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OPTICAL DATA TRANSMISSION AT THE SUPERCONDUCTING SUPER COLLIDER

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ABSTRACT

Digital and analog data transmissions via fiber optics for the Superconducting Super Collider have been investigated. The state of the art of optical transmitters, low loss fiber waveguides, receivers and associated electronics components are reviewed and summarized. Emphasis is placed on the effects of the radiation environment on the performance of an optical data transmission system components. Also, the performance of candidate components of the wide band digital and analog transmission systems intended for deployment of the Superconducting Super Collider Detector is discussed.

I. INTRODUCTION

The concept of guided lightwave communication along optical fibers has stimulated a major new technology over the past two decades. This technology profoundly impacts communication and instrumentation systems as well as computer interconnections and system architecture. Fiber optic links provide several major advantages over conventional electronic systems. These include immunity to electromagnetic interference, and low transmission losses for very high data rates. It also makes possible thinner and lighter cables and has a strong potential for long data transmission link capabilities extending to the gigahertz region.

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. The technology of optical fiber communication systems is advancing at a very rapid rate. As the short optical wavelength multimode fiber systems are being field-proven and used commercially, the technology is progressing towards single-mode fiber systems in the long-wavelength region. For example, significant advances have been made in the fabrication of low-loss and low-dispersion

optical fibers. Losses of approximately 0.20 dB/km at 1300 nm have been achieved for single mode fibers with minimum dispersion wavelengths near 1300 nm. Furthermore, the development of optical sources, and optical receivers, for long wavelength applications is also advancing rapidly. 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}

Fig. 1. Performance and cost of fiber optics communication systems.

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 the present time practical high data rate optical transmission systems are operating between 45 Mbit/s and 1.7 Gbit/s. Figure 1 shows the communication system performance in the Gbit/s region and relative cost per Gbit/s x km as a function of time.³ There has been approximately a tenfold improvement in the system performance every three years and a corresponding decrease in the cost per Gbit/s x km.

In addition to the requirements placed on the optoelectronic components of these systems, considerable attention was paid to the associated logic circuit families with switching speeds in the microwave region.

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Such capability is necessary for multiplexing and demultiplexing functions. These functions have been implemented using both silicon and gallium arsenide (GaAs) technology. Devices based on GaAs technology have become available recently for applications in practical systems⁴ with a data rate capability of 1.5 Gbit/s.

Although the major thrust for development of high data rate fiber optic systems has been for long distance communication links, the local data communication needs have given an new impetus for the development of advanced system components. The recent systems for local communication, such as computer interconnections, rf distributions in phased array radars and instrumentation for basic and applied research, required a high data rate capability.

II. SSC DETECTOR SYSTEM CONSIDERATIONS

The Superconducting Super Collider Detector System will contain calorimetry, particle tracking, electron and muon identification subsystems, each involving typically 100,000 to 200,000 channels of readout electronics.

The overall detector system should be capable of operating with luminosity corresponding to an interaction rate of the order of 10^8 events per second. The required dynamic range is determined by the maximum energy that must be measured without saturation and by the precision that is required at low energy. Typically, the dynamic range will be of the order of 8 bits for the particle tracking chamber and 14 bits for the calorimeter subsystems. Furthermore, the nonlinearity should be less than 1% over the operating range for some subsystems. The high interaction rate, requires adequate time response capability of the readout electronics. In addition to wide dynamic range and fast time response, the readout electronics should have a power dissipation as low as possible, typically less than 50 mW/channel. This low power dissipation would make it possible to locate the entire front end readout electronics directly on or very close to the detector elements thus preserving the hermeticity of the calorimetry.

In general, for the SSC Detector System, if the signal transmission from the detector elements to the remote signal processing electronics and data acquisition subsystems were done by conventional cables it would present an extremely difficult packaging problem and would require an enormous space allocation. This in turn would compromise performance because of electromagnetic interference and signal loss as well as reduced maintainability and

reliability of the complete detection system. To reduce the cable subsystem size and to simplify the overall system architecture it will be necessary to multiplex readout electronics. Using digital and analog fiber optics transmission links and radiation-hardened components will lead to further simplification and size reduction.⁷⁻¹² Furthermore, because the cost of electronics subsystems for SSC detectors will be a major part of the cost of the total detector system, the application of multiplexing digital and analog fiber optics transmission links in front end electronics, triggering and data acquisition will significantly reduce this cost.

An example of the use of fiber optic transmission links is given in Fig. 2 where signals are multiplexed onto the fiber optic waveguide after the Level I Trigger.¹¹ Only sparse data are digitized from all signals emanating from the detector and stored in the buffer memory. After the Level I Trigger has selected the potential events of interest, the data are passed on to the time division multiplexer. The time division multiplexer converts the data from parallel bits to serial bit form for transmission over fiber optic waveguide. After reception of the optical signals, the demultiplexer converts the serial signals back to parallel bits for storage in another buffer memory. The data are then passed through the Level II Trigger, the Software Trigger and on to the Processing Subsystem.

Similarly, another example of the use of fiber optics transmission links is given in Fig. 3 where detector signals are multiplexed before the Level I Trigger.

Another application of fiber optic transmission links is with the use of highly segmented detector subsystems in SSC detectors which require a large number of signal channels even with innovative schemes for sparse data scan logic. For example, high resolution pixel devices might be used for vertex detector which would require many signal channels to be read out from deep within the SSC detector. Highly multiplexed signal channels onto just a few high-speed fiber optic systems could be employed here. Multiplexing would alleviate the problem of the large number of wires which would otherwise be required for parallel dataways operating at tens of Mbit/s speeds.

The hermeticity of SSC detectors will be significantly improved by the use of fiber optics because of their lower space requirements as indicated in the above examples. Furthermore, the immunity to noise pickup and the low mass of fiber optic cables are additional advantages.

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Fig. 2. Simplified block diagram for optical fiber transmission link in SSC detector system where signals are multiplexed after the Level I Trigger.

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Fig. 3. Simplified block diagram for optical fiber transmission in SSC detector system where signals are multiplexed before the Level I Trigger.

Similarly, an application of optical fibers appears attractive for a number of other data transmission and communication tasks in various SSC accelerator systems.

For example data base for the collider beam monitoring subsystems and control system must accommodate approximately 62,000 monitoring and control points.⁶ Each of these points has a number of words in the data base for its description and specification of properties. Monitoring the control points in the data base are divided among the various control subsystems. The control system of the collider consists of a host computer cluster, eight sector computers, two cluster computers, five injector subsystem computers, and approximately 400 distributed front-end processors. These computers and processors are connected together by local networks and a major long haul network of approximately 80 km in length. All the necessary communications from the central control

facility to subsystems around the main accelerator ring will be accomplished by a ring information network which could profitably use optical fiber links instead of broad band coaxial cables. However, analog and digital transmission links and associated electronics components which will be used in the SSC detector and primary beam tunnel will be required to withstand exposure to the nuclear radiation background. Presently preliminary existing radiation background estimates for the dose rate and neutron fluence are $10^{2.5} \times 10^6$ Gy/year and 10^{12} - 10^{13} n/cm²/year, respectively.¹² These values of background radiation are high enough to cause an increase of the transmission loss in optical fibers and measurable degradation of operating characteristics of optical transmitters, receivers and associated electronics.

The author has investigated the feasibility of designing and developing high speed digital and analog data transmission

systems to meet demand of various SSC detector subsystems. Furthermore, a short review of radiation damage in optical fibers, optical transmitters and receivers as well as associated electronics components and subassemblies will be given.

III. TIME DIVISION MULTIPLEXER

A time division multiplexer scheme using parallel to serial data conversion is shown in Figure 4. This multiplexer scheme demonstrates the principle by which data can be prepared for transmission over optical fiber cables.¹⁰ By appropriately controlling the Parallel in/Serial Out lines for the two shift registers (SRA and SRB), SRA is parallel loaded from the Digital Buffer Register A and then serially read out. In the meantime while SRA is being read out, SRB is parallel loaded with data from Digital Buffer Register B and awaits its turn to be read out. Then while SRB is being read out, SRA is again parallel loaded with new data. SRA now awaits its turn to be read out serially. This procedure is repeated until all of the data from the buffer registers are transmitted. Control signals A and B steer the serial data through their respective gates, and the data are combined in the OR gate for presentation to the optical transmitter.

In this manner relatively slow digital operations handle the data to and from the digital buffer registers while extremely high serial data rates are handled by the optical fiber transmission system.

In order to preserve the high data rate capabilities of an optical fiber system, light emitting diode or laser diode transmitters are coupled to single-mode optical fibers. Non-return to zero (NRZ) digital coding format for transmission of data is proposed for wide band data transmission system because bandwidth requirements are effectively one-half that of a return to zero (RZ) pulse code format. The NRZ pulse code format, because of its lower bandwidth requirements, will also contribute to lower bit error rates. Other pulse code formats such as bi-phase, amplitude modulation, frequency modulation and phase modulation are too complex or requiring more bandwidth than NRZ. In conjunction with NRZ pulse coding, 4 bit/5 bit or 5 bit/6 bit encoding/decoding could be used to further improve reliability.

The idle and fiducial words which are OR'ed with the serial data will be described. Their functions are helpful in the operation of the optical fiber system.

Fig. 4. Time division multiplexer.

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Idle words composed of some arbitrary alternating bit pattern are transmitted at the beginning of any new transmission signal. Moreover, idle words are transmitted whenever gaps occur in the transmission signal and loss of synchronization would result at the receiver. More detailed information about data synchronization will be given later in the description of the receiver system.

Fiducial words are transmitted to alert the receiver system that the words immediately following are real data. In addition, fiducial words are transmitted periodically to pull the receiver system back into step in the event that data have become garbled and unrecoverable. Parity bits and other error detecting schemes will also be employed to enhance reliability.

IV. LIGHT SOURCES FOR OPTICAL DATA TRANSMISSION SYSTEMS

Light emitting diodes and semiconductor lasers are the most frequently employed as light sources in optical systems.⁸⁻¹⁰ Light emitting diodes (LED's) 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.

Two basic LED structures are widely used for optical sources in the second generation transmission systems operating at wavelengths of about 1300 nm. These are the surface-emitting and the edge-emitting structures. Both structures use an n-type InP substrate over which four epitaxial layers are grown by liquid-phase or vapor phase epitaxy. The first is an n-InP buffer layer, followed by the light emitting InGaAsP region with the composition chosen to emit an approximately 1300 nm. The light emitting region is followed by a p-type InP cladding layer and a p-InGaAsP contact layer. For the surface emitting structure the light is emitted perpendicular to the grown layer. In the edge limiting structure the light is emitted along the phase of the epitaxially grown layer. The surface emitting LED and edge emitting LED is used as a light source for multimode and single mode fiber systems, respectively.

A surface emitting InGaAsP LED operating at 1300 nm wavelength, having a monolithically form lens for efficient optical coupling, can launch 50-200 μ W of light into a multimode fiber and up to 50 μ W into single mode fiber. The amount of injected

optical power depends on the numerical aperture of the fiber and its core diameter. Although the total available power from an edge emitting LED is smaller than that of surface emitting LED, the higher coupling efficiency to optical fiber compensates for it. Furthermore, edge emitting LED's can be conveniently packaged in an array creating a number of individual addressable elements. At present, an array consisting of 12 LEDs with center-to-center spacing of 250 μ m is available. The array can be aligned to a 12-optical fiber ribbon using a silicon block.

In digital data transmission conventionally designed light emitting diodes are mostly used for moderate speed applications, up to approximately 100 Mbit/s. For higher speeds LEDs having double heterostructures and high-doped active layers are combined with monolithic GaAs integrated circuit drivers. A bit rate of approximately 400 Mbit/s non-return-to-zero (NRZ) pulse transmission have been demonstrated.¹³ The incident light power has been about 15 μ W to 50 μ W-core graded index fiber when a micro-ball lens and spherical ended fiber were used.

A peak electroluminescence wavelength of a surface emitting LED output spectrum is primarily determined by the bandgap composition of the active layer. The peak wavelength value increases with ambient temperature shifting by 0.6 nm/ $^{\circ}$ C for InGaAsP surface emitting diode. The spectral width of the same LED, emitting at 1300 nm, is approximately 100 nm, FWHM. As a result of self absorption along the length of the active layer the spectral width of an edge emitting LEDs is approximately 50 nm. The spectral width of LED should be as small as possible because the rms pulse broadening in the transmission link is directly proportional to the light source spectral linewidth. This results in a limitation on the bandwidth-length product which may be obtained using a particular optical source and fiber.

Analog data transmission by fiber optics in SSC detector systems is highly desirable because it will result in significant reduction of electromagnetic interference and ground loop currents. It will also allow a multiplexing of analog data by means of specially developed hybrid electronics which can be mounted directly on detectors. This will lead to a substantial reduction of the cable plant. However, the operating conditions of the LED, in optical transmitter should be optimized to reduce the device nonlinearity (harmonic and intermodulation products) and temperature dependence to an acceptable level. Accurate nonlinearity measurements performed on

several LEDs showed that the output light intensity depends on the driving current in a nonlinear but predictable way. Therefore, the LED intrinsic nonlinearity will be reduced by the local nonlinearity compensation using predistortion.

Semiconductor lasers are the most frequently employed as light sources in optical broadband systems because of their compactness and high level of efficiency in comparison to light emitting diodes. The semiconductor compounds, indium gallium arsenide phosphide $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ has emission wavelengths between 920 and 1620 nm, depending on its composition, making it particularly suitable for 1300 nm zero dispersion wavelength of an optical silica fiber.

Various types of semiconductor lasers, their structure and characteristics as well as pertinent optical processes, such as absorption, spontaneous emission and stimulated emission are extensively treated in the literature.⁶⁻¹⁴ For the wide band data transmission system of particular interest are laser structures that employ a variation in the real-refractive index along the junction plane to form an optical waveguide. These index-guided injection InGaAsP lasers are almost free from the light output nonlinearities because of excellent mode stability. The index-guided laser with a thermoelectric cooler, temperature sensor unit power monitor and associated circuitry are packaged in a single module.⁸ The integral thermoelectric cooler maintains the laser and power monitoring photodiode temperatures at 25°C over an ambient temperature range of -40°C to +65°C. Also, an internal InGaAsP PIN photodiode, mounted directly behind the laser diode functions as a power detector. The photodiode monitors the emission from the rear facet of the laser and controls the optical power level sent into the fiber.

Using an index-guided injection InGaAsP laser the optical transmitter has the following characteristics: emission wavelength = 1300 nm, maximum data rate capability = 1.7 Gbit/s, CW optical power = 2.5 mW (+4dBm), spectral width = 4 nm, rise and fall time smaller than 100 ps, RMS spectral width smaller than 2 nm, laser threshold current = 20 mA, laser forward current for maximum optical output = 40 mA, laser forward voltage at output power of 1 mW = 1.3 V, and life greater than 10⁵ hours. A typical optical spectrum of the output light is shown in Fig. 5.

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Fig. 5. Typical spectrum of the laser diode transmitter output.

V. OPTICAL SOURCES IN A RADIATION ENVIRONMENT

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.¹¹⁻¹⁵ 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.

Irradiation test performed on InGaAsP LEDs with γ rays, operating at 1300 nm, showed that no significant degradation of parameters can be observed¹⁶ with total doses of less than 10⁵ Gy. The light output power decreased by 5% from its initial value upon an irradiation dose of 10⁶ Gy. It was also estimated, that the light output power decreases to 50% of its initial value for the total dose of 2 $\times$ 10⁷ 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. 6. The data are shown for the following devices: Plessey InGaAsP-High Radiance LED, Laser Diodes Laboratories GaAlAs IRE-160-High Radiance LED, Texas Instruments GaAlAs LED, Radio Corporation of America InGaAs LED, Hewlett Packard GaAs 4120 LED, and Texas Instrument GaAs: Si, Si 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 at typical operating conditions. These devices can provide sufficient light output for many applications even after neutron fluences in excess of 2×10^{14} n/cm².

Devices with GaAs:Si,Si junction are significantly more sensitive to radiation. The minority carrier lifetime in these LEDs is very long, typically 200-400 ns. Consequently, the output light decreases for approximately 10^3 when compared with typical GaAlAs LEDs at neutron fluence of 10^{14} n/cm², Fig. 6. The GaAs:Si,Si devices were originally developed for high light output.

More recent studies of the effect of neutron irradiation on LEDs fabricated from strained-layer superlattice structures in the GaAs/GaAsP configuration show that there is no light output degradation until a fluence of approximately 3×10^{14} n/cm² is exceeded.¹⁵

Radiation induced degradation of the light output from the semiconductor laser diode is caused by a reduction of minority carrier lifetime resulting from displacement damage. Total light output of a GaAs laser diode as a function of current density with neutron fluence as a parameter is shown in Fig. 7. In the subthreshold region 1 of the characteristics, the laser behaves like a light emitting diode. The light output, at constant current, decreases with neutron fluence at about the same rate as for LEDs. At the beginning of lasing action (region 2) the neutron irradiation causes a stronger decrease in light output. Finally, when the device is deeply in the lasing action (region 3), irradiation does not have a significant effect until the increase in the threshold current density prevents the laser from reaching region 3. Minority carrier lifetimes are of order 1 to 10 ps in GaAs junctions under intense stimulated emission. The lifetimes are of order

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Fig. 6. Normalized light output as a function of the neutron fluence for various LEDs under constant current operating conditions.

1-10 ns in sub-threshold region. Therefore, a much larger concentration of radiation induced defects is required to influence the radiative recombination rate in lasing region. Consequently, for a radiation environment a semiconductor laser diode should be selected with a low threshold current and a very high maximum operating current. Recently developed double heterostructure GaAs laser diodes are still capable of lasing action after a neutron fluence in excess of 2×10^{14} n/cm².

VI. TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

The basic transmission mechanisms of the various types of optical fiber waveguide have been discussed elsewhere.⁸⁻¹⁷ Basically, the most important transmission characteristics of optical fiber are attenuation and bandwidth.

The attenuation or transmission loss, of optical fibers is influenced by the material composition, the fiber preparation technique and the waveguide structure. In particular, the attenuation is determined by material optical absorption, material scattering, macrobending and microbending losses, mode coupling radiation losses and

Fig. 7. Light output as a function of current density with neutron fluence as parameter for GaAs laser diode.

losses due to leaky modes. Furthermore, there are also losses at the input and output connectors. In Fig. 8 the typical attenuation spectrum is shown for some state-of-the-art single-mode optical fibers.⁶⁻¹⁷ The attenuation characteristics are shown for three major fiber preparation processes: (a) inside vapor deposition, (b) vapor-phase axial deposition and (c) outside vapor deposition.

In practical optical fibers, prepared by above mentioned processes, a major cause of signal attenuation below a wavelength of about 1500 nm is Rayleigh scattering resulting from excitation of small irregularities (on the order of $\lambda/10$), in the medium by the propagating electromagnetic wave. It is strongly wavelength dependent. The attenuation coefficient per unit length $L_s = A/\lambda^4$, where A is a constant which depends on the refractive index of the medium, the average photoelastic coefficient, the isothermal compressibility and the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the annealing temperature. This λ^{-4} dependence results in considerable attenuation at shorter wavelengths.

In addition to the Rayleigh scattering, attenuation in optical fiber can be caused by Mie scattering from large defects and by Brillouin scattering from the thermally driven density fluctuations that are present in fibers at room temperature. Furthermore, at high power levels, nonlinear loss mechanism such as stimulated Raman and Brillouin scattering can further increase the attenuation and limit the dynamic range of the fiber. Another major extrinsic loss mechanism in fibers is caused by absorption of light in negative hydroxyl ions (OH) trapped during fiber processing. This produces sharp absorption peaks at 1250 nm and 1390 nm and smaller peaks at 750 nm and 970 nm. Since these peaks are present to some degrees in even the highest quality fiber, transmission at these wavelength is usually avoided. The ultraviolet absorption loss is also shown in Fig. 8. This loss is due to the stimulation of electron transition within the silica glass by higher energy excitations. Its value was estimated by extrapolating the data from GeO_2 -doped silica glass. Furthermore, in Fig. 8 the infrared absorption loss is shown. This loss was obtained by extrapolation from the loss characteristics of GeO_2 -doped silica-core fiber and optical data for pure glass at long wavelengths where strong absorption bands are caused from the interaction of photons with molecular vibrations within the glass.

It appears from Fig. 8 that three major manufacturing processes are giving approximately the same attenuation levels. In general, the single-mode attenuation level is intrinsically slightly lower than that for multimode attenuation because of lower core dopant concentrations.⁸ In the figure the typical attenuation highest level is also shown indicating tolerances of the fiber manufacturing process.

The information carrying capacity or bandwidth of a fiber is inversely related to its total dispersion. The total dispersion consists of mode, material and waveguide dispersions. Mode dispersion in multimode fibers is dependent only on the fiber, while the material and waveguide dispersions depend on the width of the wavelength spectrum from the light source.

Mode dispersion occurs in multimode fibers because different modes travel different effective distances through the fiber. This causes light pulse to spread out temporarily as it travels along the fiber.⁸ For multimode graded index fiber this effect limits the bandwidth to approximately 1 GHz per kilometer of length, or 1 GHz $\times$ km.

Fig. 8. Attenuation as a function of transmission wavelength for single mode optical fibers.

Multimode dispersion in a data transmission system can be completely avoided by using a single-mode fiber which carries light only in a single-wavelength mode. In such a fiber no dispersion between modes can exist and very large bandwidths are possible. However, material and waveguide dispersions limit the bandwidth of a single-mode fiber. Waveguide dispersion occurs because light in a single-mode fiber is not confined completely to the core. About 20% of the light travels in the cladding adjacent to a step-index core. The refractive index of the cladding is lower than that of core and so the light travels somewhat faster than in core. The wavelength dispersion is wavelength-dependent, although the change in wavelength dispersion with wavelength is smaller than that of material dispersion. Furthermore, the material and waveguide dispersion can have different signs and thus completely cancel each other out. In conventional germanium-doped silica fibers this "zero-dispersion" wavelength is near 1300 nm.

In Fig 9 the material dispersion of silica, curve (a), and the waveguide dispersion of step-index fibers having core diameters of 3.5 and 11 μm are presented as a function of the wavelength, curves (b) and (c). The combined effect of material and waveguide dispersion is also shown, curves

(d) and (e). Reducing the core diameter has two effects. The zero dispersion point is shifted to longer wavelengths and the gradient of the dispersion in the vicinity of zero gradient point is reduced.

In addition to the dispersion components considered above for single-mode fibers, there are other higher order effects which impose limitations on the maximum bandwidth. These together with secondary effects, such as birefringence which arises from ellipticity or mechanical stress in the fiber core, give a fundamental lower limit to pulse spreading of between 3.5 and 5 ps/km $\times$ nm. The theoretical bit rate for an optical channel is estimated to be between 40 and 57 Gbit/s if an injection laser with rms spectral linewidth of 1 nm is used as a pulsed light source and there is a small amount of intersymbol interference in the channel.⁸

VII. RADIATION-INDUCED ATTENUATION OF OPTICAL FIBERS

The optical properties of fiber waveguide are degraded by exposure to nuclear radiation, primarily through 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. In addition to the

Fig. 9. Dispersion curves of step-index single mode fibers.

radiation-induced absorption light is generated in fibers during pulsed irradiation by photoexcitation of the color centers or by the Cerenkov process.

Radiation-induced attenuation consists of a permanent and metastable components. The permanent component lasts for a long period of time after initial exposure. The metastable component consists of a transient part which decays by 10 dB/km in less 1 s after pulse irradiation and a component which decays after 10 s after irradiation. The detailed behavior of the induced absorption depends on a number of factors such as the fiber 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).

The radiation-induced attenuation of fiber initially increases linearly with increasing dose under steady state irradiation as it is shown in Fig. 10. However, at higher doses, the loss characteristic shows saturation due to the recovery processes that occur simultaneously with the fiber darkening. The level of saturation depends upon fiber, radiation and system parameters. In multimode polymer clad silica fibers, having the high OH content core, such as Suprasil,¹¹ manufactured in the last 1970's, saturation levels were near 70 dB/km at a total dose of 10^2 Gy and operating wavelength of 820 nm. At doses higher than 10^2 Gy the induced loss decreased with increasing dose due to the radiation and photobleaching of color centers causing the absorption loss. Also, at doses larger than 10^4 Gy the fiber loss increased drastically because of embrittlement of the polymer. In multimode pure silica core fibers with fluorine doped cladding manufactured in the middle 1980's saturation levels are near 5 dB/km at dose of 10^2 Gy.¹¹⁻¹⁸

Radiation induced attenuation for multimode Dainichi-Nippon St-100B fiber is shown in Fig. 10 using a LED injected optical power of 1 μ W and a fiber length of 50 m. This fiber has a SiO₂ 100 μ m-diameter core, with a fluorine/boron doped SiO₂ 140 μ m-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.¹¹

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Fig. 10. Radiation-induced attenuation in Dainichi-Nippon St-100 B fiber for 1.9 and 3 Gy/min γ dose rate.

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. 11.¹⁹ This fiber was fabricated by the vapor axial deposition process. The fiber core diameter and cladding diameter is 8.5 μ m and 125 μ m, 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 ⁶⁰Co 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. 11 that the radiation-induced attenuation is 20 dB at total dose of 7×10^4 Gy and dose rate of 10^3 Gy/hour.

Similar measurements were performed on the fiber waveguide with the same geometry as given above but with germanium doped silica core and pure silica cladding. Under identical measuring conditions this fiber

Fig. 11. Radiation-induced attenuation as a function of total dose with dose rate as parameter for single mode Sumitomo fiber having pure silica core.

showed a radiation-induced attenuation of 20 dB at a total dose of 1.5×10^4 Gy and dose rate of 10^2 Gy/hour.

Furthermore, both fiber waveguides were irradiated with 14 MeV neutrons. The neutron induced attenuation of 20 dB was obtained after approximately 0.6 hour of irradiation for germanium doped core fiber. The attenuation increased up to 70 dB/km after 3.5 hours of irradiation (neutron fluence of 1.5×10^{14} n/cm²). However for pure silica core fiber the induced attenuation reached approximately 10 dB/km after the same irradiation time. Experimental results have clearly showed that a pure silica core fiber has significantly lower radiation sensitivity than a germanium doped silica core fiber for both γ -ray and neutron irradiation.

VIII. OPTICAL RECEIVER CONSIDERATIONS

The optical fiber receiver design requires careful attention for data transmission systems having a high-bit-rate capability. The receiver performance characteristics, such as sensitivity, dynamic range, bit rate transparency, bit pattern independency and acquisition time are functions of both the photodetector and receiver preamplifier configuration as well as operating bit rate.²⁰

A simplified block diagram of a typical digital optical receiver is shown in Fig. 12. The input optical signal is detected by a photodetector. The photodetector is followed by a low-noise preamplifier, an automatic gain control amplifier and a shaping filter. The regenerator samples and detects the signal and regenerates the original data that is being transmitted. The shaping filter minimizes noise and intersymbol interference at the regenerator input. The clock pulses required for sampling are recovered by the timing extraction circuitry which is a typically phase-locked-loop.

After the data are reconstituted by the data recovery circuit they are applied to the shift register along with a clock signal. When the shift register is filled with appropriate data, the data are transferred to the buffer registers via a load command. The act of translating data from serial to parallel demultiplexes the data. Flags will be raised whenever data are improperly transmitted or received. The data from the buffer registers are placed on the dataway for further signal processing. The most important components in determining receiver performance are the photodetector and low-noise preamplifier.

A. Photodetector Characteristics

The most useful photodetectors for optical fiber systems are the PIN and avalanche photodiode. The APD is more sensitive than the PIN diode because of its internal avalanche gain. For the wavelength region around 850 nm photodiodes are fabricated from germanium or several of the III-V components (InGaAsP, GaAlAsSb). At present long-wavelength transmission systems have achieved better performance with III-V compound APD's than with Ge APD's. Ge APD's have relatively higher dark current, unfavorable ratio of ionization coefficients and low absorption coefficient compared with III-V compounds APD's at these wavelengths.²⁰⁻²¹ The APD structure which has achieved very good performance to date has separate absorption and multiplication regions (SAM-APD's).²²

The APD's of this type utilize InP in the multiplication region and a lattice-matched epitaxial layer of InGaAs in the absorbing region. The SAM APD's were developed to eliminate the tunneling component of the dark current in InGaAs APD's. In this structure the p-n junction, and thus the high field region, is located in InP where tunneling is insignificant and absorption occurs in an adjacent layer of InGaAs. To improve the frequency response of the SAM APD's single (or more) InGaAsP transition layer(s) is interposed between the InP multiplication region and the InGaAs

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Fig. 12. Simplified block diagram of a typical digital optical receiver.

absorption region. The transition layer(s) grades stepwise the bandgap energy between that of InP and InGaAs. The net effect of adding the transition layer(s), is to reduce the valence band discontinuity which results in the elimination of most of the charge accumulation at the heterojunction interface. Such structures are called SAGM-APD, where G denotes the presence of one or more grading layers.

The state-of-the-art performance of photodetectors for long wavelengths (1000 - 1600 nm), such as InGaAs APD, InGaAs PIN and InP/InGaAsP/InGaAs SAGM-APD devices, have a quantum efficiency of approximately 80%, response time of 100 ps and a diode capacitance less than 1 pF.²⁰⁻²² The SAGM-APD device with optimized parameters exhibits excellent performance, such as dark current of 2-50 nA, ionization ratio of 0.35, and avalanche gain-bandwidth product of 70 GHz.

B. Digital Receiver Sensitivity

As receiver bandwidth is increased to accommodate higher transmission bit rates its sensitivity decreases mostly because the preamplifier noise increases rapidly with bit rate. The receiver sensitivity is defined as the minimum optical power level required at the receiver input so that it will operate reliably with a bit error rate less than a desired value. In this case it is given as the average optical power $\bar{P}$ required for a bit error rate, (BER), of 10^{-9} .

Bit error rate is defined as the ratio of bits incorrectly identified to the total number of bits transmitted. The receiver sensitivity is also often specified in terms of the average optical power $\eta\bar{P}$ which is detected by the photodetector, where η is the quantum efficiency of the photodetector. Until recently, PIN photodiodes fabricated from InGaAsP alloys grown epitaxially on high quality InP substrates were regarded, as most suitable for use in the low-noise optical receivers of long wavelength communication systems. However,

recently, at high bit rates, reverse biased, avalanche photodiodes exhibit high-speed response in the absence of large dark currents.

Depending on their configuration, preamplifiers for optical receiver are classified into two types: high impedance and transimpedance designs. The high impedance preamplifiers offer the lowest noise level and hence the highest detection sensitivity. However, the frequency response is limited by the RC time constant at the input making necessary an equalizer following the preamplifier to extend the receiver bandwidth. Furthermore, this design has a limited dynamic range due to the high-input load resistance. The transimpedance amplifiers have a large dynamic range and bandwidth due to their negative feedback. However, because of the thermal noise of the feedback resistor the preamplifier noise level is higher and sensitivity is lower than that of a high-impedance design.

Because a detailed analysis of the optical receiver sensitivity have been discussed elsewhere,^{17,20} only results (Fig. 13) will be given here.

It can be seen from this figure that the FET high impedance preamplifier provides the lowest noise level. In general, the advantage of the FET high impedance design over the bipolar transistor high impedance and transimpedance designs is reduced as the operating bit rate increases. As a matter of fact the FET noise power increases at a faster rate than the bipolar transistor noise power with an increase of the operating bit rate. Thus above 5 Gbit/s the bipolar transistor application can result in a smaller noise power level. The exact crossover point is dependent on particular characteristics of the photodiode and receiver preamplifier components.

Also included in Fig. 13 are calculated values of the optical receiver sensitivity for three preamplifier designs using InGaAs avalanche photodiode and PIN photodiode-FET

preamplifier. It can be seen from the figure that if PIN photodiode is used, a low-noise FET preamplifier is necessary to achieve high sensitivity. Furthermore, it can be seen that InGaAs APD's offer receiver sensitivity which is approximately 5-10 dB better than PIN FET receivers at high operating bit rates.

Fig. 13. Optical receiver sensitivity and equivalent input noise power versus operating bit rate.

Germanium avalanche photodiodes can be also used in receiver designs. The sensitivity of a Ge APD receiver is more dependent on temperature because of dominant noise effect of their dark current. Furthermore, Ge APD receiver sensitivity is 5-10 dB lower than that of a receiver of the same design using InGaAs APD.

The dependence of the receiver sensitivity on the preamplifier noise current is also given in Fig. 13. For PIN photodiodes the receiver sensitivity is proportional to $\langle i_n \rangle^{1/2}$. For InGaAs APD with negligible dark current the receiver sensitivity is approximately proportional to $\langle i_n \rangle^{1/4}$. Also from the same expressions the optimum avalanche gain can be calculated as a function of bit rate for various photodetector and preamplifier designs. In general, the optimum avalanche gain is such that the photodetector shot noise is comparable to receiver preamplifier noise. Thus the optimum avalanche gain is higher for a photodetector having lower dark current and lower excess noise. Similarly, optimum gain is lower for a preamplifier having lower noise level. Typically, the

optimum avalanche gain values are from 10 to 35 for InGaAs APD. For the SAGM APD's the optimum gain is approximately 12 at a bit rate of 5 Gbit/s.

At very high bit rates, the limiting gain-bandwidth product, f_{GB} , of an avalanche photodiode can prevent operation at the optimum gain causing a decrease of the receiver sensitivity. Calculations have been made in Ref. 20 for a 1300 nm APD with f_{GB} values of 20 and 50 GHz assuming negligible intersymbol interference and a preamplifier using a GaAs FET having $f_T = 20$ GHz, $C_d = 0.5$ pF and $I_{GATE} = 100$ nA. Calculations have shown that at 5 Gbit/s data rate the sensitivity decrease is 1 and 4 dB for photodiode with $f_{GB} = 50$ GHz and 20 GHz, respectively.

The dark current of a photodetector degrades the receiver sensitivity, as shown in Fig. 13, depending upon the operating bit rate. Our studies have shown that for PIN FET preamplifier, having a photodetector dark current of 10 nA, the receiver sensitivity will be reduced by 0.5 and 1.0 dB from values given in Fig. 13 for bit rates of 10 Mbit/s and 100 Mbit/s, respectively. For an InGaAs APD's with dark current of 6 nA the receiver sensitivity will be reduced by 0.5 dB at 1 Gbit/s.

Very high speed avalanche photodiodes and high-sensitivity optical receivers will have considerable impact on future Gbit/s SSC detector data transmission systems. Results of experimental receiver sensitivities as reported in literature for bit rates up to 8 Gbit/s are summarized in Ref. 20. In general, the receiver sensitivities are still approximately 20 dB above the quantum limit due to the lack of low noise long-wavelength APD's and imperfections of the receiver electronic circuitry. The highest experimental sensitivities have been obtained with InGaAs APD's and high impedance GaAs FET preamplifiers. These best results are still lower than theoretical sensitivities, calculated for an APD receivers by 3 dB at 1 Gbit/s and 8 dB at 8 Gbit/s. The larger difference at the higher bit rate reflects both the limited APD gain-bandwidth product and greater difficulties achieving ideal operation of the electronic circuitry at very high bit rates. Electronic components and subassemblies for bit rates near 1 Gbit/s, such as preamplifiers, decision circuits, multiplexers, and demultiplexers have very good performance. However the same components at 4 and 8 Gbit/s are still in the experimental stage and they will require considerable development before the performance obtained at lower data rates can be achieved. Limited capabilities of

8 Gbit/s electronics components and circuitry causes inter-symbol interference and imperfect receiver equilization.

The 420 Mbit/s and 1 Gbit/s receivers have demonstrated sensitivity of -46.2 dBm and -42.1 dB, respectively.²³ These receivers employed APD's with 18 GHz gain-bandwidth product, and quantum efficiencies $\eta = 95\%$. Results obtained are within 4-6 dB of the best results obtained for receiver sensitivity with receivers employing Si APD's.

The measured sensitivity of the 2 and 4 Gbit/s receivers were -36.6 and -31.2 dBm, respectively.²³ These receivers used SAGM-APD with a gain-bandwidth product of 18 GHz, and a quantum efficiency $\eta = 71\%$. The preamplifier employed high impedance GaAs FET.

The 8 Gbit/s receiver with -25.8 dBm sensitivity employed a SAGM-APD with a gain bandwidth product of 60 GHz, quantum efficiency $\eta = 62\%$ and a high impedance GaAs preamplifier.

IX. OPTICAL RECEIVER IN RADIATION ENVIRONMENT

High sensitivity optical receivers will be required for use in some SSC 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. To achieve the required high performance the best possible detector and receiver configuration should be selected.

The same physical process that make photodetector sensitive for optical radiation also make most detectors sensitive to ionizing radiation. However, the ionizing radiation generates electron-hole pairs uniformly throughout the semiconductor material of the photodiode while optical radiation generates carriers only in the active region of the photodiode pn junction. Consequently low ionizing radiation sensitivity can be achieved by (1) reducing the volume of the active region and at the same time keeping the responsivity of the device to optical signals high, and (2) reducing the volume of the optically nonactive regions of the photodiode. Also, it is beneficial to reduce the collection at the photodiode junction of the ionization radiation-induced carriers from optically non-active regions. The first task can be accomplished by fabricating the photodiode from III-V semiconductors, such as GaAs which has a large absorption coefficient at the wavelength of the optical radiation. In this case the photodiode active region is

very thin, typically several tenths of a micron, offering a very small volume to ionizing radiation. The second task can be accomplished by a heterostructure configuration of the photodiode.¹⁵ In such configuration additional barrier layers are introduced and the geometry of the active region is precisely defined preventing collection of carrier from optically non-active regions of the device.

Various radiation studies were performed on these radiation hardened devices, measuring the increase of leakage current caused by ionization and neutron irradiation.¹⁵ For comparison purposes a figure of merit was introduced, M_{PD} , defined as the ratio of the photodiode signal current per unit of incident optical flux to the ionization induced current per unit of dose rate. The figure of merit $M_{PD} = 40-70 \times 10^{-10}$ Gy/optical photon for a GaAs photodiode in a heterostructure configuration. For comparison $M_{PD} = 0.5-2.0 \times 10^{-10}$ Gy/optical photon for a typical Si photodiode. This and other data 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 photodiodes¹⁵ 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 7×10^{14} n/cm². At this neutron fluence there is no optical responsivity degradation of AlGaAs/GaAs photodiode while 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.

X. ELECTRONIC CIRCUITS IN RADIATION ENVIRONMENT

Associated electronic circuits and subassemblies of digital and analog data transmission systems will suffer a measurable degradation of their operating characteristics when exposed to the SSC nuclear radiation background. Various damaging mechanisms, such as ionization effects and

atom-displacement phenomenon, are responsible for the device degradation. In general, it is assumed that the ionization effects and displacement phenomenon are independent processes, so that damage characterization can be done separately.

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 the respective 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. 14 and 15, respectively.

The long term ionization damage for semiconductor devices depends strongly on the electrical bias condition during exposure and after exposure, measurement time after exposure and ionization radiation energy spectrum at the device. 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. 14. Estimated ranges of total dose damage susceptibility for silicon and gallium arsenide devices.

Fig. 15. 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 on neutron irradiation. Therefore, Si, C MOSFET, JFET and GaAs FET devices are suitable for applications where a high neutron irradiation levels are expected.

A considerable effort is being made in industry to develop radiation hardened semiconductor electronic components and circuits. The hardening techniques include selection of technology, special process procedures, device layout and circuit design, circuit computer simulation and selection of optimum operating conditions to achieve the desired value of radiation tolerance.²⁷

XI. 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 will be realized with 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 expected in the SSC environment. Systems design will then include adequate optical power margins to maintain the signal-to-noise ratio necessary for reliable operation. It is essential to evaluate the expected incremental optical power loss in various SSC data transmission systems.

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 in the SSC detector system and primary beam tunnel. 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.

It will be necessary to evaluate contemporary low radiation sensitivity fibers made by several manufacturers at long wavelengths for total doses large than 10^2 Gy and dose rates typical for various SSC subsystems.

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