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Naval Research Laboratory and  
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**Research Studies on Short Wavelength by  
Selective Auger Processes**

Final Technical Report for the period ending December 31, 1990

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Principal Investigator:  
S. E. Harris  
Edward L. Ginzton Laboratory  
Stanford University  
Stanford, CA 94305

Contract Monitor:  
Dr. Paul Kepple  
COTR, Code 6720  
Naval Research Laboratory  
4555 Overlook Ave., S. W.  
Washington, DC 20375-5000  
5346

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# 1. INTRODUCTION

Efforts during this contract period are divided into two areas: (1) development of short wavelength coherent sources and (2) studies of lasers without inversion. In the first area, gain in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) was observed in the in Xe, Zn, Kr, Cs and H<sub>2</sub> gases. Methods for saturating the laser transitions in Xe and Cs were developed and produced microjoule level fully saturated outputs at 109 nm and 96.9 nm, respectively. Efforts to construct the next generation laser driver for such studies were also completed during this time period. In the second area, theoretical studies of different methods for creating transparency in atomic vapors were explored. Various applications of these transparencies were investigated, including the possibility of systems which would exhibit laser gain without the necessity for population inversion and the enhancement of nonlinear optical processes in the presence of such a transparency. Experiments demonstrated enhanced sum-frequency generation of 104.8-nm radiation with a naturally occurring transparency in Zn vapor.

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## **2. DEVELOPMENT OF COHERENT SHORT WAVELENGTH SOURCES**

### **2.1 Xenon 109-nm Laser**

Saturation of the Xe III 109-nm laser was accomplished using a traveling-wave laser-produced-plasma excitation. The laser was pumped by soft x-rays emitted from a laser-produced plasma. Using a 3.5-J, 300-ps, 1064-nm laser pump pulse, we measured a small-signal gain of  $\exp(40)$ . The laser was fully saturated and produced an output energy of 20  $\mu\text{J}$  in a beam with 10-mrad divergence.

Studies of prepulsing to increase the efficiency of the laser-produced-plasma pumping were conducted. By using a low energy prepulse we were able to enhance the soft-x-ray emission of the laser-produced plasma in the parameter range used to pump the Xe III laser and other photoionization-pumped lasers. Conversion efficiency and output pulse duration as a function of input intensity, pulselength, and prepulse conditions were determined.

With increased laser-produced plasma efficiency and better traveling-wave excitation it was possible to create a 2-Hz 109-nm mirrorless laser. This new device had a single pass gain of  $\exp(33)$  and a saturated output energy of 1  $\mu\text{J}$ . The laser required only 500 mJ of 1064-nm energy in a 500-ps pump pulse. Because of the high repetition rate of this source it was possible to perform two slit coherence experiments and to test the focusability of the laser output. Intensities of greater than  $10^9 \text{ W/cm}^2$  were produced at 109 nm.

Gain at 90 nm in analogous system in Kr III was also observed during several of these studies. However, the total gains were small and saturated output was never obtained.

## **2.2 Zinc III Laser**

Gain in a super Coster-Kronig-pumped Zn III laser system was demonstrated. Using a 5-J, 300-ps pump pulse of 1064-nm radiation, we observed gain on transitions in Zn III at 127.0, 130.6, and 131.9 nm with total gains of exp (2.4), exp (5.1), and exp (3.2), respectively. The large branching ratios of the rapid super Coster-Kronig decay into a small number of final levels made high-efficiency operation possible. However, because of the longer wavelength and the increased complexity of working with atomic Zn vapor, further study and saturation of this system was not attempted.

## **2.3 Cesium 96.9-nm Laser**

Fully saturated operation of a 96.9-nm laser transition in neutral Cs vapor was demonstrated. This was the first operation of a new class of XUV lasers in which the upper level of the laser transition was embedded in the continuum of the valence electron. The laser employed a grating-assisted traveling-wave geometry that created an ~ 20-ps-long pulse of laser-produced soft x-rays traveling synchronously with the generated 96.9-nm radiation. In order to create such a short pumping pulse, a new short pulse laser source for producing excitation plasmas was developed. This laser system was based on the concept of chirped pulse amplification

and was the first demonstration of multijoule output using this concept. Typical system parameters were 3 J in 10 ps at 1064 nm. With this pumping source the gain coefficient of the Cs 96.9-nm laser system was as high as  $4.9 \text{ cm}^{-1}$  over a 17 cm length. This results in a very high extrapolated small signal gain of  $\exp(83)$ . After about 4 cm, the output energy grew linearly with length indicating that the laser transition was fully saturated. The total output at 96.9 nm was  $\sim 1.5 \mu\text{J}$ . Several studies were conducted to investigate the spectroscopy and atomic physics of this system. Other experiments investigated the nature of the pumping mechanism. It was concluded that, unlike the Xe, Kr and Zn systems, this laser was pumped by photo-generated electrons which were the by-product of the partial photoionization of the Cs vapor by soft x-rays from the laser-produced plasma. This new electron pumping scheme is capable of producing very high excitation current densities on the order  $10^6 \text{ A/cm}^2$ . Implementation of this pumping scheme to traditional electron-pumped molecular lasers resulted in saturated output in the VUV and deep UV when hydrogen and nitrogen were used in place of Cs.

#### **2.4 Molecular Hydrogen 116-nm Laser**

Using the photoionization electron source similar to that described above, a 116-nm laser in the Werner band of molecular hydrogen was demonstrated. Studies indicated that, even though the free electrons have an average temperature of  $\sim 10 \text{ eV}$ , the hydrogen molecules retain an ambient temperature of  $\sim 0.01 \text{ eV}$ . This allowed an extrapolated small-signal gain of  $\exp(43)$  with a 1064-nm pumping energy of 580 mJ in 200 ps. Several longer-wavelength transitions in the Werner and Lyman bands also exhibited saturated output.

## **2.5 High Peak Power Laser Development**

The next generation laser plasma driver was developed. This system was based on amplification in Ti-doped sapphire. At its completion it was one of only two in the world to be able to produce terawatt level 125-fs infrared pulses. The system was again based on chirped pulse amplification. The laser output at 807 nm contained 60 mJ of energy in a 125 fs pulse. The system produced a nearly diffraction-limited beam that was focusable to an intensity of  $10^{18}$  W/cm<sup>2</sup> with an f/6 optic.

### **3. STUDIES OF LASERS WITHOUT INVERSION**

#### **3.1 Interference of Dressed Lifetime-Broadened States**

The use of a coupling electromagnetic field to provide a general method for producing inversion-free laser systems was investigated. The interference between dressed states produces a zero in absorption while allowing gains of that of the uncoupled system. This important concept allows interferences between nearly arbitrary states to be created with a tunable coupling laser, thus removing the atomic constraints from many experiments.

#### **3.2 Single-Atom Transient Response**

The effect of the transient response on the dynamics of lifetime-broadened lasers that operate without the need for population inversion was investigated. A relationship between the steady-state absorption transition probability rate and the transient gain and loss was determined. This relationship often implies that, in order to achieve lasing without inversion, the rate into the lower level must be less than that into the upper level.

#### **3.3 Closed Lifetime Systems**

A model three-state laser system which operates by an electromagnetically induced interference was studied. Provided that an inversion condition for the thermal radiation field is satisfied, the system lases without atomic population inversion in steady state. The system is pumped by incoherent radiation on the transition on which lasing occurs.

### **3.4 Nonlinear Optics Within an Absorption Window**

Besides the possibility of lasers without inversion, the types of transparency described above also have applications in nonlinear optics. Two autoionizing levels which are separated by a few decay widths may exhibit a sharp interference or window in their absorption profile and also make canceling contributions to the refractive index at the absorption minimum. A correct choice of intermediate mixing levels prevents a similar cancellation in the nonlinear susceptibility. Using UV lasers with energies of about a millijoule and pulse lengths of 5 ns, 0.23  $\mu\text{J}$  per pulse at 104.8-nm radiation was generated in zinc vapor.

### **3.5 Nonlinear Optics and Electromagnetically Induced Transparency**

While the previous nonlinear optics experiment relied on a naturally occurring transparency this need not be the case. By applying a strong coupling field between a metastable state and the upper state of an allowed transition to ground one may obtain a resonantly enhanced third-order susceptibility while, at the same time, inducing transparency of the media. Theoretical studies indicated that an improvement in conversion efficiency and parametric gain, as compared to weak-coupling field behavior, of many orders of magnitude is possible.

#### 4. LIST OF PUBLICATIONS

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4. M. H. Sher and S. J. Benerofe, "Prepulsing to Increase the Efficiency of Laser-Produced-Plasma Pumped Lasers," in **Short Wavelength Coherent Radiation: Generation and Applications**, edited by Roger W. Falcone and Janos Kirz (Washington DC, Optical Society of America, 1988), vol. 2, pp. 60-64.
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