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ABSTRACT

This paper proposes and tests a design of electro-thermal bimorph actuators for alignment of flexible photonic waveguides fabricated in 16 µm thick SiO_2. The actuators are for use in a novel alignment concept for multi-port photonic integrated circuits (PICs), in which the fine alignment is taken care of by positioning of suspended, mechanically flexible waveguide beams on one or more of the PICs. The design parameters of the bimorph actuator allow to tune both the initial relative position of the waveguide end-facets, and the motion range of the actuators. Bimorph actuators have been fabricated and characterized. The maximum out-of-plane deflection of the bimorph actuator (with 720 µm-long poly-Si) can reach 18.5 µm with 126.42 mW, sufficient for the proposed application.

Keywords: SiO_2 MEMS, bimorph actuators, short-loop, poly-Si, out-of-plane deflection

1. INTRODUCTION

PHASTFlex (Photonic Hybrid ASsembly Through Flexible Waveguides) proposes an on-chip micro-electro-mechanical systems (MEMS) alignment scheme for the next generation of hybrid photonic packages. In these packages, two photonic integrated circuits (PICs), a TriPleX* interposer chip[1] and an indium phosphide (InP) chip, are assembled on a common carrier for a wide range of applications and performance. The TriPleX chip is used to establish mode and pitch matching between a fiber array unit (FAU) and the InP chip (see Figure 1). Waveguide beams in the TriPlex chip are released from the substrate, to make them mechanically flexible.[2] The structural layers of these waveguide beams are two SiO_2 layers as waveguide cladding (bottom cladding: 8 µm thermal SiO_2, top cladding: 8 µm SiO_2 grown by low pressure chemical vapour deposition) and an approximately 200 nm thick Si_3N_4 layer of waveguide core. The free ends of waveguide beams are connected by a crossbar structure, so that all waveguide beams are actuated together using the on-chip MEMS actuators. The waveguide alignment includes two steps. The first step is a coarse pre-alignment using flip-chip technology to mount the TriPleX and InP chips on the common carrier. Precision levels are typically in the order of a few µm. The second step (fine-alignment) consists of actuating the flexible waveguide beams to the optimal position using an in-plane (x direction) actuator and bimorph out-of-plane (y direction) actuators, with respect to the waveguides in the InP PIC (see Figure 1). After this, the aligned waveguides are fixed by locking functions. A final alignment precision of ~0.1µm waveguide to waveguide is targeted. With this concept we aim to increase the cost-efficiency of assembling multi-port chips in a potentially fully automatic procedure.

Due to the fact that all MEMS functions are integrated into the TriPleX platform, the main structural material we used is the thick SiO_2 stack (16 µm) instead of Si commonly used in traditional MEMS devices. Very few research on thick (> 10 µm) SiO_2 MEMS can be found in literature. The purpose of this paper is to demonstrate that bimorph actuators built with such a thick SiO_2 layer is able to position the flexible waveguide beams along the out-of-plane direction. In previous research, the same thickness of SiO_2-cantilever structures proved to be fabricatable using a front-side fabrication method, which involves etching Si from the front side to

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*TriPleX technology is based on a silicon dioxide/silicon nitride(SiO_2/Si_3N_4) platform on a silicon (Si) substrate.

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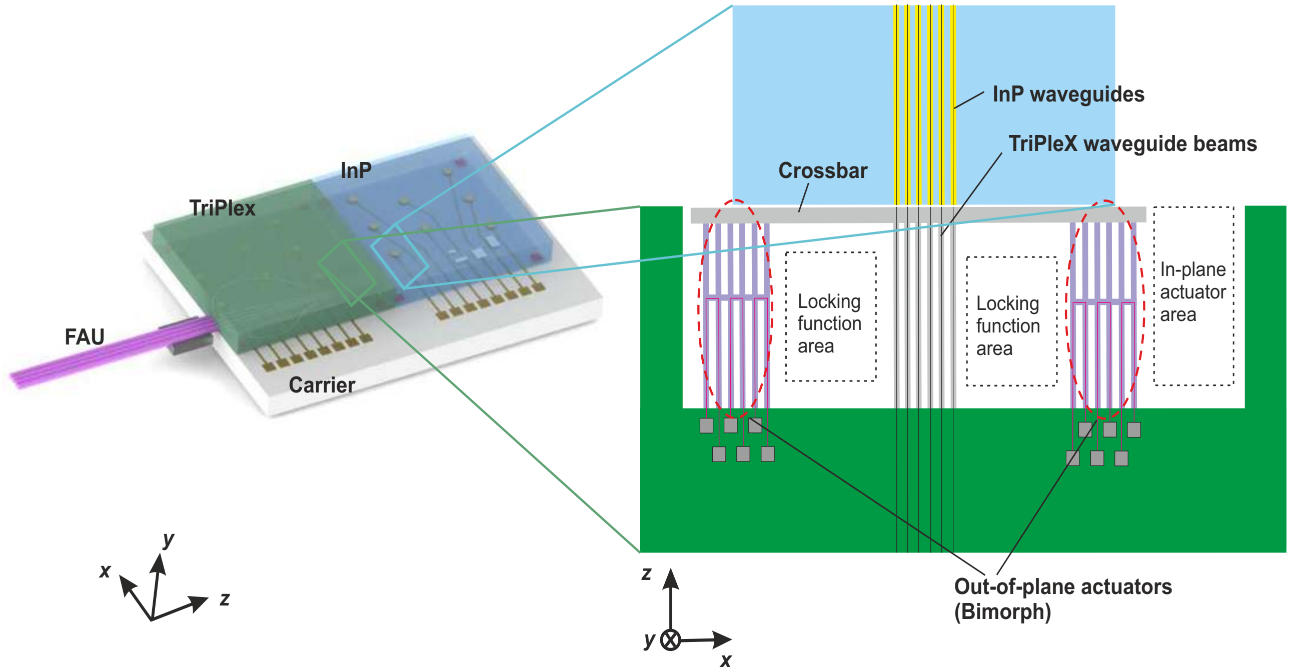


Figure 1: 3D-schematic overview of the entire photonic assembly package and 2D-top-view image of the waveguide alignment scheme. Left: TriPleX and InP chips are flip-chip bonded on the common carrier by pick-and-place machines. Right: The waveguide beams and two sets of bimorph actuators are connected at their free ends by the crossbar structure. During the fine alignment, the in-plane actuator and bimorph actuators can actuate the crossbar, hereby positioning the waveguide-beam array in plane (x direction) and out of plane (y direction), respectively. Space allocated for the in-plane actuator and locking functions are schematically shown.

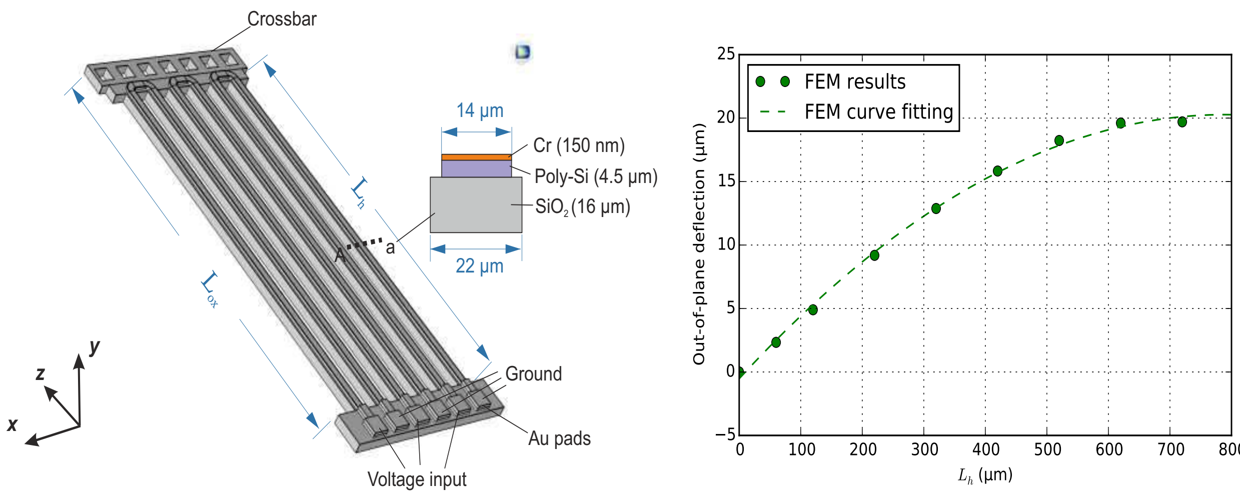
release the SiO_2-cantilever structures.[3] Pure SiO_2 cantilevers are found to have a certain level of initial deflection after fabrication, depending on the dimension of the suspended structures.

When the TriPleX and InP chips are bonded to the carrier, there is a nominal offset in vertical direction (y direction) of about 6 µm. This results from the definition of the waveguide and cladding layers in the chips. It is not obvious to compensate this height difference by making a step in the carrier. Our ambition is to compensate the height difference in the TriPleX MEMS design. Hence, there are two important requirements for the MEMS design: provide height compensation and provide a motion range that is sufficient. To this end, we introduce the concept of a short loop bimorph actuator.

Since this paper focuses on the bimorph actuator, Section 2 will start with the design of the bimorph actuator and some relevant finite element modeling (FEM). Experimental results (from two chips) and discussion of results will be given in Section 3, including initial deflection measurements, out-of-plane actuation and power dissipation measurements. At the end, Section 4 will summarize the design and experimental work.

2. DESIGNS AND MODELING

For out-of-plane positioning, the bimorph actuator included in this paper consists of a layer of lightly doped polycrystalline silicon (Poly-Si) with ∼4.5 µm thickness on top of 16 µm thick SiO_2 beams, heated up by a 150 nm thick chromium (Cr) heater (see Figure 2a). For flip-chip bonding, all electrical contact pads are coated with gold (Au) with ∼300 nm thickness. Due to the difference between thermal coefficients of poly-Si and SiO_2, these two layers will expand differently upon heating, leading to an out-of-plane deflection. To be more precise, because the thermal coefficient of poly-Si is larger than that of SiO_2, the poly-Si/SiO_2 stack will bend towards the substrate (y direction).



(a) (b)

Figure 2: FEM in COMSOL Multiphysics. (a) Basic structure of the bimorph actuator. L_{ox} is constant (800 µm), and L_{h} varies from 60 µm to 720 µm. 'Aa' indicates the cross section of bimorph beam. (b) Simulation results showing the out-of-plane deflection as a function L_{h}. The maximum temperature on the surface of bimorph actuator is kept at ∼909 K during all simulation.

The design of bimorph actuators we propose includes various lengths of poly-Si patterns (L_{h}) on the SiO_2 beams (L_{ox}). These two variables influence the static out-of-plane end-position of the SiO_2 cantilevers, including bimorph beams and waveguide beams. However, the actuation range is also affected by this set of variables. Therefore, the challenge is to find a set of values for L_{ox} and L_{h} which meets both the demands on initial position and on motion ranges. This section will start with FEM simulation of the out-of-plane deflection of bimorph actuators.

To investigate the bending behavior of bimorph actuators, we simulated the bimorph actuator with different L_{h} by using COMSOL Multiphsics (v.5.1), as shown in Figure 2. For the thin layers (Cr and Au), a free triangular mesh is used, and other layers use a free mesh with tetrahedral-shaped elements. A linear solver is applied to simulate the model. The properties of materials used can be found in Table 1. In the thermal convection setting, the heat transfer coefficient of sidewalls was chosen to be 20 000 W/(m^2K), and 400 W/(m^2K) for the bottom surface.[4] We also tried different thermal convection settings, such as the heat transfer coefficient of 20 W/(m^2K) used by Chang et al,[5] but the temperature reached in the structure turned out to be enormously high (over a few thousand K). This simulation reveals that the thermal convection setting greatly influences the temperature generated, so the heat transfer coefficient needs to be carefully chosen.

In this model, in order to investigate how L_{h} influences the motion range, L_{ox} was set as a constant value (800 µm) which has the same dimension as one of the bimorph actuators we fabricated, and L_{h} was chosen to be 60 µm, 120 µm, 220 µm, 320 µm, 420 µm, 520 µm, 620 µm, 720 µm. The simulation shows a non-linear relationship between L_{h} and the out-of-plane deflection (see Figure 2b). The rising trend suggests that the out-of-plane deflection increases less when L_{h} is longer than 400 −500 µm. Notice that the same maximum temperature (∼909 K) is set for all the simulations.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental result includes characterization work on two chips (Chip150 and Chip720). Chip150 contains two sets of short-loop bimorph actuators, which are located on the left and right sides of the waveguide array respectively (see Figure 3a). In contrast, bimorph actuators in Chip720 (with long-loop poly-Si) are disconnected from the waveguide beams. Table 2 describes specific parameters of these two bimorph actuators. Initial-deflection measurements were done on Chip150, and both chips were used to characterize the motion range of

Table 1: Parameters used in COMSOL Multiphysics.

	SiO_2	Poly-Si	Cr	Au
Electrical conductivity (S/m)	1×10^{-16}	1×10^{-12}	7.9×10^{6}	45.6×10^{6}
Coefficient of thermal expansion (1/K)	0.5×10^{-6}	2.6×10^{-6}	4.9×10^{-6}	14.2×10^{-6}
Heat capacity at constant pressure (J/(kgK))	730	678	448	129
Relative permittivity	4.2	4.5	12	6.9
Density (kg/m^3)	2200	2320	7150	19 300
Thermal conductivity (W/(mK))	1.4	34	93.7	317
Young's modulus (Pa)	70×10^{9}	160×10^{9}	279×10^{9}	70×10^{9}
Poisson's ratio	0.17	0.22	0.21	0.44

bimorph actuators. In particular, we used Chip720 to measure the power dissipation of the long-loop bimorph actuator.

We used a backside-release method to realize all the MEMS structures in TriPleX chips. Fabrication of the MEMS structures starts with deposition and patterning of the metallization (Cr for heaters and Au for conductors) on the front side of the wafers. Next, the 16 µm thick SiO_2 on the front side is patterned to define the MEMS actuator structures. This is followed by poly-Si actuator patterning. Then the flexible structures are released by an anisotropic Si etch from the backside.

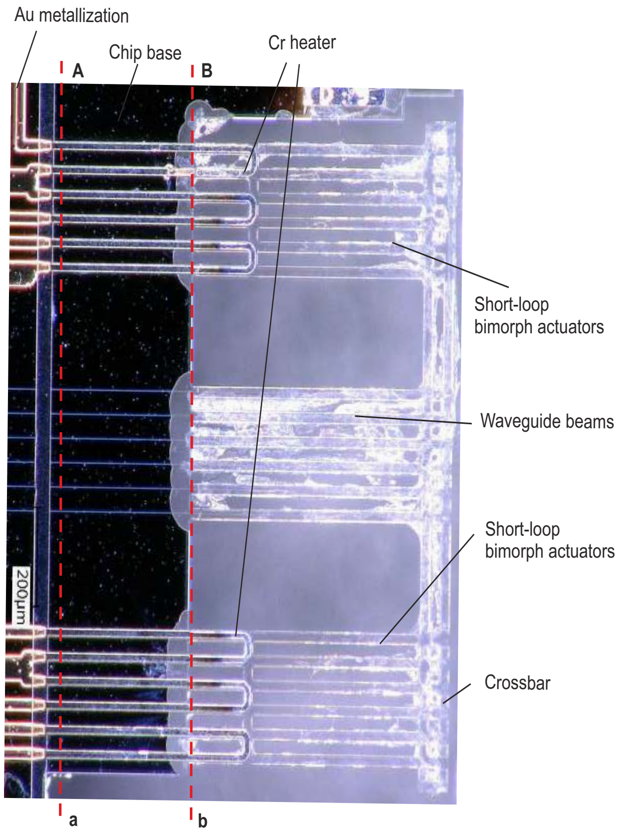
Table 2: Parameters of bimorph actuators.

Chip ID	Chip 150	Chip 720
$\mathbf{L}_{\mathrm{h}}$	~150 µm	~720 µm
$\mathbf{L}_{\mathrm{ox}}$	~650 µm	~800 µm
Waveguide pitch	50 µm	N/A
SiO_2 beam width	~22 µm	
Bimorph pitch	50 µm	

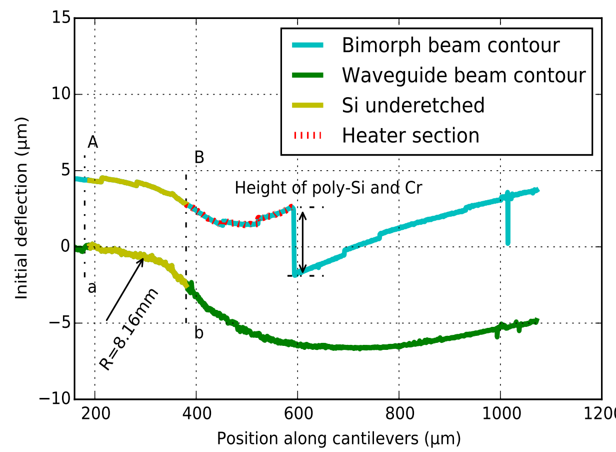
3.1 Initial Deflection

An interferometric profilometer (Bruker Contour GT-K) was used to measure the static initial deflection of the suspended cantilevers. Figure 3b shows that the suspended waveguide beams and bimorph actuators have an out-of-plane deformation after release. In the region between dashed lines 'Aa' and 'Bb', a downward curvature can be observed. In this area, we suspect that there is a layer of Si present underneath the SiO_2, resulting from the Si backside etching step, leading to a double-layer membrane of Si and SiO_2 (and local poly-Si lines). The compressive stress in the SiO_2 layer explains the curvature of the membrane. A curve fitting of this membrane is approximated, and its radius is about 8.16 mm. This directly affects the end position of the waveguide beam and the bimorph beam. For the bimorph beam, with the heater section (poly-Si and Cr), it shows a concave upward curvature. This is because after releasing the cantilever, the SiO_2 layer, under compressive stress, expands more than the poly-Si and Cr layers. For comparison, an isolated SiO_2 cantilever has been shown to have a downward bending curvature.[3] In Chip150, since all the waveguide beams are connected with the bimorph actuators via the crossbar, the waveguide beams actually are pulled up by the adjacent bimorph cantilevers.

Although the measurement confirms that the proposed short-loop poly-Si structures have the potential to tune the initial out-of-plane end-facet position, the specific design presented here does not yet meet the height compensation demand which the PHASTFlex alignment scheme requires. Further optimization of the relevant design parameters L_{ox} and L_{h} is part of our future work.



(a)



(b)

Figure 3: Optical observation and interferometric profilometry results of Chip150. In the region between dashed lines 'Aa' and 'Bb', a downward curvature can be observed. (a) Microscopic image of Chip150. (b) Height profiles of a bimorph beam and a waveguide beam in Chip150. Both bimorph and waveguide beam contours show the downward bending curvature with the radius of approximately 8.16 mm on the chip base area. The thickness of the poly-Si-Cr stack is approximately 4.5 µm.

3.2 Motion Measurements

The out-of-plane motion of bimorph actuators was characterized using a laser Doppler vibrometer (LDV, Polytec MSA-400-PM2-D). Figure 4 shows the setup for measuring the out-of-plane deflection of bimorph actuators. We used Chip150 to characterize the deflection of the short-loop bimorph actuator. Each set of the bimorph actuator consists of three pairs of bimorph beams, and they are electrically connected in parallel. The AC-voltage input is a square wave, with amplitude (U_{amp}) of 5 V, offset (U_{os}) of 5 V, frequency (f) of 2 Hz, provided by a function generator (BK Precision 2013B). Each set of bimorph actuators was separately tested with this AC voltage. One pair of beams in the left-side bimorph set was observed to be electrically defect, which may explain why the maximum deflection of this bimorph cantilever is different when the left or right bimorph are operated individually. Then both sides of bimorph actuators were powered by the same AC voltage, and we observed that the shape of waveguide-beam end position is not a straight line. The height difference between the highest and lowest points of the waveguides was measured to be $\sim$200 nm, and a deflection of 3.5 µm was measured at this voltage (see Figure 5). This actuator was not yet tested to failure, hence the maximum motion range was not experimentally determined.

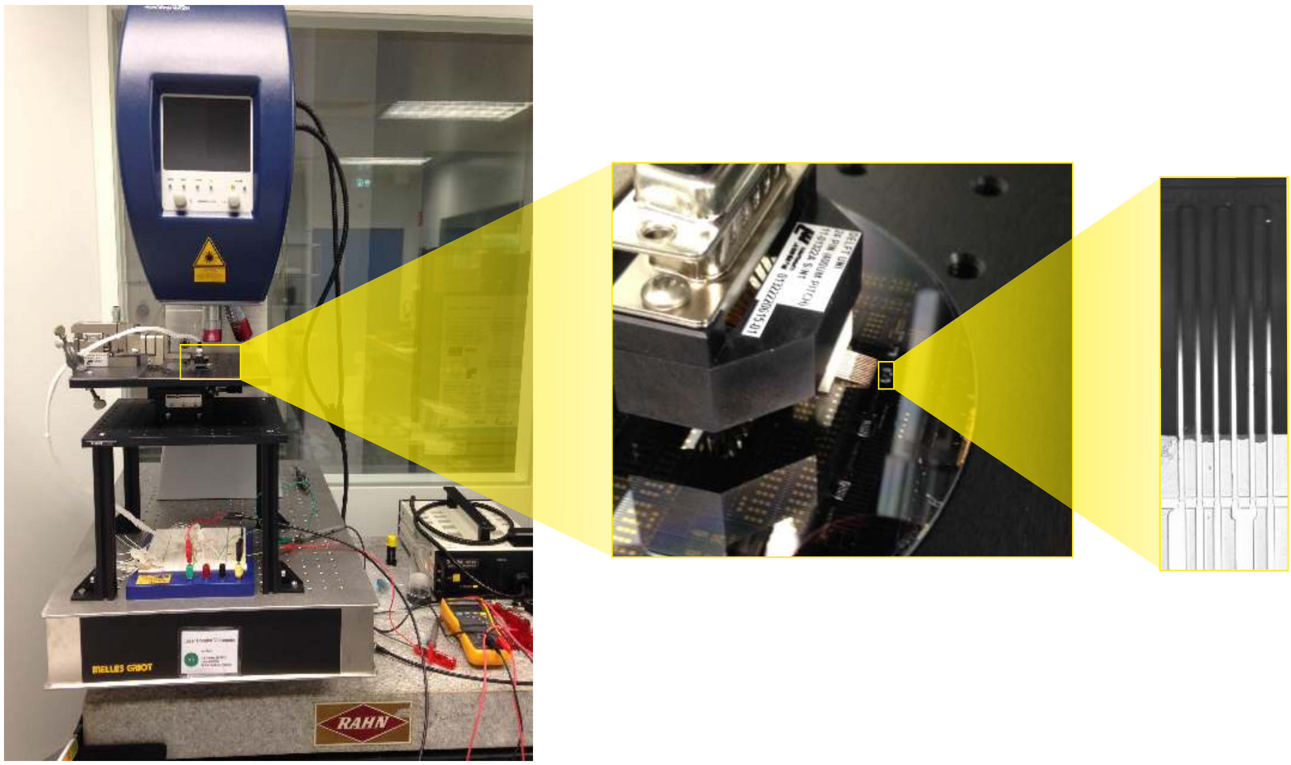


Figure 4: Setup for out-of-plane measurements of the bimorph actuator. Left: overview image of the laser Doppler vibrometer. Middle: zoom-in image of the TriPleX wafer electrically probed by an array of probe needles. Right: microscope snapshot of the bimorph actuator in Chip720. Chip150 was also characterized by this LDV.

3.3 Power Dissipation Measurements

To investigate the power dissipation of the bimorph actuator, the long-loop bimorph actuator in Chip720 was powered by the same AC power supply (square wave, $U_{\mathrm{amp}} = 4\,\mathrm{V}$, $U_{\mathrm{os}} = 4\,\mathrm{V}$, $f = 2\,\mathrm{Hz}$) mentioned in Section 3.2, and Figure 6 schematically depicts the electric circuit for this measurement. In this circuit, three pairs of bimorph actuator were also electrically connected in parallel. The resistance of each pair of bimorph loop was measured at ambient temperature ($T_0 = 293\,\mathrm{K}$), which is approximately $1740\,\Omega$. Notice that one pair of bimorph beams is also electrically defect in this chip. A small resistance ($R = 46\,\Omega$) was connected in series in the circuit, and the voltage (U_{R}) over this resistance was measured by a digital oscilloscope (Micsig TO102), to allow computing the current. Meanwhile, the out-of-plane motion of this long-loop bimorph actuator was measured by LDV.

The voltage (U), current (i), dissipated power (P) and out-of-plane deflection of the long-loop bimorph actuator were measured as a function of time, as shown in Figure 7. The transient time ($t_{\mathrm{t}} = 100\,\mathrm{ms}$) is indicated in Figure 7b and 7c. A small current drop of $0.9\,\mathrm{mA}$ occurs when i starts flowing into the heater, because the heater material has a positive temperature coefficient of resistance (higher temperature resulting in an increase in electrical resistance). This leads to a decrease of $9\,\mathrm{mW}$ in the power dissipation curve. Additionally, the thermal response time ($t_{\mathrm{tr}} = 150\,\mathrm{ms}$) in Figure 7d was also observed. This implies that the bimorph materials need time to heat up and cool down.

Moreover, out-of-plane deflection and power dissipation of the same bimorph actuator in Chip720 were also measured using a DC power supply (EA Elektro-automatik EA-PS 3065-05B). The measurement circuit is similar to the one used in the AC measurement, except for the power supply. The out-of-plane deflection shows a non-linear rising trend when the voltage increases, for both experimental data and FEM simulation (see Figure

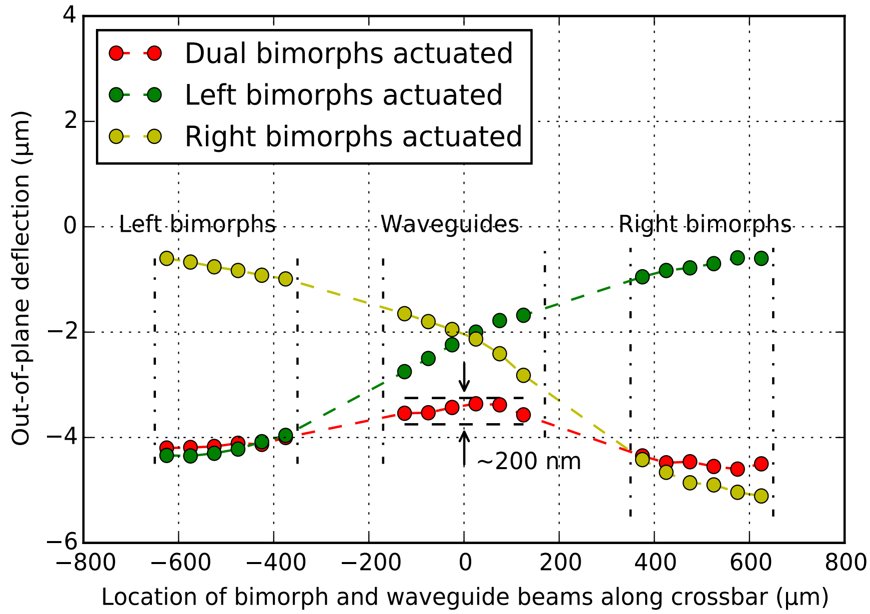


Figure 5: Out-of-plane measurement results of Chip150. Each measurement point (laser points from LDV) is on the top surface of the free end of each cantilever (along the crossbar), so this graph also reflects the bending shape of the crossbar. When both sides of short-loop bimorph actuators are actuated, it was observed that the difference between the highest point and the lowest point of the waveguide beams is approximately 200 nm.

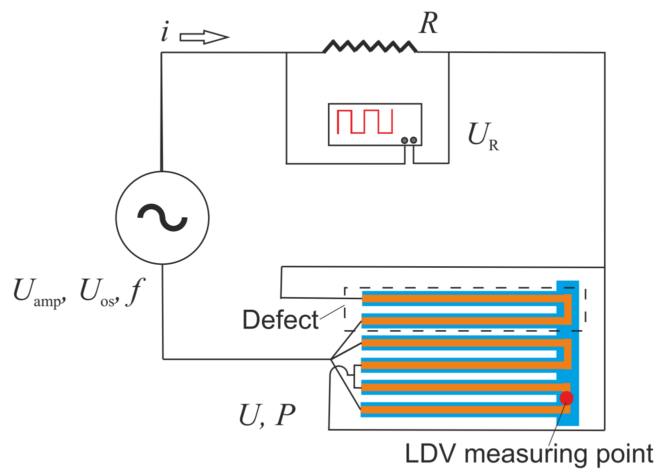


Figure 6: Schematic of the electrical circuit for measuring the power dissipation. The red dot is the measurement point of LDV at an example location. The oscilloscope is used to measure the voltage (U_R) over the small resistance (R=46 Ω).

8a). As mentioned beforehand, one of the loops in the bimorph actuator of Chip720 is defect. To compare the experimental results with the FEM simulation, Figure 8a contains FEM results for both the intact and the partially defective actuator model. A larger discrepancy occurs between the experimental and FEM curves when the voltage applied is higher. This may result from the heat transfer parameter setting in FEM simulation. Figure 8b shows an almost linear relationship between the power dissipation and out-of-plane deflection. Yang et

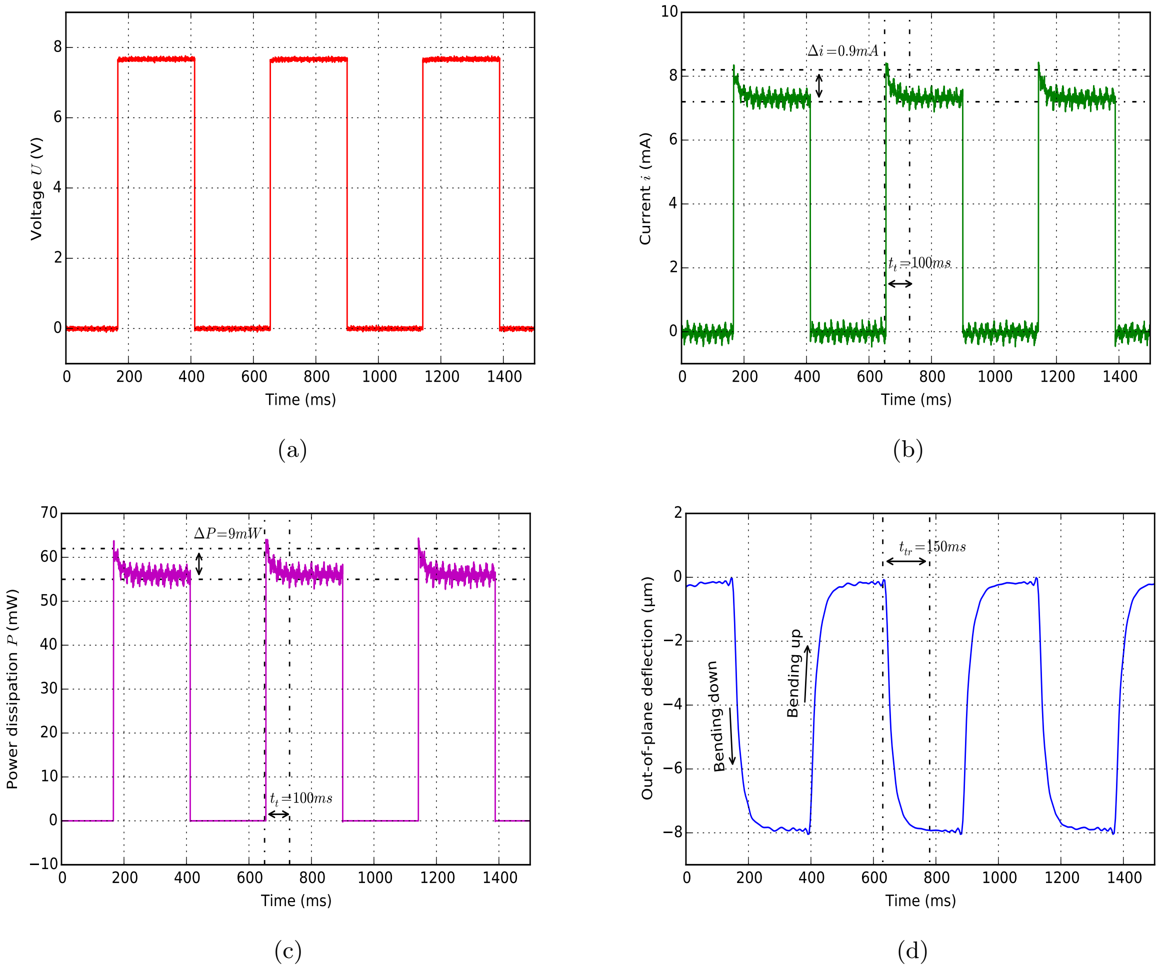
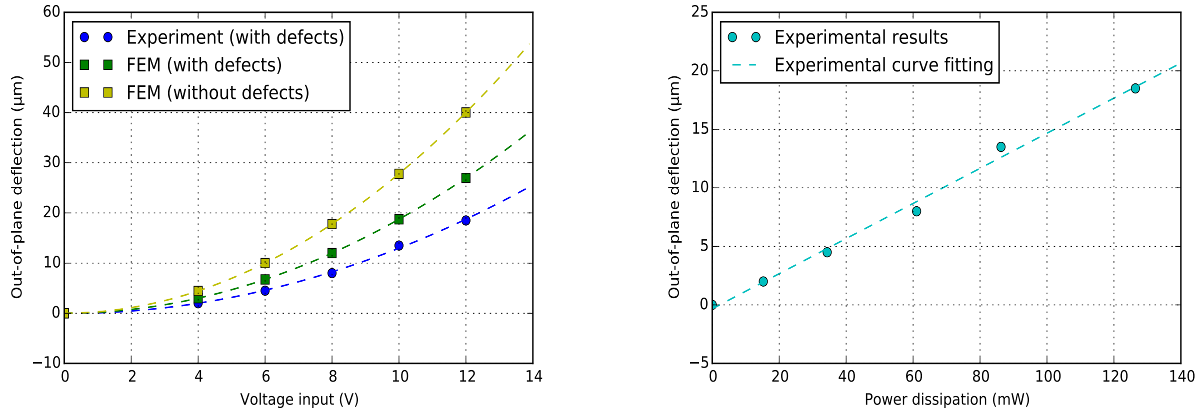


Figure 7: Measurement results of the long-loop bimorph actuator in Chip720. All graphs share the same horizontal axis (time domain). (a) Voltage (U) curve. (b) Current (i) curve. A 0.9 mA current decrease occurs at every first 100 ms in every period. (c) Dissipated power (P) curve. Likewise, during the transient time (t_{t}), the power dissipation drops 9 mW. (d) Out-of-plane deflection curve. The thermal response time (t_{tr}) of this bimorph actuator was observed to be 150 ms.

al reported the same behavior of their Si-SiO_2-stack bimorph actuators.[6] The maximum out-of-plane deflection was detected to be 18.5 µm at a DC voltage of 12 V, and its power dissipation is 126.42 mW. When a voltage of 14 V was applied, the bimorph actuator immediately burned down.

4. CONCLUSION

We designed bimorph actuators based on a 16 µm thick SiO_2 platform, aiming at positioning on-chip waveguide beams. Two kinds of bimorph actuators (with short-loop and long-loop poly-Si) have been successfully fabricated by using a backside release method. We demonstrated that the short-loop bimorph actuator was able to actuate the waveguide array with approximately 3.5 µm out-of-plane deflection. We also characterized the AC and DC behaviors of the long-loop bimorph actuator. It can reach up to 18.5 µm out-of-plane deflection, dissipated power less than 130 mW. The paper presented first results for out-of-plane tuning and the motion range using short-loop bimorph actuators. The parameters of the design have to be further tuned to meet all demands from the PHASTFlex alignment scheme.



(a) (b)

Figure 8: DC measurements and FEM simulation of the bimorph actuator in Chip720. (a) Out-of-plane deflection comparison between experiments and FEM simulation. FEM simulation includes the bimorph actuator with and without the defective poly-Si electrical-loop. The dashed lines indicate the curve fitting. (b) Curve of out-of-plane deflection versus power dissipation.

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