Picosecond air breakdown studies at 0.53 μm

William E. Williams, M. J. Soileau, and Eric W. Van Stryland
Center for Applied Quantum Electronics, Department of Physics, North Texas State University, Denton, Texas 76203

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The laser induced breakdown thresholds of laboratory air at 0.53 μm were measured for pulses varying from 30 to 140 ps for a variety of focal spot sizes. The breakdown threshold fields were found to be proportional to $1/\sqrt{t_p}$, where t_p is the laser pulse width. Comparison with an earlier work at 1.06 μm under similar conditions indicates that the breakdown thresholds are higher at 0.53 than at 1.06 μm. However, this increase falls short of the λ^{-2} dependence exhibited by cascade ionization.

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In this letter we report the results of a study of the breakdown of laboratory air with single pulses of 30–140-ps duration at 0.53 μm. The laser induced breakdown field E_B the rms field corresponding to the peak-on-axis irradiance, was found to increase as the pulse width was decreased. Over the range of pulse widths used in this study, the breakdown field was found to scale as $1/\sqrt{t_P}$, where t_p is the full width at half-maximum temporal width of the pulse. This is a stronger dependence than that seen in a similar study conducted earlier by us at 1.06 μm (Ref. 1). We used this earlier work along with the present data to determine the wavelength dependence of the breakdown threshold. For conditions of equal pulse width and the same focal spot size, E_B was greater at 0.53 than at 1.06 μm. However, the increase was weaker than the dependence predicted by cascade ionization.[2] A multiphoton initiated cascade ionization process could possibly account for the observed wavelength dependence.[3]

The laser used in this study was a microprocessor-controlled, mode-locked, neodymium:yttrium aluminum garnet (Nd:YAG) oscillator-amplifier system operated at 1.06 μm. A single pulse of measured Gaussian spatial profile was switched out of the resulting mode-locked train and amplified. The pulse width of the laser was varied from 30 to 200 ps by selecting various etalons as the output coupler of the oscillator. Shot to shot variations in both pulse width and energy were monitored in the manner described in Ref. 1.

A temperature-tuned CD*A crystal was used with the Nd:YAG laser to produce pulses at 0.53 μm. Care was taken to filter out any residual 1.06-μm radiation from the 0.53-μm beam. The energy in the 1.06-μm pulse used to produce the second harmonic was kept below values which would produce saturation effects in the spatial profile of the second harmonic beam. Two-dimensional scans of the 0.53-μm beam with an optical multichannel analyzer (OMA) verified the absence of saturation effects and the Gaussian spatial profile of the 0.53-μm beam. Vidicon scans of the spatial beam profile showed no shot to shot variations in the beam width (within the $\pm 1\%$ limits of sensitivity of the measurements). Light-by-light scattering measurement in a $LiIO_3$ crystal confirmed that the 0.53-μm pulse width scaled as the 1.06-μm pulse width divided by $\sqrt{2}$ [4] and a Gaussian shape fit the autocorrelation function well. This scale factor was used to compute the 0.53-μm pulse widths from the measured 1.06-μm pulse width.

The experiment was performed in an environmentally controlled laboratory in which temperature and humidity fluctuations were kept to a minimum. The average temperature was 23 °C and the relative humidity was 40%. Filtration systems in the air ducts minimized the problem of particle contaminants in the laboratory air. The laser beam was focused in laboratory air using single element lenses of "best form" design, i.e., designed for minimum spherical aberrations. Three lenses of focal lengths 37, 75, and 150 mm, were used at a fixed position from the beam waist to produce the focal spot radii for this experiment. The lowest f-number condition used in this experiment is $f/10.3$. In each case the input beam diameter was kept below maximum values tabulated for each lens necessary to ensure diffraction-limited performance. The beam energy was varied by changing the voltages used on the laser amplifier. Vidicon scans of the spatial beam profile confirmed that over the range of amplifier settings used in this work the spatial beam width remained constant. The output energy of the CD*A crystal was continually monitored using a sensitive photodiode peak-and-hold detector, absolutely calibrated with respect to a pyroelectric energy monitor.

The breakdown thresholds for air at 0.53 μm are summarized in Table I. The uncertainties listed in the table are relative errors obtained by the method of Porteus *et al.*[5] The absolute errors which include the relative errors plus absolute errors in energy, pulse width, and focal spot radius are estimated to be $\pm 20\%$ in the breakdown electric field. No air breakdown was observed for the 14-μm spot size for the highest output value available for the laser.

The functional dependence of the breakdown electric field, E_B, for air at the second harmonic wavelength is more clearly seen by plotting E_B versus the inverse pulse width on a log-log plot. In Fig. 1 we have plotted E_B for the smaller spot sizes in just such a manner. Over the limited range of pulse widths used in this study, linear least squares fit of the data indicates that

$$E_B \alpha t_p^{-x},$$

where $x = 0.48 \pm 0.08$, approximately an inverse $\sqrt{t_p}$ dependence. An inverse $\sqrt{t_p}$ dependence of the breakdown field

TABLE I. Laser induced breakdown data for air at 0.53 μm. The error values listed are the relative uncertainties in the threshold for damage determined by the method used in Ref. 5. The absolute accuracy of these data is estimated to be $\pm$ 20% in the breakdown field. In this table w is the focal spot radius (HW1/e^2M) in microns, t_p is the laser pulse width (FWHM) in picoseconds, I_B = breakdown irradiance, E_B = breakdown field, P_B = breakdown power, and ϵ_B the breakdown fluence.

Air breakdown $\lambda = 0.53\ \mu$m					
W_0 (μm)	t_p (ps)	E_B (MV/m)	I_B (TW/cm^2)	P_B (MW)	ϵ_B (kJ/cm^2)
	20	~170	~72	~13.1	~1.5
3.4	33 $\pm$ 5	120 $\pm$ 6	38 $\pm$ 3	7.0 $\pm$ 0.7	1.3 $\pm$ 0.1
	80 $\pm$ 5	83 $\pm$ 7	18 $\pm$ 2	3.3 $\pm$ 0.4	1.5 $\pm$ 0.2
	100 $\pm$ 10	70 $\pm$ 5	13 $\pm$ 2	2.4 $\pm$ 0.3	1.4 $\pm$ 0.1
	140	65 $\pm$ 4	10.7 $\pm$ 2	1.9 $\pm$ 0.2	1.6 $\pm$ 0.2
	32 $\pm$ 3	129 $\pm$ 9	44 $\pm$ 5	35.8 $\pm$ 4	1.5 $\pm$ 0.2
7.2	89 $\pm$ 5	80 $\pm$ 7	17 $\pm$ 3	13.8 $\pm$ 1.4	1.6 $\pm$ 0.2
	110 $\pm$ 10	66 $\pm$ 4	11.5 $\pm$ 1.2	9.4 $\pm$ 1.0	1.4 $\pm$ 0.2

also implies that the breakdown *fluence* is constant. This trend is clearly seen in Table I. Also note the lack of spot size dependence of E_B for the two spot sizes for which breakdown thresholds are available.

The observed pulse width dependence of E_B at 0.53 μm is characteristic of a cascade ionization process in the high electric field limit.[6] This limit corresponds to a situation in which the increase in energy of the free electrons is simply proportional to the input irradiance and all losses are negligible. For the low field limit, the ionization rate is exponentially dependent on E (the electric field), and the resulting pulse width dependence is relatively weak.[6]

In the study conducted two years ago the breakdown thresholds for laboratory air under similar conditions to those used in this study were determined using the same laser system at 1.06 μm (Ref. 1). Over the range of pulse widths used in the earlier study the breakdown threshold fields were found to show an inverse fourth root of t_p dependence; a weaker dependence than that shown at 0.53 μm. The weaker t_p dependence observed at 1.06 μm could be due to the fact that E_B is lower at 1.06 than at 0.53 μm (as will be shown later in the letter). The weaker pulse width dependence for lower E_B values is consistent with the previously mentioned avalanche breakdown model.[6]

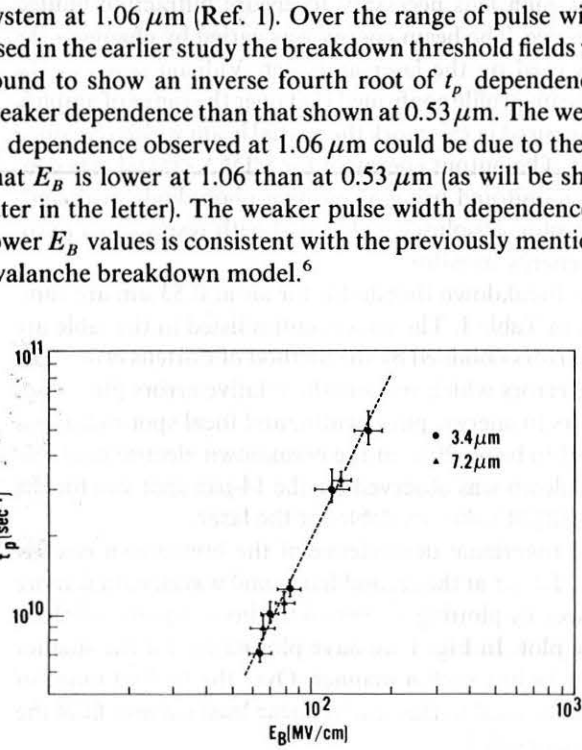

FIG. 1. Pulse width dependence of E_B for air at 0.53 μm. The slope of the linear least squares fit of the data is 0.48 $\pm$ 0.08 which is an approximate inverse $\sqrt{t_p}$ dependence. Owing to the lack of spot size dependence exhibited at this wavelength both sets of data were used in the linear least squares fit.

The 1.06-μm data in Ref. 1 showed a marked focal spot size dependence in contrast to the data in this work (Table I). Spot size dependences in E_B have been attributed to the presence of aerosol contaminants[7–9] and diffusion of free carriers from the focal volume.[9] The latter process is believed to be important for longer pulses (> 1 ns) but should be negligible for picosecond pulses.[9] One possible explanation for the lack of focal spot size dependence seen at 0.53 μm is that aerosol contaminants play a lesser role in air breakdown at higher photon energies.

Using the data obtained in Ref. 1 for comparable focal spot radii and pulse widths we can determine the wavelength dependence for air breakdown. In Fig. 2, we have plotted, in bar graph form, the breakdown irradiance for the two wavelengths for a fixed focal spot radius of 7.2 μm. Since the data for the two wavelengths did not exactly overlap in pulse width or focal spot radius we interpolated the 1.06-μm data between two pulse width and two focal spot radii for which data was available. The error introduced by this interpolation is estimated to be within the error bars shown in Fig. 2. The parameter I_R is the ratio of the breakdown irradiance at 0.53 μm to the breakdown irradiance at 1.06 μm for a given pulse width. In each case the ratio is greater than 1, indicating an increase in the breakdown irradiance with decreasing wavelength. However, the increase falls short of the λ^{-2} dependence observed in the midinfrared spectral region[10] and predicted by cascade ionization.[2] Multiphoton processes may be coming into play for these irradiance levels[11] at 0.53

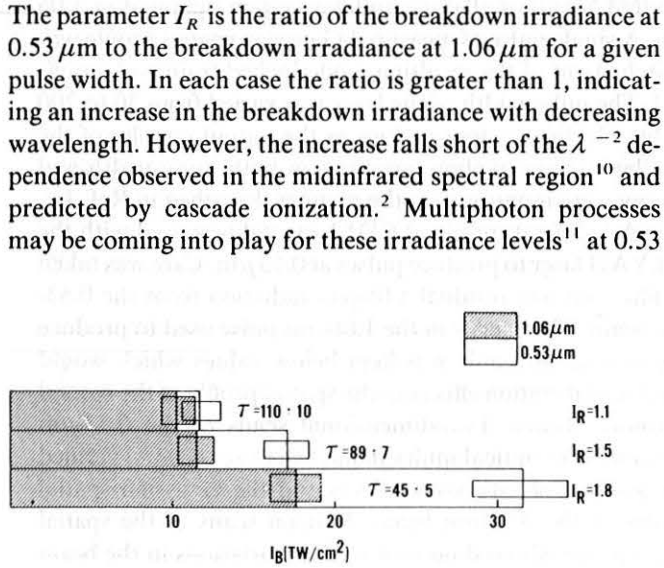

FIG. 2. Wavelength dependence of the breakdown field, E_B, for air for a variety of laser pulse widths. The 1.06-μm thresholds are taken from Ref. 1 and are interpolated from measurements made at spot sizes of 6.1 and 10.3 μm. The parameter I_R is the ratio of the threshold at 0.53 to the threshold at 1.06 μm.

μm. They may initiate the breakdown process which is then taken to completion by cascade ionization.[3] Thus, one possible explanation for the observed frequency and pulse width dependence is that laser-induced breakdown at 0.53 μm is due to a combination of multiphoton and cascade ionization.

The results obtained in an earlier pressure and wavelength-dependent study of the breakdown thresholds of N_2 and O_2 support the plausibility of this mechanism.[12] For pulses as short as 7 ps at 1.06 μm and 18 ps at 0.69 μm Dewhurst[12] found that, for pressures below 1000 Torr, the breakdown irradiance levels for N_2 showed very little pressure dependence. This lack of pressure dependence is a strong indication that multiphoton ionization dominates the breakdown process. For longer pulses at 0.53 μm (25 ps) Dewhurst found that the breakdown irradiance levels showed a pressure dependence indicative of cascade ionization.[12] However, the breakdown irradiance levels were an order of magnitude below those found at 1.06 μm. Since multiphoton ionization is strongly dependent on irradiance, the lower irradiance levels for longer pulses may play a factor in the contribution that multiphoton ionization makes to the breakdown process. A similar pressure dependence to that exhibited at 0.53 μm (Ref. 12) was seen for comparable pulse widths at 1.06 μm by Ireland and Morgan.[13] While cascade ionization seems to dominate the breakdown process for longer pulses the contribution made by multiphoton ionization cannot be ignored.

In summary, the breakdown thresholds for laboratory air were determined as a function of wavelength and pulse width. The breakdown irradiance thresholds at 0.53 μm exhibited a $1/\sqrt{t_p}$ dependence, a stronger dependence than that seen at 1.06 μm under similar conditions.[1] The thresholds at 0.53 μm are in good agreement with the results obtained by others for N_2 under comparable conditions of pressure and pulse width.[12] The thresholds at 0.53 μm are higher than those at 1.06 μm; however, the increase is weaker than the λ^{-2} dependence predicted for cascade ionization. A multiphoton-assisted cascade ionization process is suggested as the breakdown mechanism for air under the conditions of this work.

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[1]E. W. Van Stryland, M. J. Soileau, Arthur L. Smirl, and William E. Williams, Phys. Rev. B **23**, 2144 (1981).
[2]N. Kroll and K. M. Watson, Phys. Rev. A **5**, 1883 (1972).
[3]S. L. Chin, Can. J. Phys. **48**, 1314 (1970).
[4]E. W. Van Stryland, W. E. Williams, M. J. Soileau, and A. L. Smirl (to be published).
[5]J. O. Porteus, J. L. Jernigan, and W. N. Faith, NBS Spec. Publ. **509**, 507 (1977).
[6]C. Grey Morgan, Rep. Prog. Phys. **38**, 621 (1975).
[7]David C. Smith, J. Appl. Phys. **48**, 2217 (1977).
[8]G. H. Canavan and P. E. Nielson, Appl. Phys. Lett. **22**, 409 (1973).
[9]I. P. Shkarotsky, RCA Rev. **35**, 48 (1974).
[10]M. J. Soileau, Appl. Phys. Lett. **35**, 309 (1979).
[11]L. A. Lompre, G. Mainfray, C. Manus, S. Repoux, and J. Thebault, Phys. Rev. Lett. **36**, 949 (1976).
[12]R. J. Dewhurst, J. Phys. D **11**, L191 (1978).
[13]C. L. M. Ireland and C. Grey Morgan, J. Phys. D **7**, L87 (1974).