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Laser-Alignment System with Transparent Silicon Strip Sensors and its Applications

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Abstract

A novel optical monitoring system has been developed for precision alignment of **particle tracking** detectors. Collimated laser beams traversing transparent optical position sensors are used to **measure the** relative positions of the detector elements. Custom designed silicon strip photodiodes provide **very high** position resolution of order $1\ \mu\text{m}$ for the incident laser beam and are semi-transparent at **wavelengths** in the red to infrared range emitted by laser diodes. Transmission rates up to more than 90 % **allow to** align many stations along a common laser beam over long distances. The flexibility of the **multi-point** alignment system has lead to its application in several modern particle physics experiments which **require** high precision optical monitoring systems.

*Contribution to the 6th Topical Seminar on Experimental Apparatus for Particle Physics
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Laser-alignment system with transparent silicon strip sensors and its applications

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A novel optical monitoring system has been developed for precision alignment of particle tracking detectors. Collimated laser beams traversing transparent optical position sensors are used to measure the relative positions of the detector elements. Custom designed silicon strip photodiodes provide very high position resolution of order $1\text{ }\mu\text{m}$ for the incident laser beam and are semi-transparent at wavelengths in the red to infrared range emitted by laser diodes. Transmission rates up to more than 90 % allow to align many stations along a common laser beam over long distances. The flexibility of the multi-point alignment system has lead to its application in several modern particle physics experiments which require high precision optical monitoring systems.

1. THE PRINCIPLE

The required alignment accuracy of modern large-area precision tracking detectors has become a challenge. 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 sensors with respect to position resolution and measurement range. A novel optical monitoring system has been developed for the precision alignment of particle tracking detectors. The main components are collimated laser beams and semi-transparent optical position sensors. Systems of several consecutive transparent sensors traversed by a common laser beam form multi-point straightness monitors which have a large variety of applications in detector alignment (see Figure 1). Several multi-point monitors can be combined to measure the relative position of detector elements in space (see Figure 2).

The optical position sensors are custom designed silicon strip photodiodes which are semi-transparent in the red to infrared wavelength

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

range. Collimated laser beams with Gaussian beam profile and high pointing stability can be produced with semiconductor laser diodes connected to collimator optics via single-mode optical fibers (SMF). Using fiber splitters, the light of a laser diode can be distributed to several alignment monitors.

The alignment system has the following char-

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Figure 2. Application of the multi-point alignment monitors with transparent optical sensors for 3D relative position measurement. Such an alignment scheme is foreseen for the forward parts of the ATLAS muon spectrometer [1]. The coordinates of a grid of carbon fiber bars are reconstructed with interconnecting multi-point monitors. The muon chamber positions are determined with respect to the reference grid with additional optical monitors.

acteristics. It allows for the alignment of many stations along one laser beam. With sensor light-transmission rates of $> 90\%$, more than 10 sensors per beam can be used without loss in precision at the last position measurement. In addition, several monitors can be concatenated. Collimated laser beams provide alignment references over large distances.

The optical sensors are designed to provide high precision two-dimensional position measurement for the incident laser beam with a resolution of order $1\ \mu\text{m}$ linearly over large measurement ranges of more than $20 \times 20\ \text{mm}^2$. The sensor resolution is insensitive to high magnetic fields. In addition, the sensors are expected to be particularly insensitive to irradiation.

2. LIGHT DISTRIBUTION SYSTEM

Collimated laser beams with Gaussian beam profile (TEM_{00} mode) and high pointing stability

Table 1

Collimation of diffraction limited laser beams for laser diode wavelengths of 690–790 nm for which the optical sensors are transparent

Distance	Focal length [mm]	$d_{\min}$ [mm]	$d_{\max}$ [mm]
2 m	11	1.9	2.1
10 m	17	2.0	3.0
20 m	24	3.0	4.2

can be produced with semiconductor laser diodes coupled to single-mode optical fibers with collimator optics at the exit. The single-mode fiber acts as a filter against higher spatial modes which show larger divergence than the ground mode and distort the Gaussian beam profile.

The collimator produces a diffraction limited Gaussian laser beam defined by the location and the diameter $d_{\min}$ of the beam waist which depend on the wavelength and on the focal length of the collimator optics. The laser beam diameter can be limited over a given distance from the collimator to values between $d_{\min}$ and $d_{\max} = \sqrt{2} \cdot d_{\min}$ as given in Table 1. The Gaussian shape of the beam profile is invariant along the beam. For complex alignment systems with many laser beams (more than 100 in the case of the ATLAS muon spectrometer [1]), the distribution of the laser light to the alignment monitors is an important aspect. Using commercially available fiber splitters or switches, each laser diode can supply several alignment monitors. The compact collimator optics can be installed in inaccessible areas while the laser connected by optical fiber can still be replaced when necessary.

3. TRANSPARENT SILICON STRIP SENSORS

3.1 Concept and properties

The optical sensors have to combine high position resolution over a large sensitive range with high light transmission rates. They consist of a

Figure 3. Cross section of the amorphous silicon strip sensors. The two ITO layers are segmented into orthogonal strip rows (in the picture parallel for simplicity).

thin film of hydrogenated amorphous silicon (a-Si:H) deposited between two electrode layers of indium-tin oxide (ITO) on a glass substrate (see Figure 3). The top electrode forms a Schottky diode with the amorphous silicon while the bottom electrode acts as ohmic contact. The ITO electrodes are segmented with photolithographic methods into two orthogonal rows of strips forming double-sided silicon strip photodiodes. The laser light absorbed by the amorphous silicon generates photo currents on the top and bottom strips. The laser spot position on the sensor can be determined as the center-of-gravity of the signal strips weighted with the photo currents on the strips. With this principle very high position resolution and linearity of the position measurement can be achieved over the required large sensitive regions which exceed the capabilities of other large area optical position sensors. High uniformity of the signal response can be achieved since the thin a-Si layer is fully sensitive; the diffusion length in amorphous silicon ($\approx 1 \mu\text{m}$) is larger than the a-Si thickness.

The strip pitch has been optimised for the measurement of typical laser beam diameters (4σ) of 2–4 mm (see Table 1). The strips are separated by only a small gap in order to minimise distortions of the traversing laser beam. The active area of the sensors of $20 \times 20 \text{ mm}^2$ was chosen according to the requirements of the ATLAS muon spectrometer alignment [1]. It can be adapted for specific applications.

Figure 4. Conceptual design of silicon strip sensor readout electronics.

The sensors are manufactured by EG&G Heimann Optoelectronics in Wiesbaden. The sensor layers are deposited with plasma enhanced CVD techniques as thin films on an $\approx 0.5 \text{ mm}$ thick glass substrate. For the deposition of the hydrogenated amorphous silicon film glow-discharge decomposition of silan (SiH_4) is used at low temperatures (200–300°C) to achieve proper hydrogen concentration. The latter is essential for the electrical and optical properties of the material. These techniques are commonly used for the fabrication of large area solar cells.

The optical absorption coefficient of amorphous silicon, with an effective band gap of 820 nm, drops fast towards the red end of the visible spectrum and decreases with increasing hydrogen concentration. The thicknesses of the sensor layers have been optimised for maximum transmittance, i.e. minimum absorption and reflection rate, for different wavelengths in the visible red to the near infrared range emitted by Ga(Al)As laser diodes. The a-Si layer thickness varies between 0.5 and

Table 2

Properties of amorphous silicon (a-Si) strip sensors

Sensor type for	690 nm	790 nm
Transmittance	> 80 %	> 90 %
Sensitivity	0.1 A/W	0.01 A/W
Bias voltage	1 V	3 V
Size	25 × 25 mm ²	
Active area	20 × 20 mm ²	
# Strips	2 × 64	
Strip pitch	312 μm	
Strip gap	10 μm	
Strip width	300 μm	
Strip thickness	≤ 100 nm	
a-Si thickness	≤ 1 μm	
Glass thickness	5 mm	
Hall mobility		
μ_p^H [cm ² /Vs]	10 ⁻⁴	
μ_n^H [cm ² /Vs]	10 ⁻² – 10 ⁻³	

1 μm. The ITO films are 50 – 100 nm thick with transmittance of about 95 % in the visible range.

At $\lambda = 690$ nm, transmission rates greater than 80 % have been achieved for one sensor type at room temperature and perpendicular incidence while the second type transmits more than 90 % of the incident light at 790 nm. Taking into account reflection losses, the results for the a-Si absorption coefficient of are in agreement with other measurements for hydrogenated amorphous silicon [2]. Further improvement of the transmittance is possible with antireflective coating of the back side of the glass substrate. The sensitivities and recommended bias voltages for the different wavelengths and layer thicknesses are given in Table 2.

The a-Si sensors are expected to be less sensitive to irradiation than crystalline silicon sensors because of the thin layer and the amorphous structure without doping. Degradation of the transmittance of the glass substrate due to irradiation can be avoided by the appropriate choice of glass. Irradiation tests of the a-Si sensors are planned.

Figure 5. Map of the variations of the residuals Δy [μm] (see text) over the surface of an amorphous silicon strip sensor (x coordinate horizontal, y vertical). The rms value of the variations is 1.6 μm.

3.2 Readout electronics

The lasers are operated in continuous mode and the sensors are read out continuously with the internal clock frequency of their electronics. The readout electronics of the strip sensors [3], is designed to require no calibration. The photocurrents on the strips are multiplexed, amplified by a common current voltage transformer, digitised by a 11-bit ADC and stored in a local memory which can be addressed via a custom designed VME interface board [3].

The maximum photocurrent on an individual strip is 5 μA. Typical noise from detector and electronics is on level of 0.1 % of the maximum signal. Very good channel-to-channel stability on the order of 0.1 % is achieved.

Each VME board can control up to 16 sensors and transmits their data serially to a VME single board processor or a computer with VME interface. A data acquisition system for the readout of large numbers of sensors has been developed and is in use on several platforms.

Figure 6. As Figure 5, for another sensor which shows clear periodic variations in the Δy distribution. The rms value of the variations is $3.9 \mu\text{m}$.

An integrated version of the readout electronics (ASIC chip) [4] has been developed and successfully tested. With compact and inexpensive readout electronics, the sensor system is available for a large variety of applications. The ASIC chip can be realised in radiation hard technology for applications in high radiation environments.

3.3 Test results

Extensive tests of the sensors and the readout electronics have been performed. 150 sensors have been glued on precision mounting plates and equipped with discrete readout electronics [3].

Due to the low noise level, the local position resolution, i.e. the statistical error or the stability of the position measurement, is a fraction of a micron. The photocurrent measurements are averaged 20 readout cycles. The photocurrent distributions on the top and bottom strips are fitted with a Gaussian.

More important is the linearity of the position measurement over the large active area of the sensors. This has been studied by scanning the surface of the sensors with a laser beam of

$2 - 4 \text{ mm}$ diameter (4σ) using a computer controlled stepping motor. The differences Δx and Δy between the measured position of the laser spot and the true position defined by the stepping motor within $1 \mu\text{m}$ was recorded for the top (y) and bottom (x) strips.

The systematic uncertainty in the position measurement due to sensitivity variations across the sensor surface varies between 2 and $5 \mu\text{m}$ for 90 % of the 150 sensors tested. Two extreme examples from this range of measurements are shown in Figures 5 and 6. This result confirms the expected high uniformity of the response of the thin film a-Si sensors. Alternative optical strip sensors based on crystalline silicon which are only sensitive in a thin depleted surface region show considerably larger sensitivity variations (see [5]). The high linearity over a large measurement range cannot be achieved with unsegmented position sensitive detectors (PSD) using resistive current division.

The sensitivity variations can be explained by variations in the thickness of the amorphous silicon since for the transparent sensor application laser wavelengths have been used for which only a fraction of the light is absorbed in the active layer. Correlations between variations in the sensitivity and in the transmission rate have been observed. For shorter wavelengths with higher absorption the sensitivity variations should be even smaller.

Most of the a-Si thickness variations that could be identified are remarkably regular across the sensor surface (see Figure 6). These periodic thickness variations can be caused by resonant effects in the plasma CVD apparatus. Improvements to the apparatus are planned to eliminate this effect.

It is important to note that the high position resolution of the sensors is not affected by high magnetic fields because of the very low Hall conductivity of amorphous silicon (see Table 2) and the short charge carrier drift distance to the electrodes.

For large distance applications of multi-point monitors with transparent sensors, uncertainties in the deflection of the laser beam by the sensors

due to refraction have to be taken into account (see [5]). The glass substrate of the sensors can be polished to optical quality in order to eliminate deflections and distortions of the traversing laser beam. Commercially available glasses for liquid crystal displays already show satisfactory behaviour in this respect [5]. Thickness variations in the amorphous silicon film on the order of 10 % make non-negligible contributions to the beam deflection uncertainty which have to be corrected. Methods for such corrections have been described in [5].

6. APPLICATIONS

The multi-point laser-alignment system has been developed for the muon spectrometer of the ATLAS detector for which accurate alignment is essential. Misalignment errors on the measured muon sagitta have to be kept below $30\ \mu$ [1]. Multi-point straightness monitors will be used for the global alignment of the barrel part of the muon spectrometer over distances of up to 13 m.

For the forward sections of the spectrometer a special concept has been developed to minimise the number of alignment rays passing through the muon chamber planes [1]. The coordinates of a grid of thermally stable carbon fiber bars integrated into the chamber layers are reconstructed with multi-point monitors connecting the bars (see Figure 2). The chambers are aligned with respect to this reference frame with additional optical monitors. More than 100 laser beams and 1000–2000 sensors will be used for the ATLAS muon spectrometer.

The transparent sensor system is also under investigation for the global alignment of the ATLAS central tracker and for the forward muon spectrometer of the CMS experiment at the LHC. In both cases, radiation hardness of the sensors (and of their readout electronics) is important.

Multi-point alignment monitors with transparent sensors are foreseen for the silicon vertex detector and for the tracking detectors of the HERA-B experiment at DESY [6] where several monitors are already in operation in a test setup.

The amorphous silicon sensors are under con-

sideration for the optical alignment of the superconducting LHC magnets because of their insensitivity to very high magnetic fields. The concept of transparent silicon strip sensors also offers solutions for laser-alignment of the silicon detector telescope of the AMS experiment for the search of antimatter on the international space station Alpha. In this application, the previously studied crystalline silicon strip sensors [5] may be useful because they can be integrated on the silicon detector wafers.

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