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Optical Data Transmission Systems in Radiation Environment

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OPTICAL DATA TRANSMISSION SYSTEMS IN RADIATION ENVIRONMENT

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ABSTRACT

The rapidly expanding field of optical data transmission includes a wide variety of particle accelerator, detector and nuclear power facility applications in which transmission systems are required to withstand exposure to the radiation background. Fiber optic links provide several major advantages over conventional electronic data transmission systems. These include immunity to electromagnetic interference and low transmission losses for very high data rates. In this paper the state of the art of optical transmitters, low loss fiber waveguides and receivers in radiation environment is reviewed and summarized. Emphasis is placed on the effects of irradiation on the performance of light emitting and laser diodes, optical fiber waveguides, photodiodes and associated electronics components and subassemblies.

INTRODUCTION

The emergence of optical communication using fibers was made possible by the parallel development of low loss fibers, heterojunction lasers, light-emitting diodes (which emit in spectral regions of low fiber loss) and sensitive photon detectors. Losses of approximately 0.20 dB/km at 1300 nm have been achieved with single mode fibers having minimum dispersion wavelengths near 1300 nm. Several experimental transmission systems capable of operating at a 4 Gbit/s rate over a distance of 155 km and 16 Gbit/s over 8 km have been reported.[1,2]

Although these impressive results were obtained under highly optimized experimental conditions they do give an indication of future capabilities. It should be pointed out that at present practical optical transmission systems are operating at rates between 45 Mbit/s and 1.7 Gbit/s. Furthermore, communication systems have demonstrated approximately a tenfold improvement in their performance in every three years, expressed in Gbit/s × km, and a corresponding decrease in the cost.[3]

In addition to the requirements placed on the optoelectronic components of these systems, considerable attention has been paid to the associated logic circuit families with switching speeds in the microwave region. Such capability is necessary for multiplexing and demultiplexing functions. These functions have been implemented using both silicon and gallium arsenide (GaAs) technologies. Devices based on GaAs technology have become available recently for applications in practical systems[4] with data rate capabilities of 1.5 Gbit/s.

Although the major thrust of development of high data rate fiber optic systems has been for long distance communication links, local data communication needs have given a new impetus to the development of advanced system components. Recent systems for local communication, such as computer interconnections, and instrumentation for particle accelerators, detectors and nuclear power facilities require a high data rate capability.

An example of the use of fiber optics data transmission system in particle accelerators, detectors and nuclear power facilities is given in Fig. 1 where signals from sensors are multiplexed onto the fiber optic waveguide after a buffer memory and a digitizer. The time division multiplexer converts the data from parallel bits to serial bit form for transmission over a fiber optic waveguide. After reception of the optical signals, the demultiplexer converts the serial signal back to parallel bits for storage in another buffer memory. The data are then passed through a software trigger to the processing subsystem.

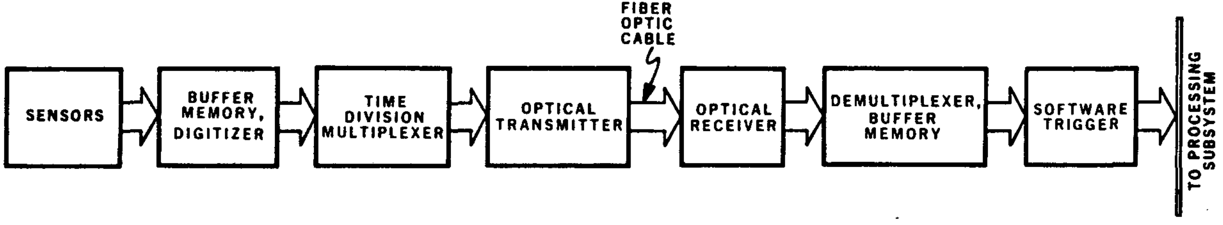

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Fig.1. Simplified block diagram for optical fiber transmission link in nuclear power facility.

Similarly, an application of optical fibers appears attractive for a number of other data transmission and communication tasks in particle accelerators, detectors and nuclear power facilities. For example, the safety parameter display system in nuclear power plants requires use of numerous process computers and at least one environment monitoring computer.[6] These computers are connected to a loop type local area network and central computer facility employing high speed optical fiber data ways.

However, digital and analog transmission links and associated electronics components and subsystems may be required to withstand exposure to a nuclear radiation background. This is particularly important in nuclear fuel recycling plants where extensive instrumentation and control systems are used for reactor inspection, remote handling and radiation monitoring.[5] Such systems have significantly increased the facility operating time and decreased the radiation exposure of technical personnel.

Based on our previous work[6,11] further effort has been expanded to include the latest development in the understanding of the behavior of optical fiber waveguides when they are exposed to ionizing and neutron radiation. Furthermore, a short review of radiation damage in associated electronics components and subassemblies, such as light emitting diodes, injection lasers, and optical receivers will be given.

LIGHT SOURCES FOR OPTICAL DATA TRANSMISSION SYSTEMS IN A RADIATION ENVIRONMENT

Light emitting diodes and semiconductor lasers are the most frequently employed as light sources in optical systems. Light emitting diodes (LEDs) offer the advantages of simple fabrication and operation as well as low cost, high reliability and good linearity and small temperature dependence of the light output. Semiconductor index-guided injection laser diodes offer high output power level, efficiency and bit rate modulation capability as well as extremely narrow spectra and excellent mode stability of the emitted light.

The physical mechanism which causes radiation-induced degradation of the light output from LEDs is that nonradiative recombination centers are introduced which compete with radiative centers for excess carriers.[13] This results in a decrease in minority carrier lifetimes. These various centers, such as unintentionally added impurities, dislocations, growth-induced lattice defects and radiation induced lattice defects can act as sites for non-radiative recombination events producing heat rather than light.

Irridiation test performed on InGaAsP LEDs, operating at 1300 nm, showed that no significant degradation of parameters can be observed[14] with total doses of less than 10^5 Gy. It was also estimated, that the light output power decreases to 50% of its initial value for the total dose of 2×10^7 Gy.

The normalized light output characteristics as a function of the neutron fluence for various LEDs under constant current operating conditions are shown in Fig. 2. The data are shown for the following devices: Sandia GaAsP/GaAs LED, Plessey InGaAsP-High Radiance LED, Laser Diodes Laboratories GaAlAs IRE-160-High Radiance LED, Texas Instruments GaAlAs LED, and Radio Corporation of America InGaAs LED. The high radiance (HR) devices, show the smallest sensitivity to radiation. These LEDs have very small source and junction areas, so that the injected minority carrier current density is large even at moderate current levels. Consequently, it can be expected that the radiative recombination rate is enhanced under typical operating conditions. These devices can provide sufficient light output for many applications even after exposure to neutron fluences in excess of $2 \times 10^{14} \mathrm{n/cm^2}$.

More recent studies of the effect of neutron irradiation on LEDs fabricated from strained-layer superlattice structures in GaAs/GaAsP show that there is no light output degradation until a fluence of approximately $3 \times 10^{14} \mathrm{n/cm^2}$ is exceeded.[13]

Radiation induced degradation of the light output from semiconductor laser diodes is caused by a reduction of minority carrier lifetimes resulting from displacement damage. For radiation environments semiconductor laser diodes should be selected with a low threshold current and a very high maximum operating current. Recently developed double heterostructure GaAs laser diodes have shown that they are still capable for lasing action after a neutron fluence in excess of $2 \times 10^{14} \mathrm{n/cm^2}$.

RADIATION-INDUCED ATTENUATION OF OPTICAL FIBERS

The optical properties of fiber waveguide are degraded by exposure to nuclear radiation, primarily because of the generation of color centers in the fiber core. Color centers are formed by radiolytic electrons and holes which are trapped on defects that either exist in fiber prior to irradiation or are created by the exposure. These centers cause the optical attenuation which can be significantly greater than the intrinsic fiber loss.

The detailed behavior of the induced absorption depends on a number of factors such as the fiber parameters (fiber structure, core and cladding compositions fabrication and dopands), radiation parameters (total dose, dose rate, time after irradiation, and energy, nature and history of the radiation), and system parameters (operational wavelength, light intensity and temperature).

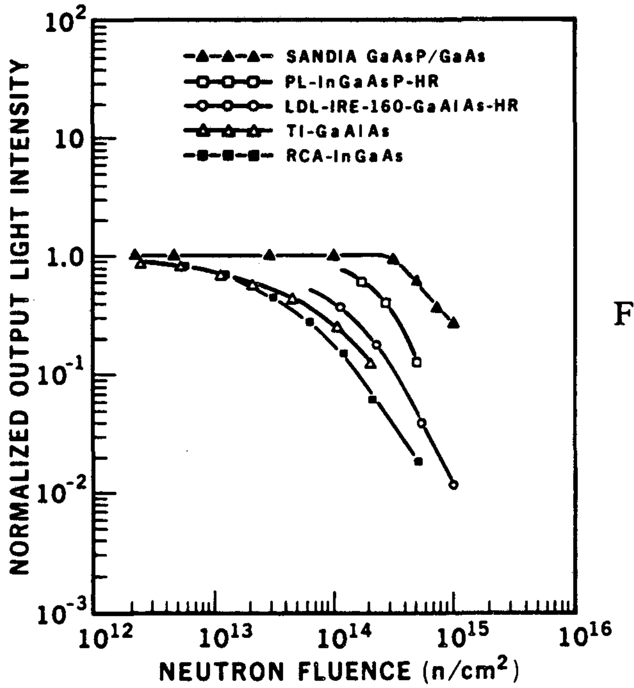

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Fig. 2. Normalized light output as a function of the neutron fluence for light emitting diodes under constant current operating conditions.

The radiation-induced attenuation of a fiber initially increases linearly with increasing dose under steady state irradiation as it is shown in Fig. 3. However, at higher doses, the loss characteristic shows saturation due to the recovery processes that occur simultaneously with fiber darkening. The level of saturation depends upon fiber, radiation and system parameters. In multimode pure silica core fibers with florine doped cladding manufactured in the middle 1980's saturation levels are near 5 dB/km at dose of 10^2 Gy.[14,15]

Radiation induced attenuation in multimode Dainichi-Nippon ST-100B fiber is shown in Fig. 3 using a LED injected optical power of 1 μW and a fiber length of 50 m. This fiber has a SiO$_2$ 100 μm-diameter core, with a fluorine/boron doped SiO$_2$ 140 μm-diameter cladding. The OH content and intrinsic attenuation is 5-10 ppm and 6.7 dB/km, respectively. The wavelengths of the injected optical signals were 840 and 850 nm. The fiber showed a radiation induced attenuation of 4.6 ± 0.27 dB/km at 30 Gy total dose with a γ-rays dose rate of 3 Gy/min.[14]

Radiation-induced attenuation as a function of total dose with dose rate as parameters for a single mode Sumitomo fiber having a pure silica core and a fluorine doped cladding is shown in Fig. 4[16]. This fiber was fabricated by the vapor axial deposition process. The fiber core diameter and cladding diameter was 8.5 μm and 125 μm, respectively. Depending upon the grade of the fiber, the preirradiation attenuation varies from 0.4 to 0.7 dB/km. Dispersion is smaller than 3.5 ps/nm/km for the range from 1285 to 1330 nm.

Measurements were performed using a ^{60}Co source and changing the dose rate from 1.0 to 10^3 Gy/hour. The injected optical power level was 20 nW at a wavelength of 1300 nm. It can be seen from Fig. 4 that the radiation-induced attenuation is 20 dB/km at total dose of 7 × 10^4 Gy and dose rate of 10^3 Gy/hour.

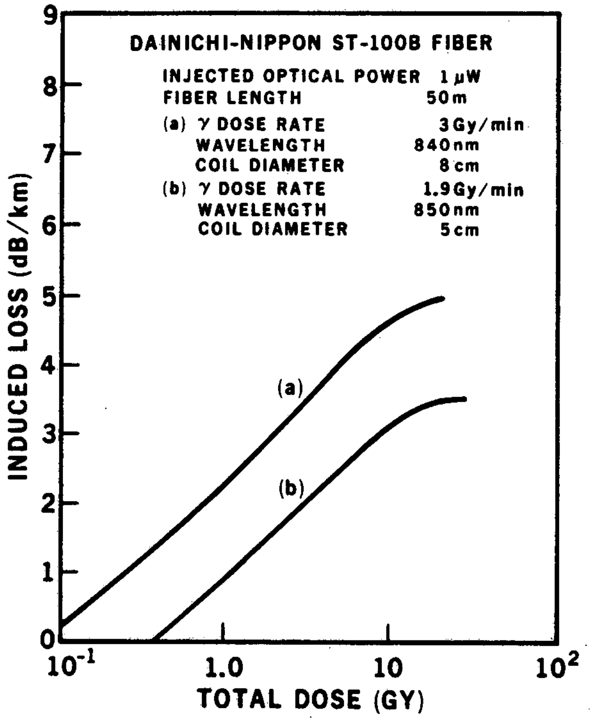

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Fig. 3. Radiation induced attenuation in Dainichi-Nippon ST-100B fiber for 1.9 and 3 Gy/min γ dose rate.

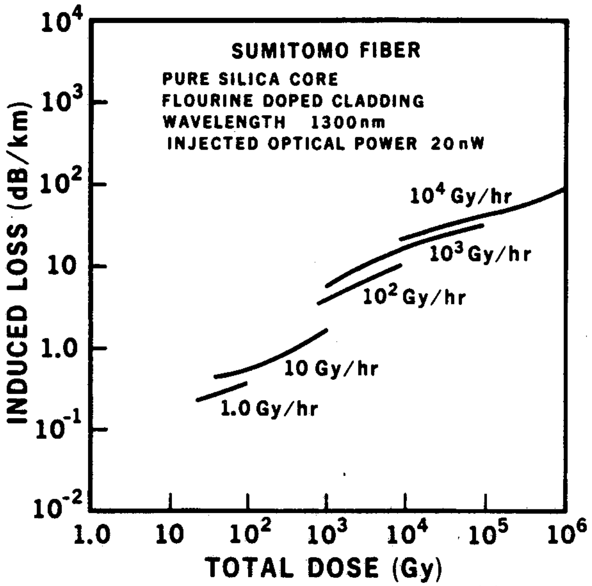

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Fig. 4. Radiation induced attenuation as a function of total dose with dose rate as parameter for single mode Sumitomo fiber having pure silica core.

OPTICAL RECEIVER CONSIDERATIONS

High sensitivity optical receivers may be required for use in some nuclear power facility networks particularly those in high data rate long haul link. In radiation environment in which the optical data transmission systems will operate, the photodetector of the receiver can be the limiting component.

Various radiation studies were performed on these radiation hardened devices, measuring the increase of leakage current caused by ionizing and neutron irradiation.[13] These studies have revealed that double heterostructure AlGaAs/GaAs devices are far superior to Si radiation hardened photodiodes. GaAs devices were able to operate up to 10^6 Gy/s, a level several orders of magnitude above the capability of Si PIN photodiodes.

It can be concluded from the measurements of neutron irradiation effects on photodiodes[13] that the device leakage current increases by a factor of 10 in the AlGaAs/GaAs photodiode and factor of 10^3 in the Si devices after exposure to a neutron fluence of $7 \times 10^{14} n/cm^2$. At this neutron fluence there is no optical responsivity degradation of an AlGaAs/GaAs photodiode while a Si device responsivity decreased to 60% of its preirradiation level.

Similarly, in InGaAs photodiodes, intended for data transmission links operating at wavelengths of 1300 nm, no degradation of optical and electrical characteristics were observed up to 10^6 Gy dose, with an exception of some increase of leakage current. The leakage current increases up to a factor of 6 from the pre-irradiation value when the total radiation dose is 10^6 Gy.

ELECTRONIC CIRCUITS IN RADIATION ENVIRONMENT

Associated electronic circuits and subassemblies used in digital and analog data transmission systems will suffer a measurable degradation of their operating characteristics when exposed to nuclear power facility radiation background. Various damaging mechanisms, such as ionization effects and atom-displacement phenomenon, are responsible for the degradation. Nearly all important device parameters, such as current gain, transconductance, cut-off frequency, speed, breakdown voltage, noise figure, power output and resistance are degraded by irradiation to some degree. The estimated ranges of total ionizing dose and neutron damage susceptibility of various silicon and gallium arsenide devices are shown in Fig. 5 and 6, respectively.

The long term ionization damage of semiconductor devices depends strongly on the electrical bias condition during and after exposure, measurement time after exposure and the ionization radiation energy spectrum. Furthermore, the damage susceptibility is extremely sensitive to processing temperature and chemistry. Very small processing changes can introduce an order of magnitude change in total dose damage susceptibility. Also the damage level depends upon the dose rate at which the total dose is delivered. In ionization radiation environment a variety of technologies provide the total dose damage susceptibility of 10^4-10^6 Gy. These include radiation hardened Si CMOS, bipolar and GaAs FET technologies.

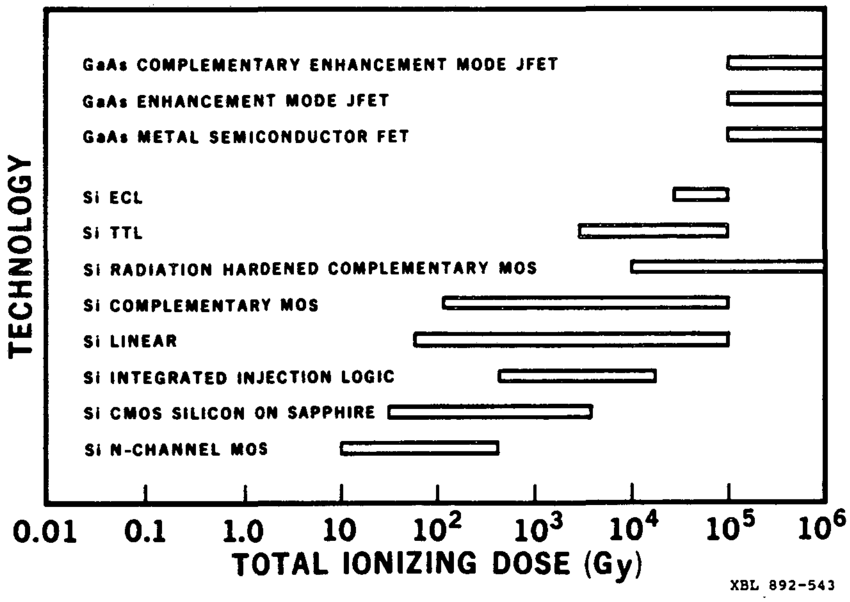

Fig. 5. Estimated ranges of total dose damage susceptibility for silicon and gallium arsenide devices.

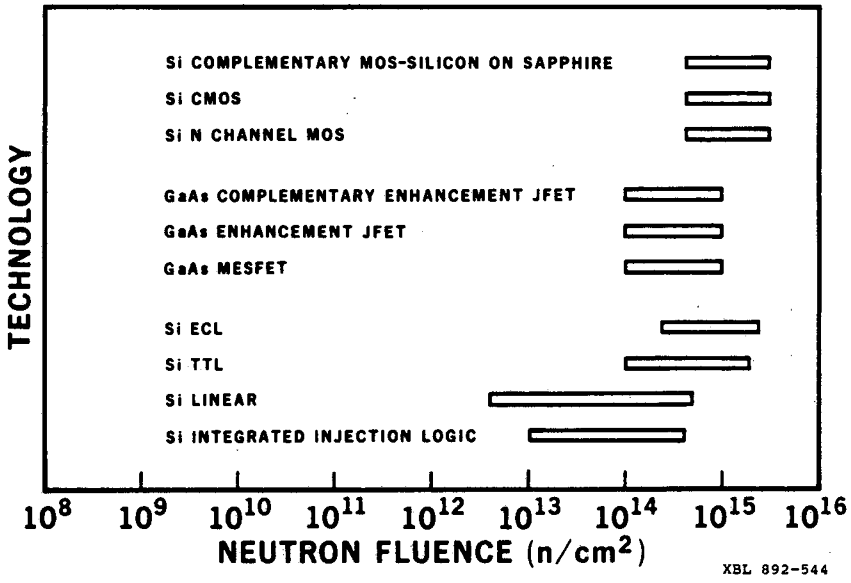

Fig. 6. Estimated ranges of neutron damage susceptibility for silicon and gallium arsenide devices.

In neutron environments FET technologies have 1 to 3 orders of magnitude smaller damage susceptibility than bipolar technologies. Also, compound semiconductors can additionally have yet another order of magnitude smaller susceptibility to neutron irradiation. Therefore, Si, CMOSFET, JFET and GaAs FET devices are suitable for applications where a high neutron irradiation levels are expected.

CONCLUSIONS

Using available digital IC's, electro-optical and opto-electrical transducers and fiber optic cable, the design and implementation of a digital optical wide band data transmission system with approximately 1 Gbit/s data rate capability can be accomplished. This limit is at present determined by the characteristics of electronic circuits which will be used for multiplexing and demultiplexing functions. The transmission and reception of data over single mode fiber optic cables at 1300 nm wavelength can be realized with the very low bit error rates (BER) of 10^{-9}.

Analog data transmission in the optical wavelength regions of 850 and 1300 nm can be also accomplished over a very wide bandwidth. However, the operating conditions of light emitting and laser diodes must be optimized to reduce the device harmonic and intermodulation products as well as their temperature sensitivity to an acceptable level.

Optical sources, fiber waveguides, optical receivers and associated electronics circuits will suffer a measurable degradation of their operating characteristics when exposed to radiation. However, by using existing radiation hardened components and choosing an appropriate operating wavelength, digital and analog fiber optics transmission links can be designed to function during the exposure to ionizing radiation and neutron fluence in many applications. Systems design should include adequate optical power margins to maintain the signal-to-noise ratio necessary for reliable operation.

Accurate evaluation of the expected optical power loss in data transmission systems involves specific data on the amount and spatial distribution of the total dose, dose rate, required bandwidth and the environmental temperature. The total dose and dose rate data are particularly important because the net radiation-induced attenuation in a fiber waveguide strongly depends on the competing processes of color center formation and recovery. In general, for smaller dose rate the induced attenuation is smaller, providing that the fiber recovers in the time scale of the exposure. Also, the attenuation can be significantly reduced by photobleaching effects, increasing the injected optical power levels and by higher environmental temperatures. In especially critical radiation environments the optical data link should be operated at longer wavelength, such as 1300 or 1500 nm, where the induced attenuation is smaller in comparison with that at shorter operating wavelengths.

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