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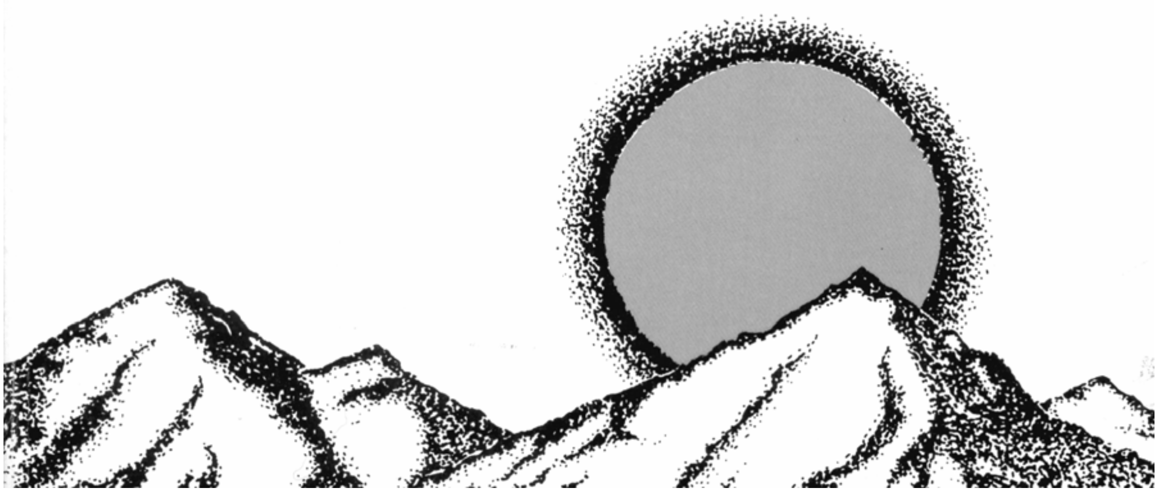

ELECTRO-OPTICS APPLICATIONS FOR ALLEVIATING EMC/EMP/EMI PROBLEMS*

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Abstract

Electro-optics is probably the most promising new technology for alleviating electromagnetic interference problems in future systems. This paper discusses the attributes and limitations of the technology for solving electromagnetic problems. The paper emphasizes EMP considerations. A major limitation for their application for mitigating nuclear electromagnetic system effects is their radiation susceptibility. This drawback is discussed at length. System design concepts for optimizing electromagnetic immunity benefits of electro-optical devices are presented. Arguments for wider application of the devices are delineated.

Introduction

The EMP community characteristically develops protection designs using conventional EMC/EMI measures including shielding, and the installation of electrical surge arrestors. An approach to hardening which has not been effectively developed for EMP hardening (for that matter EMC or EMI applications) is the integration of electro-optical links into system designs. This paper will explore the reasons for this state of affairs, present the strengths and weaknesses of electro-optical technology, and develop principles for its application in system EMP protection design.

It is clear that electro-optical technology will find increased application in defense electronic systems in the decade of the 80's. It has already gained increased acceptance in the civilian sector as attested by AT&T's installation of fiber optics telecommunications links along the northeast corridor of the United States. The pace of electro-optical applications is being driven by many inherent advantages over hard-wire links.** These advantages include lower costs, lighter weight (particularly significant for aircraft applications), higher data rate transmission over longer distances (up to 500 Mb/s), and increased immunity to electromagnetic interference. Recent technology breakthroughs promise to accelerate electro-optics applications. For instance, within the past year, optical fibers have been developed with less than 1 dB/km signal attenuation.[1] Better manufacturing processes have improved tensile strength, bandwidth, and data density capabilities of fiber-optics bundles. Manufacturers' costs have decreased dramatically as well.

Electro-optical technology has been touted as the end-all solution to the EMP hardening problem. It is true that when employed properly† in system designs, electro-optical links can dramatically improve EMP survivability of critical electronics. However, when employed in a haphazard manner fiber optics will not necessarily improve EMP immunity, and in some cases can conceivably degrade EMP hardness.

The EMP community must recognize three facts:

1. Electro-optical technology will find its way into more and more systems irregardless of potential EMP/EMC/EMI immunity benefits.
2. If we stand idly by, electro-optical technology will probably not significantly improve the EMP hardness of systems which use them.
3. If, instead we take an active role in developing and pushing guidelines for proper integration of electro-optic links in system designs, we can bring about maximum EMP immunity benefits.

Nuclear Weapon Effects on Electro-Optics

The Introduction discussed the many benefits of electro-optical links relative to hard-wire. For systems which must survive in a nuclear environment, the degree of susceptibility of the technology to ionizing radiation is the limiting factor in determining the advisability of their use. It should be remembered that electro-optical transmitting, receiving, and signal processing circuits use semiconductor technologies not unlike those used for hard-wire applications. Thus, their radiation (and electrical upset and burnout) susceptibilities are similar.

The electro-optical components with radiation susceptibilities which differ from those of hard-wire link circuit components are photoemitters, photodetectors, and optical fiber light guides (see schematic, Figure 1). The radiation susceptibilities of each component type are discussed in the following subsections.

Photoemitters

Two types of semiconductor photoemitters are most likely to be used by the military in fiber optic communications systems. These are light-emitting diodes (LEDs) and laser diodes, both of which can be fabricated from many different semiconductor materials to give somewhat different properties, primarily different wavelengths of the emitted light. The wavelength chosen must be compatible with the transmission properties of the fiber and range from 0.6 micrometers to approximately 1.3 micrometers. The tendency

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**"Hard-wire" refers to traditional thin metallic strands usually covered by a dielectric sheath, and sometimes also covered by a coaxial metallic shield.

†What is proper will be explained in the section on Design Concepts.

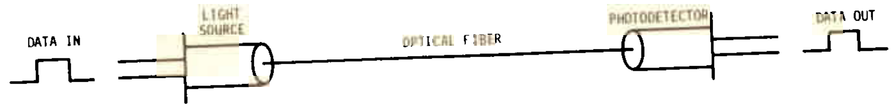

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Figure 1. Fiber optic transmission link

at present is toward development of sources that emit in the 1.0- to 1.3-micrometer range since some of the most promising fibers have lower optical attenuation and possibly less ionization radiation response at these wavelengths. Alloy combinations such as InGaAs, InGaP, InGaAsP, and GaAℓSnSb have been used to construct these emitters, but the most serious efforts are presently centered around InGaAsP. Another reason for this developmental trend is that the pulse dispersion of optical signals in the fibers is less at these wavelengths. This is significant because it makes possible longer transmission distances without repeaters at higher frequencies of operation.

The effects that radiation can have on optical sources and the general range of thresholds for observation of these effects are presented in Table 1.

Table 1. Damage thresholds for optical sources

Degradation Level	Specific Effect	Optical Source LED	Optical Source Laser Diode
Catastrophic Damage	Ionization-induced burnout	10^{10} rad(Si)/sec	10^{9} rad(Si)/sec
	Electrical pulse burnout (100 msec)	50 - 3000 μJ	0.5 - 30 μJ
Transient Ionization Effects	Transient upset	3×19^{9} rad(Si)/sec	10^{12} - 10^{13} rad(Si)/sec
Permanent Degradation	Light output loss, ionization	10^{7} rad(Si)	10^{7} rad(Si)
	Light output loss, neutron	10^{12} - 10^{14} n/cm^2	10^{13} - 10^{15} n/cm^2
Thermomechanical Effects	Mechanical failure	1 cal/g(Au)	1 cal/g(Au)

Catastrophic Damage. The ionization-induced threshold of 10^{10} rad(Si)/s for LEDs is a conservative figure, since this was the maximum test level in the only experiments reported[2,3] and only a few devices failed. The threshold may be lower for laser devices because they are operated at higher current densities and have smaller junction areas. The 10^{9} rad(Si)/s listed in Table 1 is just an estimate, but it is conservative since it is an order of magnitude lower than the LED threshold.

The electrical pulse burnout thresholds where the devices failed were measured directly in certain GaAs, GaP, and $GaAs_xP_{1-x}$ devices.[1] These devices generally are fast and, thus, are small-area devices. According to the Wunsch-Bell/Tasca model[4,5] for burnout, the threshold is area-dependent, as was found to be true over the limited area range of the tested devices. Hence, the thresholds for the larger-area, high-power LEDs and the smaller-area laser diodes were scaled from the measured data by the area ratio. The GaP device tested has a large area and was a slow unit. Faster ones of this type might have lower thresholds. The $Ga_xAℓ_{1-x}As$ LEDs were assumed to be similar to $GaAs_xP_{1-x}$ LEDs.

Laser diodes are small-area devices, and since the threshold is proportional to area, they are predicted to be more vulnerable than LEDs. Experimental information is almost entirely lacking in this field, except for an operating-life test which showed that $Ga_xAℓ_{1-x}$ LEDs CW devices fail at about 1 μJ for 100-ns pulses.[6] This agrees reasonably with the estimate in the table and reinforces its credibility. Since the estimated thresholds are low, this area is a very important one in which experimental information is needed.

Transient Ionization Effects. Transient upset causes a false signal that decays rapidly after the burst. There have been almost no studies of ionization-induced emission in LEDs or laser diodes. This is because these devices are operated at forward bias with high current densities, and photocurrents would be relatively less important. For estimation purposes, the photocurrent response of GaAs diodes is used. This value is $\sim 3 \times 10^{9}$ (A/cm^2)/[rad(Si)/s].[7] The predictions agree reasonably with the results from the reported experiments on devices made from GaAs, GaP, $GaAs_xP_{1-x}$, and $Ga_xAℓ_{1-x}As$.[3]

Another transient ionization effect is the light produced by the steady-state ionization encountered in the space environment or the delayed gammas from a prompt burst. In light sources, this would produce a background light level which would be akin to added noise. This effect would remain while the radiation remained and disappear when the radiation was not present. There is no experimental data in this area, and the numbers shown in the table are the predictions from the photocurrent response relationship. Again, laser degradation thresholds are much higher than LED thresholds because of their higher operating current density.

Permanent Degradation. Permanent ionization effects are produced by the total ionizing dose absorbed by a device. Surfaces or interfaces are affected primarily through increased leakage current, with some change in capacitance. The light sources are essentially unaffected by leakage current, and no ionization mechanisms (as opposed to displacement damage mechanism) has been reported.[4,8,9] Even though it is displacement damage that causes the degradation, most studies were performed with gamma fluence,[10-19] so this is how the thresholds are shown in Table 1.

Displacement effects in the light sources produce competing nonradiative recombination centers and degrade the light output of the LEDs. In laser diodes, a more important process is the lasing threshold shift. Lasers operated well above threshold will not show much degradation at low fluences. Eventually, the threshold shifts enough that the output drops drastically. The fluence required for this to occur in devices operated at a power a factor of 3 from the maximum is considered the threshold.

The thresholds shown in Table 1 are taken from a large number of studies.[10-29] The range of thresholds shown is apparently due to varying device quality, with the better-quality devices being more vulnerable. The better-quality devices have higher efficiency and, thus, fewer initial nonradiative recombination centers; therefore, it takes a lower radiation fluence to introduce a comparable number of new centers.

The $Ga_xA\ell_{1-x}As$ devices are relatively new and have not been heavily tested. Where they have been tested, they appear to be comparable to $GaAs_xP_{1-x}$ devices, and both these types seem to be about an order of magnitude harder than GaAs devices. In fact, use of ternary compounds to fabricate devices has been proposed as a hardening technique.[9,22,23] At times, the limited testing of the ternary material devices has given degradation thresholds only at one end of the expected range. Some early GaAs work indicated neutron degradation thresholds higher than those listed in the table. The tested devices were probably of lower quality than ones currently available, and this resulted in their being less vulnerable.

Thermomechanical Effects. No data exists concerning thermomechanical damage in light sources. The thresholds listed in Table 1 assume that the light sources behave similarly to silicon semiconductor devices. This means that the contact bonds are the most vulnerable point of the devices. A point to be made here is that the light sources will almost assuredly be protected from the direct x-ray beam, so it is unlikely that any of the damaging low-energy x-rays would reach them.

Cables

Table 2 presents the damage thresholds for fibers. Almost all effects depend on fiber length, so the thresholds are quoted per unit length. To calculate the thresholds, it has been assumed that, in most receivers, the noise level would be equivalent to an input signal of a few nanowatts. Thus, the minimum signal required for a 20 dB S/N ratio would be about 100 nW, and this is assumed to be the conservative signal leaving the fiber.

Table 2. Damage thresholds of fibers

Degradation Level	Specific Effect	Special Glass-Clad Silica Fibers	Polymer-Clad Silica Fibers	Plastic Fibers
Transient Ionization Effects	Transient upset signal	10^6 - 10^8 rad(Si)/sec-m	10^4 - 10^6 rad(Si)/sec-m	10^4 - 10^5 rad(Si)/sec-m
	Transient signal loss (immediate)	10^{10} rad(Si)/sec-m	3×10^{10} rad(Si)/sec-m	3×10^{10} rad(Si)/sec-m
	Transient signal loss (1 msec)	10^9 - 10^{11} rad(Si)/sec-m	3×10^{11} rad(Si)/sec-m	10^{11} - 10^{12} rad(Si)/sec-m
Permanent Degradation	Ionization-induced signal loss	10^0 - 10^3 rad(Si)/sec-m	10^0 - 10^3 rad(Si)/sec-m	10^5 - 10^7 rad(Si)/sec-m
Thermomechanical Effects	Mechanical failure	10 cal/g(Au)	10 cal/g(Au)	10 cal/g(Au)

Catastrophic Damage. Optical fibers, having no junctions, are immune to this effect. They are also immune to electromagnetic pickup, and therefore do not produce electrical pulses capable of burning out other components. This is the primary reason that fiber optic systems are considered for radiation-hardening.

Transient Ionization Effects. Transient ionization effects are the most important radiation vulnerability mechanisms in fibers, and most of the studies of radiation effects in fibers have examined this point.[30-48]

Two transient effects in fibers can be produced by ionization. One is luminescence, which would produce an upset signal. The second is the increase in attenuation. The latter is the most important radiation effect in fibers because it decays slowly with time following exposure. This slow decay means that the transmission capability of a link will be lost not only during exposure but possibly for a long period following exposure. The thresholds shown in Table 2 assume a 100-ns pulse width. This is an arbitrary choice picked simply to be in the general area of pulse widths at which exposure might occur. Scaling to other pulse widths should be done by the ratio of pulse widths.

The initial high absorption can produce a transient loss of signal if the dose is high enough. The threshold depends on the time interval after the burst that is required for the system to return to operation. The thresholds shown are for continuous operation (labeled "immediate"), for operation 1 ms after the burst, and for operation 1 s after the burst. These times are arbitrarily chosen to show how the threshold is affected. Recovery of the plastic fibers takes longer in a vacuum than in room ambient conditions, apparently because of some atmospheric constituent (probably oxygen) scavenging the absorption centers.[37,39-41] The range of thresholds shown for transient upset signal depends on whether the data was measured using x-rays or low-energy electrons, with electrons giving the lower threshold.

Steady-state transient effects in fibers are much the same as the above pulse effects. These could be produced by either delayed gammas or space electrons, both of which produce ionization for much longer periods of times than the prompt pulse; hence, the term steady-state. The most important effect is signal loss. This does not occur at the same dose rate as for prompt transient pulses because recovery is occurring at the same time as generation. To predict the amount of attenuation produced by a steady-state environment, it is necessary to combine the production rate and the recovery rate, keeping track of how much time has elapsed since any exposure increment.[37,40,41] The threshold depends on the exposure time and the magnitude of the steady-state flux. The thresholds shown in the table assume a 10-s exposure to a constant flux, and require that the attenuation be low enough for low link operation, at the end of this period. Some data does exist on the steady-state response of fibers,[41,42] but none on the performance of a fiber optics system; therefore, the thresholds are the result of calculations.

A second effect of a steady-state environment is the increased noise due to increased background light, which would be the result of luminescence. This increased noise could degrade the available S/N level of a fiber optic link, but it has not been reported.

Permanent Degradation. The ionization-induced permanent degradation is the increase in fiber absorption which decreases the transmitted signal.[3,30-48] This absorption is the same effect as the transient absorption described above. Although the increased absorption decays indefinitely, the portion considered permanent degradation is that present one, or two days after exposure.

Displacement damage cannot be measured in the fibers because the accompanying ionization produces more damage than displacement dose.[3,30,36-39,42] The fibers are, for the purposes of this study, immune to displacement damage.

Thermomechanical Effects. The most likely effect of thermomechanical damage in fibers is surface cracking produced by heating,[48] and this is the threshold shown. It is a higher threshold than for similar effects in devices because there are no wire bonds in the fibers, and these bonds are the weak points. Another effect in the fibers could be dielectric breakdown caused by fiber charging. Calculations indicate that the threshold for breakdown is the same order of magnitude as that for cracking caused by heating in the extreme case of using a gold converter, and assuming that all the electrons are absorbed at the surface of a plane of fiber material with no leakage. Since this is worse than would occur in practice, dielectric breakdown would probably not be a vulnerability problem for an x-ray threat. However, for the natural or weapon-enhanced space environments, this could be a problem.

Detectors

Limited studies[49] of the radiation effects in photodetectors have been made, but not with any degree of completeness, and unfortunately many of the threshold levels must be inferred. The information presented is summarized in Table 3.

Table 3. Damage threshold of photodetectors

Degradation Level	Specific Effect	Pin Diode	Avalanche Photodiode
Catastrophic Damage	Ionization-induced burnout	10^9 rad(Si)/sec	10^9 rad(Si)/sec
	Electrical pulse burnout (100 nsec)	100 - 40,000 μJ	200 - 4,000 μJ
Transient Ionization Effects	Transient upset	1-100 rad(Si)/sec	0.01-1 rad(Si)/sec
Permanent Degradation	Ionization-induced response degradation	$>10^8$ rad(Si)	$>10^8$ rad(Si)
	Ionization-induced dark current increase	10^4 - 10^6 rad(Si)	10^4 - 10^6 rad(Si)
	Neutron-induced response degradation	10^{13} - 10^{14} n/cm^2	10^{13} - 10^{14} n/cm^2
	Neutron-induced dark current increase	10^{10} - 10^{13} n/cm^2	10^{10} - 10^{14} n/cm^2
	Electron-induced response degradation	10^{14} - 10^{15} e/cm^2	10^{14} - 10^{15} e/cm^2
	Electron-induced dark current increase	10^{11} - 10^{14} e/cm^2	10^{11} - 10^{14} e/cm^2
Thermomechanical Effects	Mechanical failure	1 cal/g(Au)	1 cal/g(Au)

In determining upset and noise thresholds, some knowledge of the input light level and system operation, including system noise and bandwidth, is required. To be on the pessimistic side, it is assumed that the noise level is not set by the photodetector itself but by the amplifier, where the noise is about an order of magnitude higher in well-designed systems. System bandwidth would also be somewhat less. Therefore, the listed thresholds of diode devices are low by at least this order of magnitude in systems using currently available electronics. However, improvements could lower the noise of the electronics and make the detector noise more important. Thus, the listed thresholds are minimum ones for a system that might be approached in the future.

Catastrophic Damage. This is an area in which essentially no work on photodetectors has been performed, but the similarity of photodetectors to other silicon devices can be used to estimate thresholds.[8,49-51]

For ionization-induced burnout, sensitive silicon devices are damaged at about 10^9 rad(Si)/s, so this is taken as the threshold. For electrical pulse burnout, all silicon junction devices behave similarly, and their thresholds can be calculated by the Wunsch-Bell/Tasca model of junction burnout.[4,5] In this model the thresholds depend on the semiconductor junction area (which is not necessarily the active optical area of a photodetector), allowing results for other devices to be scaled by the area ratio. The question that arises in scaling photodetector data is that their junction areas are larger than those of normal devices, and the burnout area may be less than 1/10 of the junction area assumed by the model. This would mean that the formula over-estimates the threshold. To allow for this possibility, the estimates shown in Table 3 are 10% of the scaled values; so as to be pessimistic. The range of thresholds shown for any device type is caused by the range of device sizes.

However, it has been calculated[52] that the fields in the depletion region of a pin photodetector will begin to collapse at dose rates of around 10^7 rad(Si)/s; therefore, the radiation-induced photocurrents will tend to saturate at levels above this threshold and the recovery times will become longer with increasing dose rates.

The ionization-induced burnout mechanisms of these devices are the same as for normal silicon devices, and hardening by normal techniques (e.g., current-limiting) can be used on them. For all but the smallest devices, the electrical pulse burnout thresholds are high. However, the thresholds are only estimates which are uncertain, even by the low accuracy of burnout threshold standards. Therefore, the largest need in this area is an experimental investigation of the thresholds so that the area can be properly assessed.

Transient Ionization Effects. Photodetectors are designed to be very sensitive to optical radiation. As a result, they are also very sensitive to radiation ionization, a similar phenomenon. Taking the definition of a rad and converting the energy deposited into electron-hole pair current in silicon, the theoretical current produced in devices without gain is

$$I = 6.4 \times 10^{-6} \, V \dot{\gamma} \quad ,$$

where I is in amperes, V is the volume in cm^3, and $\dot{\gamma}$ is the dose rate in rad(Si)/s. Pin diodes used as ionization detectors and the sparse experimental information available on detectors[7,8,11] tend to substantiate this theoretical value. For devices with gain, the gain multiplies the current found in this manner.

The limited bandwidth of photovoltaic and transistor devices and their fast roll-off (~100 ns) increase the threshold. The larger-area devices are somewhat more sensitive, which is why the smaller pin diodes and avalanche photodiodes show higher thresholds than the other diode devices.

All of these transient upset thresholds are quite low. However, since they are directly related to the optical detection ability of the devices, little can be done to increase them except to change the material from which the detector is constructed. The smallest detector possible should be used to minimize the response and the bandwidth narrowed to roll-off the fast ionization response. Also, the signal-to-noise ratio should be made as high as possible by increasing the optical signal, thus requiring a larger upset pulse. This indicates that over-optimization of the receiver to reduce the noise and thus increase the S/N ratio should be avoided because it could make the system more vulnerable to upset. Obviously, shielding also decreases the vulnerability.

Steady-state noise increase is similar to transient ionization upset in that the former effect is produced by the current attributable to the latter. The difference is that steady-state effects are produced by a continually present source of ionization, such as the space-electron environment or a delayed-gamma environment. The primary effect of the steady-state ionization is to increase the noise current in the photodetector. Once the ionization ceases, the steady-state ionization effects will cease as well, so they are actually transient.

In principle, the radiation noise current can be calculated in the same manner as the transient upset signal, since the calculation radiation-induced noise current is the same type of "white" noise as the "dark" current noise. However, in these calculations the average current produced per penetrating ionization particle must be taken into account. Each type of ionization particle has a different generation rate for the production of electron-hole pairs, and therefore, the average current per particle is different for different types of particle fluxes. But the rms value for the radiation-induced noise current scales as the square root of the dose rate in the material, independent of the radiation particle.[4] The threshold is independent of system bandwidth for all but the photovoltaic types, where a maximum system bandwidth is assumed. These calculations give thresholds which agree reasonably with those that have been found in the few experiments that have been performed on pin photodiodes.[40,41,49,53]

As in the case of transient upset vulnerability, the steady-state ionization vulnerability cannot be usefully lessened in a given material by material property changes because it is related to optical sensitivity. However, switching to completely different semiconductor materials such as GaAs may raise the threshold because the generation rate in the materials may be reduced due to larger bandgaps. In fact, some of these detectors are being developed for the longer-wavelength LEDs, and these may have a higher threshold.

Permanent Degradation. Permanent ionization or displacement effects could increase the device surface leakage and thus the noise, or degrade the device gain and thus the optical response. Unfortunately, very little data exists in the area of noise increase,[40,53] and only little more in the area of responsivity degradation,[11,40,41] and most of this is for pin photodiodes. Estimates of the vulnerability of the other device types are made from knowledge of similar effects in normal silicon devices.[8,42,50,51,54,55] All of the diode devices except the photovoltaic cells are usually biased to depletion, which means that the response is governed by carrier sweepout and not lifetime, so they should be relatively hard to displacement damage. The photovoltaic cells should be similar in vulnerability to solar cells because both are unbiased "ON" junction devices. The phototransistors should be similar to other transistor devices. In most cases, the thresholds are only estimates with little or no experimental justification.

The dark-current changes are likely to be dependent on device geometry and construction, and it is very difficult to estimate damage thresholds. Therefore, the numbers in the table have a very large range. This is not true for electron effects on photovoltaic cells, based on data from a silicon vidicon tube[56] and solar cell experiments.[57] An experiment examined changes in dark current in large-area pin diodes and found increases of about a factor of 3 to 5 after 1.3×10^{11} n/cm^2.[40] Since large-area devices are likely to be most vulnerable, this threshold supports the estimates.

Thermomechanical Effects. Since the photodetectors will probably be protected from the direct x-ray beam, it is unlikely that they will suffer thermomechanical damage. The most vulnerable point of the devices will be the wire bonds, and the listed thresholds are those found for devices without wire bonds.

Implications

It should be stressed that while individual electro-optical components can survive moderate levels of radiation, it requires intelligent selection of available electro-optical components in order to assemble links which will withstand radiation environments comparable to those associated with human incapacitation thresholds. For systems (such as aircraft, tactical equipment, C^3 facilities) where radiation tolerance levels are dictated by operator survivability, careful use of electro-optical links will not limit system nuclear survivability (see Reference 58 for further discussion of this subject).

Design Concepts for EMP Mitigation

At first glance electro-optical links may seem to present a total solution to the EMP protection problem. However, for most system applications, electro-optics will be only a subset of a larger conglomeration of hard-wire circuitry, shielded boxes, metal racks, and power lines (electro-optics are incapable of efficient delivery of large amounts of power). The mere presence of electro-optical links in a system with many hard-wire conductors does not guarantee system hardness. In order for electro-optical links to afford any measurable reduction in EMP susceptibility, the links must be carefully integrated into a system's design. It is the task of the system designer to employ electro-optics in a manner that maximizes system EMP/EMC/EMI immunity. This section first discusses the more traditional hardening approaches and then presents some basic guidelines for the proper integration of electro-optical components into system EMP hardened designs.

Traditional EMP Hardening Approach

EMP hardening may be accomplished at one or more of three conceptual levels: the system level, the rack (or box level) and the circuit level. Figure 2 presents a heuristic diagram of these three hardening levels. Normally, hardening at one level is not sufficient to insure EMP hardness.

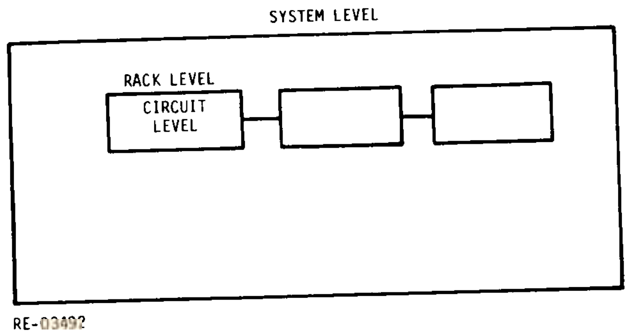

Figure 2. Hardening levels

System Level Hardening. Presently used system level hardening practices would include:

1. Installation of external shields on facilities, aircraft, ships, etc.
2. Shielding external power and C^3 lines
3. Facility grounding-installation of ground rods, ground planes
4. Current limiting devices installed at external system electrical penetrations.

System level hardness design would normally fall under the purview of civil and structural engineers.

Rack Level Hardening. Rack or box level hardening design would be accomplished by electrical engineers. Traditional rack level hardening measures include:

1. Proper placement of racks/boxes within facility
2. Power and signal cable routing to avoid cross talk, ground loops
3. Rack/box shielding
4. Shielding of connecting cables (power and signal)
5. Installation of current limiting devices and box terminals
6. Proper rack/box grounding schemes.

Circuit Level Hardening. Circuit level hardening design is accomplished by electronic and semiconductor engineers and would normally include:

1. Choice of radiation and electrical overstress hardened, screened circuit components
2. Integral limiters on circuit boards, line replaceable units, and chips
3. Common-mode rejection designs
4. Circumvention/reset function capability.

Electro-Optical Design Approaches

Electro-optical hardening approaches and devices find application at each of the three hardening levels. Most importantly, the proper use of electro-optical techniques can eliminate the need for many of the more costly and unwieldy traditional hardening measures listed above.

System Level Electro-Optics Integration. At the system level, fiber optic links should be used for inter-system communication and data transfer, replacing hard-wire lines in these capacities. Figure 3 depicts the employment of a system level link. Because the power handling capabilities of electro-optical devices is miniscule in comparison with large system needs, it is not possible to replace power lines with photovoltaic power generation for most applications. It is recommended that power lines be the only allowable hard-wire penetration to the system and that these should be equipped with filters and electrical surge arrestors (ESAs). For hardened targets, such as missile shelters, internal power generation should be used if at all possible. Except for power, the system should be electrically isolated from its surroundings, including other systems, either nearby or distant. The presence of metal cladding on optical fibers, and metallic pipes and ducts should therefore be avoided.

CONSIDERATIONS:
- WELL-PROTECTED POWER PENETRATION
  - DISCONNECTS
  - ESA's
  - FILTERS
- ON-SITE POWER GENERATION IF POSSIBLE
  - GENERATORS
  - BATTERIES
- EXCEPT FOR POWER, A AND B ELECTRICALLY ISOLATED
  - NO METAL SHEATH ON FIBER BUNDLES
  - NO OTHER CONDUCTING PATHS

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Figure 3. System level data link

Rack Level Electro-Optics Integration. At the rack level, inter-box fiber optic data/communication links should be used in place of hard-wire. Figure 4 shows a suggested scheme for employing fiber optics between boxes. As with system level design, power lines should be the only hard-wire box penetration. Individual box power should be well-filtered and limited at the power input terminal. Note from the figure that the use of interbox optical links virtually eliminates ground loops.

Circuit Level Electro-Optics Integration. Electro-optical links may also be used in circuit design to provide electrical isolation. One example of a circuit level application is shown in Figure 5. Here a photon coupler (photoemitter and detector packaged together on a small chip) is used to isolate two circuits. This design is particularly appropriate at a circuit-line interface to isolate line drivers or other types of buffer

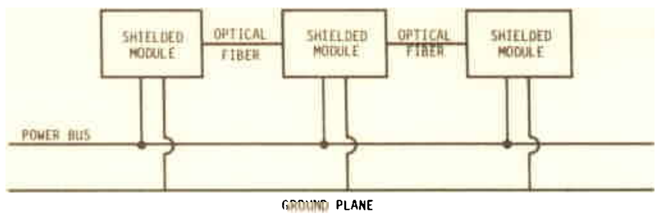

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Figure 4. Inter-box data links

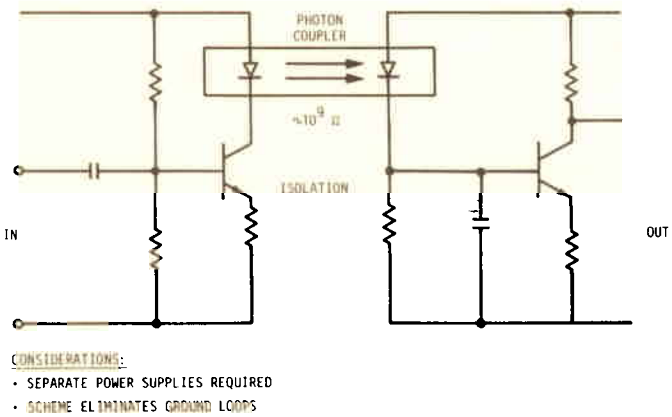

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Figure 5. Circuit level link

circuits from internal electronics. This concept may eliminate damage or at least limit damage to easily replaceable front end components. Just as with the box level and system level approaches, individual optically isolated circuits must have separate power supplies, or have their own separate power filters and limiters.

As was previously mentioned, one of the key benefits of using electro-optical links in EMP hardening designs is the partial elimination of the need for more costly traditional hardening measures. The requirement for data/C^3 cable shielding can be entirely eliminated. No filters or ESAs are required at optical fiber terminations. For systems with well-shielded boxes, using optical fibers for all data and communication links, the need for a contiguous external system level shield is eliminated. Fiber optical links can also offer a 10-1 weight savings over hard-wire. The optical links themselves are less costly than hard-wire links for many applications. A cost analysis of fiber optic systems may be found in References 59 and 60.

Present and Future System Applications

Electro-optics have, up until now, been employed in only a few defense critical systems. Some of the reasons for this are:

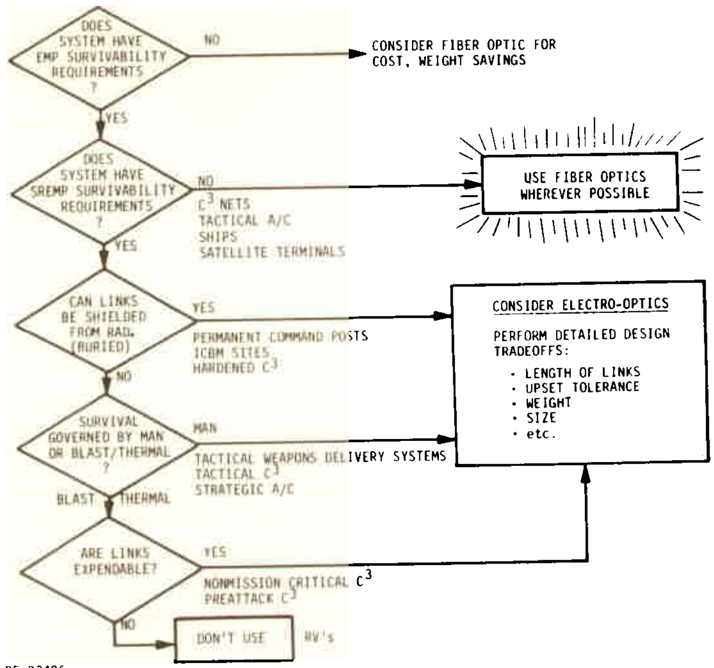
1. Fiber optics technology is new and only within the last five years have significant technology performance and reliability drawbacks been overcome.
2. Despite the many technology attributes, there has been an unwillingness on the part of defense system project managers to incorporate electro-optical links, mainly because of a lack of operational experience with the devices.
3. The nuclear survivability community has stressed the radiation problems of the technology to the exclusion of its EMP/EMC/EMI immunity benefits. It is believed by the authors that for a significant number of military applications the degree of electromagnetic hardness afforded by electro-optical components outweighs any radiation susceptibility problems they may introduce.

Figure 6 is a flow diagram showing the major decisions involved in determining whether electro-optics' radiation susceptibility would prevent their use in a given system. The diagram illustrates that electro-optical components can be employed in most defense system classes.

Although there are not many, space does not permit a detailed discussion of defense systems which include electro-optics in their design. Four systems using fiber optics are presently in engineering development including the Harrier (AV8B); the ground launched cruise missile (Figure 7); the Army's TTC-39 tactical data and control system; and the MX system (Figure 8). Systems in advanced engineering development include the Army's Long Haul Optical Transmission System (LHOTS), the Marine Integrated Fire Support System, and the Advanced Digital Optical Control System for helicopters. Several satellite earth terminals have been retrofitted with fiber optics links between their control buildings and dish antennas (Figure 9). See References 61 through 64 for details on systems applications.

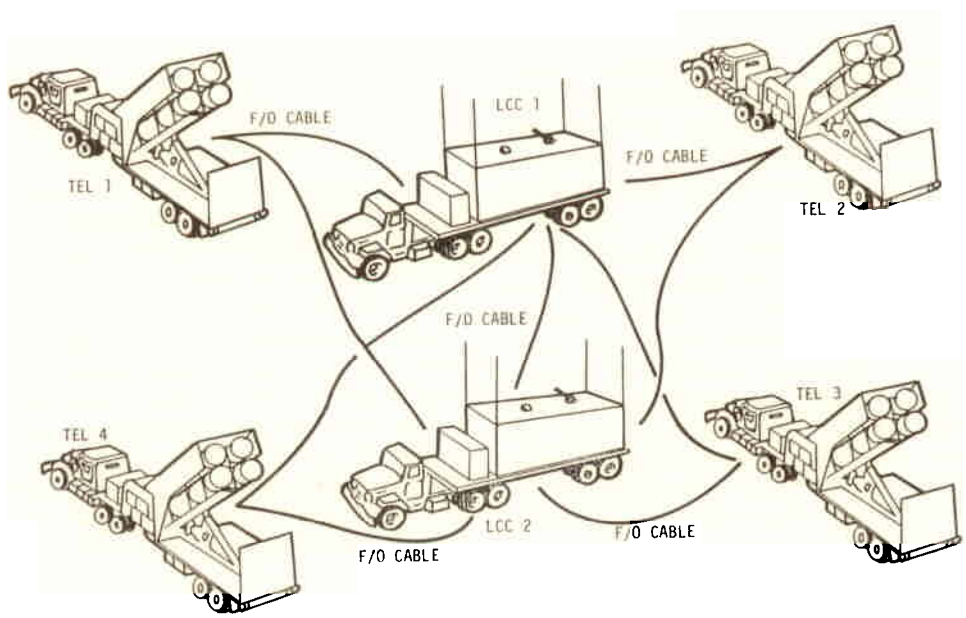
Conclusions

During the present decade, the number of defense systems utilizing electro-optical components in their designs will multiply considerably. In most cases, electro-optics will be chosen based on the cost and weight savings rather than their EMP/EMC/EMI immunity benefits relative to hard-wire links. Haphazard installation of electro-optical links in systems can mean little or no reduction of EMP/EMC/EMI susceptibility. It will be up to EMP/EMI practitioners to insure that electro-optical links are properly integrated into system designs to maximize EMP/EMC/EMI immunity. Hopefully, the EMP/EMC/EMI community will rise to the challenge and take an active role in developing and advocating intelligent engineering guidelines for this purpose.



RE-03496

Figure 6. System use decision tree



RE-03497

Figure 7. GLCM flight interconnection using fiber optic cables

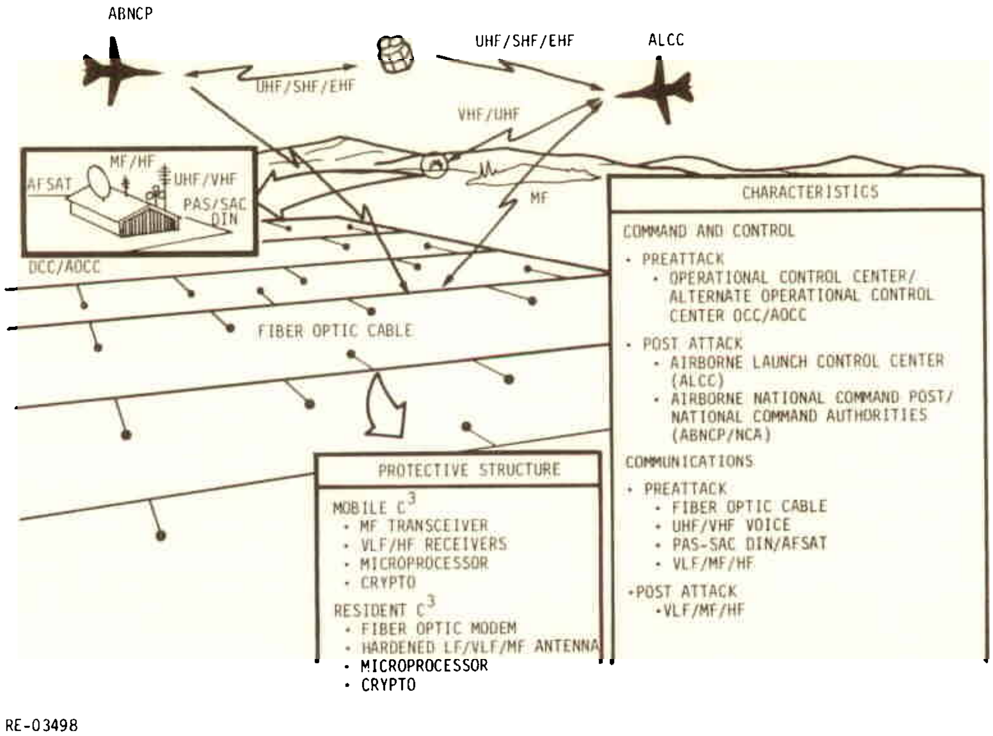


Figure 8. The C^3 MX system concept

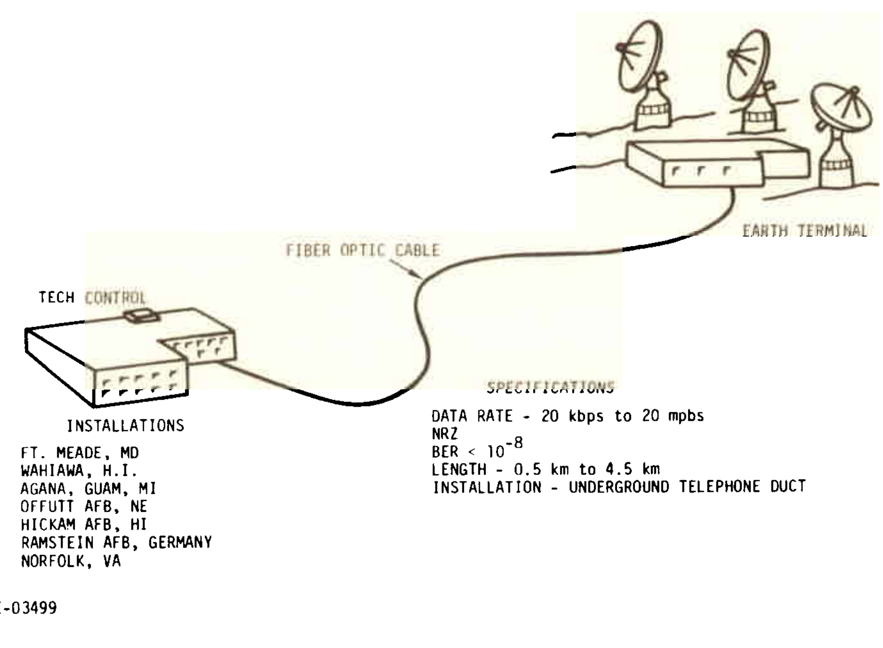


Figure 9. AN/FAC-1 fiber optic systems

References

1. A. H. Kalma and C. J. Fisher, "Electrical Pulse Burnout Testing of Light-Emitting Diodes," IEEE Trans. Nucl. Sci. NS-22, 2510 (1975).
2. "Fiber Optic Radiation Test and Evaluation Program," IRT final report for AFWL, Kirtland AFB, December 1978.
3. A. H. Kalma, "An Assessment of Fiber Optics Technology for Satellite Hardening," AFWL-TR-74-302 (1975).
4. D. C. Wunsch and R. R. Bell, "Determination of Threshold Failure Levels of Semiconductor Diodes and Transistors Due to Pulse Voltage," IEEE Trans. Nucl. Sci. NS-17, 364 (1970).
5. D. N. Tasca, "Pulse Power Failure Modes in Semiconductors," IEEE Trans. Nucl. Sci. NS-17, 364 (1970).
6. J. T. O'Brien, et al., "Recent Developments in Injection Lasers," pres. at Conf. on Laser and Electro-Optical Systems, San Diego, May 25-27, 1976.
7. H. D. Southward and R. H. Schnurr, "Radiation Effects on GaAs Devices and Schottky Diodes," AFWL-TR-68-31, Vol. 2, August 1968.
8. J. P. Raymond, et al., "Study of Radiation Effects in Bulk CMOS Microcircuits, IIL/LSI Logic Cells, and Optic Couplers," Northrop report DNA3776F (1975).
9. C. E. Barnes, "Development of Efficient Radiation-Insensitive GaA:Zn LEDs," IEEE Trans. Nucl. Sci. NS-24, No. 6, December 1977.
10. J. D. Schroeder, et al., "Radiation-Damage-Induced Time Delay in GaAs Lasers," IEEE Trans. Nucl. Sci. NS-19, 391 (1972).
11. A. S. Epstein and P. A. Trimmer, "Radiation Damage and Annealing Effects on Photon-Coupled Isolators," IEEE Trans. Nucl. Sci. NS-19, 391 (1972).
12. C. E. Barnes, "Radiation Effects in Electroluminescent Diodes," IEEE Trans. Nucl. Sci. NS-18, 322 (1971).
13. B. W. Noel, et al., "Neutron Irradiation Effects on Diffused GaAs Laser Diodes," IEEE Trans. Nucl. Sci. NS-18, 378 (1971).
14. C. E. Barnes, "Neutron Damage in Epitaxial GaAs Laser Diodes," J. Appl. Phys. 42, 1941 (1971).
15. H. Schade, et al., "Defect Centers in GaAsP Electroluminescent Diodes Due to High-Energy Electron Irradiation," J. Appl. Phys. 41, 3783 (1970).
16. C. E. Barnes, "Neutron Damage in GaAs Laser Diodes at and Above Laser Threshold," IEEE Trans. Nucl. Sci. NS-19, 382 (1972).
17. A. S. Epstein, et al., "Effect of Neutron Irradiation on GaAsP Electroluminescent Diodes," Appl. Phys. Lett. 23, 472 (1973).
18. A. G. Stanley, "Comparison of Light-Emitting Diodes in a Space Radiation Environment," IEEE Trans. Nucl. Sci. NS-17, 239 (1970).
19. C. E. Barnes, "Radiation Effects in Light-Emitting Diodes and Laser Diodes," Sandia report SC-RR-710686 (1972).
20. K. J. Soda, et al., "The Effect of Gamma Irradiation on Optical Isolators," IEEE Trans. Nucl. Sci. NS-22, 2475 (1975).
21. R. A. Polimadei, et al., "Performance of GaAℓAs Light-Emitting Didoes in Radiation Environments," IEEE Trans. Nucl. Sci. NS-21, 96 (1974).
22. S. Share, et al., "Radiation Effects and Hardening on Compensated GaAs Light-Emitting Diodes," IEEE Trans. Nucl. Sci. NS-20, 256 (1973).
23. A. S. Epstein, et al., "Radiation Effects on Active and Passive Optical Components," pres. at DoD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference, NELC, San Diego (1974).
24. C. E. Barnes, "Neutron Damage in GaP Light-Emitting Diodes," Appl. Phys. Lett. 20, 110 (1972).
25. D. M. J. Compton and R. A. Cesena, "Mechanism of Radiation Effects on Lasers," IEEE Trans. Nucl. Sci. NS-14, 55 (1967).
26. G. W. Arnold, "Luminescence in Intrinsic and Annealed Electron-Irradiated GaAs:Cd," Phys. Rev. 183, 777 (1969).
27. C. E. Barnes, Appl. Phys. Lett. 20, 86 (1972).
28. C. E. Barnes, "Tunneling to SiC Electroluminescent Diodes," J. Appl. Phys. 45, 193 (1974).
29. C. E. Barnes "Increased Radiation Hardness of GaAs Laser Diodes at High Current Densities," J. Appl. Phys. 45, 3485 (1974).
30. B. D. Evans and G. H. Sigel, Jr., "Radiation-Resistant Fiber Optic Materials and Waveguides," IEEE Trans. Nucl. Sci. NS-22, 2462 (1975).
31. P. L. Mattern, et al., "Effects of Radiation on Absorption and Luminescence of Fiber Optic Waveguides and Materials," IEEE Trans. Nucl. Sci. NS-21, 81 (1974).
32. B. D. Evans and G. H. Sigel, Jr., "Permanent and Transient Radiation-Induced Losses in Optical Fibers," IEEE Trans. Nucl. Sci. NS-21, 113 (1974).
33. G. H. Sigel, Jr., "Radiation Effects in Fiber Optic Waveguides," NRL memorandum report 2704, Dec. 1973.
34. P. L. Mattern, "Radiation-Induced Absorption and Luminescence in Glass and Plastic Optical Waveguides," pres. at DoD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference, NELC, San Diego (1974).
35. G. H. Sigel, Jr., et al., "Radiation Effects in Fiber Optic Waveguides," NRL memorandum report 2934 (1974).
36. J. A. Wall, "Transient Radiation Effects Tests of a Corning Radiation-Resistant Optical Fiber," AFCRL-TR-74-0012 (1975).
37. J. A. Wall and J. F. Bryant, "Radiation Effects on Fiber Optics," AFCRL-TR-75-0190 (1975).
38. P. L. Mattern, et al., "Effects of Radiation on Optical Fibers and Materials," IEEE Trans. Nucl. Sci. NS-22, 2468 (1975).
39. C. D. Skoog, "A Summary of Radiation-Induced Transient Absorption and Recovery in Fiber Optic Waveguides," Sandia report SAND76-8056, Nov. 1976.
40. A. H. Kalma and W. H. Hardwick, "Fiber Optics Test Program for Satellite Applications," IRT report INTEL-RT 8111-089, Dec. 1975.
41. A. H. Kalma and W. H. Hardwick, "Radiation Testing of a Fiber Optics Data Link," IEEE Trans. Nucl. Sci. NS-23, 1769 (1976).
42. R. D. Maurer, et al., "Effect of Neutron and Gamma Radiation on Glass Optical Waveguides," Appl. Opt. 12, 2024 (1973).
43. G. H. Sigel, Jr., and B. D. Evans, "Effects of Ionizing Radiation on Transmission of Optical Fibers," Appl. Phys. Lett. 24, 410 (1974).
44. M. A. Acharekar, "Multimode Radiation-Resistant Glass Fiber for Data Transmission Applications," pres. at DoD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference, NELC, San Diego (1974).
45. G. H. Sigel, Jr., "Radiation Damage in Fiber Optics," pres. at DoD/Industry-Wide Integrated Optics and Fiber Optics Communications Conference, NELC, San Diego (1974).
46. E. J. Friebele, et al., "Radiation Protection of Fiber Optics Materials: Effects of Oxidation and Reduction," Appl. Phys. Lett. 24, 412 (1974).

47. E. J. Friebele, et al., "Defect Centers in a Germanium-Doped Silica-Core Optical Fiber," J. Appl. Phys. 45, 3424 (1974).

48. A. Baba, et al., "Effect of Simulated Nuclear Thermal Pulses on Fiber Optic Cables," IEEE Trans. Nucl. Sci. NS-26, No. 6, Dec. 1979.

49. W. H. Hardwick and A. H. Kalma, "Radiation Testing of Photodetectors, final report under contract F29601-76-C-0034, Feb. 1978.

50. R. P. Donovan, et al., "Survey of Vulnerability of Contemporary Semiconductor Components to Nuclear Radiation," AFAL-TR-74-61 (1974).

51. R. K. Thatcher, "TREE Handbook," Vol. I, DNA 1420H-1 (1971).

52. C. W. Gwyn, "Analysis of Radiation Effects in Semiconductor Junction Devices," IEEE Trans. Nucl. Sci. NS-14, No. 6, Dec. 1967.

53. A. H. Kalma and R. A. Cesena, "Irradiation Testing of Optics Components," IRT report INTEL-RT0039-001, Sept. 1976.

54. L. D. Cotter and M. A. Donaldson, "Status of Integrated Circutis," Gulf-RT-C12375, Nov. 1975.

55. A. H. Kalma, "Test of MIRIS Radiometer Detectors," IRT report INTEL-RT0040-001, Aug. 1976.

56. G. J. Brucker and A. D. Cope, "Radiation Sensitivity of Silicon Imaging Sensors on Missions to Outer Planets," IEEE Trans. Nucl. Sci. NS-19, 147 (1972).

57. J. R. Carter, Jr., and H. Y. Tada, "Solar Cell Radiation Handbook," Jet Propulsion Laboratory report 21945-6001-RV-00, June 1973.

58. R. A. Greenwell, "Use of Electro-Optic Techniques to Achieve Electromagnetic Pulse Hardness," NOSC TR564, June 1980.

59. J. R. Ellis and R. A. Greenwell, "A-7 Aloft Economic Analysis Development Concept," NELC TD435, 7 July 1975.

60. R. A. Greenwell, "A-7 ALOFT Life Cycle Cost and Measures of Effectiveness Models," NELC TR1982, March (1976).

61. R. A. Greenwell, R. J. Kochanski, and D. N. Williams, "Fiber Optic Systems Application in the U.S. Navy," NOSC, 29 April 1980.

62. R. D. Harders, R. A. Greenwell, and G. M. Holma, "A-7 Airborne Light Optical Fiber Technology (ALOFT) Demonstration Project," NELC TR2024, Feb. 1977.

63. J. R. Campbell and J. F. Bryant, "Fiber Optic Technology Summary for the Defense Communications System," NOSC TN3236.

64. A. Mondrick and J. Wright, "Fiber Optic Communications Systems for the U.S. Army," U.S. Army Communications Research and Development Command.

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