A microengineered cold gas thruster system for a Co-Orbiting Satellite Assistant (COSA)

Adam Huang, William W. Hansen, Siegfried W. Janson and Henry Helvajian
Center for Microtechnology, The Aerospace Corporation, El Segundo, CA

ABSTRACT

Miniaturization technologies such as Micro-Electro-Mechanical Systems (MEMS) have been used to fabricate a prototype 100-gm class cold gas propulsion system suitable for use on a Co-Orbiting Satellite Assistant (COSA). The propulsion system is fabricated from bonded layers of photostructurable glass (Foturan® manufactured by Schott Corp. Mainz, Germany) using a developed UV laser-processing technique. The laser volumetric patterning fabrication process has been able to yield extremely high aspect ratios (>50:1) for 2D and 3D structures. The fabrication technique uses a merged process approach where serial (direct-write) UV laser processing is used to deposit the pattern without masking layers and a batch chemical etching process is used to remove the material. The serial process utilizes automated laser patterning imported from computer-aided solid modeling software. These flexible fabrication options allow batch fabrication for mass production and customization on the same fabrication run. Furthermore, embedded features such as intertwined, multilevel 3D fluidic channels are possible with such techniques. By using bonded layers, a modular design approach is utilized to allow simple integration of various satellite layers such as the fuel tank and the cold gas thruster fuel lines. In addition, further expansion of the propulsion system can be simply done by bonding on more layers of the patterned Foturan® glass; the design is based on fabricating integrated modular parts. Thus, the propulsion system is mass producible, expandable, expendable (low unit cost), and highly integrated.

Keywords: Foturan, MEMS, propulsion, thruster

1. INTRODUCTION

Microelectromechanical systems (MEMS) have historically focused on terrestrial applications which currently dominate MEMS development and usage. MEMS offers a capability for mass-producing small, intelligent instruments with high reliability and low cost through reduction of the number of piece-parts, elimination of manual assembly steps, and better control of material variability. These attributes, along with reduced mass and power requirements, are ideal for space applications.1

Major differences between terrestrial and space hardware result from radical differences in operating environment and the substantial cost to deliver a kilogram to Earth orbit or beyond. Launch cost to low Earth orbit (LEO), which is roughly between 200 km and 1500 km altitude, is about $10,000 U.S. per kilogram. Placing a spacecraft at geosynchronous Earth orbit (GEO) costs about $50,000 U.S. per kilogram. Spacecraft fabrication typically costs at least as much as the launch cost, resulting in a final cost between $20,000 U.S. and $100,000 U.S. per kilogram of spacecraft. Micro/nanoelectronics and MEMS are key technologies that can substantially reduce mass, and ultimately cost. In addition, these technologies offer additional status monitoring and anomaly recovery capability with modest impact on spacecraft mass and cost.

Additional capabilities can be microengineered into spacecraft at the device, subsystem, or system level. An example of a reliability-enhancing system-level capability is the use of Co-Orbiting Satellite Assistants (COSAs) with a host spacecraft. These spacecraft would be deployed on command from the host vehicle to provide imaging of exterior surfaces, on-orbit calibration of spacecraft sensors, or close-range mapping of spacecraft optical and radio emissions. The imaging mission can be particularly important for on-orbit anomaly resolution, e.g., did the solar arrays or antennas deploy properly and/or is there any impact damage? Examples of COSAs include the German-built “Inspector” which attempted to fly around the Mir space station and the 16-kg mass NASA-built Autonomous Extravehicular Activity Robotic Camera (AERCAM) which actually flew within the U.S. Space Shuttle Columbia’s cargo bay.2,3 The U.S. Air Force Research Laboratories, Information Directorate, has proposed a kilogram-class COSA called MEPSI (MEMS
Satellite Inspector) which could be readily-integrated onto conventional spacecraft. Our interest is in micromachined propulsion systems for kilogram-class COSAs.

2. ROCKET SCIENCE FOR MECHANICAL AND ELECTRICAL ENGINEERS

Rockets generate thrust by throwing away propellant mass. Since thrust is equal to propellant mass flow rate times the average exit velocity, the goal is to eject propellant at the highest possible speed in order to minimize the loss rate of non-renewable propellant. Specific impulse ($I_{sp}$), defined as the thrust divided by the mass-flow-rate of propellant through the thruster, is proportional to the propellant exit velocity.

Cold gas thrusters are the simplest thrusters that allow modulation of thrust; they can be started and stopped thousands of times. These devices use a converging/diverging nozzle to expand gas from a plenum at pressure $p_1$ and temperature $T$ (so-called “stagnation conditions”) to much lower ambient pressure $p_2$. The nozzle converts propellant enthalpy into directed kinetic energy and hence thrust; the propellant expands, accelerates, and cools while traversing the nozzle. The converging section accelerates the flow until the flow velocity reaches the local sound speed, at which point a diverging section is required for continued expansion. The theoretical specific impulse for these gasdynamic thrusters is approximately given by:

$$I_{sp} = \frac{1}{g_0} \left( \frac{2kR'}{(2k-1)} \right) \left[ \frac{T}{M} \right] \left[ 1 - \left( \frac{p_2}{p_1} \right)^{(k-1)/k} \right]^{1/2}$$  \hspace{1cm} (1)

where $g_0$ is the gravitational acceleration at the Earth’s surface (9.8 m/s$^2$ in mks units), $k$ is ratio of specific heats for the propellant in the plenum, $R’$ is the universal gas constant (8314.3 Joule/k mol·K), $M$ is the mean molecular weight of the exhaust gas, and $p_2$ is the pressure at the exit plane. Note that eq. (1) is purely thermodynamic; physical scaling does not enter into the simple theoretical calculation of specific impulse. Values of $I_{sp}$ for room-temperature expansion into a perfect vacuum can range from 31 s for Xenon, a heavy monatomic gas, to 300 s for hydrogen, a light diatomic gas. Practical considerations such as high-density propellant storage without resorting to cryogenic temperatures or extremely high pressures usually drives the system designer to utilize propellants that can be readily liquified such as ammonia, butane or one of the Freons. These propellants yield ideal $I_{sp}$ between 50 s and 110 s.

To calculate the maximum change in velocity $\Delta V$ that can be imparted to a spacecraft, one uses the rocket equation,

$$\Delta V = g_0 I_{sp} \ln \left( m_i / m_f \right)$$  \hspace{1cm} (2)

where $m_i$ is the initial spacecraft mass, $m_f$ is the final spacecraft mass, and the propellant used is $m_i - m_f$. Figure 1 shows the propellant mass fraction (required propellant mass / initial spacecraft mass) as a function of specific impulse and $\Delta V$. For a specific impulse of 50 s, the velocity increment in m/s is roughly five times propellant mass fraction in percent for $\Delta V$ less than 100 m/s; velocity increments up to 50 m/s require propellant mass fractions below 10%.

The mission $\Delta V$ requirement for a COSA is a strong function of mission lifetime, thrusting errors, relative position and velocity determination errors, and the number and rate of angular slews required if attitude control is provided by thrusters. Under ideal conditions, the $\Delta V$ can be well below 1 m/s. As an example, assume that a COSA is released at rest with respect to a host spacecraft that is in a 700-km altitude circular orbit about the Earth. To “orbit” about the host spacecraft, the COSA must first move behind the host a comfortable distance, e.g., ~50 meters for a spacecraft with maximum dimensions of 5 meters or less. This phasing maneuver is readily accomplished by first firing a thruster pointed parallel to the instantaneous direction of travel, and firing a thruster pointed in the opposite direction one orbit period later to cancel the relative velocity. Figure 2 shows the path of the COSA with respect to the host vehicle where the horizontal axis is the change in radial distance from Earth and the vertical axis is distance from the host along the orbit; Earth is to left and you are looking down onto the orbit plane. The dots are 3 minutes apart and the path is curved
in this reference frame because the COSA is initially put into a new orbit with a slightly higher energy than the host orbit; the average radius is larger. Since this orbit has a slightly longer period, when it returns to cross the host orbit, it is behind the host. With initial and final $\Delta V$s of 3 mm/s, the COSA moves 53 meters behind the host in 98.8 minutes. More rapid maneuvers are possible, but require correspondingly larger $\Delta V$. Once at rest with respect to the host, the COSA can be placed into an “orbit” about the host by applying radial and orbit-normal thrusts. The application of a 28 mm/s radial $\Delta V$ with a 49 mm/s orbit-normal $\Delta V$ puts the COSA in a relative orbit about the host with a 53 meter radius. Figure 2b shows two possible relative orbit planes about the host. Total translational $\Delta V$ for the COSA to enter one relative orbit and eventually switch to the other is $\sim$180 mm/s. Thrust levels of $\sim$1 mN per kilogram of COSA will provide reasonable thrusting times, e.g., times much less than an orbital period.

As spacecraft shrink in size, it becomes easier to perform attitude control using thrusters. Spacecraft moments-of-inertia scale as $l^5$ where $l$ is a characteristic length for constant density and geometric configuration. Thruster-induced
torques scale as $T^*l$ where $T$ is thrust. The tangential thrust required to generate a given angular acceleration therefore scales as $l^4$. Figure 3 shows required force per thruster and total $\Delta V$ to perform a 90° change in orientation for a 1-kg mass COSA with a 5-cm radius as a function of maneuver time. This slewing maneuver uses two oppositely-directed thrusters on opposite sides of the COSA to generate a torque couple which changes sign halfway through the maneuver. A slewing time of tens-of-seconds is reasonable, resulting in an average thrust requirement of about 0.1 mN. About twenty of these angular reorientations can be done for a total $\Delta V$ of 0.1 m/s.

![Figure 3. Thruster force and velocity increment requirements to slew a representative 1-kg mass COSA through 90°.](image)

The velocity increment for a simple satellite inspection mission can be as low as 0.3 m/s (translations plus ~20 “hard” angular reorientations). More realistic $\Delta V$s are ~2 m/s due to attitude and position determination errors and the expected variability in COSA ejection velocity from the host vehicle. Average thrust levels of ~0.1 mN are appropriate for angular slewing while thrust levels of ~1 mN are appropriate for translational maneuvers assuming a 1-kg mass COSA. Thrusters with ~1 mN continuous thrust level and faster than 100 msec response time are ideal for this application. Cold gas thrusters can easily meet the $\Delta V$ requirements with propellant mass fractions less than 0.5%. Information on other microengineered propulsion systems can be found in reference 4.

### 3. PROPULSION SYSTEM DESIGN

A primary objective of our project is to demonstrate the feasibility of a ~100-gram cold gas propulsion module suitable for a 1-kg class COSA. Another objective is to demonstrate a batch-producible manufacturing technology that will enable mass-production of miniature propulsion modules. Foturan®, a photosensitive glass/ceramic material available from Schott, enables photolithographic patterning of propellant fuel lines, tanks, and structural elements. Ideally, MEMS type valves would be readily integrated with Foturan® structural layers. However, due to the immaturity of current MEMS valve technology with respect to leakage rates and response time, conventional solenoid valves were used for this project. The face-sealing High Density Interface (HDI) version of the 3 way solenoid valve from The LEE Company provided optimum low size, mass, and power characteristics along with adequate response times and leak rates. This valve can operate at 4-5 Volts (100-150mA), which is directly compatible with TTL logic levels. It can also handle flow rates up to 10 L/min and withstand a pressure drop up to 50 psig. We chose hexafluoropropane (DuPont® HFC-236fa) as the propellant because its vapor pressure curve was ideal for the expected on-orbit temperatures and valve pressure limits. In addition, it has a good storage density of 1.37 g/cc. Figure 4 shows the double-throw HDI valve with a common center port. One port is always on, or when one of the outputs is sealed, the valve acts as a pure on/off valve.
The mobility of our COSA propulsion module was fixed to three degrees of freedom for demonstration on an air table. This subset of two orthogonal X-Y linear motions and one rotation CW/CCW (clockwise/counter-clockwise) about the Z-axis was deemed sufficient since extension to full three-dimensional motion is straightforward. A COSA can have multiple propulsion modules for extra degrees-of-freedom and redundancy. Figure 5 shows the six thrust lines and coordinate system for our propulsion module. Figure 5 also shows the plan view of the internal flow channels we used to feed six micronozzles. Instead of using one valve per nozzle (which requires 6 valves), 5 valves were used to take advantage of the 3-way valve design. This limits thrusting options to left/right, up/down, and CW/CCW rotation. Three valves were used to port the 6 nozzles and two valves as flow gates to nozzles AB and CDEF, respectively; the Y- and Z-rotational directions share the same gate valves. If left/right motion is needed simultaneously with rotation, then a duty based control scheme and/or discrete control sequencing can be used to share the thrust nozzles. For example, in order to turn a corner, a duty based control scheme allows smooth turning, while a discrete control sequencing is more jagged due to the single axis control at any one time. However, the discrete turning is easier to implement if smooth turning is not required for the given task. An onboard PIC-based Micro Controller Unit (MCU) handles the required thrusting control. Notice that the 5-valve thrusting scheme also decreases the maximum power required when thrusting is required for both two-axis and three-axis motions simultaneously.

Due to the vaporization of the fuel while thrusting, significant fuel tank chilling occurs during normal operation. To prevent loss of propellant tank pressure, a nichrome wire heater is embedded beneath the fuel tank layer. A thermocouple sensor with fixed-temperature set point circuitry controls the heater and provides over-temperature protection with power cutoff. In addition, a pressure sensor is also used to measure the fuel pressure for providing overpressure protection and for calculating real-time thrust levels. This is the primary self-monitoring task provided by the on-board computer.

Our propulsion module contains an onboard computer in the form of a Micromint PICStick 3_2K microprocessor that is based on Microchip’s PIC16F628 MCU. The PIC16F628 MCU has a FLASH program memory of 2048 14-bit words, 128 bytes of EEPROM data memory, and 224 bytes of program RAM. This has sufficient computing power and memory storage to provide both RF downlink data processing, system self-monitoring, and preprogrammed “inertial waypoints” based on timing. The PICStick 3 also includes 8 bits of TTL-compatible input/output (IO) and two 0-5V

Figure 4. HDI solenoid valve schematic. (from ref. 5)

Figure 5: Thruster arrangements with three degrees of freedom.

<table>
<thead>
<tr>
<th>Thruster ON</th>
<th>Reaction</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>B</td>
<td>-X</td>
</tr>
<tr>
<td>D&amp;E</td>
<td>Y</td>
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<td>CW_Z</td>
</tr>
<tr>
<td>D&amp;F</td>
<td>CCW_-Z</td>
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</table>
analog input channels (analog-to-digital converters, ADCs). External interrupts can be achieved through one of the IO bits. This particular processor was selected due to the extremely simple, yet powerful and efficient, Basic-based programming language compiler from Micromint. After rapid prototyping with the PICStick 3, the PIC16F628 MCU and the ADC can then be directly transferred to a custom-made circuit board (or even using Foturan glass as circuit board substrate) using the same assembly codes for the PICStick 3. This offers considerable savings in time and technical troubleshooting. Figure 6 shows the tasks assigned to each IO pin and the ADC inputs.

Our propulsion module was designed with two control schemes for ground-based testing. Preliminary tests were done using commercially-available transmitter/receiver sets and a joystick interface for manual operation. We selected the OKW Electronics FMRTF3/FMRRF1 transmitter/receiver boards operating at 433.93 MHz with a 9.6Kbps data rate for our wireless interface. These miniature boards are shown in Figure 7. Again, like the computing electronics, this wireless set was selected based on ease of use and no development time. Future generations of the propulsion module will incorporate chip-based wireless designs that are integrated on the same PCB as the rest of the onboard electronics.

The propulsion module uses a dual 5 Volt bus powered by two 3.6 Volt rechargeable lithium ion cells mounted in series. Two separate 5 Volt regulators were used to separate the signal (processor and wireless) power supply and solenoid valve power supply with their grounds properly filtered to avoid sporadic electronic impulses from the valves.

Our propulsion module is based on bonded layers of Foturan and stacked electronic boards. In terms of system integration, this is 2D modular stack design. There are 7 Foturan layers which were modeled in solids-based CAD (SolidWorks®). Figure 8 shows an exploded view of these layers. Layers A and B sandwich the NiCr heater and are the bottom of the fuel tank. A type K thermocouple is also embedded between layers A and B. Layers C and D are the fuel tank walls. Layer E is the top of the fuel tank. This layer contains ~1200 100 µm holes that act as a liquid phase separator to prevent liquid fuel from entering the fuel lines. Layer F contains the gas manifold and delivery lines to the thruster nozzles. Layer G caps the manifold and provides an interface to the HDI solenoid valves. The current nozzles are 2D and we are developing methods to fabricate true 3D axis-symmetric conical nozzles. All fuel line channels are

**Figure 6:** PICStick 3_2K® micro controller and the associated I/O and ADC tasks. (Photograph courtesy of The Aerospace Corporation)

**Figure 7:** Transmitter an receiver boards from OKW Electronics. Operational frequency is 433.93MHz with a 9.6 Kbps data rate. (Photographs courtesy of The Aerospace Corporation)

<table>
<thead>
<tr>
<th>Channels</th>
<th>Type</th>
<th>Setting</th>
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</thead>
<tbody>
<tr>
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<td>Digital</td>
<td>IN</td>
<td>Micro-Controller Interrupt/Transmit</td>
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<tr>
<td>DIO_1</td>
<td>Digital</td>
<td>OUT</td>
<td>Valve 1</td>
</tr>
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<td>Valve 2</td>
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<td>Digital</td>
<td>IN</td>
<td>Temperature Switch Signal</td>
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<tr>
<td>DIO_7</td>
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<td>Heater Switch Signal</td>
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<tr>
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<tr>
<td>Analog_2</td>
<td>Analog</td>
<td>IN</td>
<td>Battery Power Monitoring</td>
</tr>
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500 µm x 1000 µm in cross section. The 2D nozzle used has a conservative nozzle half angle of 27.98 degrees and an expansion of 2.38.

4. FOTURAN FABRICATION

A laser direct-write microfabrication technique has been developed at The Aerospace Corporation that incorporates the advantages of direct-write processing (e.g. maskless processing and true 3D processing) with the ease and cost-effective aspects of batch processing (i.e. parallel processing nominally provides process uniformity over a wafer scale)\textsuperscript{8}. We can take the advantages of laser direct-write processing and merge it with that of batch processing if the direct-write segment is utilized only for volumetric patterning of the material and not for material removal. The patterning can include any complex shape that the direct-write tool can fashion. The resulting impregnated pattern can then be chemically batch processed to either remove the exposed or non-exposed regions. A key aspect of this merged process is the material. It must be made of photolytically active ingredients, like photoresist polymer materials, that upon exposure can either resist chemical etching or be dissolved. The Aerospace technique is based on a class of glass/ceramic materials called photositalls that can be photo-structured in 3D.\textsuperscript{9} Our technique permits microfabrication of very high aspect ratio structures (>50) with resolution approaching 5 microns. It enables fabrication of the fluid/gas distribution system in our propulsion module.

Photositalls function via a three step process; an illumination step, a ceramization step and a preferential isotropic etching step.\textsuperscript{10} For Foturan\textsuperscript{TM}, manufactured by Schott, Germany, the photosensitive character arises from trapped Ce\textsuperscript{3+} (admixture CeO\textsubscript{2}) and Ag\textsuperscript{+} (admixture Ag\textsubscript{2}O) ions that are stabilized by Sb\textsubscript{2}O\textsubscript{3} in lithium aluminosilicate.\textsuperscript{11,12} Using the conventional linear absorption model, Ce\textsuperscript{3+} can be photoionized to form Ce\textsuperscript{4+} and a free electron at photon energies near 3.97 eV (318 nm). The free electron neutralizes a nearby Ag\textsuperscript{+} ion (i.e. Ag\textsuperscript{+} + e\textsuperscript{-} \xrightarrow{GC6} Ag\textsuperscript{0}) leaving a latent image of the absorption event. In the ceramization step, migration and local clustering of the Ag\textsuperscript{0} nuclei lead to formation of lithium silicate crystals. In a 5% solution of HF these crystals etch 20-40 times faster than the unexposed amorphous material. An aspect that is critical to the surface finish of the final microstructure or the degree of ceramization is the growth rate of the crystals and the maximum bake temperature. Both growth rate and phase of the lithium silicates can be controlled during the bake step. A low temperature (~600 C) bake results in multi-phase crystals that dissolve in HF acid, while a high temperature bake (>700 C) forms a true ceramic phase that is resistant to HF.
The Aerospace microfabrication process utilizes the Foturan UV wavelength dependence in absorption to control the volume of material that is exposed. By changing the laser wavelength from 248nm (OD=3.0) to 355 nm (OD=0.1) it is possible to vary the penetration depth of the laser light from less than 100 microns to over 1 mm. During exposure we also control the incident laser fluence and applied dose (i.e. number of laser shots). Finally, great care is taken to control the shape of the laser beam, the focal volume, and the depth of focus (i.e. confocal parameter \( b = \frac{2\pi\omega_0^2}{\lambda} \), where \( \omega_0 \) is the beam radius at waist and \( \lambda \) is the wavelength). All these controls insure against thermal runaway damage within the focal volume region and also permit better precision in the depth of exposure. Figure 9 shows that for a constant laser fluence, the exposure depth depends on the number of shots applied. This data suggests that by controlling the laser shot number (i.e. for constant fluence) the material can be made to “cut” to a predetermined depth.

![Figure 9: Laser penetration depth, which is related to exposure and etching depth as a function of laser pulses for 266 nm wavelength](image)

The aforementioned process controls are integrated with an XYZ micro-stepper that is accurate to 5 microns over 100 mm XY translation and an automated system that can transfer one of four incident laser wavelengths to the sample surface. Three individually selectable microscope objectives can be used to focus the laser beam unto the sample (5X, 10X and 20X). Two high repetition lasers “feed” the exposure tool; a 2kHz excimer laser (Potomac Photonics SGX1000) and a 1kHz diode seeded Nd-Yag laser (Continuum HPO-1000). Automated fast shutters flag on/off the various laser beams and power meters are used for average power readings. Local dose control can be set through software commands to the stepper motor speed parameter or via burst-commands to the laser. For a multi-color exposure process, the various wavelength patterns are drawn separately, as layers, using AutoCAD™ software. The DXF output of the AutoCAD software is converted to machine control language using a translator program. All or any selected number of wavelength specific layers can be run automatically. We have used this in-house developed direct-write laser exposure tool to fabricate various microstructures including resonant beams, springs and fluidic channels in glass or ceramic materials. This capability enables the development of ceramic or glass based MEMS.

The complete propulsion system and fuel tank of the COSA is comprised of seven laser-processed Foturan wafers. Two wafers are from 2 mm thick stock and the rest are from 1mm thick stock. All of the individual layers have lateral dimensions of 50 x 50 mm but were patterned from larger 100mm dia wafers. The non-ablative laser processing technique was also used to pattern the propulsion system “die” size (50 x 50mm) so that during the timed chemical
etching step, the wafer would also be “diced” thus saving a cutting/dicing operation. In the first prototype all seven layers will be fused using high strength epoxy while for the second prototype, we intend to fuse all the glass/ceramic layers using a pressure/heating process. The fuel tank cavity and the support structures have been designed to maximize the fuel volume and maintain an adequate safety margin for containing the ~40 psi liquid fuel. The current seven layer design could be reduced to four layers by further integration in fabrication design and the use of imbedded channels and cavities. Figure 10 shows two views of the stacked layers prior to etching and coupon release. Six of the seven layers are shown in the figure. The inclusion of the very dense plenum layer would obscure all the other layers and is not included in the figure. Three UV laser wavelengths were used to fabricate all the microstructures. After etching, the wafers could be left in a semi ceramic or near vitreous state or be converted to a full ceramic material that is not only resistant to HF chemical etching and but is also stronger.

Figure 11: Two views of the gas fluid distribution system for the COSA. Six of seven layers are shown. The photograph was taken prior to etching. All pattern portions etch to a selected depth. Circled regions locate the microthruster nozzles. Inset shows a blowup of two of the micronozzle regions. (Photographs courtesy of The Aerospace Corporation)

5. SUMMARY

We have presented basic COSA mission requirements, propulsion module layout, and fabrication techniques for a COSA cold gas propulsion module. It is a mass-producible system which is scalable to a multitude of sizes and shapes. The complete COSA module, including electronics, battery and fuel weighs approximately 100 grams.

ACKNOWLEDGMENTS

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