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A Novel Laser Alignment System for Tracking Detectors Using Transparent Silicon Strip Sensors

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Modern large-area precision tracking detectors require increasing accuracy of the geometrical alignment over large distances. A novel optical multi-point alignment system has been developed for the muon spectrometer of the ATLAS detector at the Large Hadron Collider. The system uses collimated laser beams as alignment references which are monitored by semi-transparent optical position sensors. The custom designed sensors provide very precise and uniform position information on the order of $1\ \mu\text{m}$ over a wide measurement range. At suitable laser wavelengths, produced by laser diodes, transmission rates above 90% have been achieved which allow to align more than 30 sensors along one laser beam. With this capability and equipped with integrated readout electronics, the alignment system offers high flexibility for precision applications in a wide range of detector systems.

1. Introduction

For large-area precision tracking detectors, like the muon spectrometer of the ATLAS detector [1] at the Large Hadron Collider, accurate alignment of the chambers is essential for achieving the desired momentum resolution. Continuous monitoring of the relative chamber positions is necessary in order to guarantee the alignment tolerances over time. Increasing demands on the precision of the optical monitoring systems require new alignment concepts and improved performance of the optical devices with respect to position resolution and measurement range.

Fig. 1. The principle of multi-point laser alignment systems with transparent sensors and light distribution by single-mode optical fibers (SMF).

A novel electro-optical alignment system has been developed for the ATLAS muon spectrometer. It uses collimated (diffraction limited) laser beams as alignment references which are detected by semi-transparent optical position sensors in

multiple consecutive layers (see Figure 1). The custom designed sensors provide high precision beam position measurement uniformly over a large range of up to several centimeters, depending on the application.

The multi-point alignment monitors offer conceptually simple and flexible solutions for a variety of alignment problems, allowing to relax the constraints on the detector layout imposed by the alignment requirements.

The system is foreseen for the optical alignment of the ATLAS muon spectrometer (see [1]). It is also considered for the tracking detectors of the HERA-B experiment at DESY (see [2]). Possible further applications of the system in high energy physics experiments range from the optical monitoring of large silicon or gas tracking detectors to the alignment of accelerator structures.

2. Transparent Sensors

Two types of custom designed optical position sensors, based on the principle of silicon strip photodiodes, have been studied. For the two transparent sensor technologies, crystalline silicon (c-Si) and amorphous silicon (a-Si), respectively, are used as active material. The properties of the sensors are summarized in Table 1. The sensor size can be adapted to the required measurement range. $20 \times 20\ \text{mm}^2$ active area was selected for the ATLAS application.

Both sensor technologies combine excellent position resolution with high light transmission rates which are desirable when many sensors must operate in the same laser beam. The readout electronics requires no calibration. The photocurrents on

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the strips are multiplexed, amplified by a common current-voltage transformer and digitized. An integrated version of this readout chain is under development.

Fig. 2. Cross section of transparent crystalline silicon strip photodiodes parallel to the p^+ strips.

The beam spot position $\langle x \rangle$ is determined as the centre-of-gravity of the signal strip positions weighted with the photocurrents I_k on the strips:

$$\langle x \rangle = \frac{\sum_{k=1}^N x_k I_k}{\sum_{k=1}^N I_k}.$$

The intrinsic position resolution depends on the signal-to-noise ratio $\Delta I_k / \sum_k I_k$ and on geometrical factors including the strip pitch and the number of strips N above a predefined threshold for pattern recognition.

The sensor parameters are optimized for typical laser beam diameters of $d = 3 - 5$ mm over distances of $\ell = 10 - 20$ m (according to the relation $\ell = \frac{\pi d^2}{4\lambda}$) in the interesting wavelength range of $\lambda = 690 - 1064$ nm (see below). By using the full dynamic range of the photodiodes, intrinsic resolutions of better than $1 \mu\text{m}$ are reached without special readout electronics. In this precision regime, the sensor resolution is limited by non-linearities in the sensor response and stray light background (see below).

2.1 Crystalline Silicon Strip Sensors

The crystalline silicon strip sensors (produced by CSEM, Neuchâtel; see Figure 2) are realised with p^+ strip implants in n -type silicon (with doping concentration $2 \cdot 10^{14} \text{ cm}^{-3}$ and the $[100]$ crystal orientation perpendicular to the surface) which cover the whole active area with only small gaps between the strips. The strips are contacted at both ends via aluminium pads outside the active area and the bulk via an implanted n^+ ring patterned with aluminium surrounding the active region on the front side. The sensors are designed to

be operated without bias voltage and therefore are only sensitive near the surface of the pn junction.

Crystalline silicon wafers become transparent in the near infrared range, where Nd:YAG lasers or InGaAs laser diodes at $\lambda = 1064$ nm can be used. The sensitivity of the sensors is still about 0.1 A/W at this wavelength. Antireflective coating on both surfaces, consisting of a double layer of silicon oxide and silicon nitride (see Figure 2), reduces the reflection rate at each silicon surface from 32% to 2.6%. A total transmission rate of 71% has been reached for $300 \mu\text{m}$ thick sensors at room temperature and $\lambda = 1064$ nm, which is in agreement with the upper range of previous measurements [3].

Fig. 3. Distribution of the laser beam deflection (in coordinates perpendicular (x) and parallel (y) to the strips) by a typical c-Si sensor before and after correction from a $0.14 \text{ mm} \times 0.14 \text{ mm}$ calibration scan of the sensor surface.

Studies have been performed in collaboration with CSEM to increase the transmittance by thinning the sensor material from the back side by me-

chanical polishing or anisotropic chemical etching (applicable to the [100] wafer material used for the sensors) down to $\sim 50 \mu\text{m}$ thickness.

Fig. 4. Residual errors on the corrected laser beam direction (for beam deflection by c-Si sensors and two types of a-Si sensor glass substrates: ordinary fire polished glass, type 1, and specially treated LCD glass, type 2) and on the c-Si sensor position measurement after calibration as a function of the surface scan grid distance (see text).

The wafers have to be carefully polished on both surfaces in order to minimize varying refraction of the traversing laser beam. Uncertainties in the beam deflection between 10 and 25 μrad (rms) have been observed for the tested 300 μm thick sensors. The beam deflections can be corrected and the rms error reduced to the level of 1 – 1.5 μrad (see Figures 3 and 4) by measuring the deviations in an automated laser scan of the sensor surface and interpolating between the measurements.

The dominating systematic error on the position measurement with the strips is due to non-uniform strip response. The effect of varying sensitivity over the sensor surface increases with the square of the beam diameter, as expected from simulations (see [4]). For a beam diameter of 2.7 mm, the non-linearity error amounts to 10 – 25 μm depending on the sensor (see Figure 5). The sensor response can be calibrated with a similar surface scan as explained above. After corrections, a position resolution of 2 μm has been achieved (see Figure 4 and the distributions in Figure 6).

The second coordinate measurement is provided by current division on the strips which are read out at both ends. The position resolution on each strip is limited to about 25 μm due to non-linear response caused by varying strip resistance. The resolution degrades near the edges of

Fig. 5. Linearity of c-Si sensors: deviations Δx of the measured from the true beam position (x) in a laser scan perpendicular to the strips with 2.7 mm beam diameter.

the sensor. For certain applications, like the ATLAS muon spectrometer, the highest precision is needed only in one coordinate. Sensors with twodimensional strip position measurement can also be realized by using implanted p^+ strips on both surfaces.

Table 1
Properties of crystalline (c-Si) and amorphous (a-Si) silicon strip sensors

Sensor type	c-Si	a-Si
Active area	$20 \times 20 \text{ mm}^2$	$20 \times 20 \text{ mm}^2$
# Strips	67	2×64
Strip pitch	300 μm	312 μm
Strip gap	40 μm	10 μm
Strip width	280 μm	300 μm
Si thickness	300 μm	$\leq 1 \mu\text{m}$
Sensitive depth	$\sim 20 \mu\text{m}$	$\sim 1 \mu\text{m}$
Hall mobility		
μ_p^H [cm^2/Vs]	310	10^{-4}
μ_n^H [cm^2/Vs]	1650	$10^{-2} - 10^{-3}$
Max. Lorentz shift (for $B=4 \text{ T}$)	$< 1 \mu\text{m}$	negligible
Transmittance (wavelength)	71% (1064 nm)	$> 80 \%$ (690 nm) $> 90 \%$ (790 nm)
Resolution		
σ_x	2 μm	$< 1 \mu\text{m}$
σ_y	25 μm	1 μm

2.2 Amorphous Silicon Strip Sensors

Thin films of amorphous silicon are transparent for visible light emitted by semiconductor laser diodes. The amorphous silicon strip sensors (produced by Heimann Optoelectronics; see Figure 7)

Fig. 6. Residual non-linearity error in the strip position measurement with two c-Si sensors after corrections from a 0.14 mm × 0.14 mm surface scan.

Fig. 7. Cross section of the amorphous silicon strip sensors. The two ITO layers are segmented into orthogonal strip rows (in the picture parallel for simplicity).

provide high precision position measurement with strips in two coordinates at relatively low cost.

The sensor layers are deposited with CVD methods as thin films on an about 0.5 mm thick glass substrate. The photo-sensitive layer consists of a $\leq 1 \mu\text{m}$ thick film of hydrogenated amorphous silicon (a-Si:H) which is fully active. It is placed between two $\leq 100 \text{ nm}$ thick transparent electrodes of indium-tin oxide (ITO) which are segmented into two orthogonal strip rows with photolithographic methods. The bottom strips act as ohmic contacts while the top electrodes form Schottky diodes operated at about 3 V bias voltage. The film materials are commonly used for the fabrication of solar cells.

Position resolutions of $1 \mu\text{m}$ have been obtained in both coordinates, uniformly over the whole sensor surface. Figure 8 shows deviations of the measured from the true beam position in a

Fig. 8. Linearity of a-Si sensors: deviations Δx of the measured from the true beam position (x) in a laser scan perpendicular to the top layer strips with 1.8 mm beam diameter ($\sigma_{\Delta x} = 0.9 \mu\text{m}$).

scan of the sensor perpendicular to the top strip row. In contrast to the crystalline silicon sensors, no long-range variations in the strip sensitivity are observed. This is attributed to the full sensitivity of the amorphous silicon layer.

The oscillations in the position response with period equal to the strip pitch (see Figures 5 and 8) are a geometrical effect of the strip weighting algorithm. The amplitude of the oscillations decreases with increasing beam diameter in agreement with simulations (see [4]). The effect can be suppressed with software corrections and fitting methods. Electronics noise is the final limitation for improvements of the sensor precision.

The sensor precision is insensitive to the presence of magnetic fields because of the very low Hall conductivity of amorphous silicon and the short charge carrier drift distance.

The a-Si:H sensor layers are designed to be transparent for visible light. The optical absorption of amorphous silicon drops fast towards the red end of the visible spectrum and decreases with increasing hydrogen concentration. The ITO layers transmit more than 95% in the visible range. Suitable laser wavelengths are produced by silicon laser diodes at $\lambda = 690 \text{ nm}$ and GaAlAs laser diodes at $\lambda = 790 \text{ nm}$. At 690 nm, the sensitivity of a sensor with $1 \mu\text{m}$ thick a-Si layer is about 0.1 A/W. The more than an order of magnitude lower sensitivity at 790 nm can be easily compensated by higher laser power.

With optimized layer thicknesses, transmission rates above 80% have been achieved at $\lambda = 690 \text{ nm}$ and $\geq 90\%$ at $\lambda = 790 \text{ nm}$. Taking into account reflection losses, the results are in accordance with other measurements for hydrogenated amorphous

Fig. 9. Distribution of the laser beam deflection in two coordinates by an a-Si sensor glass substrate (type 2 in Figure 4) before and after correction from a 0.7 mm $\times$ 0.7 mm surface scan.

silicon [5]. Further improvement is possible with antireflective coating on the back side of the glass substrate. The high transmission rates allow to use more than 30 sensors in one laser beam.

The glass substrate can be polished to optical quality in order to eliminate deflections and distortions of the traversing laser beam; small variations in the thickness of the thin sensor films have negligible effect. Standard substrate glasses without additional treatment already show satisfactory behaviour with minor or without calibration effort (compare Figures 4 and 9).

3. The Light Distribution System

For complex alignment systems with many laser beams (several hundreds in the case of the ATLAS muon spectrometer [1]), the distribution of the laser light to the alignment monitors is an

important aspect. Collimated laser beams with Gaussian beam profile and very good pointing stability can be produced in the interesting wavelength range with relatively cheap and compact diode lasers by coupling them to single-mode optical fibers with collimator optics at their ends (compare Figure 1).

The laser light can be transported via the optical fibers to the individual alignment stations where the collimator optics are mounted (without need for access after the installation). From each fiber connected to a laser module, the light can be supplied to several alignment monitors via commercially available fiber splitters. All components of such a light distribution system have been tested and fulfill the requirements for reliable operation.

4. Conclusions

Two types of transparent optical position sensors with resolutions on the order of 1 μ m have been studied for a high precision multi-point laser alignment system for tracking detectors. The amorphous silicon strip sensors are distinguished by their high position resolution in two coordinates without calibration effort and by the high transmission rate for laser light in the visible wavelength range. With integrated readout electronics, which is under development, a complete and compact system will be available for a large variety of applications.

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