

AEROSPACE INFORMATION REPORT

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Fiber Optic Sensors for Aerospace Applications

RATIONALE

The purpose of this document is to aid in sensor system selection for aerospace applications. It describes both generic and specific qualities of key fiber optic sensing technologies and the range of measurement tasks they are able to perform. This includes:

- A critical and comprehensive comparison between specific optical sensor technologies, currently available, and corresponding non-optical sensing methods. This will assist aircraft component and subsystem designers to assess their suitability and potential for specific applications.
- An appraisal of technology maturity levels and technology gaps.
- Guidelines on the use and application of classes of fiber optic sensors are given including:
 - o sensor and system compatibility (including fiber cable, connectors, interrogator, signal conditioning, network interface, and power requirements),
 - o compatibility with aircraft systems,
 - o standard forms of interrogation/interface,
 - o proposed methods of standardization, and
 - o qualification recommendations.

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1. SCOPE

This document is intended to describe technologies available, application needs, and operational requirements relating to the use of fiber optic sensing systems on aerospace platforms:

- a. To define standard terminology used in describing fiber optic sensing systems and their performance.
- b. To identify current interfaces used for fiber optic sensing systems.
- c. To define environmental, reliability, and maintainability capabilities of fiber optic sensing system components.
- d. To describe the fiber optic sensor and instrumentation technologies that forms the current state of the art.
- e. To describe current and future unmet needs of the aerospace industry for measurements using fiber optic sensors.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4982	Aerospace Fly-by-Light Actuation Systems
ARP5061A	Guidelines for Testing and Support of Aerospace Fiber Optic Interconnect Systems
AIR5271	A Guidline for Application of High Density Fiber Optic Interconnects to Aerospace Platforms
ARP5602	A Guideline for Aerospace Platform Fiber Optic Training and Awareness Education
AIR5667	Fiber Optic Wavelength Division Multiplexed (WDM) Singlemode Interconnect and Component Standards Mapping for Aerospace Platform Applications - Device Level Specification
AS5659	WDM LAN Specification
AIR6004	Optical Networking Terminology
AIR6005	General Requirements for WDM Backbone Networks
AIR6006	Modeling and Simulation Capabilities for Aerospace WDM LAN Application
AS6021	Aerospace Fiber Optic Cable Assembly Drawing Specification
ARP6031	Fiber Optic Cleaning

2.2 U.S. Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

MIL-HDBK-217	MILITARY HANDBOOK RELIABILITY PREDICTION OF ELECTRONIC EQUIPMENT
MIL-STD-810	ENVIRONMENTAL ENGINEERING CONSIDERATIONS AND LABORATORY TESTS
MIL-STD-1773	FIBER OPTICS MECHANIZATION OF AN AIRCRAFT INTERNAL TIME DIVISION COMMAND/RESPONSE MULTIPLEX DATA BUS
MIL-DTL-83723	CONNECTORS, ELECTRICAL, (CIRCULAR, ENVIRONMENTAL RESISTING), RECEPTACLES AND PLUGS, GENERAL SPECIFICATION FOR
MIL-DTL-38999	CONNECTORS, ELECTRICAL, CIRCULAR, MINIATURE, HIGH DENSITY, QUICK DISCONNECT (BAYONET, THREADED, AND BREECH COUPLING), ENVIRONMENTAL RESISTANT, REMOVABLE CRIMP AND HERMETIC SOLDER CONTACTS, GENERAL SPECIFICATION FOR
MIL-PRF-29504	TERMINI, FIBER OPTIC CONNECTOR, REMOVABLE, GENERAL SPECIFICATION FOR
MIL-PRF-49291	PERFORMANCE SPECIFICATION, FIBER, OPTICAL (METRIC), GENERAL SPECIFICATION
MIL-PRF-85045	PERFORMANCE SPECIFICATION, CABLES, FIBER OPTICS, (METRIC), GENERAL SPECIFICATION FOR

2.3 Other Documents

TIA-440B	Fiber Optic Terminology
ARINC 801	Fiber Optic Connectors
ARINC 802	Fiber Optic Cables
ARINC 805	Fiber Optic Test Procedures
ARINC 806	Fiber Optic Installation and Maintenance
IEC 62627	Fiber Optic Interconnecting Devices and Passive Components – Fiber Optic Connector Cleaning Methods
ANSI Z136.2	American National Standard for the Safe Use of Lasers
RTCA DO-160	Environmental Conditions and Test Procedures for Airborne Equipment

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- [3.3.1] ANSI 2136.1 – 2000
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2.5 Definitions

2.5.1 Acronyms

The following acronyms may be used in this document:

ADOCS	Advanced Digital Optical Control System
AEEC	Airline Electronic Engineering Committee
AGC	Automatic Gain Control
AOPT	Advanced Optical Position Transducer
APC	Angled Physical Contact
APD	Avalanche Photo Diode
ARD	Aerospace Resource Document
ARP	Aerospace Recommended Practice
ASIC	Application Specific Integrated Circuit

AWG	Array Waveguide Gratings
BER	Bit-Error-Rate
BIT	Built-In-Test
CCD	Charge-Coupled-Device detector array
CW	Continuous Wave (not sine wave, etc.)
CWD	Coarse Wavelength Division Multiplexing
CMOS	Complementary Metal Oxide Semiconductor
DOD	Department of Defense
DWDM	Dense Wavelength Division Multiplexing
EMC	Electromagnetic Compatibility
EMI	Electro-Magnetic Interference
EMP	Electro-Magnetic Pulse
FADEC	Full Authority Digital Engine Control
FBG	Fiber Bragg Gratings
FP	Fabry-Pérot
FSR	Free Spectral Range
FWHM	Full Width at Half Maximum
HALT	Highly Accelerated Life Test
IDP	Integrated Detector Preamplifier
IEC	International Electrotechnical Commission
LED	Light Emitting Diode
LD	Laser Diode
LPG	Long Period Grating
MI	Michelson Interferometer
MT	Multifiber Termination
MZI	Mach-Zehnder Interferometer
OBR	Optical Backscatter Reflectometer
OFCS	Optical Fiber Communication System

OFDM	Optical Frequency Division Multiplexing
OFDR	Optical Frequency Domain Reflectometer
OTDR	Optical Time Domain Reflectometer
PC	Physical Contact (connector)
PCF	Photonic Crystal Fiber
PD	Photodiode
PIN	Positive-Intrinsic-Negative photo diode
PSD	Position Sensitive Device
RL	Return Loss
SDM	Spatial Division-Multiplex
SLD	Superluminescent Diode
SWAMP	Severe Wind and Moisture Problem
TDM	Time-Division-Multiplex
UPC	Ultra Physical Contact (connector)
WDM	Wavelength-Division-Multiplex

2.5.2 General Definitions

Within this document certain terms related to fiber optic sensors and their avionics application are defined as follows:

BUILT-IN-TEST (BIT): A testing routine that is initiated to assist in diagnosing a suspected system fault.

DIAGNOSTICS: A system of self-generated routines that detect and isolate faults. These routines are usually performed during the initial power-up phase ("power-up test"), but may also provide system fault detection during the normal operational state.

DETECTOR: A transduction device that transforms optical to electrical energy according to a defined relationship; a photodetector.

EMITTER: A transduction device that transforms electrical to optical energy, and launches optical radiation, according to a defined relationship; an optical source.

EXTRINSIC: Wherein modulation of the light beam by the measurand within the sensor occurs externally to the fiber's light guiding regions.

FIBER OPTIC: Examples of preferred usage include: Adjective. The "fiber-optic" data link is 200 meters long; common industry usage is, however, "fiber optic". Singular noun: Each cable has a single "optical fiber". Plural noun: "Optical fibers" are being tested. Plural, singular construction: "Fiber optics" is in test. (Obsolete: "Fiber optics" from four vendors were tested.)

FIBER OPTIC SENSOR: A sensor containing mechanical components that include a fiber optic transducer and that is connected to a fiber optic signal path(s).

FIBER-OPTIC-BASED SENSOR: Any sensor employing a fiber optic signal path.

HEALTH MONITORING: The acquisition of data from specialized sensors that measure various parameters related to structural integrity, readiness, ability to perform a mission, or other similar attributes of a major subsystem.

INTERFACE: (1) A shared boundary. (2) That part of a sensor system that includes the optical detector and receiver plus circuits to reformat the electrical signal for the end user (may also contain an optical emitter for generation of a transducer driving signal). (3) Those parts of a data bus system where optical/electrical conversion takes place.

INTERFACE, OPTICAL: An arbitrary point at which signals are in optical form.

INTERFACE, SIGNAL: An arbitrary point at which the effect of the measurand is available in a form directly usable for control or measurement purposes.

INTERROGATOR, (1) That part of a sensor system that includes the optical detector and receiver plus circuits to reformat the electrical signal for the end user (may also contain an optical emitter for generation of a transducer driving signal). (2) Those parts of a data bus system where optical/electrical conversion takes place.

INTRINSIC: Wherein modulation by the measurand of the light beam within the sensor occurs internally to the fiber's light guiding regions.

MEASURAND: That physical phenomenon, parameter, quantity, property, or condition that is to be measured.

MULTIPLEX: The act of combining several signals on a common transmission path. In the sensor usage "WDM" and "TDM", the term MULTIPLEX refers to the combining of those signals from a SINGLE transducer that represent the different digits or aspects of the encoded intelligence. More generally, MULTIPLEXING refers to the combining of signals from SEVERAL sensors.

OPTICAL MULTIPLEXER: A bi-symmetric device for separating two or more optical signals arriving on a single fiber path onto separate paths, or for combining such signals arriving from separate paths to a single fiber path. Also called a splitter/combiner.

RECEIVER, FIBER OPTIC: A fiber optic detector (optical to electrical converter) plus signal conditioning circuits.

SELF-CHECK: A means to passively verify the accuracy of output data.

SELF-TEST: A means for a circuit or system to acquire a real time measure of its capacity to perform within design limits.

SENSOR: A transducer plus the means for formatting a signal that carries intelligence about the measurand plus mechanical packaging suited to the intended application and environment. The sensor is that essential device or combination of devices that measures some property of the real world and informs the user of the measurement results.

SENSOR, HYBRID, (FIBER-OPTIC COUPLED): A sensor having an electrical transducer and associated circuits that employs a fiber optic signal transmission path. One example is the "power-by-light" scheme that is powered remotely through optoelectrical conversion.

SENSOR, MODULATED, FIBER OPTIC: A sensor having a transducer that modulates an optical carrier signal supplied by its interface module. One example is a time (or wavelength) division multiplexed code-plate device.

SENSOR, SELF-LUMINOUS, FIBER OPTIC: A sensor having a transducer that derives optical power from the transducer environment, or internally generates optical power, the nature of which is determined by the measurand. Examples include a pyrometer and a black-body radiation thermometer. Such sensors require no source of optical or electrical power from the interrogator or interface module.

SENSOR SYSTEM: A sensor together with the necessary interconnection line(s) and the interrogator or interface circuits.

STANDARD SENSOR INTERFACE: A universal interface circuit capable of interchangeably servicing the sensing elements for many types of measurand.

TERMINI: Hardware used to constrain and physically position optical fibers at a signal-path disconnect point. A terminus is the optical equivalent of an electrical pin or socket contact.

TRANSDUCER, FIBER OPTIC: That portion of a fiber optic coupled sensing system that responds to the measurand based on some defined physical relationship; also known as the "sensing element". Any such mechanism, internal or external to the fiber, that causes a change to the characteristic parameters of light injected into or propagated by an optical fiber (phase, intensity, wavelength, polarization, pulse frequency) in accord with the measurand (pressure, temperature, acceleration, displacement, field strength, etc.). It is one part of a sensor; not a stand-alone device.

TRANSMITTER: A device comprising an emitter plus its driving and controlling circuitry. **Sensor Definitions:** The universal or "standard" sensor interface, as above defined, is sought after as an improvement over the common proliferation of different electrical interfaces. Consequently, it is logical to group transducers and sensor systems on the basis of this important parameter. However, the complexity and nature of the sensor itself is also a logical means of classification. Examination of the literature shows ambiguity and contradiction between various organizations in their sensor classification schemes. Since general agreement on meaning of the terms "passive" and "active" is lacking, this document will abstain from using these terms. The term "hybrid", as used herein, appears to be better accepted.

3. LASER SAFETY

3.1 General

LASER stands for Light Amplification by Stimulated Emission of Radiation. Light transmitted from a light bulb (or flash light) will diverge, while light emitted from a laser will remain a tightly focused beam. So the radiant energy (energy per unit area) reaching an eye from a laser will be more concentrated than from a light bulb, when both are at the same distance from the eye. A more concentrated beam of light results in more potential damage to the eye.

Lasers can be characterized by power level, divergence, and wavelength. Optical power level is measured in Watts (joule/sec) or dBm. Joule (J) is the unit of measurement for energy, and power is the energy per unit time. The radiance is the radiant energy emitted in a specified direction by a unit area of an emitting surface. Radiant energy (or radiant exposure) is the accumulated amount of incident energy per unit area, while irradiance expresses the power emitted from a surface. Refer to Table 1 for a list of units.

TABLE 1 - UNIT OF MEASURE FOR TRANSMITTED LIGHT

	Energy	Power	Radiance	Irradiance
Definition	Force x Distance	Energy/ Time	Energy/Area	Power/Area
	Newton (N) x m	J/sec	J/m ²	Watt (W)/m ²
Unit	J	W		

3.2 Eye Hazards

Damage to the eye occurs by the absorption of a large amount of light. The eye structure and transmission path of light is shown in Figure 1. Light transmitted but not absorbed and light that is reflected by the eye cause no eye damage. Table 2 lists the wavelength regions of light, with the eye parts primarily affected, and with the types of damages possible.

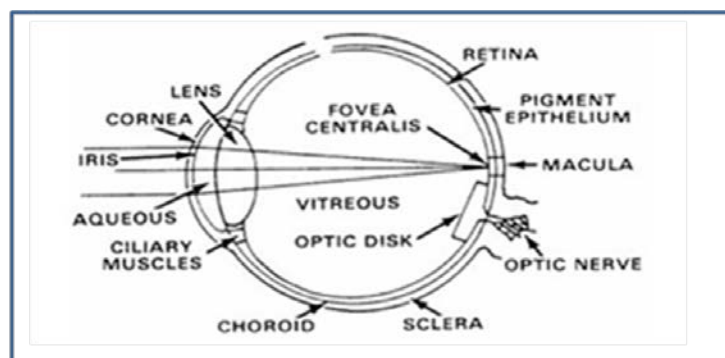


FIGURE 1 - EYE STRUCTURE AND TRANSMISSION PATH OF LIGHT

TABLE 2 - EYE INJURIES AFFECTED BY LIGHT

Region	Wavelength Range (nm)	Absorption Reaction	Affected Part of Eye	Type of Damage
VISIBLE	400-780	Photochemical Thermal	Retina	Retinal Injury
INFRARED A	780-1400	Thermal	Retina	Cataract, Retinal burn, Lens damage
INFRARED B	1400-3000	Thermal	Cornea	Corneal burn, Aqueous flare cataract

3.3 Laser Classification

The American National Standards Institute (ANSI) is an organization which sets industry consensus standards in various fields. The ANSI Z136 Committee has published seven standards specific to the laser field [3.3.1]. The version of the main ANSI Z136.1 Standard (Z136.1-2000) assigns lasers into broad hazard Classes (I, II, IIIA, IIIB, and IV) depending on the potential for causing biological damage. Classification is determined by calculations based on exposure time, laser wavelength and average power for Continuous Wave (CW) or repetitively-pulsed lasers and total energy per pulse for pulsed lasers. Tables 3 and 4 show the 2001 laser classification for CW laser and its control measures.

TABLE 3 - LASER CLASSIFICATION FOR CW LASER [ANSI]

Wavelength	Class I	Class II	Class IIIA	Class IIIB	Class IV
Safety rules	No	Moderate	Yes	Yes	Yes
Ultraviolet 180-302 nm 302-400 nm	$< 9.6 \times 10^{-9} \text{ W}$ $< 3.2 \times 10^{-6} \text{ W}$	None	$< 5 \text{ mW}$	5-500 mW	$> 0.5 \text{ W}$
Visible 400-700 nm	$< 0.4 \times 10^{-6} \text{ W}$	$< 1 \text{ mW}$	1-5 mW	5-500 mW	$> 0.5 \text{ W}$
Near IR 700-1400 nm	$< 9.6 \times 10^{-3} \text{ W}$	None	$< 5 \text{ mW}$	5-500 mW	$> 0.5 \text{ W}$

TABLE 4 - CONTROL MEASURES FOR THE LASER CLASSIFICATION [ANSI]

Laser Classification	I	II	IIIA	IIIB	IV
Protective housing	X	X	X	X	X
Labels	X	X	X	X	X
Warning signs			S	X	X
Protective barrier & curtain				S	X
Key control				S	X
Remote Interlock				S	X
Standard operating procedure				S	X
Training		S	S	X	X
Protective equipment					
Eye protection				S	X
Skin protection				X	X

X: Shall (required) S: Should (recommended)

ANSI modified the laser classification in 2007, while the earlier lasers are still following the 2001 classification and control measures. The current laser classification and its control measures are published on the ANSI Z136.1 document. Table 5 is the basic summary of the classification [3.3.2].

TABLE 5 - BASIC SUMMARY OF THE LASER CLASSIFICATION [ANSI]

Laser Class	Power limit	Summary
1	$< 0.4 \times 10^{-6} \text{ W}$	Safe for direct beam viewing under all conditions (i.e., with and without optical aids). Maximum exposure duration is assumed to be 30 000 seconds (8 hour period) for visible light lasers and 100 seconds for infrared lasers.
1M	$< 4 \times 10^{-6} \text{ W}$	Safe for viewing only without optical aids. Not safe for viewing with magnifiers or microscopes for a diverging beam or with binoculars or telescopes for collimated beam.
2	$< 1 \text{ mW}$	Safe for momentary viewing of direct beam under all conditions. Class 2 only to visible light lasers. There is a hazard potential if viewed for an extended period. The beam may be viewed directly only under carefully controlled exposure conditions. Class 2 is not hazardous for viewing periods up to 0.25 s.
2M	$< 1 \text{ mW}$	Safe for momentary viewing of direct beam only without optical aids. Limited to visible light lasers. Class 2M is not hazardous for viewing periods up to 0.25 s only by the unaided eye. Not safe for viewing with magnifiers or microscopes for a diverging beam or with binoculars or telescopes for collimated beam.
3R	1-5 mW	Potentially hazardous under some direct and specular reflection viewing conditions if the eye is appropriately focused and stable, but the probability of an actual injury is small. This laser will not pose either a fire hazard or diffuse-reflection hazard.
3B	5-500 mW	Hazardous for direct beam viewing. Not hazardous for viewing of reflection off diffuse surface. Direct beam viewing does include the viewing of reflections from specular surfaces
4	$> 0.5 \text{ W}$	Hazard for both eyes and skin of the direct beam and reflections off diffuse surface. This class laser can be a fire hazard also. The class is applicable to high power lasers, not the lower power, semiconductor diode lasers used in OFCS (optical fiber communication systems).

4. INTRODUCTION TO FIBER OPTIC BASIC THEORY

4.1 Optical Fiber

4.1.1 Propagation of Light

Optical fiber is a light transmitting medium based on total internal reflection. Optical fibers are comprised of core and cladding. Generally the core is the light transmitting medium, and the cladding is the boundary material which insures that the light will be totally internally reflected (or "bound") in the core (see Figure 2).

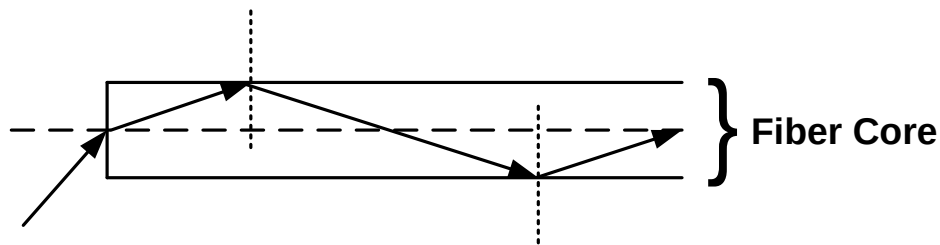


FIGURE 2 - TOTAL INTERNAL REFLECTION

For total internal reflection in the core two conditions must be satisfied.

- The index of refraction of the core material must be larger than the index of refraction of the cladding material,
- The light incidence angle at the core-cladding interface must be larger than the critical angle.

INDEX OF REFRACTION, n

The index of refraction of a material n is defined as the ratio of the velocity of light in vacuum to the velocity of light in the medium, as expressed below:

$$n = \frac{c(\text{velocity of light in vacuum})}{v(\text{velocity of light in medium})} \quad (\text{Eq. 1})$$

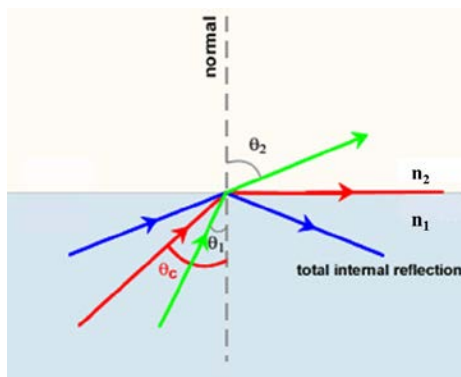
The most common values of n are well known. $N = 1$ in vacuum, $n = 1.003$ in air, $n = 1.33$ in water, $n = 1.5 - 1.9$ in most common glasses, and $n = 1.45 - 1.49$ in common optical fibers.

TOTAL INTERNAL REFLECTION:

Light propagates between two media according to Snell's law, which can be expressed as:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 ,$$

where n_1 and n_2 are the indices of refraction in the two media and θ_1 and θ_2 are the angle of incidence and angle of refraction. An illustration of the light propagation is shown in Figure 3. The velocity of light, v , in a medium depends on the index of refraction of the medium.



$$\frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad (\text{Eq. 4.1.2})$$

FIGURE 3 - SNELL'S LAW

Total internal reflection occurs when θ_2 is greater than 90 degrees and all incident light is reflected.

If θ_2 is 90 degrees, $n_1 \sin \theta_1 = n_2$, and θ_1 is expressed as critical angle, θ_c . If the incident angle is greater than the critical angle, the incident light will be reflected totally (total Internal reflection), and this is the way light is transmitted in an optical fiber.

NUMERICAL APERTURE:

Numerical aperture, NA, is a parameter to express the light gathering ability of an optical fiber as shown on Figure 4. For a fiber in a medium with index of refraction, n , the numerical aperture can be expressed as $NA = n \sin \theta_{\max}$. If $n=1$ (air), $NA = \sin \theta_{\max} = (n_1^2 - n_2^2)^{1/2}$. So the value of numerical aperture must be between 0 and 1.

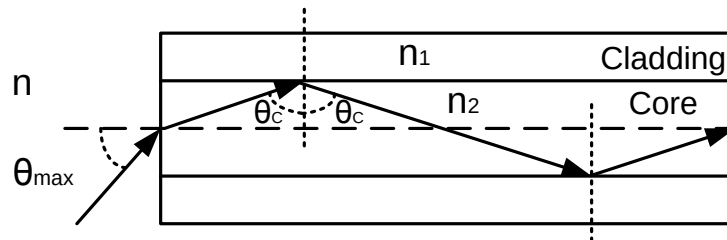


FIGURE 4 - LIGHT PROPAGATION AND NUMERICAL APERTURE

ACCEPTANCE CONE:

The angles at which rays will be propagated into core of a fiber ($< \theta_{\max}$), and these angles form a cone (see Figure 5).

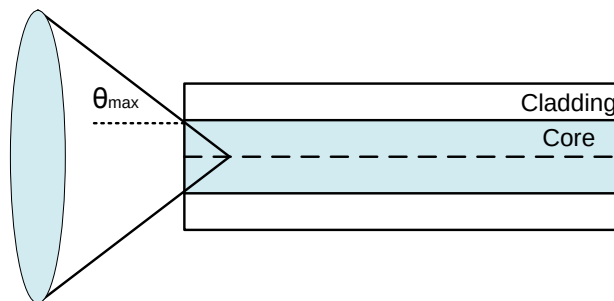


FIGURE 5 - ACCEPTANCE CONE

4.1.2 Optical Fiber Cable

Optical fiber cable is constructed by adding strength member and jacketing over the optical fiber. One example of the basic components of optical fiber cable is shown in Figure 6.

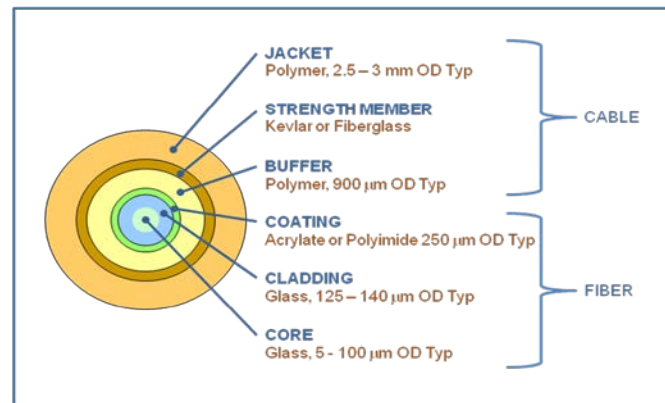


FIGURE 6 - TYPICAL FIBER OPTIC CABLE

4.1.3 Fiber Characteristics

Light propagation through fiber depends on the size of the fiber, the fiber type, the materials of which it is made, and its index profile.

FIBER TYPES

Fiber types can be expressed by the core/cladding sizes and the index profile. For example, 50/125 micron (μm) fiber indicates that the core is 50 μm in diameter and the cladding is 125 μm in diameter. There are two general types of fiber on the market, single mode and multimode fiber. Also, fiber can be classified as step-indexed or graded-indexed.

- **Single mode fiber:** Single mode fiber transmits one transverse mode of light only. Single mode fiber has a small core, generally 5 to 10 μm in diameter, and is most often used in the 1310 to 1550 nm wavelength regions.
- **Multimode fiber:** Multimode fiber has a larger core size, typically 50 to 200 μm in diameter, and transmits many modes of light.
- **Step indexed fiber:** The index of refraction of the core is uniform throughout.
- **Graded index fiber:** The index of refraction of the core varies with radial distance from the center.

FIBER INDEX PROFILE

Light propagation inside a fiber depends on the index profiles as illustrated in Figure 7 [4.1.1].

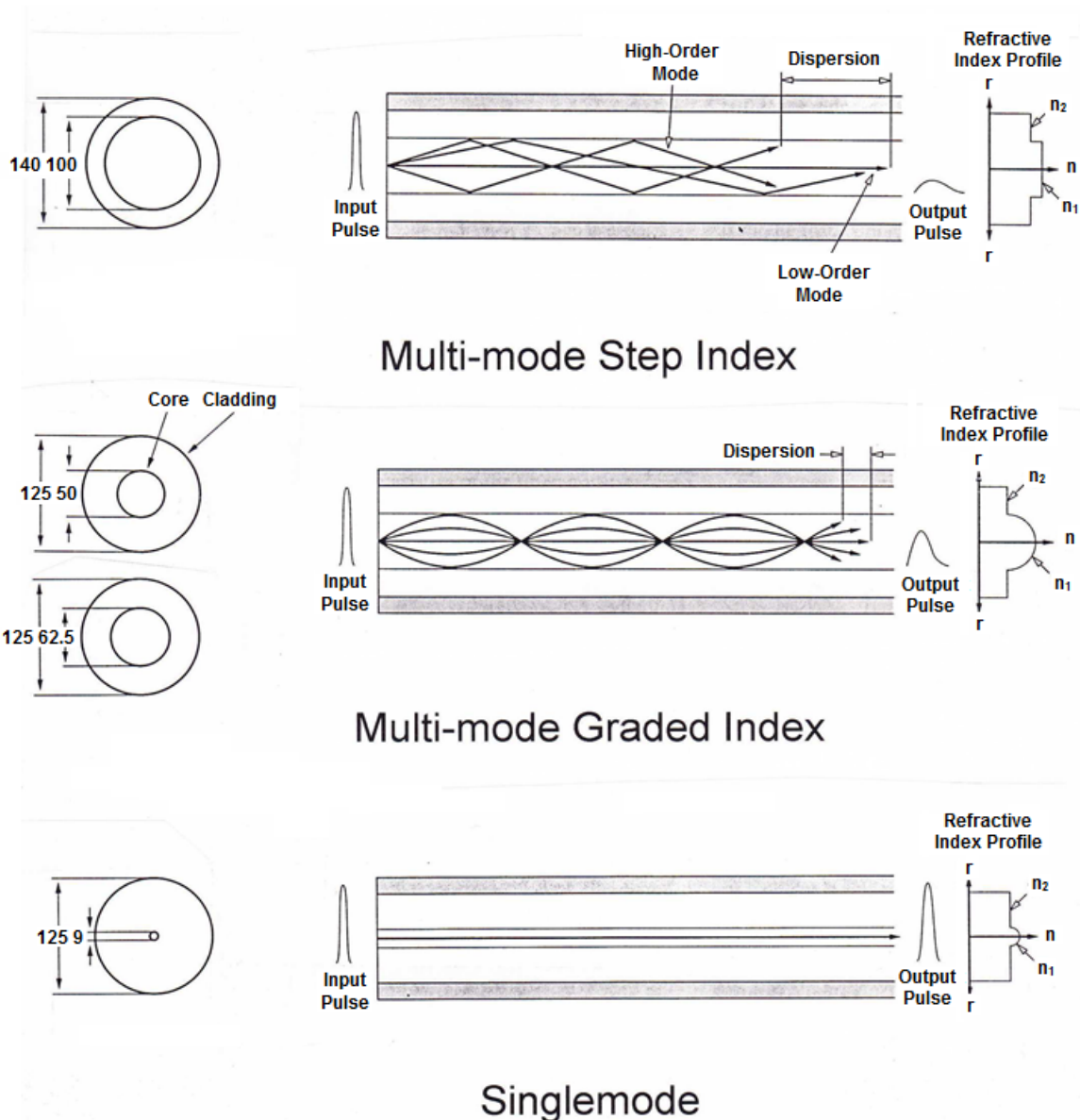


FIGURE 7 - LIGHT PROPAGATION IN COMMON TYPES OF FIBER

DISPERSION

The spreading of light pulses as they travel through an optical fiber is referred to as dispersion. Dispersion depends on the path length (l), wavelength (λ), index of refraction (n), and polarization of the light.

- Modal dispersion: occurs since the optical path length of each mode is different in multimode fiber.
- Material (chromatic) dispersion: occurs since different wavelengths of light travel at different velocities through most materials including most fibers.
- Wave guide dispersion: occurs since light travels at different speeds in different materials.
- Polarization mode dispersion (PMD): occurs due to different polarization states travelling at different speeds.

ATTENUATION

When light travels through a fiber the power is attenuated by scattering, absorption, and other faults of the materials. Also the light can be attenuated by bending, temperature, and other stresses on the fiber depending on the environmental conditions. The typical attenuation of a silica fiber is shown in Figure 8 [4.1.1].

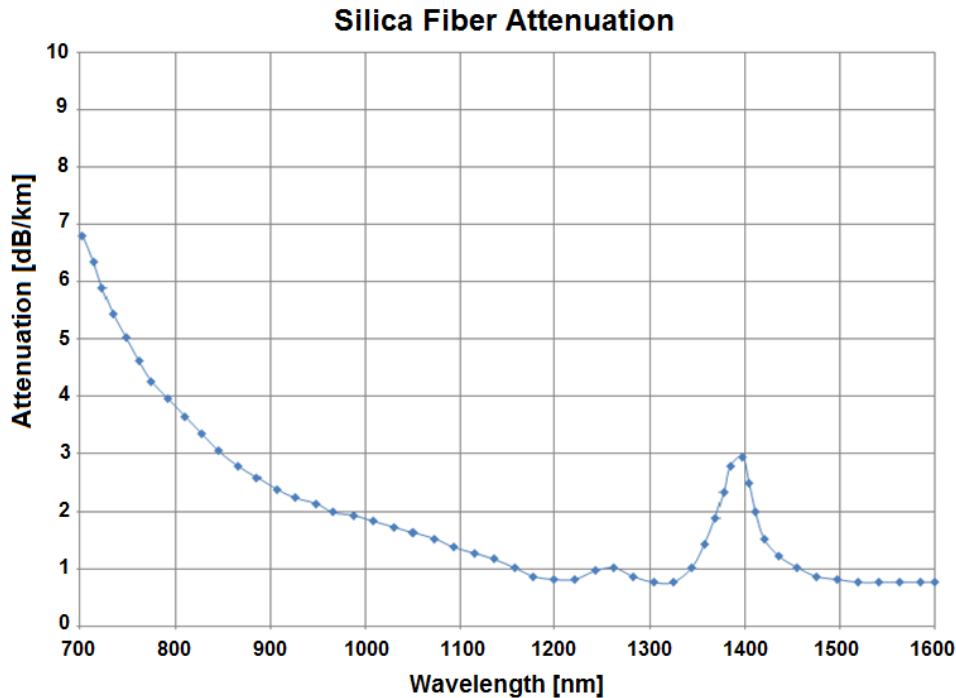


FIGURE 8 - TYPICAL ATTENUATION OF A SILICA FIBER AS A FUNCTION OF WAVELENGTH

4.2 Fiber Optic System Active Components

4.2.1 Sources

The choice of an optical source generally depends on the type of sensor used. In most cases, the small core diameter and the low numerical aperture of an optical fiber calls for a source with a small size and a low emission angle.

Semiconductor emitters are generally the components of choice for the coupling of optical power into optical fibers for aerospace systems, compared to lamps or gas lasers because of their better reliability, high efficiency, and small size. A key advantage of semiconductor emitters is their ability to be directly modulated: as the output optical power is generally linear with the driving current, a variation of current at the input will give a modulated optical power at the output.

Fiber lasers, where the active gain medium is an optical fiber doped with rare earth elements, can also be used when high coupled power is needed in a fiber. Those lasers work with a pump laser working at a second wavelength that will charge the doped medium inside the fiber. Optical power at the first wavelength is then amplified as it travels through the pumped medium.

Depending on the sensing application, several parameters of a semiconductor emitter should be specified. Those parameters are described below:

- Output power: The typical power at the output of the emitter for the typical current used.
- Output power ex-fiber: The typical optical power coupled into a defined fiber. This value depends on the diameter of the core and on the numerical aperture of the fiber.

- Emitting wavelength: The central wavelength at which the emission occurs.
- Spectral width (also defined as FWHM): The spectral bandwidth at which the emitted power drops by 50% compared to the peak wavelength.
- Threshold: The threshold current is defined for lasers as the minimum current needed to induce lasing behavior. Over the threshold current, the output optical power is approximately linear with current.
- Efficiency: The ratio between the optical power emitted and the electrical driving power.
- Slope Efficiency: The ratio between the optical power emitted and the electrical driving current. For a semiconductor laser, the driving current is the current added over the threshold current.
- Active area surface: Defined by the length and width of the area which physically emits light.
- Emission angle: The angle at which the optical power drops by 50%.
- Typical coupled optical power: Optical power coupled into a fiber with a defined core size.
- Temperature coefficient for the wavelength: Describes the shift of the central emitting wavelength versus temperature.
- Temperature coefficient for the optical power: Describes the variations of the optical output power versus temperature.
- Electrical bandwidth: The modulation frequency at which the optical output power to current efficiency drops by 50% compared to the continuous efficiency. This parameter can be replaced by the rise time and fall time.
- Forward voltage: Voltage across the electrical pins of the emitter for the typical operation mode.
- RIN: Relative intensity noise: This typical laser noise is defined by the ratio between the square of the optical noise power level in a bandwidth of 1 Hz over the square of the mean emitted optical power.

4.2.2 Photodetectors – Semiconductor Detectors

The optical power level detection function is performed for most sensor applications by semiconductor detectors. Semiconductor detectors are formed by a P-N junction, in which incident photons separate holes from electrons, creating a current called photocurrent. The band-gap energy of the semiconductor used for this junction determines the wavelength range of detection.

The semiconductor detector is one example of the photodetector. There are generally two modes of detection for the photodetector:

- A photovoltaic mode, in which the detector is left unbiased, and where the optical flux creates voltage and current variations at its output. This mode of operation is usually used when low noise is needed and the signals are relatively low in frequency.
- A photoconductive mode, in which the detector is reverse biased. The photodetector outputs a photocurrent proportional to the optical flux. This mode of operation increases the linearity and the speed of response of the detector.

The typical parameters of the photodiode are as follows:

- Responsivity (A/W): This parameter, amps of electrical current generated relative to the incident optical power in watts, indicates the efficiency of the photodetector. Responsivity is specified for a range of wavelengths, and is dependent on the wavelength used.
- Spectral response: Defines the range of wavelengths over which the detector can be used. A filter can be added in front of the photodiode active area if desired in order to reduce the wavelength detection range of the sensor.

- Active area size: Defines the size of the chip area which receives the light that effectively participates in generating output.
- Dark current (A): Defines the minimum current at the output of the photodetector when not illuminated. Dark current can be a problem for two reasons:
 - Dark current is added to the continuous photocurrent and can be a problem when detecting continuous optical levels.
 - Dark current adds shot noise at the output of the converter.
- Noise equivalent power ($\text{W/Hz}^{1/2}$): Defines the amount of optical power incident on the detector which generates a photocurrent equal to the noise current in a 1 Hz bandwidth.
- Bandwidth: Defined by the frequencies at which the photodetector response decreases by 50%. It is usually defined with the photodetector connected to a 50 ohms impedance. Bandwidth depends on the voltage applied at the photodetector.
- Saturation level (W): Optical power at which the photocurrent remains constant with further increasing optical input power.

4.2.3 Front-End Amplifier

For the amplification of the current from the photodetector, a transimpedance amplifier is generally used. A transimpedance amplifier is an operational amplifier circuit that converts current to voltage. Its gain is measured in units of resistance. The circuit is shown in Figure 9.

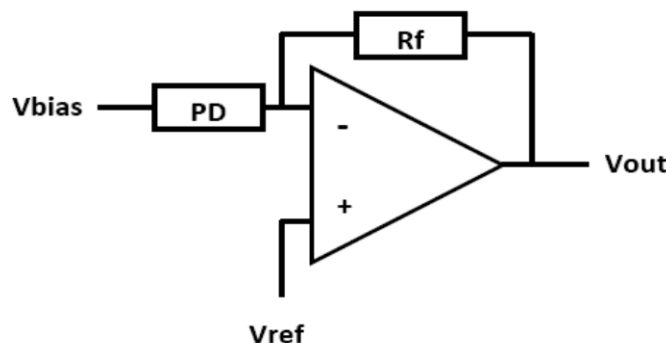


FIGURE 9 - TRANSIMPEDANCE AMPLIFIER CIRCUIT

In this case, a photodetector (PD) is connected between a bias voltage source and the amplifier itself.

During operation, an operational amplifier will drive V_{out} so that the voltage at the junction of PD and R_f is equal to V_{ref} . A consequence of this is that the sum of currents at the junction is zero.

$$\text{Current through } R_f = \text{Current through PD}$$

$$V_{out} / R_f = \text{Current through PD}$$

$$V_{out} = \text{Current through PD} * R_f$$

In the equation above, V_{out} is the output and the photocurrent is the input. R_f is denoted as the gain, which is given in units of resistance. The amplifier circuit actually translates the photocurrent into output voltage, hence the name “transimpedance amplifier.” This assumes that the photodetector is not in saturation, and that the amplifier circuit is being used within its specified operating range.

4.2.4 Spatial Detector

In case a spatial detector is needed, different kinds of components can be used.

- A position sensing device (PSD) can be used. The behavior is the same as the photodiode except that the output depends on both the optical power and the position of the optical spot on the active area.
- Distinct photodetectors can be used, each being connected to detection electronics,
- A CMOS or CCD image sensor can be used, and both are metal oxide semiconductors divided in pixels. Electrical charges are accumulated in each pixel proportionally to the local optical power received. In a CCD sensor, the charges collected are transferred sequentially to a common output structure where they are converted to a sequence of voltages. In a CMOS sensor, the charge-to-voltage conversion is performed in each pixel. The outputs of those sensors are generally digital.

4.2.5 Diplexers

Some devices can combine the emitting part with the receiving part. As they are packaged in front of the same fiber, a coupler or a dichroic filter may separate the two optical signals: one going into the fiber and the other one coming out of the fiber.

4.2.6 Integrated Devices

The emitting or receiving optoelectronic devices can be integrated with the control electronics in a unitary package. Some definitions generally hold for those integrated assemblies:

- The transmitter is a package including both the emitter and its driving electronics,
- The receiver packages both the detector and the preamplifier in order to have a usable signal and minimum noise,
- The transceiver is a package including both the transmitter and the receiver and their electronics.

4.3 Fiber Optic Cables and Connectors

General

The interconnect system between the sensor head, the interrogator, and the ultimate platform processor that uses the information can determine whether the fiber optic sensor is cost effective to implement on any given platform. Careful consideration in the design of the interconnect system together with the sensor/interrogator is required if a fiber optic sensor system is going to gain acceptance for any particular application. Non-standard fiber, cable, connectors and/or cable routing could be considered too expensive or too high risk, especially if a program is already over budget, overweight, and behind schedule. The sensor system designer must work closely with the platform Subject Matter Expert (SME) to develop an insertion strategy that includes the interconnect system, optical power margins, environmental considerations, and Size, Weight, and Power (SWAP) data before presenting it to the appropriate program management. They must have a complete story to address any concerns that management might have and a clear picture of the potential benefits of the system to get any consideration for implementation.

When implementing a fiber optic sensor network design the integrity of the sensor or sensor array is crucial, and an important factor that must be addressed is the transmission of the sensor array signals from the material or installation, be it embedded or surface mounted, to the aircraft interconnection system. This transmission may be in the form of a jumper cable between the sensor array and the aircraft network, or a fixed optical link from the network to the sensor array interface.

In addition, the designer must identify what type of interconnect solution is required for the sensor array. For an embedded system an interconnect integrated into the actual material where the sensor array is installed may be an option; this could be a surface or edge mount type interconnect. As of this writing, however, such embedded or edge-mount type connectors are not yet commercially available. For surface mounted or discrete sensor systems a standard inline or bulkhead type connector may be suitable. Examples are shown below. In any case, suitable protection of the sensor array fiber is vital in the transition area.

Optical Fiber

The transition must allow optimal performance of the sensor or sensor array and minimize additional losses that would affect the operation or capability of the sensors. With this in mind, a designer should ensure that any transition link optical fiber generally be of the same size, performance, and NA as the fiber used in the sensors. The cabled fiber must conform to aerospace requirements and be routed in such a way that it conforms with installation procedures. Where a link is routed through high maintenance or SWAMP areas suitable additional protection is required.

Optical Interconnects

The selection of the correct fiber to provide the optimum performance of the sensors is one element of the transition, the other being the interconnect. There are different interconnect technologies available for aerospace applications. Depending on the requirements, one interconnect solution may be more suited for an application. Among characteristics for choice, there are:

- Optical performance (insertion and return loss)
- Environmental performance (including thermal behavior)
- Mechanical performance (including vibration, mating cycles)
- Locking mechanism
- Single channel or multipin connectors

To ensure that optimum performance is maintained a designer should identify suitable aerospace qualified interconnects that are capable of supporting the type of fiber and cable being utilized and maintaining the required low losses on the range of environmental conditions to be seen by the system.

Physical Contact Interconnect

These have been the common and standard form of aerospace fiber optic interconnects for many years. Each fiber is typically bonded into a precision ferrule with high performance adhesive for strength, stability, and environmental endurance. The dimensional tolerances on the ferrule must be extremely close, because the accuracy with which two fibers can be aligned with each other, each held in a ferrule, depends on them almost entirely. Ferrules are typically made of zirconium oxide, which is strong and refractory and can be fabricated to the very close tolerances required. At the endface the fiber and ferrule are polished to a specific end face geometry (see Figure 10), so that light emerging from one fiber or being captured by a second fiber suffers as little attenuation as possible from scattering or refraction.

In an interconnect, two ferrules with their bonded and polished fibers are brought into contact, end to end, and held together under pressure exerted by a spring in the rear of each terminus. Axial alignment of the two ferrules is provided by a close-fitting alignment sleeve. If the cores of the two fibers can be kept in intimate contact, light loss due to partial reflections at air/silica interfaces can be kept close to zero, thus minimizing insertion loss. Low insertion loss and low back reflection are important for most fiber optic sensors, as signal to noise ratio can limit sensor performance. This is illustrated in Figure 10.

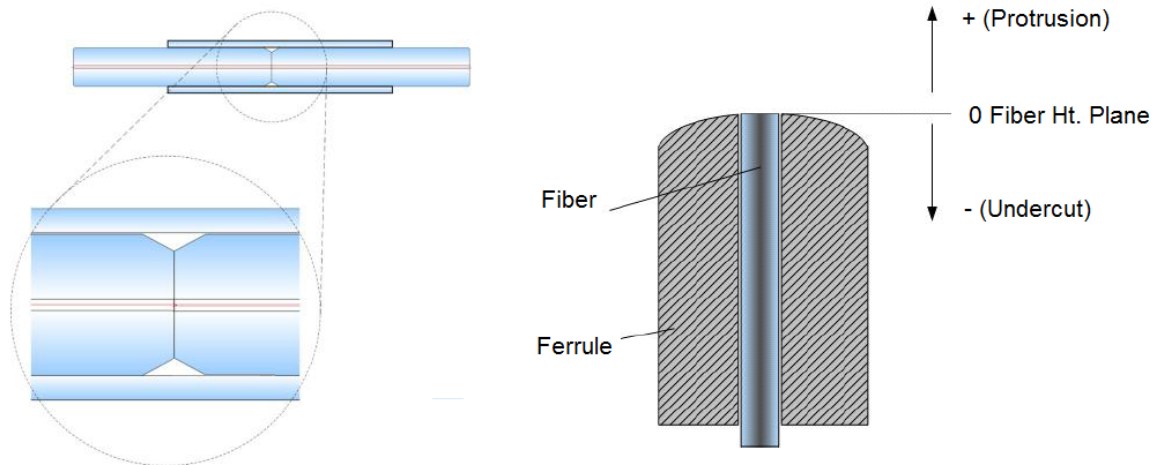


FIGURE 10 - SCHEMATIC DIAGRAM OF PHYSICAL CONTACT FIBER INTERCONNECTION

Physical contact interconnects have many advantages, not least of which is long production experience of manufacturers that helps to insure consistent performance. Some key advantages:

- Superior optical performance (low insertion loss), at least initially, compared to lensed expanded beam interconnects (see below). With multimode fibers the insertion loss can be typically 0.2 dB or better.
- Lower cost than lensed expanded beam interconnects, due both to production volume and the smaller number of close-tolerance parts.
- Lower back reflection if the polish is good and the scattering minimal. Current technology can achieve -40 dB, and new technology in development can produce -60 dB.
- Using the so-called APC technique (Angled Physical Contact), the back reflection can be even lower, even below -60 dB. This can be critical in single mode systems with laser sources, which can be destabilized by back reflections.
- Physical contact termini are available in a variety of forms and well-adapted to single- and multi-terminus circular or rectangular connectors (e.g., MIL-DTL-38999, AS5590, ARINC 801 / EN4639, EN4640, EN4645, EN3733, EN 4531).
- Available for a number of different fiber and coating sizes and types.
- Many physical contact termini meet commonly-accepted MIL and aerospace standards, particularly MIL-PRF-29504.
- Typically, PC termini do not degrade in flight, it has been proven that if a system works at start up, they will not degrade over full environmental exposure; unless the termini are contaminated.

However, physical contact termini have some disadvantages:

- The typical long aspect ratio of the fiber bonded into the ferrule imposes severe thermal stresses on the adhesive bond during extreme temperature cycling (e.g., -65 to +175 or +200 C). This sometimes results in bond failure, after which the fiber can “piston” from its proper position and either lose contact with the opposite fiber or ram into it, ruining the endfaces.
- The optical interface is very sensitive to contamination and damage. Even small particles of dirt on an endface can seriously degrade the optical performance and even damage the end face, because the cores are so small. Cleaning is the single biggest issue in deployment of a PC interconnect system.
- The endfaces are not easy to clean properly, both because it takes so few dirt particles to cause serious occlusion, and because it is difficult to inspect and clean them (see AIR6031).

These shortcomings have led to requirements to improving termini processing and training. However, there are certain areas where the endfaces are exposed to adverse environments, and this has created strong interest in the principle alternative, lensed expanded beam interconnects.

Lensed Expanded Beam Interconnect

In this type of interconnect, a lens is interposed between each fiber and the corresponding interconnect (see Figure 11). The lens serves several important functions. By focusing the light at infinity or a planned distance, it can reduce the normal spreading or emission pattern of the light from 24 degrees (50/125 μm MMF), 31 degrees (100/140 μm MMF) or more to near zero, eliminating a key advantage of physical contact. There can also be benefits for single mode. The focusing allows transmission between termini that are not in contact, or are even separated by some distance, with little insertion loss penalty. Because the two termini need not come into contact, they suffer little or no degradation from high vibration. Most important, because the near field pattern at the front surface of the lens is very large compared to a fiber core, the small particles of dirt which could otherwise cause problems have very little effect. Expanded beam interconnects are both highly tolerant of dirt and easy to clean.

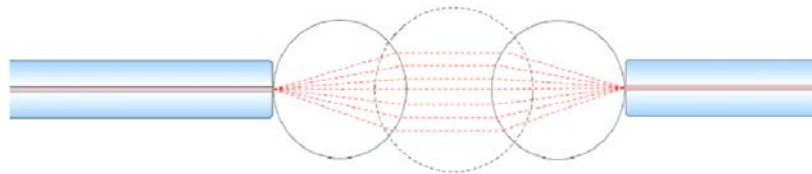


FIGURE 11 - SCHEMATIC DIAGRAM OF A LENSED EXPANDED BEAM INTERCONNECTION

Some key advantages of lensed expanded beam interconnections:

- The optical interface is much less sensitive to contamination.
- The end faces are much easier to keep clean.
- Higher number of matings without damage or degradation.
- Some expanded beam interconnections have become MIL spec and proven high performance (e.g., tactical expanded beam connectors, MIL-DTL-83526/20 and 21).

Not unsurprisingly, expanded beam interconnects also have some disadvantages relative to physical contact interconnects:

- Typically more expensive (because there are more precision components required).
- Higher insertion loss, mainly due to the greater number of interfaces and components, all with extremely close tolerances to control. In addition, the air/silica interfaces within the termini and between two termini all contribute reflection losses, even with high-performance anti-reflective coatings (which themselves add to the cost).
- Higher back reflection, again due to the air/silica interfaces, can render the interconnects questionable for laser-powered systems (although in-line filters can help alleviate this problem).
- With single mode fibers in particular, the tolerance stack-up can render expanded beam interconnects marginal at best.

Due to strong interest in lensed expanded beam interconnects for their ease of cleaning and resistance to dirt and vibration, the aerospace community is working actively on new standards. See AIR6112 for more information.

Optical Interconnects

The selection of the correct fiber to provide the optimum performance of the sensors is one element of the transition, the other being the interconnect. Interconnect losses can be introduced through a number of factors including;

- Fiber misalignment
- Poor end face polish and geometry
- Poor component selection

To ensure that optimum performance is maintained a designer should identify suitable aerospace qualified interconnects that are capable of supporting the type of fiber being utilized and providing the required low losses.

There are a number of qualified aerospace fiber optic connectors and termini, including:

MIL-PRF-29504

Fiber optic termini for use with MIL-DTL-38999 type connectors (see Figure 12). MIL-PRF-29504/4 and /5 with 1.6 mm diameter ferrules and MIL-PRF-29504/14 and /15 with 2.0 mm diameter ferrules. There are termini available for 140 μm , 172 μm , and 125 μm cladding diameter fibers.



FIGURE 12 - EXAMPLES OF MIL-PRF-29504 FIBER OPTIC TERMINI AND MIL-DTL-38999 SERIES III CONNECTORS [courtesy of Deutsch]

NOTE: MIL-DTL-38999 defines the interface requirements for circular connectors.

ARINC 801

Fiber optic termini with 1.25 mm ferrules. Supports 125 μm cladding diameter multimode and single mode fibers.



FIGURE 13 - EXAMPLES of ARINC 801 (EN 4644) RECTANGULAR CONNECTORS [courtesy of Deutsch]

Connectors are available in EN 4644, MIL-DTL-3899 single- and multi-way circular, ARINC 600 rectangular formats.

EN 3733

Connector singleway (single terminus), circular with 2.5 mm ferrule. Supports 200/280 μm step index fiber.



FIGURE 14 - EXAMPLES OF EN 3733 CONNECTORS

EN 4531-101 (ARINC 801 Annex C)

Fiber optic termini with 2.5 mm ferrule. Supports 125 μm clad multimode fibers.

Connectors are available in singleway and multiway MIL-DTL-38999 circular and ARINC 600 rectangular formats.



FIGURE 15 - EXAMPLES OF EN 4531 CIRCULAR CONNECTOR WITH EN 4531-101 CONTACTS (ARINC 801 Annex C) [courtesy of Deutsch]

EN 4639-101

Fiber optic termini with 1.25 mm ferrules. Supports 125 μm cladding diameter multimode and single mode fibers.

Can be used with EN 4639 rectangular, modular, EN 4640 rectangular connectors (ARINC 600), EN 4644 rectangular, modular, EN 4645 connector, single way, multiway circular MIL-DTL-38999.

MC-5

Fiber optic termini with 1.25 mm ferrules. Supports 125 μ m cladding diameter multimode and single mode fibers.



FIGURE 16 - EXAMPLES OF CIRCULAR, SINGLEWAY AND MULTIWAY CONNECTORS [courtesy of Deutsch]

Connectors available in singleway and multiway MIL-DTL-38999 circular formats.

RSC

Ruggedized singleway connector, 2.5 mm ferrule. Supports 125 μ m cladding diameter multimode and singlemode fibers.



FIGURE 17 - EXAMPLES OF RUGGEDIZED SINGLEWAY CONNECTOR [courtesy of Deutsch]

EXPANDED BEAM CONTACT

FIGURE 18 - EXAMPLES OF RUGGEDIZED SINGLEWAY EXPANDED BEAM CONNECTOR [courtesy of Deutsch]