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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

This report describes 2 custom optoelectronic components for a 100-W continuous-wave erbium-doped fiber amplifier. The first is an interlock to protect the amplifier from damage resulting from too much light in the backward direction or too little light in the forward direction. The second is a device for measuring the optical power coupled from a pump diode to the pump combiner, using the light scattered at the splice between the 2 fibers.

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1. Introduction

This report describes 2 custom optoelectronic components for a 100-W continuous-wave erbium-doped fiber amplifier. The first is an interlock to protect the amplifier from damage resulting from too much light in the backward direction or too little light in the forward direction. The second is a device for measuring the optical power coupled from a pump diode to the pump combiner, using the light scattered at the splice between the 2 fibers. High power lasers are candidates for defending against rockets, artillery, mortars, and missiles. A fiber laser based weapon system (LaWS) is currently being tested onboard a Navy ship in the Persian Gulf. The Space and Missile Defense Command is currently testing solid-state slab and fiber lasers at White Sands Missile Range, New Mexico. All of these lasers operate at 1.06 µ, where the eye is particularly vulnerable. Concern about inadvertent eye damage due to scattered light has motivated the development of high power "eye-safer" lasers operating at wavelengths greater than 1.5 µ. Erbium is a rare-earth element that emits at ~1.55 µ and can be added to common laser host materials, including silica optical fibers.

2. Minimum and Maximum Threshold Interlocks

An erbium-doped fiber amplifier (ErFA or EDFA) develops its gain through optical pumping by fiber-coupled laser diodes (Zervas 2014). During the operation of an ErFA, there are several unsafe situations that call for immediate disconnection of the amplifier's power supply. To realize this requirement, we developed an interlock circuit to detect the unsafe conditions, quickly shunt the current to the laser diodes, and then turn off the power supply.

Conventional built-in interlocks typically shut down a power supply in ~1 ms, which is too slow for the laser system we are developing. Furthermore, while the output of a *laser diode* current supply is guaranteed to stay below a user-defined voltage on startup, it can behave erratically and create voltage spikes when it shuts down. In order to prevent these issues, we considered building a circuit to rapidly shunt the laser diodes. Nufern, a company that builds laser amplifiers, confirmed that they use this approach. When the interlock is activated, the shunting scheme provides a low-impedance path across the power supply's output, providing a means to prevent potentially damaging voltages from destroying the laser diodes. This will reduce the power output of the pump diodes almost completely.

There are 2 events that necessitate immediately shutting down the ErFA. One event is the rapid growth of stimulated Brillouin scattering (SBS). SBS is a nonlinear optical effect that is caused by a coherent interaction between the forward propagating light in a medium, a forward propagating acoustic wave, and a backward propagating Stokes wave. The acoustic wave is generated by an electrostrictive effect. These phonons cause a small periodic shift in the fiber's refractive index, which reflects the laser light. The reflected light, referred to as a Stokes wave, interacts with the forward propagating wave and produces considerably more phonons in less than 1 ms. This process can repeat aggressively and generate a powerful Stokes wave in less than 1 ms and cause a high amount of laser light to propagate backwards into an amplifier and destroy it. Therefore, we needed an interlock that would shunt the power supplies in a time short compared to a millisecond. One way to suppress this phenomenon is to rapidly change the frequency of the seed laser (J O White 2012).

The second event is insufficient light propagating in the core of the ErFA. This causes the gain in the fiber to rise to the point where a small amount of feedback can cause inadvertent lasing. The lasing typically occurs in the form of powerful, short pulses while our system is built for continuous light.

3. Interlock Circuit Design

The interlock circuit (Fig. 1) taps a small amount of laser light from the fiber in both the forward and backward directions with 2 photodiode modules, designated PD1 and PD2 in the schematic. Each photodiode generates a voltage proportional to its incident light power. The forward-light detection PDM monitors the light level going into the following stage of the ErFA. This is important, because if the level is too small, the gain in the fiber may rise to a point where unintended feedback causes inadvertent lasing. Such lasing can destroy the ErFA.

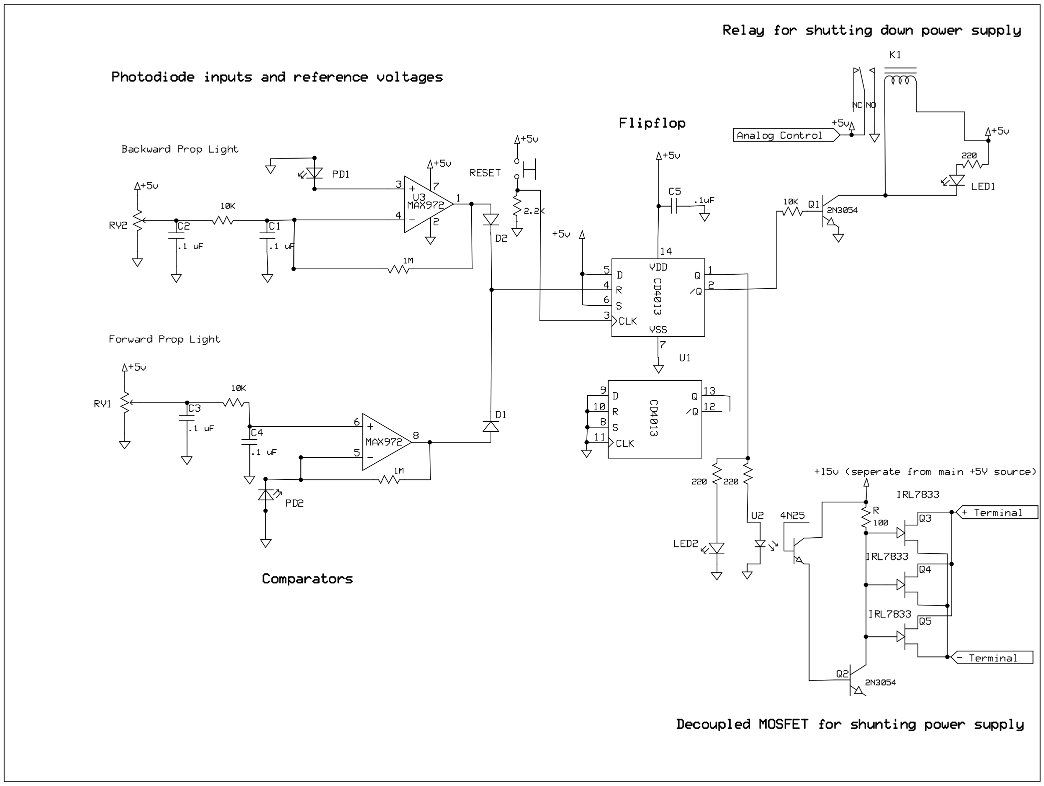

Fig. 1 Interlock circuit design

The photodiode voltages are compared to reference voltages set by potentiometers RV1 and RV2. The comparator U3 has an output that is high if the photodiode's output is above threshold and vice versa. Each comparator output feeds the input of a diode "OR" gate, which, in turn, feeds the "SET" input of a flip-flop. A flip-flop is useful in our design, because its memory keeps the interlock tripped until the user presses a reset button.

The "Q" output of the flip-flop, which becomes logically high upon the detection of a fault condition, drives both a visible status light-emitting diode (LED), LED2, and an optocoupler, U2, via transistor Q2. The optocoupler drives another transistor, Q2, which controls the gate of power metal-oxide-semiconductor field-effect transistor (MOSFET) transistor, Q3-5. The MOSFET provides the crucial shunt path across the power supply's output. The optocoupler is used to provide electrical isolation between the interlock circuit and the ErFA to preclude the conflict of differing potentials between the interlock circuit's ground and the power supply's ground.

Due to our decoupling scheme, a floating +15-V power supply is shown to guarantee that the MOSFETs see a full 15 V across their source and drain. This ensures that current will flow adequately through the MOSFET.

In addition, the flip-flop's "Q" output drives a relay, K1, via another transistor, Q1. The relay contacts are connected to the "Analog Control" of the power supply, which turn it off. Visible LED1 is also provided to indicate that the relay has been activated.

After prototyping and testing the circuit, we designed a printed circuit board (PCB) (Fig. 2), procured 3, and populated them.

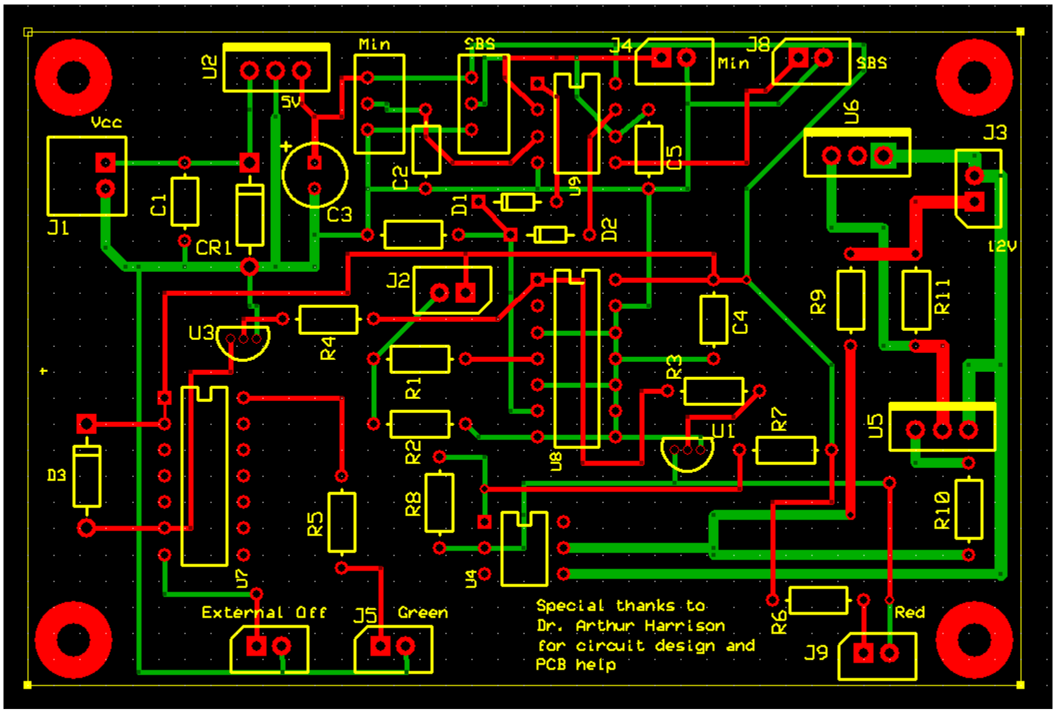

Fig. 2 The PCB for implementing the circuit in Fig. 1

4. Splice Protector and Power Monitor System

We also fabricated several transimpedance amplifiers and designed a fiber-optic mount that will serve as both a splice protector and a power monitor. Splices are situated between the fiber pigtails of the 6 pump diodes and 6 input fibers of the 6+1=1 pump combiner. On top of the splice protector, we placed a photodiode to collect some of the small amount of light scattered from the (imperfect) splice. We expect that each splice will cause some amount of light to escape from the core and then radiate into the surrounding air. Although there is no way to predict how much light will radiate, an approximation was made to estimate the intensity. The photodiode, resting directly above the splice, would collect some of this radiating light. Under the assumption that it radiates isotropically, we estimated the percentage of light that would be collected by the photodiode and then converted into current. The maximum output for a pump diode is 60 W and may go as low as

0.6 W. Both scenarios need to be detectable. Lastly, we assume that the typical splice loss of 4% is all radiated from the core.

$$r = distance\ from\ photodiode\ to\ splice \cong 5.72mm \quad (1)$$

$$\frac{Area\ of\ Photodiode}{Surface\ area\ of\ radiating\ light} = \frac{5\ mm^2}{4\pi r^2} = \frac{5}{411.15} = 1.2\%$$

$$photodiode\ Watts - Amps\ conversion\ rate = 0.75\frac{A}{W} \quad (2)$$

$$60\ W\ \times\ 4\% \times 1.2\% \times 0.75\frac{A}{W} =\ 21.6\ mA$$

$$0.6\ W\ \times\ 4\% \times 1.2\% \times 0.75\frac{A}{W} =\ 0.216\ mA;$$

Using these equations, we could predict that the photodiode needed to output current between 0.216 and 21.6 mA. The current from the photodiode is converted to voltage using the transimpedance amplifiers that I built (Fig. 3). The output voltage is then displayed with a voltmeter or captured with a data acquisition system. In this way, we can measure the output of each pump diode while the ErFA is running.

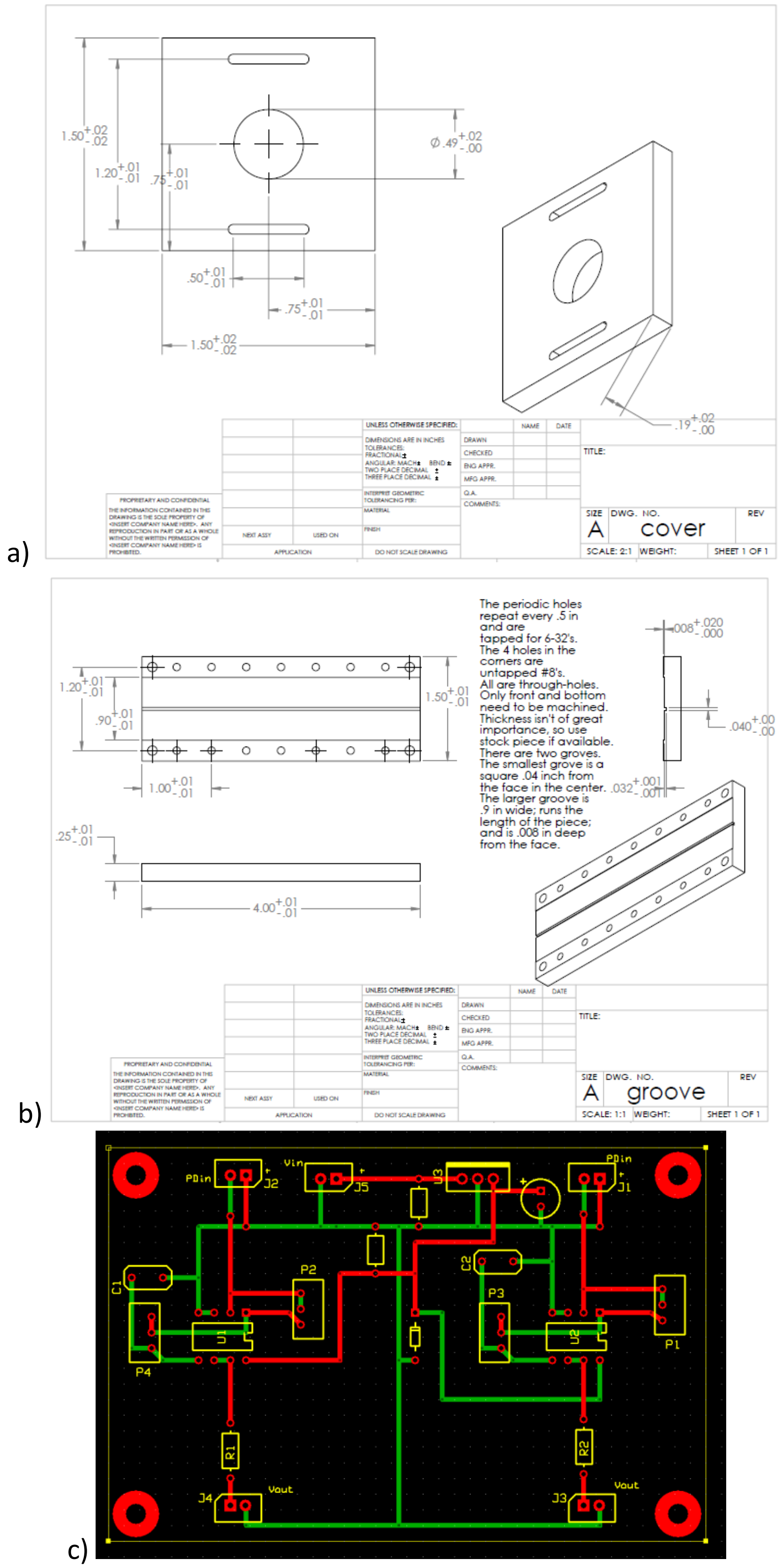

Fig. 3 **a) Photodiode holder, b) splice holder, and c) current to voltage circuit**

5. Conclusion

An ErFA can be damaged by too much light propagating in the backward direction, generated, for example, by Fresnel reflections or SBS. An ErFA can also be damaged by too little light propagating in the forward direction, which allows the gain to build up to the point where a small amount of feedback can cause the amplifier to oscillate and generate pulses that exceed the damage threshold. This report describes the design and fabrication of an electronic circuit to protect an ErDA from these phenomena. It also describes the design of another component designed to protect a splice against mechanical stresses, and to measure the power of light propagating in the core of the fiber.

6. References

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Zervas MN. High power ytterbium-doped fiber lasers - fundamentals and applications. International Journal of Modern Physics B. 2014;28:1442009.

List of Symbols, Abbreviations, and Acronyms

DEPS	Directed Energy Professional Society
ErFA or EDFA	erbium-doped fiber amplifier
HEL-JTO	High Energy Laser Joint Technology Office
LaWS	laser based weapon system
LED	light-emitting diode
MOSFET	metal-oxide-semiconductor field-effect transistor
PCB	printed circuit board
SBS	stimulated Brillouin scattering

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