Optical Incremental Rotary Encoder in Low Cost Design

D. Hopp*, C. Pruss*, W. Osten*, J. Seybold**, V. Mayer**, H. Kück**

*Institut für Technische Optik (ITO), Universität Stuttgart,
Pfaffenwaldring 9, 70569 Stuttgart
**Hahn-Schickard-Gesellschaft, Institut für Mikroaufbautechnik (HSG-IMAT),
Allmandring 9b, 70569 Stuttgart

Introduction

Rotary encoders are used for angular measurements in numerous applications like rotating machine parts, electrical motors or for example to detect the steering angle in cars. [SIL06] There are different encoding principles available such as potentiometric, capacitive, inductive or optical, with the optical systems reaching the highest angular accuracy. As a disadvantage the resolution enhancement of optical encoder systems is associated with increasing cost.
Considering the need for competitive sensors, we have developed a new concept for low cost optical rotary encoders [HOP08],[MAY07]. The basic idea is to use a micro patterned plastic disc with a metal coating, as it is used for a Compact Disc or DVD. This encoder disc can be manufactured by a conventional DVD injection compression moulding process. With this well known technique it is possible to create highly precise micro patterns while running a cost effective process for high numbers of parts.
The mechanical and electronic design and the realization of this new kind of optical rotary encoders is performed by our project partner, HSG-IMAT. ITO focuses on the optical design as well as the fabrication of the testmaster discs. The testmasters are directly written into photo resist on the circular laser writing system CLWS 300M. [POL99]

Optical design

The system was designed for a conventional VCSEL (Vertical Cavity Surface Emitting Laser) operating at 850 nm. A polymer lens and an aperture, both manufactured by injection-moulding, are used as imaging elements to obtain a diffraction limited spot. (Fig. 1)

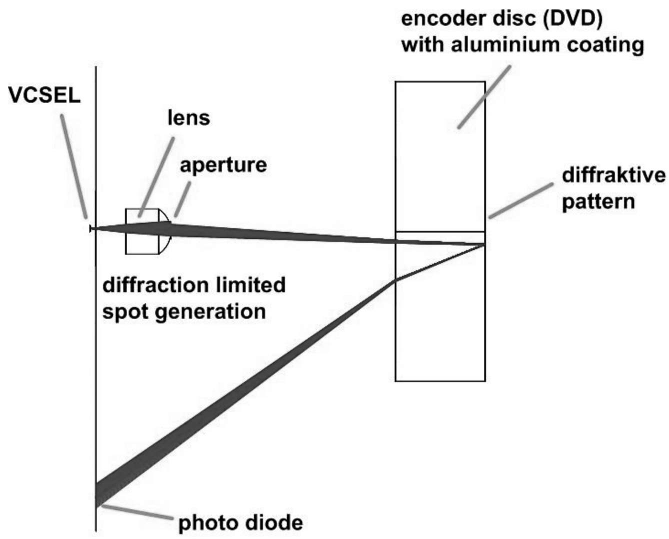

Fig. 1. optical path: principle

The Gaussian beam from a single mode VCSEL is directly focussed onto the diffractive pattern on the encoder disc. This is achieved using a spherical polymer microlens as well as a circular polymer aperture. The diameter of the generated spot is controlled by the diameter of the aperture.
In analogy to the optical path of a standard CD or DVD player, the incident light is reflected back by an aluminium coating on the disc's backside. At the same time, the diffractive pattern determines the angle and intensity of the reflected light. This is used to detect the rotation of the disc.

Solid measure design

The solid measure consists of a micro pattern of diffracting gratings placed in a circle on the outer radius of the encoder disc. An incremental code is generated by a periodic arrangement of patterned and unpatterned fields, which diffract the incident coherent beam into different diffraction orders.
Having an alternating pattern of fields without and with a diffractive grating (Fig. 2), the intensity of the first diffraction order of the reflected beam results in a sinusoidal signal, which can be detected by a photo diode. A sinusoidal signal is the desired signal for most applications.

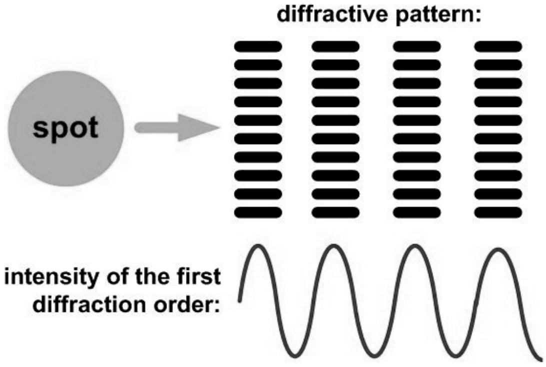

Fig. 2. generation of a sinusoidal signal: principle

To not only achieve an incremental measurement but also a detection of the rotation direction, it is necessary to implement a second incremental track that is 90° phase shifted towards the first. The usage of a different grating leads to a second set of diffraction orders where again the first order is detected by a photo diode. To obtain an offset-compensated output signal this setup is used twice in a nested configuration having four different gratings per period (Fig. 3 and 4).

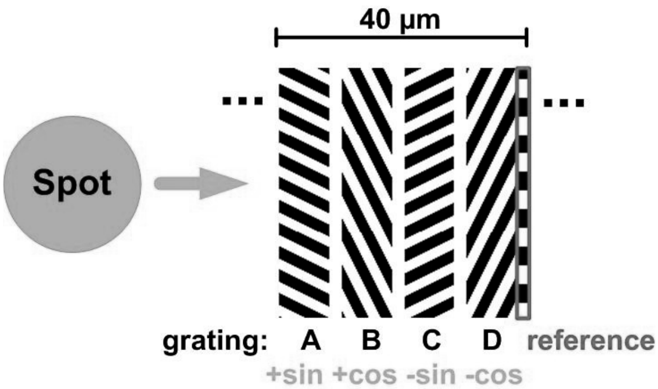

Fig.3. alignment of one period of gratings in the solid measure pattern

The spatial separation of the resulting four first diffraction order spots is achieved by using different angles for each set of gratings per signal. To meet the common request for a reference mark, a fifth grating is implemented to mark the zero position once on the circumference. This generates a reference signal on a fifth photo diode.

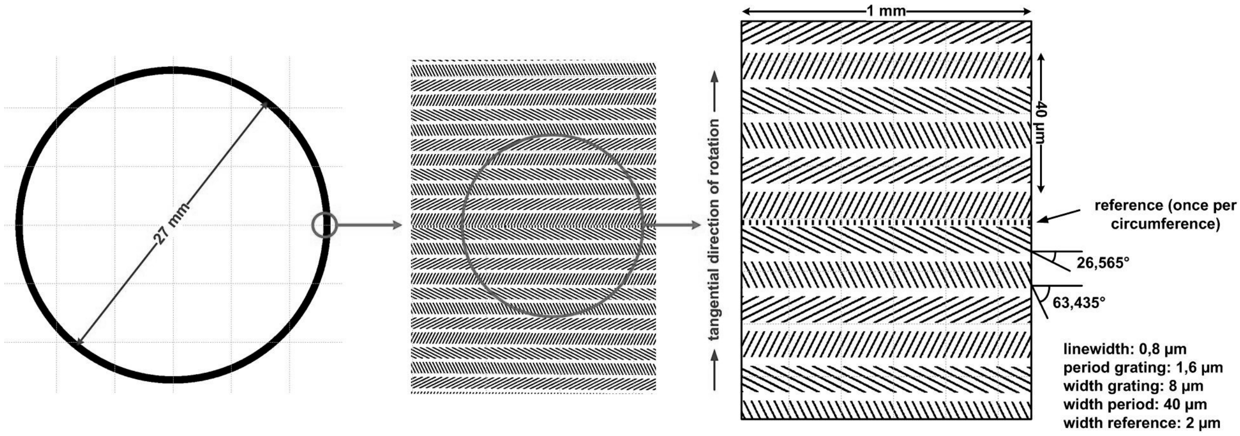

Fig.4. circular arrangement of the solid measure pattern on the encoder disc

Figure 5 shows a scheme of the optical path for the five different gratings which result in five deflection angles.

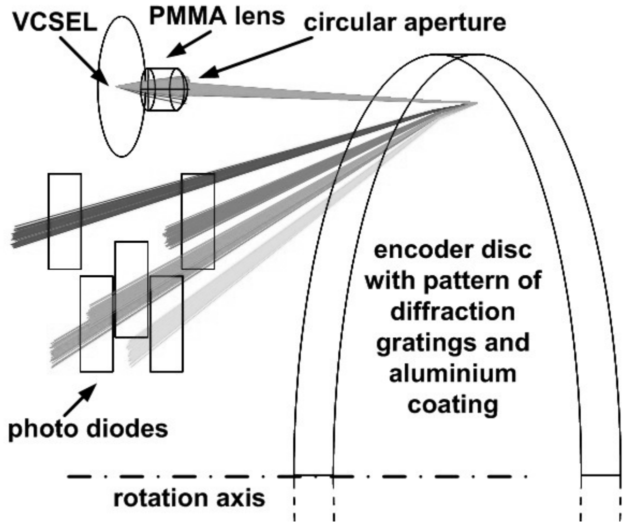

Fig.5. optical path setup for five signals

The quality of the sinusoidal signals directly depends on the interaction between the spot profile and the geometry of the solid measure, namely the width of the gratings. We developed an optical model of the system based on scalar diffraction theory to simulate and optimize the signal generation process.
To optimise the shape and arrangement of the diffractive pattern we simulated in this model the spot movement on the encoder disc. The resulting intensity signals on the photo diodes as well as the output signals of the system are calculated using the fast fourier transform. Different fieldwidths and grating periods can be combined with various spot geometries. The best constellation results in the lowest THD+N number.

Simulations with a constant diffraction limited spot falling on grating patterns with different fieldwidths were performed, The luminosity at the first order spots positions in the detector plane are used for the signal calculation. Fig. 6 shows some resulting signals that we analyzed in terms of the distortion factor THD+N (Total Harmonic Distortion including Noise). We found the following: Too small field widths reduce the amplitude of the signal, while too wide grating patches lead to distorted signals of triangular shape..

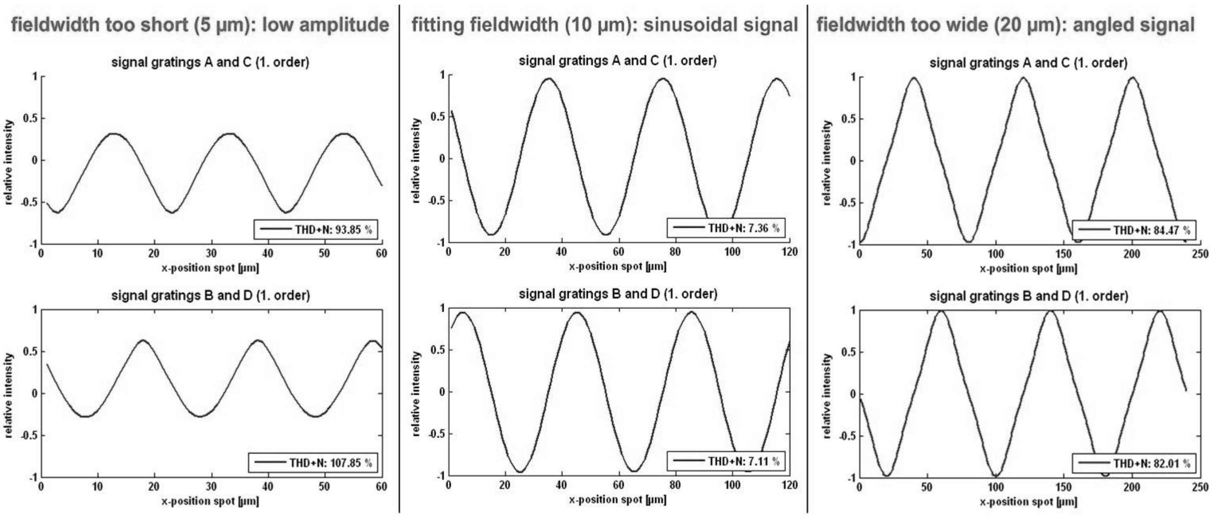

Fig.6. simulation results for different fieldwidths

The result of the optimization is shown in Fig. 7. With the theoretical examination of the system a THD+N lower than 2% for both sine and cosine output signals could be reached. The reference signal on the fifth diode can be read out with a sufficient contrast.

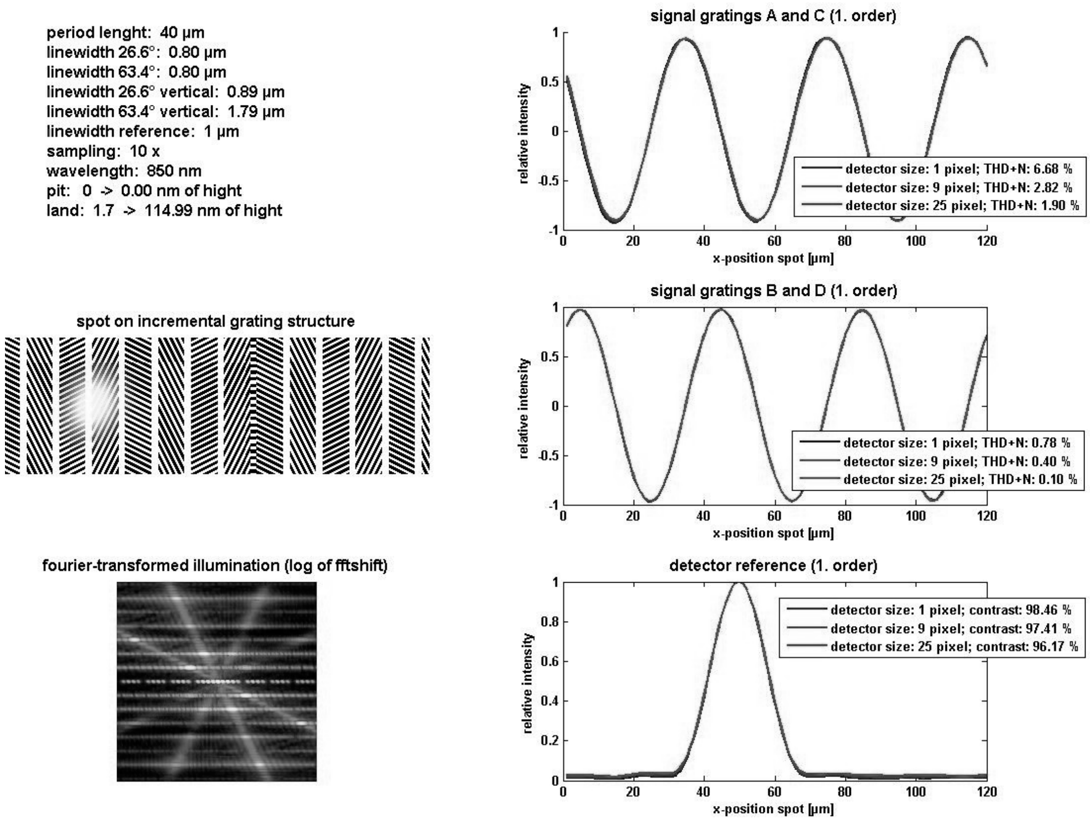

Fig.7. simulation results for fitting fieldwidth

In addition to the simulations, laboratory tests were performed with laser structured testmasters. Instead of the photo diodes a CCD camera was used to detect the first order spots. With the experimental setup a THD+N lower than 0.5% could be obtained.

In figure 8 we can see a series of four pictures showing one full increment cycle. The different first order spots are situated on a circle around the zero order spot in the middle and vary their intensity according to the movement of the solid measure.

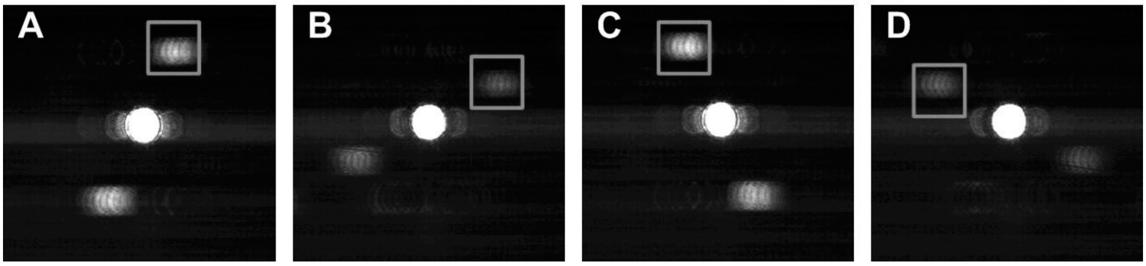

Fig. 8. Varying intensity distribution in the detector plane for four angular positions. Squares indicate the positions of the photo diodes.

Assembly of the sensor

The dimensions of the patterns of the gratings and therefore the angular resolution of the encoder depend directly on the illumination spot size and the geometry. In turn this defines the fabrication tolerances of the system. To cope with the mechanical tolerances, the optical components of the sensor are assembled on a MID (Moulded interconnect Device) (Fig. 9). The photo diodes and the light source are directly bonded onto the MID. The assembly of the polymer lens and aperture is done without any alignment procedure.

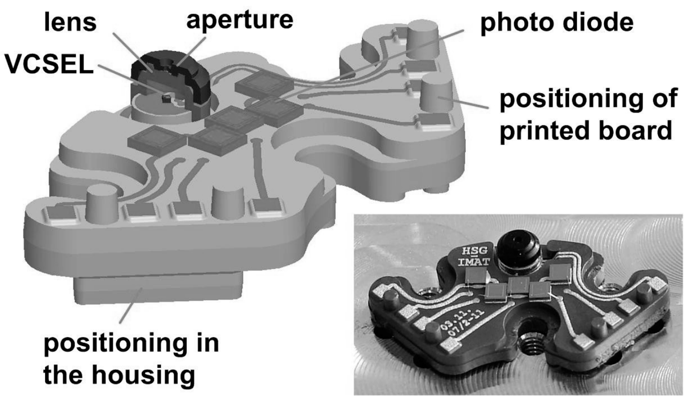

Fig. 9. MID optic module

In the current concept a disc of 27 mm diameter is chosen to fit into a housing with about 37 mm outer diameter. With an incremental tangential period of 40 µm the hardware resolution results in 2048 periods per revolution, what can be easily interpolated electronically with a standard circuit in order to obtain a higher resolution output if necessary. The MID optic module is attached to an integrated printed board where the signal processing is performed.

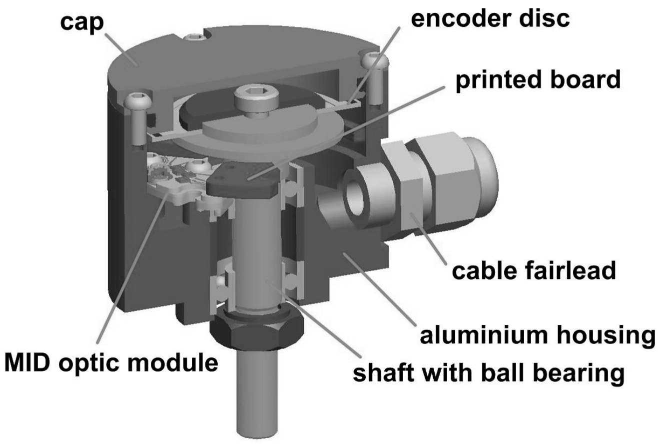

Fig.10. assembled sensor demonstrator

Signals

In an experimental setup the signals of a first sensor demonstrator where recorded (Fig. 11). A distortion factor of less than 1.2 % was determined for both output signals. The deviation of the phase allows at least a tenfold interpolation of the resulting signal which leads to an incremental resolution of more than 14 bit, respectively one arcminute.

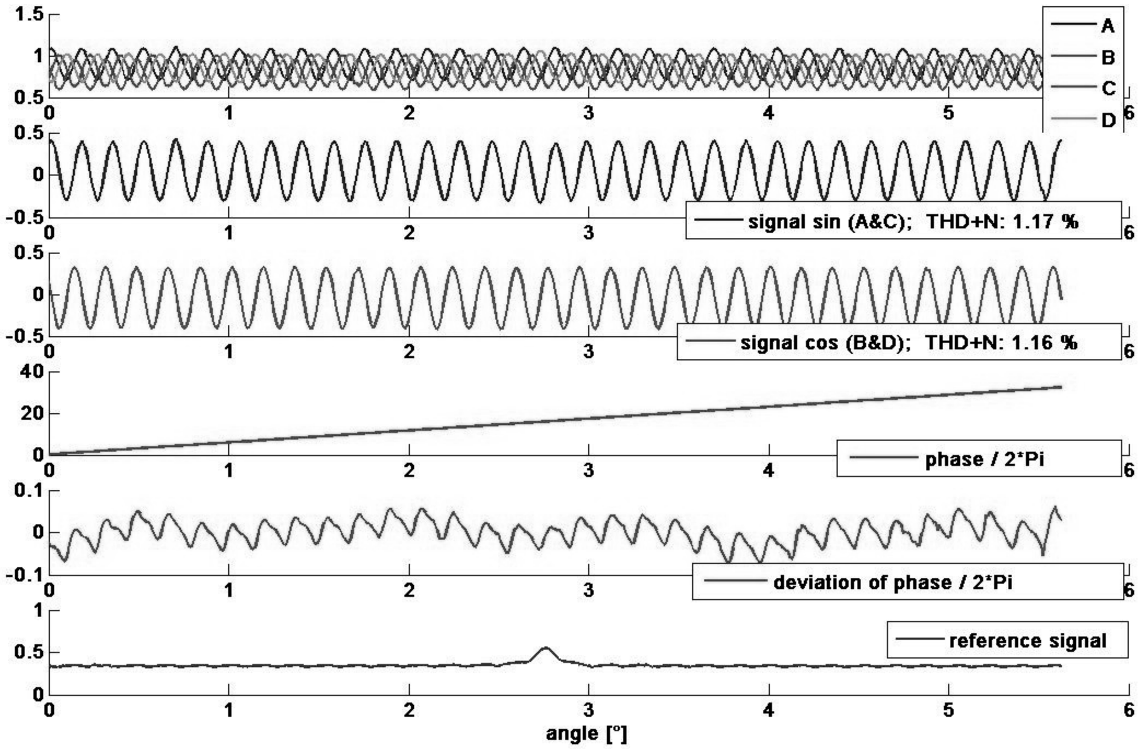

Fig 11. signals of the sensor demonstrator

Summary

An incremental optical rotary encoder was realized in a compact and low-cost design. Furthermore the sensor is designed for plug and play assembly without any adjustment procedure. The typical output signals for incremental encoders allow an angle resolution of one arcminute as well as a reference signal for the zero position.
By variation of the geometry of the diffraction gratings and the radius of the solid measure the new sensor concept can be easily adapted to various demands and fields of application.

Literatur

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