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Development of a Miniaturized Multisensory Positioning Device for Laser Dicing Technology

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Abstract

In this study we propose a multisensory laser tracker system for measuring and tracking the TCP (Tool Center Point) of e.g. high precision motion systems. An experimental platform composed of four tracker modules is developed in order to track the TCP of a linear positioning system based upon the length measurement (multi-lateration). Concepts and first devices for miniaturization of the tracker system are presented.

Keywords: multisensor; positioning measurement; laser dicing; 3 d; trilateration; micromirror; micro interferometer

1. Introduction

For efficient laser processing of complex tasks with even smaller components and structures, the accurate position tracking during the process is a core issue. The challenge is a non-contact measurement of the TCP. High precision measurements along the machine axis are state of the art, but increasing the weight of the moving masses and do not allow detection of dynamic effects in the Tool Center Point (TCP) of the machine-tool. Light and compact systems achieve high accuracy but also higher dynamics due to small moving masses. That can be achieved by the presented multi sensor micro tracker. Each tracker module consists of a precise laser interferometer as well as a beam deflection system to keep the measurement beam at the TCP. Miniaturization by microsystems technology enables the fabrication of small and inexpensive tracker modules. This allows the combination of several modules to a multi-tracker system for precise and robust position control. A minimum of three interferometric distance measurements is required in order to identify the TCP position. As interferometric distance measurement is usually more precise than angular measurement this is a great benefit compared to the most common systems using just one interferometric distance measurement and two angular measurements by decoder. Moreover, the common tracker systems [1, 2, 3] are large and expensive. The mentioned laser tracker systems work as standalone static measuring devices in order to calibrate robots or coordinate measuring machines.

The developed system aims for a measurement resolution of 1 µm in a range of measurement of 1 m x 1 m x 1 m.

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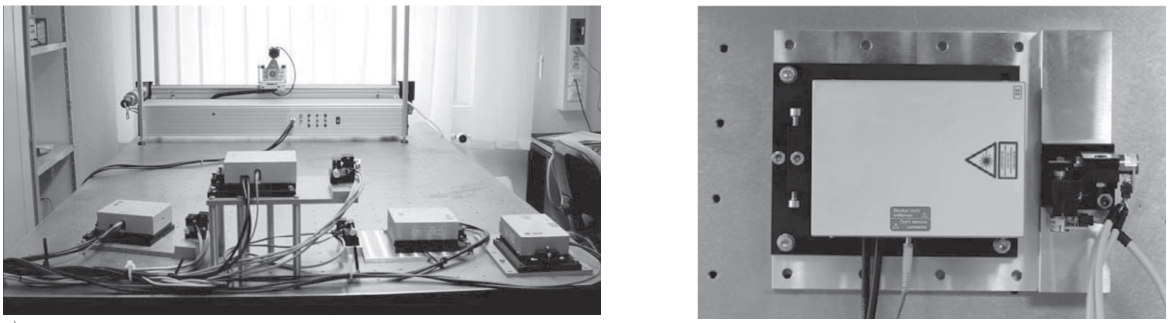
2. The experimental platform system

The multi laser tracker system (MLTS), which is developed at the Ilmenau University of Technology is shown in Figure 1a. The multi sensor system is build up out of four laser trackers. These trackers provide the length measurements, which are needed to determine the TCP position of a moving kinematic. The macroscopic system consists of stabilized HeNe homodyne laser interferometers and galvanometer scanners (Figure 1b). The measurement beam leaves the interferometer and hits the galvanometer scanner. The galvanometer scanner deflects the measurement beam into the retro-reflector, which is initially found by a search algorithm [4]. This algorithm is used while initialization of the tracker in order to search for the retro-reflector within the working range of the laser tracker. Once the laser beam hits the retro-reflector, the tracking control is activated. Then the retro-reflector reflects the measurement beam through the galvanometer scanner into the interferometer. The TCP position in the Euclidian space can be calculated utilizing the length signal of several laser tracker moduls (multi-lateration). This method of measurement provides high stability as well as robustness.



a) *b)*

Figure 1. (a) The developed MLTS tracking a positioning stage (b) The laser tracker, which is build up out of a He-Ne laser interferometer as well as a galvanometer scanner

2.1. Experimental set-up of the laser tracker

This section describes the concept of a contactless sensor, which is used to track moving kinematics (Figure 2). A stabilized He-Ne laser source is used. The beam is coupled to the interferometer through an optical fibre. Inside the interferometer the laser beam hits the first polarizing beam splitter B1 and the beam is divided in a reference beam and a measuring beam. The reference beam hits the fixed reference mirror and returns to the first beam splitter B1. Coeval the measuring beam passes the second beam splitter B2 and leaves the interferometer. Starting from the interferometer the measurement beam hits the first mirror of the galvanometer scanner, which is rotating about the y-axis (y-scanner). The y-galvanometer scanner deflects the measurement beam to the second mirror, which is rotating about the x-axis (x-scanner). The x-galvanometer scanner deflects again the measurement beam into the retro-reflector. The retro-reflector is fixed on the TCP of the moving kinematic. The retro-reflector reflects the measurement beam back to the x-galvanometer scanner. The measurement beam goes back to the interferometer through the galvanometer scanner and the second beam splitter B2. A part of the measurement beam reaches the position sensitive detection unit (PSD). In this study a so-called four-quadrant diode with an active area of 5x5 millimetres is used as the PSD unit. This kind of diode detects misalignment between interferometer and retro-reflector and this signal is used to track the target. Another part of the measurement beam passes through the second beam splitter B2 and superimpose with the reference beam in beam splitter B1. Furthermore, the superimposed beam hits the opto-electronic detection unit for length measurement with a resolution less than 0.1 nanometres [5].

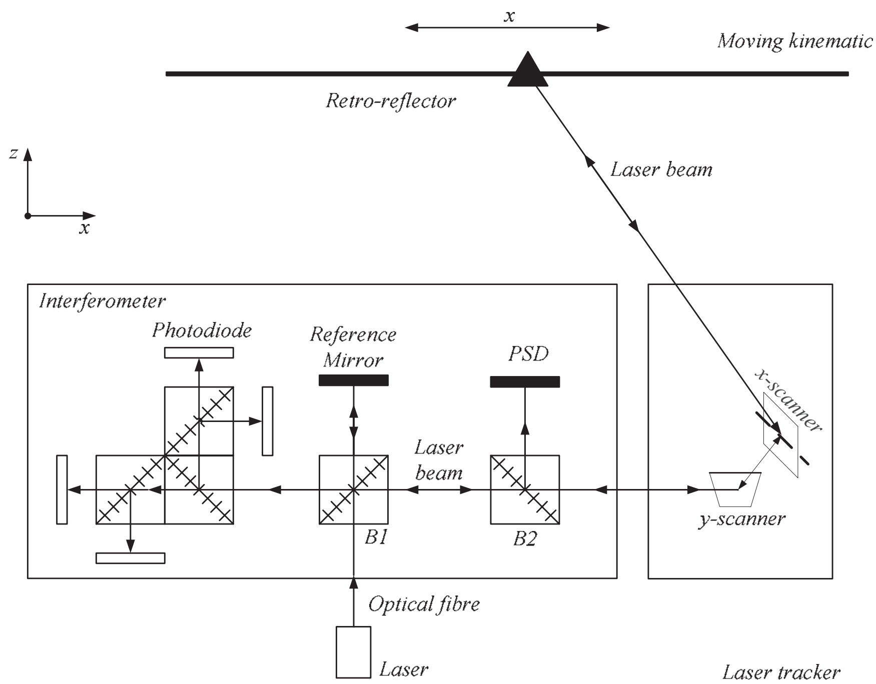


Figure 2. The design of the designed laser tracker in detail

2.2. Control approach

To realize the contactless measurement a tracking control is designed to follow the retro-reflector. The PSD is used as a feedback sensor in a tracking control scheme and consists of x_{PSD} - and y_{PSD} - signals. If the beam hits the target center, then the laser beam is found in the origin of the PSD ordinates. Hence the x_{PSD}-signal only affects the x-scanner and the y_{PSD}-signal only affects the y-scanner. Figure 3 shows the structure of the closed loop tracking control scheme for one axis. The motion of the positioning stage x_{Retro} in x-direction generates a PSD signal (x_{PSD}) and this is treated as a dynamic disturbance. The error e between the set point w_{PSD} and the disturbance signal x_{PSD} is compensated by a PID controller, which generates an output, $\varphi_{feedback}$. The output φ_{dis} is computed by the disturbance compensation block G_D, which suppress the influence of the moving stage. This is realized under usage of the inverse system dynamics of the galvanometer scanner G_M and the beam path G_B. Moreover, the disturbance compensation block acts as a feed forward controller and reduces the tracking error of the laser beam, which tracks the positioning stage. The regulating variable φ_{ref} is a summarization of outputs $\varphi_{feedback}$ and φ_{dis}, and drives the motors of the considered beam deflection unit [4].

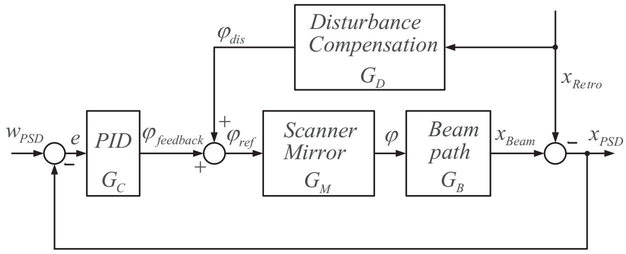


Figure 3. The structure of the proposed tracking control

2.3. Calculation of the absolute TCP position

Due to the fact that four laser trackers are utilized to follow the retro-reflector the TCP position can be calculated by the relative length measurement of all interferometers. The Figure 4 shows the four laser trackers (T_1, T_2, T_3 and T_4) in a defined Cartesian coordinate system as well as the position of the retro-reflector (X, Y, Z), which is moved from the point P_j to the point P_{j+1}. Every laser tracker has three position parameters $T_i = [x_i, y_i, z_i]^T$ in the Euclidian space and hence the parameters, which describe the whole multi-laser tracking system are twelve. To reduce the position parameters from twelve to six as well as to simplify the calculation of the TCP position we choose the configuration depicted in Figure 4. The tracker T_1 is located in the origin of coordinate system. Hence the position of the tracker T_1 is known with $[0, 0, 0]^T$. The tracker T_2 is located on the x-axis, the tracker T_3 is located on the x-y-plane and the position of the tracker T_4 is freely selectable.

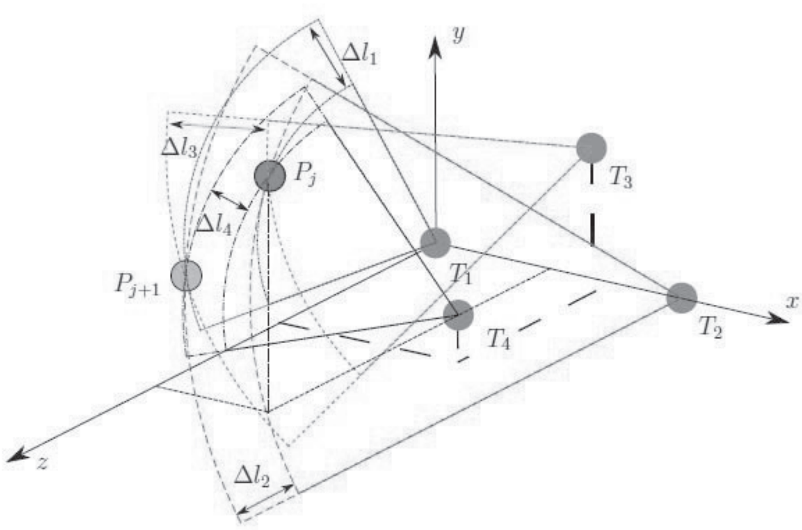


Figure 4. The measured length variation of the retro-reflector

In the case that the retro-reflector moves from the point P_j to the point P_{j+1} the interferometers detect the relative radial distance Δl_i, for i = 1…4. The absolute radial distance between tracker and retro-reflector is summarized as follows:

$$l_i = l_{0i} + \Delta l_i \; with \; i = 1...4 \tag{1}$$

The parameter l_{0i} describes the absolute distance after the system initialization. If the positions of all trackers as well as all distances l_{0i} are known, then the TCP position is determined by a method called multi-lateration. The four spherical equations in the Euclidian space are given as follows:

$$X^2 + Y^2 + Z^2 = \left(l_{01} + \Delta l_1\right)^2 \tag{2}$$

$$\left(X - x_2\right)^2 + Y^2 + Z^2 = \left(l_{02} + \Delta l_2\right)^2 \tag{3}$$

$$\left(X - x_3\right)^2 + \left(Y - y_3\right)^2 + Z^2 = \left(l_{03} + \Delta l_3\right)^2 \tag{4}$$

$$\left(X-x_4\right)^2+\left(Y-y_4\right)^2+\left(Z-z_4\right)^2=\left(l_{04}+\Delta l_4\right)^2 \tag{5}$$

After the insertion of Eqn.(2) in Eqn. (3),(4), as well as (5) and the utilization of $l_i = l_{0i} + \Delta l_i$, the following linear system of equations can be defined:

$$2\underbrace{\begin{bmatrix} x_2 & 0 & 0 \\ x_3 & y_3 & 0 \\ x_4 & y_4 & z_4 \end{bmatrix}}_{M}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}=\begin{bmatrix} l_1^2-l_2^2-x_2^2 \\ l_1^2-l_3^2+x_3^2+y_3^2 \\ l_1^2-l_4^2+x_4^2+y_4^2+z_4^2 \end{bmatrix} \tag{6}$$

The TCP position can be calculated if the matrix M can be inverted:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}=\frac{1}{2}M^{-1}\begin{bmatrix} l_1^2-l_2^2-x_2^2 \\ l_1^2-l_3^2+x_3^2+y_3^2 \\ l_1^2-l_4^2+x_4^2+y_4^2+z_4^2 \end{bmatrix} \tag{7}$$

The inverted matrix M is given as follows:

$$M^{-1}=\begin{bmatrix} 1/x_2 & 0 & 0 \\ -x_3/x_2y_3 & 1/y_3 & 0 \\ -\left(x_4/x_2z_4\right)+\left(x_3y_4/x_2y_3z_4\right) & -y_4/y_3z_4 & 1/z_4 \end{bmatrix} \tag{8}$$

The proposed model of the TCP position includes in total ten system parameters (l_1, l_2, l_3, l_4, x_2, x_3, y_3, x_4, y_4; z_4). Due to the fact that the system parameters cannot be identified by experimental data with the precision needed, a calibration is indispensable. By using four laser trackers at least the system parameters can be self calibrated [2] and therefore a reference kinematic is not necessary. The self calibration method requires only M static point-measurement of the retro-reflector. The equation for the static point-measurement is given by:

$$l_{ij}=\sqrt{\left(X_j-x_i\right)^2+\left(Y_j-y_i\right)^2+\left(Z_j-z_i\right)^2}\ \ with\ i=1...4;\ j=1...M \tag{9}$$

Thereby the parameter l_{ij} is defined as follows:

$$l_{ij}=l_{0i}+\Delta l_{ij} \tag{10}$$

Eqn. (9) shows, that for every point-measurement there are the three unknown TCP position parameters (X_j, Y_j, Z_j) and four known length measurements (l_{1j}, l_{2j}, l_{3j}, l_{4j},). Due to the fact that the nonlinear system of equations is overdetermined the system parameters can be calculated by using a nonlinear numerical optimization method at least as ten static point-measurements. Hence the objective function for the optimization can be defined as follows:

$$R=min\sum_{j=1}^{M}\sum_{i=1}^{4}\left\{\left[\left(X_j-x_i\right)^2+\left(Y_j-y_i\right)^2+\left(Z-z_i\right)^2\right]^{1/2}-\left(l_{0i}+\Delta l_{ij}\right)\right\}^2 \tag{11}$$

3. The micro multi laser tracker system (µMLTS)

The miniaturization of the main tracker components, - scanner and interferometer, - by microsystems technology leads to a small unit size. The parallel production of identical tracker components during one fabrication step is a great benefit of microsystems. This makes low-cost production possible and, therefore, enables the use of more than tree tracker modules within a highly precise multi tracker system.

3.1. Micromirror fabricated by aluminium nitride (AlN) technology

For deflecting the measuring beam, a micromirror with large static deflection is necessary. The core requirement for large-angle deflections is the torsional spring. In common devices, silicon is used as spring material due to its excellent elastic properties. Unfortunately, silicon springs are relatively stiff resulting in large forces for static deflection. Here, aluminum nitride (AlN) is used for the spring because of the excellent material properties. It is possible to fabricate very thin Al/AlN torsion springs [6] with low polar moment of inertia and, therefore, large static rotation angles at moderate operating voltage can be obtained. For highly dynamic mirror deflection, an electrostatic actuation with planar-plate electrodes is used. For tracking the 3D position, a mirror with two degrees of freedom with at least 10° rotation angle is necessary [7]. This can be achieved by gimbal mounting (Figure 5a). The first samples exhibit a 1D mirror with a surface up to 2 x 2 mm² (Figure 5b). The Al/AlN torsion springs are 10 to 30 µm in width, 20 µm in length and 600 nm thick, only. The mirror surface area is stiffened by a silicon mesa. Maximum static deflections of 31° to 44° respectively are already achieved.

a) *b)*

Figure 5. (a) Drawing of an electrostatic actuated and gimbal mounted micromirror (b) Photograph of an actuated micromirror (2 x 2 mm² mirror surface)

Figure 6 shows a simplified mathematical description of the 2D mirror from Figure 5a. The mirror surface size is with 2 x 2 mm² equal to the fabricated 1D mirror from Figure 5b. The mathematical description neglects the Al film, used as reflective layer and top electrode, films stresses, nonlinear and other effects, but shows the principal behavior of a gimbal mounted mirror. The angular position of the outer axis influences the voltage and angular relationship from the inner axis. The use of planar-plate electrodes effects in nonlinear curves.

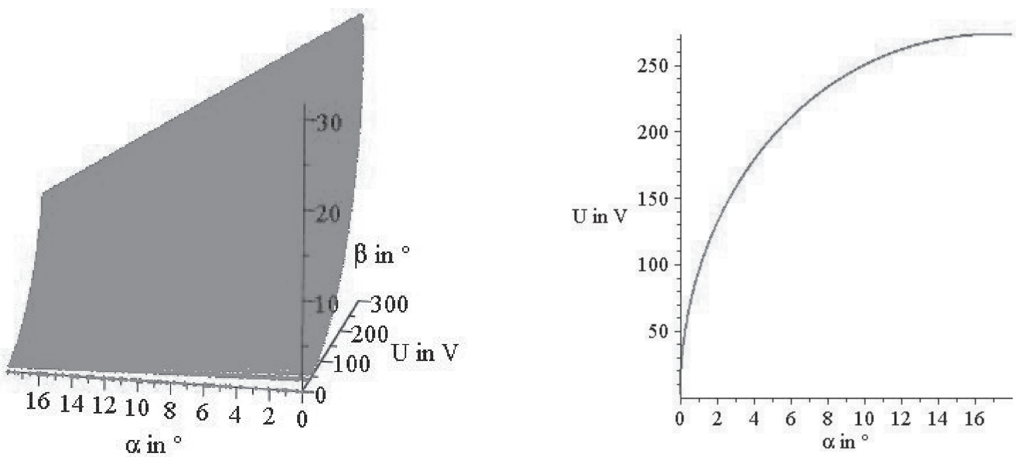
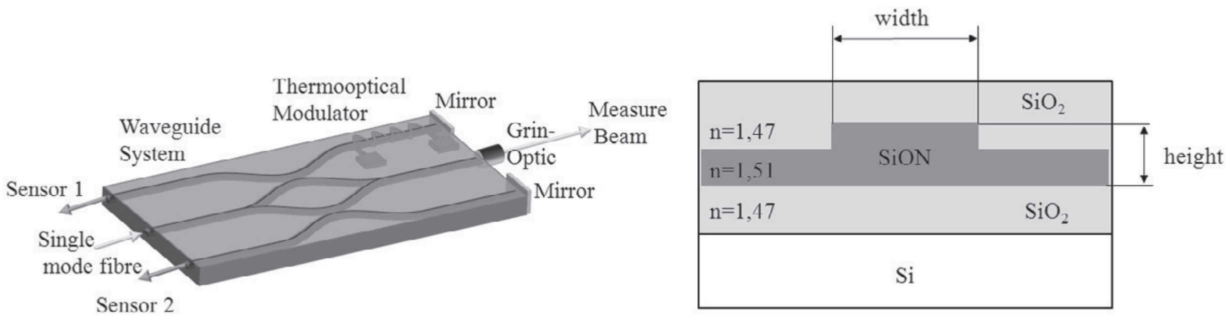


Figure 6. Mathematical description of the gimbal mounted micromirror

For a precision interferometric length measurement, errors by deflecting the laser beam must be avoided or taken into consideration for compensation during signal analysis. An offset between the reflective film and the rotation axis leads to errors. The use of thin springs (600 nm) reduces this error. A typical problem by gimbal mounted mirrors is an offset between the axes, but the fabrication by microsystems technology leads to high accuracy in the mirror shape. The advantage of a 2D mirror in comparison to the use of two 1D mirrors is that only one laser beam reflexion is necessary. This reduces signal loss and avoids an alignment between two 1D micromirrors, which would be difficult to realize.

3.2. Integrated microinterferometer in silicon oxynitride (SiON)-technology

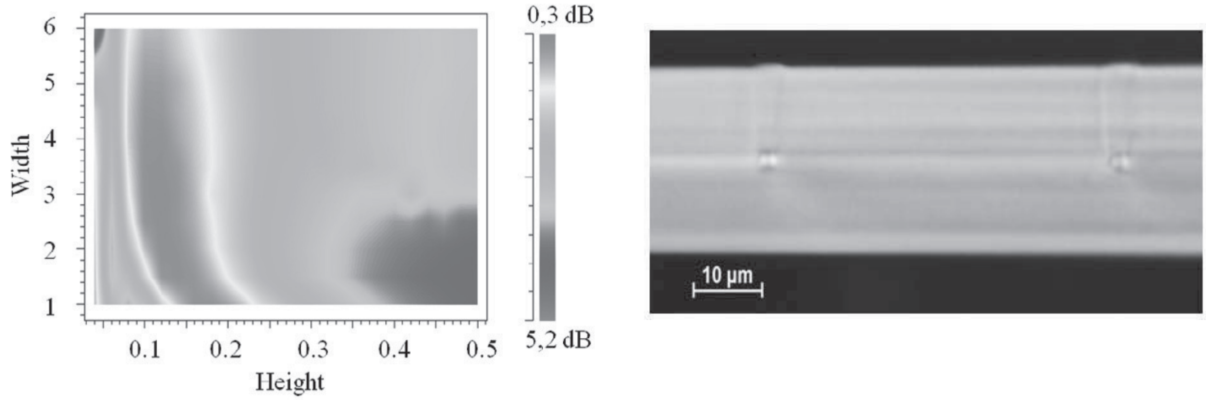
The integrated waveguide interferometer is a modified Michelson interferometer [9]. A drawing of the working principal is shown in Figure 7a. A single mode fibre for 632.8 nm is positioned to the waveguide system. The guided beam is split into two light paths. In additional 3 dB couplers, these two beams are split into two reference arms. The two other branches are combined and pass into free space by collimating via a grin optic. This measurement beam is reflected at the target by a retro-reflector. The returning beam is coupled into the waveguide system through the lens and interferes at the coupler with the beam from the reference arm. These interfering beams are analysed by two photodiodes. The movement of the target causes a modulation of the signal by changing the elapsed time between reference and measurement arm. A thermooptical modulator at one reference arm allows a tuning the angular phase shift in order to reach s/4 to perform a forward-backward detection.



a) *b)*

Figure 7. (a) Schematic drawing of the modified integrated Michelson interferometer (b) Schematic cross- section of a waveguide in SiON- technology

The waveguide system is made of SiON- rib waveguide- technology inspired from integrated waveguide systems for optical communication technology [10]. A cross-sectional view is shown in Figure 7b. The waveguide films are fabricated utilizing ICP-CVD (inductively coupled plasma chemical vapour deposition) by doping the waveguide film with nitrogen the refractive index difference is increased to 3.5 % against the enveloping silica films. The rib of the waveguides is masked with photo resist and etched in a standard RIE (reactive ion etch)-process. The waveguides are designed for single mode operation at 632.8 nm wavelength. The waveguide geometry is optimized for an efficient coupling to a single-mode fibre by beam propagation simulation. As shown in Figure 8a low loss coupling is obtained at a waveguide height of 120 nm and a width of 3 μm.



a) *b)*

Figure 8. (a) Simulation result for insertion loss by changing the critical dimension of the waveguide (b) cross- section of produced SiON waveguides

To prevent influence of the high refractive index from the substrate, the underlying silica has to be at least 3.5 µm. The heater of the thermooptical modulator is built of sputtered chrome-nickel. To insulate the guided light from the metal the upper cladding has to be at least 10 µm. The so far achieved attenuation of the waveguides shown in Figure 8b is less than 0.5 dB cm^{-1}. The measurement was performed by a cut-back technique. These values are sufficiently low for integrated optic devices.

4. Conclusion

We demonstrate a multi laser tracker system as experimental platform. This MLTS is the initial point for developing a miniaturized multi laser tracker system. Using several micro trackers as a non contact position feedback sensor is an important improvement in tracking TCP in many applications. The micro trackers allow monitoring the position in space, independent from the coordinate axes of the moving system. If redundant tracker modules are provided, the system can also deal with disorders in the field of view. Once the multi sensor system is referenced to the machine coordinate system, an absolute positioning in the work area is possible. A further aspect is not yet attainable: referencing several handling and processing machines to an absolute multi machine coordinate system. This allows the tracker system cooperative assembly and handling processes of micro parts by several specialized robots on one work piece. This concept requires miniaturized, inexpensive tracker modules that are produced by microsystems technology. We demonstrated a concept to minimize the different components of the macroscopic laser tracker. In addition to the cost benefit of multi tracker laser systems by microsystems technology it is possible to reduce different sources of negative effects.

Acknowledgement

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