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4. TITLE AND SUBTITLE
Fused silica Ion Trap Chip with efficient optical collection system for timekeeping, sensing, and emulation

Final Technical Report

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FA9550-11-C-0047

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bado, Philippe

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Translume, Inc.
655 Phoenix Drive
Ann Arbor, MI 48108

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0001AC

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Goal was to develop Atom chips with dual integrated and miniaturized optical and electromagnetic capabilities. Proposed to fabricate traps out of fused silica, a material that is transparent at the wavelengths of interest (and which has good RF characteristic). Surmised that the material transparency would allow for optical beams to approach the trap from all directions. We also imagined that our demonstrated capability to fabricate numerous integrated optical elements in devices made from fused silica wafers would provide the optical functionalities required for trap control and trap monitoring. This approach was successfully demonstrated during our Phase I. We fabricated a variety of microtrap geometries, concentrating on symmetric three-dimensional traps as these offer deeper trapping potential. We showed that we could also fabricate highly-shaped 3-dimensional electrodes. We showed that we could integrate or insert optical pathways and optical elements within the trap substrate and address the trapped ions from all directions. We demonstrated the fabrication of large NA fluorescence collection optics.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Sharon Stemple
U	U	U	UU	7	**19b. TELEPHONE NUMBER** *(Include area code)* (734) 528-6371

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

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3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

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5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

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14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

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Translume
Guiding Optical Solutions

Cover Page

Contractor's name: Translume, Inc.

Contractor's address: 655 Phoenix Drive, Ann Arbor, MI 48108

Contract number: FA9550-11-C-0047

Nomenclature program: "Fused silica ion trap chip with efficient optical collection system for timekeeping, sensing, and emulation"

Date of report: April 30, 2012

Period covered by report: July 1, 2011 to April 30, 2012

Title of report: Final Technical Report

Contract Line Item: 0001AC

Security Classification: Unclassified

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Arlington VA 22203

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Table of Contents

Program's Objectives

This is our third and final progress report on this Phase I STTR contract FA9550-11-C-0047. This STTR proposal is undertaken in collaboration with Dr. Chris Monroe (Joint Quantum Institute, University of Maryland).

In our Phase I proposal we proposed to fabricate traps out of fused silica, a material that is transparent at the wavelengths of interest (and which has good RF characteristic). We surmised that the material transparency would allow for optical beams to approach the trap from all directions. We also imagined that our demonstrated capability to fabricate numerous integrated optical elements in devices made from fused silica wafers would provide the optical functionalities required for trap control and trap monitoring.

This approach was successfully demonstrated during our Phase I. We fabricated a variety of microtrap geometries, concentrating on symmetric three-dimensional traps as these offer deeper trapping potential. We showed that not only could we fabricate complex trap geometries, but that we could also fabricate highly-shaped three-dimensional electrodes. While a handful of microtraps with some 3D elements have been previously fabricated, they generally do not include 3D electrodes. Being forced to use only two dimensional (plane) electrodes, albeit potentially stacked, drastically limit the options available to trap designers. We also showed that we could integrate or insert optical pathways and optical elements within the trap substrate, and that using these optical features we could address the trapped ions from all directions. In addition we demonstrated the fabrication of large NA fluorescence collection optics. Large NA optics can be used to efficiently collect optical signals, such as fluorescence, emitted by the trapped ions. Testing alignment accuracy of this optical platform was done on several test samples where mirror-image transmitting receiving pairs were machined along with small precision apertures at their common focus. Fiber to fiber transmission efficiencies were measured to be within a few percent of simulated values. We had not previously demonstrated this capability with inserted optical components (Although we have worked extensively with fully integrated components machined directly into the substrate).

Description of progress made against tasks or milestones during reporting period

This is a 9-months Phase I STTR program. At the kick-off meeting we were made aware by the TPOC that the main tasks/objectives need to be completed by early January 2012. The project timeline has been adjusted accordingly. In our previous progress report we stated that we had completed all our tasks with the exception of the preparation of our Phase II proposal. During this period we prepared and submitted a Phase II proposal. This proposal was later selected for funding. As of this writing we are not aware of the Phase II start date.

In parallel we are also pursuing commercialization efforts. We are working with the group of Helmut Häffner (UC Berkeley). We delivered several demonstrators to his group during the period covered by this report. The Häffner has now placed an order for eight custom chips. This is our first commercial order for ion traps. While modest (in comparison with the funding obtained through this STTR), we expect the Häffner's order will promote our commercial capability and will lead others to consider us for their ion trap needs.

The Häffner's traps are surface-electrode traps (*i.e.* asymmetric traps, in which the RF node is not symmetrically located with respect to the electrodes) with three-dimensional loading ports (back side loading) and deep recesses between adjoining electrodes. A model is shown in Figure 1.

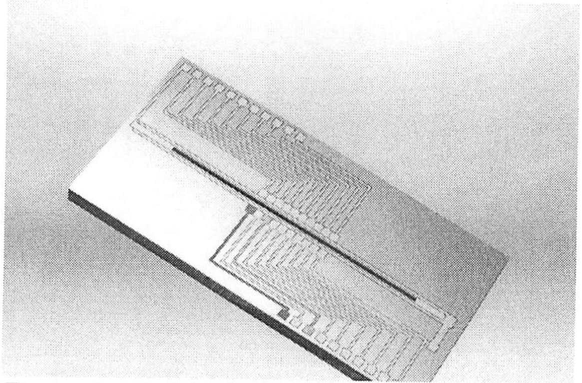


Figure 1: Model of one of the Häffner surface traps

These traps are designed to explore a very important issue: It has been reported by almost all groups working with ion traps that performances are affected by various sources of noises. Surface electrode traps are known to be especially susceptible to electric field noise, believed to generate by random patch potentials on the trap electrodes and /or impurity atoms adsorbed on the electrodes. As a result the ions heat up orders of magnitude faster than would be expected from Johnson-Nyquist noise alone. Noise that overlaps the vibrational frequency of an ion in the trap -about 1MHz-is especially troublesome. Many in the field have studied this phenomenon, including Professor Monroe our STTR collaborator. The intensity of this noise appeared to drop with the ion's distance "d" from the electrode as $1/d^4$ although this data is not accepted universally.

Professor Häffner is testing a hypothesis that by carefully selecting the electrode metal one can reduce the noise generated by random patch potentials. To test this theory, we are fabricating a batch of custom-designed surface-electrode traps. These traps are expected to be extremely susceptible to electrode noise. In order to minimize or eliminate other sources of noise, the traps include a through slot which allows for ion loading from the back side of the trap. These traps also have deep (30-50 micron depth) recesses between the various surface electrodes (as shown in Figure 2), thus reducing the noise contribution associated with bare dielectric surface charging.

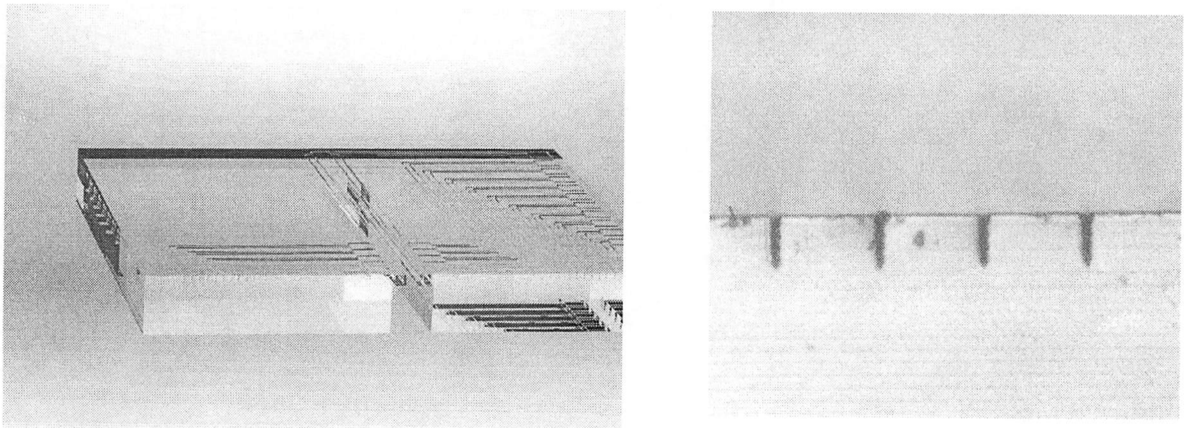


Figure 2: (Left) Model showing deep recess between surface electrodes. (Right) Test piece used for deep recess process optimization

Note that all of our Phase I demonstrators have electrodes made of Gold with a thin Titanium underlayer. According to Professor Häffner, preliminary data indicate that Gold is a relatively poor material as far as noise in concerned. Other metals, such as Aluminum, maybe much better candidate for low-noise electrode fabrication. We expect that the Berkley's group will be able to provide quantitative data in time to optimize the electrode coating for the traps we will be fabricating during our Phase II. (Note that according to Professor Haeffner, the deep 3D traps we have been fabricating during our Phase I should be one or two orders of magnitude less sensitive to random patch potentials than the surface-electrode traps he is using.)

It should also be noted that the Berkley surface electrode traps fabrication does not require a mask. Rather, the deep trenches that ultimately define the electrode boundaries are laser-fabricated (with our femtoEtch process) at the same time than the body of the trap is defined. Later on the full surface is coated (without mask). The recesses that defined the electrodes are so deep (by lithographic standards that the evaporative deposition (or sputtered deposition) does not reach the bottom of the recess. This provides a means to create electrical discontinuities, which form the electrodes boundaries. This maskless fabrication approach lowers production costs.

Results obtained to previously identified problem areas with conclusion and recommendation

None

Significant changes in contractor's organization or program milestones

None

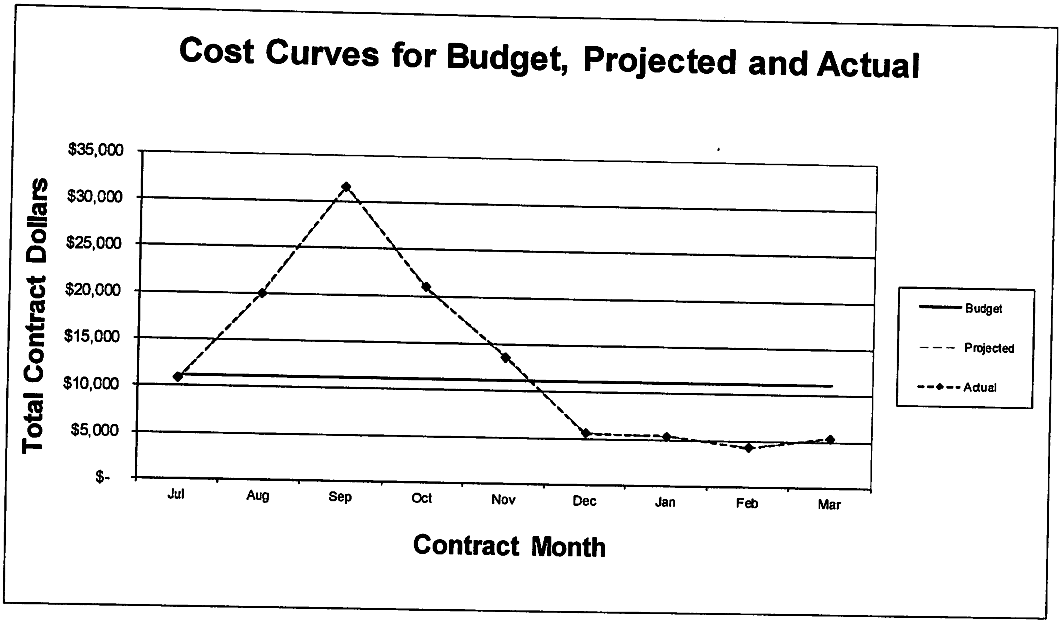
Problem areas affecting technical and scheduling elements

None

Problem areas affecting cost elements

None

Cost curves



Cost incurred for the reporting period and total contractual expenditure as of reporting date

SBIR Contract #W15QKN-10-C-0002
Costs Incurred As of 4/30/12

	January	February	March	April	Total To Date	Budget To Date	Act to Bud Variance
Direct Labor	-	-	-	-	21,158.61	16,378.74	(4,779.87)
x DLO Rate	*21.71%*	*21.71%*	*21.71%*	*21.71%*	*21.71%*	*21.71%*	*0.00%*
Direct Labor Overhead	-	-	-	-	4,593.53	3,555.81	(1,037.72)
TDL Subtotal	-	-	-	-	25,752.14	19,934.55	(5,817.59)
Material	-	-	-	-	198.53	1,016.82	818.29
Travel	-	-	-	-	-	2,057.04	2,057.04
Subcontractor	5,000.00	4,000.00	4,000.00	1,000.00	39,000.00	38,999.97	(0.03)
Other Direct Cost	-	-	-	-	4,179.17	-	(4,179.17)
x G&A Rate	*257.68%*	*357.68%*	*457.68%*	*557.68%*	*157.68%*	*157.68%*	*0.00%*
G&A (Rate x TDL)	-	-	-	-	40,605.98	31,432.77	(9,173.21)
Subtotal	5,000.00	4,000.00	4,000.00	1,000.00	109,735.83	93,441.15	(16,294.68)
x Profit Rate	*7.00%*	*7.00%*	*7.00%*	*7.00%*	*7.00%*	*7.00%*	*0%*
Profit	350.00	280.00	280.00	70.00	7,681.51	6,531.57	(1,149.94)
Subtotal	5,350.00	4,280.00	4,280.00	1,070.00	117,417.34	99,972.72	(17,444.62)

Person-hours expended for the reporting period and cumulative for contract

SBIR Contract #W15QKN-10-C-0002
Costs Incurred As of 4/30/12

	January	February	March	April	Total To Date
Philippe Bado, CTO	-	-	-	-	67
A. Said, PhD, Scientist	-	-	-	-	-
M. Dugan, PhD, Scientist	-	-	-	-	107
G. Wang, Technician	-	-	-	-	-
J. Spencer, Technician	-	-	-	-	55
T. Haddock, PhD, Scientist	-	-	-	-	30
C. Schenck, Engineer	-	-	-	-	58
	-	-	-	-	-
Total Hours	-	-	-	-	317

Trip and significant results

None

Record of any significant telephone calls and any commitments made by telephone or by email

None

Summary of engineering change proposal status

NA – No ECP proposed, or approved, or implemented

Contract schedule status

On Schedule

Plans for activities during following reporting period

None. The Phase I is completed.

Preparer of this report:

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E-mail: pbado@translume.com

Appendixes

None