The Fourth International Workshop on
Micro and Nanotechnology for Power Generation
and Energy Conversion Applications
**PowerMEMS 2004**
November 28 - 30, 2004
Kyoto, Japan

# Chemical Lasers on A Chip: A New Direction for Power MEMS

**A.H. Epstein, C. Livermore, B. A. Wilhite, Y. Gong, and K. F. Jensen**
Massachusetts Institute of Technology
77 Massachusetts Ave., 31-264
Cambridge, Massachusetts 02139 USA

**Abstract**

The concept of Power MEMS is expanded to include chemical lasers on a chip. Chemical lasers generate optical power directly from chemical reaction in a moving fluid. The exciting species are usually expanded through a nozzle and the lasing takes place in a high speed gas at low pressure. The principal advantage of chemical lasers is that, unlike solid-state lasers, they are not heat rejection-limited and thus can be scaled up to very high average powers, kilowatts-to-megawatts. The specific chemistry explored is that of the chemical oxygen iodine laser (COIL), in which chemically generated singlet oxygen collisionally excites an iodine laser. A chip-based, μCOIL has three principal MEMS subsystems: a singlet oxygen generator (SOG), a micro-chemical reactor which generates singlet oxygen by reacting $Cl_2$ with alkaline $H_2O_2$; a gain module consisting of a supersonic expansion nozzle, iodine injection system, and supersonic gain cavity; and a pressure recovery system (PRS) which uses steam ejectors to exhaust the sub-atmospheric gain cavity. Each chip-scale MEMS COIL module would produce about 10 W of optical energy when integrated into a suitable optical system. A 5 kW array of such modules is an attractive tool for many metal-cutting applications.

*Keywords: MEMS, chemical laser, Power MEMS, microlaser*

## INTRODUCTION

The term “Power MEMS” was first suggested by Epstein and Senturia [1] in 1996 to describe microsystems which generated power or pumped heat. Their particular interest was MEMS heat engines, specifically Brayton cycles (such as gas turbines) and Rankine cycles (such as steam engines) and subsystems thereof. The promise identified was microsystems whose power densities equaled or exceeded those of the more familiar large-scale devices. Since that time, Power MEMS has evolved into a broader concept which includes other traditional thermal cycles, new heat engine concepts which may only be attractive at microscale, energy harvesting schemes, and micro-fuel cells. Heat engines convert chemical energy into heat which can be used to pump heat (chillers), make electricity (thermoelectric), or be converted into mechanical work (microturbines or IC engines). The mechanical energy may then be used directly for applications such as vehicle propulsion, fluid pumping, or converted into electric power. Another use for the chemical energy released in a MEMS device is direct conversion into light, specifically laser light. In this paper we review the concept of a MEMS chemical laser.

A chemical laser uses a chemical reaction to pump energy into the upper laser state rather than electricity (a diode or $CO_2$ laser) or incoherent light (a YAG laser). The reaction usually takes place in a rapidly moving fluid to inject fresh reactants into the lasing volume and remove reaction products. The physical processes in a chemical laser are such that the lasing typically must take place in a low pressure gas, at 0.1 atmosphere or less. Of course, only a fraction of the chemical energy is converted into light; the remainder ends up as heat. This waste heat is convected by the flow from the lasing volume along with the reaction products.

A solid-state diode laser is a common way to generate coherent light from a chip. They are reliable, simple to use, and readily available (over a billion diode lasers are produced a year). Of course, solid-state lasers require electric power, but conceptually that can be supplied by a MEMS power source such as a microturbine or IC engine to make a complete chip-based system. Why then consider a chemical laser which requires a lasant (fuel) supply, an exhaust or recycling system, and complex plumbing (valves, pumps, etc.)? The simple answer is scalability. The average power output of a solid-state laser is constrained by the rate at which heat can be removed from the solid laser medium. This is currently limited both by conduction in the solid and by heat transfer at the solid surface to a few watts of high optical quality light output. To reach larger powers, many diodes can be ganged together but with degraded optical quality. One remedy to the problem of optical quality is to use the light from the diodes to optically pump another lasing medium such as Nd:YAG glass. This, of course, introduces another source of inefficiency and another heat re-

moval problem (from the glass). An alternate approach is to fabricate fiber optics of the laser glass and use diodes to pump the fibers. To realize high beam quality at high powers, many fibers must be mode-locked together, currently a challenging problem. If the electric laser is on a mobile platform, then the mass, volume, and efficiency of the power supply such as a diesel or gas turbine generator and its fuel must be considered as well.

One conclusion from the above is that, while solid-state lasers are a very attractive way to generate average power in the milliwatt-to-watt scale, their complexity, weight, and cost do not currently scale well to larger sizes, kilowatts and above. For this reason, flowing gas lasers, principally $CO_2$, have predominated in the larger industrial applications. Commercial $CO_2$ lasers excite the $CO_2$ with an electric discharge. In larger lasers, the gas is recirculated by compressors, flowed through the laser cavity, and then through heat exchangers for cooling.

Chemical lasers use chemical reactions in the laser cavity to directly pump the laser states, i.e. chemical-optical without going through the intermediates steps of chemical-mechanical-electrical-electrical-optical. There are several chemistries that can be used. At MIT, we have focused on the Chemical Oxygen Iodine Laser (COIL). In a COIL, the lasing species is atomic iodine [2]. The iodine is excited by collision with singlet-delta-oxygen (a metastable state of $O_2$ with a lifetime of a few minutes) which is generated by chemical reaction in the laser.

There has been significant interest in developing COIL systems for industrial applications as an alternative to $CO_2$ gas lasers owing to their improved power outputs, wavelength characteristics, and compatibility with glass optics [3-6]. High power (1-10 kW) industrial $CO_2$ lasers currently employed for metal cutting and welding in the machining and automobile industries are limited to a maximum output of ~10 kW, while industrial COIL systems are capable of producing up to 30 kW, allowing faster cutting rates and greater welding depths. Greater cutting precision can be realized via a decrease in focus spot diameter, owing to the characteristic wavelength of the COIL system being approximately an order-of-magnitude shorter (1.315 micrometers) than that of $CO_2$ lasers (10.6 micrometers). Because glass is transparent at 1.315 micrometers, more precise and cost-effective optics can be employed by COIL systems, as compared to zinc selenide and gallium arsenide lenses necessary for $CO_2$ systems. In addition, the applicability of glass optics also allows the use of fiber optic cables for more flexible beam delivery. However, the application of COIL systems in industry is limited by current system size, reliability, and safety.

A COIL system is comprised of four sections: (i) a chemical reactor for generating singlet-oxygen, (ii) a supersonic nozzle for mixing and reaction of molecular iodine with singlet-oxygen, (iii) an optical cavity for harnessing stimulated emission of excited-state atomic iodine, and (iv) a pressure recovery system to increase the low exhaust pressure of the optical cavity to one suitable for recirculation or exhaust to atmosphere. While a variety of chemistries for singlet-oxygen generation exist, the two-phase reaction of alkaline hydrogen peroxide and chlorine gas is most commonly used and the one discussed herein. The spin-excited singlet-oxygen provides the energy necessary for iodine dissociation and excitation of atomic iodine within the supersonic mixing nozzle. The near-resonance of the $O_2(^1\Delta)$-$I^2P_{1/2}$ system results in energy transfer with a minimum of excitation loss. Emission from the excited atomic iodine is then collected in the optical cavity. To minimize deactivation of singlet-oxygen and excited iodine from homogeneous and heterogeneous collision losses, the COIL system is operated at low pressure, with nozzle plenum stagnation pressures of ~100 torr and cavity static pressures of ~10 torr being common. For this reason, a pressure recovery system is also employed to pump the gas exiting the cavity to higher pressure. More detailed information on μCOIL modeling and design can be found in Wilhite *et al*. [7]. In the following sections, we discuss the three μCOIL subsystems–the singlet-oxygen generator (SOG), the gain module, and the pressure recovery system (PRS)–illustrated in Figure 1.

## SINGLET-OXYGEN GENERATOR

The singlet-oxygen generator is a microchemical reactor tailored to the chosen two-phase reaction of alkaline hydrogen peroxide and chlorine gas. Previous experimental studies have demonstrated significant improvements in heat and mass transfer in MEMS-based microreactors, as a result of increased surface area-to-volume ratios. For the highly exothermic reaction of chlorine gas with basic hydrogen peroxide (BHP), the primary design concerns of existing, conventional-scale systems are efficient heat removal and maximizing the gas-liquid contacting area. Given the improved wall area-to-flow volume ratio at small length scales and high thermal conductivity of single-crystal silicon, efficient cooling of the reaction zone can be achieved in a MEMS approach. Gas-liquid mass transfer coefficients in microchannels are an order of magnitude greater than those reported for conventional approaches such as gas-sparger, rotating disk, or liquid-jet systems. For these reasons, a

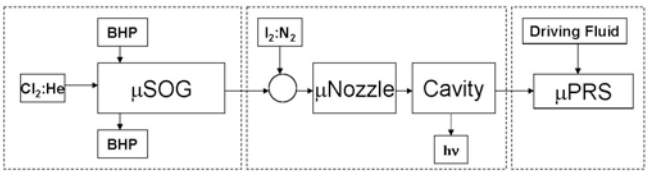


**Figure 1.** Modeling concept for μCOIL system.

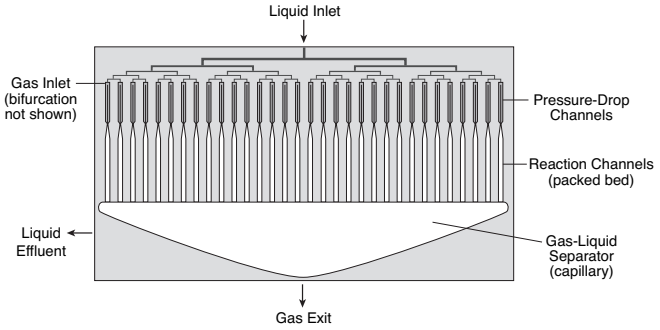


**Figure 2.** Illustration of singlet-oxygen generator (SOG) concept, fabricated upon a 2.5 cm x 2.5 cm x 0.05 cm chip.

microscale singlet-oxygen generator may prove superior to existing macroscale systems.

An individual SOG unit is shown in Figure 2. This is an adaptation of a previous microchemical reactor design [8]. It contains 32 gas-liquid reaction channels with appropriate inlet bifurcation for each phase in conjunction with pressure-drop channels to ensure even distribution. A gas-liquid separation section is included, along with cooling channels on the underside of the device for removing excess reaction heat. One side of the chip contains the liquid inlet bifurcation, pressure drop channels, reaction channels, and separation section, while the other contains the gas inlet bifurcation and coolant channels.

## GAIN MODULE

Gas exiting the singlet-oxygen generator unit is pre-mixed via injection ports immediately prior to the nozzle inlet with a secondary 50:1 He:$I_2$ flow to achieve an overall molecular iodine-to-total oxygen ratio of 0.015. At the nozzle inlet, all iodine is assumed to be in the molecular state. The geometry of the supersonic expansion nozzle is shown in Figure 3.

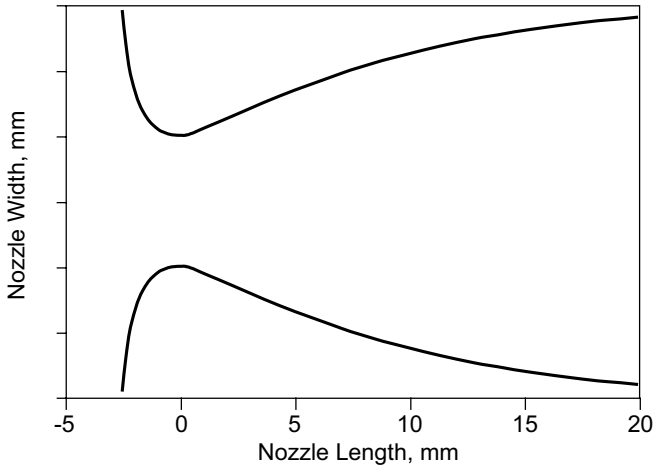


**Figure 3.** Supersonic mixing nozzle geometry.

The objective is to rapidly expand the flow without creating significant shock waves. The throat width and height are both 1 mm, compatible with current micromachining technology, while the ratio of throat to exit area is 2.64 to result in a nozzle exit Mach number of 2.8. The nozzle is followed by the gain cavity in which the optical energy is extracted. This is a nominally constant Mach number flow channel, straight-walled with minor corrections for the boundary layer growth and energy extraction. The fraction of the energy in the excited state which can be optically extracted increases with channel length. For these conditions, more than 90% of the available energy can be extracted in a 5 cm long channel.

## PRESSURE RECOVERY SYSTEM

The role of the pressure recovery system (PRS) is to maintain stable flow in the laser gain cavity by pumping the exiting low pressure (~10 torr) fluid to atmosphere. To ensure compatibility and scalability within the μCOIL design, a basis of one nominal PRS corresponding to one nominal nozzle is assumed. The overall size of one PRS is about 5 cm in length, and it has the same cross-sectional area as the nozzle exit. The PRS has three major components: a supersonic diffuser, a multi-stage ejector, and a subsonic diffuser (Figure 4). The role of the supersonic diffuser is to recover pressure from the kinetic energy of the flow exiting the cavity, by converting kinetic energy to static pressure via a series of oblique shocks, followed by a normal shock to reduce the flow velocity to subsonic conditions, as illustrated in Figure 4b. Because the supersonic diffuser cannot recover the gas static pressure above the original nozzle plenum pressure,

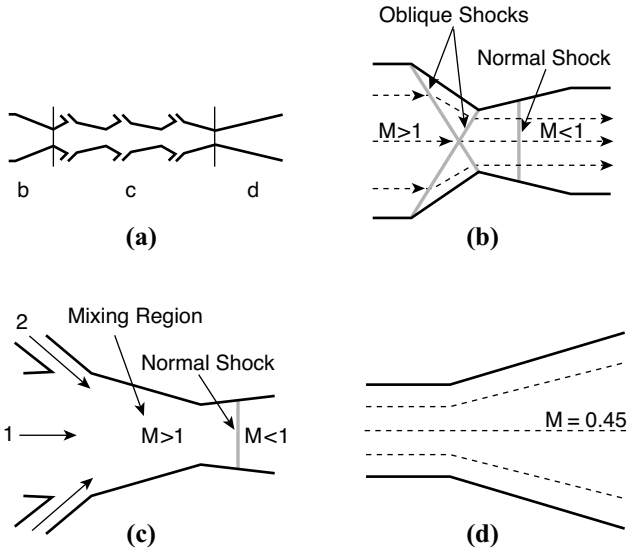


**Figure 4.** Illustration of pressure recovery system (PRS) concept; (a) overall system design, (b) supersonic diffuser, (c) steam-ejector single stage, and (d) subsonic diffuser.

subsequent steam ejectors are used to approach atmospheric conditions. Each stage of the ejector is comprised of a constant pressure mixing section, in which supersonic driving fluid is mixed with the subsonic primary flow; the resulting supersonic mixture then undergoes a normal shock to recover static pressure (Figure 4c). The ejector is driven by 500K and 15 atm steam generated from the catalytic decomposition of a 70% hydrogen peroxide aqueous solution in a microreactor. A three-stage design for the ejector was chosen to strike a balance between complexity and efficiency. Lastly, the subsonic diffuser converts the remaining kinetic energy to static pressure while further reducing the effluent velocity via gradual expansion of the flow area. The power-to-weight ratios of flow systems such as the PRS scale inversely with the flow diameter, given that power scales with flow area while device weight scales with volume, allowing more mass-efficient flow systems to be achieved by operating on the microscale.

## OVERALL SYSTEM CONFIGURATION AND PERFORMANCE

There are many design factors which influence the performance of a COIL, including reactant and diluent mixture ratios, component geometries, and operating temperatures and pressures. A many-parameter optimization is required to design a balanced system. One example is shown in Figure 5, which presents the system performance in terms of energy output per unit of total system mass (for 100 sec operation) as a function of SOG molar feedrate and nozzle plenum pressure. These results can be understood by recognizing that, for a constant mass flow through an individual SOG unit, decreasing the plenum pressure reduces collisional deactivation of singlet-oxygen, within both the SOG and mixing nozzle, and so increases output power. However, this

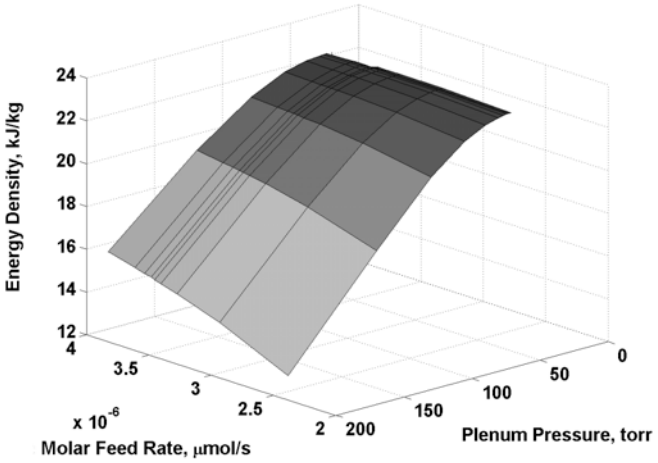


**Figure 5.** Energy density as a function of nozzle plenum pressure and SOG per-channel gaseous molar feed rate.

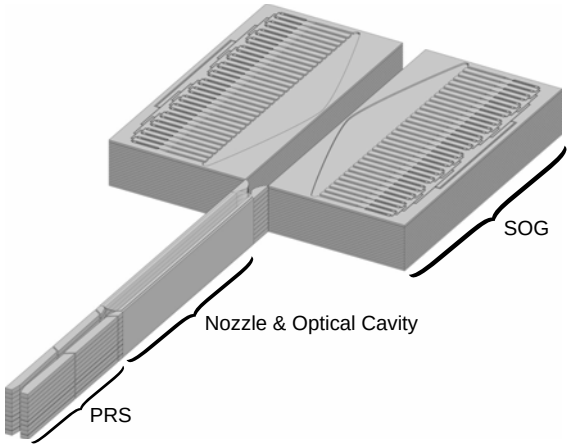


**Figure 6.** Schematic of stacked μCOIL modules.

advantage is balanced by an increased $H_2O_2$ flow required for the PRS. For the case of constant plenum pressure, increasing the molar feedrate to each unit SOG decreases the number of SOGs needed, thus reducing system weight. However, given fixed plenum pressure (and therefore SOG outlet pressure), increasing the per-SOG molar feedrate elevates the pressure drop across the reaction channels, increasing the collisional deactivation of singlet-oxygen, and resulting in a reduced singlet-oxygen yield and cavity output power.

The individual subsystems must be integrated into a complete laser module. One possible arrangement, consistent with established microfabrication technology, is shown in Figure 6. Six SOGs feed one nozzle with a 1 mm square throat, downstream of which is a gain cavity and pressure recovery system. Each 150 mm long by 1mm high laser module would produce about 10 watts of optical energy. Modules are stacked as shown in the figure to achieve higher powers, resulting in a long slit-shaped laser cavity. Windows and mirrors would be added top and bottom to complete the laser. (Obviously, other arrangements of the subsystem components are feasible as well.) Sufficient beam path length in the gain medium is required to achieve lasing and the optical properties of the gain medium are not length scale-dependent. In this case. 30-50 cm is needed, implying that the minimum gain length laser size is 3-5 kW. Table 1 summarizes laser system mass and power output for both 5 kW (minimum gain-length) and 100 kW-class systems. In addition to the subsystems discussed above, a complete laser would require appropriate storage tanks; cooling subsystem; and flow control valves, sensors, and pumps–many of which could be implemented in MEMS.

## SUMMARY AND CONCLUSIONS

Chemical lasers are large-scale devices in both power output and physical size but a MEMS-based, microscale approach

**Table 1.** Sizing estimations for minimum device and 100 kW-class device

| Power Level | Low | High |
|---|---|---|
| Output | 5.19 kW | 104 kW |
| # SOGs | 3000 | 60000 |
| # Nozzles | 500 | 10000 |
| System runtime | 100s | 100s |
| Total BHP weight | 19.3 kg | 386 kg |
| Total He weight | 0.12 kg | 2.48 kg |
| Total $Cl_2$ weight | 0.03 kg | 0.65 kg |
| Total $I_2$ weight | 0.03 kg | 0.60 kg |
| Total driving fluid weight | 2.08 kg | 41.6 kg |
| Total reagent weight | 21.5 kg | 431 kg |
| Device weight | 1.47 kg | 29.4 kg |
| Total system weight | 23.0 kg | 460 kg |
| Energy density | 22.53 kJ/kg | 22.53 kJ/kg |

offers many benefits, on both the component and integrated system level. The component advantages mainly accrue in the singlet oxygen generator and pressure recovery system. The SOG is improved by faster mixing, smaller dead volumes for singlet-oxygen deactivation, integrated cooling, and independence from orientation. The PRS is much shorter and thus has improved power-to-weight ratio. The optical cavity cannot be equivalently scaled down because of constraints of desired total gain and residence times sufficient for power extraction. Nevertheless, integration of the nozzle and optical cavity with the SOG offers a system level performance advantage by minimizing the interconnect volume between the SOG, nozzle, and cavity, thus minimizing deactivation losses.

At the system level, replacing one macroscale system with multiple microscale modules can yield greater system reliability. Large systems comprised of multiple, redundant subsystems may have benign failure modes characterized by gradual performance degradation rather than abrupt failure. Development of exchangeable modules via appropriate packaging techniques would allow for easy replacement of faulty modules, allowing faster recovery and longer operating times, as required by industry. By utilizing a system comprised of multiple units, each handling a small quantity of hazardous (corrosive, toxic) chemicals, the potential for chemical exposure is likewise minimized.

The results of the present study suggest that the μCOIL system may provide a superior alternative to existing COIL devices, reducing system volume and weight while improving reliability and safety.

## REFERENCES


[1] A.H. Epstein and S.D. Senturia, "Macro Power from Micro Machinery," *Science*, vol. 276, p. 1211, May 1997.

[2] P.V. Avizonis and K.A. Truesdell, "The Chemical Oxygen-Iodine Laser (COIL)," *SPIE*, vol. 2502, pp. 180-202, 1995.

[3] S. Takeda, K. Nanri and T. Fujioka, "Industrial and Reverse-Industrial Applications of COIL," *SPIE*, vol. 2702, pp. 191-194, 1996.

[4] H. von Bulow and W.O. Schall, "Oxygen-Iodine Lasers for Industrial Applications," *SPIE*, vol. 2502, pp. 258-265, 1995.

[5] M. Endo, F. Wani, S. Nagatomo, D. Sugimoto, K. Nanri, S. Tadeka and T. Fujioka, "Development of Industrial COIL," *SPIE*, vol. 3574**,** pp. 253-264, 1998.

[6] K.R. Kendrick, C.A. Helms and B.G. Quillen, "Determination of Singlet-Oxygen Generator Efficiency on a 10-kW Class Supersonic Chemical Oxygen-Iodine Laser (RADICL)," *IEEE Journal of Quantum Electronics*, vol. 35, no. 12, pp. 1759-1764, 1999.

[7] B.A. Wilhite, C. Livermore, Y. Gong, A. Epstein and K. F. Jensen, "Design of a MEMS-based Micro-Chemical Oxygen-Iodine Laser (μCOIL) System, *IEEE Journal of Quantum Electronics*, vol. 40, no. 8, pp. 1041-1055, August 2004.

[8] M.W. Losey, M.A. Schmidt and K.F. Jensen, "Microfabricated Multiphase Packed-Bed Reactors: Characterization of Mass Transfer and Reactions," *Ind. Eng. Chem. Res*., vol. 40, pp. 2555-2562, 2001.