Hydrogen Fluoride Overtone Chemical Laser Technology

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The Hydrogen Fluoride Overtone Chemical Laser Technology Program has exploited the technology base developed over the last two decades for hydrogen fluoride lasers and successfully demonstrated a short wavelength chemical laser. This technology development centers on overtone lasing of the hydrogen fluoride molecule to produce laser radiation at 1.33 μm rather than the conventional fundamental lasing at 2.8 μm. The overtone wavelength can lead to significant improvements in brightness potential as well as atmospheric propagation properties. The concept has matured from initial demonstrations at the 10 W scale to the currently demonstrated multikilowatt level. In the course of these test programs, it was necessary to develop new highly reflective coatings that permitted short wavelength lasing while completely suppressing lasing on the fundamental. This paper briefly reviews the performance of both discharge-driven and combustion-driven chemical laser devices and the optical configurations employed in the scalability steps. Appropriate diagnostics are discussed, including power, efficiency, spectra, and small signal gain.

Introduction

HIGH-POWER hydrogen fluoride (HF) chemical lasers have been the subject of research in the United States for approximately two decades. The basic principle of operation for continuous wave chemical lasers has been presented in several places.[1-3] During this period, the technology advanced from the laboratory to major demonstration systems, including baseline demonstration laser (BDL), Navy-ARPA chemical laser (NACL), mid-IR advanced chemical laser (MIRACL), and ALPHA. Cylindrical as well as linear concepts have been investigated. Reference 4 presents a review of the high power laser programs. Emphasis during this period was placed on improvements in efficiency, scalability of concepts, and improvements in beam quality. For space-based applications, size and weight considerations are critical. Planned growth to include addressing responsive strategic threats requires substantial increase in power as well as efficiency. An alternate approach to increasing the power requirements on the laser is to shorten the wavelength, thereby increasing brightness. Several efforts are ongoing to address this issue; however, success in the area is limited.[5] Among the potential candidates for a shorter wavelength laser is the overtone chemical laser that builds directly on the hydrogen fluoride technology base. The overtone chemical laser uses the same chemical reaction and produces the same excited populations as does the conventional hydrogen fluoride laser. It differs in that the optics employed suppress lasing at 2.8 μm and allow lasing at 1.33 μm, see Fig. 1.

Subsonic Experiments

Before this development under the Overtone Chemical Laser Program, overtone lasing had been observed at very low levels using techniques that were not scalable to the power levels necessary for the envisioned applications.[6] Overtone lasing has been observed at low levels in other laboratories, but no attempts were made to improve the modest performance.[7-9] In 1984, a Helios CL-I chemical laser, Fig. 2, demonstrated about 10 W of laser energy at a wavelength of approximately 1.33 μm.[10,11] Significantly, this level represented approximately 20% of the corresponding lasing power on the fundamental transition. Only the optics were changed to allow the overtone lasing. Transmissive optics designed for Nd-YAG applications were used in the demonstration test. The device illustrated in Fig. 2 measures 15 cm in gain length. Improvements were made in the optics, eventually allowing the demonstration of 31% of the fundamental power at the shorter wavelength.[10,11] Limited scalability of the concept was achieved by increasing the gain length to 30, 45, and finally 75 cm by combining individual 15-cm modules, see Fig. 3. The performance of these devices is summarized in Fig. 4. The data illustrated in Fig. 4 suggest an upper performance limit of approximately 30% of the fundamental power. Suppression of the fundamental lasing in the longer gain length devices tended to be a problem. Techniques of multiple mirror resonator designs prevented the fundamental wavelength from achieving lasing threshold by multiple reflections. Figure 5 illustrates the four-mirror design used in the 75-cm device experiments. Representative spectra for these lasing tests are illustrated in Fig. 6.

The multiple optical surfaces required to suppress the fundamental wavelength introduced an additional source of loss in the cavity design, which to the low-gain overtone laser was significant. Subsonic performance was improved by the introduction of a new nozzle design of greater flow height, optics/optical coatings specifically designed to suppress the fundamental and support overtone lasing, and hemispherical calorimeters designed to measure any radiation scattered from the highly reflective mirror surfaces. This improved design called the ZEB laser has demonstrated 55% of the fundamental performance at overtone power levels of approximately 200

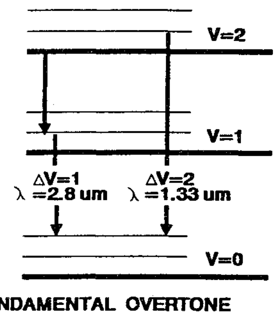

Fig. 1 Overtone concept.

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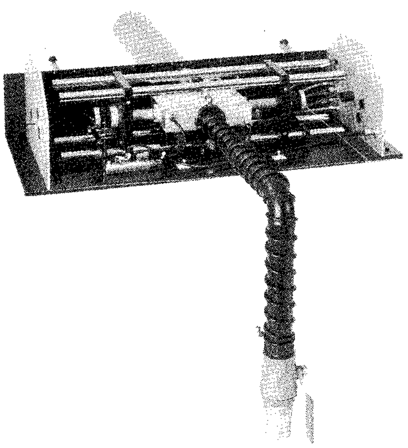

Fig. 2 CL-I laser.

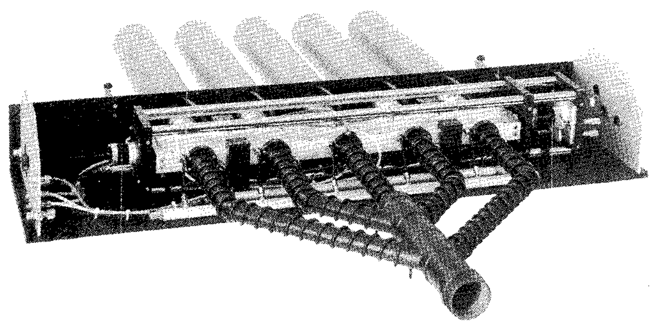

Fig. 3 CL-IV laser.

W or approximately an order of magnitude power scalability with a doubling of the efficiency.

Supersonic Experiments

The subsonic designs do not lend themselves to being scalable to truly high-power levels analogous to BDL, NACL, MIRACL, etc. The Overtone Chemical Laser Development Program made a transition into scalable supersonic chemical laser hardware in 1986. Tests performed at TRW demonstrated overtone performance at 24–35% of the fundamental power using two chemical laser hardware configurations, the hypersonic wedge nozzle (HYWN) and the hypersonic low temperature (HYLTE) nozzle, conceptually illustrated in Figs. 7 and 8. Reference 12 describes these laser concepts in more detail. The reactants used were nominally deuterium, fluorine, hydrogen, and helium as a diluent. Mode lengths were found to be somewhat shorter than for the fundamental wavelength, and the lasing spectra were quite similar to the subsonic Helios experiments, see Fig. 9. The resonator configuration consisted of transmissive Nd-YAG mirrors as in the initial Helios subsonic tests.

The success of these first supersonic experiments was somewhat misleading as to the true understanding of the overtone chemical laser concept. This fact was dramatically illustrated in the failure to demonstrate the scalability to higher power levels using larger nozzle hardware. ALPHA verification module (VM). To scale to higher power levels, the more conventional closed-cavity reflective optics were used. The gain length of the VM was such that the reflectivity suppression of the first generation optical coatings was inadequate to prevent fundamental lasing. The initial tests failed due to inadequate optical discrimination at the low fundamental rotational transitions. Improvements were made in coating design that achieved complete suppression of the fundamental transitions and allowed the demonstration of overtone performance at 25% of the fundamental power at a total power level of ap-

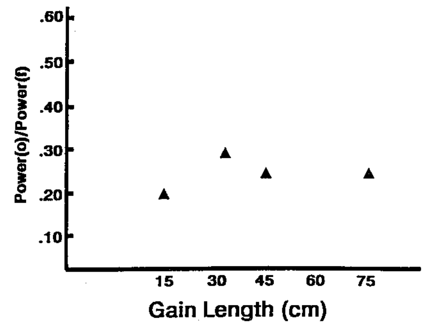

Fig. 4 Subsonic device performance summary.

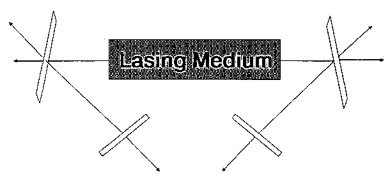

Fig. 5 Four mirror configuration.

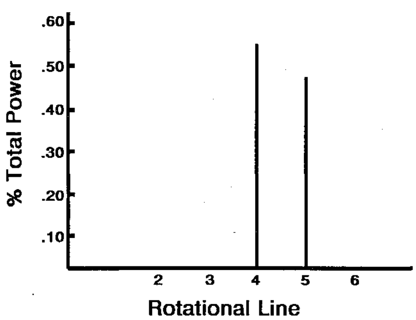

Fig. 6 CL-I overtone spectrum.

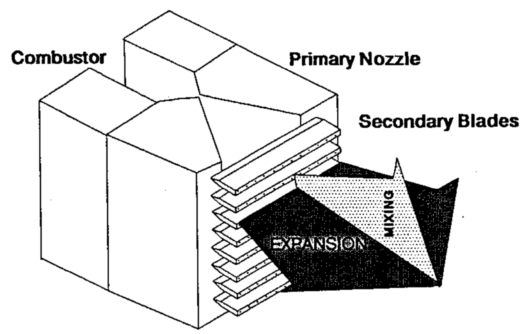

Fig. 7 HYWN nozzle.

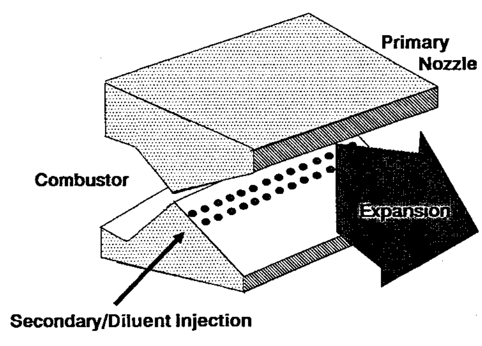

Fig. 8 HYLTE nozzle.

proximately 4 kW. However, these results were limited by repeated optical coating failure at flux levels greater than 30 kW/cm^2. The following section will discuss the optical coating development in more detail. These VM tests did provide a much better understanding of the difficulties in the design of optical coatings highly reflective at one wavelength, totally absorbing in another, and having a characteristic damage threshold sufficiently high to support high-power lasing.

Differences in mode lengths between the overtone and fundamental lasing indicated that the optimum overtone nozzle design would not necessarily be identical to that for the fundamental laser. All supersonic lasing tests to this point had been run using existing hardware from previous chemical laser technology development programs that addressed fundamental lasing. The ZEBRA nozzle, Fig. 10, was designed, fabricated, and tested to better understand the geometric influences of the HYWN nozzle on overtone lasing. This hardware, along with redesigned optics and resonator configuration, demonstrated overtone lasing at 56% of the fundamental at a total power level in excess of 4 kW. The overtone lasing spectrum is again simple as compared to the transition rich fundamental. Figure 11 provides a chronological summary of the overtone performance data.

Previous calculations and experiments indicated a large difference between the magnitude of the small signal gains (SSG) of the HF overtone transitions as compared to the HF fundamental, thereby creating a difficult gain competition to overcome. Experimental SSG data is vital to guide optical coating and resonator design requirements to achieve discrimination and efficient overtone operation. The ZEBRA device was used to make experimental SSG measurements. Figure 12 shows typical SSG traces in scanning from the centerline of a primary nozzle throat to the centerline of an intervening base region between nozzles. Figure 13 is a summary of the vibrational and rotational transitions included in the measurements.

Optics/Optical Coating Development

The development of unique optical coatings has proven to be critical to the current success of the overtone chemical laser development and will likely continue to be a critical component. Initially, the role of the optical coating was not totally appreciated or understood. Several iterations in the development of successful coatings have been necessary to support overtone lasing at the current levels. It was understood that coatings must be developed that were highly reflective to the overtone transition and nearly totally absorbing to the fundamental wavelength radiations. These coatings had to be such that the absorbed energy was transmitted efficiently to the cooled mirror substrate and also withstood relatively high

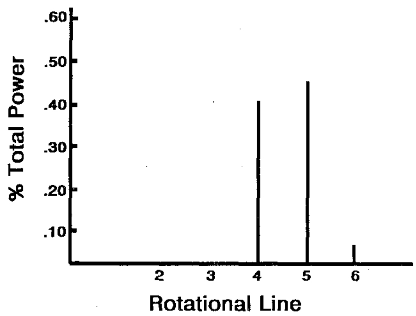

Fig. 9 HYLTE overtone spectrum.

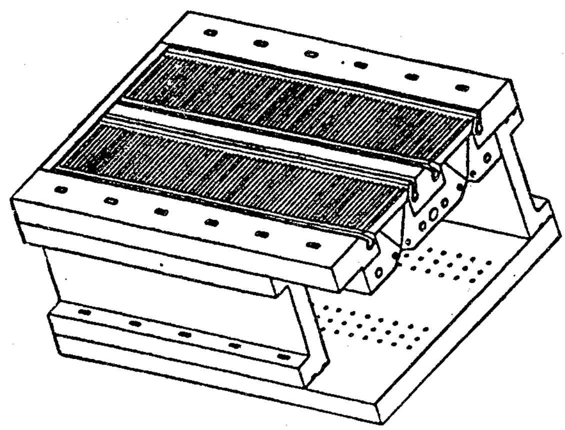

Fig. 10 ZEBRA nozzle; this shows how the nozzle of Fig. 7 is assembled in the test hardware.

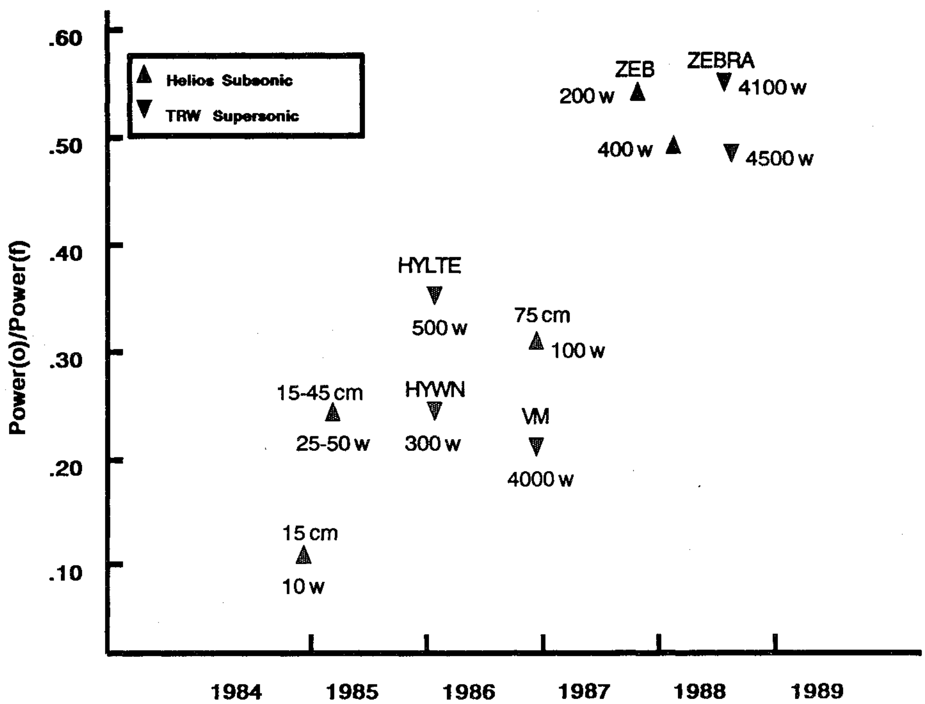

Fig. 11 Overtone lasing performance summary.

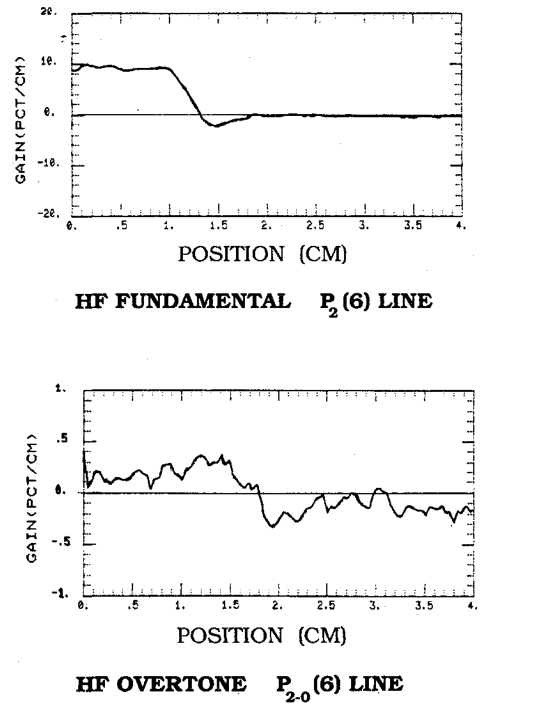

Fig. 12 Typical ZEBRA SSG traces; fluctuations in the overtone gain are noise in the signal.

- HF Fundamental v=2-1 Transitions
  Measured ssg of $P_2(3)$, $P_2(4)$, $P_2(5)$, $P_2(6)$, $P_2(8)$ Lines

  v=1-0 Transitions
  Measured ssg of $P_1(3)$, $P_1(4)$, $P_1(5)$, $P_1(6)$, $P_1(8)$ Lines

- HF Overtone v=2-0 Transitions
  Measured ssg of $P_{2-0}(3)$, $P_{2-0}(4)$, $P_{2-0}(5)$, $P_{2-0}(6)$ Lines

- SSG Summary
  HF_f Range 3 - 12 %/cm
  HF_o Range 0.1 - 0.4 %/cm

Fig. 13 ZEBRA small signal gain summary.

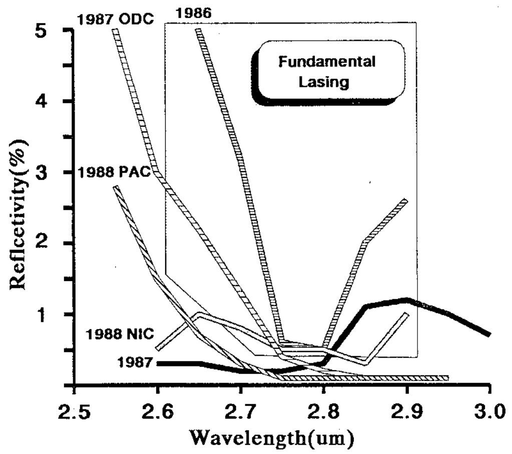

Fig. 14 Overtone lasing optics summary.

power fluxes. What was not initially appreciated was the wavelength band over which the fundamental lasing had to be suppressed. An error was made in the specification of the coating characteristics for the early verification module tests. Fundamental lasing typically occurred at wavelengths from 2.7 to 2.9 μm in this hardware. The coatings developed adequately suppressed lasing in this band. However, this suppression caused the lasing process to occur at shorter wavelengths, approximately 2.6 μm on lasing transitions not normally observed. The optical coating developed and used in these early tests had sufficient reflectivity in this region to allow inefficient fundamental lasing to occur. Subsequent developments in the optical coatings for the overtone chemical laser progressed to the point of approximately 0.3% reflectivity over the entire fundamental lasing band and highly reflective in the overtone lasing band. Figure 14 summarizes the development in optical coatings and illustrates performance of current designs. Typical designs are multilayer stacks of approximately 25 layers. Typical stack materials are ZnS, ThF_4, and SiO.

The coating designations on Fig. 14 are identified as follows: 1) 1986,1987—multilayer dielectric coatings (MLDC) from Optical Coating Laboratory (OCLI) for tests on the alpha verification module; 2) 1987 ODC—optical diagnostic coating from Deposition Sciences, Inc. (DSI); 3) 1988 PAC—partially absorbing coating from DSI for metal substrate, heat exchanger mirrors; and 4) 1988 NIC—normal incidence coating from DSI. Details of the DSI coatings are available upon request from the authors at the Army Missile Command.

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