AIP | Journal of Applied Physics

Increasing lifetime of the plasma channel formed in air using picosecond and nanosecond laser pulses

V. Narayanan, V. Singh, Pramod K. Pandey, Neeraj Shukla, and R. K. Thareja

Citation: J. Appl. Phys. **101**, 073301 (2007); doi: 10.1063/1.2713997
View online: http://dx.doi.org/10.1063/1.2713997
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v101/i7
Published by the AIP Publishing LLC.

JOURNAL OF APPLIED PHYSICS **101**, 073301 (2007)

Increasing lifetime of the plasma channel formed in air using picosecond and nanosecond laser pulses

V. Narayanan, V. Singh, Pramod K. Pandey, Neeraj Shukla, and R. K. Thareja[a]
Department of Physics and Centre for Laser Technology, Indian Institute of Technology Kanpur, Kanpur-208016, India

(Received 7 October 2006; accepted 22 January 2007; published online 2 April 2007)

We report experiments on a pump-probe configuration to elucidate the formation of a plasma channel by the hydrodynamic evolution of air breakdown in laser focus. A stable air breakdown was produced by focusing a picosecond laser pulse to create a shock driven plasma channel in the laser focus for propagating a nanosecond pulse. A four fold increase in the lifetime of the channel estimated by monitoring the temporal evolution of the fluorescence of a spectral line at 504.5 nm of N^+ transition $3p\ ^3S-3s\ ^3P^0$ is reported. Assuming plasma in local thermal equilibrium plasma temperature of ~ 8.2 eV and an electron density of $\sim 1.4\times 10^{18}$ cm^{-3} were determined using a Stark broadening of 649.2 nm line of $N_{\rm II}$ transition $3d\ ^3D^0-4p\,^3D$ in the channel. An enhancement in the electron density of the plasma channel was observed at the 7 ns delay of the nanosecond laser pulse relative to the picosecond laser pulse. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2713997]

I. INTRODUCTION

The guiding of intense optical pulses in long plasma channels provides a large intensity interaction length product. Therefore, it is of immense current interest in advanced technological areas such as fast ignition of nuclear fusion targets,[1] laser wake field accelerators,[2] x-ray lasers,[3] high harmonic generation,[4] remote sensing of atmosphere to find out the chemical and dynamical processes responsible for global warming, ozone layer depletion, and tropospheric pollution,[5] and lighting control for protecting sensitive sites, such as electrical installations or airports, from direct striking and electromagnetic perturbations.[6,7]

Depending on the peak power of the laser pulse, a plasma channel in air may form either by a Kerr lensing of a laser pulse[8] or by hydrodynamic evolution of air breakdown in the laser focus.[9] The focused laser radiation of high intensity results in the creation of a dense plasma which tends to defocus the laser pulse. However, when the Kerr induced self-focusing counter balances the plasma induced defocusing the laser pulse keeps on propagating in a plasma channel of constant diameter. When an intense laser pulse is focused in air, depending on the laser pulse duration, ionization in air may be initiated either by electron avalanche or by multiphoton absorption. For example, picosecond pulses predominantly produce ionization in air by the multiphoton absorption.[10] The plasma so formed is further heated by the inverse bremsstrahlung process, expands, and drives a shock wave into the cold surrounding. This results in the reduction in the ion density on the axis and the enhancement at the periphery. Consequently, a sharp electron density gradient is formed between the axis and the periphery. This sharp electron density gradient acts like a plasma channel for the delayed laser pulse, similar to conventional optical fiber. The Rayleigh length, a measure of the length over which diffraction causes the beam to defocus, has been shown to increase by propagating a laser pulse in the preformed plasma.[9,11] However, the lifetime of the plasma channel has been limited to several nanoseconds[12] because of the recombination of electrons to parent ions[13] and strong attachment to the oxygen molecules.[14,15] This time is too short for most applications. In order for this channel to have any practical application it is imperative to prolong the lifetime of the channel. In this paper we report the prolongation in the lifetime of the plasma channel in air at a moderate laser intensity ($\sim 10^{13}$ W/cm^2) using a two-pulse technique in a pump probe configuration. The paper is organized as follows. Section II gives the experimental layout used to generate the channel followed by results and discussion in Sec. III. The conclusion of the work is presented in Sec. IV.

II. EXPERIMENTAL SETUP

A schematic layout of the experimental setup is shown in Fig. 1. The experiment was carried out by using picosecond and nanosecond Nd: yttrium aluminium garnet (YAG) laser

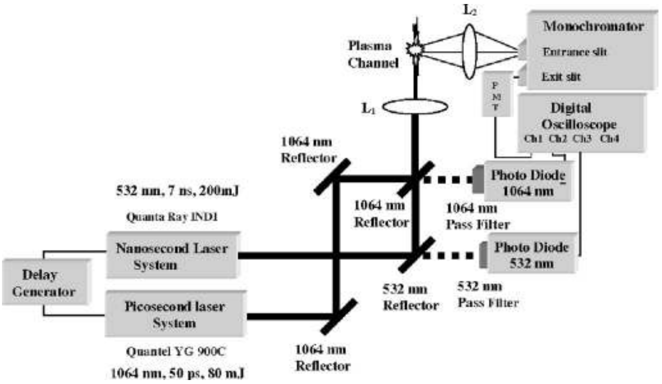

FIG. 1. A schematic layout of experimental setup.

---

[a] Author to whom correspondence should be addressed; electronic mail: thareja@iitk.ac.in

0021-8979/2007/101(7)/073301/4/$23.00

systems. The picosecond laser (Quantel: YG 900C) consists of an active passive mode locked oscillator and a double pass amplifier. This laser system provides an optical pulse of duration of ~50 ps [full width at half maximum (FWHM)] and a maximum energy of ~80 mJ at the fundamental wavelength of 1064 nm with a repetition rate of 10 Hz, whereas the nanosecond laser (Quanta Ray INDI) consists of an active Q-switched oscillator. This laser provides an optical pulse of duration ~6 ns (FWHM) and an energy of ~200 mJ at the second harmonic, 532 nm, with a repetition rate of 10 Hz. A stable air breakdown was produced by focusing a 50 ps laser pulse upto a maximum intensity of $\sim 6\times 10^{13}$ W/cm^2. To prolong the lifetime of the plasma channel a 532 nm, 6 ns laser pulse ($\omega_0 = 35\ \mu$m) was injected into the channel at various delays relative to the picosecond laser pulse. A variable delay between the nanosecond and picosecond laser pulses was achieved using a homemade delay generator.[16] The plasma temperature is estimated using the ratio of the intensity of spectral lines by assuming the plasma in local thermal equilibrium. The density of plasma is determined using the stark broadened profile of NII transition $3d\ ^3D^0 - 4p\ ^3D$ at 649.2 nm.

III. RESULTS AND DISCUSSION

It is known that for a Gaussian optical pulse of given energy and pulse duration the product of the intensity $[\alpha(1/\omega_0^2)]$ and interaction length (the confocal parameter $2z_0$, where $z_0 \alpha \omega_0^2$ is the Rayleigh length) is a constant. In recent times several schemes have been proposed to off set this limitation, wherein the refractive index profile of the plasma balances the diffractive spreading of the beam.[8,9,17,18] In the present work we have used a two pulse technique based on guiding of a delayed laser pulse of longer duration in a preformed plasma channel due to a shorter pulse. In this scheme a short laser pulse is focused to produce a stable breakdown in air or a gas wherein a shockwave induced plasma channel is formed after few nanoseconds. It has been shown that a Gaussian pulse of spot size ω_0 is optimally guided in the channel if the electron density difference Δn_e between $r=0$ (axis) and $r=\omega_0$ (wall) is $\Delta n_e = 1/\pi r_e \omega_0^2$, where r_e is the classical electron radius.[9,11] For example, to guide a laser pulse focused to spot size of $\omega_0 = 35\ \mu$m, the value of Δn_e must be at least of the order of 10^{17} cm^{-3}. The electron density difference Δn_e of $\sim 10^{20}$ cm^{-3} has been reported in hydrodynamic evolution of air breakdown at a laser intensity of $\sim 8\times 10^{13}$ W/cm^2.[19]

In many applications such as lighting control, plasma channel of long lifetime is a primary requirement. However, the lifetime of the plasma channel is limited by the attachment of electrons to the oxygen molecules to form negative ions O^- and O_2^- in air. It is possible to increase the lifetime by heating the plasma by a laser pulse of longer duration so as to detach the electron from O^- and O_2^- ions.[20] The lifetime of the plasma can be monitored by following the time history of the fluorescence from the electron-ion recombination in the channel. In the present experiment the lifetime of the plasma channel was measured from the temporal evolution of the fluorescence emitted at 504.5 nm $(3p\ ^3S - 3s\ ^3P^0)$ of N^+ by the electron-ion recombination in the channel. The fluorescence emitted from the plasma channel was detected using a photomultiplier tube (PMT) attached to the monochromator. In order to separate the fluorescence from other radiation the monochromator was tuned to 504.5 nm. The photomultiplier signal was monitored on a digital oscilloscope, as shown in Fig. 1. Since the fluorescence from N^+ ion persists as long as plasma channel exits, the lifetime of the plasma channel can be approximated to the temporal evolution of 504.5 nm spectral line.

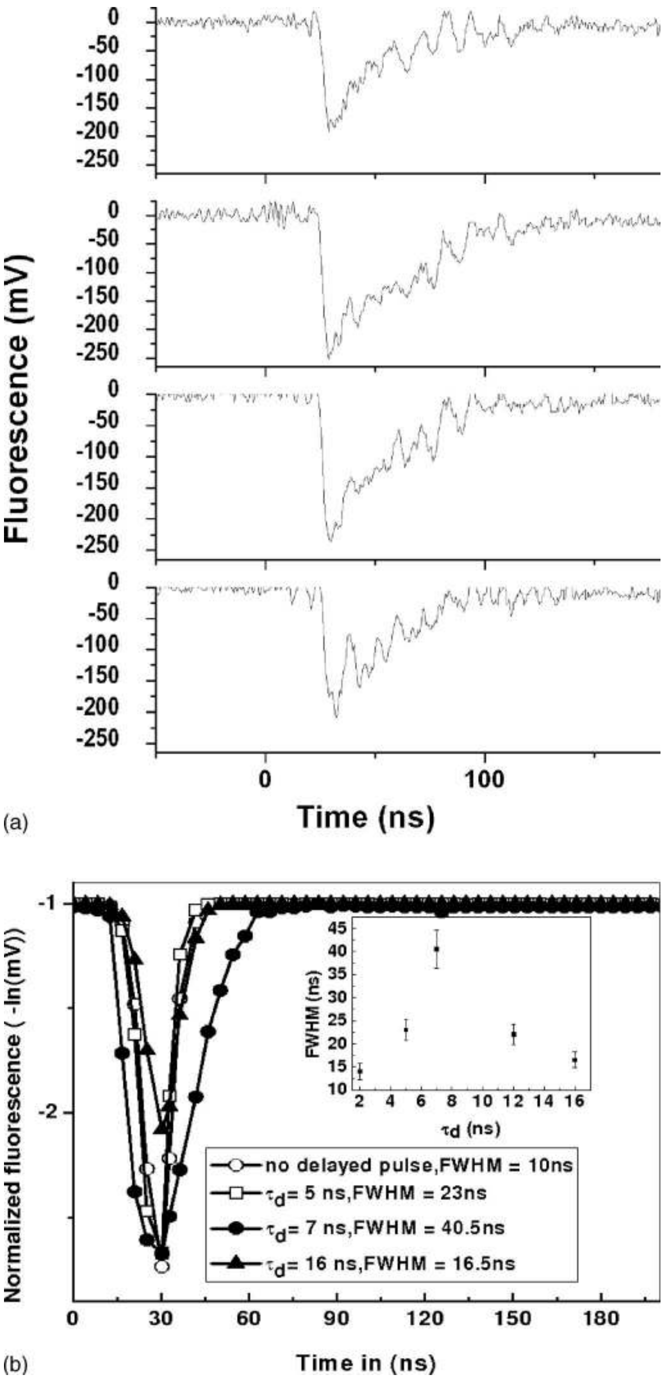

FIG. 2. (a) Temporal evolution of the fluorescence signal at various delays τ_d between the picosecond and injected nanosecond laser pulses. (b) Temporal evolution of fluorescence signal plotted on a log scale. The inset shows the variation of the FWHM of the fluorescence with τ_d.

Figure 2(a) shows the temporal evolution of the

504.5 nm spectral line of N^+ with a delayed nanosecond pulse. The lifetime [full width at half maxima (FWHM)] of the plasma channel formed by a single picosecond pulse was ~10 ns. When a nanosecond pulse was injected into the channel at delays of 5, 7, and 16 ns relative to picosecond laser pulse, the lifetime of the plasma channel was observed to be 23, 40.5, and 16.5 ns, respectively. In order to make the observations more lucid the temporal evolution of the fluorescence is plotted on a log scale in Fig. 2(b). The inset in figure shows the variation of the FWHM of the fluorescence with delay of the injected pulse. The increase in the lifetime of the plasma channel is consistent with the increase in the thermal kinetic energy of the electrons in the plasma channel due to the inverse bremsstrahlung absorption of the nanosecond laser pulse. The increase in the thermal kinetic energy of electrons produces extra electrons by ionizing air molecules and reduces the process of electron attachment with the oxygen molecules.[14,15] The lifetime of the plasma channel first increases and then decreases with increase in delay [Fig. 2(b)]. This is due to the fact that the electron density takes some time to evolve for efficient guiding of the injected pulse. The electron density decreases exponentially with time, and the decrease in the electron density reduces the laser energy deposition into the plasma by inverse bremsstrahlung absorption. Therefore, the lifetime of the plasma goes on decreasing with the increase in delay of the nanosecond laser pulse relative to the picosecond laser pulse. It is worth mentioning that the prolongation of the channel has been reported earlier[21] where a plasma channel was formed in air by the Kerr lensing of a femtosecond laser pulse. However, the peak power of the laser pulse used in our experiment was much smaller than the threshold for the Kerr lensing in air and hence the channel in our case is formed by the shock driven hydrodynamic evolution of the air breakdown.

In order to corroborate the prolongation in lifetime of the plasma channel, we need to find out the electron density at various delays of the nanosecond laser pulse relative to the picosecond laser pulse. In the present experiment optical emission spectroscopy was employed to find the plasma temperature and density.[22,23] Assuming the plasma in local thermodynamical equilibrium (LTE) we have used the relative intensity of various nitrogen lines and the expression $\ln I_{ji}\lambda_{ji}/g_jA_{ji}=\ln(n_i/Z)hc-E_j/k_BT$ to get the plasma temperature. Here, λ_{ji} is the wavelength of the line emitted in the transition from upper level j to the lower level i, A_{ji} is the transition probability from upper level j to the lower i, and k_B is the Boltzmann constant. The values of various parameters used in the expression were taken from the literature.[24] The slope of the plot of $\ln I_{ji}\lambda_{ji}/g_jA_{ji}$ vs E_j gives a temperature of ~8.2 eV of the plasma. The broadening of the emission line in the case of a charged particle is an essential attribute of the Doppler and Stark broadenings. However, in dense plasmas such as laser produced plasmas, the Doppler broadening is very small compared to the overall broadening. For example, in case of the 649.2 nm nitrogen line at a temperature of ~8.2 eV, the half width of the Doppler broadening, $\Delta\lambda_D=[(2k_BT\ln 2/mc^2)^{1/2}\lambda]$ equals 0.02 nm, which is at least one order smaller in magnitude compared to the observed line broadening. The Stark broadening technique is based on the principle that the energy levels of an ion are perturbed by the presence of neighboring electrons. Consequently, the ionic emission lines get broadened. The Stark broadening in ionic emission lines induced by the presence of electrons is given by $\Delta\lambda_{1/2}=2W(n_e/10^{16})$ Å, where $\Delta\lambda_{1/2}$ is the half width of the Stark broadened line, W is the electron impact width parameter, and n_e is the plasma electron density. The parameter W is a weak function of temperature and its value is available in the literature.[22] A typical Stark broadened profile of 649.2 nm line of N_{II} at transition $3d\,^3D^0$-$4p\,^3D$ in a laser induced air breakdown plasma is shown in Fig. 3 (line profile *a*). A Lorentzian fit to the line has a FWHM of ~0.36 nm with the corresponding electron density of 1.4×10^{18} cm^{-3}. The spectral emission from the plasma was recorded using an intensified charge couple device (ICCD) (DH720, Andor Technology) in place of the PMT in Fig. 1. In order to ascertain the assumption used of LTE we have used the minimum electron density requirement[25] for the plasma to be in LTE given by $n_e \geqslant 1.4\times10^{14}T_e(\Delta E)^3$ cm^{-3}, where T_e is the electron temperature in eV, and ΔE is the energy difference between upper and lower states in eV. For the largest energy gap of 2.2 eV in our experiment we get $n_e\sim1.2\times10^{16}$ cm^{-3}, two orders smaller in magnitude compared to the observed value of electron density in our experiment justifying our assumption for the local thermodynamical equilibrium of plasma.

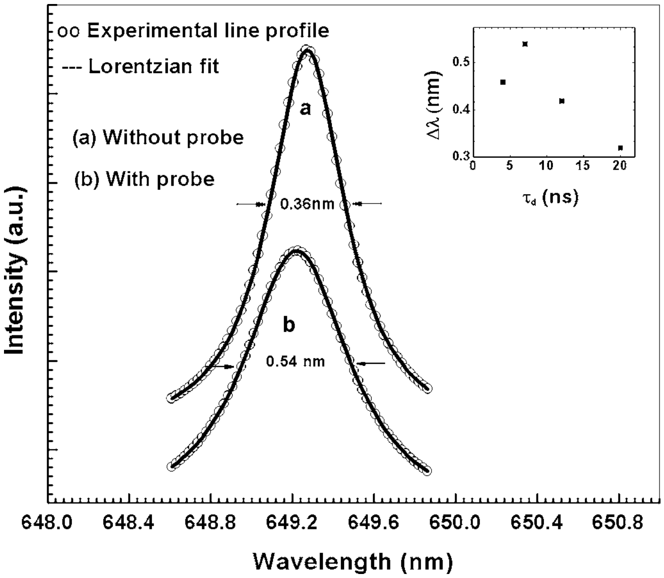

FIG. 3. Stark broadened profile of N_{II} transition $3d\,^3D^0$-$4p\,^3D$ at 649.2 nm without and with a probe pulse at a delay of 7 ns. The inset shows the variation of Δλ with τ_d.

In order to ascertain the increase in electron density, a 6 ns laser pulse of 12 mJ energy was injected into the channel at 4, 7, 12, and 20 ns delays relative to the picosecond laser. The energy of the nanosecond laser pulse was kept just below than that required for air breakdown. Typical Stark broadened line profiles of the 649.2 nm line of N_{II} transition $3d\,^3D^0$-$4p\,^3D$ with a probe pulse at $\tau_d=7$ ns and without a probe pulse is shown in Fig. 3 with broadenings of 0.54 and 0.36 nm, respectively. The respective electron densities are $(2.2 \text{ and } 1.4)\times10^{18}$ cm^{-3}, an increase in density by a factor

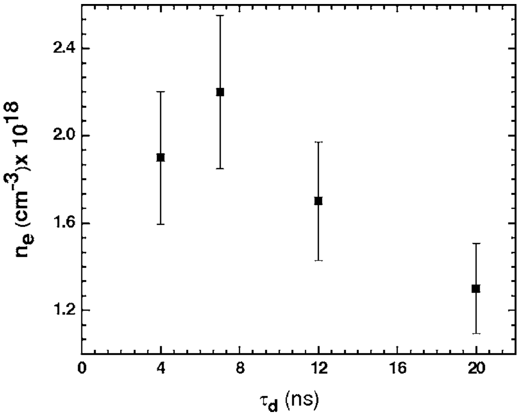

FIG. 4. Variation in the electron density of the plasma n_e with τ_d.

of 1.5 with the probe pulse. The inset in the figure shows a variation of the Stark width with delay τ_d. The observed enhancement in the electron density in case of a delayed nanosecond laser pulse is consistent with the inverse bremsstrahlung absorption of the incoming laser pulse by the plasma electrons in the channel. The variation of the electron density with τ_d is shown in Fig. 4.

We observe a high electron density in the channel at the injection delay of 7 ns and thereafter the electron density decreases because of the recombination of electrons to parent ions[13] and strong attachment to the oxygen molecules.[14,15] The electrons in the plasma channel gain energy from the nanosecond laser pulse by the process of inverse bremsstrahlung absorption. The increase in the kinetic energy of electrons results in extra ionization and slowing down the electron recombination rate as well. Due to extra ionization and reduced recombination rate the electron density in the plasma channel is enhanced and survived for a longer time. For example, in case of the 7 ns delay of the nanosecond laser pulse an enhancement of about 50% in the electron density was observed as compared to that of the plasma formed by a single pulse. However, at longer delays the injected nanosecond laser pulse essentially interacts with decreasing electron density in the channel that results in a weak inverse bremsstrahlung absorption and a diminishing enhancement in the electron density. For example, at 12 ns delay the electron density enhancement is reduced to 28% from 50% at the 7 ns delay.

IV. CONCLUSION

We have reported a two-pulse technique for prolongation in lifetime of the plasma channel in air. The channel was formed by focusing a 50 ps laser pulse in air to a maximum laser intensity of $\sim 6 \times 10^{13}$ W/cm^2. The prolongation in lifetime of the plasma channel was observed up to a factor of ~4 at a 7 ns delay of the nanosecond laser pulse relative to the picosecond laser pulse. A plasma temperature of ~8.2 eV was calculated using a Boltzmann plot for nitrogen lines. An electron density of $\sim 1.4 \times 10^{18}$ cm^{-3} in the plasma was determined using the Stark broadening in the 649.2 nm line of N_{II} transition $3d\ ^3D^0$-$4p\ ^3D$.

ACKNOWLEDGMENT

We acknowledge support of the Department of Science and Technology, New Delhi.

[1] A. J. Mackinnon *et al.*, Phys. Plasmas **6**, 2185 (1999).
[2] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979); P. Sprangle, E. Esarey, A. Ting, and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988).
[3] N. H. Bernett and P. B. Korcum, J. Opt. Soc. Am. B **6**, 1195 (1989).
[4] X. F. Li, A. L'Huillier, M. Ferray, L. A. Lompré, and G. Mainfray, Phys. Rev. A **39**, 5751 (1989).
[5] J. Kasparian *et al.*, Science **301**, 61 (2003).
[6] H. Pépin *et al.*, Phys. Plasmas **8**, 2532 (2001).
[7] M. Rodriguez *et al.*, Opt. Lett. **27**, 772 (2002).
[8] M. Rodriguez *et al.*, Phys. Rev. E **69**, 036607 (2004).
[9] C. G. Derfee III and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).
[10] R. A. Armstrong, R. A. Lucht, and W. T. Rawlins, Appl. Opt. **22**, 1573 (1983); A. Sircar, R. K. Dwivedi, and R. K. Thareja, Appl. Phys. B: Lasers Opt. **63**, 623 (1996).
[11] C. G. Derfee III, J. Lynch, and H. M. Milchberg, Phys. Rev. E **51**, 2368 (1995).
[12] X. Lu, T. T. Xi, Y. J. Li, and J. Zhang, Acta Phys. Sin. **53**, 3404 (2004).
[13] S. Tzortzakis, B. Prade, M. Franco, and A. Mysyrowicz, Opt. Commun. **181**, 123 (2000).
[14] X. M. Zhao, J.-C. Diels, C. Y. Wang, and J. M. Elizondo, IEEE J. Quantum Electron. **31**, 599 (1995).
[15] H. Yang *et al.*, Phys. Rev. E **66**, 016406 (2002).
[16] V. Narayanan, Ph.D. thesis, I.I.T, Kanpur, India, 2004.
[17] Y. Ehrlich, C. Cohen, A. Zigler, J. Krall, S. Prangle, and E. Esarey, Phys. Rev. Lett. **77**, 4186 (1996).
[18] A. Braun, G. Korn, X. Liu, D. Du, J. Squier, and G. Mourou, Opt. Lett. **20**, 73 (1995).
[19] N. I. Vogel and N. Kochan, Phys. Rev. Lett. **86**, 232 (2001).
[20] J. Zhu, Z. Ji, Y. Deng, J. Liu, R. Li, and Z. Xu, Opt. Express **14**, 4915 (2006).
[21] Z. Q. Hao *et al.*, Appl. Phys. B: Lasers Opt. **80**, 627 (2005).
[22] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).
[23] W. Lochte-Holtgreven, *Plasma Diagnostics* (North-Holland, Amsterdam, 1968).
[24] J. Reader, C. H. Corliss, W. L. Wiese, and G. A. Martin, *Wavelengths and Transition Probabilities for Atoms and Atomic lines*, Natl. Bur. Stand. (U.S.) Circ. No. 68 (U.S. GPO, Washington, D.C., 1980).
[25] G. Bekefi, *Principles of Laser Plasmas* (Wiley-Interscience, New York, 1976).