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Optically Powered Firing System for the Procyon High Explosive Pulsed Power System

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ABSTRACT

An optically powered fireset has been developed for the Procyon high explosive pulsed-power generator at Los Alamos National Laboratory. The fireset was located inside this flux compression experiment where large magnetic fields are generated. No energy sources were allowed inside the experiment and no wire connections can penetrate through the wall of the experiment because of the high magnetic fields. The flux compression was achieved with high explosives in the experiment. The fireset was used to remotely charge a $1.2\mu F$ capacitor to 6500V and to provide a readout of the voltage on the capacitor at the control room. The capacitor was charged by using two 7W fiber coupled GaAlAs laser diodes to illuminate two fiber coupled 12V solar cells. The solar cell outputs were connected in parallel to the input of a DC-DC converter which step up a 12V to 6500V. A voltmeter, powered by illuminating a third 12V solar cell with 1W laser diode, was used to monitor the charge on the capacitor. The voltage was measured with a divider circuit, then converted to frequency in a V-F converter and transmitted to the control room over a fiber optic link. A fiducial circuit measured the capacitor firing current and provided an optical output timing pulse.

Keywords: solar cell, power down a fiber, high power semiconductor laser diode

INTRODUCTION

Fiber optic control and monitor systems have been used more frequently to replace copper wire systems in adverse environments for safety, reliability and electrical isolation. Experiments which involve high voltage, high currents, explosives and electrical ground loop problems can be greatly enhanced with fiber optic connections for a variety of signals. Typically fiber optic systems are constructed with commercial optoelectronic components and custom fabricated electronics to produce a custom system. The environment of the experiment dictates requirements on the fiber optic system which cannot be met using totally commercial equipment. However, a custom system can be designed and fabricated at reasonable cost since a wealth of optoelectronic and fiber optic components exist. Thus, new unique systems which meet a customers needs can be designed if one understands the components specifications, the assembly and packaging of a variety of components, and the integration of components into a system.

The concept of powering a remote electronic circuit from optical energy delivered down a fiber (power down a fiber) has been proven[1,2,3,4,5]. The development of fiber-coupled cw laser diodes operating at high power combined with fiber-coupled high efficiency solar cells[6] facilitates many new types of system design. Remote electronic circuits can be powered with many watts of electrical power at voltages from 2V and 16V using laser diodes and solar cells.

The Procyon project was most unusual in its requirements. The experiment was outdoors and was located 100 feet from the control room. Voltages and currents on the order of 40kV and 20MA respectively were present. Electrical ground loops presented both safety and operations problems. A typical experiment included 300 pounds of high explosives and a large number of detonators which were fired in a specific sequence. The experiment had only one shot to operate and the cost per shot was approximately $750K. The experiment was operated, data was taken and the experiment was then completely destroyed. All control, monitor and diagnostic signals were transmitted over fiber optics for electrical isolation. The detonator firing system had portions inside the experiment, outside the experiment and inside the control room. The firing system inside the experiment will be discussed in this paper.

The internal firing system was located inside a magnetic field coil. When maximum current was flowing in this coil, explosives were fired to perform flux compression which amplifies the peak current to the 20 MA level. No wires can penetrate the coil to reach the fireset since the magnetic field would be perturbed and current flow patterns modified. Fiber cables can penetrate the coil if there were no conductive material in the cable or coating. Armor coated fiber cable would violate our requirements.

SYSTEM DESIGN

The heart of the system design was the electrical and optical power budget. Figure 1 shows a typical optically powered remote electronic circuit application.

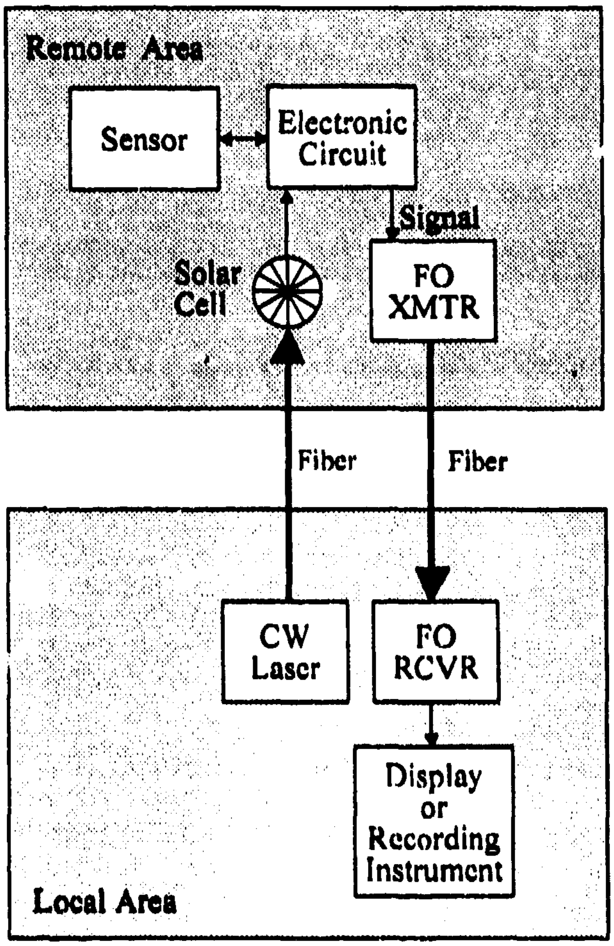

Figure 1 Block diagram for typical optically powered remote circuit.

The electrical power requirements of the remote circuit dictate the choice of the optoelectronic components. The required voltage and current determine the choice of solar cell and the total power required determines the power of the CW laser. The system can be enlarged by adding additional lasers, solar cells, circuits and sensors. The result was a remote electronic application with power being supplied from a fiber when it is needed. Electrical isolation was the primary goal of this system and the need for batteries was eliminated. The requirements for the optically powered system were:

1. A 1.2μF capacitor must be charged to 6500V in 30 seconds or less.

2. The firing system remote optoelectronics and electronics must be packaged in a 20 in^3 volume.

3. Voltage monitor of the high voltage capacitor.

4. Capacitor shorting mechanism with fiber optic short position monitor.

5. Bleeder resistor in parallel with capacitor with 500 MΩ value for safety.

6. Interlock system for the high power lasers.

The firing system block diagram is shown in Figure 2. The two areas shown in the block diagram are the control room and the test area. All connections between the control room and the test area were fiber optic cables. Six 100 ft. fibers were used in this firing system. The parameters for these six signals and fibers were as follows:

1. High power (7W) CW laser #1 in Spectran HCN 600μm fiber (NA=0.48).

2. High power (7W) CW laser #2 in Spectran HCN 600μm fiber (NA=0.48).

3. High power (1W) CW laser #3 in Amphenol Series 907 100μm fiber cable assemblies.

4. Fireset READY (short position monitor) signal in Amphenol Series 907 100μm fiber cable assemblies.

5. Fireset voltmeter signal in Amphenol Series 907 100μm fiber cable assemblies.

6. Fireset fiducial (FIDU) signal in Amphenol Series 907 100μm fiber cable assemblies.

The reliability of the system was improved and the capacitor charge time decreased by using two high power lasers and two solar cells. In this way, the system will still operate if one solar cell or one laser fails. Also, if both lasers and cells operate correctly, twice the energy transfer rate will occur. The voltage monitor circuit was remotely powered from a third laser and third solar cell. Thus, the monitor will operate independently from power being applied to the main solar cells. The two 7W lasers were GaAlAs laser diodes from OptoPower Corp. model OPC-E007-813-FCPS. These lasers operated at 800nm wavelength and were typically run at 4W each. The output of each laser was fiber bundle coupled to a 600μm fiber using a manufacturers supplied converter. These lasers were cooled thermoelectrically. The lasers were packaged in a rack mounted chassis with a safety keylock and interlock connections added. The 1W laser was a GaAlAs laser diode from Spectra Diode Labs model SDL-2372-P3 driven by an SDL-820 current source. This laser operated at 800nm and was operated at a power level of 0.75W. The SDL-2372-P3 was supplied with a 100μm fiber pigtail.

The fiber optically coupled solar cells used in our system were produced by Photonic Power Systems, Inc. which have models from 2V to 16V. In our system, the 12V model PPC-12ST was used. The spectral response of these solar cells showed good operation in the 750 to 850nm band. Thus, they work very well with the GaAlAs high power lasers in our system which operate between 795 and 825nm. The optical power operating point for the solar cells was determined through experimental means and by consulting with the manufacturer of the solar cells. The cell efficiency decreases as the optical power was increased above 3.5W. Reliability was also considered in the optical power selection. The manufacturers data base on the solar cell performance was mainly in operation below 5W. The solar cell efficiency was also a function of the cell load impedance. The maximum efficiency of the solar cells was between 25 and 30%. Since our load was a charging capacitor on the output of a DC-DC converter, the load impedance of the solar cell changes from low to high in the charging cycle. Thus, the solar cell efficiency was changing with time.

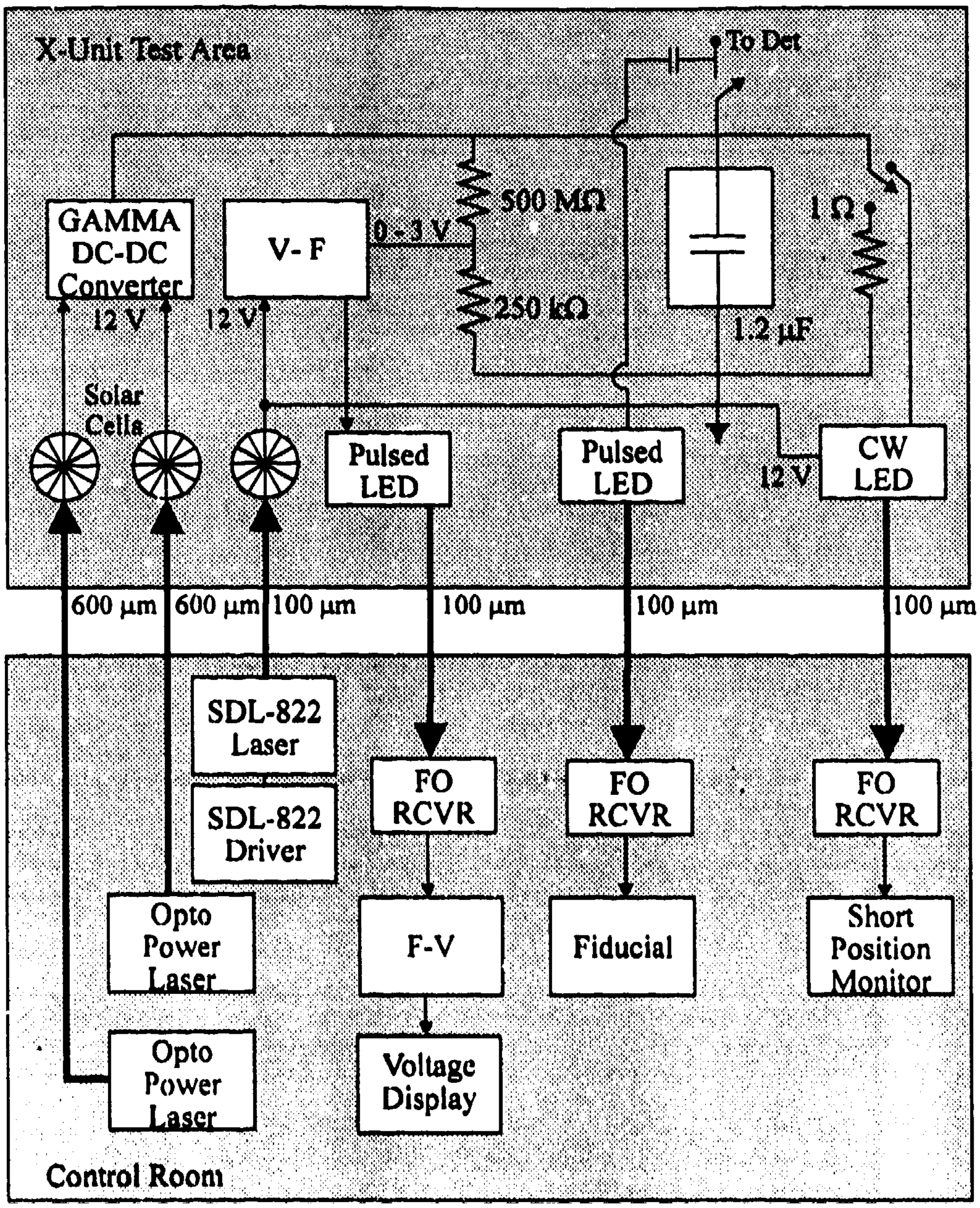

Figure 2 Block diagram for optically powered firing system.

The DC-DC converter in the system must generate 6500V from a nominal 12V input. A custom Gamma High Voltage Research Inc. converter model SM80P was selected after testing. Its small size, input impedance, and conversion efficiency were better than other available DC-DC converters. The average output current from the converter needed to be greater than 200µA. One requirement of the DC-DC converter was that its input to output voltage be somewhat linear for operation above 5V on the input. Since the power source was the solar cell, the large current turn-on caused the nominal 12V voltage to drop down to less than 8V.

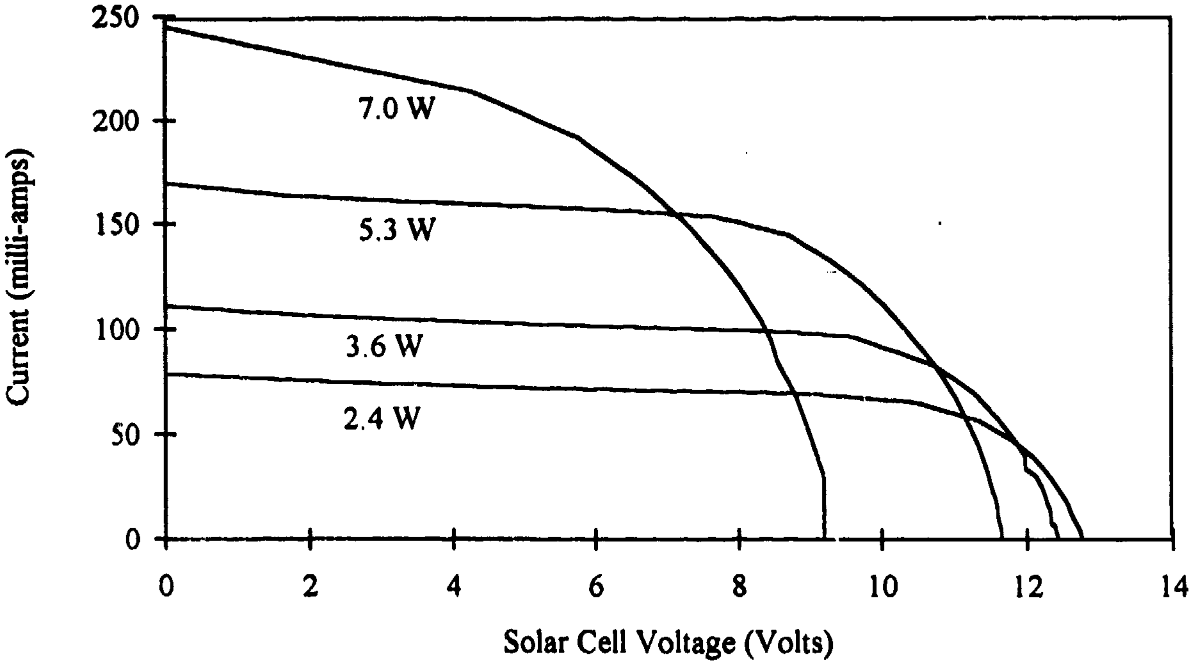

Figure 3 Solar cell V-I curves for several laser powers.

Figure 3 shows a typical I-V curve for the PPC-12ST solar cell. The solar cell I-V curves were measured using a resistive decade box as the load with resistance values varying from 2 Ω to 10 kΩ. The solar cell was bonded to a heat sink for these high power tests.

The three monitor signals, voltmeter, fiducial and short position, were transmitted with Honeywell LEDs model HFE-4854-014 which are packaged in ST receptacles. These three signals used the 100μm fiber cables. The voltmeter used a V-F circuit based on the Analog Devices chip AD537 since it has excellent linearity and low power consumption. The AD537 requires only a few milli-amps to operate. The voltmeter pulsed LED circuit operated at 1300Hz for a voltage of 6500V on the fireset capacitor. The pulse width was 500ns to reduce power consumption. The voltmeter signal was received in the control room with a Honeywell Schmitt trigger model HFD-3880-002. The signal was then sent into a counter circuit and display. The pulsed LED for the fiducial only operates for one pulse when the fireset is triggered. A small portion of the 15 kA current which flows to the detonators is capacitively coupled, then attenuated, and fed into the pulsed LED. A single pulse of a few microseconds was sent out from the LED. This pulse was used as a timing mark for the flux compression experiment and was displayed together with data on a digitizer. The short position LED was operated in the CW mode. A 1Ω shorting resistor was connected across the main fireset capacitor when not in operation for safety. When the short was connected the LED was ON. The short was connected/disconnected mechanically. The LED was OFF when the short was removed. The short position is displayed on a panel in the control room with an indicator light.

SYSTEM CHARACTERISTICS

The complete firing system was tested to determine the charge time of the capacitor load as a function of the power level for the two main high power lasers. Figure 4 shows the capacitor charge time as a function of laser power for each of the two OptoPower Corp. 7W lasers.

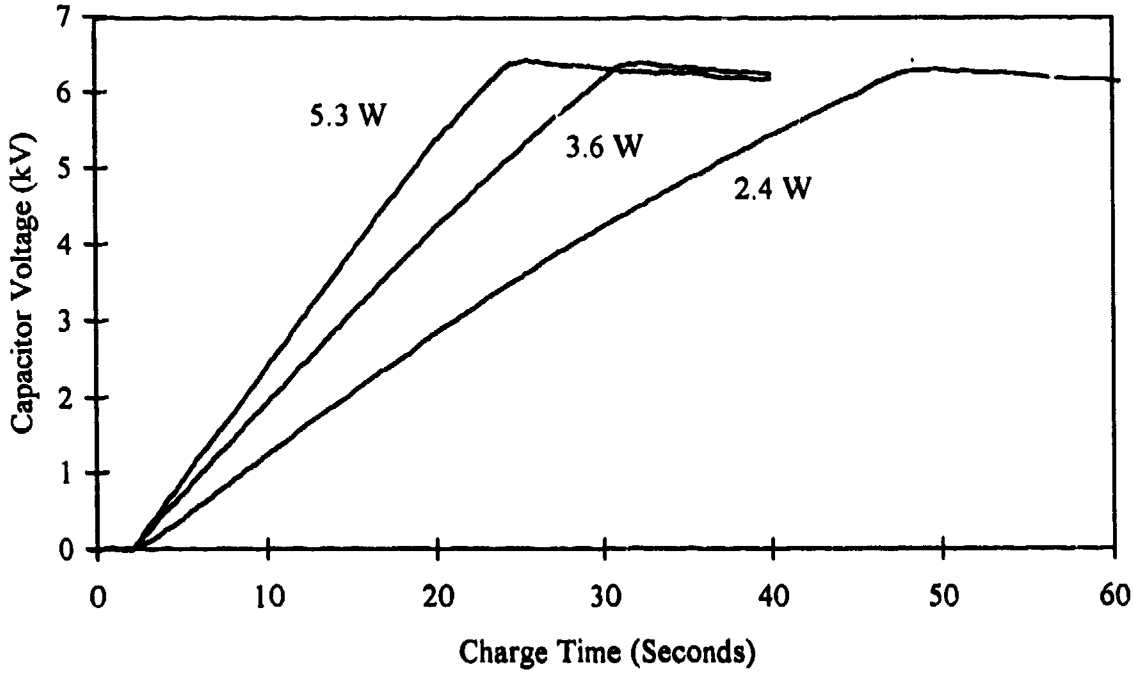

Figure 4 Capacitor voltage vs. charge time for several laser powers.

Each laser was operated at the same power level for all tests. Figure 4 shows that to achieve the 30 second charge time, each laser must operate above 3.5W. This power was measured at the solar cell position at the end of the 100 ft. section of 600μm fiber. The optical loss of the fiber and connectors was approximately 1dB. Figure 4 also shows the nonlinear effects of the laser power on the solar cell efficiency. Operation at 5.3W gave a small improvement in charge time but at the price of heating the solar cell and reducing efficiency. A simple feedback control system was used to maintain the fireset capacitor at 6500V. A circuit monitored the voltmeter signal and turned the OptoPower Corp. lasers OFF when 6500V was reached. The charge on the 1.2μF capacitor bleeds down slowly with an RC time constant of 600 seconds. Until the fireset was triggered, the control loop maintains the voltage of 6500V within 100V. Thus, the high power lasers are turned on and off as the control mechanism.

Figure 5 shows the solar cell output voltage as a function of laser power for the operating system configuration. The operating point for the cells varies on its I-V curve as a function of laser power. The current demand of the DC-DC converter forces the cell output voltage to drop for lower laser powers. The voltage then varies in time as the input impedance of the DC-DC converter changes in time. There was a point where reducing the laser power further would cause the charging process to stop completely. Figure 6 shows the charge time to 6500V for the capacitor load as a function of laser power. The reason for variation was the combination of energy transfer combined with solar cell efficiency and solar cell heating.

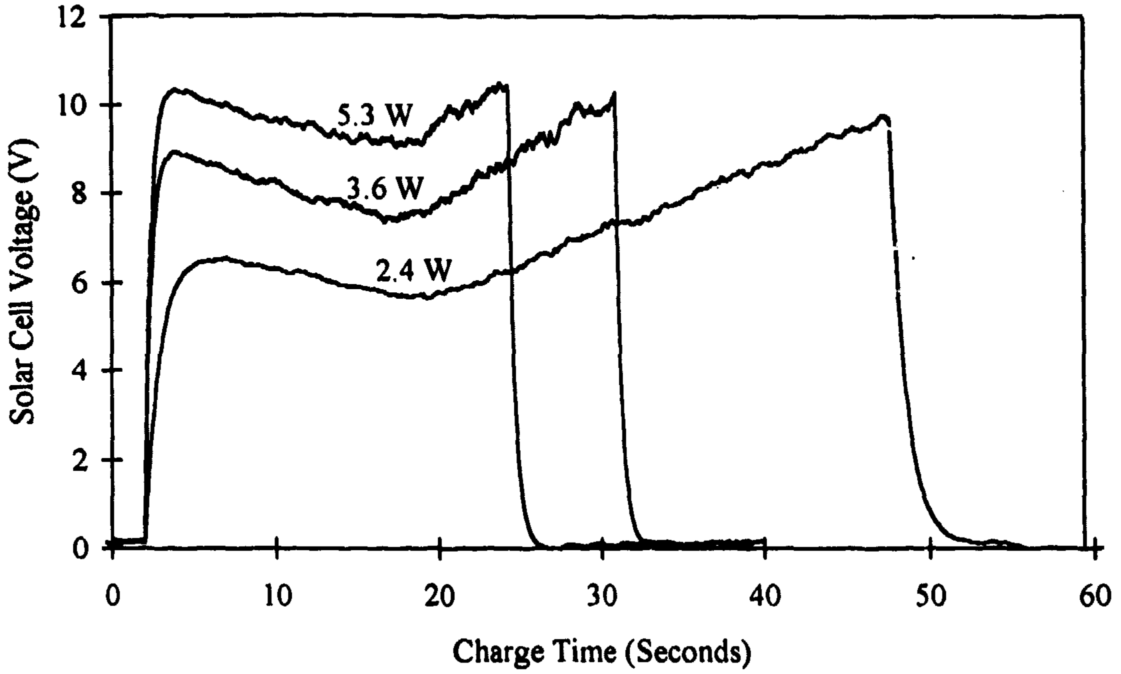

Figure 5 Solar cell output voltage vs. capacitor charge time for several laser powers.

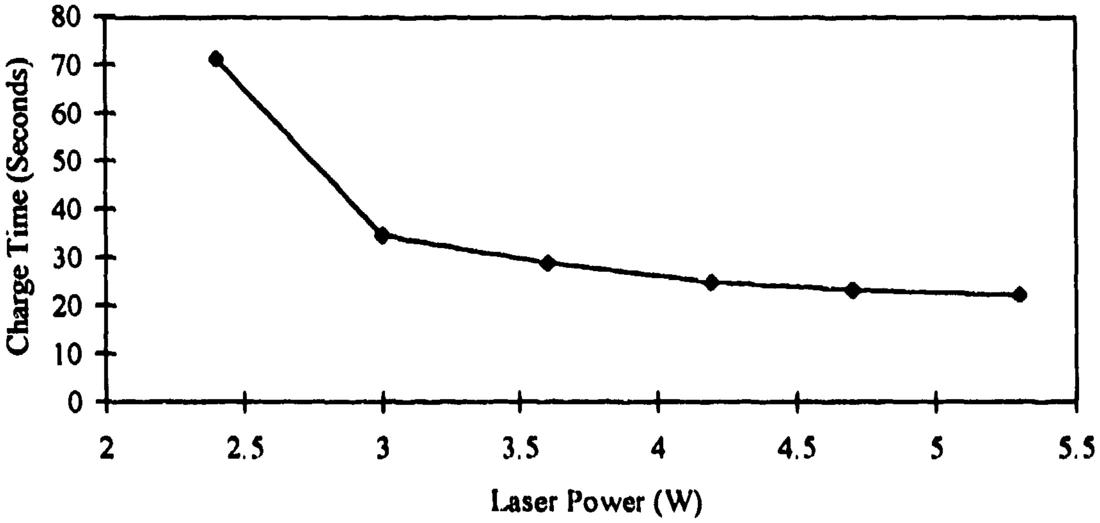

Figure 6 Capacitor charge time vs. laser power.

SYSTEM OPERATION

The completed optically powered firing system was tested separately many times prior to operation in the flux compression experiment. The system was operated remotely to check the capacitor charging to 6500V. The voltmeter display was calibrated against an external voltage measurement of the capacitor voltage. The V-F circuit in the voltmeter had a calibration adjustment. After several voltage tests, actual detonators were attached to the firing system and fired in a manner as close to an actual experiment as possible. The firing fiducial signal was tested in this way to measure the amplitude and waveform of the signal. The detonator tests also allowed safety procedures and operating checklists to be evaluated. The firing system had to be integrated into the command and control system for the complete flux compression experiment. Laser safety was also considered in all aspects of the system operation. Most personnel involved were familiar with fiber optics, but rarely were personnel expecting to have up to 10W CW present in fiber optic cables. Broken fiber connections could present a serious eye hazard during setup, calibration and dry run operations.

SUMMARY

A new explosive firing system was developed which received all its operating power from optical energy delivered down a fiber optic cable. This application to the new field of power down a fiber was developed in response to requirements of electrical isolation and safety. The system was designed with mostly commercial optoelectronic components with a few custom circuits added. The fiber coupled high power laser diodes used to provide the majority of the optical energy were new commercial products which allowed large amounts of energy (8W) to be transmitted to power remote electronics. The recent improvement in large core fibers with excellent characteristics improved the operation of this system. In the future it will be possible to operate a system like this with long fibers with lengths greater than several kilometers. The fiber coupled solar cells were operated at power levels near their maximum rating in an application different from previous applications. The system as a whole was the important development which was made possible through the combination of new and improved commercial products.

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