Optical and Colorimetric Characterization of a Micro Mirror Based Spectral Image Capturing System

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Abstract

A spectral imaging system is presented where the color information of an original image is separated by a diffraction grating. The grating is applied on a micro mirror, which is actuated by a fluctuated electrostatic field causing a high frequency oscillation of the device. Due to the vibration different spectral intervals of the diffracted light can be detected by a CCD-line. Altogether 35 spectral intervals in a range between 400 to 740 nm are recorded.

The used diffraction gratings are manufactured using three different processes. Besides the classical mechanical scribing of gratings, also standard methods of micro technologies are used like dry and wet etching. The applicability of these gratings depends from their optical properties. Therefore the measurements and their results of the important optical parameters for each grating type are presented.

Especially the quality of the spectral reproduction process influences the color accuracy of the presented image capture device (ICD). Therefore spectral properties of an original are measured with the ICD. These characteristics are compared with the spectral properties measured by a spectrometer. Finally a colorimetric characterization of the ICD is done. The color accuracy is evaluated and the size of the color space depending from the different grating types is shown.

Introduction and System Design

Digitizing of analog image information like photos, books, etc. is a standard application in the nowadays computer era. This is normally done with color scanners and digital cameras, which are based on the so-called RGB-method. Due to the known theoretical limitations of RGB-techniques, the color space of these devices is limited and device dependent.

There are some critical color matching applications like digitizing of high quality illustrated books, artwork imaging or catalogue selling where the color accuracy of standard RGB-systems is not sufficient. Therefore several multi-channel image capture methods have been introduced during the recent years[1-4] to increase the recordable color space. Besides the use of a multitude of color filters for the color-channel separation, there have been also methods introduced using for example a diffractive optical element like a prism or an optical grating.[5,6] This allows a real spectroscopic measurement of the spectral properties of each pixel leading to a spectral image acquisition.

The advantage of such spectral working systems is that they are independent from the used light source during the image capturing process. Because of the knowledge of the spectral properties of each pixel also metamerism problems can be avoided.[7] The number of usable spectral intervals is only limited by the wavelength resolution of the grating and the resulting amount of data, which has to be handled and stored by a computer.

The spectral image capture device that has been realized is illustrated in Figure 1. Due to the well-known and linear dispersion properties,[8] a diffraction grating is used. To realize a small and compact system design the grating is applied on a micro mirror. The gratings are manufactured using standard methods of micro technology or classical mechanical scribing.[9] A fluctuated electrostatic field actuates the mirror causing a high frequency oscillation (≈ 800 Hz) of the device. The polychromatic light, which has been modulated by the through-light original, is guided onto the micro mirror where it is separated into its spectral parts. The diffracted light is detected by a monochrome CCD-line, which is orientated perpendicular to the spectrum. Because of the general grating equation

$$d\,(\sin\alpha - \sin\beta) = m\lambda\,, \qquad (1)$$

the wavelength interval reaching the CCD-line is a function of the angular position of the micro mirror and therefore a function of the time.[10] In this equation d is the grating period, α is the angle of the incident light beam, β is the angle of the diffracted light beam, m is the diffraction order, and λ is the wavelength,

Overall 35 spectral intervals in a range between 400 to 740 nm are recorded. The gratings have a period of 1 μm, and a size of 5.12 x 3.0 mm^2. Echelle gratings with a blaze angle of 20° and rectangular gratings are used. The echelle gratings are manufactured using classical mechanical scribing or a two-step wet etching process. The rectangular gratings are realized using dry etching The mirror is driven in resonance with a frequency of 800 Hz and a maximum angle of deflection of +/- 10°. A photo of such a micro mirror device (MMD) is shown in Figure 2.

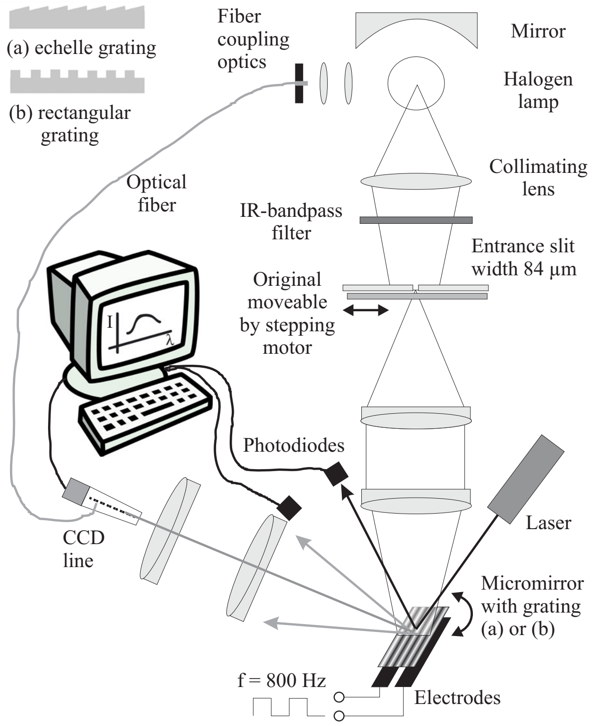

Figure 1. Principle illustration of a spectral image capture device based on a micro mirror with a diffraction grating. The laser beam and the photodiodes are determining the beginning and the ending of the measurement. The optical fiber guides a reference signal of the light source onto the CCD.

Optical Characterization

The realized spectral image capture system (ICD) and the completed gratings have to be studied regarding to their optical properties. Important parameters are the spectral resolving power, the diffraction efficiency and the modulation transfer function (MTF) of the system. Below the used experimental methods and the obtained experimental results are presented.

Spectral Resolving Power of the ICD

As mentioned before three different procedures manufacturing the gratings have been used. The spectral resolving power and diffraction properties of these different gratings are essential for the function of the ICD.

The diffraction properties are measured using an experimental setup similar to figure 1. In order that the angular position of the micro mirror can be determined exactly the normally self-contained oscillation is emulated with a rotary stage. A micro mirror is mounted onto a rotary stage changing the angle of the incoming light in small steps. Various narrowband interference filters with known spectral transmission properties are placed successively in the optical path in front of the mirror.

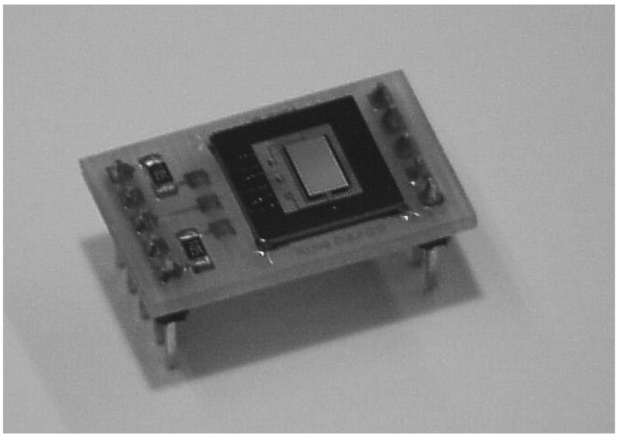

Figure 2. An actuator with a micro mirror and a diffraction grating.

The CCD measures the intensity signal, which depends from the position of the rotary stage and the used interference filter. Using Eq. 1 the wavelength reaching the CCD can be determined. The results for the three different grating types are shown in Figure 3 where the measured relative intensity is plotted versus the wavelength. The solid line represents the known transmission properties of the used interference filters.

Figure 3 shows, that the spectral properties of the ICD are very good if a mechanical scribed or dry etched grating is used. The transmission functions of the interference filters are reproduced as well as the specific spectral distributions are separated. In contrast the spectral properties of the wet etched gratings are not sufficient. Further investigations of these gratings show, that there is a periodical failure in the grating structure leading to an additional grating period of 2 µm.

Modulation Transfer Function (MTF) of the ICD

Besides the color information of the original, the reproduction of the image structure is also very important. Each optical transformation leads to losses compared to the original. The reasons are aberration and limitations caused by diffraction. As a consequence the contrast and the modulation respectively of the image decreases. The modulation M is defined as

$$M = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \qquad (2)$$

where L is the minimum or maximum luminance. The modulation transfer factor T is the ratio between the modulation of the image and the modulation of the original

$$T = \frac{M_{\mathrm{Image}}}{M_{\mathrm{Original}}} \qquad (3)$$

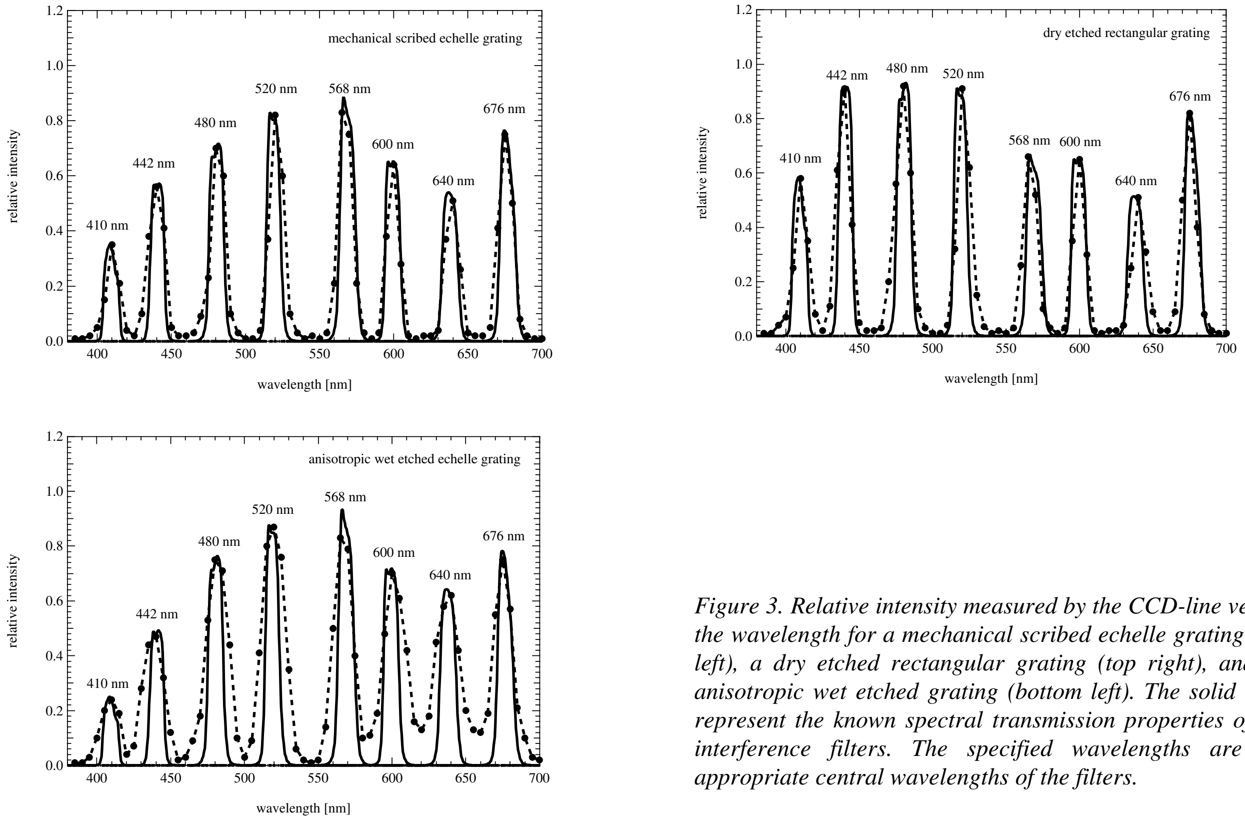

Figure 3. Relative intensity measured by the CCD-line versus the wavelength for a mechanical scribed echelle grating (top left), a dry etched rectangular grating (top right), and an anisotropic wet etched grating (bottom left). The solid lines represent the known spectral transmission properties of the interference filters. The specified wavelengths are the appropriate central wavelengths of the filters.

For determining the influence to the MTF of the different gratings a black and white test chart with a spatial frequency of ξ = 300 lpi is used as original. The different gratings are inserted in the ICD illustrated in Figure 1, and the transferred modulation is measured with the CCD-line. Additionally a MTF-measurement is done where the micro mirror with grating is replaced by a micro mirror without a grating. Finally the MTF is measured without any micro mirror in the experimental set-up to identify the quality of the imaging optics.

The results for the different measurements are illustrated in Figure 4. As expected the MTF of the system without any micro optical component is the best. Further on already inserting a micro mirror into the optical path reduces the MTF of the whole system. For the micro mirrors with grating the modulation varies between values of 0.9 and 0.73 depending from the wavelength. The mechanical scribed grating has the best optical transform properties. Despite the periodical grating mistakes mentioned above the MTF of the wet etched grating is better than the MTF of dry etched one.

Diffraction Efficiency of the Gratings

Another important optical parameter is the diffraction efficiency of the gratings. The high oscillation frequency of 800 Hz of the micro mirrors leads to light exposure times of less than 5 µs for each spectral interval. Therefore a small diffraction efficiency of a grating can have a negative influence to the system capability.

The diffraction efficiency is measured using an experimental set-up illustrated in Figure 5. First of all the luminous flux occurring onto the micro mirror is measured. Hence a rectangular aperture is inserted instead of a micro mirror and the passing radiant power is measured with a photometer. Afterwards the different micro mirrors with grating are inserted into the experimental set-up and the luminous flux diffracted in the first diffraction order is measured. The quotient between the diffracted and incident light is the diffraction efficiency.

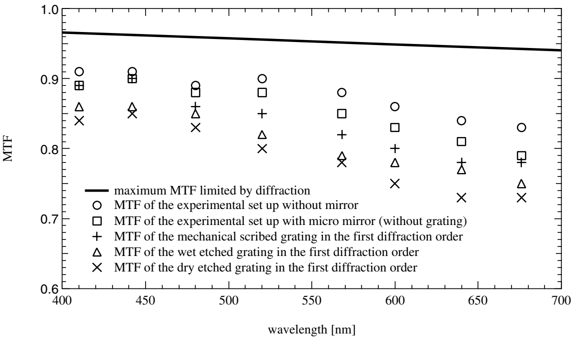

Figure 4. Measured MTF depending from the wavelength of the different experimental set-ups. The solid line represents the theoretical, maximum MTF limited by diffraction.

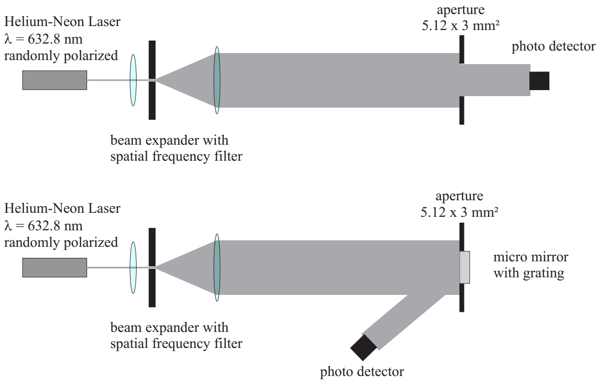

Figure 5. Principle illustration of the experimental set-up for determining the diffraction efficiency.

The results of these measurements are shown in Figure 6. The mechanical scribed grating has the highest absolute diffraction efficiency. Taking into account that the measurement has not been done at the blaze wavelength of the grating at 550 nm, the obtained values are in a normal range of such gratings. The diffraction efficiency of the wet etched grating is much smaller caused again by the failure in the grating period mentioned above. The efficiencies have been measured in the first diffraction order of the 2-μm structure. The rectangular gratings have the smallest efficiencies of less then 10%.

Further on the diffraction efficiency depends from the incident angle of the light onto the grating. This can be observed for each of the three grating types. Because of the oscillation of the micro mirror during the image capturing process, this is also an important point, which has to be taken into account.

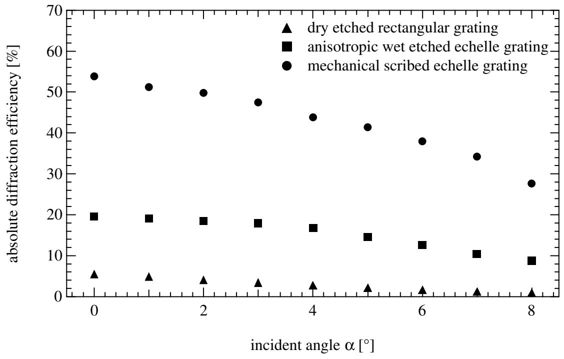

Figure 6. Absolute diffraction efficiency depending on the incident angle for the three grating types.

Colorimetric Characterization

After the optical properties of the ICD have been analyzed the colorimetric characteristics need to be studied. The color accuracy depends on the correctness of the spectral image capture process. Therefore a through-light KODAK IT8.7/1 test chart is used as an original. The different color fields are scanned with the ICD and a UV-VIS spectrophotometer Shimadzu UV-3101. Afterwards the measured results are compared with each other.

Figure 7 illustrates for example the results for the measurements of the L19 color field of the IT8 test chart. The solid line represents the reference spectrum measured by the spectrometer. On a first view there seems to be a good matching between the two measurements. But especially in the range between 550 nm and 660 nm the values measured by the ICD are up to two times higher than the values measured by the spectrometer.

The influence of the deviations between the two spectral distributions to the color accuracy has to be evaluated. Therefore the corresponding color values regarding to light source D65 are estimated using the CIE formulas.[11] To quantify the color accuracy, the color distance ΔE between the two measured spectra is calculated. In this example, this leads to a ΔE_{ab} of 7.6. This measurement has been repeated for various color fields of the test chart. The values of the measured ΔE_{ab} are in a range between 5 and 10.

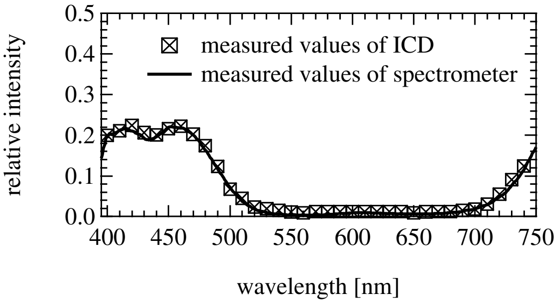

Figure 7. Measured spectra of the color field L19 of the KODAK IT8.7/1 test chart. The solid line represents the measured spectrum with the spectrometer.

Although the color accuracy of the system is not as high as expected until now, an approximation of the resulting color space depending from the used grating shall be given. This approximation is based on the 35 measuring points of the ICD. The color space is calculated using a spectral interval between 400 nm and 740 nm with a step width of 10 nm. Normally a Gaussian spectral distribution with a full width at half maximum of 30 nm should be the smallest one which can be detected certainly if 35 color channels are used. The resulting chromaticity values of these spectral distributions terminate the possible color space. If a wet etched grating is used in the ICD, a Gaussian spectral distribution should not have a full width at half maximum of less than 60 nm to be detected certainly because of the smaller spectral resolution of the grating. According to this the color space of the ICD decreases. An illustration of these limitations depending on the grating type is given in Figure 8.

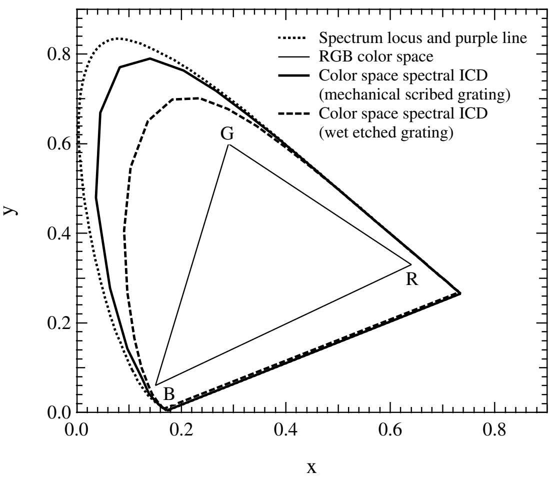

Figure 8. Color space of the spectral image device with 35 color channels depending on the used grating. The limitations are calculated in respect to the CIE light source D65. The RGB values are based on the standard of the European Broadcasting Union for television phosphors.

Conclusion

The optical and the resultant colorimetric properties of a spectral image capture device, which is based on a MMD with a diffraction grating, have been presented. From these results the applicability of the different gratings in the presented ICD can be evaluated.

The measurements of the spectral resolving power show that the mechanical scribed echelle grating and the dry etched rectangular grating can separate the individual color channels sufficiently. The spectral resolving of the wet etched echelle gratings is essential smaller. Therefore this grating type is not sufficient for an ICD with 35 spectral intervals in opposite to the two other grating types. But for an ICD with not more than 20 color channels, the spectral resolving power is high enough.

The MTF at resolutions of 300 lpi is sufficient for each grating. But compared to modern high-end scanners, the image quality still has to be increased.

The diffraction efficiency of the blazed gratings is high as expected. The smaller efficiency of the wet etched echelle grating can be explained with the additional grating period of 2 µm. This grating failure cannot be avoided because of limitations during the manufacturing process. Without this grating defect, diffraction efficiencies in the region of the mechanical scribed gratings are expected. The efficiency of the used rectangular gratings is very low compared to the theoretical limitations of such gratings.[8] With a diffraction efficiency of less than 10% this grating type is not applicable in a spectral ICD. These enormous losses of light intensity can be compensated only using a combination of a very strong light source and very sensitive light detectors. One reason of the poor diffraction efficiency is that there are small recesses in the grating structure of the rectangular grating.[9] These grating faults are centers where the light is scattered.

The quality of the color accuracy is not as high as expected. Although on a first view the derivations between the reference spectrum and the measured spectrum of the ICD are not very high these derivations lead to color distances ΔE_{ab} of more than 5. One reason could be the very short light exposure times of less than 5 µs. Especially if the light signal is very small the signal to noise ratio is not sufficient. Further work has to be done at this point.

Independent from this problem it could be shown that a spectral image capture device based on micro mirrors with a diffraction grating can be realized.

Acknowledgements

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Biography

Martin Flaspöhler received his diploma degree in physics from the University of Osnabrück (Germany) in 2000 specializing in holographic data storage. Since 2001 he works at the Institute of Print- and Media Technology at the Chemnitz University of Technology. Here he is working in the field of micro systems for spectral image capturing. Further interests are color science, digital image capture and color management. He is a member of the Deutsche Physikalische Gesellschaft (German Physical Society).