ELECTRONIC SAFING OF A DIODE LASER ARM-FIRE DEVICE

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Abstract

Semiconductor diode lasers that can generate one watt or more of optical energy for tens of milliseconds (quasi continuous wave) are now readily available. Several researchers have demonstrated that this power level, when properly coupled, can reliably initiate pyrotechnic mixtures. This means that the initiator containing the pyrotechnic can be protected against inadvertent initiation from electromagnetic radiation or electrostatic discharge by a conducting Faraday cage surrounding the explosive. Only a small dielectric window penetrates the housing of the initiator, thereby eliminating the conductors necessitated by a bridgewire electroexplosive device. The diode laser itself, however, functions at a low voltage (typically 3 volts) and hence is susceptible to inadvertent function from power supply short circuits, electrostatic discharge or induced RF energy. The rocket motor arm-fire device described in this paper uses a diode laser, but protects it from unintentional function with a Radio Frequency Attenuating Coupler (RFAC). The RFAC, invented by ML Aviation, a UK company, transfers power into a Faraday cage via magnetic flux, thereby protecting the diode, its drive circuit and the pyrotechnic from all electromagnetic and electrostatic hazards.

The first production application of a diode laser and RFAC device was by the Korean Agency for Defense Development.

1. Background

It has been known for at least 20 years that the optical energy generated by lasers could initiate a deflagration in energetic materials. Initially, solid state lasers were used with focusing optics to create sufficient energy density to light the explosive. The coherent radiation could then be piped to the explosive through fiber optic cable with very low losses. The early solid state lasers were bulky, required high voltages to fire flash lamps, and were electrically inefficient. Although there have been improvements in materials and electronics packaging, these disadvantages of the flash lamp pumped solid state laser remain today. More recently, the development of high power diode semiconductor lasers have made laser initiation of explosives more practical. However, these devices present other problems for the ordnance system designer.

Why bother going to the trouble of converting electrical energy to optical energy to heat energy as opposed to the direct conversion of electricity to heat in a hot bridgewire electroexplosive device? There are three reasons. First, optical radiation can be conducted into the explosive via a dielectric path, typically a glass fiber optic cable or a small glass window. This allows the explosive powder to be surrounded by a Faraday cage, thereby eliminating hazards from electrostatic discharge (ESD) and electromagnetic radiation (EMR). Since the hot bridgewire device requires conductors to penetrate the housing, elaborate measures are required to protect the device from ESD and EMR. Even then, there are hazards in manufacturing and disposal that cannot be alleviated by these measures. The second advantage of lasers is that they can generate higher energy densities than a hot wire, and can hence initiate less sensitive energetic materials, another safety advantage. Third, the absence of the bridgewire eliminates the possibility of bridgewire corrosion, thereby improving reliability.

In addition to the evolution of lasers, the ordnance community has recently developed all-electronic safing and arming mechanisms to replace electromechanical, out of line safe-arm and arm-fire devices. Electronic safe-arms were first introduced for warhead applications. An in line explosive train was permitted since the explosive in the initiator was insensitive (nearly as insensitive as the warhead booster explosive which is in line). The electrical stimulus to initiate the device was unique and not likely to be inadvertently generated by a malfunction in the device or by abnormal environments. The exploding foil initiator (EFI), using a secondary explosive HNS (hexanitrostilbene), and a high (typically 2-3 kV) voltage, low impedance firing circuit became the initiator of choice for electronic safe and arm devices. The EFI had another advantage for warhead initiation: It was very fast, typically functioning in a few microseconds. This explains its initial application in nuclear weapons.

The same concepts used for the electronic safing of high voltage initiators can also be effectively used for rocket motor arm-fire devices. This paper describes a motor arm-fire device which uses diode lasers for initiation energy but provides an all electronic method for protecting the diode from inadvertent initiation from abnormal environments, ESD, EMR or malfunction of a component. The primary objective of the design is to achieve extremely high levels of safety and reliability at low cost, and to satisfy the requirements of MIL-STD-1901, "Safety Criteria for Munition Rocket and Missile Motor Ignition System Design."

2. Diode Laser Initiation

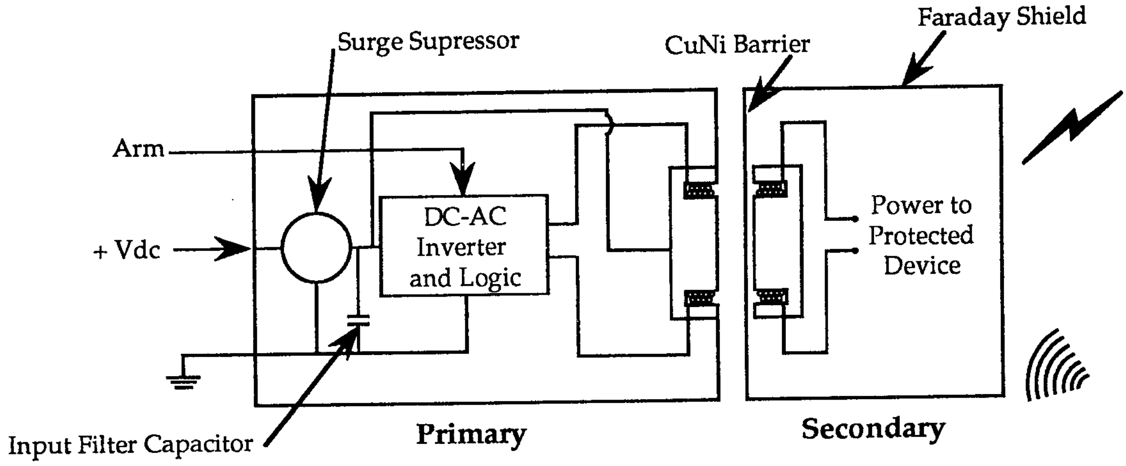
The use of diode lasers to initiate energetic materials will be described first. Since many papers have been presented on this subject, this section is brief. The diode is fabricated from a semiconductor material and when energized with a low voltage (typically 3) source, it emits coherent radiation with wavelengths in the .9-.96 micron region (these frequencies are well suited to ordnance initiation). The power supply must be current limited or the diode can be destroyed by excessive energy density at the face of the diode. The semiconductor die is quite small, on the order of 10^{-4} cm^3. While the optical energy is coherent and intense, it is also diverging over a 45° or greater angle at the output facet, and hence must be collected immediately or optically focused if it is to be inserted into a light pipe. As expected, the price of high power diodes is dropping rapidly as vendors are improving their yields and processes. Now, the cost of packaging the diode and coupling the energy to a fiber exceeds the cost of the semiconductor die.

Diodes with 1-2 watts of quasi-CW output are sufficient for most deflagration ordnance applications and are readily available from multiple vendors. In the design described here, a 1 watt Indium-Gallium-Arsenide quantum well type diode is used. The emitting facet of a typical 1 watt diode is 1 micron wide and 75 microns long. Thus, the power density at the facet is over 1 megawatt/cm^2. If this 1 watt output is coupled into a 100 micron glass fiber, the power density drops to approximately 10 kilowatts/cm^2, which is sufficient to initiate insensitive pyrotechnics and some explosives. A 10 ms pulse from a 1 watt diode provides 10 mJ of energy.

This energy and power density is sufficient to initiate Zirconium Potassium Perchlorate (ZPP) (used in the NASA standard initiator) or Boron Potassium Nitrate ($BKNO_3$), a commonly used energetic material used in solid rocket motor igniters, and approved as an inline material by MIL-STD-1901. Of course, since the initiation energy is delivered over a small area, it is imperative that the initiation powder be homogenous and properly interfaced with the optical surface. The optical energy must be absorbed efficiently by the powder so it is not dissipated. This may necessitate a dopant if the powder is transparent to the diode frequency. Thus, the igniter design and assembly process is critical for reliability just as in the case of hot bridgewire devices.

3. Radio Frequency Attenuating Coupler (RFAC)

The second element of the laser arm-fire device design is the RFAC. The Radio Frequency Attenuating Coupler (RFAC) is a method of providing electrical power to an electroexplosive or electronic device while it is surrounded and protected by a conducting Faraday cage. The continuous Faraday enclosure completely protects the interior from external radio frequency (RF) radiation, ESD or transient voltages on the source power line. Thus, electrical power is transferred into the Faraday cage only when a proper voltage is present on the source power line and the RFAC is enabled. The power transfer occurs via an oscillating magnetic field, which is a unique stimulus unlikely to be produced in either normal or abnormal environments. All other forms of electromagnetic energy are rejected. The principle of the RFAC's operation is illustrated in Figure 1. The electronic section, on the left,



RFAC Principle of Operation

Figure 1

transforms the direct current (DC) input power into an alternating current (AC) signal which creates an oscillating magnetic field (the unique stimulus) at the face of the primary transformer. In practice, the transformer is constructed using a cylindrical ferrite pot core having a cross section in the form of an E, one half incorporated in the primary and the other half in the secondary. The secondary, on the right, is enclosed in a Faraday cage formed by a metallic housing. The end closure over the secondary transformer is an electrically conducting but magnetically permeable alloy of copper and nickel. Due to the small size of the transformer, it is essential that the magnetic flux pattern have high divergence in order to efficiently couple the energy. This prevents external magnetic fields, generated at some distance from the transformer, from transferring energy into the secondary. Another advantage of this design is that the device inside the Faraday cage is electrically floating and not connected to ground. Thus, the protected device is immune to lightning or electrostatic discharge.

Several of the more important features of the RFAC are:

- Complete isolation of electronic or electroexplosive devices from RF and electrostatic hazards in both the hand-held and installed modes.

- Intelligent power processing in the DC-AC inverter which prevents voltages below or above preset thresholds, and short duration power transients, from activating the power transfer electronics.

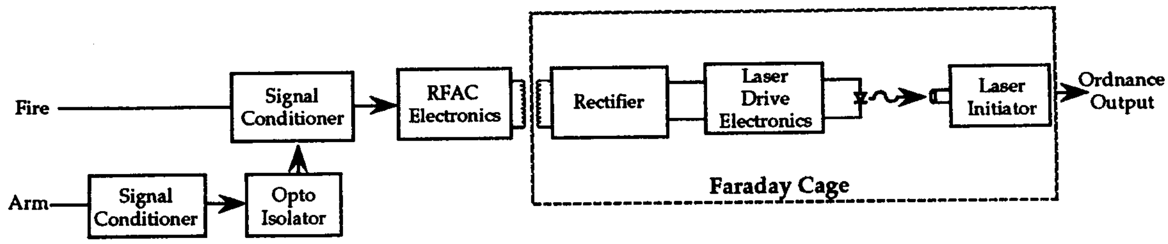
- Flexible packaging that allows the electronics assembly, which occupies less than 3 cm^3, to be placed at the convenience of the user.

- A standard TTL enable or arm interface, which prevents function until both the enable and fire signal are received.

- A standard, qualified design which can be used in most applications, thereby reducing qualification costs.

4. The All-Electronic Laser Arm-Fire Device

Figure 2 is a block diagram of the diode



Diode Laser Arm-Fire Device - Block Diagram

Figure 2

laser arm-fire device. The RFAC electronics assembly is implemented on a small multi-chip module (MCM) with an analog ASIC (application specific integrated circuit).

Several discrete components are on the MCM for filtering and power switching. The RFAC must be enabled by an arm signal as well as having power applied. The oscillating magnetic field generated by the primary half of the transformer is transferred into the interior of the Faraday cage. The power is then conditioned to reliably drive the diode, which in turn initiates the energetic material. Diode lifetimes are typically in excess of 10^7 pulses, therefore the device is highly reliable.

The Korean Agency for Defense Development has supported the development of this laser arm-fire device, and has begun testing of the first production lot in missile motors. This application required the device to be packaged in a configuration identical to that used in the Hellfire missile. Figure 3 is a cross section view of this particular implementation. The overall package size of this device is approximately 2.5 cm in diameter by 8 cm in length. The diode laser drive printed wiring assembly (PWA), the diode itself and the explosive powder are all surrounded by a Faraday cage, and are isolated from the RFAC PWA by the EMI gasket and hence from all electromagnetic radiation. All electrical energy is transferred into this area through the transformer, which has a conducting material separating the primary and secondary.

Ten engineering models were initially built and successfully tested. These devices used an initiation charge of ZPP and an output charge of $BKNO_3$. The approximate all fire energy to initiate the ZPP was under 2 mJ at ambient temperatures. A fine particle, $BKNO_3$ charge was directly initiated as well at approximately 5 mJ all fire. Clearly, the output power of the diode provided a significant margin above the all fire energy, even for the $BKNO_3$.

Additional motor firings and environmental testing is being performed by the Korean Agency for Defense Development on an additional 47 LAFD units. These tests are described in Table 1.

Inert tests: (10 units)
1) Electrical and laser output (10)
2) Electrical Interface (10)
   - normal (5)
   - worst case (5)
   - reliability (10)
   - laser output
3) Temperature
   - high (55°C) (3)
   - low (-40°C) (3)

Ordnance function:
1) Closed bomb (explosive output) (5)
2) Motor firing-ground (10)
3) Qualification test (18)

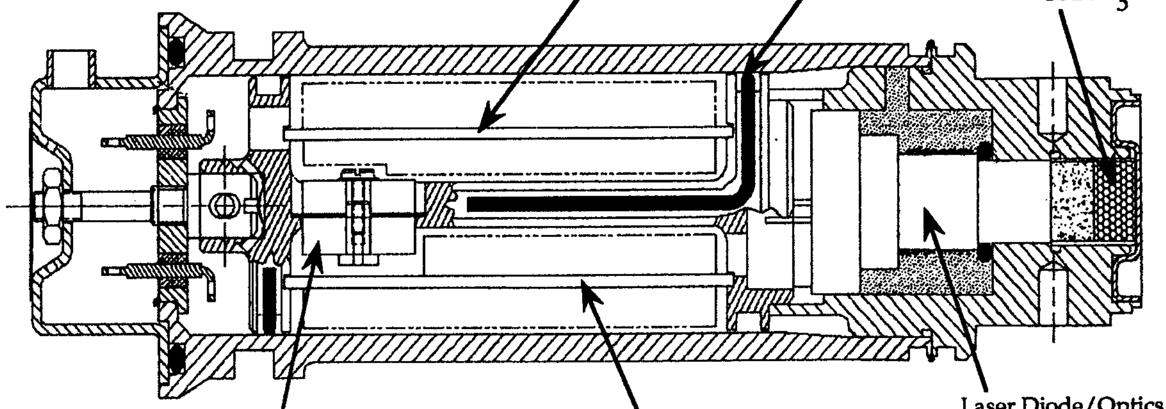
Flight Test (12)
Non-destructive Reliability Test (1000 firings) (10)

LAFD Test Plan

Table 1

5. Safety

The laser arm-fire device was designed to meet all of the requirements of the new MIL-



Diode Laser Arm-Fire Device - Cross Section

Figure 3

STD-1901. The only acceptable non-explosive allowable "in-line" by MIL-STD-1901 is BKNO3, and the laser energy can reliably initiate this material. Two independent inhibit switches, located on different semiconductor substrates, are used to enable the power transfer function. The basic RFAC module has been qualified (by the Navy) to MIL-STD-1385B HERO (hazards of electromagnetic radiation to ordnance) environments. Finally, the requirement that the initiator not be functioned by any applied voltage under 500 V is satisfied; in fact, the application of much higher voltages directly to the initiator will not cause it to function since it is surrounded by a Faraday cage.

In addition to the explicit safety requirements of MIL-STD-1901, the laser AFD has additional safety features to prevent inadvertent arming. For example, the RFAC electronic module self-tests the input voltage and if it is above or below a specified range, the device will not function. The device also examines the input power and verifies that it stays within high and low limits for a programmable period before enabling the output; this prevents spurious transients on the power line from turning the device on. And of course, both inhibit switches must be activated and firing power applied for the device to function. Finally, if BKNO3 is used as the initiation mix, the initiator is as insensitive as the typical igniter materials for a solid rocket motor.

All of the electronic components used (other than the RFAC integrated circuit and laser diode) are standard, off-the-shelf materials. Standard surface mount printed circuit assembly methods are used.

In addition to the high levels of safety and reliability, the laser arm-fire device offers other advantages. The weight and volume is substantially less than the electromechanical S&As. Also, the electromechanical initiators are subject to HERO induced initiation in the safe position and in the armed position prior to firing. The first event results in a dud; the second in a missile firing prematurely.

In summary, this technology offers a more reliable, lower weight and lower cost alternative to the electromechanical, out-of-line arm fire devices in use today. As the cost of diode lasers continues to decline, the cost advantages over electromechanical devices will increase.