Photonic Integration and Usage Guidelines Manual

D-18228

by

George Lutes

with assistance from

Meirong Tu

1999
NASA Electronics Packaging Program (NEPP)

September 27, 1999

Contents

1.0 Introduction

Photonic technology is developing in much the same way that semiconductor technology developed. The first electronic semiconductor devices that came to market were discrete devices that had to be assembled into functions and systems by connecting them together with wire and solder. As the material and fabrication technologies became more sophisticated the manufacturers began to combine functions onto a single substrate. The interconnections were fabricated right on the board with the devices. These were called integrated circuits.

The first electrical integrated circuits were digital functions because they were easier to fabricate. Then came analog functions such as the operational amplifier. For many years digital circuits and analog circuits were not fabricated in the same integrated circuit. This was because of difficulties involved in doing so. Eventually those difficulties were overcome and combined analog and digital integrated circuits were produced.

Over the years integrated electronic circuits have become increasingly sophisticated and device counts on a single substrate have approached a million devices.

Photonic technology is still, for the most part, in the discrete device stage of development. A few simple integrated optical circuits (IOCs) have been developed but the level of sophistication is in its infancy. Most of today's photonic assemblies and systems are still assembled from discrete photonic devices which are connected together with optical fibers or free-space light beams.

The technology for making reliable connections between discrete photonic devices is still often unreliable and almost always labor intensive and therefore costly. This has limited the use of photonic system to applications where the benefits were so overriding that the cost is of no consequence. This has left many applications begging for the benefits of photonics but held back by the cost.

There is a tendency for industry to neglect the current problems with interconnections between discrete photonic devices in its quest for IOCs which will eventually mitigate these problems by making these connections on the chip level. To neglect today's problems while waiting for the development of IOCs would not be wise for the photonics industry for it will delay the infusion of photonic technology into systems such as synthetic aperture radar which can be greatly improved by its use now.

As the problems with interconnects between discrete photonic components are resolved the reliability will improve and the price will come down. This will entice more manufacturers to take advantage of the benefits of photonic technology and incorporate it into their systems. This will lead to more competition which will in turn increase the demand for more sophisticated photonic assemblies with reduced quantities of discrete devices and more IOCs.

Eventually IOCs will become as sophisticated as their electronic counterparts are today. Many reliability issues will surface as they are developed.

The reliability issues of discrete photonic devices must be addressed now because NASA projects need photonic systems they can use now. They cannot wait for IOCs to be developed before taking advantage of photonic technology. The benefits are too great. At the same time we must begin to plan for resolving the reliability issues related to IOCs as they move out of the laboratory.

This manual will point out some of the advantages of using photonic technology. It will give some examples of photonic systems that have potential space applications. It will explain why these systems work well when implemented in photonics and why the performance cannot be duplicated when implemented in copper based radio frequency systems. There is a description of one of these systems that was implemented in the Shuttle Radar Topographic Mapper (SRTM). There is an analysis on the safety of the laser transmitter used on SRTM.

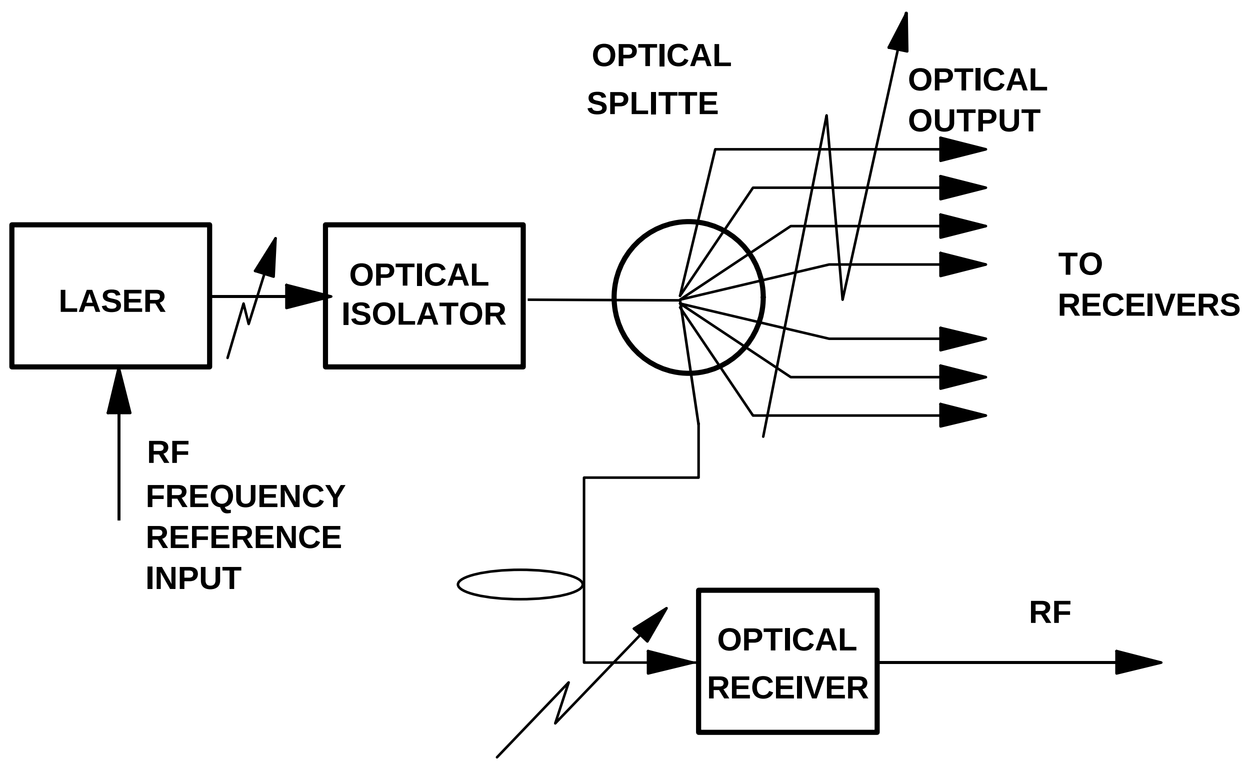
There is a section on fiber optic cables and connectors. It includes the analysis showing why no shielding in additional to the jacket would be needed on optical fiber used in SRTM. There is an overview of fiber optic connector and cable assemblies and a comparison of fiber optic cable versus the best available coaxial cable that was small enough to fit in the SRTM mast. The newly introduced low profile fiber optic connectors are described and some typical performance data is given on traditional fiber optic connectors.

Finally there is a list of some of the better known photonic parts and device manufacturers with their addresses and phone numbers and a list of some of the components they manufacture. The manual ends with a list of references related to implementation of photonic systems.

2.0 Photonic Systems with Potential Space Applications

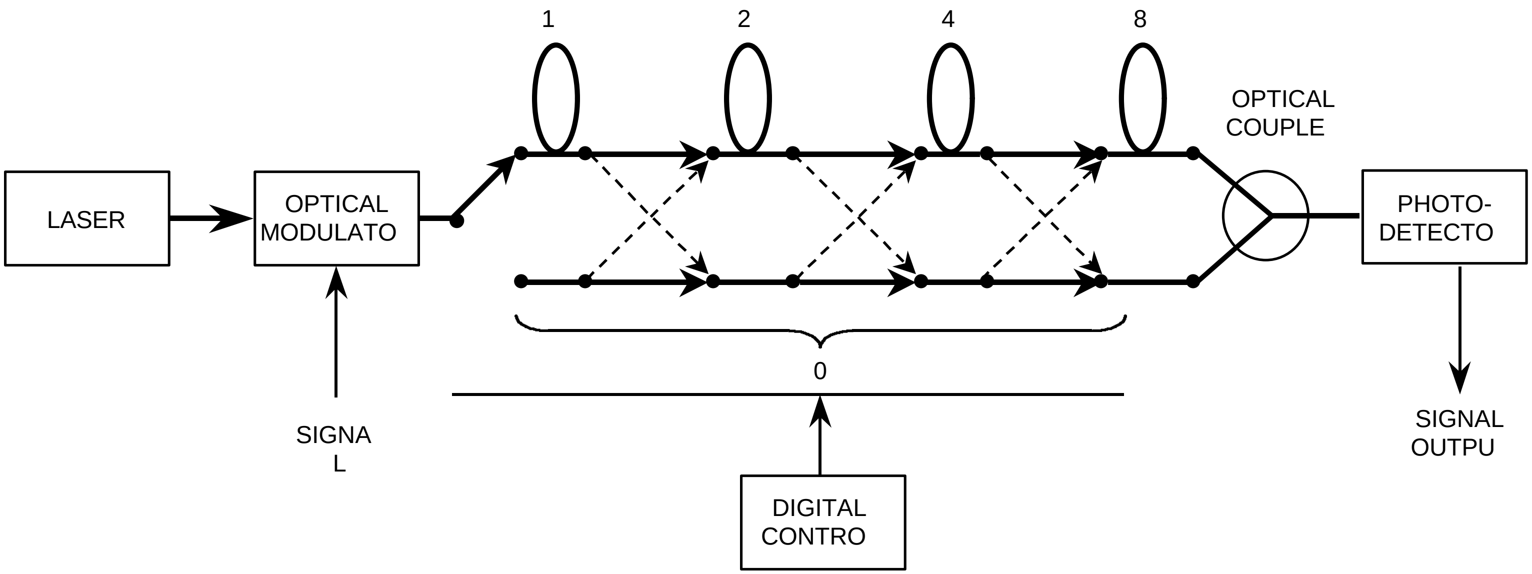
The block diagrams shown in this section are a few examples of analog photonic systems that have potential for space applications.

The cable stabilizer and reference signal distribution system is used on SRTM. It could not have been implemented in a metallic transmission line and achieved the stability that was achieved with the photonic system using optical fiber.

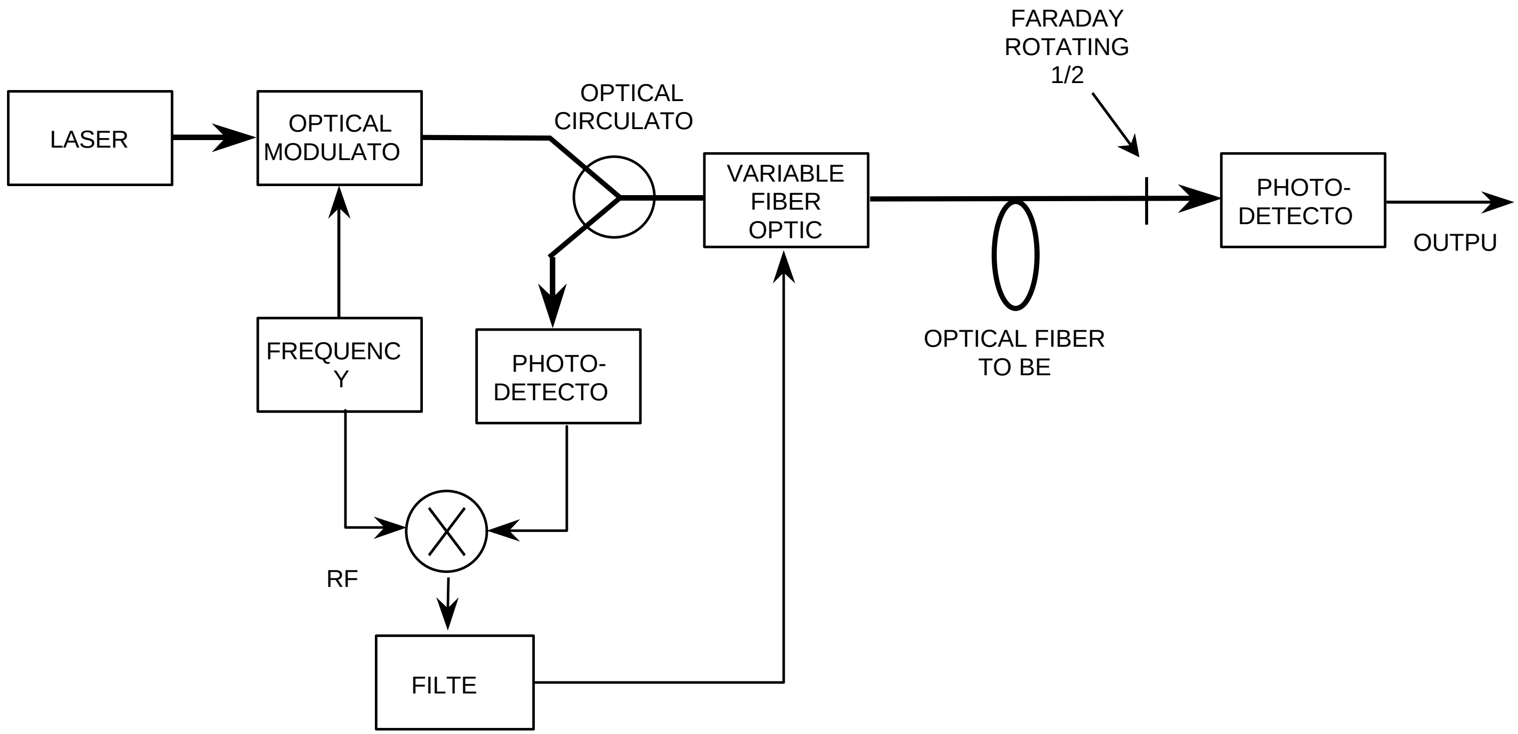


This is a block diagram of a fiber optic frequency reference distribution system used in the NASA Deep Space Network. It has greater than 200 dB isolation between outputs and can distribute the reference signal over tens of kilometers. It has extremely low phase noise and exceptional frequency stability due to the low thermal coefficient of delay of the optical fiber. Coaxial cable has much greater loss and thermal coefficient of delay than

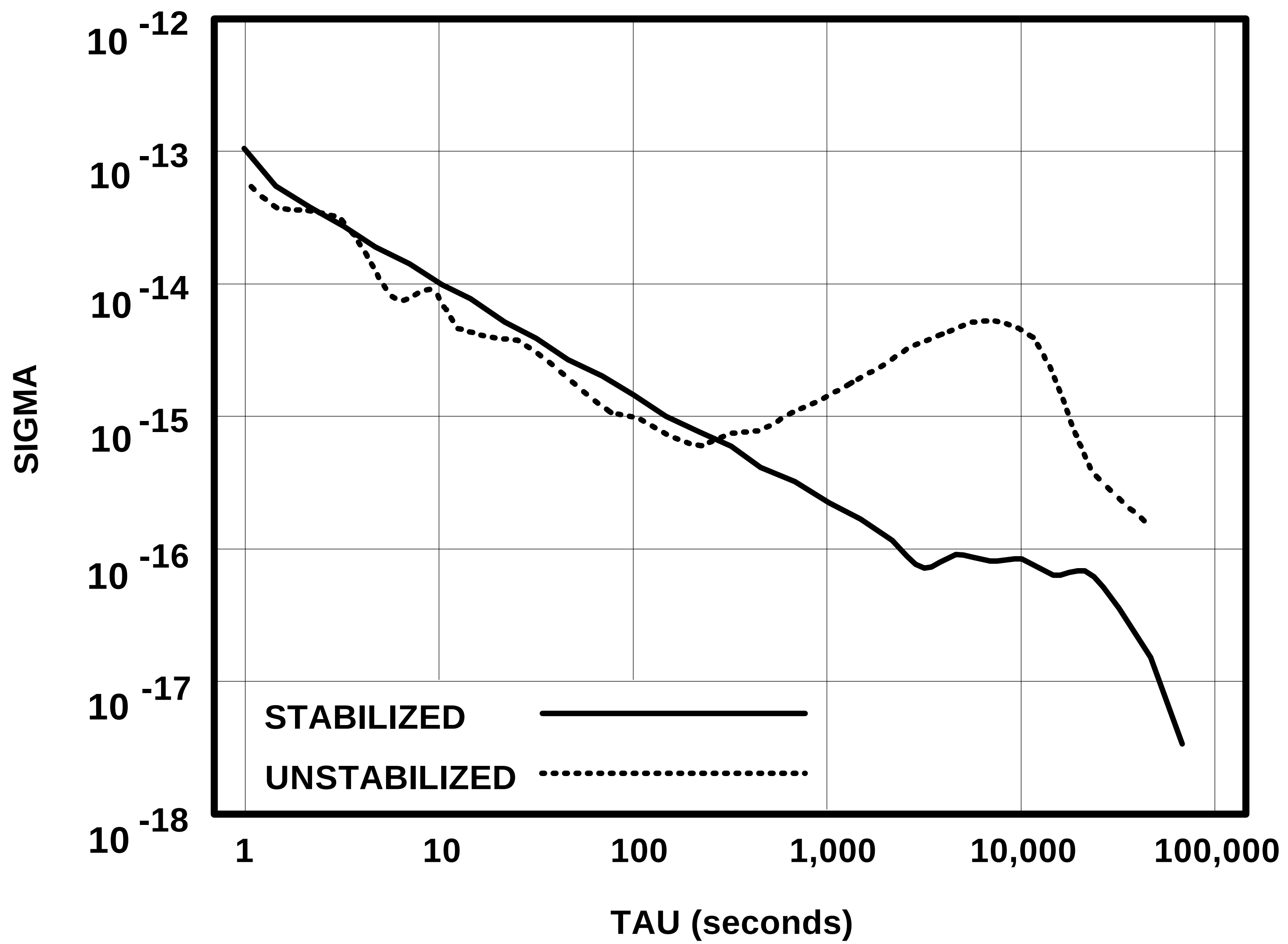
optical fiber. Coaxial cable systems, as a result of this, have a very limited distribution distance and much worse



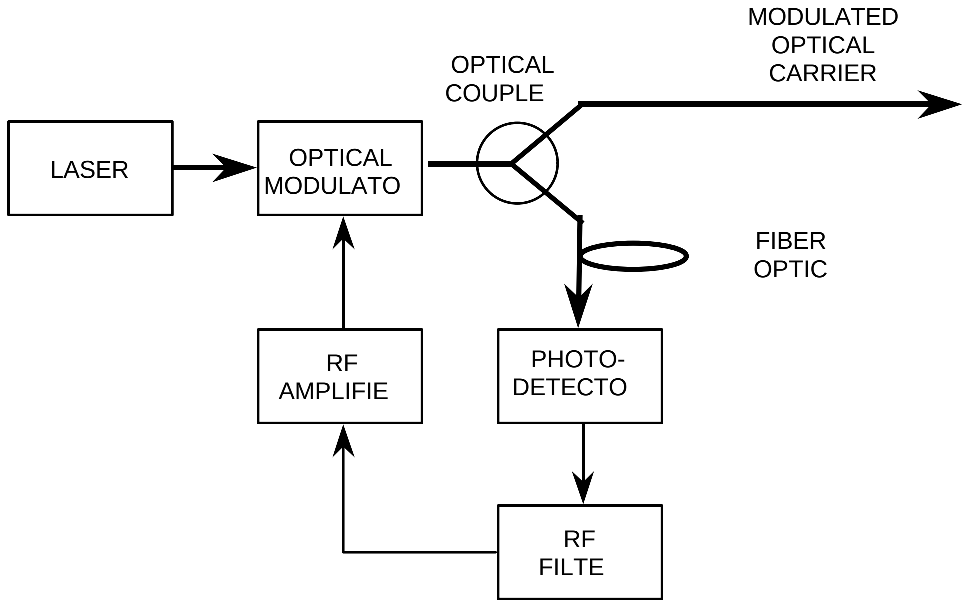
This is a four bit variable optical delay line. Its performance is limited by the switches. There are two kinds of
optical switches, mechanical and optoelectronic. Mechanical switches have higher isolation but they are relatively slow(1 millisecond). Optoelectronic switches are very fast, < 1 nanosecond, but their isolation is not as good as the mechanical switches. Switches have loss but in this configuration the loss is constant because the signal always travels through the same number of switches. If fast switches are used the phase



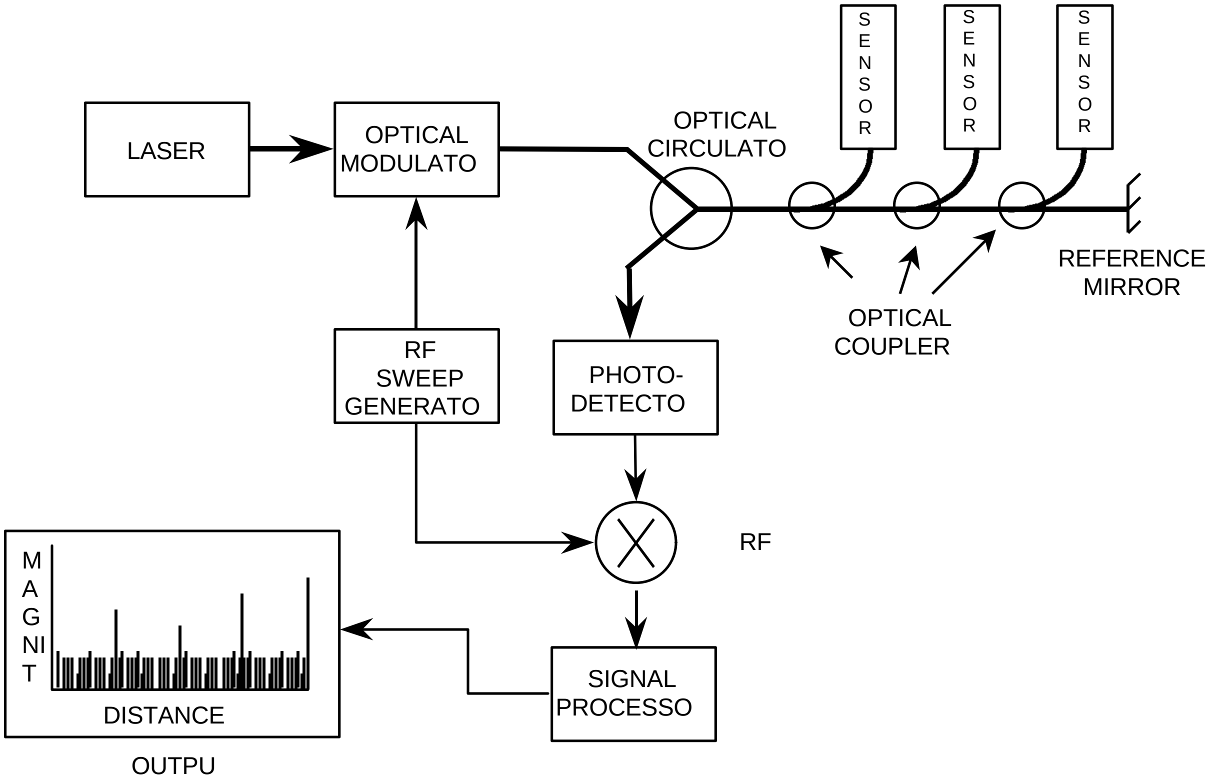
Fiber optic cables can be stabilized using the scheme shown here. The degree of stabilization depends on the isolation in the optical circulator and very low extraneous reflections as well as the accuracy of the Faraday rotator. It is not practical to implement this system using copper based RF sytems because the isolation in the components is not high enough and the extraneous reflections are too large. Because of the low dispersion, an optical fiber can be stabilized at one wavelength and a wideband signal can be transmitted through it at a second



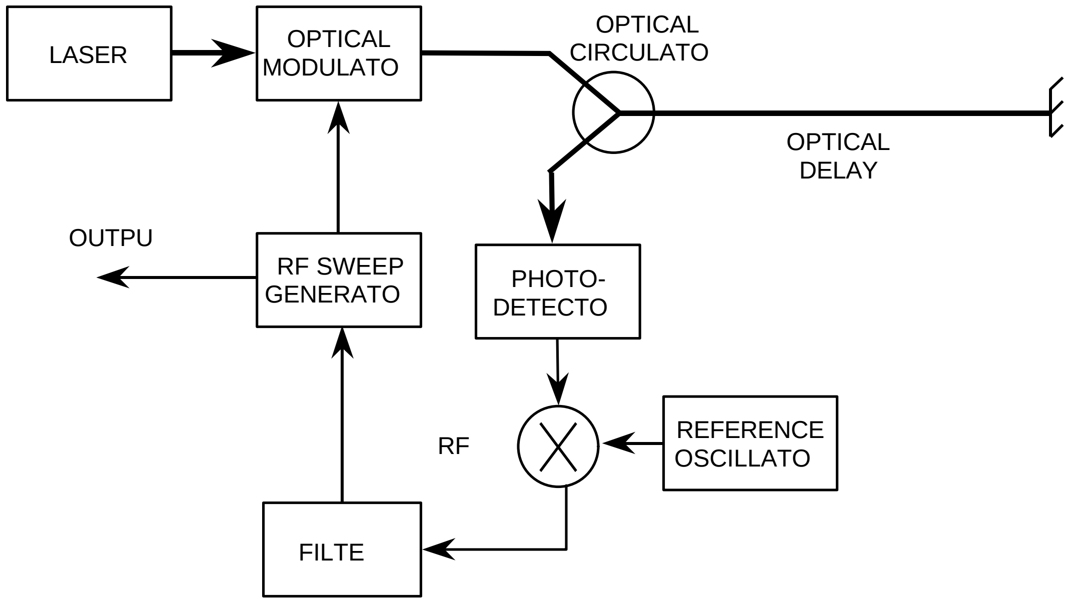
This plot shows the improvement in frequency stability provided by a fiber optic cable delay stabilizer.



Oscillators using optical feedback through a fiber optic delay line provide the lowest phase noise at 30 kHz from the carrier. When fully developed, these oscillators promise substantial improvements in phase noise performance



This system queries multiple analog sensors connected along a single optical fiber. Each sensor is a reflector that changes its reflectivity as a function of the concentration of the material it is designed to detect. The reflection from each sensor is compared in magnitude to the reference reflection from the reference mirror. Therefore, changes in the optical power transmitted down the optical fiber does not change the accuracy of the reading. This system's bandwidth is small and it is therefore more sensitive than an optical time domain reflectometer for a given average power level transmitted down the optical fiber. It is also a much less expensive system to implement. Copper based RF systems do not work well for these types of functions because of insufficient isolation between the outgoing and incoming signal



Fiber optic delay lines may be used to hold the sweep rate of a sweep generator constant. This can provide extremely linear frequency sweeps. A very long delay is required for slow sweep rates. The low loss and high bandwidth of optical fiber permits the implementation of very long fiber optic delay lines at high frequencies. It is not practical to implement long delays in copper based RF systems due to the large loss and low bandwidth
of copper transmission lines. The effectiveness of this type of system depends on the high isolation of the

3.0 Fiber Optic Reference Signal Distribution and Cable Stabilizer Implemented in SRTM

3.1 Introduction

The Shuttle Radar Topography Mission (SRTM) will use radar interferometry to map 80% of the earth's surface in 3D in 11 days (Ref. 1,2). In radar interferometry, two radar images are taken from slightly different locations. Differences between these images allow for the calculation of surface elevation, or change. To get two radar images taken from different locations the SRTM hardware consists of one transmit/receive antenna array in the shuttle payload bay and a receive only antenna array attached to the end of a mast extended 60 meters out from the shuttle. The accuracy of the produced maps partly depends on accurate knowledge of delay variations between the two paths of received signals.

3.2 Problem

The problem is that the temperature of the mast and outboard electronics varies as the shuttle flies in and out of the earth's shadow during each orbit. Since cable delay varies with temperature, this results in excessive delay variations in the coaxial cables and outboard electronics that would reduce mapping accuracy. A solution would be to inject a known phase into the inboard and outboard electronics to calibrate out the system phase vs. temperature fluctuations. But any cable that would carry this reference signal along the mast would be affected too. Therefore a self-compensating reference distribution to the outboard had to be designed in order to meet the system requirements.

When in orbit the mast cables will change temperature semi-sinusoidally by as much as 12 degrees C peak-to-peak with a 90 minute orbital period. The average temperature of the cables will be between -10^{o} C and –60^{o} C. Using coaxial cables with the very lowest thermal coefficient of delay (TCD) available still leaves us with a thermal coefficient of delay of up to 40 ppm/^{o}C. In our temperature range the delay change without compensation could be as high as 5 ps. This is equal to 100 degrees of phase at the reference signal frequency of 5.3 GHz. The maximum allowable phase change allocated to the down-link coaxial cable by the system designers is 3 degrees.

3.3 Solution

Two approaches to this problem were considered. The first approach was to actively stabilize the delay of the cable through which the received echo signals traveled from the end of the mast back to the shuttle bay. The second approach was to inject a reference tone which would accompany the ground echo signals and be used to later extract the phase of the ground echo signals using computer signal processing of the mission data.

The first approach was abandoned for several reasons. Active delay compensation doesn't work well in a coaxial cable system because of large reflections and low isolation in the system components. Even though delay compensation works very well for fiber optic links, the designers didn't want to risk the use of new technology to carry the received radar signals from the end of the mast back to the shuttle bay. Loss of this link would scrub the mission.

The designers chose to use the second approach. Should the fiber optic link fail, a backup reference tone will be injected, uncompensated into the mast cables, traveling up the mast, then injected back down the mast now to accompany the ground echo signal. The reference tone phase will be assumed to vary by the same amount in the up-mast cable as in the identical down-mast cables and its phase contribution will be extracted accordingly.

To best meet the reliability, bandwidth, and radiation resistance requirements we used a single-mode fiber optic link operating at 1550 nm wavelength.

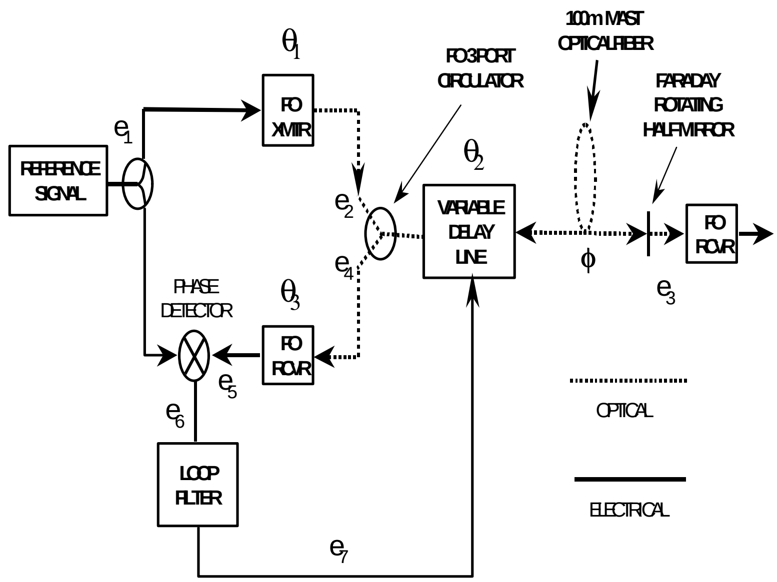


Fig. 1. A block diagram of the stabilized microwave fiber optic link.

3.4 Analysis

This is an analysis of the phase relationships in the stabilized fiber optic link. In this analysis the amplitude is not considered. Since the amplitude is not considered, for the sake of simplicity we will also not consider the optical to electrical and electrical to optical conversions. Furthermore we will assume the gain of the negative feedback loop is infinity.
Referring to Fig. 1, the input reference signal is,

$$e_1(t) = A_1 \cdot \sin(w \cdot t) \tag{1}$$

This signal, after traveling through a length of cable and the fiber optic transmitter to the fiber optic circulator is,

$$e_2(t) = A_2 \cdot \sin(w \cdot t + q_1) \tag{2}$$

where, θ_1 = the phase delay between the reference signal generator and the input to the fiber optic circulator.

The signal at the output of the fiber optic cable at the end of the mast is,

$$e_3(t) = A_3 \cdot \sin(w \cdot t + q_1 + q_2 + \Delta q_2 + f + \Delta f) \tag{3}$$

where,

θ_2 = the delay through the variable fiber optic delay line,

$\Delta\theta_2$ = the delay change in the variable fiber optic delay line,

ϕ = the nominal delay of the optical fiber in the mast, and

$\Delta\phi$ = the change in delay of the optical fiber in the mast.

The reflected signal at the return port of the fiber optic circulator is,

$$e_4(t) = A_4 \cdot \sin[w \cdot t + q_1 + 2 \cdot (q_2 + \Delta q_2) + 2 \cdot (f + \Delta f)] \qquad (4)$$

The reflected signal at the input of the phase detector is,

$$e_5(t) = A_5 \cdot \sin[w \cdot t + q_1 + 2 \cdot (q_2 + \Delta q_2) + 2 \cdot (f + \Delta f) + q_3] \qquad (5)$$

where, θ_3 = the phase delay from the reflected port of the circulator through the fiber optic receiver to the phase detector.

The output of the phase detector is the product of (1) and (5),

$$e_6(t) = e_1(t) \cdot e_5(t) \qquad \text{or,}$$

$$e_6(t) = A_6 \cdot \{\cos[q_1 + 2 \cdot (q_2 + \Delta q_2) + 2 \cdot (f + \Delta f) + q_3] + \cos[2 \cdot w \cdot t + q_1 + 2 \cdot (q_2 + \Delta q_2) + 2 \cdot (f + \Delta f) + q_3]\} \qquad (6)$$

After low pass filtering (6) we get the loop error signal,

$$e_7(t) = A_7 \cdot \cos[q_1 + 2 \cdot (q_2 + \Delta q_2) + 2 \cdot (f + \Delta f) + q_3] \qquad (7)$$

It can be shown that there are values for θ_2 that result in (7) being equal to zero. The loop will force θ_2 to one of these values thereby forcing (7) to equal zero. Thereafter, assuming θ_1 and θ_3 are constant, for any change in $\Delta\phi$ the loop will force $\Delta\theta_2$ to change by an equal amount in the opposite direction to keep (7) equal to zero. In other words ($\Delta\theta_2$) will be forced to equal ($-\Delta\phi$).

The result of this is made clear if we substitute ($-\Delta\phi$) for ($\Delta\theta_2$) in (3),

$$e_3(\Delta f) = A_8 \cdot \sin[w \cdot t + q_1 + q_2 + f + (\Delta f - \Delta f)] \qquad (8)$$

It can be seen that variations in the delay of the optical fiber, $\Delta\phi$, fall out and the phase of the output signal is constant relative to the phase of e_1, the reference signal.

3.5 Control Loop Design

We used a thermally controlled spool of optical fiber as a variable delay line. Its design is described in the next section. The relatively long, 180 second, time constant of this complex variable delay complicated the loop design. This delay provided the first pole in the design. Another zero and another pole were added using active electronics. We simulated the response of the loop using SPICE. The control loop design achieved the required acquisition range, tracking range and stability and its simulated performance was verified by extensive testing.

To test the loop's characteristics, we used a network analyzer to measure the phase difference between its input and output. We placed the long mast fiber in an oven and varied its temperature to simulate orbital variations expected in the mission. Because air provides undesired thermal paths that change the time constant of the optical fiber spool, we placed the fiber spool in a vacuum chamber during testing to achieve the in situ thermal response.

A real time data acquisition system collected network analyzer phase and amplitude measurements for analysis.

3.6 Photonic Hardware Description

The unique feature of this stabilized fiber optic link is the hardware used to implement it. To our knowledge it is the first use of a 1550 nm single-mode fiber optic system and the first microwave fiber optic system used in a space application. The hardware was, for the most part, commercial-off-the-shelf (COTS). However, it was carefully chosen and modified as needed to operate reliably in the space environment to which it would be exposed. An operating wavelength of 1550 nm was used because the laser was considered to be more reliable and the optical fiber has lower ionizing radiation induced attenuation at this wavelength.

Uniphase Telecommunications Products (UTP) Transmission Systems Division fabricated the stabilized microwave fiber optic link under contract with JPL. This included all of the components shown in the block diagram (Fig. 1) with the exception of the reference signal generator. The fiber optic transmitter module is a slightly modified version of their COTS Small Integrated Transmitter Unit (SITU).

The SITU consists of a 1550 nm high power single-mode CW laser followed by a Mach-Zehnder modulator. The optical output power of the SITU is $\geq$ 5 dBm and the bandwidth is 1-18 GHz. The relative intensity noise (RIN) is $\leq$ -150 dB/Hz and $V\pi$ is $\leq$ 7 volts at 2 GHz. The non-operating temperature range is –55^{o}C to +85^{o}C and its operating temperature is 0^{o}C to +60^{o}C (Ref. 3). The entire stabilized fiber optic system must meet its specifications when the SITU is subjected to any 10^{o}C peak-to-peak temperature variation within the temperature range of +5^{o}C to +45^{o}C.

The 3 port circulator is a COTS device fabricated by E-Tek Dynamics. Its specified wavelength is 1550 nm $\pm$ 20 nm. Its insertion loss from 0^{o}C to 60^{o}C is < 1.3 dB over its entire wavelength range. Its minimum peak isolation is 45 dB. The optical return loss is $\leq$ -50 dB.

The FRHM is a modified COTS device fabricated by E-Tek Dynamics. It was modified from a full mirror to a half mirror to allow half of the light to pass through into another optical fiber on the backside of the mirror. Its center wavelength is 1550 nm with a spectral width of 30 nm.

The following table contains typical tests applied to devices fabricated by E-Tek Dynamics (Ref. 4).

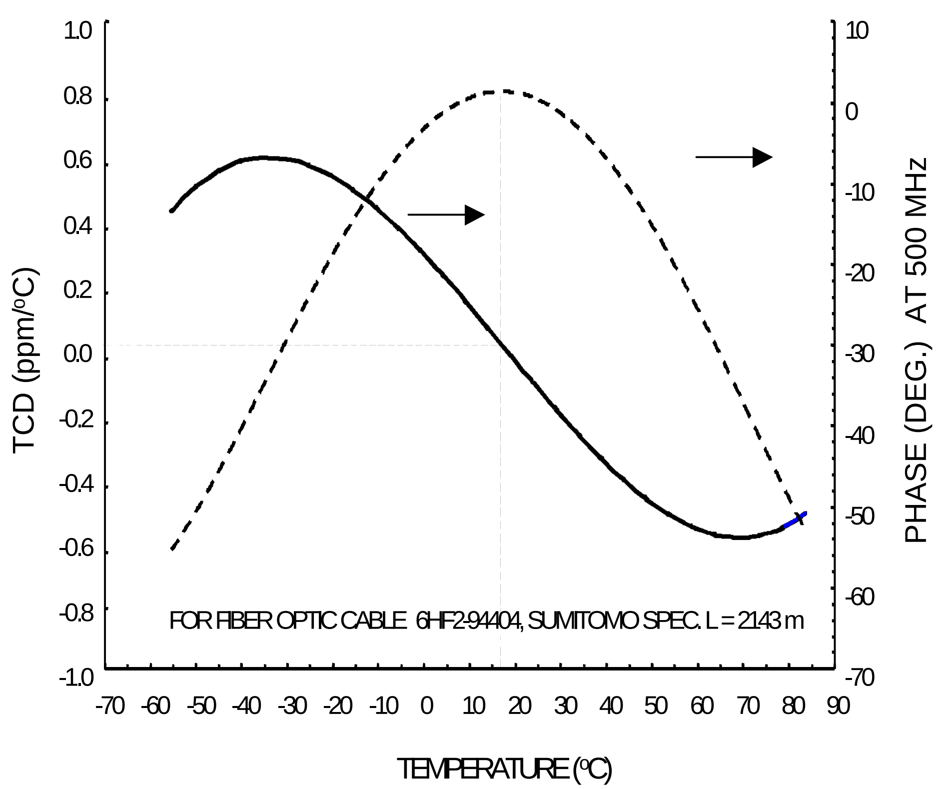
Temperature Cycling	-40°C to +80°Cfor 14 days; rate 1°C/min; dwell 1 hour at the extremes
High temperature bake	80°C for 2,000 hours
Vibration	3 axis 20 g's at 20 ~2,000 Hz
Shock	3 axes, 100 g's, 11ms
Max. Tensile Strength	10 N force for 10 seconds

Table 1. Typical tests applied to components by E-Tek Dynamics

The fiber optic photodetector is a COTS device fabricated by Lasertron and is incorporated into the fiber optic receiver unit fabricated by UTP. Its has a 1,000 ohm output resistor and a bandwidth of 0.01 to 12 GHz when loaded with 50 ohms. The spectral range is 1100 nm to 1650 nm. The responsivity is 0.8 A/W at 1300 nm and the optical return loss is ≥ 40 dB. The operating temperature range is –40°C to +85°C. This device is tested to Bellcore Technical Advisory TA-TSY-000983 at minimum (Ref. 5).

The optical fiber in the mast is a low thermal coefficient of delay (LTCD) fiber manufactured only by Sumitomo (Refs. 6 and 7). It is coated with layers of liquid crystal material having a negative thermal coefficient of expansion and a soft buffer material to achieve a TCD of < 1 part-per-million/°C. Fig. 2 is a plot of the TCD of this optical fiber. It is compatible with Corning SMF-28 and it met our out-gassing requirements. Rifocs, Corporation installed AVIM angle polished connectors on the fiber optic cable. These connectors are designed for rugged applications and have excellent reliability (Ref. 8).

Fig. 2. The TCD for the mast optical fiber.



The variable delay line is a thermally controlled winding of optical fiber. It consists of a thin walled aluminum cylinder which has approximately 260 meters of optical fiber bonded to its outer surface and resistive foil heaters on the inside wall. The base of the aluminum cylinder is heat sunk to the chassis of the fiber optic transmitter module through a fiber glass washer which provides a calibrated thermal resistance. The chassis is bolted to the cooling plate in the spacecraft. The optical fiber is standard single-mode communications fiber manufactured by Spectran.

Thermal expansion or contraction of the aluminum cylinder and optical fiber, and thermally induced change in the index of refraction of the optical fiber all contribute to the delay change through the optical fiber when it is heated or cooled. The phase delay change versus temperature is $59^o/^oC$.

3.7 Tests and Results

The fiber optic cable assemblies were tested many times for connector reliability and TCD over a temperature range as wide as $–60^oC$ to $+85^oC$. Some cable tests were run in conjunction with testing other parts of the system. In these cases the temperature range was typically from room temperature down to $–50^oC$ and then cycled sinusoidally $\pm 8^oC$ around 50^oC. In addition to these tests the flight cables were cycled sinusoidally $\pm 10^oC$ around $–25^oC$ for two weeks.

Two LTCD optical fibers were installed in the mast, one primary and one backup. One of these optical fibers was broken by technicians when they removed and rerouted it. The mast was extended and retracted approximately 32 times. It was extended and retracted once at a temperature of $–60^oC$.

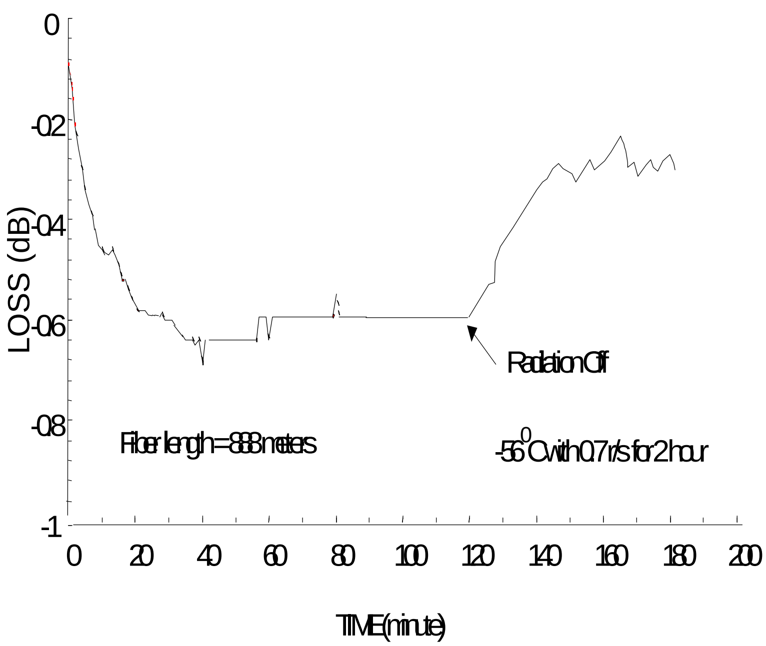


Fig. 3. Radiation induced loss in the LTCD optical fiber at $–56^oC$.

With the exception of the mast fiber that was broken in the rerouting incident, there were no cable or connector failures. One LTCD optical fiber was subjected to ionizing radiation at –60°C. A plot of this data is shown in Fig. 3.

For the thermal vacuum test we placed the fiber optic transmitter, receiver, and optical fibers all in the same vacuum test chamber. Each of these three system components was subjected to a different temperature range. The transmitter was subjected to a sinusoidal temperature variation of ± 10°C over the average temperature range from 5°C to 45°C. The receiver was subjected to a sinusoidal temperature variation of ± 10°C over the average temperature range from -40°C to +15°C. The optical fiber was subjected to sinusoidal temperature variation of 12°C over the average temperature range from –10°C to –60°C.

The stabilized fiber optic link locked up properly and met its 3° phase stability specification over the entire range of test temperatures.

The fiber optic transmitter and receiver were subjected to vibration according to the following tables.

Direction	Frequency (Hz)	Design, Qual Test PF Test	Accept Test
Fiber Optic Transmitter Out of plane	20-80 80-250 250-350 350-600 600-2,000 2,000 overall	+6.5 dB/octave 0.10 g^2/Hz +20.3dB/octave 1.0 g^2/Hz -13.2 dB/octave 0.005 g^2/Hz 22.0 g_{rms}	+6.5 dB/Octave 0.04 g^2/Hz +20.3 dB/octave 0.4 g^2/Hz -13.2 dB/octave 0.002 g^2/Hz 22.0 g_{rms}
Fiber Optic Transmitter In plane	20-80 80-200 200-250 250-500 500-2,000 2,000 overall	+6.5 dB/Octave 0.10 g^2/Hz +12.4 dB/octave 0.25 g^2/Hz -8.5 dB/octave 0.005 g^2/Hz 12.2 g_{rms}	+6.5 dB/Octave 0.04 g^2/Hz +12.4 dB/octave 0.10 g^2/Hz -8.5 dB/octave 0.002 g^2/Hz 7.7 g_{rms}

Table 1. Fiber optic transmitter vibration test.

Direction	Frequency (Hz)	Design, Qual Test PF Test	Accept Test
Fiber Optic Receiver Out of plane	20-50 50-400 400-2,000 overall	+6 dB/octave 0.2 g^2/Hz -7.5 dB/octave 11.0 g_{rms}	
Fiber Optic Receiver In plane	20-50 50-400 400-2,000 overall	+6 dB/octave 0.1 g^2/Hz -7.5 dB/octave 15.6 g_{rms}	+6 dB/octave 0.16 g^2/Hz -7.5 dB/octave 9.8 g_{rms}

Table 2. Fiber optic receiver vibration test.

3.8 Conclusion

The SRTM project had a unique problem with the systems stability that was best resolved with a microwave fiber optic link. A suitable fiber optic link was designed and implemented using primarily COTS hardware with minor modifications where needed to improve reliability. To our knowledge this is the first 1550 nm single-mode fiber optic link to be implemented for use in space.
We extensively tested the stabilized fiber optic link over the entire worst case range of potential environmental conditions including temperature, vacuum, and vibration. It met all of its specifications and worked flawlessly without a single failure in any part.
This work has shown that complex photonic systems implemented with carefully chosen and minimally modified COTS devices can meet the reliability requirements of some space applications.

3.9 Acknowledgements:

The authors would like to thank Dr. X. S. Yao, for his helpful inputs, Dr. Boris Lurie, for his help with the control loop analysis, Mimi Paller and Louise Veilleux for their support of this effort, Edward Caro, for his support and for giving us the benefit of his vast experience, Brad Finamore, for his expertise in automating the test system and running tests, and the entire SRTM team for their help which was always there when we needed it. We also thank Dr. Lute Maleki for his guidance throughout the course of this work.

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

3.10 References:

1. George Lutes, Dalia McWatters, and Meirong Tu, “A 60 Meter Delay Stabilized Microwave Fiber Optic Link for 5.3 GHz Reference Signal Distribution on the Shuttle,” Radar Topographic Mapper

2. Seeing Earth’s Surface in 3D, http://southport.jpl.nasa.gov/html/projects/srtm-what.html

3. Specification sheet for the SITU, Uniphase Telecommunications Products, Inc., Transmission Systems Division, 500 Horizon Drive, Chalfont, PA 18914.

4. Specification sheet for the Faraday mirror, E-Tek Dynamics, 1885 Lundy Ave., San Jose, CA 95131

5. Product Guide, Lasertron, Inc., 37 North Ave., Burlington, MA01803

6. Y. Shuto, F. Yamamoto, and Y. Takeuchi, “High-Temperature Stability of Optical Transmission Properties Attained by Liquid-Crystal Polymer Jacket,” J. Lightwave Tech., vol.LT-4, No. 6, June 1986.

7. Lutes, G., and W. Diener, "Thermal Coefficient of Delay for Various Coaxial and Fiber-Optic Cables,"TDA PR 42-99, July-Sept. 1989, pp. 43-59, Nov. 15, 1989.

8. Specification sheet, RIFOCS Corp., 1340 Flynn Road , Camarillo, California 93012

4.0 Safe use of the UTP Fiber Optic Transmitter to be used on SRTM

The UTP fiber optic system is operated as a Class 1 system being completely enclosed during operation according to ANSI Standard Z136.2. However, the Service Group classification, which provides for safety during service when connectors are disconnected by service personnel, is Class 3a.

Although the UTP fiber optic transmitter contains an enclosed Class 3b laser its output passes through a Mach-Zehnder modulator before it is accessible outside of the module which contains it. The module is not serviceable in the field and should never be opened except at the manufacturers facilities. The light out of the modulator is only accessible through a single-mode optical fiber which passes through the wall of the module to the outside world and is terminated with a standard single-mode fiber optic connector.

The power at the end of the optical fiber is approximately 5 mW and is therefore below the 6.6 mW maximum Accessible Emission Limit (AEL) for a Class 3a laser system. The system should therefore have a Class 3a service classification. The AEL for a Class 3a system was calculated as shown below using the equation given in ANSI Standard Z136.2 Table 6. Where,

$\omega_o := 8$ = the core diameter of a single-mode fiber,

$d_o := 0.5$ = the normal aperture for viewing,

$\lambda := 1.55$ = the wavelength of the laser,

$MPI := 100$ = the maximum permissible irradiance from Table 3, and

$\Phi_o := 5$ = the average output power of the optical fiber.

$$AEL := 0.8 \cdot \left[1 - e^{-\left(\frac{\pi \cdot 9}{200 \cdot 1.55} \right)^2} \right] \qquad AEL = 6.627 \cdot 10^{-3} \quad W$$

The minimum safe viewing distance was calculated using the equation in ANSI Standard Z136.2 and the MPI from Table 3. It is less than 2.5 cm.

$$r := \frac{\pi \cdot \omega_o \cdot d_o}{2 \cdot \lambda} \cdot \left[\frac{-1}{\ln\left(1 - \frac{\pi \cdot d_o^2 \cdot MPI}{4 \cdot \Phi_o} \right)} \right]^{\frac{1}{2}} \qquad |r| = 2.225 \quad cm$$

This fiber optic system poses no danger to the user and is very safe for service personnel as well. An injury could only result if someone held an open connector very near their eye or viewed an open connector with a magnifying glass while power is on.

5.0 Radiation Darkening of the SRTM Optical Fiber

Reference: IOM #CEB-514-E-96-14 from C. Barnes to G. Lutes 2/19/96

After further consultation and study I have concluded that no additional shielding is needed on the optical fiber in the SRTM boom. The fiber we have decided to use is a special low thermal coefficient of delay fiber, SFH2-97409A, manufactured by Sumitomo Electric Industries, Ltd. The coating on this fiber provides more than the suggested equivalent of 1 mil of aluminum shielding for the fiber.

The following is a history of the radiation shielding concern and an explanation of our conclusion that no additional shielding is needed.

Dr. Charles Barnes, who is an internationally known expert on radiation effects on optical fiber and other photonic parts, works here at JPL in Section 5070. In February 1996 we asked him to perform a study on radiation effects on the proposed photonic equipment for SRTM. This included the degree of darkening of the SRTM fiber.

Michael Cherng, an expert on the space radiation environment, provided Charles with an estimate of the total radiation dose that would be expected in the SRTM environment. This estimate assumed the equivalent of 1 mil of aluminum shielding around the fiber. The 1 mil of aluminum shielding is used as a baseline because it eliminates most of the low energy radiation and leaves only the more predictable high energy radiation.

Using Michael's estimate of the total radiation dose Charles concluded that the only potentially significant radiation effect for the SRTM fiber optic link is the possibility of radiation induced attenuation in the 60 m long single-mode optical fiber. Our choice of a 1550 nm wavelength system reduces the radiation effects for all of the link components including the fiber.

By analogy with previous work in the literature on single-mode fibers Charles estimated, conservatively, that the radiation induced darkening would not exceed 0.54 dBo (optical) over the life of the SRTM mission. This is equivalent to 1.08 dBe for the RF signal.

The assumption of the equivalent of 1 mil of aluminum shielding brought up concerns about how we would achieve that. Adding 1 mil of aluminum shield would pose several problems for the designers and implementers of the boom, such as the additional weight and the methodology for installing it. This prompted further study of the need for additional shielding.

Our conclusion that no additional shielding will be needed on the fiber is based on,

a radiation test to verify the conclusions of the study, and

analysis of the radiation shielding provided by the coating on the optical fiber.

We exposed an 880 meter long sample of the optical fiber to 5 krads of radiation which is twice the equivalent to the total dose the fiber would see during the SRTM mission. During the test the fiber was maintained at -56 degrees C, the lowest temperature the fiber is expected to see during the mission. This was done to simulate the worst case condition since radiation darkening increases as the temperature decreases.

During the test the optical fiber darkened by 0.6 dBo. Since the test fiber is 8.8 times longer than the actual fiber used on the SRTM boom the attenuation of the test fiber is divided by 8.8 which gives an attenuation of only 0.07 dBo or 0.14 dBe over the duration of the mission.

The radiation source in the JPL radiation test facility emits only high energy radiation. Therefore, the test only verified the conclusions of the study but did not resolve the question of shielding needed to reduce low energy radiation.

I had further discussions with Michael Cherng who verified that if the product of density times thickness was equal to that of aluminum the shielding provided by other materials would be nearly the same. I then went to the manufacturer of the optical fiber to get the density and thickness of the coating material on the fiber. I was also able to get an average density for the fiber coating by weighing the fiber, measuring its volume, and subtracting the weight and volume of the bare fiber which I already knew. I did this just to verify the information the vendor gave me.

The result is as follows.

One mil is 25.5 microns and the density of aluminum is 2713 kg/m^3 so the product of the thickness and the density is 69,182. The fiber coating consists of three layers, a layer of silicone next to the fiber, a layer of liquid crystal material, and finally a color coat of UV cured polymer. The density of the silicone and color coat are the same at 1,100 kg/m3 and their total thickness is 127.5 microns so the product of the thickness and density for these layers is 140,250. Finally the density of the liquid crystal material is 1,400 kg/m3 and its thickness is 310 microns the product of the thickness and density for this layer is 434,000.

To obtain the shielding margin add the products of the coating layers to get 574,250 and then divide by the product of 1 mil of aluminum which is 69,182 to get a margin of 8.3 times. In other words the coating on the fiber is equivalent to approximately 8.3 mils of aluminum.

In conclusion we see no need for additional shielding on the fiber.

Reference: Interoffice Memo #335.10-97-013

Date: 10/23/97
To: Brian Harrington Sect.: 352
From: George Lutes Sect.: 335

6.0 DEVELOPMENT OF FIBER OPTIC CABLE ASSEMBLIES FOR SPACE APPLICATIONS

6.1 Introduction

Fiber optic cable and connector manufacturers are working with a consortium of NASA and private industry partners to develop a family of reliable fiber optic cable assemblies for space applications. This paper explains some of the problems they are addressing. We start by breaking fiber optic cable assemblies into four major categories and discussing the problems or potential problems of each category. Some of the materials issues are discussed with pros and cons. Finally, we make recommendations for cable assemblies which are available now and discuss future trends.

6.2 Basics

There are two main categories of fiber optic cable assemblies, using terms coined by John Kolasinski at Goddard,

Pull-proof, and

Non-pull-proof.

There are also two main categories of cable construction,

tight buffered, and

loose tube.

There are, therefore, four possible main categories of fiber optic cable assemblies,

pull-proof with tight buffered cable, (PPT)

pull proof with loose tube cable, (PPL)

non-pull-proof with tight buffered cable (NPPT), and

non-pull-proof with loose tube cable (NPPL).

Most cable assemblies use springs within the connectors to hold the ends of the fibers together under tension.

If two non-pull-proof cable assemblies are mated together in a feedthrough and you pull on one or both of the cables the spring(s) will be compressed and the mating ends of the fibers will be separated.

In pull-proof cable assemblies strength members in the cable are attached to the connector body such that the tension from pulling on the cable is applied to the connector body and to the feedthrough by way of the connector nut. Non of the tension is applied to the fiber or to the ferrule which holds it so the fibers are not separated.

When pull-proof cable assemblies are mated the springs are compressed and the fibers are pushed back into the cable for about 1 mm.

In loose tube fiber optic cable the fiber is contained in a tube which is many times the diameter of the fiber. This decouples the fiber from the other parts of the cable such as the strength members, and jacket.

In this paper all other cable constructions will be lumped into the tight buffer category which will include cables with widely differing degrees of fiber movement relative to the other cable parts.

6.3 Problems

If a tight buffered cable is subjected to large temperature variations the cable will expand or shrink. Since the other cable materials have a different thermal coefficient of expansion than the fiber, the fiber will be placed in tension or compression depending on whether the cable has expanded or shrunk. This causes stress on the fiber which can result in excess fiber loss and variations in the amplitude of the optical signal. This problem is worse for cables in which the fiber is tightly coupled to the other parts of the cable. The performance of some tight buffered cable over a wide temperature range can be quite good when the fiber is loosely coupled to the other parts of the cable.

The performance of loose tube cable is very good over a wide temperature range because the fiber is very loosely coupled to the other cable parts. However, in a loose tube cable assembly care must be taken to insure that the cable parts other than the fiber never get longer than the fiber due to thermal expansion or tension. If this happens the fiber will be stressed and could break.

In NPPT and NPPL cable assemblies tension will result in inadequate mating pressure or separation at the fiber interface. Tension can result from improper routing of the cable, or inadequately constrained cable during vibration. The result of this can vary from amplitude variations on the optical signal to a complete loss of signal.

If the construction of the cable in a PPT cable assembly is such that the fiber cannot be pushed into the cable by about 1 mm the fiber will bend within the connector body. In this case the fiber could bend so sharply that the attenuation would increase appreciably or it could break. In a PPL cable assembly this is not a problem because the fiber is free to move in the tube.

The PPL cable assembly is the most rugged of the four categories. Cable strength members are attached to the connector body so that tension on the cable is transferred to the feedthrough and not to the fiber. Therefore, when the cable is pulled the fiber interfaces are not separated. The fiber is free to be pushed into the cable upon mating and the fiber is isolated from stress induced by temperature variations, vibration, and cable flexure. However, care must be taken to ensure that there is enough excess fiber in the cable to allow for thermal expansion of the other cable parts.

6.4 Materials and Processes

The materials used in manufacturing commercial fiber and its buffer are generally suitable for space applications. However, the materials used in manufacturing the other cable parts in commercial cable are generally not suitable for space applications. Fortunately, several cable manufacturers have the material technology and processes to fabricate suitable cable.

One of the best jacketing material is expanded Teflon. It remains flexible at extremely low temperatures, it is strong, and it is relatively inert and free from outgassing.

7.0 A Comparison of Gore-Tex 0.190” Diameter Coaxial Cable to Fiber Optic Cable

7.1 Introduction

A cable is needed for SRTM to transmit microwave signals over the length of a 60 meter boom. This boom is folded up and stowed in an enclosure during launch. Once in orbit the boom is expanded to its full length. This folding and unfurling requires the cable to be very flexible and of small diameter. A previous study identified Gore-Tex 0.190” diameter cable to be one of the best coaxial cables for such an application. However, the performance of this cable falls short of some of the requirements of SRTM.

Fiber optic cable was identified as a potential alternative to coaxial cable for this application. This study was initiated to compare the two types of cable to enable engineering to make an informed decision about what type of cable is to be used.

7.2 Assumptions

Because the design of SRTM is still changing some assumptions were made for the sake of expediency. It is assumed that the cable will not be unfurled in a straight line so it will be longer than the boom. For the sake of this study it is assumed that the cable will be 100 meters long. It is also assumed that a cable larger in diameter than the Gore-Tex 0.190” diameter cable would not be practical from a mechanical standpoint.

7.3 Comparison

Since the Gore-Tex cable was determined to be one of the best for this application it is compared to a typical fiber optic cable. Five plots showing the performance of the Gore-Tex 0.190” coaxial cable were used from the Gore catalog. The performance of a typical fiber optic cable was superimposed on the Gore plots.

In Fig. 1 the insertion loss change vs temperature is plotted. The loss in a typical fiber optic cable is 0.05 dB/km over the temperature range of +85 ^{o}C to -60 ^{o}C.

In Fig. 2 the shielding effectiveness of the cables are plotted. Fiber optic cable has virtually no pickup or radiation of EMI of RFI.

In Fig. 3 the delay change vs flexure is plotted. Delay change vs flexure for a transmission line is a function of its diameter. The diameter of a single-mode optical fiber is normally 125 microns so its susceptibility to delay change with flexure is much less than that of a coaxial cable with a much larger diameter.

In Fig. 4 the phase change vs temperature is plotted. The delay change vs temperature in a properly constructed fiber optic cable is very predictable and constant. From -60 ^{o}C to +15 ^{o}C the Gore-Tex cable is 2 to 3 times better than a typical fiber optic cable. At higher temperatures it is as much as 7 times worse than the fiber optic cable.

In Fig. 5 the RF loss vs frequency is plotted for a 100 meter length of cable. The loss of both 0.190” diameter and 0.290” diameter Gore-Tex coaxial cable is given to demonstrate the reduction in loss for a larger diameter coaxial cable. The loss of the fiber optic cable includes the conversion loss of the fiber optic transmitter and receiver which is constant and is between 25 and 35 dB (as shown by the error bar).

The equivalent RF loss in the fiber optic cable itself is 0.08 dB in a 100 meter cable and is virtually constant through this frequency range.

Another important factor for space applications is the weight of the cable. A ruggedized 0.190” diameter fiber optic cable containing two fibers weighs 5.9 kgs per 1000 feet. A Gore-Tex 0.190” diameter coaxial cable weighs 16 kgs per 1000 feet and a Gore-Tex 0.290” diameter coaxial cable weighs 36 kgs per 1000 feet. The smaller Gore-Tex cable weighs 2.7 times as much as the fiber optic cable and the larger Gore-Tex cable weighs 6.1 times as much as the fiber optic cable.

An additional consideration is that active delay compensation schemes work much better in optical fiber than they do in coaxial cables. This is because the return loss is 30 dB higher in optical fibers and optical components and the isolation of optical components such as couplers, which are required in a compensation system, is more than 70 dB higher.

7.4 Predicted Phase Variations

The cable temperature variation with time, shown in Fig. 6, was calculated by Ray Garcia for hot and cold environmental conditions. For about the first 30 hours in orbit the average temperature of the cable cools down exponentially from 300^o K to as low as 242.5^o K. Superimposed on this long term temperature change is a sinusoidal 5^o K peak-to-peak variation with the frequency of the orbital period of about 1.48 hours. After about 30 hours in orbit the long term temperature variation reaches steady state leaving only the sinusoidal 5^o K peak-to-peak variation with the orbital period.

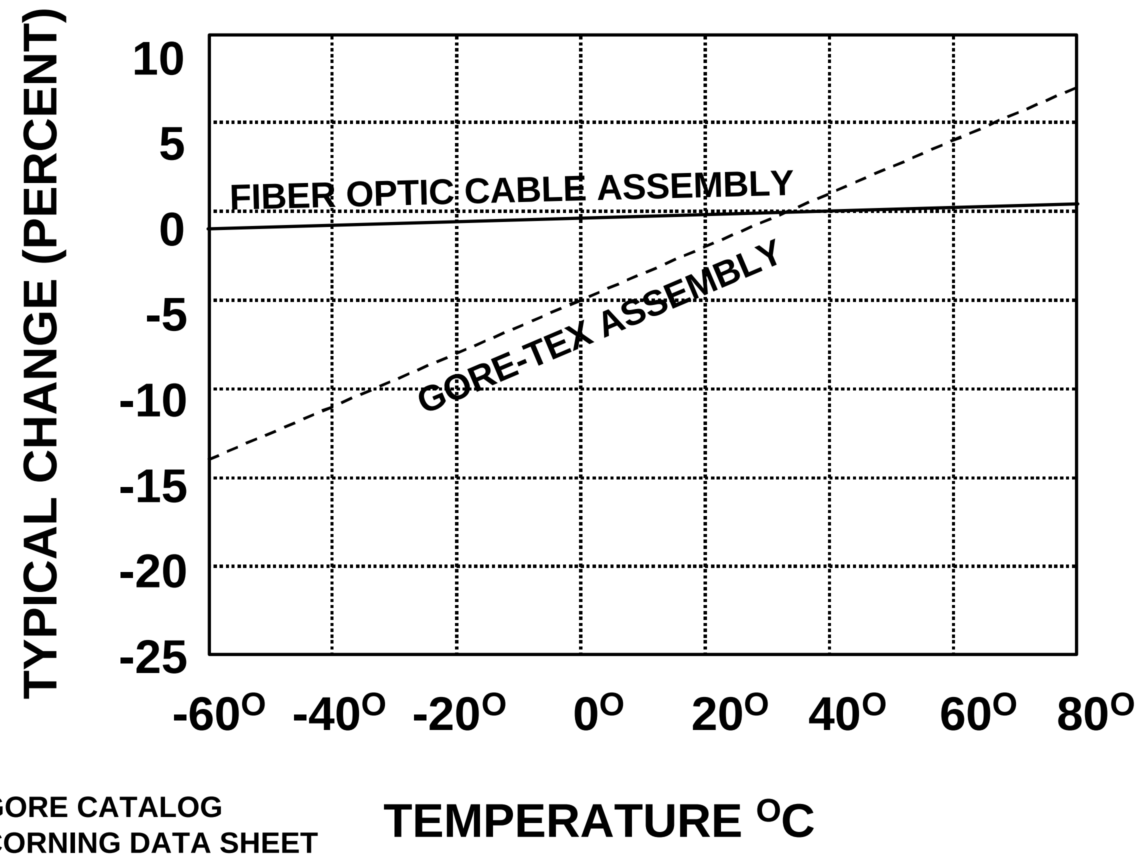
Based on this information the calculated delay variations are given in Appendix 1.

7.5 Conclusion

Fiber optic cable is obviously superior to coaxial cable in terms of change in insertion loss vs temperature, shielding effectiveness, delay change vs cable flexure, and weight. Over the temperature range from -60^o C to $+15^o$C Gore-Tex coaxial cable has a thermal coefficient of delay which is as much as 3 times lower than fiber optic cable. At higher temperatures the fiber optic cable’s thermal coefficient of delay is as much as 7 times lower than the coaxial cable. The signal loss in fiber optic cable is lower than the loss in Gore-Tex 0.190” diameter coaxial cable at frequencies above about 1 GHz and at 8 GHz it is as much as 60 dB lower. The Gore-Tex 0.290” diameter coaxial cable’s loss becomes larger than the loss in fiber optic cable at about 3 GHz and at 8 GHz it has as much as 30 dB higher loss.

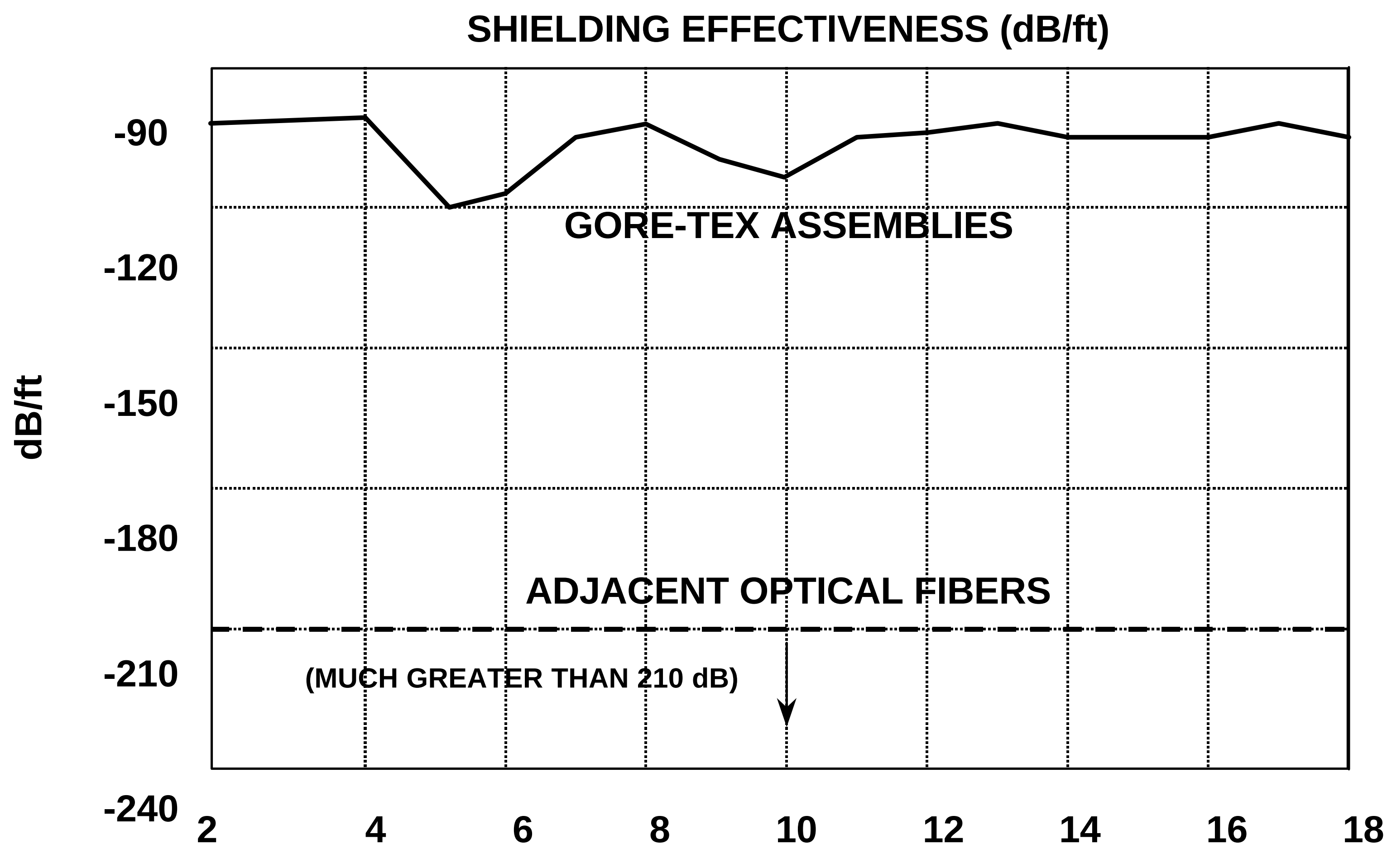
A system study would most likely find that the weight and power consumption of a fiber optic system would be lower. A coaxial system would require that 20 to 50 dB more signal power would have to be applied to the input to equal the signal level at the output of a fiber optic system.

TYPICAL INSERTION LOSS CHANGE VS TEMPERATURE



SOURCE: GORE CATALOG
CORNING DATA SHEET

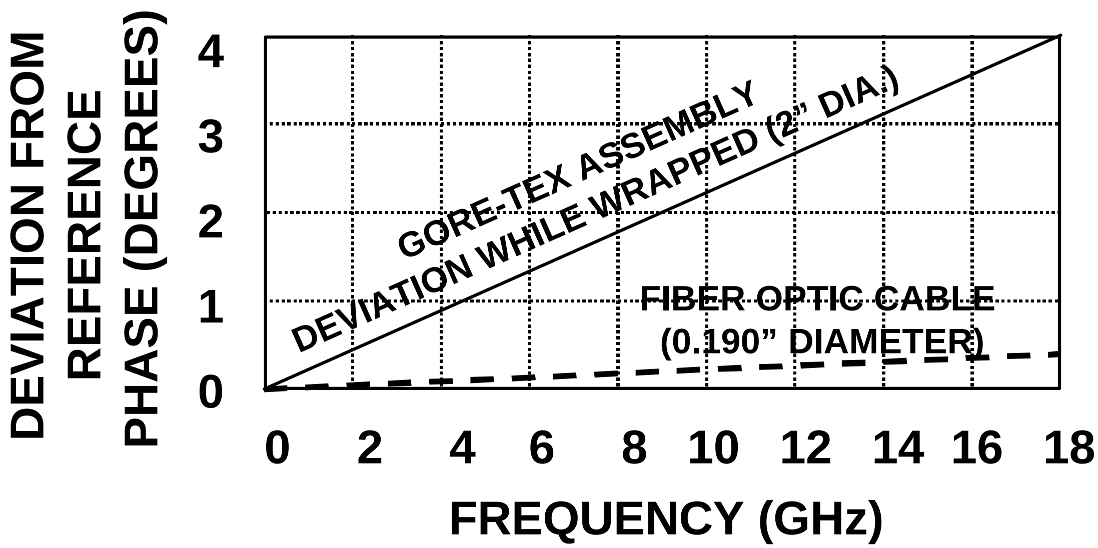
Fig. 1 - The change in insertion loss vs temperature for 0.190” diameter Gore-Tex coaxial cable and typical fiber optic cable.



Source: Gore catalog, Measured data

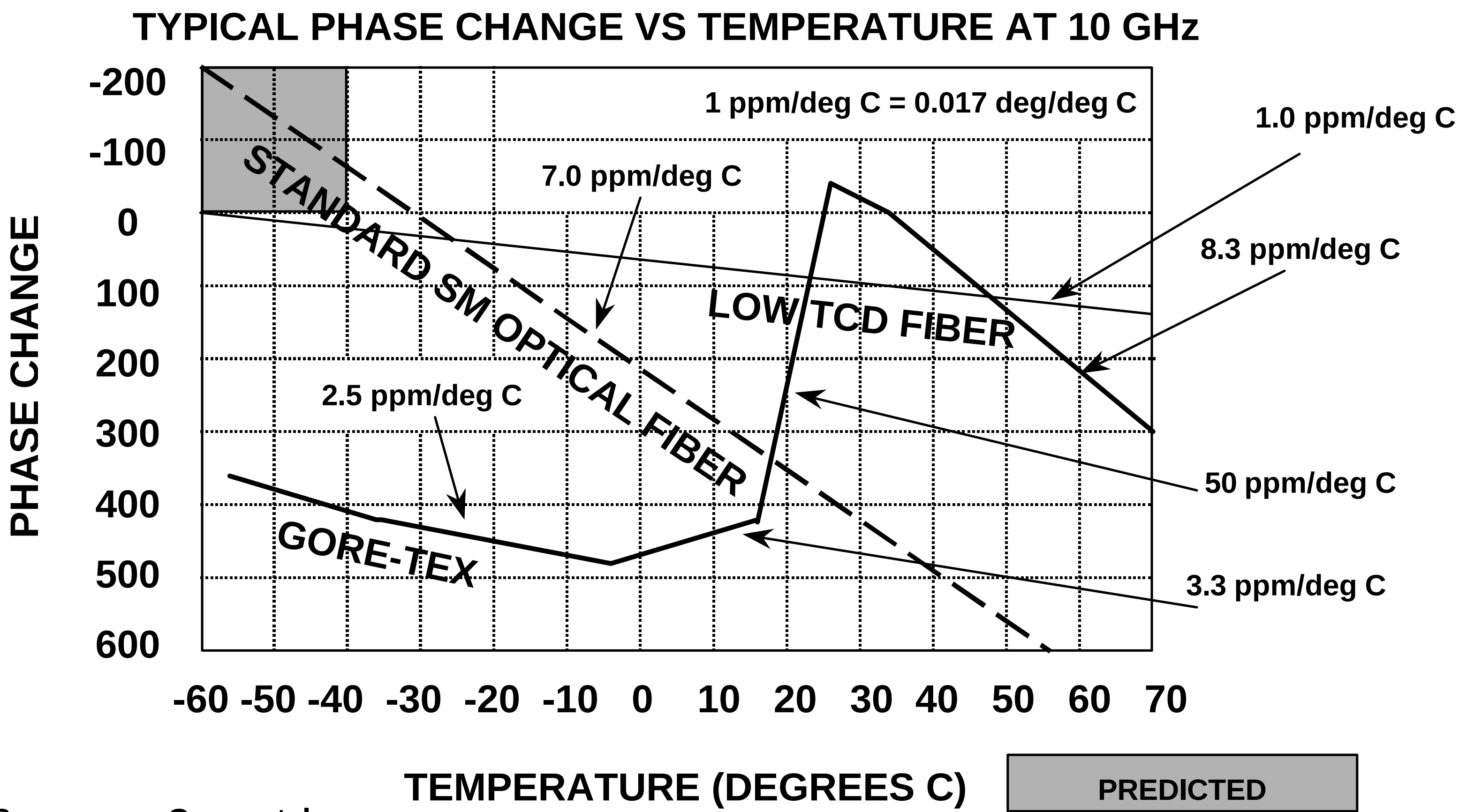
Fig. 2 - The shielding effectiveness for 1 foot of Gore-Tex 0.190" diameter coaxial cable and typical fiber optic cable.

TYPICAL PHASE STABILITY WITH FLEXURE FOR LOW LOSS 0.190 INCH DIAMETER ASSEMBLIES



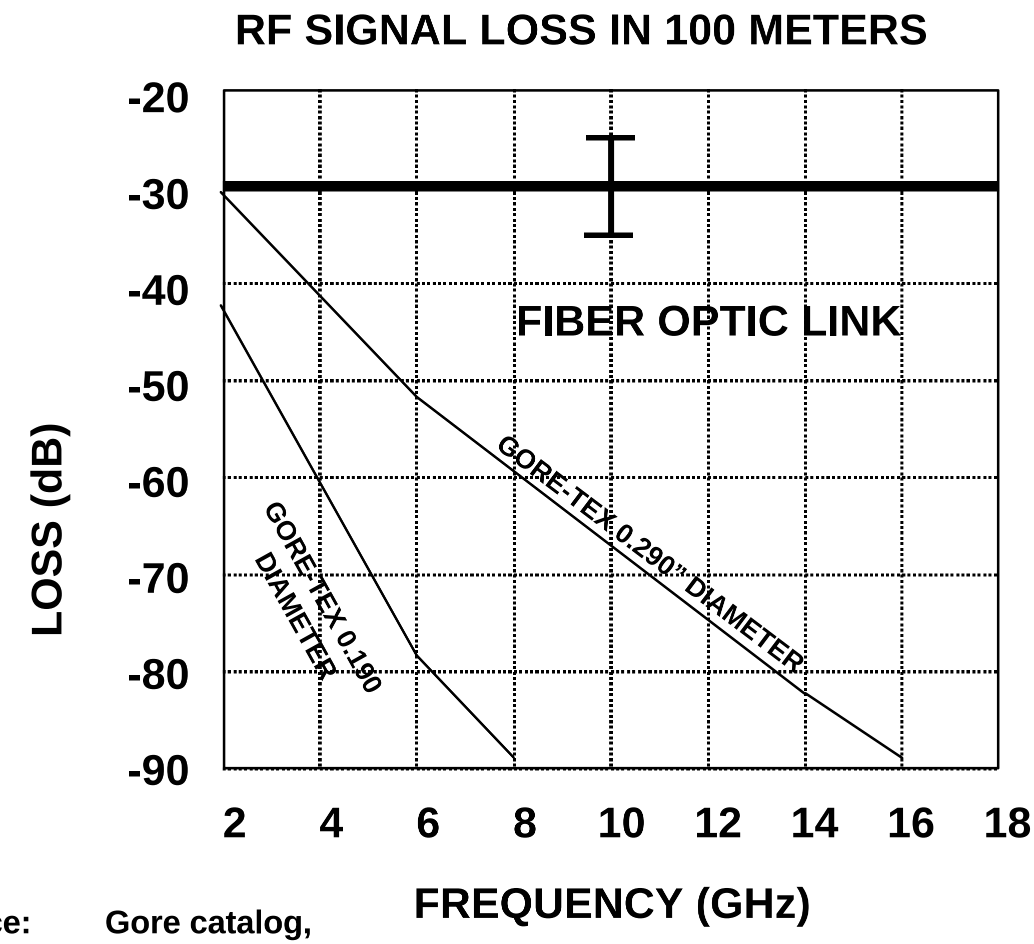
Source: **Gore catalog, Measured data**

Fig. 3 - The typical phase stability with flexure for Gore-Tex 0.190" diameter coaxial cable and typical fiber optic cable.



Source: Gore catalog, Measured data

Fig. 4 - The typical phase change vs temperature for Gore-Tex 0.190" diameter coaxial cable and typical fiber optic cable.



Source: Gore catalog, Measured data

Fig. 5 - The RF signal loss vs frequency in a 100 meter cable for Gore-Tex 0.190" diameter coaxial cable and typical fiber optic cable.

8.0 New Low Profile Connectors (MT-RJ, LC, VF-45)

Just as it has been for many years in the electronics industry, integration has become the buzzword of photonic companies. The demand for bandwidth has fueled the need for smaller, more integrated, and power efficient photonic system building blocks.

In 1998 six companies agreed to develop and manufacture small form factor transceivers and connectors. The connectors would be approximately half the size of the industry standard SC connector. Since no standard for the connector receptacle was designated in the agreement, the companies developed several competing designs. These designs include MT-RJ, LC, and VF-45 connectors.

Each company designed their connector to have what they conceived to be the proper tradeoffs between performance, cost, reliability, and ease of use. They each hoped that their connector would be the one that most appealed to the end users. The marketplace will decide which design will dominate and whether or not multiple designs will survive.

The MT-RJ has the form factor of the familiar RJ-45 wire connector used by the phone company for many years. This form factor is familiar to the installers of equipment and the manufacturers hope this will be a factor in making their connector popular.

A consortium designed the MT-RJ connector. The consortium members were AMP, Siecor, USConec, and Fujikura. There were five design objectives:

Capitalize on proven technology,

An optical replacement for the RJ-45 phone jack,

Installer friendly,

Easily integrated with small form factor transceivers being developed by other consortium members, and

To be multisourced with broad industry support.

The resulting connector is duplex and is about the same size as a single fiber SC connector.

The size of SC and ST connectors limits the fiber port density to about half that of copper interfaces. The new MT-RJ connector would result in fiber port areas with density equal to that of copper interfaces.

The designers started with the Mini-MPO connector from AMP which uses the MT-style ferrule from NTT. This approach would give high performance but the existing push-pull mechanism complicated identification of the correct orientation of the connector for installers. The latch was redesigned to operate exactly like the latch on the RJ-45.

Prior fiber optic connectors required a mating adapter to mate two plug connectors. The mating adapter aligns the ends of the two fibers to be mated. It is usually a precision sleeve that guides the connector ferrules as they are slid together and holds them in place once mated.

The MT-RJ connector contains a pre-polished fiber stub. The fiber in the cable slides into the back of the connector and butts up against the pre-polished fiber stub which is wetted with a matching gel. This provides a controlled end face finish. The fiber is held into the connector body mechanically. The termination procedure is simple and fast and does not require the use of epoxy or polishing.

Typical insertion loss for this connector is about 0.3 dB.

One of the most desirable features of this design is that the same cutouts can be used that are used for the common RJ-45 copper connector used by the phone companies today. This eliminates changes to the module package which would otherwise require redesign and additional expense.

LC Connectors

Bell Laboratories engineers designed the LC connector for single and multi-mode applications. It uses a 1.25 mm round ceramic ferrule. The current standard ferrule diameter used in SC, ST and other connectors is 2.5 mm. An adapter is available to allow equipment with a 2.5 mm diameter ferrule to interface with the smaller ferrule.

The LC connector uses features of the RJ-45 copper connector. This provides verification that the proper polarity is maintained and there is an audible click when fully inserted. Adhesive is used to secure the fiber and assuring low loss. Installation is similar to SC and ST connectors but the time required is 40% shorter.

The dual LC connector uses two individual connectors held loosely together. This minimizes stress because they have some freedom of movement to compensate for relaxed tolerances. This serves to minimize losses.

The average loss of an LC connector is 0.1 dB for both single-mode and multimode connectors. For field installations the average loss is 0.2 dB. This is better than most other common connectors. The low loss supports more connectors in series for a given system loss budget.

Lucent, Methode Electronics, Molex, and Sumitomo manufacture transceivers that are compatible with the LC connector.

The following standards recognize the LC connector:

TIA568A for areas outside of work station outlets,

ATM Forum specifications for 155 and 622 Mb/s systems,

IEEE 1394B S800 to 3200Mb/s systems, and

ISO 11801 International Cabling Standard.

VF-45 Connector

Engineers at 3M designed the VF-45 connector to give good performance at minimum cost. This design eliminates the costly ferrule used in other connectors and uses V-groove technology in its place. The connector is adhesive free and has a minimum number of components. Its installed cost is only about one-seventh of the cost of the industry benchmark duplex SC connector.

The VF-45 connector consists of 10 low cost injection-molded parts which are pre-assembled so that the installer only has to deal with 4 pieces. In contrast to this, the SC connector consists of 40 or more precision parts made of costly materials and using different manufacturing processes.

The socket uses a mechanical housing that clamps the fibers into the V-grooves. The plug housing clamps the fiber so that it sticks out from the clamp and slides into the V-grooves when mated. The fibers are forced into the V-grooves at an angle so the pressure holds them in the groove and small differences in the longitudinal alignment are compensated for by a change in bend radius. The loss in this connector depends on the precision of the optical fibers being mated.

Both the plug and the socket of the VF-45 connector have integral dust covers that slide out of the way when the connectors are mated. When the connectors eventually have to be cleaned it can be done without disassembling it. Because of greatly reduced dust and the unique construction of these connectors the loss as a function of the number of insertions is flat, even for as many as 1200 to 1500 insertions.

The design of the VF-45 connector only allows it to be inserted in the proper position so there is no risk of the connection being reversed. The connection is made parallel to the wall so it does not protrude and risk being broken off if accidentally brushed.

The VF-45 connector meets the requirements of the ISO 11801 and TIA-568A premise cabling standards as well as the corresponding component standards (ISO/IEC, TIA/EIA). It is meant to be used on multimode optical fiber but is being tested for compatibility with single-mode fiber.

The termination time is only two minutes per socket (two fibers) with a >98% yield. This is compared to 10 or 15 minutes for more traditional connectors like the dual SC.

9.0 Some Typical Fiber Optic Connector Parameters

ST Connectors Multimode

Loss: µ = 0.4 dB, = 0.2 dB
Fiber: 62.5/125 fiber, 0.29 numerical aperture
Fiber OD, nominal: 125 µm
Cable OD, nominal: 2.4 and 3.0 mm
Loss Repeat: <0.2 dB per 1000 reconnects
Axial Load, minimum: 35 pounds (15.9 kg)
Temperature Stability (-40°C to 75°C): ±0.2-dB maximum change
Materials: Tip - Ceramic
Cap - Brass, Ni plated
Body - Brass, Ni plated
Installation Time: One - 18 minutes
Twelve - 8 minutes, average

ST Connectors Singlemode

Ceramic Tip
Loss: µ = 0.35 dB, = 0.20 dB
Return Loss: -42 dB average; -35 dB worst case
8.3/125 µm fiber, 0.29 numerical aperture
Fiber OD, nominal: 125 µm
Cable OD, nominal: 2.4 and 3.0 mm
Loss Repeat: <0.2 dB per 200 reconnects
Axial Load, minimum: 35 pounds (15.9 kg)
Temperature Stability (-40°C to 75°C): ±0.2 dB, average change
Materials: Tip - Ceramic
Cap - Brass, Ni plated
Body - Brass, Ni plated
Installation Time: One - 18 minutes
Twelve - 8 minutes, average

SC Connectors (Singlemode)

Insertion Loss µ, (dB) 0.2, 0.1
Return Loss (Max) -40 dB
Fiber OD, nominal 125 µm
Cable OD, nominal, 3.0 mm cable, 0.9 mm buffer
Loss repeatability (200 insertions) <0.2 dB
Axial Load, nominal 30 lbs.
Temp. Stability (-40°C to 85°C) ±0.3 dB
Material
Tip, Zirconia
Body, Polysulfone
Mount Time
One, 18 minutes

Twelve, 8 minutes average

SC Connectors (Multimode)

Cable OD, nominal 3.0 mm cable, 0.9 mm buffer
Fiber OD, nominal, 125µm
Loss (dB), 0.3
Loss repeatability (200 insertions) <0.3 dB
Axial Load nominal 30 lbs.
Temp Stability (-40°C to 75°C) ±0.3 dB
Material
Tip, Ceramic
Body, Polysulfone
Mounting Time,
One, 18 min.
Twelve, 8 min. avg

Singlemode Biconic Interconnection Cables

Optical Insertion Loss: Standard -0.35 dB, < 1.0 dB max.
Keyed -0.35 dB, < 1.0 dB max.
Return Loss: Standard -31 dB
Keyed -42 dB
Mechanical dB Change
Insertion/Removal <=0.3 dB, 200 Insertions
Tensile Strength <=0.2 dB, 20 pounds (9.1 kg) (minimum)
Impact <=0.2 dB, Ten 2-meter drops on concrete floor
Vibration <=0.2 dB,
Ten 500 Hz, 0.73 g, 1-hour sweep
Ten 500 Hz, 10 g, 15-minute sweep
Shock <=0.2 dB
40 g, 11-millisecond, saw-tooth pulse
Flex <=0.5 dB
300 cycles, ±90°, one pound (0.,45 kg) weight
Twist <=0.2 dB
100 cycles, ±180°, 11 pound (4.99 kg) weight, 1' (2.54 cm) cable
Environmental dB Change
Storage Temperature, -40°C to +85°C
Operating Temperature <=0.3 dB, 10 cycles, -20°C to +60°C
Humidity <=0.5 dB, 60°C, 95% relative humidity, 504 hours
Thermal Shock <=0.2 dB
-40°C to +60°C, 10 cycles, 1-minute transition, 1-hour hold
Corrosion Resistance <=0.2 dB, Sale-mist, 48 hours

10.0 Photonic Components

This is list of components available to the photonic engineer. It is beyond the scope of this manual to explain what each of these components is. The reader should refer to a photonics dictionary such as the one published by, Laurin Publishing Co., Inc., Berkshire Commoon, Pittsfield, MA 01202, Phone: (413)499-0514.

Acousto-Optics

Adaptive Optics

Amplifiers, Optical

Apertures, Precision, Including Pinhole

Arc Lamps

Arrays, Detector

Arrays, Laser Diode

Arrays, Imaging

Arrays, Lens

Astronomical Optics

Attenuators

Avalanche Photodiodes

Beam Deflectors

Beam Directors

Beam Expanders

Beam Focusing Equipment

Beam Measurement Equipment

Beam Positioners

Beamsplitters

Beamsplitters, Polarizing

Beam Stabilizers

Binary Optics

Blackbody Sources

Blanks, Lens

Blanks, Mirror

Blanks, Molded

Blanks, Prism

Bolometers

Boresights

Brewster Angle Windows

Bubble Chamber Optics

Cable Duct

Cable, Fiber Optic

Camera Tubes

Cathode-Ray Tube Envelopes and Faces

Cathode-Ray Tubes (CRTs)

Cathode-Ray Tubes, Fiber Optic Faceplate

Cathode-Ray Tube Shields

Cathode-Ray Tube Sockets

Cells, Bragg

Cells, Dye Laser

Cells, Glass

Cells, Photoelectric

Cells, Refractometer

Cells, Solar

Cells, Spectrophotometer

Choppers, Electro-Optic

Choppers, Ion-Beam

Choppers, Motorized

Choppers, Optical

Choppers, Tuning Fork

Collimating Lenses

Collimators, Auto

Collimators, Laser

Comparators

Connectors

Coolers, Cryogenic

Coolers, Detector

Corner Cube Reflectors

Couplers

CRTs

Cryogenic Detectors

Crystals, Acousto-Optic

Crystals, Birefringent and Polarizing

Crystals, Electro-Optic

Crystals, Holographic

Crystals, Laser

Crystals, Liquid

Crystals, Nonlinear

Crystals, Piezoelectric

Crystals, Quartz

Crystals, Scintillation

Crystals, Ultraviolet
Dye Lasers

Crystals, X-Ray

Deflectors

Depolarizers

Detector Arrays

Detectors, APD

Detectors, CCD

Detectors, Cryogenic

Detectors, Fiber Optic

Detectors, Infrared

Detectors, Low-Light-Level

Detectors, Photoelectric

Detectors, Photoemissive

Detectors, Photomultiplier Tube

Detectors, Photovoltaic and Photoconductive

Detectors, Position Sensing

Detectors, Pyroelectric

Detectors, Scintillation

Detectors, Semiconductor

Detectors, Ultraviolet

Dewars, Cryogenic

Diamond-Turned Components

Dichroics

Dielectrics

Diffractive Optics

Diffusers

Domes, Optical

Dye Laser Cells
Fiber Optic Faceplates

Electro-Formed Optics

Electro-Optics

Etalons

Eyepieces

Faraday Rotators

Fiber-Coupled Laser Diode Arrays

Fiber-Loop Resonators

Fiber Optic Adaptors

Fiber Optic Attenuators

Fiber Optic Bundles, Imaging

Fiber Optic Cable, Fiber Bundle

Fiber Optic Cable, Radiation-Hardened

Fiber Optic Cable, Ruggedized

Fiber Optic Cable, Single-Fiber

Fiber Optic Cable Duct

Fiber Optic Connectors, Expanded-Beam

Fiber Optic Connectors, Multimode

Fiber Optic Connectors, Single-Fiber

Fiber Optic Couplers, Bidirectional

Fiber Optic Couplers, Polarization-Preserving

Fiber Optic Couplers, Star

Fiber Optic Couplers, Tee

Fiber Optic Couplers, Tree

Fiber Optic Couplers, Variable

Fiber Optic Detectors

Fiber Optic Distribution Panels
Filters, Absorption

Fiber Optic Ferrules

Fiber Optic Fibers, Dispersion-Shifted

Fiber Optic Fibers, Erbium-Doped

Fiber Optic Fibers, Infrared

Fiber Optic Fibers, Plastic

Fiber Optic Fibers, Plastic-Clad Silica

Fiber Optic Fibers, Polarization-Preserving

Fiber Optic Fibers, Scintillation

Fiber Optic Illuminators

Fiber Optic Isolators

Fiber Optic Jacketing

Fiber Optic Laser Diodes

Fiber Optic Light-Emitting Diodes

Fiber Optic Lightguides

Fiber Optic Modems

Fiber Optic Modulators

Fiber Optic Networks

Fiber Optic Polarizers

Fiber Optic Receivers

Fiber Optic Rotary Joints

Fiber Optics, Imaging

Fiber Optic Switches

Fiber Optic Tapers

Fiber Optic Transmitters

Films and Plates, Holographic

Filter Arrays
Graticules

Filters, Acousto-Optic

Filters, Birefringent

Filters, Broadband

Filters, Colored Glass

Filters, Contrast Enhancement

Filters, Dichroic

Filters, Diffractive

Filters, Holographic

Filters, Interference

Filters, Laser Line

Filters, Laser Protective

Filters, Neutral Density

Filters, Photographic

Filters, Pinhole

Filters, Plastic

Filters, Polarizing

Filters, Rejection Band

Filters, Spatial

Filters, Tunable

Filters, Wedge

Filters, X-Ray

Flats, Optical

Fourier Optics

Fresnel Optics

Glass-To-Metal Seals

Glass Tubing
Laser Q-Switches

Laser Rods

Gratings, Blazed

Gratings, Diffraction

Gratings, Echelon

Gratings, Holographic

Gratings, Laser

Gratings, Radial

Gratings, Replica

Gratings, Ronchi

Halogen Light Sources

Holograms

Holographic Films and Plates

Holographic Filters

Holographic Gratings

Illuminators

Image Sensors, Area

Image Sensors, Linear

Imaging Arrays

Infrared Sources

Interferometer Accessories

Irises

Kerr Cells

Laser Diode Arrays

Laser Diode Collimating Lenses

Laser Diode Modules

Laser Diodes

Laser Modelockers
Lenses, Plastic

Lenses, Precision Glass Balls

Laser-to-Fiber Couplers

LEDs

Lens Arrays

Lens Blanks

Lenses, Achromatic

Lenses, Anamorphic

Lenses, Aspheric

Lenses, Catadioptric

Lenses, Complex

Lenses, Condenser

Lenses, Conical

Lenses, Cylindrical

Lenses, Diamond-Turned

Lenses, Diffraction-Limited

Lenses, Diffractive

Lenses, Eyepieces

Lenses, Fourier

Lenses, Fresnel

Lenses, GRIN

Lenses, Laser

Lenses, Laser Diode Collimating

Lenses, Microscope

Lenses, Miniature

Lenses, Molded

Lenses, Monochromatic
Light Sources, Miniature

Light Sources, Plasma Discharge

Lenses, Prismatic

Lenses, Projection

Lenses, Radiation Resistant

Lenses, Relay

Lenses, Sapphire

Lenses, Simple

Lenses, Spheric

Lenses, Telephoto

Lenses, Telescope

Lenses, Wide Angle

Lenses, Zoom, Variable Focal Length

Light-Emitting Diodes, Infrared

Light-Emitting Diodes, Visible

Light Shields

Light Sources, Calibrated

Light Sources, Coherent

Light Sources, Fluorescent

Light Sources, Glow Discharge

Light Sources, Halogen

Light Sources, Hollow Cathode

Light Sources, Incandescent

Light Sources, Infrared

Light Sources, Krypton

Light Sources, Laser Diode

Light Sources, Mercury
Mirrors, Spherical

Mirrors, Ultraviolet

Light Sources, Stroboscopic

Light Sources, Tungsten

Light Sources, Ultraviolet

Light Sources, VUV

Light Sources, Xenon

Liquid Crystal Light Valves

Magneto-Optics

Metal Optics

Micro-Optics

Microscope Eyepieces

Microscope Objectives

Mirror Blanks

Mirrors, Aspheric

Mirrors, Astronomical

Mirrors, Beamsplitting

Mirrors, Cold

Mirrors, Concave and Convex, Spherical

Mirrors, Diamond-Turned

Mirrors, Fabry-Perot Etalon

Mirrors, Flat

Mirrors, Laser

Mirrors, Metal

Mirrors, Partial

Mirrors, Pellicle

Mirrors, Polygonal
Phototransistors

Pinholes

Plastic Fibers

Mirrors, X-Ray

Modelockers, Laser

Modulators, Acousto-Optic

Modulators, Electro-Optic

Modulators, Fiber Optic

Modulators, Magneto-Optic

Modulators, Mechanical

Modulators, Photoelastic

Modulators, Spatial Light

Mounts, Laser

Mounts, Optical

Mounts, Sidereal

Mounts, Telescope

Mounts, Tripods

Mounts, Vibration-Isolated

Optical Couplers

Optical Delay Lines

Optical Fibers

Optical Isolators

Optical Mounts

Optoisolators

Partial Reflectors

Pellicles, Optical

Photodetectors

Photodiodes
Sensor Cards

Shutters, Laser

Shutters, Manual

Plastic Optics

Pockels Cells

Polarizers, Fiber Optic

Polarizers, Infrared

Polarizers, Visible

Polarizing Beamsplitters

Polarizing Prisms

Prism Blanks

Prism Couplers

Prisms, Nonpolarizing

Q-Switches

Reflectors, Corner Cube

Reflectors, Partial

Reticles

Retroreflectors

Rotary Joints

Rotators, Faraday

Rulings, Precision Scale

Rulings, Ronchi (See Gratings)

Screens, Front Projection

Screens, Lenticular

Screens, Projection Television

Screens, Rear Projection

Screens, Translucent

Shutters, Optical

Sidereal Mounts

Tubing, Glass

Wave Plates

Wave Plates, Infrared

Wedges, Optical

Windows, Brewster Angle

Windows, Diamond

Windows, Infrared

Windows, Sapphire

YAG

YLF

11.0 Photonic Component and System Manufacturers

This is a list of the better known photonic manufacturers with addresses and phone numbers and some of the parts they manufacture. It should provide a starting place for searching for a particular photonic part.

ABB HAFO AB Member of the ASEA Brown Boveri Group Bruttovagen 1 P.O. Box 520 S-175 26 Jarfalla Sweden Phone: 46 8 580 24500 Fax: 46 8 580 20110	Application specific LEDs, PINs, and Duplex Devices for fiber applications. The 1A391 PIN photodiode detects 1300 nm with a responsivity of 0.8 A/W in wavelength-division-multiplexing applications while suppressing detection at 1550 nm (responsivity of 0.001 A/W). The device works with fiber cores as large as 100 µm without loss of responsivity and with a bandwidth of 2 GHz.
Acton Research Corp. 525 Main St. P.O. Box 2215 Acton, MA 01720-6215 Phone: 508/263-3584 Fax: 508/263-5086	Versitile Multi-Grating monochromators, high resolution monochromators, high power Excimer & UV Laser Optics, priecion filters & mirrors, fully integrated Spectroscopy Systems, Spectroscopy Accessories, Vacuum UV Monochromators
Adaptive Optics Associates, Inc. Subsidiary of United Technologies/Hamilton Standard 54 Cambridge Park Dr. Cambridge, MA 02140-2308 Phone: 617/864-0201 Fax: 617/864-5855	The Micro-Optics Lens Sampler consists of a 6 x 6-in. acrylic sheet on which 25 monolithic lens arrays have been compression molded. Each array measures 18 x 18 mm with apertures ranging from 200 to 1000 µm and f/numbers ranging from 2.5 to 29.3. Fill factors for the arrays range from 97 to 99%.
ADC Telecommunications, Inc. 4900 West 78th St. Minneapolis, MN 55435-5410 Phone: 612/938-8080 Fax: 612/946-3292	Fiber cable management systems, FlexLight 2000 products for terminating, connecting, and splicing fiber optic cable.
AEL Industries, Inc. 305 Richardson Rd. Lansdale, PA 19446 Phone: 215/822-2929 Fax: 215/822-9165	High-power, broadband YAG-laser transmitters for CATV and cellular-systems applications in the AELINK series operate at 1300 and 1550 nm with up to eight simultaneous outputs.
Alcatel Telecommunications Cable, Inc. Subsidiary of Alcatel Cable N.A. 2512 Penny Rd. P.O. Box 39 Claremont, NC 28610-0039 Phone: 703/265-0600 Fax: 703/459-9312	WDM Systems with up to 32 wavelengths from 1530 - 1565 nm wavelength and wavelength spacing down to 0.8 nm and wavelength stability of <0.02 nm/year.

Alcoa Fujikura Ltd. Telecommunications Div. 150 Ridgeview Circle Duncan, SC 29334-9635 Phone: 803/433-0333 Fax: 803/433-5353	Fusion Splicers, Connectorized Cable, Couplers.
3M Specialty Optical Fibers A 3M Co. 420 Frontage Rd. West Haven, CT 06516-4190 Phone: 203/934-7961 Fax: 203/932-3883	Specialty Optical Fibers, Fiber Bragg Gratings TECS 39 low-OH hard-clad fiber comes in core sizes from 200 to 1500 µm and offers improved attenuation over the standard TECS 39. Its spectral transmission range is from 400 to 2200 nm, which is particularly useful in medical-laser applications.
American Laubscher Corp. 85 Finn Court Farmingdale, NY 11735 Phone: 516/694-5900 Fax: 516/293-0935	Versions of a diffraction-grating-based miniature spectrometer operate in either the 400-1100-nm or 370-850-nm wavelength region.
AMP P.O. Box 3608 Harrisburg, PA 17105-3608 Phone: 717/564-0100 Fax: 717/986-7575	fiber optic transceivers, optoelectronic componets, couplers, WDMs, switches, connectors, cable assemblies, and fiber management systems
Amphenol Corp. A LPL Co. Fiber Optic Products Div. 1925A Ohio St. Lisle, IL 60532 Phone: 708/960-1010 Fax: 708/810-5640	complete line of interconnect products, including SC, ST, FC, and SMA connectors and adapters; custom, standard, angle polish, and super PC cable assemblies; termination systems including tooling and consumable materials
Analog Modules, Inc. 126 Baywood Ave. Longwood, FL 32750-3426 Phone: 407/339-4355 Fax: 407/834-3806	Model 8800D high-power laser-diode controller

Andersen Laboratories, Inc. 45 Old Iron Ore Rd. Bloomfield, CT 06002-1902 Phone: 203/286-9090 Fax: 203/242-4472	acousto-optic devices, ie. modulators, beam deflectors, Q-switches, mode lockers
Ando Corp. Subsidiary of Ando Electric Co., Ltd. Measuring Instruments Div. 7617 Standish Place Rockville, MD 20855-2702 Phone: 301/294-3365 Fax: 301/294-3359	AQ-6315 Optical Spectrum Analyzer, AQ-714D High Dynamic Range OTDR, AP-9455 SONET Analyazer, and Brillouin optical time domain analyzer, optical amplifier analyzer
Andrew Corp. 10500 West 153rd St. Orland Park, IL 60462-3071 Phone: 708/349-3300 Fax: 708/349-5444	The Autogyro Navigator is a compact fiberoptic gyroscope for land navigation
Andrews Glass Co. 410 South Fourth St. Vineland, NJ 08360 Phone: 809/692-4435 Fax: 609/692-5357	Glass tubing in round, rectangular, triangular, and other shapes for custom applications
Anritsu America, Inc. Subsidiary of Anritsu Corp. Communications and Data Storage 365 West Passaic St. Rochelle Park, NJ 07662-3014 Phone: 201/843-2690 Fax: 201/843-2665	ATM and SONET Test Equipment, Mini OTDR, optical power meters, optical spectrum analyzers, tunable light sources
Antel Optronics Inc. 1701 North Greenville Ave. Richardson, TX 75081 Phone: 214/690-5200 Fax: 214/690-5302	multimode and singlemode OTDRs PC computer board

AOFR Americas, Inc. A BHP Co. 800 East Campbell Rd., Ste. 108 Richardson, TX 75081 Phone: 214/644-1394 Fax: 214/480-9278	single-mode and multimode optical couplers wavelength division multiplexers
AOTF Technology, Inc. 540-6 Weddell Dr. Sunnyvale, CA 94089 Phone: 408/734-5435 Fax: 408/734-0514	acouto-optic devices, sub-systems, and systems
Applied Laser Systems 2160 NW Vine St. Grants Pass, OR 97526 Phone: 503/479-0484 Fax: 503/476-5105	Clarity Lenses provide miniature, anamorphic, and astigmatic correcting lenses for visible diode lasers to produce a round Gaussian beam.
Applied Optronics Corp. 111 Corporate Blvd., Bldg. J South Plainfield, NJ 07080 Phone: 908/753-6300 Fax: 908/753-4041	Fiber-coupled visible laser diodes provide a choice of two photosensitizer wavelengths for research in photodynamic therapy and other applications.
AstroCam Ltd. Innovation Centre, Milton Rd. Cambridge Science Pk Cambridge CB4 4GS England Phone: 44 1223 420705 Fax: 44 1223 423021	Back-illuminated CCDs, highly sensitive in blue and UV
AT&T Microelectronics Subsidiary of AT&T Dept. 500404000 555 Union Blvd. Allentown, PA 18103-1229 Phone: 800/372-2447	fiber optic communications equipment, including couplers, connectors, cables, and test equipment

Atramet Inc. 222 Sherwood Ave. Farmingdale, NY 11735-1718 Phone: 516/694-9000 Fax: 516/694-9177	Russian-made Ti:sapphire rods are available in diameters ranging from 3 to 8 mm and in lengths up to 150 mm.
Augat Photon Subsidiary of Augat, Inc. 7725 Lougheed Hgwy. Burnaby, B.C. V5A 4V8 Canada Phone: 604/420-8733 Fax: 604/420-9606	Fiber optic connectors, adaptors, cable assemblies, and fiber optic distributioin enclosures
Big Sky Laser Technologies, Inc. P.O. Box 8100 Bozeman, MT 59715-2001 Phone: 406/586-0131	Supplier of compact, rugged solid-state lasers and subassemblies.
Brimrose Corp. of America 5020 Campbell Blvd. Baltimore, MD 21236 Phone: 410/931-7200 Fax: 410/931-7206	custom acousto-optic tunable filters (AOTF), acousto-optic modulators and scanners, RF driver, mercury manganese telluride-infrared detectors
Broadband Communications Products, Inc. 305 East Dr., Ste. A Melbourne, FL 32904 Phone: 407/984-3671 Fax: 407/728-0487	High speed analog and digital fiber optic links
Burleigh Instruments, Inc. Burleigh Park P.O. Box E Fishers, NY 14453-0755 Phone: 716/924-9355 Fax: 716/924-9072	The WA-1500 Wavemeter uses proven Michelson interferometer-based technology. Inchworm Nanopositioning Systems, Nanometer resolution

Deutsch Ltd. Subsidiary of Deutsch Corp. Birches Ind. Estate East Grinstead, West Sussex RH19 1RW England Phone: 44 1342 410033 Fax: 44 1342 410005	FAST HRL OPTOCLIP connector, expanded beam, CONIX simplex and duplex custom and standard SC, ST, FC, SMA, FSD, and ESCON connectors
CASIX P.O. Box 1103 Fuzhou, Fujian 350014 China Phone: 86 591 366 6957 Fax: 86 591 362 1248	acousto-optic materials
Centronic Inc. E-O Div. 2088 Anchor Court Newbury Park, CA 91320 Phone: 805/499-5902 Fax: 805/499-7770	The BPW-34FR silicon photodiode The OSD100-5TBNC silicon photodiode offers enhanced spectral response at blue wavelengths
Corning Incorporated Opto-Electronics Group MP-RO-02 Corning, NY 14831 Phone: Fax: 607/974-7522	Polarcor polarizers, 40 dB contrast ratio, temperatures up to 400 degrees C, 99 % transmittance, acceptance angles in excess of 30 degrees,
Crystal Technology, Inc. A Siemens Co. 1040 East Meadow Circle Palo Alto, CA 94303 Phone: 415/856-7911 Fax: 415/858-0944	acousto-optic crystals and components, electro-optics, nonlinear optics, integrated optics, AO deflectors, modulators, and Q-switches: EO Q-switches, IO modulators and switches, fabricated crystals of lithium niobate, lithium tantalate, TeO(2), KTP and BBO
CVI Laser Corp. 200 Dorado Place SE P.O. Box 11308 Albuquerque, NM 87192 Phone: 505/296-9541 Fax: 505/298-9908	Optical coatings, laser optics, optical mounts, waveplates (zero order, mulriple order, dual wavelength, single order mica, ahromatic, rotary mounts)

Deutsch Ltd. Subsidiary of Deutsch Corp. Birches Ind. Estate East Grinstead, West Sussex RH19 1RW England Phone: 44 1342 410033 Fax: 44 1342 410005	Conix Duplexers permit bi-directional transmission over a fiber.
Diamond USA Inc. 119 Russell St. Littleton, MA 01460 Phone: 508/952-0164 Fax: 508/952-0166	Precision fiber optic connectors.
Diamonex, Inc. 7150 Windsor Dr. Allentown, PA 18106-9328 Phone: 610/366-7100 Fax: 610/366-7111	Diamond heat sinks with thermal conductivity of more than 1300 W/mK
DiCon Fiberoptics, Inc. 1331 Eighth St. Berkeley, CA 94710 Phone: 510/528-0427 Fax: 510/528-1519	Switches, WDMs, Bandpass Filters, (fixed and tuneable)
E-TEK Dynamics, Inc. 1885 Lundy Ave., #103 P.O. Box 611120 San Jose, CA 95131 Phone: 408/432-6300 Fax: 408/432-8550	fiber opotic isolators, couplers, WDMs, electrooptic modulators, tuneable laser sources, laser diode test system
Eastman Kodak Co. Commercial and Government Systems 1447 St. Paul St. Rochester, NY 14653-7006 Phone: 716/253-6685 Fax: 716/253-6988	high performance 1024 X 1024 pixel, full frame charge coupled device image sensor

Edmund Scientific Co. 101 East Gloucester Pike Barrington, NJ 08007 Phone: 609/547-3488 Fax: 609/573-6295	Optics ie. Lenses, prisms, etc.
EG&G Ltd. Subsidiary of EG&G, Inc. EG&G Fiber Optics Div. Mulberry Business Park Sorbus House Wokingham, Berks RG11 2GY England Phone: 44 734 773003 Fax: 44 734 773493	complete range of pulsed and CW high power laser diodes, together with silicon and InGaAs p-i-n and APD detectors
Electrophysics Corp. 373 Route 46, Bldg. E Fairfield, NJ 07004-2442 Phone: 201/882-0211 Fax: 201/882-0997	Infrared viewers 0.7 to 1.3 um +.
EPITAXX Optoelectronic Devices, Inc. Subsidiary of Nippon Sheet Glass Co., Ltd. 7 Graphics Dr. West Trenton, NJ 08628 Phone: 609/538-1800 Fax: 609/538-1684	The ETXXXXGR-TE series features 100-, 500- and 1000 um InGaAs graded photodiode The ETXXXXGR-TE series features 100-, 500- and 1000 um InGaAs graded photodiode
Epoxy Technology, Inc. 14 Fortune Dr. Billerica, MA 01821 Phone: 508/667-3805 (Inside MA) 800/227-2201 (Outside MA) 800/227-2201 Fax: 508/663-9782	Epoxies and polymers for optics and fiber optics including fiber optic pigtailing, protective coatings, recladding PCS optical fibers, potting and casting components
Evaporated Coatings, Inc. 2365 Maryland Rd. Willow Grove, PA 19090 Phone: 215/659-3080 Fax: 215/659-1275	custom manufacturer of thin vacuum deposited thin films for fiber optic components, glass, metal, and plastic substrates. coatings include optical filters, mirrors, beamsplitters, anti-reflection, and index matching designs.

EXFO Electro-Optical Engineering, Inc. 465 Godin Ave. Vanier, P.Q. G1M 3G7 Canada Phone: 418/683-0211 (Inside P.Q.) 800/663-EXFO Fax: 418/683-2170	Fiber optic test equipment.
Fermionics Corp. 4555 Runway St. Simi Valley, CA 93063 Phone: 805/582-0155 Fax: 805/582-1623	InGaAs linear array chip
Fiber Instrument Sales, Inc. 161 Clear Rd. Oriskany, NY 13424 Phone: 315/736-2206 (Outside NY) 800/445-2901 Fax: 315/736-2285	Patchcord Attenuator Power Meter A full line of fiber optic products.
FJW Optical Systems, Inc. 629 South Vermont St. Palatine, IL 60067 Phone: 708/358-2500 Fax: 708/358-2533	Find-R-Scope IR viewer
Fotec, Inc. 151 Mystic Ave. Medford, MA 02155-4615 Phone: 617/396-6155 Fax: 617/396-6395	FO tracer is a visible light source used to test fiberoptic cables for continuity
GEC Advanced Optical Products Subsidiary of GEC Marconi Research Centre West Hanning Field Rd. Great Baddow Chelmsford, Essex CM2 8HN England Phone: 44 1245 473331 Fax: 44 1245 475244	Photoreceiver for broadband analog links operates at 1.3 and 1.55 um.

Gould Electronics Inc. Fiber Optics Div. 1121 Benfield Blvd. Millersville, MD 21108-2540 Phone: 410/987-5600 Fax: 410/987-1201	Fiberoptic planar waveguide splitters are available with split counts from two to 32.
Hamamatsu Corp. Subsidiary of Photonic Management Corp. 360 Foothill Rd. P.O. Box 6910 Bridgewater, NJ 08807-6910 Phone: 908/231-0960 (Outside NJ) 800/524-0504 Fax: 908/231-1218	microchannel-plate photomultiplier tube
Hewlett-Packard Co. Microwave Technology Div. Lightwave Operation 1400 Fountaingrove Pkwy. 1USF Santa Rosa, CA 95403 Phone: 800/452-4844 Fax: 707/577-5221	Fiber optic components for SONET, HPPI, and FDDI.
ILX Lightwave Corp. 31950 East Frontage Rd. P.O. Box 6310 Bozeman, MT 59771-6310 Phone: 406/586-1244 (Inside MT) 800/459-9459 (Outside MT) 800/459-9459 Fax: 406/586-9405	laser-diode drivers
Innovative Fibers 11 Larcher P.O. Box 84148 Gatineau, P.Q. J8P 7R8 Canada Phone: 819/663-4795 Fax: 819/663-4973	Bragg gratiing experts Selective Filters for WDM, Optical Sensors, Amplifier Noise Reduction, and In-fiber lasers.
Integrated Optical Components Ltd. 3 Waterside Park Eastways Witham, Essex CM8 3YQ England Phone: 44 1376 502110 Fax: 44 1376 502125	LiNbO integrated optics ie. modulators with low drive voltage,

Janos Technology, Inc. Route 35 HCR #33, Box 25 Townshend, VT 05353-7702 Phone: 802/365-7714 Fax: 802/365-4596	For applications that require nonimaging energy collection, integrated packages that use compound parabolic concentrators are available.
JDS Fitel Inc. 570 West Hunt Club Rd. Nepean, On. K2G 5W8 Canada Phone: 613/727-1303 Fax: 613/727-8284	high-power diode-laser modules
Kyocera Industrial Ceramics Corp. Subsidiary of Kyocera International, Inc. Electro-Optics Div. 100 Randolph Rd. Somerset, NJ 08875-6700 Phone: 908/560-3666 Fax: 908/627-9594	ceramic ferrules, split sleeves, tubes, SC, FC, and D4 connectors, adapters, recepticles, optical couplers, WDM, WIC, isolators, LiNbO3, aspherical lens, saphire ball lens, lenses and optical fiber, hermetic lasaer packages, heat sinks, and laser submounts
Laser Armor Tech Corp. Member of the Cook Group Inc. 10575 Roselle St. San Diego, CA 92121 Phone: 619/453-0670 Fax: 619/453-2638	Form metal tubes around optical fibers.
Laser Diode, Inc. Member of the Morgan Crucible Group plc 4 Olsen Ave. Edison, NJ 08820 Phone: 908/549-9001 Fax: 908/906-1559	lasers, LEDs, super radiant diode emmitters, pin detectors, high sensitivity pinfet receivers, RF and video links
Lasertron 37 North Ave. Burlington, MA 01803-3305 Phone: 617/272-6462 Fax: 617/273-2694	Microwave fiber optic transmitters and receivers.

Lucent Technologies 555 Union Blvd. Rm. 21Q133BA, Dept. P83 Allentown, PA 18103 Phone: 800-372-24447 FAX: 610-712-4106	Lasers with built-in modulators. Model 266A electroabsorption modulated isolated laser module has 2.5 Gbits/sec data rate over each of 8 wavelengths. Optical fiber. Model 1720 erbium doped fiber amplifier (EDFA) for analog applications. DFB MQW lasers for analog applications.
Micracor, Inc. 43 Nagog Park Acton, MA 01720 Phone: 508/263-1080 Fax: 508/263-1448	miniature diode pumped solid state lasers, analog microwave links to 20 GHz, tuneable laser source
NEC Electronics Inc. Subsidiary of NEC Corp. 475 Ellis St. P.O. Box 7241 Mountain View, CA 94039-7241 Phone: 415/965-6000 Fax: 800/729-9288	Fiber optic equipment
New Focus, Inc. 2630 Walsh Ave. Santa Clara, CA 95051-0905 Phone: 408/980-8088 Fax: 408/980-8883	wavelength meter, modulators, etc.
Newport Corporation 1791 Deere Ave. P.O. Box 19607 Irvine, CA 92714 Phone: 714/863-3144 (Inside CA) 800/222-6440 (Outside CA) 800/222-6440 Fax: 714/253-1680	Laser-diode instrumentation is available including laser temperature controllers, laser-diode drivers, and temperature-controlled mounts. Laser welders.
Norland Products Inc. 695 Joyce Kilmer Ave. P.O. Box 7145 North Brunswick, NJ 08902-0145 Phone: 908/545-7828 Fax: 908/545-9542	bare fiber inspection interferometers, connector installation kits, optical adhesive (UV cured)

Northern Telecom, Inc. Optoelectronics Div. 8601 Six Forks Rd., Ste. 410 Raleigh, NC 27615 Phone: 919/846-4946 Fax: 919/846-4948	EDFAs, 980 nm pumps, Mini DIL (laser), pin preamp, tranceivers, MQW DFB Lasers, LCM 155-64 Laser/modulator w IIIV modulator (absorption modulators)
NSG America, Inc. Subsidiary of Nippon Sheet Glass Co., Ltd. 28 World's Fair Dr. Somerset, NJ 08873-1346 Phone: 908/469-9650 Fax: 908/469-9654	GRIN microlenses, lens arrays, 1 X N fiber couplers,
Optics for Research, Inc. P.O. Box 82 Caldwell, NJ 07006 Phone: 201/228-4480 Fax: 201/228-0915	Tunable Ho:YAG and Th:YAG isolators operate in the 2.0-2.1 um range.
Oriel Instruments 250 Long Beach Blvd. P.O. Box 872 Stratford, CT 06497-0872 Phone: 203/377-8282 Fax: 203/378-2457	Compact diode lasers designed for OEM applications are available in models with various output powers and beam sizes at wavelengths of 635, 670, 675, 785, and 830 nm. The lasers
Ortel Corp. 2015 West Chestnut St. Alhambra, CA 91803-1542 Phone: 818/281-3636 Fax: 818/281-8231	linear fiber optic products for CATV and ultrahigh stability analog systems, Fabry-Perot and DFB lasers, laser transmitters, PIN photodiodes, fiber optic receivers,
OZ Optics Ltd. West Carleton Industrial Park 219 Westbrook Rd. Carp, On. K0A 1L0 Canada Phone: 613/831-0981 (Inside On.) 800/361-5415 (Outside On.) 800/361-5415 Fax: 613/836-5089	Flanged bulkhead receptacles are designed to hold NTT-FC or AT&T-ST-style fiber connectors in place.

PD-LD, Inc. 209 Wall St. Princeton, NJ 08540 Phone: 609/924-7979 Fax: 609/924-7366	VAC is a variable attenuator and connector in one unit for single or multimode applications.
Pirelli Cables North America Communications Div. 700 Industrial Dr. Lexington, SC 29072-3799 Phone: 803/951-4800 Fax: 803/957-4628	fiber optic cables, erbium doped fiber amplifiers, Lithium niobate intensity modulators,
Polytec GmbH Polytec-Platz 5-7 P.O. Box 161 D-76333 Waldbronn Germany Phone: 49 7243 604 100 Fax: 49 7243 69944	monolithic flexure stages are piezoelectrically driven
Qualop Systems Corp. 931 Benecia Ave. Sunnyvale, CA 94086 Phone: 408/739-8300 Fax: 408/245-9872	Optical Isolators -
Queensgate Instruments Ltd. Queensgate House Waterside Park Bracknell, Berks RG12 1RB England Phone: 44 1344 484111 Fax: 44 1344 484115	miniature tuneable Fabry-Perot filters with unmatched thermal, mechanical, and wavelength stability.
Rifocs Corp. 833 Flynn Rd. Camarillo, CA 93010 Phone: 805/389-9800 Fax: 805/389-9808	high precision, low return loss fiber optic connectors, super PC, APC, DIN, Diamond, Avionics, cable assemblies, termination services,

Rolyn Optics Co. 706 Arrowgrand Circle Covina, CA 91722-2199 Phone: 800/716-0071 Fax: 818/915-1379	reflective objectives are coated and assembled to customer order
Santec USA Corp. Subsidiary of Santec Corp. Highway 35 and Union Ave. Holmdel Corp. Plaza Holmdel, NJ 07733 Phone: 908/739-5505 Fax: 908/739-5506	optical tuneable filters with polarizatiion independence, continuous tuning, low insertion loss, portable wavelength meter, incoherent wavelength tuneable light source, laser sensing head.
Schott Fiber Optics Inc. Member of the Schott Group 122 Charlton St. Southbridge, MA 01550-1960 Phone: 508/765-9744 (Inside MA) 800/343-6120 (Outside MA) 800/343-6120 Fax: 508/764-6273	Fabrication capabilities: cutting, drilling, grinding, edging commercial and precision polishing, precision machining, fused components, sagged blanks Services: glass research and development, product development assistance, contract melting of your glass, test melting, full measurement and cerification capability.
SDL, Inc. 80 Rose Orchard Way San Jose, CA 95134-1356 Phone: 408/943-9411 Fax: 408/943-1070	laser diode provides CW power, a diffraction-limited beam, and near-infrared wavelength tunability
Seiko Instruments U.S.A., Inc. Subsidiary of Seiko Instruments Inc. Electronic Components Div. Fiber Optics Group 2990 West Lomita Blvd. Torrance, CA 90505 Phone: 310/517-8113 Fax: 310/517-7792	a full line of precisioin single-mode and multimode connector products, cable assemblies, high yield polishers, and attneuators. Connectors include FC, D4, ST, and Mini-BNC.
Siecor Corp. P.O. Box 489 Hickory, NC 28603-0489 Phone: 704/327-5000 Fax: 704/327-5973	field installable connectors, interconnect panels, splicers, test equipment, cable and patch cords, high density frame and optical splice enclosures

SpecTran Specialty Optics Co. Subsidiary of SpecTran Corp. 150 Fisher Dr. P.O. Box 1260 Avon, CT 06001-1260 Phone: 203/678-0371 Fax: 203/674-8818	Special purpose optical fibers and fiber optic cables with high temperature range, radiation resistance, large core fibers,
Sumitomo Electric Lightwave Corp. Subsidiary of Sumitomo Electric Industries, Ltd. 78 Alexander Dr. P.O. Box 13445 Research Triangle Park, NC 27709-3445 Phone: 919/541-8100 Fax: 919/541-8265	optical fiber cables and related products, fusion splicing equipment, optical connectors, cable assenblies, data transmission equipment, analog and digital video transmission equipment, and air blown fiber optic cabling sytems Low Thermal Coefficient of Delay optical fiber (LTCD Optical Fiber)
UTP-Uniphase Telecommunications Products, Inc. Subsidiary of Uniphase Corp. 1289 Blue Hills Ave. Bloomfield, CT 06002 Phone: 203/769-3000 Fax: 203/769-3001	Microwave fiber optic modulators.
Wave Optics, Inc. 1056 Elwell Court Palo Alto, CA 94303-4307 Phone: 415/967-0700 Fax: 415/967-0974	A PM-FC fiberoptic connector limits rotation, thus allowing consistent extinction rations of 25 to 30 dB.
Wavelength Electronics, Inc. 521 East Peach, Unit B P.O. Box 865 Bozeman, MT 59715 Phone: 406/587-4910 Fax: 406/587-4911	MP laser-diode drivers and TE temperature controllers are designed for single-supply operation.

12.0 References

The following documents can be read from the 1996 Photonics CD-ROM published by Laurin Publications Co., Inc., Berkshire Common, Pittsfield, MA 01202 Phone: (413)499-0514. This is a great source for the photonic industry. Every engineer should have a copy.

Thermoelectric Coolers: Selecting the Right Cooling Systems for Laser Diodes and Detectors
Janet McDaniel,Marlow Industries, Inc.

Gradient Index Optics: An Old Technology, Gradient Index Lenses, Finds New Applications
Leland G. Atkinson and Douglas S. Kindred, Gradient Lens Corp.

Binary Optics: A Valuable Part of the Designer's Tool Kit
Alan Kathman and Eric Johnson, Teledyne Brown Engineering

Excimer, UV and VUV Laser Optics: Criteria to Consider When Choosing Components for an Excimer System
Glen P. Callahan and Michael A. Case, Acton Research Corp.

Diffractive Optics: Taking the Approximation Out of Diffractive Optics Design
W. Kröninger and H.-G. Heckmann, Optische Werke G. Rodenstock, Precision Optics Div.

Adaptive Optics: Wavefront Sensing Branches Out
Lawrence E. Schmutz, Adaptive Optics Associates, Inc.

Bandpass Filter Design: Using Less Expensive Technology Without Sacrificing Performance
Paul D. Stupik, Ph.D., OCA/Optical Corporation of America

Beamsplitters: What a Designer Should Look for When Choosing a Beamsplitter
Melles Griot, Catalog Div.

Polarization: Making Polarization Work in Your Application
Greg Kopp and Laura A. Pagano, Meadowlark Optics, Inc.

Mirrors: Reflecting on Materials for Substrates and Coatings
Melles Griot, Optics Div.

Mirrors: Applications in Imaging, Astronomy, Microscopes and Telephoto Systems
Optical Coating Laboratory, Inc. (OCLI)

Diffraction Gratings: Selection of Size and Type for Different Applications

Richardson Grating Laboratory, Spectronic Instruments, Inc.

Optical Components: Optical Objective Systems: A Schematic Guide
Warren J. Smith, Kaiser Electro-Optics Inc.

Prisms Frequently Used in Optical Systems
Bruce H. Walker, Walker Associates

Primary Lens Aberrations: Seven Ways a Lens Can Blur the Light It's Supposed to Focus
-- Bruce H. Walker, Walker Associates

Simple Lens Approximations
Bruce H. Walker, Walker Associates

Common Lens Formulae
-- Walker Associates

Filter Glass Transmission
Schott Glass Technologies Inc.

Filters: Neutral Density
G.J. Neville, Newark Scientific Inc.

Acousto-Optic Scanning Devices: Characteristics
Isomet Corp. and Brimrose Corp. of America

Limiting Resolution Nomogram
Juan Rayces Consulting, Inc.

Fiber Amplifiers: Co-Doped Erbium: Ytterbium Fiber Amplifiers Enable New Applications
-- Dennis L. Werth, ATx Telecom Systems, Inc.

Connectors: New Geometries and Materials Create New Generation of Connectors
-- Gregory J. Sellers and S. Sriram, FORSS, Inc.

Fiber Optic Cable Selection: Factors to Consider When Choosing Fiber Optic Cables for Your System
-- Giovanni P. Tomasi, BICC Brand-Rex Co.

Fiber Reliability: Large Flaws: The Culprit in Fiber Reliability
-- Suresh T. Gulati, Corning Incorporated

Fibers/Medical Lasers: Three Silica-Core Fibers Rise to Top in Medical Laser Uses
-- Brian P. McCann, 3M Specialty Optical Fibers

ATM: Asynchronous Transfer Mode -- Bandwidth for the Future
-- Jim Lane, Telco Systems , Inc.

Sensors: A Comparative Evaluation of the Types and Applications of Various Sensors
-- Vikram Bhatia, Kent A. Murphy, Marten J. de Vries and Millika B. Sen, Virginia Polytechnic Institute and State University, Fiber and Electro-Optics Research Center

Sensors: Two Ways of Sensing with Fibers for Two Kinds of Applications
-- David A. Krohn, 3M Specialty Optical Fibers

Fiber Optic Testing: Assessing Fiber Optics Systems and Their Major Components
-- James E. Hayes, Fotec, Inc.

Transmission Conversion: dB to %
Siecor Corp.

Coating Materials Technology: Selecting Materials and Deposition Techniques for Optical Coating
-- CERAC, inc. (Technical assistance by Pellicori Optical Consulting)

Metals for Optical Applications

Optical Thin-Film Materials

Thin Films: The Advantages and Drawbacks of Physical Vapor Deposition Technologies
-- Rolf Hora, Balzers Ltd.

Optical Design Software: Computer Software for Optical Coatings
-- Philip Baumeister, Sholem Consultants

Coatings for First-Surface Mirrors
-- Ferson Optics, Inc.

Ion-Beam Sputtering: Bringing Precise Control to Coatings Using Ion-Beam Sputtering
-- Arthur T. Howe, Amoco Technology Co.; and Dennis D. Phillips, Optical Spectrum Technology

Antireflection Coatings for the Ultraviolet, Visible and Near-IR
-- Balzers

BBAR* or MgF2 Coatings on Various Glasses: Reflectivity
Tropel

Focal Plane Arrays: Better, Smaller IR Imagers for New Applications
-- J.T. Wimmers and D.S. Smith, Cincinnati Electronics Corp.

Infrared Detection Equipment: Parameters Used in Design
-- Santa Barbara Research Center

Infrared Detectors: Expanded Applications Prompt Developments in Technology
-- Konrad J. Stahl, AEG Aktiengesellschaft, Opto- and Vacuumelectronics Div.

Sensor Technology: Recent Advances in the 3- to 5-mm Band Overcoming Some Old Drawbacks
-- Amber

Infrared Filters: Glossary, Equations, Parameters

-- Optical Coating Laboratory, Inc. (OCLI)

IR Fibers: New Designs, Methods Provide New Applications for IR Fibers
Christopher C. Gregory, Galileo Electro-Optics Corp.

Excimer Lasers: Once a Scientific Tool the Excimer Now Fills Many Roles
-- Rainer Pätzel and Heinrich Endert, Lambda Physik GmbH, Göttingen, Germany

Ion Lasers: The Ion Laser, a Truly Enabling Technology
-- Jeff Cannon and Stephen Lee, Coherent Inc., Laser Group

Gas Lasers: Reports of Gas Lasers' Demise Have Been Greatly Exaggerated
-- KateLeggett

Tunable Diode Lasers: Cavity Design Considerations for Tunable Diode Lasers
-- Dr. Timothy Day, New Focus, Inc.

Diode Lasers: Better Diode Lasers Will Expand Applications in Many Key Areas
-- Bernard Masterson and Jeffrey Webb, Melles Griot, Electro-Optics Div.

Visible Laser Diodes: The Expanding Role of VLDs into the Burgeoning Commercial World
-- David Martin, Toshiba America Electronic Components, Inc.

VCSELs: VCSELs Are Revolutionizing Optical Communications
-- Greg R. Olbright, Vixel Corp.

Semiconductor Laser Diodes: Fundamental Issues in Their Use for a Growing Number of Applications
-- David L. Begley, Ball Corp., Aerospace Systems Div.

Optical Parametric Oscillators: The Modern OPO Takes Its Place as a Reliable Research Tool
-- Michael B. Radunsky, Ph.D., Continuum

Medical Lasers: Taking the Confusion Out of Matching Medical Lasers
-- J. Michael Yarborough, Coherent Inc., Tucson Research Center

Industrial Lasers: Making the Right Decision in Choosing an Industrial Laser
-- Thomas R. Kugler and Gary Hermann, Lumonics Corp., Industrial Products Div.

Ti:Sapphire Tuning: Tuning the Continuous-Wave Ti:Sapphire Laser
-- Peter F. Moulton, Schwartz Electro-Optics, Inc.,

Beam Steering: Laser Marking Steers a New Course in Manufacturing
-- Richard L. Stevenson, Excel/Control Laser, Inc.

Laser Beam Diagnostics: Boosting Efficiency with Feedback on Beam Diagnostics
-- Roger Rypma, Coherent, Inc., Instruments Div.

Safe Handling of Excimer Laser Gases: Precautions That Prevent Accidents in the Use of Compressed Laser Gases
-- Al Dietz and Elaine Bradford, Spectra Gases, Inc.

Laser-Induced Damage Testing: Using High-Energy Exposure to Gage Optical Components

-- Steven C. Seitel, Big Sky Laser Technologies, Inc.

Materials Processing Laser Capabilities
-- Convergent Energy

Properties of Nd3+ Laser Host Materials
Ball Corp., Aerospace and Communications

Tungsten Halogen: An Economical, Reliable Choice for Illuminating Vision Applications
-- Michael Muehlemann, Illumination Technologies, Inc.

Solar Spectral Irradiance
-- Oriel Instruments

Short Arc Lamps: Fundamental Characteristics of High-Intensity Point Sources
-- ORC Lighting Products, Div. of Benson Eyecare Corporation

High-Power Light Sources: Design, Material, Power Conditioning Are Key in Choosing a Source
-- Gary G. Albach, Vortek Industries Ltd.

Standard CIE Illuminants
-- Walker Associates

High-Brightness Materials: Advances in LED Performance Open New Markets for the Technology
Frank M. Steranka and Mark Hodapp, Hewlett- Packard Co.

Global Optimization: A Powerful Lens Design Tool for the Optical Engineer
-- Thomas G. Kuper and Thomas I. Harris, Optical Research Associates

Optical Design Software: Hard- and Software Considerations for Designing with a Computer
-- Douglas C. Sinclair, Sinclair Optics, Inc.

Optical Component Specifications: Avoiding Pitfalls in Setting Tolerances for Optical Components
-- Warren J. Smith, Kaiser Electro-Optics Inc.

Cost of Manufacturing vs. Tolerances
-- Plummer Precision Optics and Walker Associates

Gaussian and Newtonian Thin Lens Formulae
-- Walker Associates

Surface Tolerances: Ensuring an Optical Element's Compatibility with Its System
-- Bruce H. Walker, Walker Associates

Designing Plastic Optics: New Applications Emerging for Optical Glass Substitutes
-- Claude Tribastone, Chuck Teyssier and William Peck, OPKOR Inc.

Laser Scanning System Design: Choosing Elements to Fit the Nature of an Application
-- Glenn E. Stutz, Lincoln Laser Co.

Single-Point Diamond Machining:
Diamond Machining: Cost-Effective Route to Precision Optics

-- Rank Pneumo, Inc.

Optical Machining: Controlling the Variables with a Well-Designed Tool
Bob Roberts, R. Howard Strasbaugh, Inc.

Beryllium Mirrors: Production Techniques Drop Costs without Altering High Reflectivity
-- Thomas B. Parsonage, Brush Wellman, Inc., Beryllium/Mining Div.; and Peter N. Richard, Hardric Laboratories, Inc.

Optical Materials: Properties and Applications
-- William L. Truett, Janos Technology, Inc.

Transmission Ranges for Some Materials
-- Janos Technology, Inc.

Optical Materials: Transmission and Refractive Index
-- Janos Technology, Inc.

Optical Glasses
-- Bruce H. Walker, Walker Associates

Maps of Optical Glasses
-- Walker Associates

Coefficients of Expansion and Densities of Optical Materials
-- Walker Associates

Fused Silica: Optical Properties
-- Dynasil Corporation

Refractive Indices of Glasses at Laser Wavelengths
Schott Glass Technologies Inc.