9600 dpi resolution. The coded image was successfully reconstructed back to the original image using matlab. The reconstruction procedure is part of another project done by Siamack V. Grayli as a section of his master thesis, thus it will not be presented in here.

As the second attempt, larger images were chosen to demonstrate the NOF’s data storage capability within a small physical area. Furthermore, as a measure of comparison between the NOF and the barcode technology, a web link was encoded using both systems. For this demonstration arrays of 50 x 50 μm² of NOF were fabricated on gold coated quartz substrate. These arrays were spaced 80 μm apart from each other (Figure 49).

In general, the decrease of the feature sizes allows more information to be stored in a smaller area, which translates in an increase in data density. Nevertheless, to read
the smaller feature sizes, a high resolution image capturing device is needed in order to prevent the cross-talk between the features.

![Image of reflective NOF arrays](image)

**Figure 49:** 50 x 50 μm² arrays of reflective NOF were used to encode two images and a web link. The longest stripe (apple) is 1.4 cm in length and contains 11 Kb of data.

In Figure 50 the enlarged NOF pattern used for encoding the image of the apple is shown. A good color distribution between the arrays is noticeable. It should be noted that a solid color distribution will help in a better and more accurate detection of the colors and patterns during the reading process.

![Image of reflective NOF array](image)

**Figure 50:** Three colors of red, green and blue can be noticed. The NOFs were tuned for the detected colors.

Figure 51 demonstrates some of common 2D barcodes which are used to store the web link http://www.ID-ME.ca/. Simple visual comparison shows how much physical spaced will be saved to represent this web link with the NOF (Figure 52).
Figure 51: Demonstration of the web link "http://www.ID-ME.ca/" by six commonly used 2D barcodes.

Figure 52: Comparison of barcodes with NOF with respect to their required physical space for representation of the same set of data.

5.4. Dual Grating

For each array of NOF, the periodicity of the nano-structures defines the color of the features. The diffraction, depending on the angle of the incident light beam, can be very directional. In a square lattice, the desired diffraction pattern is perceived along the x- and y-direction (Figure 53). In this configuration, the spacing between the grooves is the same in either direction therefore no matter how the arrays are illuminated the observed color will be always the same for a fixed angle of incident light and diffraction angle.
This directional diffracting capability of diffraction grating can be used as an advantage to create a system which is capable of diffracting light differently along x- and y-axis. In the proposed technique, the information is stored using the diffraction pattern, or in other words by changing the periodicity along one of the axis (Figure 54). This increases the capacity of each NOF array for data storage by two-folds. In this new configuration, the NOFs will be read twice (once along the x-axis and once along the y-axis) which correspond in an increase of the data density within the same surface area.
once along $y$-axis. The different color distribution on the surface confirms the difference in diffracted pattern at the scanned direction.

Figure 55: Demonstration of NOF with double periodicity: a) the NOF is scanned along the $x$ direction; b) the NOF is scanned along the $y$ direction.

As it was mentioned the dual grating structures are doubling the storage capacity of the NOF. Information can be digitally compressed before it is converted to the NOF system. The data compression techniques mostly create an error function as residue for the target file which will be used later for reconstruction of the compressed data. The dual grating configuration increases data storage capacity without increasing physical surface area and that allows digitally compressed data along with the generated error function to be stored on a document. This also can be used as a method to digitally encrypt data before representing them with the NOF.

5.5. Alternative Encoding Vs. Binary System

In a binary system each bit takes a value from a set of $S= \{0, 1\}$. Hence any number ($I$) can be represented in binary using a base 2 system as following (Haykin 1988)(Shiflet 1987):

$$ I = \sum_i S_i x s^i $$

(10)
The disadvantage of the binary encoding system is the increasing number of bits for representing a certain value. The proposed method uses a system with set S based on a broad variety of coefficients, which requires fewer units to represent any giving value. As a result, the physical storage space for encoded values also decreases in correlation with the decrease in the number of unit information required to represent the data. The maximum value that can be represented based on the binary system \( (N) \) in comparison to the NOF system \( (N') \) takes the form of (Haykin 1988)(Karris 2007):

\[
N = 2^M \\
N' = m^M
\]  

(11)

(12)

where \( M \) and \( m \) are respectively the number of unit information available to represent the information and the base of the NOF system. The improvement achieved by using a base \( m \) in the NOF system. In the NOF data representation scheme, the number of colors used in the system determines the base \( m \); therefore as many color (or wavelength) as the optical sensor detects can be incorporated.

NOF is a nano-scale diffraction grating that is used to diffract an incident beam of polychromatic light into angularly dispersed wavelengths, where for each particular wavelength, the changes made to diffraction angle as a function of grating periodicity and this can be viewed as the states of variation for that NOF. To store the decimal value 9, the binary system requires minimum 4 bits, whereas the base 4 system only needs 2 units information. Thus a natural compression ratio of 2 is achieved by merely using a system that counts bases of 4 instead of one which counts bases of 2 (binary system). An example of advantageous use of a base 4 rather than binary for storing information can be the typical 8-bit storing standard scheme where one 8-bit cluster can represent up to a maximum of 255 different values and the same range is covered by four base-4 unit information (base 4 bit). The ability of the NOF to achieve small physical dimensions along with large angular dispersion makes it a suitable choice for unit information that can have more than two states of variation based on the dispersion angle.
The possibility of having more than 2 states of variation as a new counting base enables NOF encoding system to store data in the form of numerical values. The range of the maximum achievable value is defined by the maximum number of unit information implemented in the architecture of the encoding scheme. As an example if the base is chosen to be 4 (i.e. four wavelengths are chosen to represent the states of a NOF) and 4 unit information are chosen to represent the numerical data, the range is between 0 and 255 (Gonzalez and Woods 2002), which include possible input type such as RGB images, binary files, text, biometric information, etc.. The NOF using the base 4 system can be combined with standard and innovative compression algorithms in order to decrease the amount of the data to be stored. The compression algorithm can either be lossy or lossless. A lossy compression algorithm such as JPEG family considerably decreases the amount of data at the expense of the resolution. On the other hand, the lossless compression techniques preserve the original resolution with a smaller compression ratio, which is associated to a minor decreasing in the amount of data (Sayood 2000).

5.6. Optical Coding Chart

In previous sections it was shown how arrays of NOF can be used to record and encode information by using the diffracted spectrum. The NOF recording/encoding scheme uses multi-state variation system for data representation rather than binary. But it is also beneficial to have an encoding system that is used for communication between computer equipments such as ASCII.

In the ASCII chart, the characters are encoded based on different systems such as binary, decimal, hexadecimal, HTML (used in web), octal, etc. which are recognizable for different programs and equipments. Figure 56 demonstrates the ASCII characters with their designated decimal and binary codes.
The nano-scale diffraction gratings can be also used to represent data numerically. The digits represented by the coding chart can be also assigned to a computer readable language such as ASCII to display all possible characters and symbols. This optical coding chart is based on decimal representation of numbers (i.e. based 10) which is being populated by arrays of nano-scaled gratings with different periodicities (Figure 57).

Figure 56: Representation of ASCII characters by binary and decimal codes. The figure is courtesy of “www.geocaching.com.”

<table>
<thead>
<tr>
<th>Binary</th>
<th>Decimal</th>
<th>ASCII character</th>
</tr>
</thead>
<tbody>
<tr>
<td>01000001</td>
<td>65</td>
<td>A</td>
</tr>
<tr>
<td>01000010</td>
<td>66</td>
<td>B</td>
</tr>
<tr>
<td>01000011</td>
<td>67</td>
<td>C</td>
</tr>
<tr>
<td>01000100</td>
<td>68</td>
<td>D</td>
</tr>
<tr>
<td>01000101</td>
<td>69</td>
<td>E</td>
</tr>
<tr>
<td>01000110</td>
<td>70</td>
<td>F</td>
</tr>
<tr>
<td>01000111</td>
<td>71</td>
<td>G</td>
</tr>
<tr>
<td>01001000</td>
<td>72</td>
<td>H</td>
</tr>
<tr>
<td>01001001</td>
<td>73</td>
<td>I</td>
</tr>
<tr>
<td>01001010</td>
<td>74</td>
<td>J</td>
</tr>
<tr>
<td>01001011</td>
<td>75</td>
<td>K</td>
</tr>
<tr>
<td>01001100</td>
<td>76</td>
<td>L</td>
</tr>
<tr>
<td>01001101</td>
<td>77</td>
<td>M</td>
</tr>
<tr>
<td>01001110</td>
<td>78</td>
<td>N</td>
</tr>
<tr>
<td>01001111</td>
<td>79</td>
<td>O</td>
</tr>
<tr>
<td>01010000</td>
<td>80</td>
<td>P</td>
</tr>
<tr>
<td>01010001</td>
<td>81</td>
<td>Q</td>
</tr>
<tr>
<td>01010010</td>
<td>82</td>
<td>R</td>
</tr>
<tr>
<td>01010011</td>
<td>83</td>
<td>S</td>
</tr>
<tr>
<td>01010100</td>
<td>84</td>
<td>T</td>
</tr>
<tr>
<td>01010101</td>
<td>85</td>
<td>U</td>
</tr>
</tbody>
</table>
The diffracted wavelength at each section will represent the number designated to that specific grating. Figure 58 shows an example of how numbers are being represented in this system using only one color per section.

As a demonstration, the aforementioned optical coding chart was used to encode the word “SIAMAK” with three red, green and blue colors in a decimal system. The chart was printed with these colors with a dark background. A HD Microsoft webcam was used to take an image from the chart. The image was then read and decoded by the Matlab.
code written by Siamack V. Grayli. It should be noted that the imaging, reading and decoding were automatically controlled processes. The decoded information contained the decimal representation of numbers which were used to recall the corresponded ASCII characters which results in displaying the word “SIAMAK”. Figure 59 illustrates the chart used for this demonstration. In reality these colors will be perceived from the diffracted light caused by the grating. The number of the nano-scale diffraction grating can be increased which consequently will increase the number of digits that can be represented per chart.

![Figure 59: Demonstration of the optical coding chart used for encoding the word “SIAMAK”.

5.7. Fabrication of NOF

The NOF can be fabricated using various nano-fabrication techniques. The method used for fabrication of NOF is the same as it was explained in section 4.1.1.1 (for transmission NOF) 4.2.1 (for reflection NOF). The encoded patterns shown in Figure 48 and Figure 49 are fabricated on quartz based substrates. The steps of RCA cleaning and fabrication were explained in previous chapter and thus it will not be included in this section. In order to create the NOF on flexible polymer based material, the coded pattern can be fabricated in shape of nano-pillars where it could later be transferred onto the polymer substrate using NIL technique.
5.8. Reading Device for NOF

For an array of NOF, the observed wavelength (or color) at a given angle depends on the angle with which the grating is illuminated and the periodicity of the array. Based on these parameters data storage with the NOF has been enabled. In order to read these features a device consists of a polychromatic light source and a light detecting sensor (i.e. CCD or CMOS) is required. The light source has a fixed angle and that is the angle with which the surface of the arrays of NOF will be illuminated. To maintain a homogenous illumination on all of the arrays, the device should be able to scan the entire surface without changing the angle of the light beam. The detector will then records the image of illuminated arrays as the light source continues to scan the surface. The result will be the colourful pattern of NOF as it is shown in Figure 48 and Figure 49. In Figure 60 schematic of detection over one array is illustrated.

**Figure 60: Schematic of a reading device used for reading the NOF. At the reconstruction sector authentication of the coded pattern takes place.**

In the event of using transmission NOF the reading device will record the combination of diffracted wavelengths and the authentication will take place by combination of detected spectrum rather than colors. Therefore a spectrometer like detection system is required. However the entire surface has to be scanned to eliminate the possible error which can occur due to the change of the angle of incident light.

Based on the array size of the NOF, different devices can be incorporated in the reading scheme. Consequently, different level of security is offered depending on the type of the reader (Figure 61).
Figure 61: Demonstration of reflective NOF in variety of sizes. The smaller feature sizes require readers with higher resolution

Larger arrays do not require a high resolution sensor; therefore a cell phone based detector can be simply used to record the image. The absence of scanning light source for a cell phone based reader can be a challenge for acquiring an image in which the NOF coded patterns are in the correct color combination. This problem can be resolved by creating reference arrays. These reference arrays are in fact large arrays of nano-scale diffraction gratings with fixed periodicities. There is only one correct color combination for the reference arrays and this is predefined for the software which the cell phone uses for decoding. In practice this one and only combination of the reference arrays indicates the designated angle of incident light with which the coded pattern will have the correct color combination. Figure 62 illustrates a possible cell phone based reading scheme.

Figure 62: Illustration of the cell phone based reading scheme of the NOF.
In such a reading scheme, the coded pattern will be automatically read once the right combination of colors for the reference arrays is detected.

5.9. Enhancement of the Machine readable Features with a Multilayer Optical System

It was explained and shown in the previously how the NOF can be used to store data by using diffractive property of nano-scale gratings. This innovative recording/encoding system uses the colors created by a diffraction grating to represent data. Thus far, the features were stored on one plane, and the data density was bound to the number of arrays representing one set of data (an 8 bit binary system uses 8 bits to represent data, while here we use 4). For instance by using a MOS-based technology, 4 nano-structure arrays can be stored in 4 different planes, reducing by 4-fold the surface area needed to store similar amount of data on none MOS-based devices. Figure 63 demonstrates a possible approach on how different layers are used to allocate the nano-features representing data.

![Demonstration of 4 different arrays placed in 3 layers. The arrays are in line with one another (i.e. directly underneath).](image)

Figure 63: Demonstration of 4 different arrays placed in 3 layers. The arrays are in line with one another (i.e. directly underneath).

Depending on the thickness of the layers, the nano-features can be fabricated on either one side or on both ends of the same layer. In MOS scheme, the density of the data on one surface will be reduced by factor of “n”, where “n” is the number of the layers used to store the features in.
Scanner like system can be used as an inexpensive and affordable reading device for the aforementioned optical encrypting system. The key factors for reading the features are the thickness and the refractive index of materials used to create the MOS. In contrast the features during the reading will be observed in different planes and depth (Figure 64) rather than one plane, thus a major decrease in physical data density which will be followed by increase in amount of data stored using similar physical area.

![Figure 64: The arrays which are located in multiple layers on top of each other are perceived in different colors and positions depending of the viewing angle.](image)

The detailed fabrication of the MOS has been explained in chapter IV section 4.3.1.

### 5.10. Chapter Summary

The ability of nano-scale diffraction grating offers a good selectivity for diffracted spectrum. The wavelengths which were dispersed as the result of diffraction can be used for storing information. The data then can be physically represented as a combination of colors or wavelengths using the nano-scale gratings. In this recoding/encoding technique, for a fixed angle of incident light, a unique optical signature can be detected at a fixed viewing angle (normal to the surface for example) for every array with a different periodicity. An encoding scheme as such offers two levels of security. The first level is visual authentication which is enabled by observation of...
diffraction pattern (color changing of the coded pattern). The second level of authentication is done by a reading device with which the NOF pattern will be decoded and the stored data will be displayed.

Based on the type of the grating, two types of NOF exist:

- Transmission NOF
- Reflection NOF

In the transmission NOF, the diffracted wavelengths in transmission, as a combination of different spectrum, are used for encoding information whereas in reflection NOF the reflected wavelengths, which are perceived as colors, are used for encoding.

Information can simply be represented by combining different features differing in shapes/orientations/colors, orientation/colors or only combination of different colors and by adding more variables (such as different positions, angles, geometries, colors, etc.) to the presented coding scheme the capability of the system to represent data will be increased which in turns allows NOF to encode more characters.

Storage capability of NOF can be increased by using dual grating in which the spacing between the grooves along $x$- and $y$-axis is different and thus two different colored patterns will be achieved along these directions.

The NOF encoding scheme uses a multi-state variation system for data representation and uses colors for its states of variation whereas binary uses only two states of variation. A natural physical compression is achieved by this scheme which is a great advantage for data storage.

The nano-scale grating can also be incorporated in chart with which data and characters are represented numerically. This chart uses decimal representation of numbers and that can be also used for direct mapping of the pattern encoded by this optical chart to the ASCII chart for displaying the corresponded character by the reader.
The fabrication of the NOF can be performed, but not limited to, using focused ion-beam (FIB), electron-beam lithography (EBL), laser interferometry, Nano-imprint lithography (NIL), etc. A master shim can also be fabricated using one of the aforementioned techniques to replicate the features on a substrate via hot embossing or casting. The choice of materials can differ based on the requirement of the application. A combination of transparent, semi-transparent (transparency to certain wavelength only), translucent materials can be used and implemented.

A reading device for the NOF requires a light source and a detector with fixed angles. The surface of the arrays of nano-scale diffraction grating with different periodicities will diffract the incident beam differently and thus different colors or wavelengths will be detected by the detector. The detector records every section which is scanned by the light source and the final submitted image will be used for pattern recognition and authentication.

Different reading devices can be used for authentication of the NOF and that is greatly dependent on the size of the features. For the larger NOF a cell phone based reading device can be used and for the smaller NOF high resolution sensors are required for detection of the features.

A MOS can be used to enhance the data storage capacity of the NOF system. It was shown how the NOFs are used to store data and represent information physically. In the presented data storage scheme the features are placed two dimensionally; however with the help of the MOS, the NOF bits can be stacked on top of each other creating a 3D storage device. Such a storage device reduces the physical space required for data storage dramatically and that in turns allows more information to be stored within a small area.
6. Discussion

In this work, the nano-structures that can be used as a diffraction grating has been introduced and it has been shown how these structures can be used as both visual and machine readable features. Such grating consists of arrays of nano-features which can be fabricated on either flexible polymer based or rigid glass substrates. These nano-scaled diffraction gratings are capable of diffracting light with a large angle of dispersion.

The capability of the diffractive nano-arrays in diffracting light was used to create the reflection diffraction gratings which are capable of holding the same color for a large viewing angle. Such effect was enabled using gratings in which the groove’s periodicity alternates. Three lines of grooves differing in their periodicities were used to create such effect. This combination diffracts the light in different directions but within a close range of spectrum for a given angle of view therefore one color will be perceived by eyes for a couple of tens of degrees of angle before another color appears. The large dispersion angle which is caused by the diffractive nano-structures is the reason that such an enhancement has been enabled.

The gratings as such will be able to create such a color holding effect once the light illuminates the surface of the array along the line of gratings. If the light reaches the array perpendicular to the direction of the grating’s periodicities, the expected effect will not be achieved. In this case a random and colourful pattern might be observed on the surface of the array.

A polychromatic light beam which is diffracted by a nano-scale diffraction grating creates a pattern which contains the entire visible light spectrum. The boarder of the diffracted wavelengths is broader due to the large dispersion angle with which the light beam was diffracted. This allows more distinct wavelengths to be detected and observed. Such pattern can be created by both transmission and reflection gratings. The difference between these two types of grating will be in the method with which the
diffracted light is detected. The diffracted wavelengths can be used to encode/store information. By using different combination of the wavelengths, which are distinctly detectable due to the high resolving power of the nano-scale grating, data can be stored and physically represented.

In a transmission grating, the diffracted spectrum can be used for data encoding whereas in the reflection grating it is the color which is used for representation of data. Such a system offers a natural physical compression due to the existence of multiple variables used in its encoding scheme. The small size of the arrays populated with the diffractive nano-structures also adds to the advantages of such a system.

In the field of security, the first level of authentication is usually done visually where optical features are used for showing the originality of the document. But there are also technologies used for storing personal data which are read by the designated reading device for further authentication.

The NOF presented in this work has the capability of both generating visual effect and storing data which can be read and recognized only by the specific reading system. The NOF offers a high storage capacity and that allows any types of data, image data in particular, to be stored and encoded. The size and the method which is used for encoding decreases the possibility of duplication which in turns reduces the chance of creating the counterfeited features.

The multi-state data storage scheme used in the NOF also offers a digital compression. Prior to the representing data physically on a document, the information have to be converted to the encoding scheme that the NOF is based on which leads to another level of compression.

The difference in the periodicities of the nano-scale grating is the key for perceiving different colors used in the NOF at a fixed angle of incident light. Changing the periodicity of the features along x and y direction leads to creating different diffraction pattern along these axes. The dual grating method can be used to increase the data storage capacity of the NOF system.
The nano-scale diffraction grating can be stamped (NIL) or casted in transparent materials. This is enabled at the presence of a master mould. The features can be stacked on top of each other to create a MOS in which a 3D pattern can be observed. Similar to the MOS is the interference patterns recorded in a holographic film. The thickness and the refractive index of the layers of the material used in the MOS can vary so that different visual effect can be achieved by the incorporated features. The profile of the grating used in the MOS also plays an important role. By tuning the profile of the grooves, the color of the features can be controlled for a desirable angle.

A MOS can also be used for data storage where the NOF bits will be stacked on top of each other rather than placed two dimensionally. This method will increase the amount of data stored within a small area.
7. Future Works

The capability of nano diffractive features in dispersing the light was shown. Based on the high resolving power of this type of diffraction grating, a new method of data storage was proposed and demonstrated. In this work the fabrication of these features took place in a cleanroom environment which is time consuming and costly. In order for this technology to become practical in the future a specialized reading device and an automated writing system are required.

Currently a few technique for writing are proposed in which the features are printed or milled directly onto a flexible substrate. Existence of an automated writing system will allow the NOF to be the new generation of security and authenticating features which has the capability of storing data as well as performing the visual effect for authentication. Ideally a writing device should be able to automatically convert any types of information to the defined multi-state data encoding scheme used in the NOF and transfer the pattern onto a substrate.

By far the NOF is a WORM system and this can be used to its advantage as a technology which is proposed for authentication and security of documents. In order for the NOF to become a write many read many (WMRM) technology a change in the substrate material and the writing system is necessary. A WMRM capability will allow the NOF to be more than just a technology for authentication purposes.

A reading device for the NOF should be able to scan or image the features while the surface is illuminated with a polychromatic light uniformly. The size and the type of the reading device depend on the size of the features. Smaller features require a higher resolution sensor while larger features can be detected even with a cell phone based sensors. Regardless of the size and type of the reading device, it should be able not only read the encoded pattern but also convert it back to a computer readable data encoding system which is binary. That requires a processing unit which has the capability of performing the conversion and decryption.
The MOS as technology which has enabled 3D like visualisation of images by recording them in multiple layers also requires optimization and precise calculation of the thickness of the layers as well as the refraction of the light. The difference between the refractive index of adjacent layers should be defined so that the features can be observed at the right positions.

Fabrication of the optical features with different groove profiles in nano scale can be also challenging. Transferring the nano-patterns onto a substrate with the groove profiles other than conical pillars is difficult therefore as future works these factors need to be taken under consideration for further research.

The MOS can also be integrated with photovoltaics (PVs) to enhance the power conversion efficiency. The incorporated PV can be a Si based or an organic PV (OPV). The enhancement occurs by both the layers as well as the diffraction gratings used in the MOS. High refractive index materials will change the path of light once it enters the medium. The diffraction grating diffracts the incident light beam and the dispersed wavelengths will enter the medium. Based on the thickness of the layers and their refractive index, the diffracted wavelengths will have a longer pathway before entering the air and that increases the probability of photon getting absorbed by the PV layers.

The efficiency of the Si based solar cells is greatly dependent on the angle of light at which it illuminates the surface of the cells. The larger angles of incidence are followed by more surface reflection which in turns reduces the amount of light entering the cell which results in reduction in the efficiency of the PV (Heine and Morf 1995). Adding diffraction grating to the structure of PVs can simply reduce this effect as it has been already proven and published by Heine in 1995 (Heine and Morf 1995). The enhancement which can be achieved by the MOS is not only by the incorporation of the grating but also by taking advantage of the refractive index of the materials used at each layer.

The peak of absorption of OPVs on the other hand is within the visible range and integration of these solar cells with the MOS can simply improve the efficiency by increasing the path of the light within the active polymer, hence higher absorption probability of the photons.
Figure 65 shows a nano-scale diffraction grating used to redirect the light outside the OPV boundary, which usually does not contribute to the overall photocurrent, towards the active area. For instance, for a P3HT:PCBM-based solar cell, a grating in the range of 500 nm in periodicity will redirect the green portion of the solar spectrum towards the active area, increasing the overall short-circuit current as well as the power conversion efficiency. In this configuration, the window on top of the active area can be either ITO or a surface plasmonic array.

![Figure 65: Schematic of an array of solar cells under direct illumination using a) a conventional transparent substrate, and b) a MOS that allows the unused light to be redirected towards the active area.](image)

In a different configuration, a MOS can also be used on top of the OPV active area in order to increase the photon path, thus increasing the probability of absorbing the photons (Figure 66). The periodicity of the nano-scale diffraction grating used in this configuration of MOS differs from region to region in order to direct only specific wavelengths to the active area.
Figure 66: Schematic of a solar cell under direct illumination where the (red) MOS is used to increase the photon path and (blue) MOS is used to redirect the unused light toward the active area of the solar cell.

Improving the efficiency is not the only advantage that a MOS can enhance for solar cells. This configuration also reduces the amount of space needed for a panel by adding the third dimension to the manufacturing scheme.
References


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Appendix A.

Comparison of Simulated and Experimental Results

An array of 4 mm x 5 mm of nano-diffractive structures is illuminated under a polychromatic light source. Only the diffracted wavelengths normal to the plane of the grating are detected. At the simulated figure the detection considered to be at 0° on the circle. $\alpha_i$ is the angle of incident light in the simulated results.

Simulated Results

Experimental Results

![Graph showing simulated and experimental results for various angles $\alpha_i$.]
Appendix B.

Comparison of NOF and Other Card Technologies

In Figure 67 some of the card technologies and their characteristics are listed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnetic stripe card</th>
<th>Optical memory Card</th>
<th>Memory Card</th>
<th>Processor Card</th>
<th>RFID</th>
<th>Barcode</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>With pin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Without pin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size of data memory</td>
<td>1000 bit</td>
<td>4.16 MB</td>
<td>0.256-2 KB</td>
<td>0.256-2 KB</td>
<td>1-16 KB</td>
<td>1-64 KB</td>
</tr>
<tr>
<td>Write more times</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Security of forgery</td>
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<td>High</td>
<td>Small</td>
<td>High</td>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>Copy protection</td>
<td>Small</td>
<td>Small</td>
<td>Small</td>
<td>High</td>
<td>Very High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Mechanical loadability</td>
<td>Small</td>
<td>Small</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Higher voltage</td>
<td>No influence</td>
<td>No Influence</td>
<td>Destroy Chip</td>
<td>Destroy Chip</td>
<td>Destroy Chip</td>
<td>Destroy Chip</td>
</tr>
<tr>
<td>Magnetic fields</td>
<td>Delete Data</td>
<td>No Influence</td>
<td>Small Influence</td>
<td>Small Influence</td>
<td>Small Influence</td>
<td>No Influence</td>
</tr>
<tr>
<td>Cost of the card system</td>
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<td>High</td>
<td>Middle to High</td>
<td>Middle to High</td>
<td>High</td>
<td>Middle to High</td>
</tr>
</tbody>
</table>

*Figure 67: Comparison of the NOF and other card technologies are listed in this figure.*
Appendix C.

Fabrication Steps of the Nano-Features

The following steps are used for fabrication of the nano-optical features presented in this work:

1. Sonication of the quartz substrate in acetone for 30 seconds
2. Rinsing the substrate with DI water and then blow dried by N₂ gun
3. Sonication of the quartz substrate in IPA for 30 seconds
4. Rinsing the substrate with DI water and then blow dried by N₂ gun
5. RCA1 cleaning for 10 minutes then rinsing in DI water for 2 minutes and blow drying by N₂ gun
   RCA1 consist of:
   a. 10 part DI water
   b. 1 part ammonium hydroxide (NH₄OH)
   c. 1 part hydrogen peroxide (H₂O₂)
   The solution should be heated up to 75°C before the sample is placed inside the solution.
6. Deposition of the ma-N 2403 (negative PR) by spin coating at 3000 rpm for 30 second to achieve 300 nm-400 nm thickness
7. Softbake at 90°C for 1 minute on a hot plate
8. Loading the sample on the EBL system and following the pre-patterning procedure (focusing, alignment, etc.)
9. Patterning the PR with EBL.
10. Unloading the sample when the EBL write is done and developing the PR
11. Developing the PR in ma-D 532 for 30 seconds and placing in DI water which is the stop bath.
12. Hardbake at 100°C for 5-15 minutes on a hot plate
13. Deposition of 3 nm Ti as the adhesive layer for Au with E-beam PVD
14. Deposition of 100 nm Au with E-beam PVD
15. Sonication of the substrate in acetone for 20 minutes to remove the PR pillars (Lift-Off)
16. Etching the quartz substrate through the nano-holes with RIE

The RIE recipe for etching the quartz is:
a. CF₄ gas at 125 SCCM  
b. O₂ gas at 5 SCCM  
c. Power at 200 W for 10 minutes

17. Sonication of the sample in IPA for 30 seconds  
At this point the metallic film can either be removed by wet etching or it can be left on the substrate.
Appendix D.

Further Numerical Calculation on Arrays of Nano-Scale Diffraction Grating

The following figures demonstrate further analysis on the diffractive nano-arrays with respect to the incident light (60° angle) and the periodicity of the grating:

- P = 400 nm
- P = 450 nm
- P = 500 nm
- P = 550 nm
$P = 950 \text{ nm}$

$P = 900 \text{ nm}$

$P = 1100 \text{ nm}$