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3. J. R. Birch and J. D. Dromey, "The Optical Constants of Common Low-Loss Polymers Between 4–40 cm^{-1}," Infrared Phys. 121, 225 (1981).
4. D. T. Rampton and R. W. Grow, "Economic Infrared Polarizer Utilizing Interference Effects in Films of Polyethylene Kitchen Wrap," Appl. Opt. **15**, 1034 (1976).
5. M. C. Richardson, A. J. Alcock, K. Leopold, and P. Burtyn, "Large Aperture CO_2 Laser Discharges," J. Quantum Electron. **QE-9**, 736 (1973).
6. D. A. Pinnow and T. C. Rich, "Measurements of the Absorption Coefficient in Fiber Optical Waveguides using a Calorimetric Technique," Appl. Opt. **12**, 984 (1973).
7. F. D. Rossini, D. D. Wagman, W. H. Evans, S. Levine, and I. Jaffe, "Selected Values of Chemical-Thermodynamic Properties of Materials," Natl. Bur. Stand. U.S. Publ. **500**, 120 (1952).
8. B. S. Patel, "Optical Suitability of Window Materials for CO_2 Laser," Appl. Opt. **16**, 1232 (1977).
9. A. K. Nath, U. K. Chatterjee, and D. D. Bhawalkar, "Multiline TEA CO_2 Laser," Ind. J. Phys. **54B**, 112 (1980).
10. K. M. Leung, M. Bass, and A. G. J. Balbin-Velaverde, Laser Induced Damage in Optical Materials," Natl. Bur. Stand. U.S. Pub. **435**, 107 (1975).
11. V. Wang, C. R. Giuliano, S. D. Allen, and R. C. Pastor, "Laser-Induced Damage in Optical Materials," Natl. Bur. Stand. U.S. Publ. **435**, 118 (1975).

Coupling of high-power UV laser radiation into fused silica fibers using pressurized gases

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There are many applications for excimer lasers, particularly in medicine and material processing; however, effective delivery systems for high-power UV radiation have yet to be well developed. Generally, delivery systems for intense UV radiation are based on standard, state-of-the-art fiber-optic technology. If the short-pulse (~15-ns FWHM) high-power UV radiation is focused onto the tip of an optical fiber, the energy transmission is ultimately limited by the dielectric breakdown at the fiber surface, which is an intensity-dependent phenomenon. The laser energy coupled into an optical fiber can therefore be increased by extending the pulse length of the laser. So far, however, this method is only available for the XeCl laser (308 nm).[1] Several other experiments on excimer laser transmission through optical fibers have been reported for various applications.[2–5] The best results were obtained by Pini *et al.*[5] They achieved an input damage threshold of 16 J cm^{-2} at 308 nm through a 200-μm silica core fiber using water at the coupling interface. They also reported that it decreased to 10 J cm^{-2} in the absence of water (i.e., for an air interface). In the conditions of their experiment, this corresponds to a breakdown intensity of

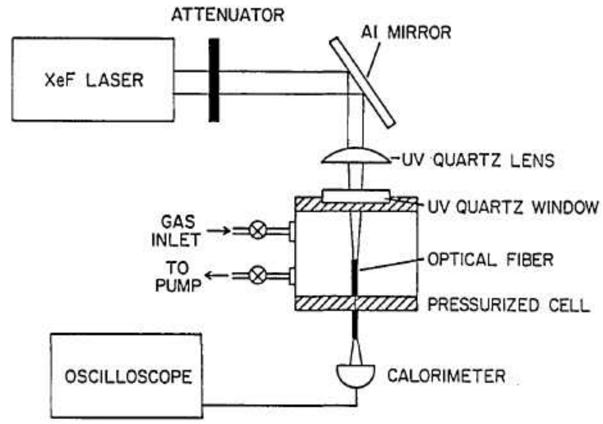

Fig. 1. Schematic diagram of the experimental setup.

~10^9 W cm^{-2}, which is considerably lower than the breakdown intensity of pure air (>10^{10} W cm^{-2}) at 351 nm, indicating that the solid surface of an optical fiber plays an important role in the breakdown mechanism. Multiphoton ionization of the gas surrounding the fiber tip should play a minor role at this intensity, so that the breakdown may primarily be attributed to the acceleration of free electrons by the laser field. The initial free electrons are either due to residual ionization of the air or may be produced through photoionization of impurities with low work functions at the fiber surface. A reduction in the number of initial free electrons, as well as collisionally produced low energy secondary electrons or a reduced mobility of these free electrons, should shift surface breakdown threshold intensities to higher values and improve the coupling efficiency into the fiber. Reducing the ambient gas density decreases the ionization rate. A reduction in initial electron densities may also be achieved by attaching the electrons to electronegative gases such as SF_6 or CO_2, whereas high gas pressures should reduce the electron mobility. As a result, higher coupling efficiencies of excimer light into optical fibers would be expected either for coupling under vacuum or high-pressure electronegative gases.

The schematic of the experimental setup is shown in Fig. 1. The excimer laser is a standard commercial discharge laser (Questek 2220), which was operated on the XeF transition at 351 nm. The maximum output energy was ~150 mJ with a pulse-to-pulse energy stability of ±5%, and the pulse width was 15-ns (FWHM). The laser beam was focused with an UV grade fused silica plano–convex lens of 250-mm focal length and introduced into a pressurized or evacuated cell through an UV fused silica window. The laser beam was coupled into the fiber by translating the cell and fiber assembly with an adjustable translation stage. The laser intensity at the surface of the fiber could be varied by changing attenuation of the laser beam. The pressurized cell was constructed of Plexiglas to allow for easy and direct observation of the alignment and surface breakdown. The cell could be pressurized up to 10 atm and evacuated down to 10^{-3} Torr. Four different gases, N_2, He, SF_6, and a CO_2/N_2/He mix, were used to pressurize the cell. The purities of the gases were 99.999%, 99.999%, and 99.8% for N_2, He, and SF_6, respectively. The gas mixture consisted of 13.8% CO_2, 25.1% N_2, and 61.1% He.

The optical fiber used in these experiments was a step-index multimode quartz fiber (ST-U800G-SY, Diaguide). The core, which was made of UV grade fused silica, was 800 μm in diameter. The outer diameter including the cladding was 1 mm, and the numerical aperture (N.A.) was 0.20. For most coupling experiments, 10-cm long fibers were used. Some experiments were also performed using longer fibers of up to 3 m. The surface of the fibers were machine polished with an Al_2O_3 fiber polishing lap (0.3 μm), and then inspected through an optical microscope. No attempt other than visual inspection was made to optimize or characterize the quality of the polished tip of the various fibers. Recent work by Taylor *et al.*[6] indicates that improvement of the quality of the optical polish may also increase the breakdown threshold.

For most experiments, the XeF laser was operated at 2 Hz, and the laser energy transmitted through the fiber was monitored with a calibrated Gentec (ED-200) calorimeter. The focused laser beam size was measured to be $\sim$900 $\times$ 600 μm^2 around the focal point, and the beam divergence after the lens was one-third of the N.A. The fiber was not placed at the focal point of the laser beam, but rather before the focal point to achieve a more uniform illumination over the surface of the fiber. In fact, the laser spot size was always larger than the tip of the fiber. Although not all the laser energy using this technique was coupled into the fiber, this method insured that all the surface of the fiber was utilized. In addition, this technique prevented the experiments from being sensitive to changes in the focal spot size resulting from attenuating the laser or changing the pressure inside the gas cell.

Because the incident laser beam was larger than the tip of the fiber, not all the input energy measured in front of the fiber surface was coupled into it. The performance of the gas cell as an effective coupling mechanism was evaluated by measuring the output energy of the fiber as a function of gas pressure in the cell and recording the output fluence when fiber damage occurred. The energy incident on the tip of the fiber was gradually changed by attenuators in the beam path as shown in Fig. 1. The surface breakdown at the input end of the fiber was detected by monitoring a sudden decrease of the output energy. Normally, breakdown was observed at the input end of the fiber, but occasionally it also occurred at the output end or middle of the fiber. This may be due to material impurities or self-focusing effects. After breakdown had occurred, the surface of the fiber was inspected by a microscope. This inspection showed that the damage occurred in the core of the fiber, and that there was no contribution by a surface breakdown of the cladding.

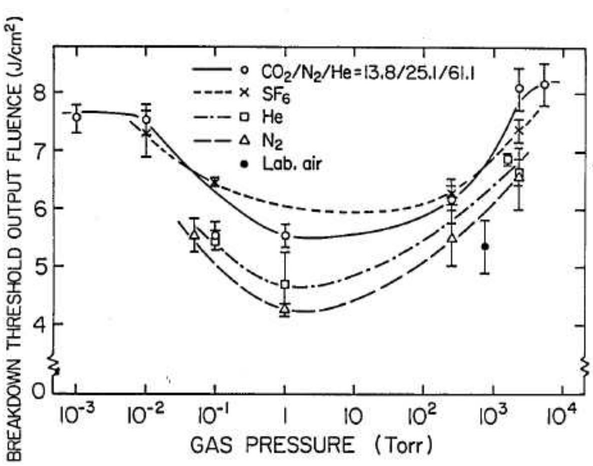

Fig. 2. Pressure dependence of the measured output fluence at the fiber breakdown threshold using four different gases; 10-cm long fused silica fibers of 800-μm core diameter were used.

The threshold output fluence for breakdown of the 10-cm long optical fibers as a function of the gas pressure is shown in Fig. 2 for several gases. Each data point is a mean value obtained from at least three different experiments—typically five. The error bars show the measured fluctuations of the optical fiber breakdown fluence at the given pressures. These fluctuations may be due to the difference in the quality of the polished input surfaces of the fibers. A breakdown threshold output fluence of more than 8 J cm^{-2} was obtained with the CO_2 mixture gas at 7 atm. At this fluence, a repetition rate of at least 2 Hz could be maintained with no damage to the fiber. Hence, the use of such electronegative gases in the pressurized cell raised the breakdown threshold output fluence by 50% compared with that in normal laboratory air (5.4 J cm^{-2} the solid circle shown in Fig. 2).

The pressure dependence shown in Fig. 2 is qualitatively similar to the optical breakdown of gases.[7] However, the breakdown thresholds at the fiber surfaces are $\sim$1 order of magnitude lower when compared to the optical breakdown thresholds in air. One explanation, as mentioned above, is that the interaction between the solid surface and the laser field may provide initial free electrons, which will be accelerated in the laser field and thus trigger the electron avalanche in the surrounding gas at the fiber tip. This electron avalanche can be inhibited by reducing the number of free electrons, or by reducing the mobility of these electrons, so that it is difficult to accelerate them to sufficient energy to produce an avalanche. The number of free electrons produced at the coupling surface can be restricted by using an electronegative gas which has a high electron attachment coefficient. This expectation is supported by the results in Fig. 2 with electronegative gases (SF_6, CO_2 mixture) which show significantly higher breakdown thresholds than those of nitrogen and helium. The number of free electrons can also be reduced by decreasing the number of donor gas atoms which contribute secondary electrons to the electron avalanche. This can explain the increased breakdown threshold at low pressures shown in Fig. 2, while at high pressures the mobility of the free electrons is reduced, which again raises the breakdown threshold.

The incident intensity on the fiber tip was estimated by measuring the fluence which passed through a 1-mm aperture at the position of the input fiber tip. Since the divergence of the laser beam was measured to be within the numerical aperture of the fiber, all the energy passing through the 1-mm aperture was used to calculate the input fluence. This fluence was compared to the measured output energy to estimate a coupling efficiency of 70%. Based on this estimate, the maximum input fluence for the 15-ns laser pulse was 12 J cm^{-2} using 7 atm of the CO_2 mixture as a coupling gas.

A maximum output fluence was also measured for longer fibers and at higher repetition rates. The maximum output fluences of 6.5 and 5.6 J cm^{-2} were obtained with a 1- and a 3.5-m flexible fiber, respectively, using 3-atm of SF_6 gas. This corresponds to an input fluence of $\sim$10.2 J cm^{-2}. In addition to these experiments at a 2-Hz pulse repetition rate, a high average transmitted power of 1.3 W was also obtained at a repetition rate of 50 Hz with a CO_2 gas mixture at 3 atm. These fluence values were found to be large enough to ablate atherosclerotic aortas for laser angioplasty[8] and also appear to be effective for laser lithotripsy using excimer lasers.

In summary, we have demonstrated a simple technique utilizing a gas cell for increasing the breakdown threshold for intense UV light coupled into a fused silica fiber. The output fluence at the breakdown threshold was raised from 5.4 to 8.2 J cm^{-2} through a 10-cm long fiber with an 800-μm core.

Meetings *continued from page 1632*

1988
June

6–10 Electro-Optical System Analysis course, El Segundo *UCLA Ext., P.O. Box 24901, Los Angeles, CA 90024*

6–10 Human Factors in Displays & Controls course, El Segundo *UCLA Ext., P.O. Box 24901, Los Angeles, CA 90024*

6–10 High-Speed Heterojunction Electronic & Optoelectronic Devices course, Ann Arbor *Eng. Summer Confs., Chrysler Ctr./N. Campus, U. of MI, Ann Arbor, MI 48109*

7–9 Optical Storage for Large Systems Mtg., New York *TOC, P.O. Box 14817, San Francisco, CA 94114*

7–10 Photographic Instrumentation Techniques course, Rochester *RIT/T&E Sem. Ctr., 1 Lomb Memorial Dr., Rochester, NY 14623*

12–15 Int. Conf. on Electronic Materials in Japan, Tokyo *T. Kamiya, Dept. Electronics Engineering, U. Tokyo, 7-3-1- Hongo Bunkyo-kum Tokyo 113, Japan*

13–17 Infrared Technology Fundamentals & System Applications course, Ann Arbor *Eng. Summer Confs., Chrysler Ctr./N. Campus, U. of MI, Ann Arbor, MI 48109*

14–19 China Optoelectronics Laser '88, Beijing *Cahners Expo. Group, P.O. Box 70007, Wash., DC 20088*

15–16 Fiber Optics in Plain English Sem., Atlanta *Trellis Communications Corp., 5 Manor Pkwy., Salem, NH 03079*

15–17 **Spatial Light Modulators & Applications Mtg.,** Lake Tahoe *OSA Mtgs. Dept., 1816 Jefferson Pl., NW, Wash., DC 20036*

17–5 July 1988 Summer Inst., History & Philosophy of Sci., Berlin *W. Woodward, Dept. Psych., Conant Hall, U. New Hampshire, Durham, NH 03824*

20–22 18th Power Modular Symp., Hilton Head *IEEE, 345 E. 47th St., New York, NY 10017*

20–23 10th Symp. on Thermophysical Properties, Gaithersburg *A. Cezairliyan, Rm. 124 Hazards Bldg., NBS, Gaithersburg, MD 20899*

20–24 14th Int. Laser Radar Conf., San Candido *L. Stefanutti, IROE, CNR, Via Panciatichi, 64-50127 Firenze, Italy*

20–24 Fluid Mechanics Measurement course, Minneapolis *J. Becker, U. of MN, Professional Dev., 107 Armory, 15 Church St. S.E., Minneapolis, MN 55455*

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This corresponded to an input fluence of ~12 J cm^{-2} without surface breakdown using this method. This coupling technique should have potential applications for excimer laser systems operating at various other wavelengths and pulse durations.

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References

1. R. S. Taylor and K. E. Leopold, "Microsecond Duration Optical Pulses from UV-Preionized XeCl Laser," Appl. Phys. Lett. **47,** 81 (1985).
2. R. Pini, R. Salimbeni, M. Vannini, A. F. M. Y. Haider, and C. Lin, "High Conversion Efficiency Ultraviolet Fiber Raman Oscillator–Amplifier System," Appl. Opt. **25,** 1048 (1986).
3. R. S. Taylor, K. E. Leopold, S. Mihailov, and J. Seregelyi, "Optical Fiber Transmission in Excimer Laser Angioplasty," in *Technical Digest, Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1986), paper TUA4.
4. Y. Itoh, K. Kunitomo, M. Obara, and T. Fujioka, "High-Power KrF Laser Transmission Through Optical Fibers and Its Application to the Triggering of Gas Switches," J. Appl. Phys. **54,** 2956 (1983).
5. R. Pini, R. Salimbeni, M. Matera, and C. Lin, "Ultraviolet Stimulated Raman Scattering in Multimode Silica Fibers Pumped with Excimer Lasers," Appl. Phys. Lett. **43,** 517 (1983).
6. R. S. Taylor, K. E. Leopold, D. L. Singleton, S. Mihailov, and B. Brimacombe, "Fiber Optics for High-Power Excimer Lasers," in *Technical Digest, Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1987), paper TUL3.
7. D. C. Smith and R. G. Meyerand, Jr., "Laser Radiation Induced Gas Breakdown," in *Principles of Laser Plasmas,* G. Bekefi, Ed. (Wiley, New York, 1976), p. 457.
8. M. P. Sartori, P. D. Henry, R. Sauerbrey, F. K. Tittel, D. Weilbacher, and R. Roberts, "Tissue Interaction and Measurement of Ablation Rates with UV and Visible Lasers in Canine and Human Arteries," in *Lasers in Surgery and Medicine,* **7,** 300 (1987).

Note added in proof: The authors became aware of further relevant work after this manuscript was submitted. The two additional references are by R. S. Taylor, K. E. Leopold, S. Mihailov and R. K. Brimacombe, entitled "Damage Measurements of Fused Silica Fibres Using Long Optical Pulse XeCl Lasers," Opt. Commun. **63,** 26 (1987), and Donald L. Singleton, George Paraskevopoulos, Roderick S. Taylor, and Lyall A. J. Higginson, entitled "Excimer Laser Angioplasty: Tissue Ablation, Arterial Response and Fiber Optic Delivery," IEEE J. Quantum Electron. **QE-23,** 1772 (1987).