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Robust precision alignment algorithm for micro tube laser forming

K.G.P. Folkersma[a,*], D.M. Brouwer[a], G.R.B.E. Römer[a], J.L. Herder[b]

[a] University of Twente, Faculty of Engineering Technology, Chair of Applied Laser Technology, Drienerlolaan 5, 7522 NB Enschede, The Netherlands
[b] University of Twente, Faculty of Engineering Technology, Chair of Design of Mechanisms and Robotics, Drienerlolaan 5, 7522 NB Enschede, The Netherlands

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ABSTRACT

Tube laser forming on a small diameter tube can be used as a high precision actuator to permanently align small (optical)components. Applications, such as the alignment of optical fibers to photonic integrated circuits, often require sub-micron alignment accuracy. Although the process causes significant scattering in bending angle and direction, this accuracy can be achieved by multiple bending steps of decreasing size once the target location is in proximity. In this paper an algorithm is proposed which, for each bending step, determines the best values of the main driving parameters; the axial laser spot position on the tube and the laser power. This algorithm is self-learning by using a statistical analysis of all previous bending steps. The algorithm is therefore robust for differences in for example the laser absorption between the tubes. A fully automated experimental micro tube bending setup has been developed using the proposed method in an algorithm to iteratively align an optical fiber to a virtual target with 0.1 μm accuracy, using tubes with a diameter between 450 μm and 700 μm. For the best performing tube geometry, this required an average of 14.5 steps, where each step uses a single laser pulse with a spot position determined by the algorithm.

1. Introduction

The ongoing development in photonic integrated circuits requires advances in manufacturing and packaging of these waveguide chips [1]. Recent developments in waveguide design allow for shorter wavelengths into the UV range, combined with high powers up to 300 mW [2]. Fibers and waveguides supporting short wavelengths have small mode field diameters, which demands an increased alignment accuracy of the fiber to the photonic chip. This means that a lateral alignment accuracy in the order of 0.1 μm is required to obtain an acceptable optical insertion loss [2]. Traditional passive alignment methods, such as etched V-grooves, are not suitable here since the geometrical tolerances of commercial available fibers do not meet the requirements [3]. Therefore, there is a need for an alignment method to (re)align the fiber actively by an integrated actuator. This one-time alignment can be done after any manufacturing processes which might disturb the alignment, e.g. due to assembly and bonding.

Such (re)alignment can be achieved by laser-forming of metallic structures. Laser micro-forming has been used widely in applications where sub-micron position adjustments are needed [4–9]. Laser forming is a contact-less process and allows for a stepwise deformation of the material under consideration. A dedicated structure that is part of the product can be used as an alignment actuator. Most studies on precision alignment using laser forming are based on planar actuators [7,10–12]. However, when multiple fibers in an array with a pitch <1 mm need to be aligned, those actuators have a too large footprint in the actuation direction. Due to this limited space, laser tube bending actuators offers great potential for a compact high precision actuation [13].

1.1. Laser micro tube bending

The tube bending mechanism is activated by heating of one side of the tube, either by a stationary laser spot or by scanning the laser spot over the surface of the tube in the axial or radial direction, see Fig. 1a. The laser parameters are chosen such that the thermal gradient over the wall thickness is small. The resulting thermal strain in the material introduces a compressive stress in the tube that exceeds the yield stress. Given the tube wall does not buckle, this results in a compressive plastic strain. Then, when the tube cools down, the heated volume of the tube wall will effectively contract. This is usually referred to as the upsetting mechanism

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[*] Corresponding author.

E-mail addresses: k.g.p.folkersma@utwente.nl (K.G.P. Folkersma), d.m.brouwer@utwente.nl (D.M. Brouwer), g.r.b.e.romer@utwente.nl (G.R.B.E. Römer), j.l.herder@utwente.nl (J.L. Herder).

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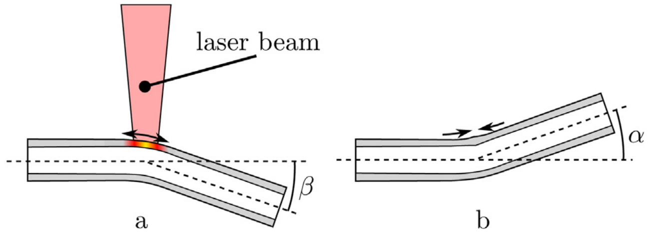

Fig. 1. Tube laser bending. (a) Laser-induced heat results in thermal expansion, and a bending of angle β away from the laser beam. (b) After cooling, the tube bends toward the laser beam, resulting in a final angle of α.

[14]. The result is a bending of the tube toward the laser beam, see Fig. 1b. This approach can be repeated multiple times to increase the bending angle.

In literature, few authors have studied laser bending of tubes with a diameter smaller than 1 mm. Jamil et al. [15] and Chandan et al. [16] recently studied the bending of nickel and stainless steel micro tubes respectively, both with an outer diameter of about 1 mm and a wall thickness between 50 μm and 150 μm. Qi and Namba studied the laser bending of 8 mm diameter 304 stainless steel rods [9], by scanning the laser spot in the axial direction of the tube. The authors achieved a repeatable minimum bending angle of the rod of 1.75×10^{-3} mrad. Moreover, it was observed that multiple scans increase the bending angle linearly, except for the first scan, which shows a significantly larger bending. This was mainly attributed to work hardening effects.

Previously reported results on laser forming of micro tubes show large uncertainties in bending angle, even if the input parameters (laser power and position) are accurately known [13]. Despite this scattering in bending angle, it was possible to position an optical fiber within a lateral accuracy of 0.1 μm by carefully selecting the process parameters for each deformation step. However, the optimal settings for the next step can only be found from empirical data.

Such a statistical approach has been applied on plate laser bending by Henninge et al. [8], where a limitation on the achievable bending accuracy has been identified in relation with the experimental variance of the bending angle. However the plate bending deformation is considered in one direction only. This is not the case for tube bending, where the bending can be in any direction provided that the laser spot can be positioned around the tube. This eliminates the risk of permanently overshooting the target bending angle. Then the final accuracy is determined by the smallest achievable bending step. Furthermore it is not required to plan the number of irradiations beforehand. Instead, new optimal settings can be calculated for every step, in an iterative learning method.

1.2. *Goal*

The goal of this research is to develop a robust algorithm that determines the optimal process parameters to align small components to a predefined position with a minimum number of steps, by laser forming of a micro-tube. The alignment of an optical fiber with respect to an optical chip is taken as an example. The alignment algorithm should be robust for the spread in response to the input parameters and minimize the number of steps to reach the target position of the fiber tip within 0.1 μm.

2. Experimental setup

To test the performance of the tube bending alignment algorithm, an experimental setup has been developed that allows for fully unattended laser bending of a micro tube to align an optical fiber tip to a pre-set destination position. The optical fibers to be aligned, are single-mode optical fibers (Thorlabs SM600) with a diameter of 125 μm. Fig. 2 shows the assembly of the tube with the fiber fixed to one end. The free end of the fiber (left in this figure) is to be aligned to a target in two directions (X, Y). This is achieved by bending the tube at a position d from the fiber tip. Assuming the bending angle α is small, the translation of the fiber tip equals $\delta_d = d \cdot \alpha$. The fiber is mounted concentrically in a 18 mm long tube that will be deformed, and centered by a 10 mm long mating tube, see Fig. 2. Both are fixed with adhesive. The tube is clamped over 2 mm length to fix it to the setup. Three different sizes of tubes are tested (Table 1). The used tube material is 304 stainless steel with a hard temper treatment after drawing.

A 100 W fiber laser (JK-100FL) with a wavelength of 1080 nm showing a Gaussian intensity distribution and a $1/e^2$ spot diameter of 400 μm is used to heat and deform the tubes. The laser spot is either positioned directly on the tube, or via one of two fixed mirrors near the tube, see Fig. 3. In all experiments, the laser spot was stationary during the laser irradiation. A camera is mounted on the focusing head to align the laser to the tube. Using the tip/tilt mirror, three radial positions spaced 120° from each other, and the complete tube length are accessible by the laser spot. Additionally, since the spot size is smaller than the tube diameter, a small deviation of ±35° from these radial positions can be tolerated by moving the laser spot off-center, see Fig. 4.

The experimental setup depicted in Fig. 3 is used to measure the displacement of the fiber tip in real-time. The displacement is measured by two duo-lateral position sensing detectors (PSD) (On-Trak PSM 2-4 and PSM 2-10). A collimator lens focuses the light emitted from the fiber on the two PSDs via two 50:50 beam-splitters (Thorlabs CM05-BS016), see Fig. 3. The tube clamp (see Fig. 2) can be translated by three translation stages, and its position and orientation is measured by 5 capacitive displacement sensors (Lion Precision CPL290 with C6D probes), with a resolution of 50 nm. The relation of the signal from the PSDs and the fiber position is calibrated by moving the tube, and measuring the translation by the capacitive sensors. By checking with the capacitive sensors, the maximum absolute error of

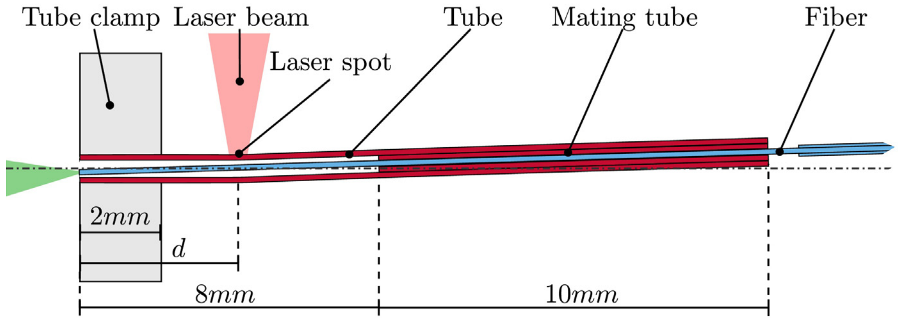

Fig. 2. Cross-section of the fiber and tube assembly.