



Photonic Integration and Usage Guidelines Manual

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by

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with assistance from

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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.

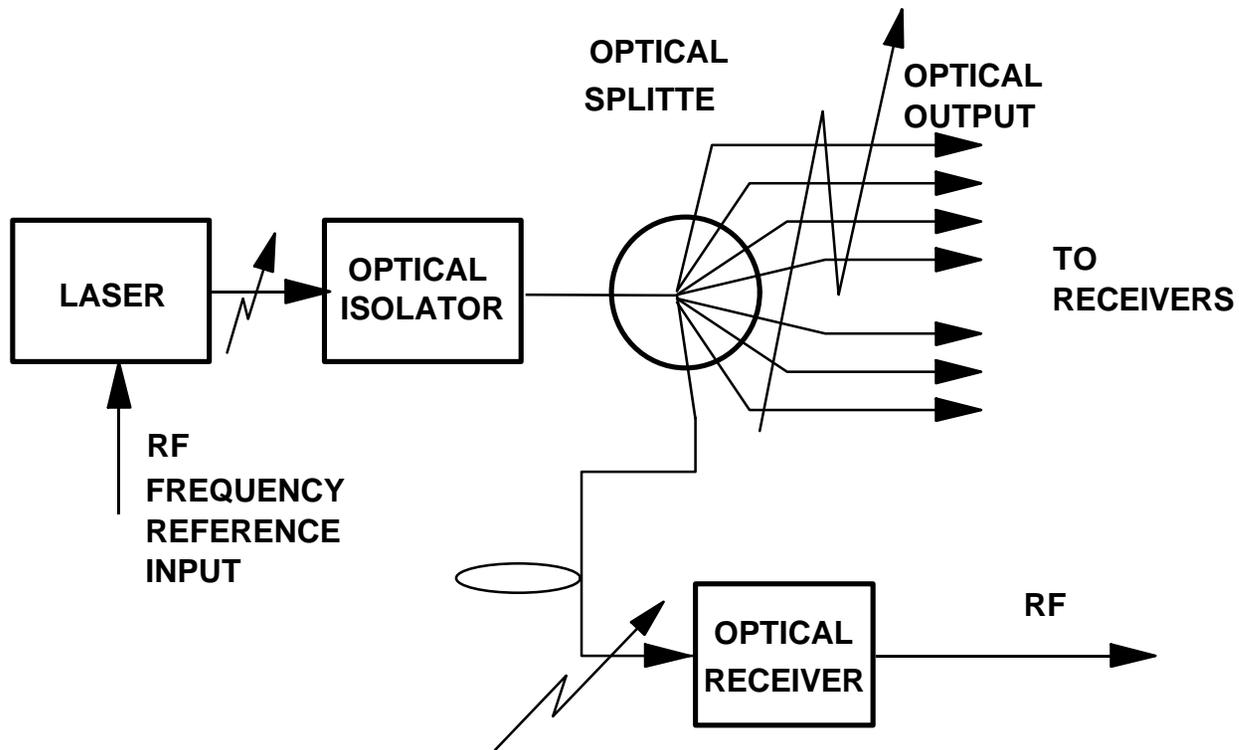
There is a section on fiber optic cables and connectors. It includes the analysis showing why no shielding in addition to the jacket would be needed on optical fiber used in SRTM. There is an overview of fiber optic connector and cable assemblies and a comparison of fiber optic cable versus the best 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.

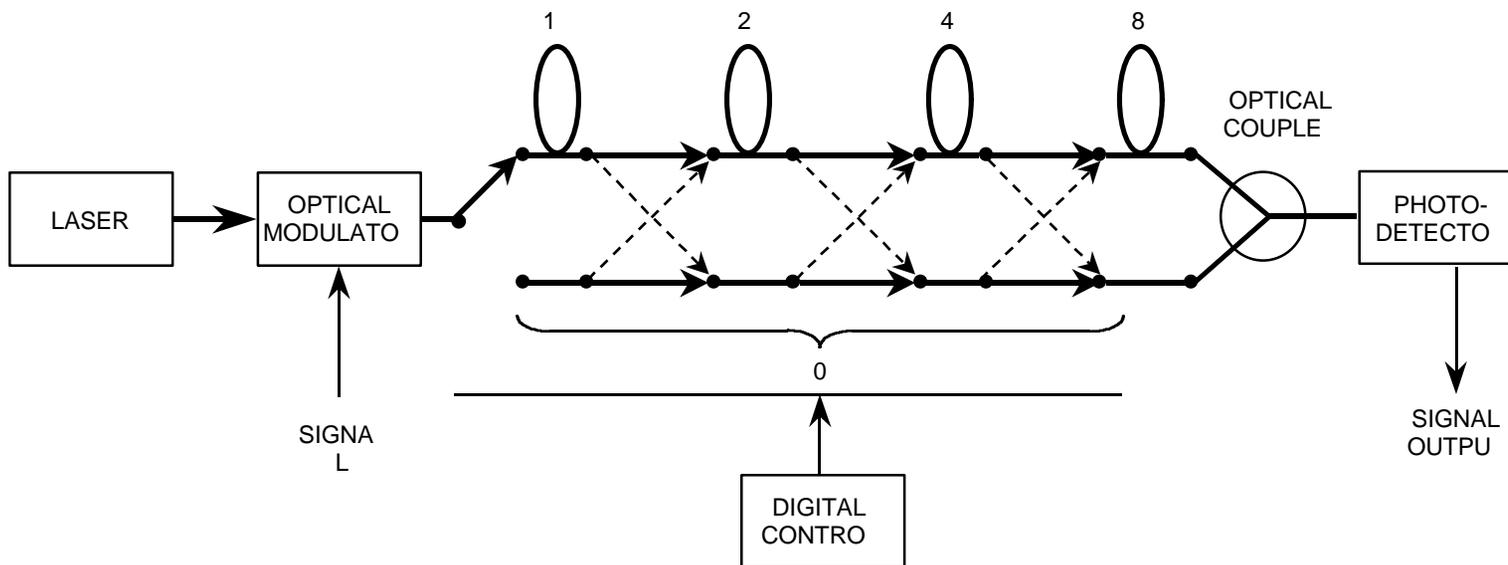
2.0 Photonic Systems with Potential Space Applications

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

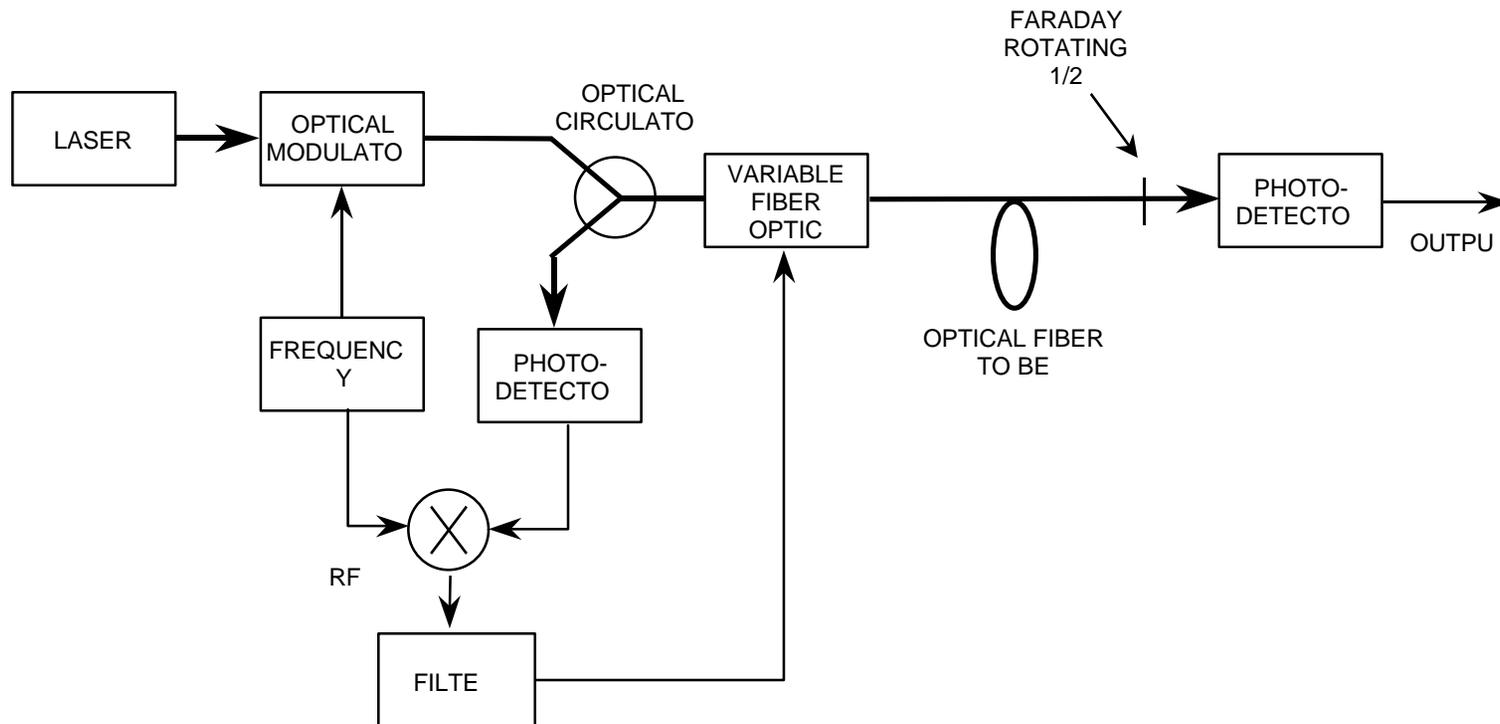
The cable stabilizer and reference signal distribution system is used on SRTM. It could not have been implemented in a metallic transmission line and achieved the stability that was achieved with the photonic system using optical fiber.



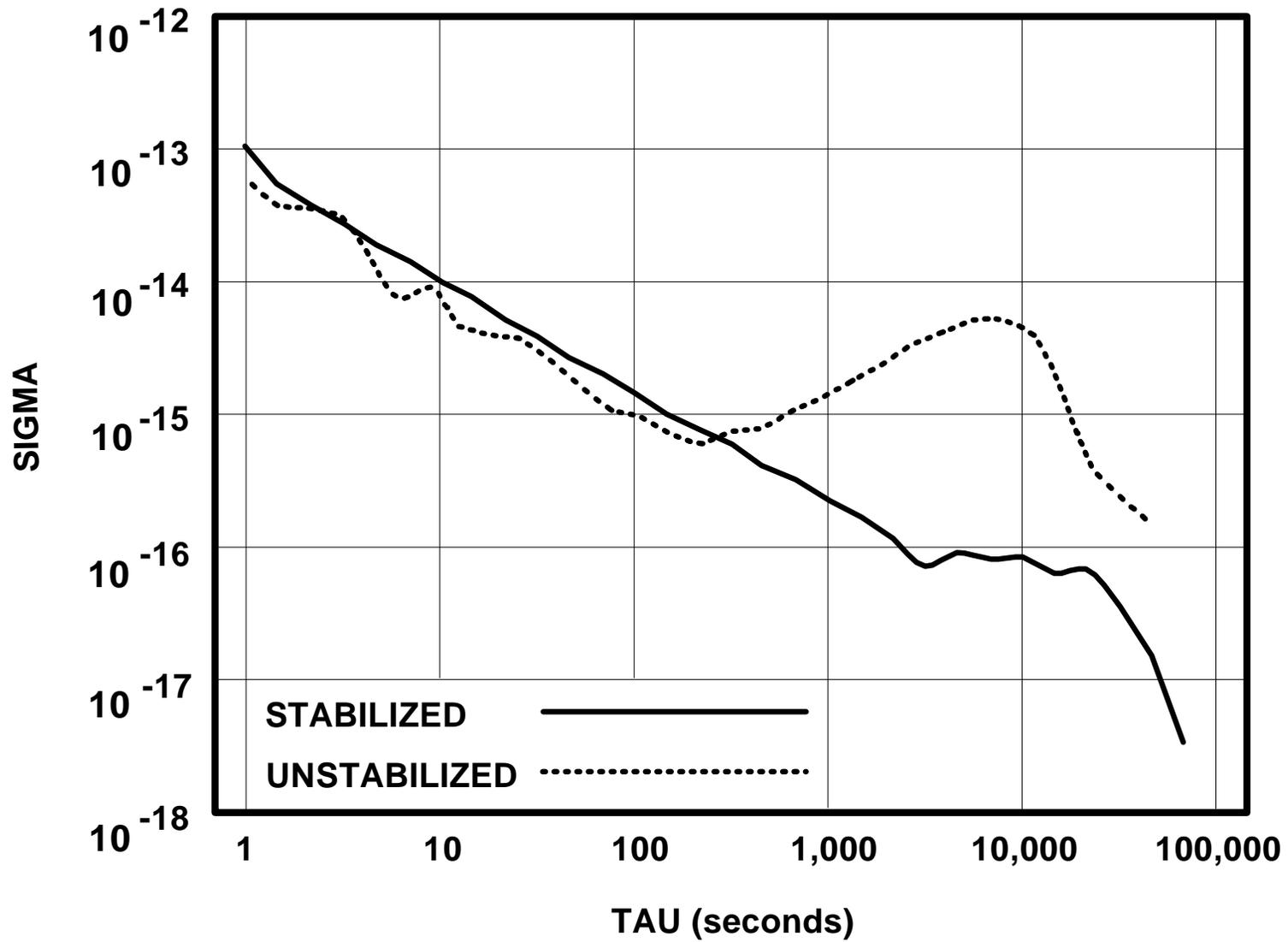
This is a block diagram of a fiber optic frequency reference distribution system used in the NASA Deep Space Network. It has greater than 200 dB isolation between outputs and can distribute the reference signal over tens of kilometers. It has extremely low phase noise and exceptional frequency stability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



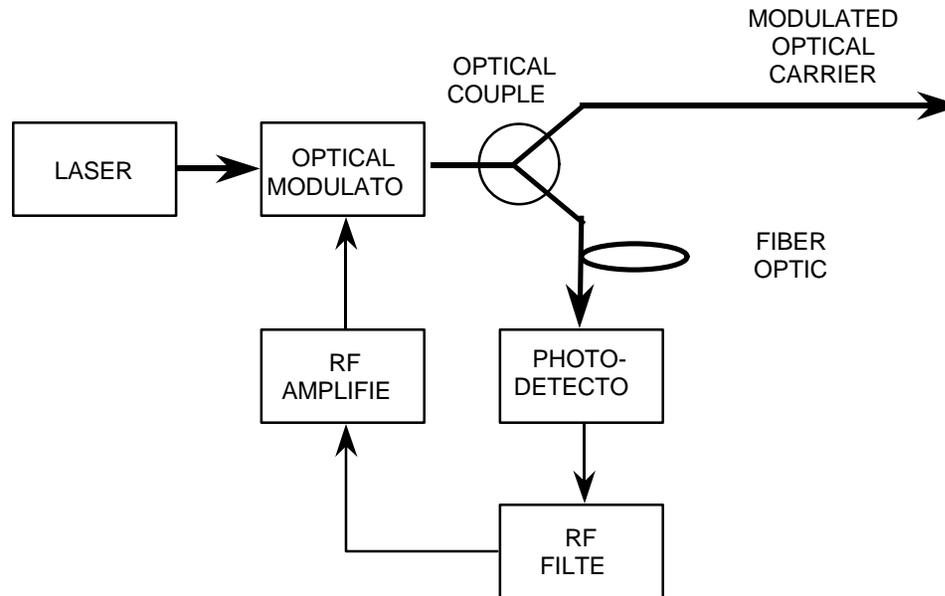
This is a four bit variable optical delay line. Its performance is limited by the switches. There are two kinds of optical switches, mechanical and optoelectronic. Mechanical switches have higher isolation but they are relatively slow(1 millisecond). Optoelectronic switches are very fast, < 1 nanosecond, 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



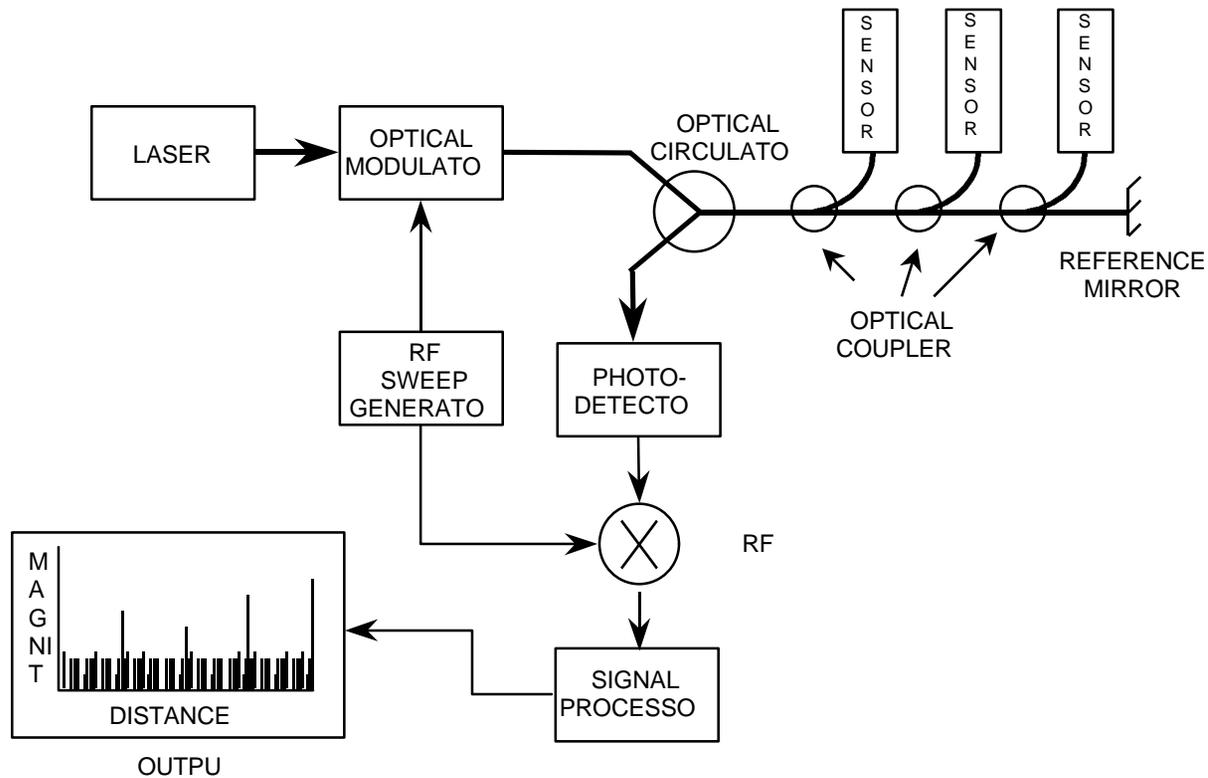
Fiber optic cables can be stabilized using the scheme shown here. The degree of stabilization depends on the isolation in the optical circulator and very low extraneous reflections as well as the accuracy of the Faraday rotator. It is not practical to implement this system using copper based RF systems 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



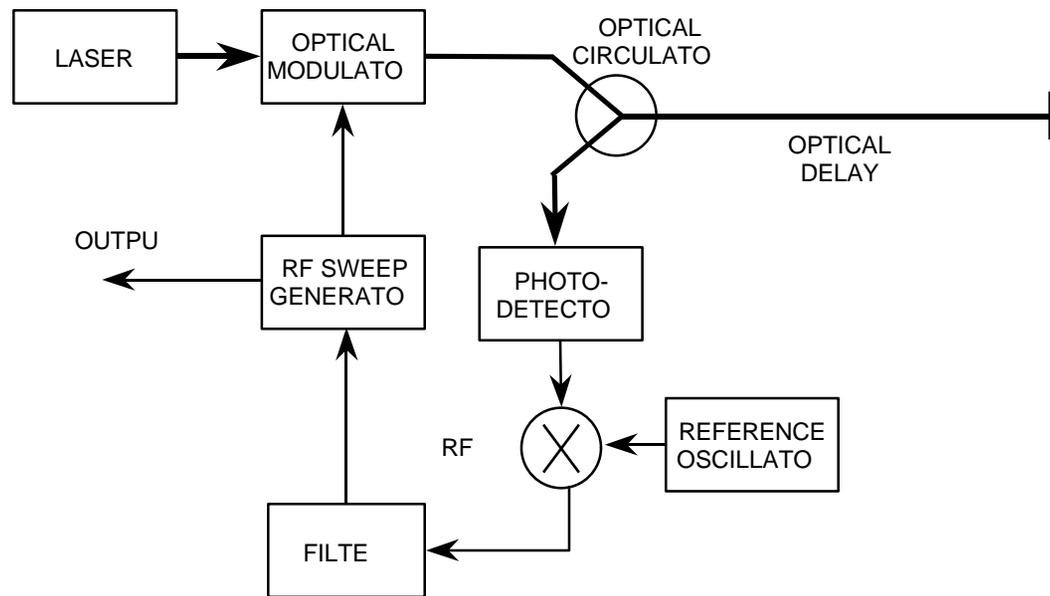
This plot shows the improvement in frequency stability provided by a fiber optic cable delay stabilizer.



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°C and -60°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 $40\text{ ppm}/^{\circ}\text{C}$. 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.

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,

$$e_4(t) = A_4 \cdot \sin[\mathbf{w} \cdot t + \mathbf{q}_1 + 2 \cdot (\mathbf{q}_2 + \Delta\mathbf{q}_2) + 2 \cdot (\mathbf{f} + \Delta\mathbf{f})] \quad (4)$$

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

$$e_5(t) = A_5 \cdot \sin[\mathbf{w} \cdot t + \mathbf{q}_1 + 2 \cdot (\mathbf{q}_2 + \Delta\mathbf{q}_2) + 2 \cdot (\mathbf{f} + \Delta\mathbf{f}) + \mathbf{q}_3] \quad (5)$$

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),

$$\begin{aligned} e_6(t) &= e_1(t) \cdot e_5(t) \quad \text{or,} \\ e_6(t) &= A_6 \cdot \{ \cos[\mathbf{q}_1 + 2 \cdot (\mathbf{q}_2 + \Delta\mathbf{q}_2) + 2 \cdot (\mathbf{f} + \Delta\mathbf{f}) + \mathbf{q}_3] + \\ &\quad \cos[2 \cdot \mathbf{w} \cdot t + \mathbf{q}_1 + 2 \cdot (\mathbf{q}_2 + \Delta\mathbf{q}_2) + 2 \cdot (\mathbf{f} + \Delta\mathbf{f}) + \mathbf{q}_3] \} \end{aligned} \quad (6)$$

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

$$e_7(t) = A_7 \cdot \cos[\mathbf{q}_1 + 2 \cdot (\mathbf{q}_2 + \Delta\mathbf{q}_2) + 2 \cdot (\mathbf{f} + \Delta\mathbf{f}) + \mathbf{q}_3] \quad (7)$$

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),

$$e_3(\Delta\mathbf{f}) = A_8 \cdot \sin[\mathbf{w} \cdot t + \mathbf{q}_1 + \mathbf{q}_2 + \mathbf{f} + (\Delta\mathbf{f} - \Delta\mathbf{f})] \quad (8)$$

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 ≥ 5 dBm and the bandwidth is 1-18 GHz. The relative intensity noise (RIN) is ≤ -150 dB/Hz and V_{π} is ≤ 7 volts at 2 GHz. The non-operating temperature range is -55°C to $+85^{\circ}\text{C}$ and its operating temperature is 0°C to $+60^{\circ}\text{C}$ (Ref. 3). The entire stabilized fiber optic system must meet its specifications when the SITU is subjected to any 10°C peak-to-peak temperature variation within the temperature range of $+5^{\circ}\text{C}$ to $+45^{\circ}\text{C}$.

The 3 port circulator is a COTS device fabricated by E-Tek Dynamics. Its specified wavelength is 1550 nm ± 20 nm. Its insertion loss from 0°C to 60°C is < 1.3 dB over its entire wavelength range. Its minimum peak isolation is 45 dB. The optical return loss is ≤ -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).

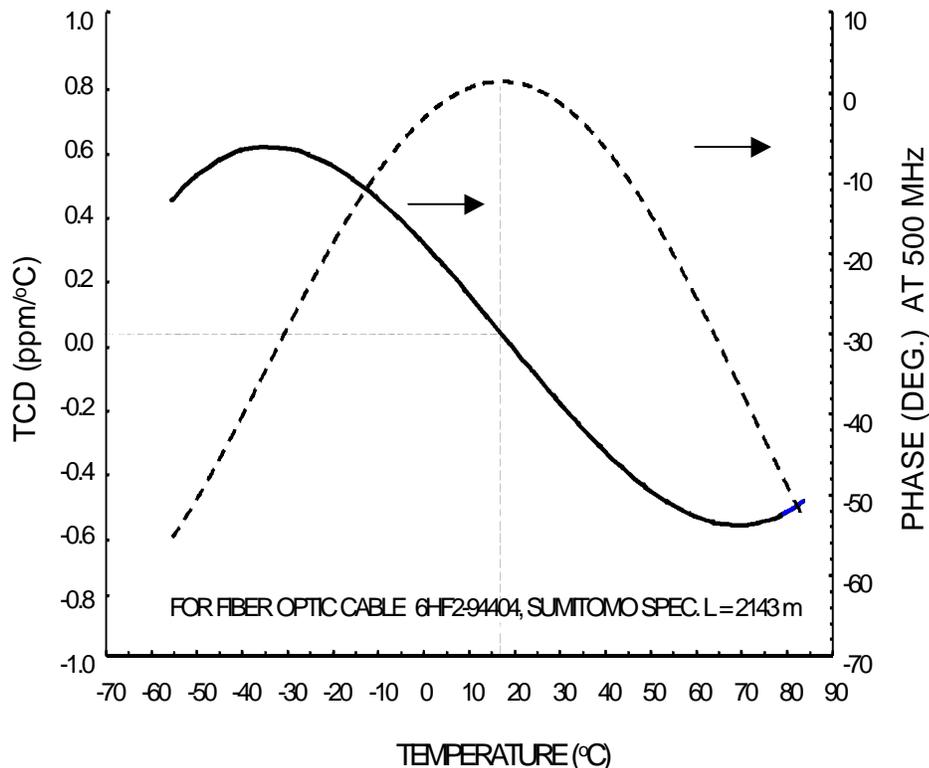
Temperature Cycling	-40°C to +80°C for 14 days; rate 1°C/min; dwell 1 hour at the extremes
High temperature bake	80°C for 2,000 hours
Vibration	3 axis 20 g's at 20 ~2,000 Hz
Shock	3 axes, 100 g's, 11ms
Max. Tensile Strength	10 N force for 10 seconds

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 $+85^{\circ}\text{C}$. 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/ $^{\circ}\text{C}$. 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. Rifocis, 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 $59^{\circ}/^{\circ}\text{C}$.

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°C to $+85^{\circ}\text{C}$. 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°C and then cycled sinusoidally $\pm 8^{\circ}\text{C}$ around 50°C . In addition to these tests the flight cables were cycled sinusoidally $\pm 10^{\circ}\text{C}$ around -25°C 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°C .

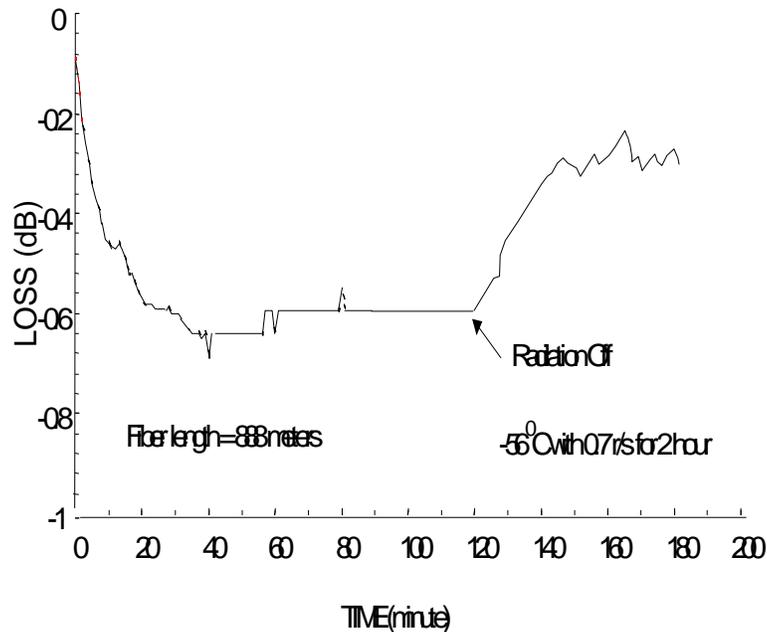


Fig. 3. Radiation induced loss in the LTCD optical fiber at -56°C .

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 $\pm 10^{\circ}\text{C}$ over the average temperature range from 5°C to 45°C . The receiver was subjected to a sinusoidal temperature variation of $\pm 10^{\circ}\text{C}$ over the average temperature range from -40°C to $+15^{\circ}\text{C}$. 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	+6.5 dB/octave	+6.5 dB/Octave
	80-250	0.10 g^2/Hz	0.04 g^2/Hz
	250-350	+20.3dB/octave	+20.3 dB/octave
	350-600	1.0 g^2/Hz	0.4 g^2/Hz
	600-2,000	-13.2 dB/octave	-13.2 dB/octave
	2,000	0.005 g^2/Hz	0.002 g^2/Hz
	overall	22.0 g_{rms}	22.0 g_{rms}
Fiber Optic Transmitter In plane	20-80	+6.5 dB/Octave	+6.5 dB/Octave
	80-200	0.10 g^2/Hz	0.04 g^2/Hz
	200-250	+12.4 dB/octave	+12.4 dB/octave
	250-500	0.25 g^2/Hz	0.10 g^2/Hz
	500-2,000	-8.5 dB/octave	-8.5 dB/octave
	2,000	0.005 g^2/Hz	0.002 g^2/Hz
	overall	12.2 g_{rms}	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	+6 dB/octave	
	50-400	0.2 g^2/Hz	
	400-2,000	-7.5 dB/octave	
	overall	11.0 g_{rms}	
Fiber Optic Receiver In plane	20-50	+6 dB/octave	+6 dB/octave
	50-400	0.1 g^2/Hz	0.16 g^2/Hz
	400-2,000	-7.5 dB/octave	-7.5 dB/octave
	overall	15.6 g_{rms}	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:

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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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.

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

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.

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

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 krad 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/m³ 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 °C to -60 °C.

In Fig. 2 the shielding effectiveness of the cables are plotted. Fiber optic cable has virtually no pickup or radiation of EMI or 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 °C to +15 °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° K to as low as 242.5° K. Superimposed on this long term temperature change is a sinusoidal 5° 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° 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° C to +13° 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

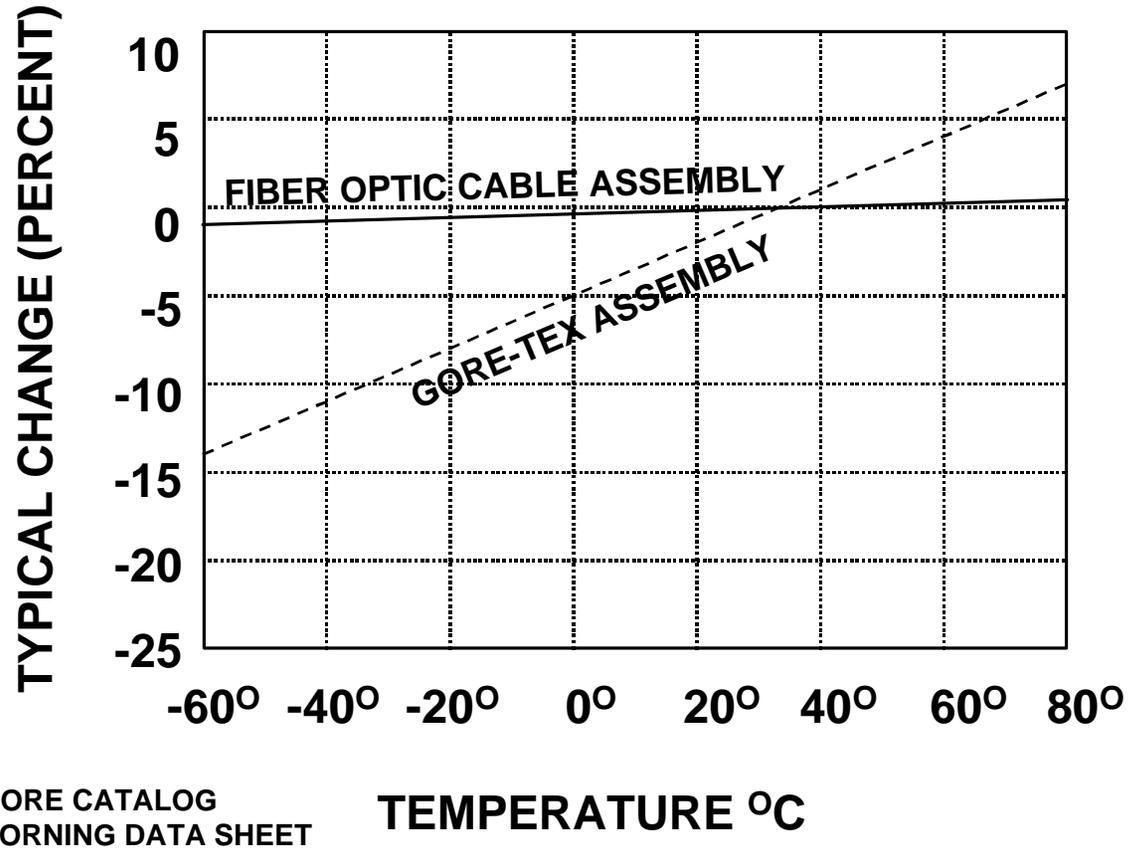


Fig. 1 - The change in insertion loss vs temperature for 0.190" diameter Gore-Tex coaxial cable and typical fiber optic cable.

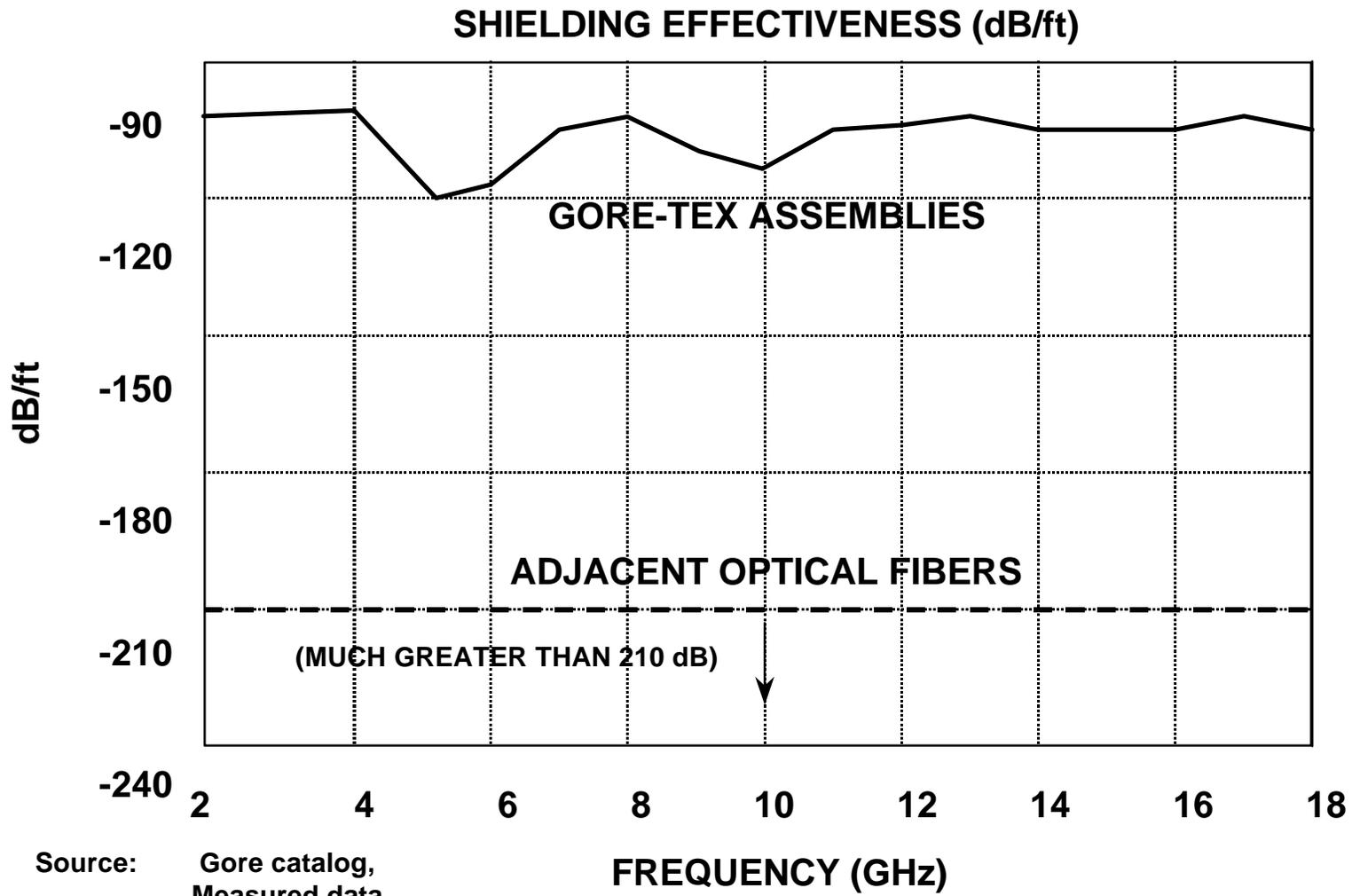
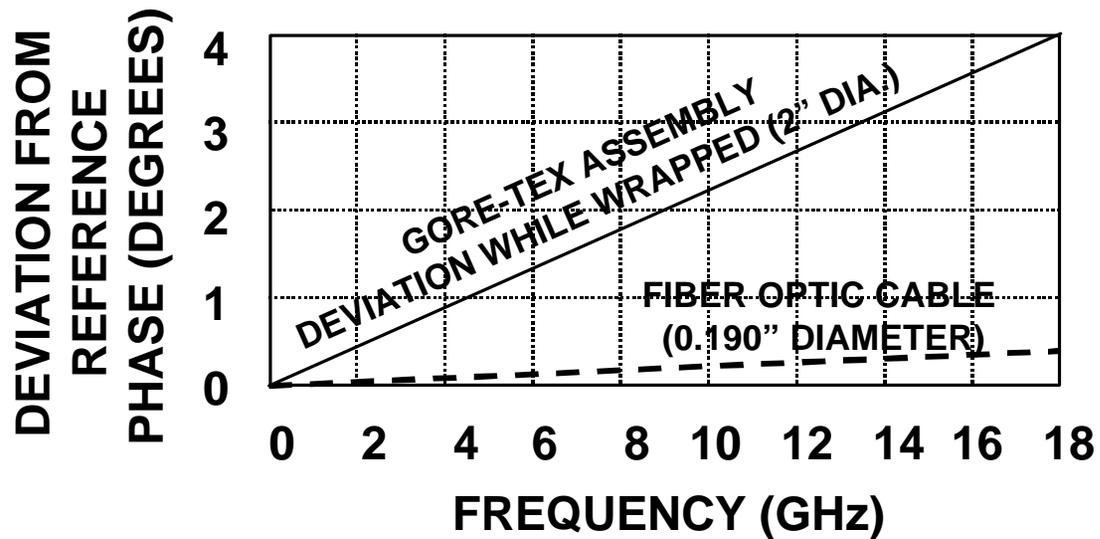


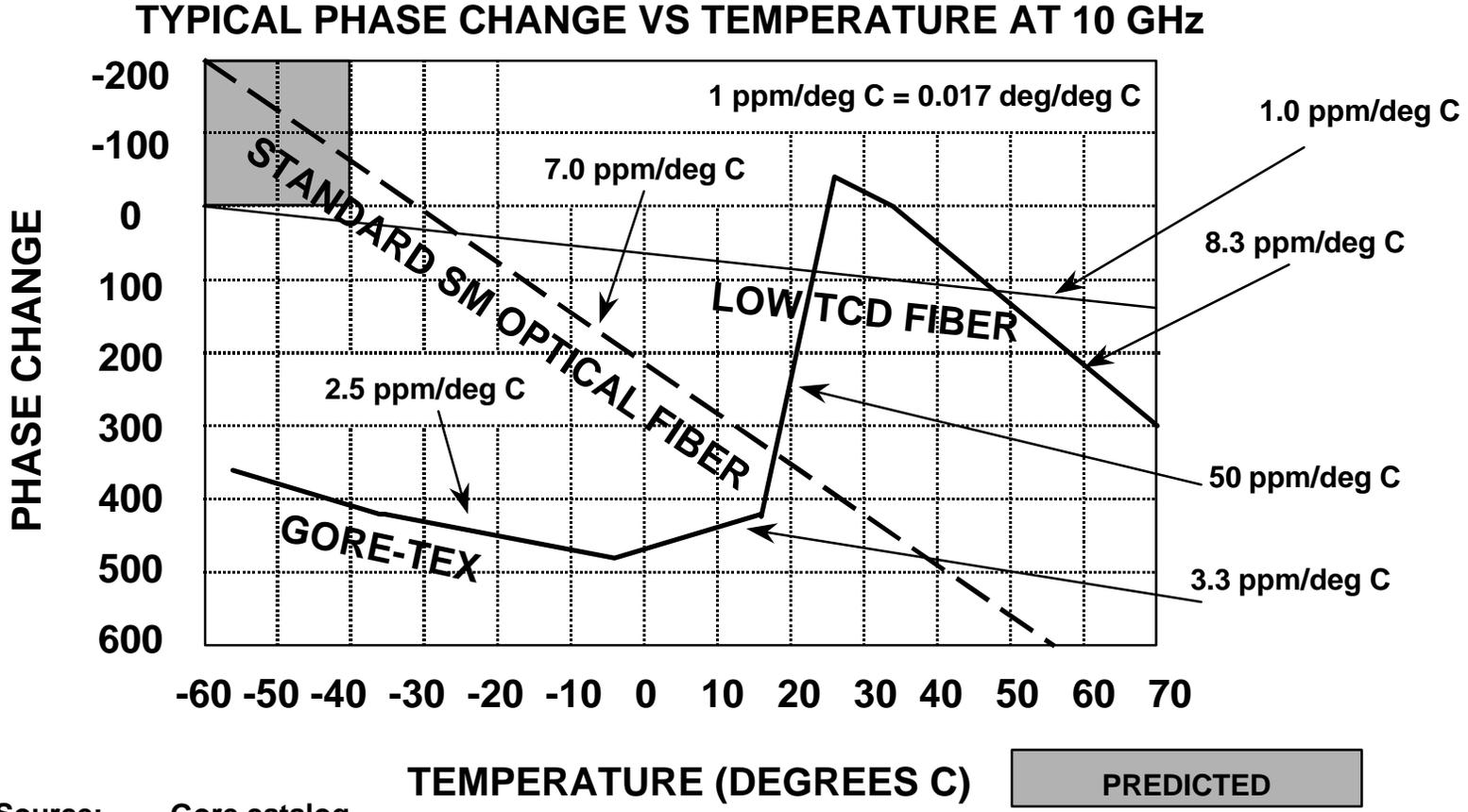
Fig. 2 - The shielding effectiveness for 1 foot of Gore-Tex 0.190" diameter coaxial cable and typical fiber optic cable.

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



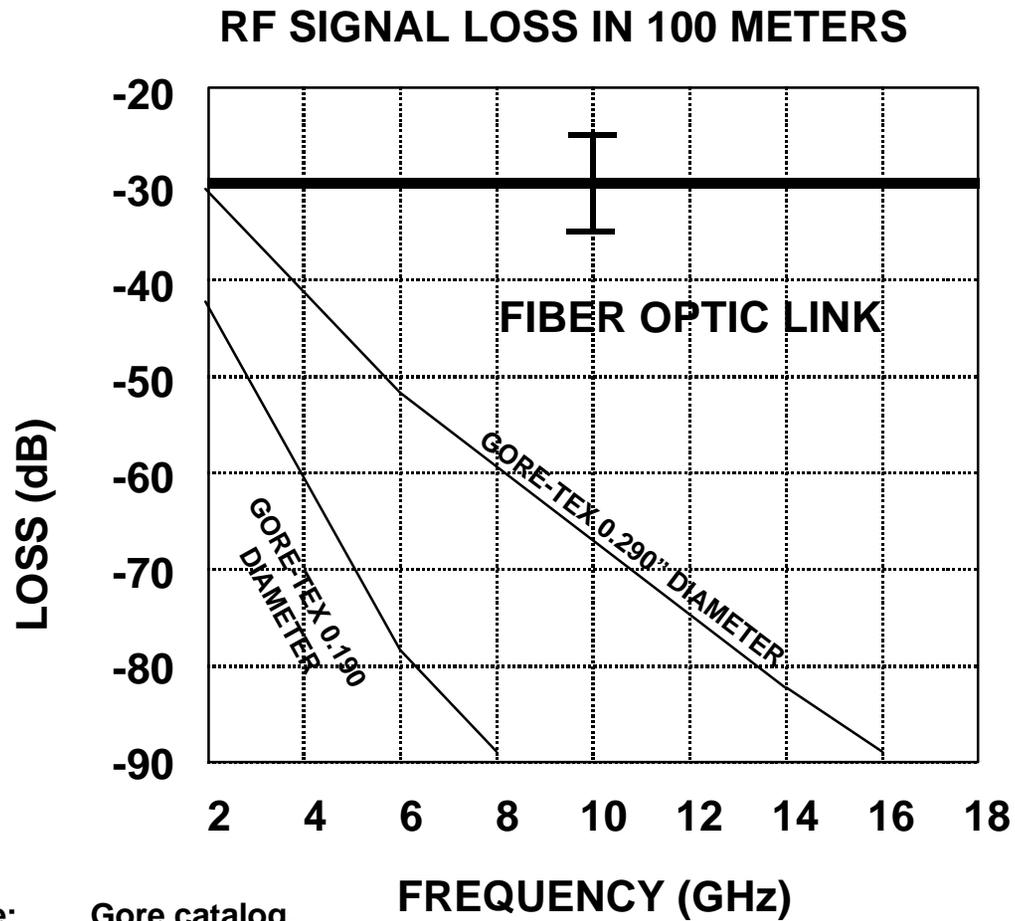
Source: Gore catalog,
Measured data

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: $\mu = 0.4$ dB, $\sigma = 0.2$ dB
Fiber: 62.5/125 fiber, 0.29 numerical aperture
Fiber OD, nominal: 125 μ m
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: $\mu = 0.35$ dB, $\sigma = 0.20$ dB
Return Loss: -42 dB average; -35 dB worst case
8.3/125 μ m fiber, 0.29 numerical aperture
Fiber OD, nominal: 125 μ m
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 μ m
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, 125 μ m
Loss (dB), 0.3
Loss repeatability (200 insertions) <0.3 dB
Axial Load nominal 30 lbs.
Temp Stability (-40°C to 75°C) \pm 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 \leq 0.3 dB, 200 Insertions
Tensile Strength \leq 0.2 dB, 20 pounds (9.1 kg) (minimum)
Impact \leq 0.2 dB, Ten 2-meter drops on concrete floor
Vibration \leq 0.2 dB,
Ten 500 Hz, 0.73 g, 1-hour sweep
Ten 500 Hz, 10 g, 15-minute sweep
Shock \leq 0.2 dB
40 g, 11-millisecond, saw-tooth pulse
Flex \leq 0.5 dB
300 cycles, \pm 90°, one pound (0.45 kg) weight
Twist \leq 0.2 dB
100 cycles, \pm 180°, 11 pound (4.99 kg) weight, 1' (2.54 cm)
cable
Environmental dB Change
Storage Temperature, -40°C to +85°C
Operating Temperature \leq 0.3 dB, 10 cycles, -20°C to +60°C
Humidity \leq 0.5 dB, 60°C, 95% relative humidity, 504 hours
Thermal Shock \leq 0.2 dB
-40°C to +60°C, 10 cycles, 1-minute transition, 1-hour hold
Corrosion Resistance \leq 0.2 dB, Salt-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 Common, Pittsfield, MA 01202, Phone: (413)499-0514.

Acousto-Optics	Blanks, Lens
Adaptive Optics	Blanks, Mirror
Amplifiers, Optical	Blanks, Molded
Apertures, Precision, Including Pinhole	Blanks, Prism
Arc Lamps	Bolometers
Arrays, Detector	Boresights
Arrays, Laser Diode	Brewster Angle Windows
Arrays, Imaging	Bubble Chamber Optics
Arrays, Lens	Cable Duct
Astronomical Optics	Cable, Fiber Optic
Attenuators	Camera Tubes
Avalanche Photodiodes	Cathode-Ray Tube Envelopes and Faces
Beam Deflectors	Cathode-Ray Tubes (CRTs)
Beam Directors	Cathode-Ray Tubes, Fiber Optic Faceplate
Beam Expanders	Cathode-Ray Tube Shields
Beam Focusing Equipment	Cathode-Ray Tube Sockets
Beam Measurement Equipment	Cells, Bragg
Beam Positioners	Cells, Dye Laser
Beamsplitters	Cells, Glass
Beamsplitters, Polarizing	Cells, Photoelectric
Beam Stabilizers	Cells, Refractometer
Binary Optics	Cells, Solar
Blackbody Sources	Cells, Spectrophotometer

Choppers, Electro-Optic	Crystals, X-Ray
Choppers, Ion-Beam	Deflectors
Choppers, Motorized	Depolarizers
Choppers, Optical	Detector Arrays
Choppers, Tuning Fork	Detectors, APD
Collimating Lenses	Detectors, CCD
Collimators, Auto	Detectors, Cryogenic
Collimators, Laser	Detectors, Fiber Optic
Comparators	Detectors, Infrared
Connectors	Detectors, Low-Light-Level
Coolers, Cryogenic	Detectors, Photoelectric
Coolers, Detector	Detectors, Photoemissive
Corner Cube Reflectors	Detectors, Photomultiplier Tube
Couplers	Detectors, Photovoltaic and Photoconductive
CRTs	Detectors, Position Sensing
Cryogenic Detectors	Detectors, Pyroelectric
Crystals, Acousto-Optic	Detectors, Scintillation
Crystals, Birefringent and Polarizing	Detectors, Semiconductor
Crystals, Electro-Optic	Detectors, Ultraviolet
Crystals, Holographic	Dewars, Cryogenic
Crystals, Laser	Diamond-Turned Components
Crystals, Liquid	Dichroics
Crystals, Nonlinear	Dielectrics
Crystals, Piezoelectric	Diffraction Optics
Crystals, Quartz	Diffusers
Crystals, Scintillation	Domes, Optical
Crystals, Ultraviolet	Dye Laser Cells
Dye Lasers	Fiber Optic Faceplates

Electro-Formed Optics	Fiber Optic Ferrules
Electro-Optics	Fiber Optic Fibers, Dispersion-Shifted
Etalons	Fiber Optic Fibers, Erbium-Doped
Eyepieces	Fiber Optic Fibers, Infrared
Faraday Rotators	Fiber Optic Fibers, Plastic
Fiber-Coupled Laser Diode Arrays	Fiber Optic Fibers, Plastic-Clad Silica
Fiber-Loop Resonators	Fiber Optic Fibers, Polarization-Preserving
Fiber Optic Adaptors	Fiber Optic Fibers, Scintillation
Fiber Optic Attenuators	Fiber Optic Illuminators
Fiber Optic Bundles, Imaging	Fiber Optic Isolators
Fiber Optic Cable, Fiber Bundle	Fiber Optic Jacketing
Fiber Optic Cable, Radiation-Hardened	Fiber Optic Laser Diodes
Fiber Optic Cable, Ruggedized	Fiber Optic Light-Emitting Diodes
Fiber Optic Cable, Single-Fiber	Fiber Optic Lightguides
Fiber Optic Cable Duct	Fiber Optic Modems
Fiber Optic Connectors, Expanded-Beam	Fiber Optic Modulators
Fiber Optic Connectors, Multimode	Fiber Optic Networks
Fiber Optic Connectors, Single-Fiber	Fiber Optic Polarizers
Fiber Optic Couplers, Bidirectional	Fiber Optic Receivers
Fiber Optic Couplers, Polarization-Preserving	Fiber Optic Rotary Joints
Fiber Optic Couplers, Star	Fiber Optics, Imaging
Fiber Optic Couplers, Tee	Fiber Optic Switches
Fiber Optic Couplers, Tree	Fiber Optic Tapers
Fiber Optic Couplers, Variable	Fiber Optic Transmitters
Fiber Optic Detectors	Films and Plates, Holographic
Fiber Optic Distribution Panels	Filter Arrays
Filters, Absorption	Graticules

Filters, Acousto-Optic	Gratings, Blazed
Filters, Birefringent	Gratings, Diffraction
Filters, Broadband	Gratings, Echelon
Filters, Colored Glass	Gratings, Holographic
Filters, Contrast Enhancement	Gratings, Laser
Filters, Dichroic	Gratings, Radial
Filters, Diffractive	Gratings, Replica
Filters, Holographic	Gratings, Ronchi
Filters, Interference	Halogen Light Sources
Filters, Laser Line	Holograms
Filters, Laser Protective	Holographic Films and Plates
Filters, Neutral Density	Holographic Filters
Filters, Photographic	Holographic Gratings
Filters, Pinhole	Illuminators
Filters, Plastic	Image Sensors, Area
Filters, Polarizing	Image Sensors, Linear
Filters, Rejection Band	Imaging Arrays
Filters, Spatial	Infrared Sources
Filters, Tunable	Interferometer Accessories
Filters, Wedge	Iris
Filters, X-Ray	Kerr Cells
Flats, Optical	Laser Diode Arrays
Fourier Optics	Laser Diode Collimating Lenses
Fresnel Optics	Laser Diode Modules
Glass-To-Metal Seals	Laser Diodes
Glass Tubing	Laser Modelockers
Laser Q-Switches	Lenses, Plastic
Laser Rods	Lenses, Precision Glass Balls

Laser-to-Fiber Couplers	Lenses, Prismatic
LEDs	Lenses, Projection
Lens Arrays	Lenses, Radiation Resistant
Lens Blanks	Lenses, Relay
Lenses, Achromatic	Lenses, Sapphire
Lenses, Anamorphic	Lenses, Simple
Lenses, Aspheric	Lenses, Spheric
Lenses, Catadioptric	Lenses, Telephoto
Lenses, Complex	Lenses, Telescope
Lenses, Condenser	Lenses, Wide Angle
Lenses, Conical	Lenses, Zoom, Variable Focal Length
Lenses, Cylindrical	Light-Emitting Diodes, Infrared
Lenses, Diamond-Turned	Light-Emitting Diodes, Visible
Lenses, Diffraction-Limited	Light Shields
Lenses, Diffractive	Light Sources, Calibrated
Lenses, Eyepieces	Light Sources, Coherent
Lenses, Fourier	Light Sources, Fluorescent
Lenses, Fresnel	Light Sources, Glow Discharge
Lenses, GRIN	Light Sources, Halogen
Lenses, Laser	Light Sources, Hollow Cathode
Lenses, Laser Diode Collimating	Light Sources, Incandescent
Lenses, Microscope	Light Sources, Infrared
Lenses, Miniature	Light Sources, Krypton
Lenses, Molded	Light Sources, Laser Diode
Lenses, Monochromatic	Light Sources, Mercury
Light Sources, Miniature	Mirrors, Spherical
Light Sources, Plasma Discharge	Mirrors, Ultraviolet

Light Sources, Stroboscopic	Mirrors, X-Ray
Light Sources, Tungsten	Modelockers, Laser
Light Sources, Ultraviolet	Modulators, Acousto-Optic
Light Sources, VUV	Modulators, Electro-Optic
Light Sources, Xenon	Modulators, Fiber Optic
Liquid Crystal Light Valves	Modulators, Magneto-Optic
Magneto-Optics	Modulators, Mechanical
Metal Optics	Modulators, Photoelastic
Micro-Optics	Modulators, Spatial Light
Microscope Eyepieces	Mounts, Laser
Microscope Objectives	Mounts, Optical
Mirror Blanks	Mounts, Sidereal
Mirrors, Aspheric	Mounts, Telescope
Mirrors, Astronomical	Mounts, Tripods
Mirrors, Beamsplitting	Mounts, Vibration-Isolated
Mirrors, Cold	Optical Couplers
Mirrors, Concave and Convex, Spherical	Optical Delay Lines
Mirrors, Diamond-Turned	Optical Fibers
Mirrors, Fabry-Perot Etalon	Optical Isolators
Mirrors, Flat	Optical Mounts
Mirrors, Laser	Optoisolators
Mirrors, Metal	Partial Reflectors
Mirrors, Partial	Pellicles, Optical
Mirrors, Pellicle	Photodetectors
Mirrors, Polygonal	Photodiodes
Phototransistors	Sensor Cards
Pinholes	Shutters, Laser
Plastic Fibers	Shutters, Manual

Plastic Optics	Shutters, Optical
Pockels Cells	Sidereal Mounts
Polarizers, Fiber Optic	Tubing, Glass
Polarizers, Infrared	Wave Plates
Polarizers, Visible	Wave Plates, Infrared
Polarizing Beamsplitters	Wedges, Optical
Polarizing Prisms	Windows, Brewster Angle
Prism Blanks	Windows, Diamond
Prism Couplers	Windows, Infrared
Prisms, Nonpolarizing	Windows, Sapphire
Q-Switches	YAG
Reflectors, Corner Cube	YLF
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	

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.

<p>ABB HAFO AB Member of the ASEA Brown Boveri Group Bruttovagen 1 P.O. Box 520 S-175 26 Jarfalla Sweden</p> <p>Phone: 46 8 580 24500 Fax: 46 8 580 20110</p>	<p>Application specific LEDs, PINs, and Duplex Devices for fiber applications.</p> <p>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.</p>
<p>Acton Research Corp. 525 Main St. P.O. Box 2215 Acton, MA 01720-6215</p> <p>Phone: 508/263-3584 Fax: 508/263-5086</p>	<p>Versatile Multi-Grating monochromators, high resolution monochromators, high power Excimer & UV Laser Optics, precision filters & mirrors, fully integrated Spectroscopy Systems, Spectroscopy Accessories, Vacuum UV Monochromators</p>
<p>Adaptive Optics Associates, Inc. Subsidiary of United Technologies/Hamilton Standard 54 Cambridge Park Dr. Cambridge, MA 02140-2308</p> <p>Phone: 617/864-0201 Fax: 617/864-5855</p>	<p>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%.</p>
<p>ADC Telecommunications, Inc. 4900 West 78th St. Minneapolis, MN 55435-5410</p> <p>Phone: 612/938-8080 Fax: 612/946-3292</p>	<p>Fiber cable management systems, FlexLight 2000 products for terminating, connecting, and splicing fiber optic cable.</p>
<p>AEL Industries, Inc. 305 Richardson Rd. Lansdale, PA 19446</p> <p>Phone: 215/822-2929 Fax: 215/822-9165</p>	<p>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.</p>
<p>Alcatel Telecommunications Cable, Inc. Subsidiary of Alcatel Cable N.A. 2512 Penny Rd. P.O. Box 39 Claremont, NC 28610-0039</p> <p>Phone: 703/265-0600 Fax: 703/459-9312</p>	<p>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.</p>

<p>Alcoa Fujikura Ltd. Telecommunications Div. 150 Ridgeview Circle Duncan, SC 29334-9635</p> <p>Phone: 803/433-0333 Fax: 803/433-5353</p>	<p>Fusion Splicers, Connectorized Cable, Couplers.</p>
<p>3M Specialty Optical Fibers A 3M Co. 420 Frontage Rd. West Haven, CT 06516-4190</p> <p>Phone: 203/934-7961 Fax: 203/932-3883</p>	<p>Specialty Optical Fibers, Fiber Bragg Gratings</p> <p>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.</p>
<p>American Laubscher Corp. 85 Finn Court Farmingdale, NY 11735</p> <p>Phone: 516/694-5900 Fax: 516/293-0935</p>	<p>Versions of a diffraction-grating-based miniature spectrometer operate in either the 400-1100-nm or 370-850-nm wavelength region.</p>
<p>AMP P.O. Box 3608 Harrisburg, PA 17105-3608</p> <p>Phone: 717/564-0100 Fax: 717/986-7575</p>	<p>fiber optic transceivers, optoelectronic componets, couplers, WDMs, switches, connectors, cable assemblies, and fiber management systems</p>
<p>Amphenol Corp. A LPL Co. Fiber Optic Products Div. 1925A Ohio St. Lisle, IL 60532</p> <p>Phone: 708/960-1010 Fax: 708/810-5640</p>	<p>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</p>
<p>Analog Modules, Inc. 126 Baywood Ave. Longwood, FL 32750-3426</p> <p>Phone: 407/339-4355 Fax: 407/834-3806</p>	<p>Model 8800D high-power laser-diode controller</p>

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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