# 116-nm $H_2$ Laser Pumped by a Traveling-Wave Photoionization Electron Source

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We report the use of a photoionization electron source to pump a 116-nm laser in the Werner band ($C\,{}^1\Pi_u \rightarrow X\,{}^1\Sigma_g^+$) of molecular hydrogen. The laser is pumped by free electrons which are created by photoionizing molecular hydrogen with soft x rays from a traveling-wave laser plasma. We show that even though the free electrons have an average temperature of $\sim 10$ eV, the lasing hydrogen molecules retain an ambient temperature of $\sim 0.01$ eV. This allows an extrapolated small-signal gain of exp(43), with a 1064-nm pumping energy of 580 mJ in 200 psec.

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We describe the use of a traveling-wave photoionization electron source[1] (PES) to pump a 116-nm laser in the Werner band of $H_2$. The PES is constructed by using a grazing-incidence, traveling-wave laser plasma[2] to make soft x rays which in turn photoionize ambient hydrogen molecules (Fig. 1). The electrons have an average energy which corresponds to the difference in energy of the pumping x rays and the ionization potential of $H_2$, and at sufficient pumping intensity may have a density which corresponds to a discharge current in excess of MA/cm$^2$. The rise time of the electron density is equal to that of the x-ray source, and may be picoseconds or shorter in duration, making PES an ideal source for pumping short-wavelength lasers.[3]

In this Letter we quantitatively demonstrate the advantages of PES over conventional electron pumping sources by generating saturated laser emission at 116 nm in the Werner band of $H_2$. We emphasize a special feature of this type of excitation, which is its ability to produce hot electrons while at the same time retaining an ambient (lasing medium) temperature which is comparatively cold. This is confirmed by measurements of the 116-nm gain as a function of the ambient $H_2$ temperature. In this work the free electrons have an average temperature of 10 eV while the lasing hydrogen molecules retain an ambient temperature of $\sim 0.01$ eV. This allows very high gain at modest pumping energy; here we obtain an extrapolated small-signal gain of exp(43), with a 1064-nm pumping energy of 580 mJ in a pulse width of 200 psec.

Before proceeding we note that previous short-wavelength lasers have operated in the focus of the incident laser and under conditions where the exciting electrons and target ions are relatively thermalized.[4] $H_2$ lasers have been constructed by using a Blumlein discharge (Waynant)[5] and by using a field-emission diode (Hodgson and Dreyfus).[6] In this work we obtain a gain coefficient which is over an order of magnitude larger than that previously obtained, demonstrating quantitatively one of the advantages of PES over conventional electron pumping sources.

Using a simple model for the PES excitation mechanism we will verify that in the present experiment the $H_2$ laser is pumped by electrons and is not directly photopumped. We will then proceed to describe the experimental setup and results. The calculation of the gain for the 116-nm laser pumped by a PES proceeds as follows: The 580-mJ, 200-psec, 1064-nm pump laser pulse creates a plasma on the target surface. Following Ref. 1 the spectral distribution of the soft x rays from the laser-produced plasma is modeled as a blackbody [see Fig. 1(a)] which has a characteristic temperature determined by the conversion efficiency of the pump laser to soft x rays and a pulse width comparable to that of the pump laser. From previous measurements of conversion efficiency done under similar experimental conditions,[7] we estimate the conversion efficiency of our laser to be approximately 2% into the energy range of interest. This implies a blackbody temperature of 12 eV. The soft x rays photoionize some of the hydrogen molecules surrounding the target, creating free electrons. In Fig. 1(b) we show the photoionization cross section for $H_2$.[8] Combining the blackbody-flux spectral distribution and the photoionization cross section, we calculate an electron density of $3\times10^{15}$ cm$^{-3}$ in the lasing region, and an average electron energy of 10 eV [Fig. 1(c)]. This is equivalent to a discharge current of about $9\times10^4$ A/cm$^2$. The cross section for electron excitation of the Werner band has been calculated by Gerhart[9] and is shown in Fig. 1(d). The cross section for pumping the 116-nm line is then calculated using Refs. 10 and 11. By multiplying the electron distribution by the electron pumping cross section for the upper laser level, and integrating, we estimate an upper-state ($C\,{}^1\Pi_u$, $v'=1$, $J'=1$) density of approximately $6\times10^{12}$ cm$^{-3}$ at room temperature [note that the upper laser level has a lifetime of approximately 600 psec (Ref. 12)]. This yields a calculated gain on the 116-nm transition of 0.35 cm$^{-1}$ at room temperature (293 K).

This PES gain calculation is to be compared to the gain calculated for direct photopumping of the upper laser level. For this calculation we use the 12-eV black-

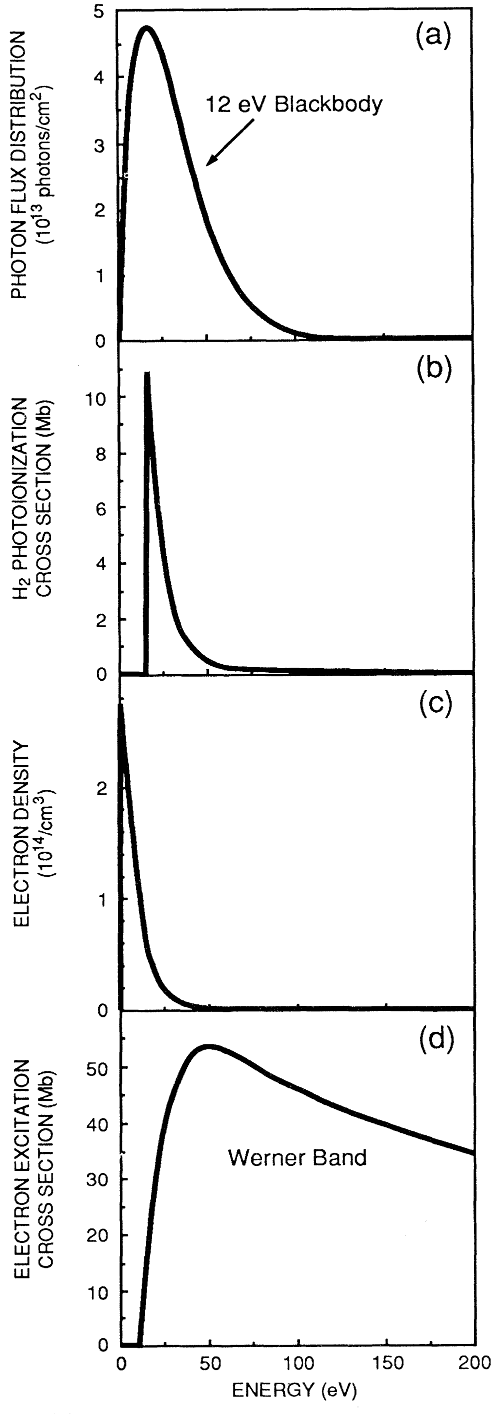

FIG. 1. (a) Photon flux vs energy for a 12-eV blackbody. (b) $H_2$ photoionization cross section vs energy. (c) Calculated electron-density energy distribution; the average electron energy is 10 eV. (d) Werner-band electron-excitation cross section vs energy.

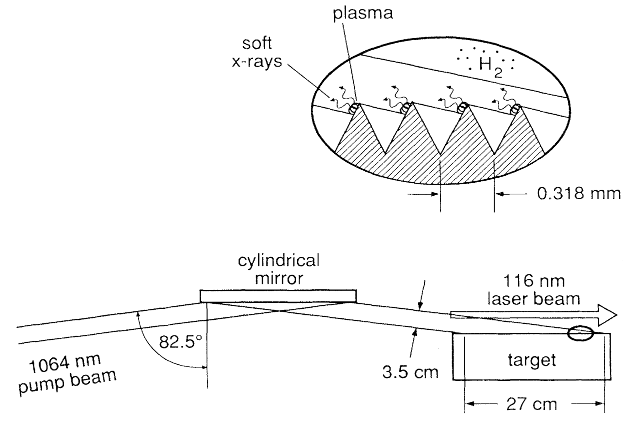

FIG. 2. Schematic of geometry used to pump $H_2$ laser.

body spectral density and the cross section for optical pumping of the upper laser level calculated using the oscillator strengths from Allison and Dalgarno.[13] We obtain a calculated gain due to optical pumping of 0.0014 $\text{cm}^{-1}$ at room temperature, a factor of 250 lower than that calculated for electron pumping. Thus, it is clear that this laser is PES pumped.

The above calculation helps to point out some qualitatively important features of a PES which makes it an ideal pumping source for short-wavelength lasers. In Fig. 1 we see that by choosing a source of the photoelectrons with an appropriate ionization potential and photoionization cross section (as compared to the blackbody spectral distribution) an electron density distribution can be set up which will overlap well with the pumping cross section for the upper laser level. Also, as we can see from Fig. 1(d) electron pumping cross sections can be very large, allowing a large acceptance bandwidth in energy to make efficient use of the pumping source. Furthermore, the fast rise time of the electron density distribution combined with the traveling-wave excitation of the experimental setup allows most of the energy put in the upper laser level to be stored until it is extracted by the stimulated emission of the laser. We also note that the rapid rise of the electron density allows the lasing medium to be excited into the upper laser level and lase before the lasing medium has been significantly heated by the surrounding high-energy electrons. The maintenance of a low temperature for the lasing medium allows the ambient temperature of the lasing medium to set the Doppler width of the transition.

Our experimental setup is shown in Fig. 2. The geometry is the 82.5°-angle-of-incidence version of the traveling-wave laser-produced-plasma geometry described in detail in Ref. 14. For this experiment, the 580-mJ, 200-psec, 1064-nm pump pulse, initially a 3.5-cm × 1.2-cm oval beam, is reflected off of an aluminum-coated cylindrical mirror at 82.5° from normal incidence with the 3.5-cm axis of the beam in the plane of incidence. The mirror focuses the beam to a line on the target with a transverse spot size of 100 $\mu$m and a length of 27 cm, yielding an intensity on the target of $8\times10^{10}$ W/cm$^2$. The target is a stainless-steel tube threaded at

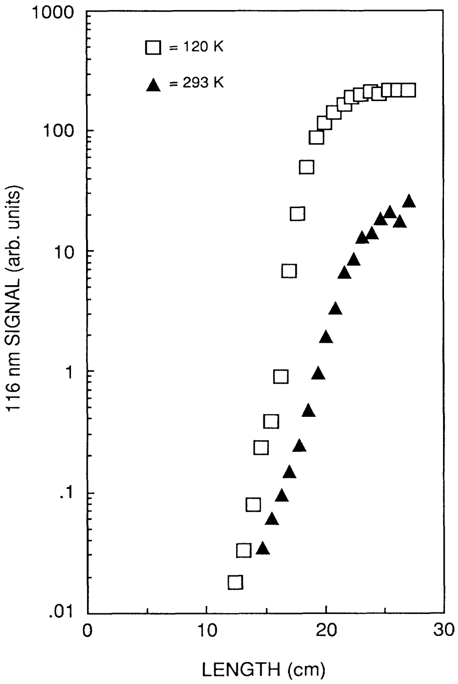

FIG. 3. Representative gain measurements. Signal vs plasma length for 116.1-nm line in the Werner band of $H_2$. Each data point represents the average of about 10 measurements.

31.5 grooves per cm; the density of the hydrogen molecules surrounding the target was fixed for all temperatures at $6\times10^{17}$ molecules/cm$^3$. The temperature of the $H_2$ gas inside the cell was measured using two separate methods: (1) A $K$-type thermocouple gauge was suspended inside the cell, and (2) we measured the pressure of the $H_2$ gas inside the cell, which for a fixed density and volume determines the temperature. Both of these methods agreed to within 10 K. The output signal of the $H_2$ laser was detected using a microchannel-plate detector mounted on a 1-m normal-incidence McPherson VUV spectrometer (model number 225). The entrance slits of the spectrometer were 75 cm away from the end of the plasma. The spectrometer and the experiment cell were separated by a 1-mm-thick LiF window. All gain coefficients were obtained by varying the plasma length, measuring the output signal, and fitting the data with an exponential curve.

We observed saturated emission in both the Lyman and Werner bands. In Fig. 3 we show two representative gain measurements on the 116-nm line, one at an ambient $H_2$ temperature of 293 K and the other at 120 K. The average gain coefficient on the 116-nm line was measured to be 0.9 cm$^{-1}$ at an ambient $H_2$ temperature of 293 K and 1.6 cm$^{-1}$ at 120 K. In Fig. 4 we have an x-ray streak-camera trace of the 116-nm line at 296 K. For this trace the laser-produced plasma is at its full length, and therefore the 116-nm signal is a result of saturated output. From the trace we see the clear indications of saturation: the sharp rising edge of the 116-nm output and the shortening of the output pulse relative to the pump pulse.

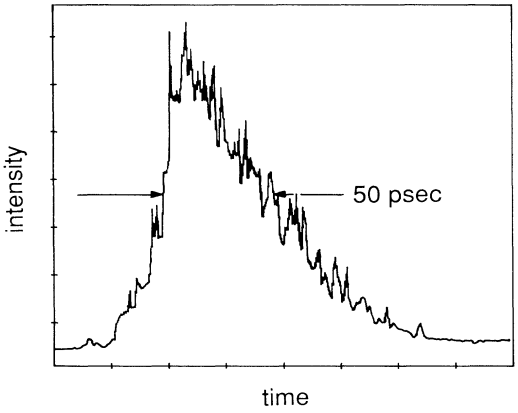

FIG. 4. Streak-camera trace of the saturated 116-nm output signal.

We have also shown quantitatively that by cooling the ambient $H_2$ gas we can increase the gain cross section of the 116-nm laser. The experiment cell, which contained the threaded target and the $H_2$ gas, was cooled to two different temperatures by either surrounding the cell with dry ice or with liquid nitrogen. Given the measured gain coefficient of the 116-nm laser at room temperature, if we assume Doppler broadening of the lasing transition, we can calculate the gain expected at other temperatures due to the change in the linewidth of the laser transition

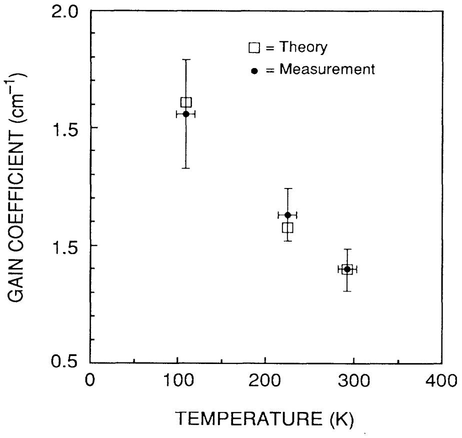

FIG. 5. 116-nm gain coefficient vs ambient $H_2$ pressure. □ denotes the calculated gain; ● denotes the average of gain. The error bars in gain on the graph are the standard deviation of the measured gain for the given temperature. The error bars in temperature represent the 10-K uncertainty in the temperature measurement of the ambient hydrogen gas because of the discrepancy between the two temperature measurement methods used.

and the redistribution of the population for the ground state of $H_2$ subject to the known selection rules.[11] As shown in Fig. 5 we see that the data support the hypothesis that the hydrogen molecules remain essentially unheated by the surrounding high-energy electrons during the pumping and lasing process. Each data point represents the average of 10–20 separate gain measurements. Each gain measurement consists of approximately 15 equally spaced measurements of the output signal versus the length of the plasma on target. Furthermore, each data point in each of the gain measurements represents 10 separate measurements of the output signal at the given length.

In summary, we have shown how a traveling-wave source of laser-produced x rays may be used to produce an electron source of high average energy, high equivalent current, and very fast rise time. This source allows laser operation with atoms at a kinetic temperature less than 1/1000th of the pumping electrons, thereby allowing high gain at modest pumping energy.

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