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HIGH FIDELITY MICROWAVE REMOTING

Uniphase Telecommunications Products

Ronald Logan, Jr.

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13. ABSTRACT *(Maximum 200 words)*

This report details contractor efforts to develop and demonstrate a high performance one octave and multiple octave microwave fiber optic link with high dynamic range performance and operation under a wide range of environmental conditiconditions. The links demonstrated in excess of 100 dB spur free dynamic range and operation over a minus 25 degree C to plus 60 degree C temperature range.

This link is now a commercial product and has been marketed to the U.S. Government for civilian applications.

The transmitter section of the wideband link is being used in the joint USAF/USN Integrated Electronic Countermeasures (IDECM) program.

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1.0 EXECUTIVE SUMMARY

This Report contains the results of experiments performed on high-dynamic-range microwave fiber optic links designed and constructed in the performance of Rome Laboratories Contract # 30602-93-C-0047. The objective of the task was to design, fabricate, and test four Advanced Development Model (ADM) field-deployable fiber-optic links for tactical antenna-remoting applications from 2 to 4 GHz and 2 to 18 GHz.

The general design goals were to provide RF fiber optic links with the highest dynamic range and lowest noise figure possible using state-of-the-art components, and in packaging suitable for field deployment of the transmitter modules in an exterior environment. Two approaches for the link design were employed. For the 2 to 4 GHz links, a high-power continuous-wave (CW) 1319nm Nd:YAG diode-pumped solid-state laser was employed as the optical source, whereas, for the 2 to 18 GHz links, a high-power CW 1550nm distributed-feedback (DFB) laser was used. For both links, a newly-developed velocity-matched lithium-niobate Mach-Zehnder integrated waveguide modulator was used. This modulator was developed in conjunction with a parallel research program funded by the Technology Reinvestment Program (TRP). These components represent the latest state-of-the-art in optical technology.

The links were designed, constructed, and tested according to previously submitted design and test documents. While state-of-the-art components were used, it is clear that the dynamic-range and noise figure goals of the original program were not met. In order to meet these goals, a more sensitive optical modulator is required than present technology affords. Such development would require a substantial research and development effort beyond the scope of this task.

2.0 PROJECT OVERVIEW

The objective of this effort was to investigate, design, verify through laboratory experiments and fabricate three, high linearity, high dynamic range, analog fiber optic links to permit distortion free transmission of radio-frequency (RF) signals over single-mode optical fiber from an exterior environment to a protected remote location at frequencies between 2 to 4 GHz and 2 to 18 GHz. One 2 to 4 GHz fiber optic link and two 2 to 18 GHz fiber optic links were fabricated and testing was completed per Section 3.0 of this document. Each link is designated as an Advanced Development Model (ADM). The ADMs were fitted with optical connectors designed to interface with U.S. Army single mode tactical fiber optic cable system (SIM-FOCS) cable. The ADM transmitters are packaged in ruggedized, weatherproof enclosures that include the laser, modulator, RF pre-amplifiers, bias control electronics, optical and RF I/O connections, and power supplies. The ADM receivers are enclosed in standard 19" rack mount enclosures that include photodetectors, bias-control display board, I/O connections, and power supply.

The transmitter section of the 2 to 4 GHz ADM fiber optic link uses a high-power, low intensity noise, diode-pumped Nd:YAG diode-pumped solid-state laser. This laser has an emission wavelength of 1310 nm, which is in the low-dispersion, low-loss window of standard telecommunications single mode optical fiber. A thermo-electric cooler plate is integrated into the mechanical packaging design to extend the laser operating temperature range to the specified -20 C to +50 C operational temperature range. Since the Nd:YAG laser is not modulated, its optical frequency does not chirp, as in a directly modulated semiconductor laser. This results in a much narrower optical spectrum for the modulated output, and less dispersion penalty.

The optical output of the laser is fed via polarization-maintaining optical fiber to an integrated-optical modulator. The modulator is a balanced intensity Mach-Zehnder interferometer structure which allows modulation of the optical wave by application of an RF voltage to its RF electrodes. The phases of the optical fields propagating in the modulator waveguides are modulated via the linear electro-optic effect, resulting in intensity modulation at the output of the interferometer. The input and output of the modulator are fiber-pigtailed and the modulators are packaged using UTPs standard commercial processes.

The modulator is fabricated using an X-cut, Y-propagating lithium niobate crystal, using UTP's patented annealed-proton-exchange (APE) optical waveguide process. The design incorporates a newly developed velocity-matched structure, which provides improved matching of the electrical and optical wave velocities, resulting in improved sensitivity. This matching is achieved through the use of a buffer layer sandwiched between the RF electrodes and the lithium-niobate crystal. In addition to improving the optical/RF velocity-match, the buffer layer also permits the RF waveguide impedance to be designed to more closely match 50 ohms than with previous designs.

A low noise figure, high gain RF amplifier module is integrated between the RF input of the transmitter and RF input of the electro-optic modulator. This enhances the link noise figure, gain, and VSWR performance.

The 2 to 18 GHz fiber optic links use a similar configuration, however, the diode-pumped Nd:YAG laser is replaced with narrow-linewidth, high-power distributed-feedback laser diodes with emission wavelength of 1550 nm. The laser, Mach-Zehnder modulator, and the control electronics are packaged into a Small Integrated Transmitter Unit (SITU). A UTP product description of this module is contained in Appendix 1. A wideband, low noise figure, high gain RF amplifier is also located between the RF input of the transmitter and the RF input to the SITU, which enhances the link noise figure, gain and VSWR performance.

Several features of the design of the 2 to 18 GHz fiber optic links are noteworthy. First, the laser diode is much more environmentally robust than the diode-pumped Nd:YAG laser. The operating temperature range of the laser is therefore increased to -40 C to +85C. Also, the DFB laser is much more tolerant of mechanical shock and vibration than the diode-pumped Nd:YAG laser. In addition, the 1550nm emission wavelength permits the use of erbium-doped fiber amplifiers to amplify the optical output of the transmitter to provide greater fan-out to multiple receivers, or to extend the transmission distance of the link. However, the 1550 nm wavelength is not in the minimum dispersion window of the fiber, so that the transmission distance will be limited to approximately 25 kilometers or less, but this is well within the link specifications.

The receiver section of each fiber optic link consists of a wideband photodiode, diode current monitor/display PCB and power supply. The photodiode is a square-law detector, converting optical power linearly to electric current. The photodiode is loaded with 50 ohms internal to the receiver chassis.

These links represent the state-of-the-art in RF transmission at these frequencies. They are suitable for receiving antenna-remoting applications in which the transmitter must be exposed to exterior weather conditions.

3.0 R&D ACCEPTANCE TEST PLAN

The acceptance test criteria contained in this section has been implemented and completed on one (1) 2 to 4 GHz Fiber Optic Link and two (2) Broadband 2 to 18 GHz Fiber Optic Links under Phase II of contract number F30602-93-C-0047.

3.1 Ambient Temperature Testing

1. Link frequency response and total link gain performance over the specified frequency band.

2. RF phase linearity (group delay) over the specified operational frequency range.

3. Input VSWR over the specified operational frequency range.

4. Noise figure performance measured at 3 GHz or 10 GHz (midband) using a spectrum analyzer noise figure measurement technique.

5. Two-tone, third order input intercept point (IIP_3) measured at 3 GHz or 10 GHz (midband). Two tones are spaced 100 MHz apart.

6. Two-tone, second order input intercept point (IIP_2) measured at 3 GHz or 10 GHz (midband). Two tones are spaced 100 MHz apart.

3.2 Temperature Testing at -20 C and +50 degrees C

1. Link frequency response and total link gain performance over the specified frequency band.

2. Noise figure performance measured at 3 GHz or 10 GHz (midband) using spectrum analyzer noise figure measurement technique.

4.0 OPTICAL LINK PERFORMANCE RESULTS

4.1 Narrowband ADM 2 to 4 GHz Fiber Optic Link

An Advanced Development Model (ADM) optical link operating over the frequency band of 2 to 4 GHz was designed, fabricated and tested. The test results are presented in this document as completion of Phase II contractual requirements. Plotted frequency-response measurements and link noise figure measurements are used to demonstrate the performance of the optical link. The 2 to 4 GHz Link Compliance Matrix summarizing the link performance specifications and measured performance data is outlined in Section 5.0 of this document.

4.1.1 Frequency Response and Total Link Gain

The following frequency response plots depict the total link gain performance as well as the frequency response of the link over the specified 2 to 4 GHz bandwidth. Tests were performed at +25 degrees C, +50 degrees C and -20 degrees C. The worst case minimum total link gain is +6.0 dB at +50 degrees C. The total link gain specification is 0 dB RF less loss of the optical fiber and connectors. The total link gain specification was achieved inclusive of the optical interface losses.

4.1.2 RF Phase Linearity (Group Delay)

The RF phase linearity was measured over 2 to 4 GHz using an HP8722D Network Analyzer. The linearity performance is specified in terms of group delay and is specified as 2 nsec, maximum. The measured group delay shown in Figure 4-4 is 0.8 nsec maximum.

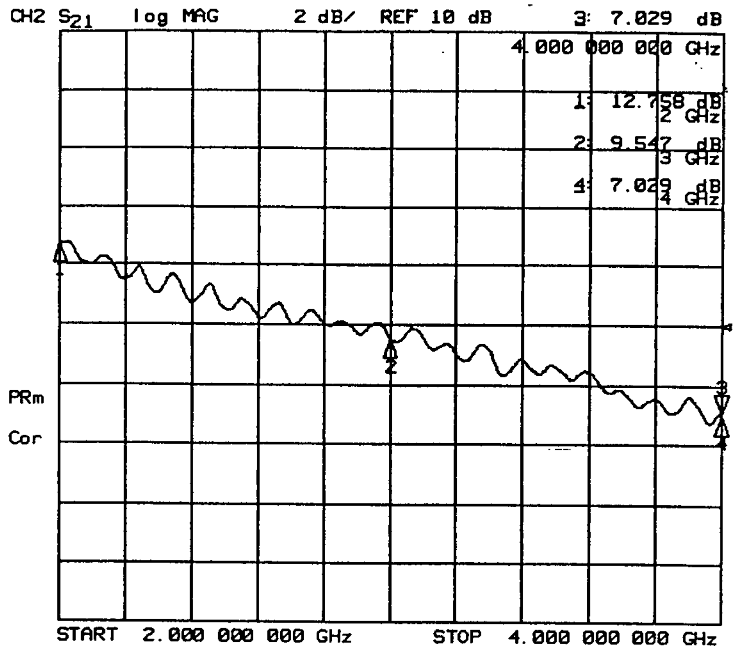


Figure 4-1 Total 2 to 4 GHz Link Gain Performance at +25 C .

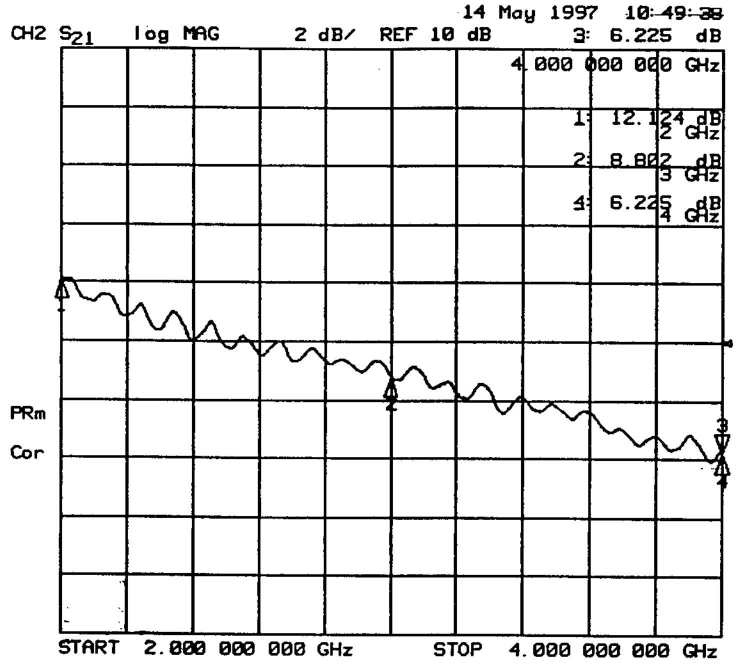


Figure 4-2 Total 2 to 4 GHz Link Gain Performance at +50 C.

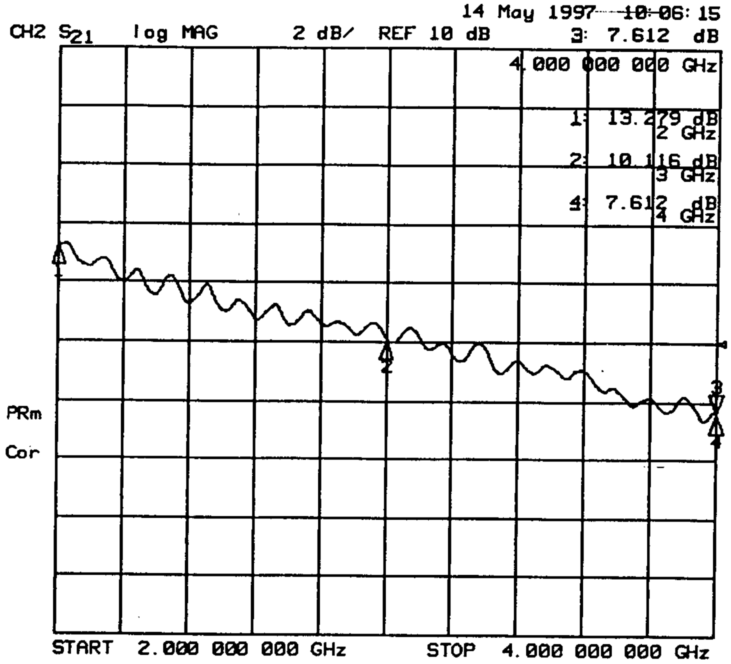


Figure 4-3 Total 2 to 4 GHz Link Gain performance at -20 C.

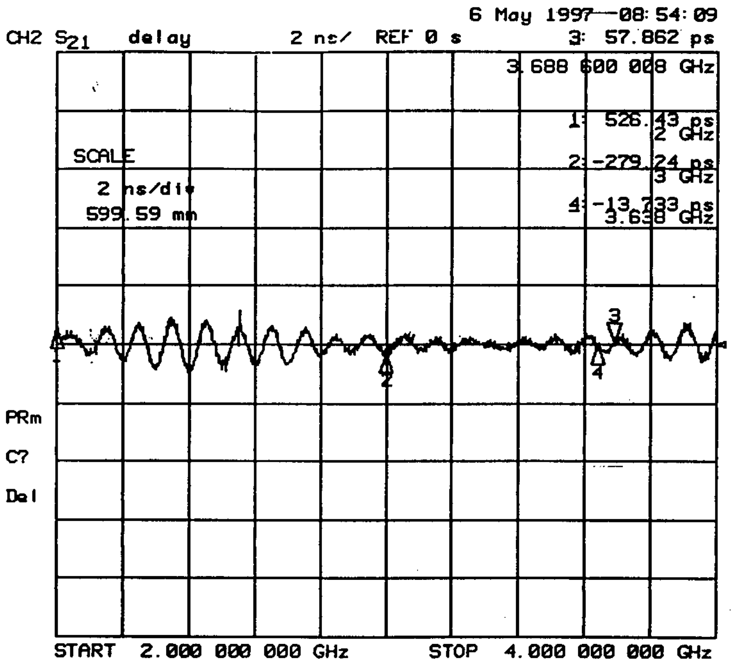


Figure 4-4 Phase Linearity (Group Delay) for 2 to 4 GHz Optical Link.

4.1.3 Transmitter Input VSWR

The Transmitter Input VSWR (S11) was measured over the 2 to 4 GHz operational bandwidth. Figure 4-5 shows the VSWR performance measured as input return loss. Worst case VSWR was 1.55:1 (i.e. -13.39 dB return loss), which is better than the VSWR specification = 1.75:1, maximum.

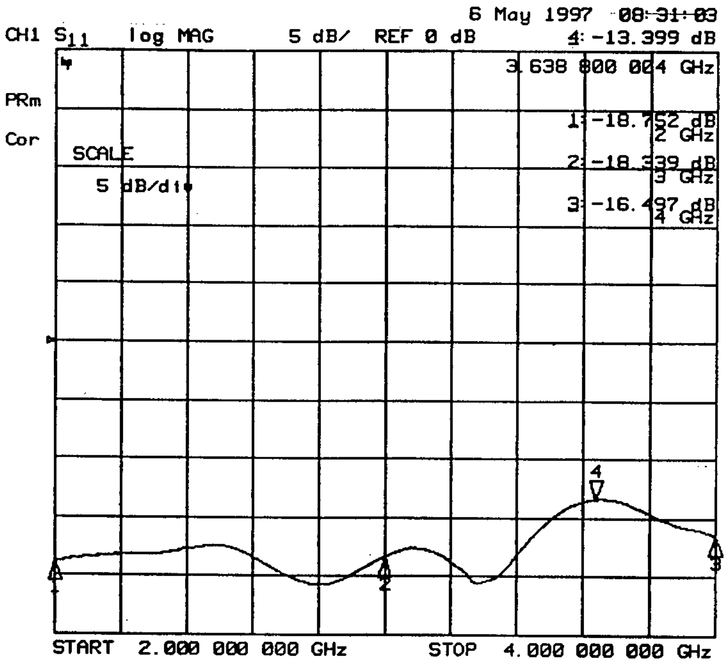


Figure 4-5 Input Return Loss for the 2-4 GHz ADM Optical Link.

4.1.4 Noise Figure

The link noise figure performance was measured using an RF spectrum analyzer set to measure output noise power of the link in dBm/1 Hz bandwidth. The output noise power of the link ($Po|_{link}$) is then referred to the link input by subtracting the link gain to obtain the equivalent input noise (EIN in dBm/Hz). Noise figure (in dB) is then equal to the EIN + 174 dBm/Hz (thermal noise floor at 300 K). Since the output noise is close to the measurement system noise floor, the measurement noise is subtracted out by recording the spectrum analyzer displayed noise level with no input. These computations are displayed in Appendix 1. Worst case measurements were taken at the high end of the operating frequency range. Noise figure measurements were also performed at +25 degrees C, +50 degrees C and -20 degrees C. Noise figure test results are summarized in the 2-4 GHz ADM Compliance Matrix shown in Table 5-1. The design goal of 6 dB maximum was marginally exceeded with the maximum worst case noise figure equal to 7.84 dB for link S/N 001 at +50 degrees C.

4.1.5 Third Order Input Intercept Point (IIP_3)

The Input Third Order Intercept Point (IIP_3) was measured using two RF tones at 3.0 GHz (F1) and 3.1 GHz (F2) incident at the transmitter RF input port. The input power level of each tone was set to -30 dBm to avoid overdriving the pre-amplifier. The third-order intermodulation distortion tones at frequencies 2F2-F1 and 2F1-F2 were measured at the RF output of the link and the input third order intercept point was then calculated using the following equation:

$$IIP_3 \text{ (in dBm)} = \frac{R_S \text{ (in dBc)}}{n-1} + \text{Input Power Level (dBm)}$$

where: $n = 3$, order of intermodulation distortion,
R_S = intermod suppression in dB below input.

The total link test result at +25 degrees C yielded an IIP_3 of -10.6 dBm. This is well below the +2 dBm requirement for IIP_3, and was primarily caused by the input intercept point performance of the low noise RF amplifier and the high extinction voltage (V_π) associated with the optical intensity modulator. The amplifier chosen was a Watkins-Johnson model number 6881-813, since it provided low noise figure performance of less than 3.5 dB, and high IIP_3 performance of -1 dBm. Although this is the highest IIP_3 performance available at this noise figure, it is already below the desired IIP_3 level of +2 dBm for the system. The amplifier gain is 28 dB (typical) which corresponds to an output third order intercept point (OIP_3) of +28 dBm. Cascading the amplifier OIP_3 with the optical modulator IIP_3 of +21 dBm further degraded the overall system IIP_3 performance level to -10.6 dBm.

The amplifier performance parameters were selected based upon a trade-off between total link noise figure performance and IIP_3 performance. The IIP_3 specification and noise figure specification for the link result in a two-tone intermodulation-free dynamic range requirement of 113 $dB\text{-}Hz^{(2/3)}$. The noise figure and IIP_3 of the RF pre-amplifier corresponds to a two-tone intermodulation-free dynamic range of 113 $dB\text{-}Hz^{(2/3)}$, but when cascaded with the fiber-optic link, the input intercept point is degraded. This is because of the high level of gain required to overcome the loss of the fiber-optic link to meet the gain and noise figure specifications. Thus, it is possible to *either* optimize the total link to meet the gain and noise figure specifications, *or* to meet the IIP_3 specification. In this design, the link was optimized for gain and noise figure at the expense of IIP_3. Improving the Mach-Zehnder optical modulator design to reduce its V_π level is to achieve the performance objectives required for this link.

4.1.6 Second Order Input Intercept Point (IIP_2)

The Input Second Order Intercept Point was measured using two fundamental tones at 3.0 GHz (F1) and 3.1 GHz (F2) incident at the Transmitter RF input port. The power level of each tone was set to -30 dBm. The second order intermodulation distortion tone at frequency F1 + F2 was measured at the RF output of the link and the input second order intercept point was then calculated using the following equation:

$$IIP_2(\text{in dBm}) = \frac{R_S\ (\text{in dBc})}{n-1} + \text{Input Power Level (dBm)}$$

where: n = 2, order of intermodulation distortion,
R_S = intermod suppression in dB below input.

The worst case F1 + F2 intermod yielded a second-order input intercept point of IIP_2 = +7.67 dBm, which is 4.33 dB below the specified +12 dBm minimum requirement. This was most likely due to the second-order intermodulation distortion due to the RF pre-amplifier, since the Mach-Zehnder bias point is actively controlled to maintain the bias at the quadrature point, at which second-order distortion terms are minimized.

4.2 Broadband 2.0 to 18.0 GHz Fiber Optic Link (2 each)

Two ADM fiber optic links operating over the frequency band of 2 to 18 GHz were designed, fabricated, and tested. The test results are presented in this document as completion of Phase II contractual requirements. Plotted test results of frequency response and VSWR, along with the calculations necessary to extract the noise figure values from the spectrum analyzer measurements are used to demonstrate the performance of the optical link The detailed noise figure calculations are contained in Appendix I. The 2 to 18 GHz Link Compliance Matrixes summarizing link performance specifications and measured test results are contained in Section 5.0 of this document.

4.2.1 Frequency Response and Total Link Gain

The following frequency response plots depict the total link gain performance as well as the frequency response of the link over a 2 to 18 GHz bandwidth. Tests were performed at +25 degrees C, +50 degrees C and -20 degrees C. The worst case minimum total link gain is -13.0 dB at +50 degrees C for S/N 001 and -7.0 dB at +50 degrees C for S/N 002. The total link gain specification is 0 dB RF, less loss of the optical fiber and connectors. The effective RF link gain specification inclusive of the optical interface losses is 0 dB RF - [6.5 dB optical X 2] = -13.0 dB. The reader is reminded that a 1 dB optical loss results in a 2 dB RF loss, since RF power is proportional to the squared photocurrent, and photocurrent is linearly proportional to optical power. Therefore, the minimum link gain specification is achieved when the optical loss is accounted for in the total link gain budget. Figures 4-7 through 4-12 show the link frequency response and gain at +25 degrees C, +50 degrees C and -20 degrees C for link serial numbers 001 and 002.

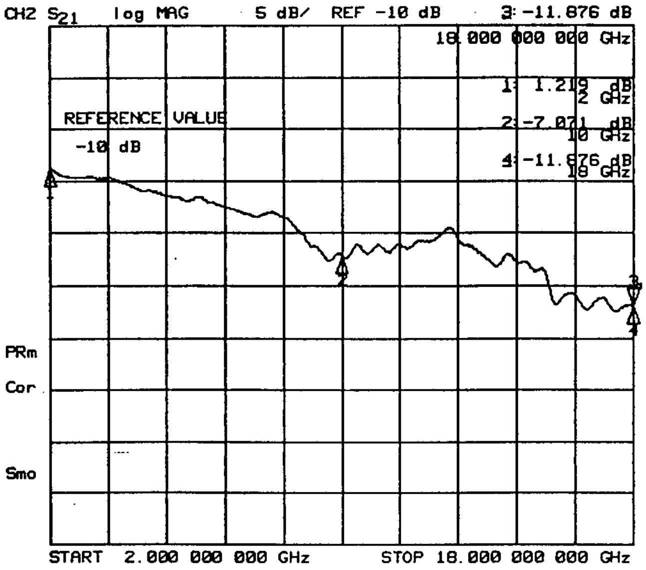


Figure 4-6 Link Gain Performance at +25 degrees C (Serial #001).

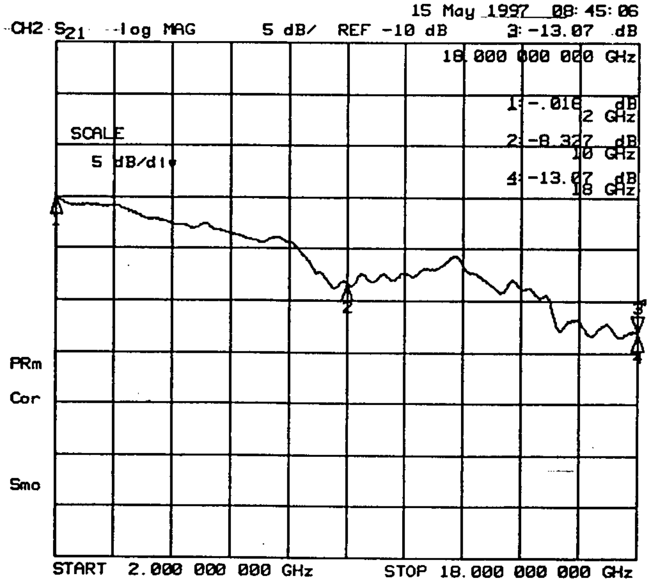


Figure 4-7 Link Gain Performance at +50 degrees C (Serial #001).

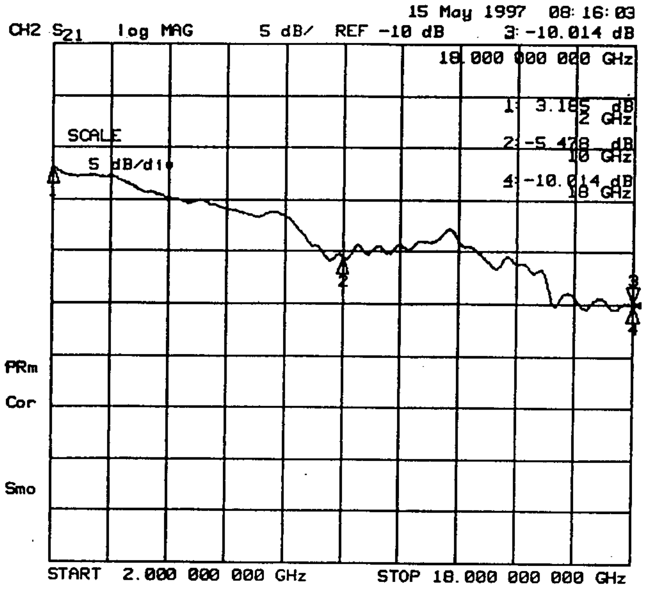


Figure 4-8 Link Gain Performance at -20 degrees C (Serial #001).

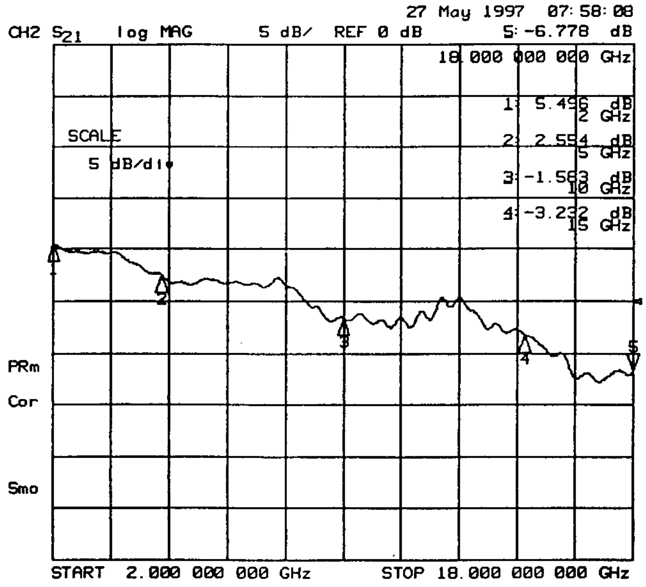


Figure 4-9 Link Gain Performance at +25 degrees C (S/N 002).

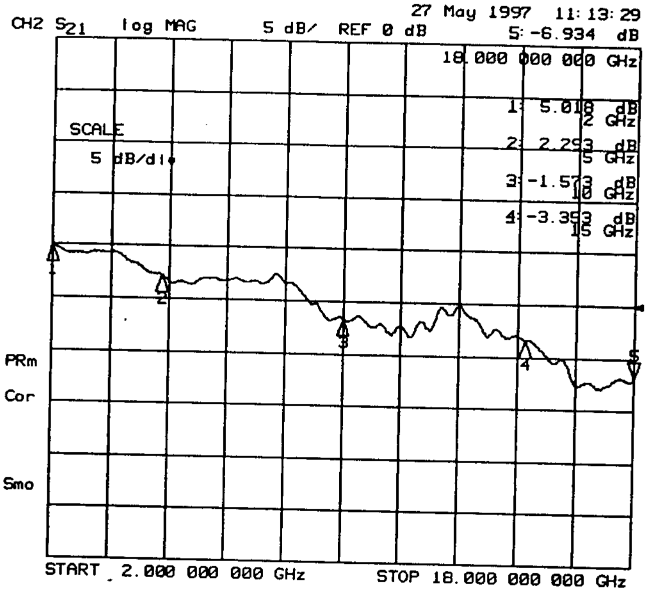


Figure 4-10 Link Gain Performance at +50 degrees C (S/N 002).

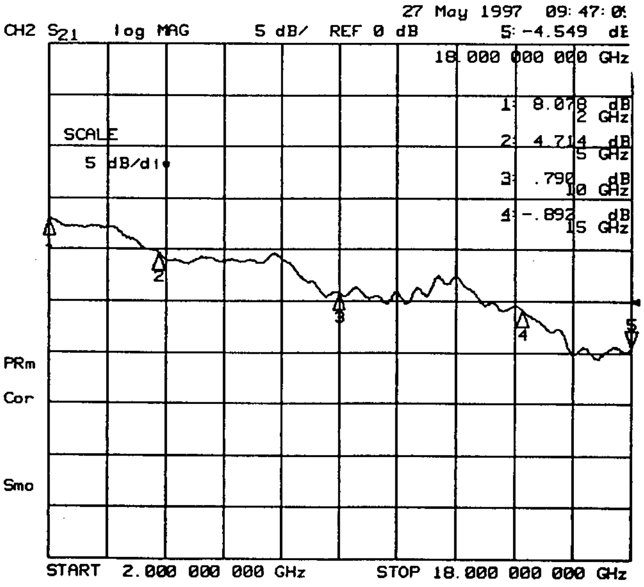


Figure 4-11 Link Gain Performance at -20 degrees C (S/N 002).

4.2.2 RF Phase Linearity (Group Delay)

The RF phase linearity was measured over 2 to 18 GHz using an HP8722D Network Analyzer. The phase linearity performance is specified in terms of group delay and is specified as 2 nsec, maximum. The measured peak group delay as shown in Figures 4-13 and 4-14 was 267 psec for Serial number 001 and 385 psec for Serial number 002.

4.2.3 Transmitter Input VSWR

The input VSWR (S11) was measured over the 2 to 18 GHz operational bandwidth. Figure 4-15 and Figure 4-16 show the measured input return loss in dB which can be converted to VSWR. Worst case VSWR is 3.0:1 (i.e. -6.0 dB Return Loss) for S/N 001 and 3.6:1 for S/N 002. The VSWR specification is 1.75:1, maximum. This VSWR performance can attributed directly to the input impedance characteristics of the input RF pre-amplifier. It is quite difficult to produce full broadband VSWR performance of 1.75:1 over 2 to 18 GHz; however, as shown in Figures 2.1-15 and 2.1-16, 85% of the frequency response return loss is below the highlighted specification limit of -12.8 dB return loss.

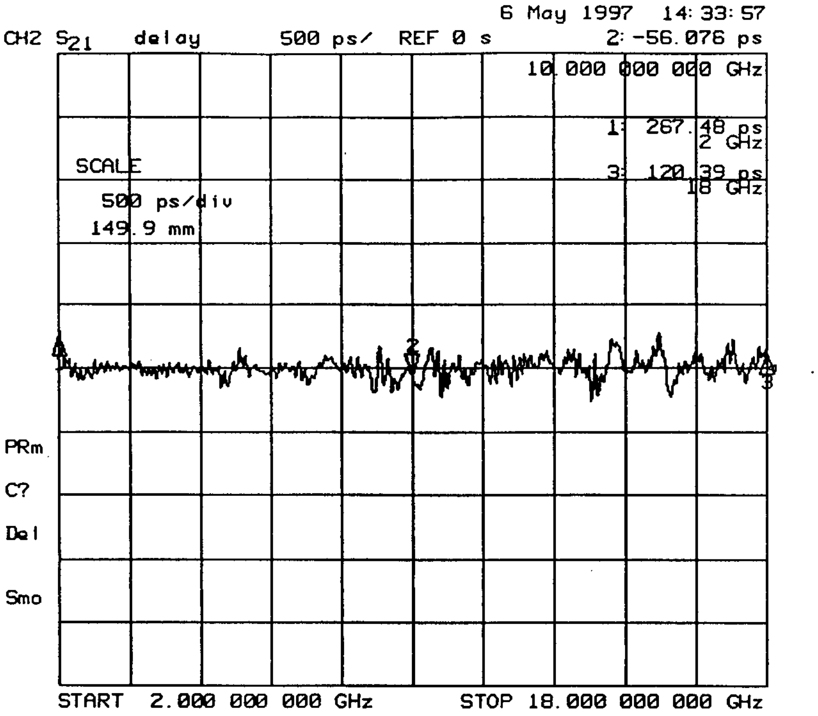


Figure 4-12 Phase Linearity (Group Delay) Response for S/N 001

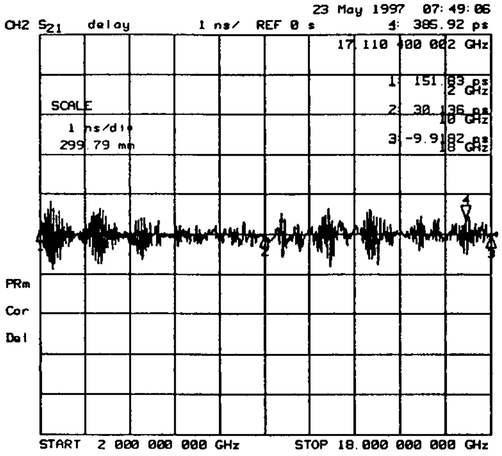


Figure 4-13 Phase Linearity (Group Delay) Response for S/N 002.

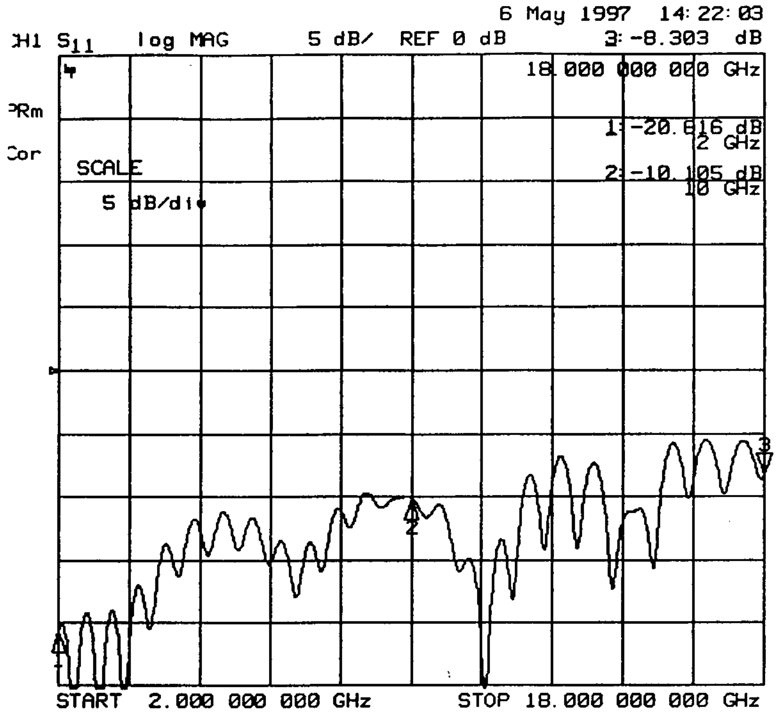


Figure 4-14 Input Return Loss performance for S/N 001

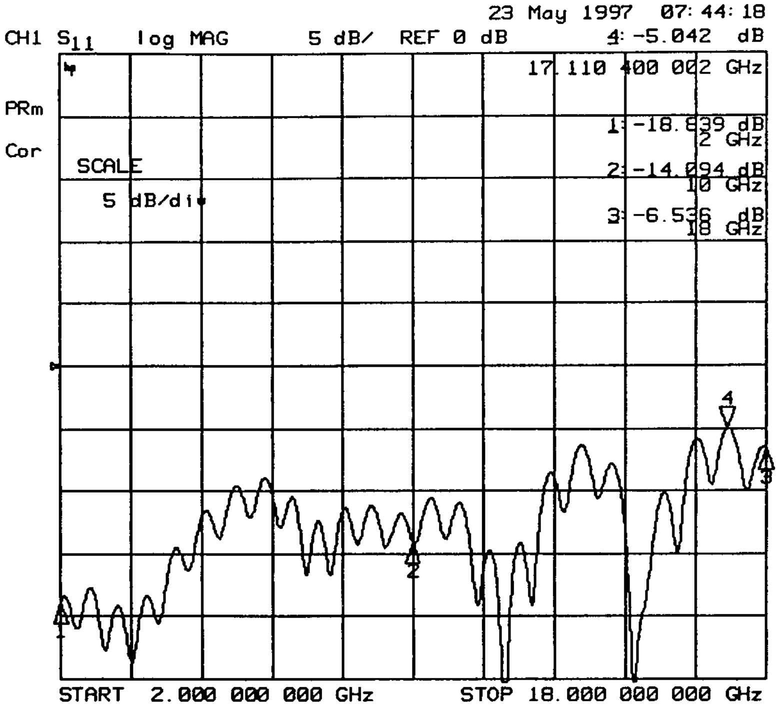


Figure 4-15 Input Return Loss performance for S/N 002

4.2.4 Noise Figure

The link noise figure performance was measured using spectrum analyzer set to measure output noise power of the link in dBm/1 Hz bandwidth. The output noise power of the link ($Po|_{link}$) is then referred to the link input by subtracting the link gain to obtain the equivalent input noise (EIN in dBm/Hz). Noise figure (in dB) is then computed as EIN + 174 dBm/Hz. Since the output noise is close to the measurement system noise floor, the measurement noise is subtracted out by recording the spectrum analyzer displayed noise level with no input. These computations are displayed in Appendix 1.

Measurements were taken at low, mid and high frequency points over the operating band. Noise figure measurements were performed at +25 degrees C, +50 degrees C and -20 degrees C. Test results are summarized in the 2-18 GHz ADM Compliance Matrixes shown in Tables 5-2 and 5-3. Worst case test results were obtained at the high end of the frequency band (i.e. 18 GHz). This was anticipated based on the performance data described for UTP's Small Integrated Transmitter Unit (SITU) which were integrated into the 2 to 18 GHz ADMs. Typical noise figure performance for the SITU is 47 dB at 18 GHz. A SITU data sheet is contained in Appendix 1. The input pre-amplifier provides 30 dB of RF gain and has a noise figure of 4.0 dB maximum. The best case measured cascaded noise figure of the input RF amplifier and the SITU is 17.2 dB at 4 mA of photodiode current.

In short links with low losses, the dominant output noise source at microwave frequencies is the laser noise, comprised of relative intensity noise (RIN) generated in the laser, and shot noise generated in the photodetection process. Since the link gain is proportional to optical power, the link noise figure is inversely proportional to the amount of photodiode current. The expected link noise figure at the input of the optical modulator can be calculated using the following expressions:

1) $NF_{link\_}\ dB = (N_{total\_}dBm/Hz - Gain\_\ dB) + 174\ dBm/Hz$

2) $N_{total\_}dBm = 10\ Log_{10}\ (N_{shot} + N_{thermal} + N_{RIN}) + 30$

3) $N_{shot} = 2*e*I_{ph}*R_L$; $N_{thermal} = kT$; $N_{RIN} = (I_{ph})^2*10^{RIN(dBm)/10} * R_L$

where: I_{ph} = Photodiode Current
R_L = Load Impedance (50 ohm)

RIN = Laser Relative Intensity Noise
(-150 dB/Hz max. for the SITU DFB Laser,
<-170 dB/Hz max. for the Nd:YAG Laser)

These equations predict noise figure values at the input of the optical modulator on the order of 35 dB to 45 dB over the range of input powers considered in this work. The relatively high noise figure performance for these links is caused primarily by the high RF insertion loss associated with the fiber optic link. Currently, a SITU unit provides +6 dBm minimum optical output level. Optical losses associated with the fiber and optical connectors further attenuate the optical level prior to the photodiode, thus degrading the link gain and noise figure performance. Increasing the optical power incident at the receiver is one approach to improving the link gain and noise figure performance. The front end RF gain of the pre-amplifier can also be increased to further improve noise figure, however, this will typically result in degradation of the intercept point performance and dynamic range.

4.2.5 Input Third Order Intercept Point (IIP_3)

The IIP_3 was measured using two fundamental tones at 3.0 GHz (F1)** and 3.1 GHz (F2)** incident at the transmitter RF input port. The input power level of each tone was set to -30 dBm to avoid overdriving the pre-amplifier. The third-order intermodulation distortion tones at frequencies 2F2-F1 and 2F1-F2 were measured at the RF output of the link and the input third order intercept point was then calculated using the following equation:

$$IIP_3 \text{ (in dBm)} = \frac{R_S \text{ (in dBc)}}{n-1} + \text{Input Power Level (dBm)}$$

where: $n = 3$, order of intermodulation distortion,
R_S = intermod suppression in dB below input.

The test results at +25 degrees C yielded an IIP_3 of -7.0 dBm for S/N 001 and -7.6 dBm for S/N 002. This is well below the +2 dBm requirement and is primarily caused by the RF amplifier input intercept point performance.

** Note: 3.0 GHz and 3.1 GHz input tones were used for this test due to the availability of isolators in this frequency band at UTP. The isolators were required in the test setup to enhance the accuracy of the measurement by avoiding unwanted interaction between the two CW signal sources. It is expected that the IIP_3 will follow the frequency response of the link at frequencies away from the test frequency.

4.2.6 Input Second Order Intercept Point (IIP_2)

The Input Second Order Intercept Point was measured using two fundamental tones at 3.0 GHz (F1) and 3.1 GHz (F2) incident at the Transmitter RF input port. The power level of each tone was set to -30 dBm. The second order intermodulation distortion tone at frequency F1 + F2 was measured at the RF output of the link and the input second order intercept point was then calculated using the following equation:

$$IIP_2(\text{in dBm}) = \frac{R_S\ (\text{in dBc})}{n-1} + \text{Input Power Level (dBm)}$$

where: $n = 2$, order of intermodulation distortion,
R_S = intermod suppression in dB below input.

The worst case F1 + F2 intermod yielded an input intercept point of +18.0 dBm for S/N 001 which is 6 dB above the +12 dBm minimum requirement. S/N 002 performance was quite different. Its second order intercept point was +6.27 dBm which is approximately 6.0 dB below the specification limit of +12 dBm. The difference in second order intercept point performance may have been caused by Mach Zehnder modulator bias point drift. The bias point is set to maintain the $V_\pi /2$ bias point which suppresses second order products. The control circuitry used to stabilize the bias point for S/N 002 may have drifted from the quadrature set point causing degradation in second order suppression. It is also possible that the RF pre-amplifier used in S/N 002 had a degraded second-order intercept point. However, time did not permit final diagnosis of this problem.

5.0 COMPLIANCE MATRIX

A Compliance Matrix is presented in each of Tables 5-1, 5-2 and 5-3 listing the performance summary for the narrowband 2 to 4 GHz ADM link and the two broadband 2 to 18 GHz ADM links.

Table 5-1. Narrowband 2 to 4 GHz ADM Link Compliance Matrix

PARAMETER	SPECIFICATION		Units	MEASURED PERFORMANCE		
	Min Limit	Max Limit		+25 C	+50 C	-20 C
Optical Wavelength	1300	1310	nm	1319		
RF Frequency Range	2	4	GHz	see Plotted results		
Total Link Gain	0	-	dB	9.5	8.8	10.1
RF Phase Linearity (group delay)		2	nsec	0.8	-	-
Transmitter Input VSWR		1.75	:1	1.55	-	-
Noise Figure		6	dB	6.54	7.84	6.03
IIP_3	+2		dBm	-10.6	-	-
IIP_2	+12		dBm	+7.67	-	-
Primary Power Requirements	AC Prime: 115 or 200/230 Volts single phase , 47 - 440 Hz DC Prime: 28 VDC		-	Compliance		

Table 5-2. Broadband 2 to 18 GHz Link Compliance Matrix

2-18 GHz Link Serial Number 001

PARAMETER	SPECIFICATION		Units	MEASURED PERFORMANCE		
	Min Limit	Max Limit		+25 C	+50 C	-20 C
Optical Wavelengh	1545	1555	nm	Compliance		
RF Frequency Range	2	18	GHz	see Plotted results		
Total Link Gain (Optical level @ RX photodiode = +3.25 dBm)	0	-	dB	-12.1	-13.0	-10.3
RF Phase Linearity (group delay)		2	nsec	0.26	-	-
Transmitter Input VSWR		1.75	:1	3.0	-	-
Noise Figure		6	dB	18.7	21.1	17.1
IIP_3	+2		dBm	-7.0	-	-
IIP_2	+12		dBm	+18	-	-
Primary Power Requirements	AC Prime: 115 or 200/230 Volts single phase , 47 - 440 Hz DC Prime: 28 VDC		-	Compliance		

Table 5-3. Broadband 2 to 18 GHz Link Compliance Matrix

2-18 GHz Link Serial Number 002

PARAMETER	SPECIFICATION		Units	MEASURED PERFORMANCE		
	Min Limit	Max Limit		+25 C	+50 C	-20 C
Optical Wavelengh	1545	1555	nm	Compliance		
RF Frequency Range	2	18	GHz	see Plotted results		
Total Link Gain (Optical level @ RX photodiode = +5.5 dBm	0	-	dB	-6.7	-7.0	-5.1
RF Phase Linearity (group delay)		2	nsec	0.38	-	-
Transmitter Input VSWR		1.75	:1	3.6	-	-
Noise Figure		6	dB	16.6	17.6	14.8
IIP_3	+2		dBm	-7.6	-	-
IIP_2	+12		dBm	+6.27	-	-
Primary Power Requirements	AC Prime: 115 or 200/230 Volts single phase , 47 - 440 Hz DC Prime: 28 VDC		-	Compliance		

6.0 SUMMARY AND RECOMMENDATIONS

The general design goals of this program were to provide an RF fiber-optic link with the highest dynamic range and lowest noise figure possible using state-of-the-art components, and in packaging suitable for field deployment of the transmitter modules in an exterior environment. While state-of-the-art components were used, it is clear that the dynamic-range goals of the original program were not met. In order to meet these goals, a more sensitive optical modulator is required than present technology affords. Also, photodiodes with higher optical saturation power levels are required. To obtain these components requires substantial research and development efforts beyond the scope of the present contract.

While it is possible to obtain an arbitrarily low input noise figure for the link by placing an appropriate RF pre-amplifier preceding the optical modulator, the input intercept point of the fiber-optic link will limit the ultimate dynamic range of the cascaded pre-amp/fiber-optic link. The only possible way to achieve the design goals of the program is to have a fiber-optic link with at least as much dynamic range as the system design goal, preceded by an RF pre-amplifier that has an even higher dynamic range, so that the intrinsic fiber optic link dynamic range dominates the link performance. With the state-of-the-art components used, it is not possible to achieve this goal.

The fundamental limitation to the dynamic range performance of an external-modulation fiber optic link is determined by the saturation current of the photodiode, and the optical noise level. In a shot-noise limited link, it is theoretically possible to increase the dynamic range without bound by increasing the optical power on the photodiode, since the detected RF signal power increases as the square of the optical power, but the shot-noise level is only linearly proportional to the photocurrent. Therefore, the signal-to-noise ratio of the shot-noise limited link increases 1 dB for each 1 dB increase in optical power. In a link where laser RIN is larger than the shot-noise, such as is the case with the DFB lasers used in the 2 to 18 GHz links, the signal-to-noise ratio is independent of optical power in the high power limit. This is because the RIN is actually a modulation of the laser power, so that its RF power level increases as the square of the optical power. The dynamic range has an upper bound for the RIN-limited link, but not for the shot-noise limited link.

Therefore, to obtain substantially higher dynamic range with a Mach-Zehnder external-modulation fiber optic link, a shot-noise limited laser must be used with very high power on the photodiode. Electronic and optical techniques are available to “linearize” the Mach-Zehnder modulator response, but these are typically limited to low frequencies below 1 GHz for electronic predistortion, or to sub-octave bandwidths, as is the case for “low-biased”

Mach-Zehnder modulators. "Optically linearized" modulators have been demonstrated, but these typically require multiple modulator sections in cascade that each require independent bias control and/or RF drive signals, which increase the optical losses and complicate their use in practical systems.

In summary, this research effort has resulted in field-deployable fiber-optic transmission links that represent the current state-of-the-art in performance for microwave fiber-optic transmission. To achieve the stated dynamic range goals of the program would require optical modulators with higher sensitivity and photodiodes with higher saturation current than were available to the program.

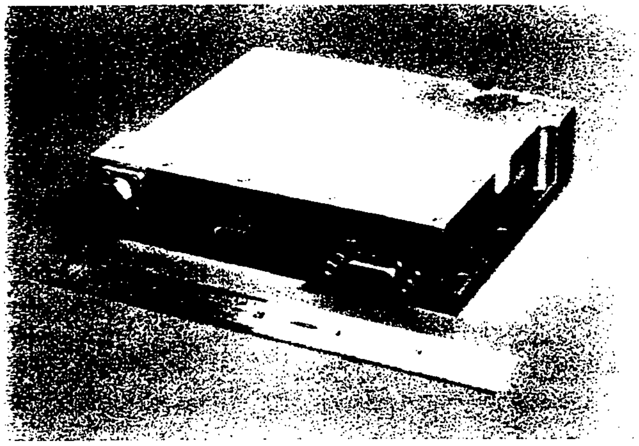
APPENDIX 1 - Noise Figure Numerical Calculation Summary

Noise Figure Numerical Calculation Summary

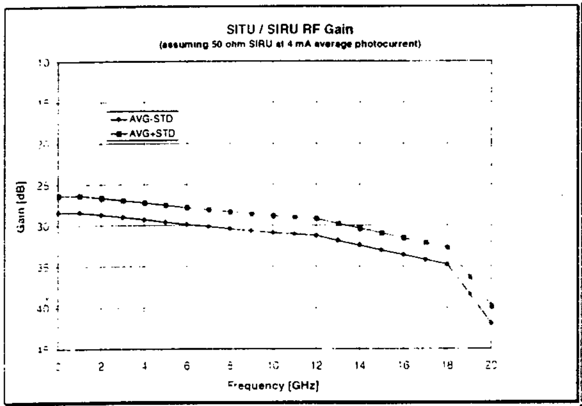
Contract F30602-91-C-0050
Data Item B005

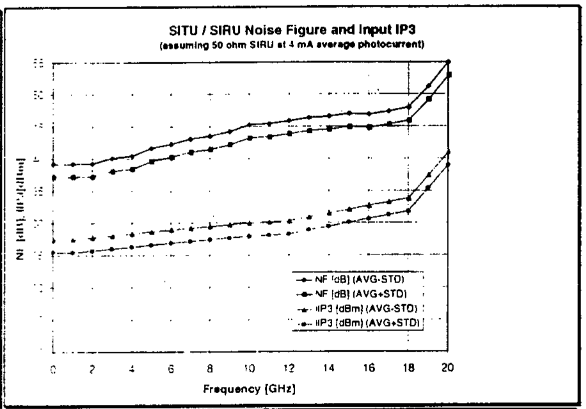
This Appendix contains the numberical calculations for Noise Figure over Temperature for ADM Optical Links and a product description of the UTP Small Integrated Transmitter Unit (SITU)

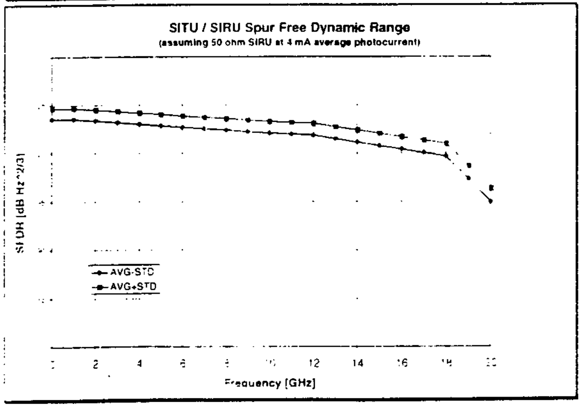
Microwave Fiber-Optic
1550 nm
Small Integrated
Transmitter Unit (SITU)

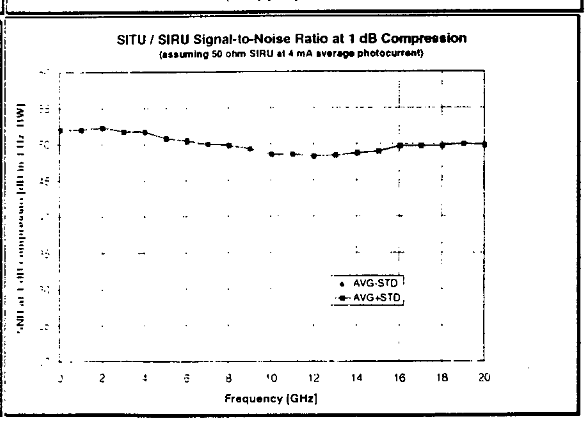


SITU /SIRU (50 ohm, 4mA) Typical Performance


SITU / SIRU RF Gain
(assuming 50 ohm SIRU at 4 mA average photocurrent)


SITU / SIRU Noise Figure and Input IP3
(assuming 50 ohm SIRU at 4 mA average photocurrent)


SITU / SIRU Spur Free Dynamic Range
(assuming 50 ohm SIRU at 4 mA average photocurrent)

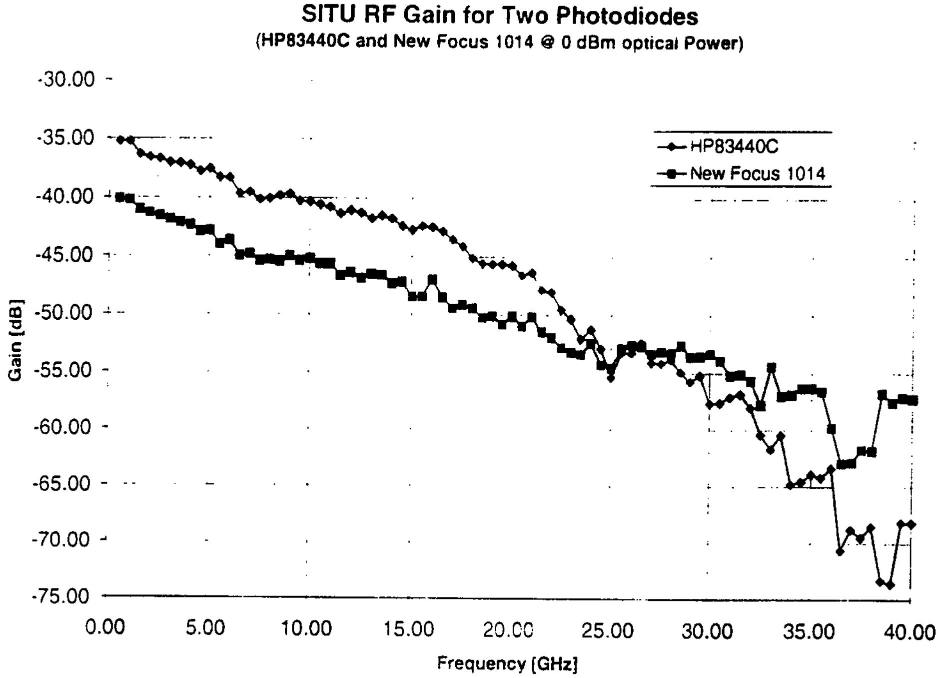

SITU / SIRU Signal-to-Noise Ratio at 1 dB Compression
(assuming 50 ohm SIRU at 4 mA average photocurrent)

Note: RF Gain and NF degrade 2 dB for 1 dB less optical power on photodiode

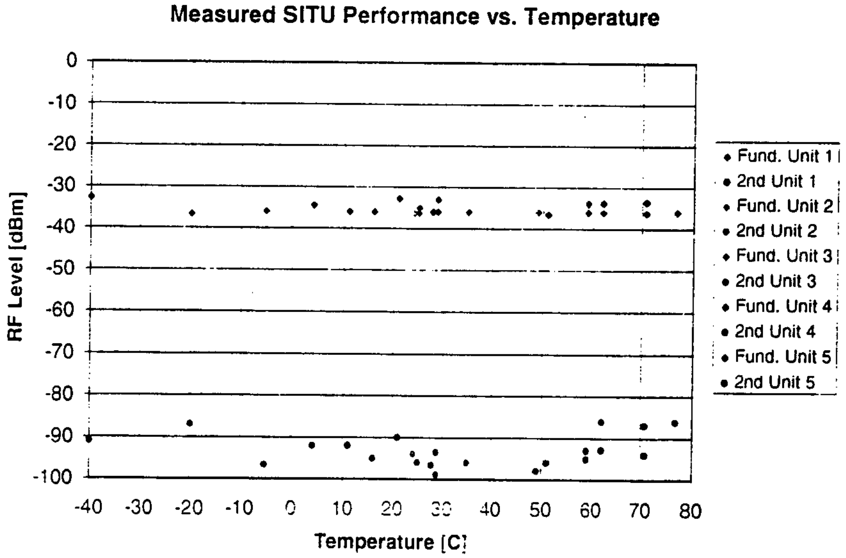
UTP
Uniphase Telecommunications Products
Transmission Systems Division

500 Horizon Drive, Chalfont, PA 18914

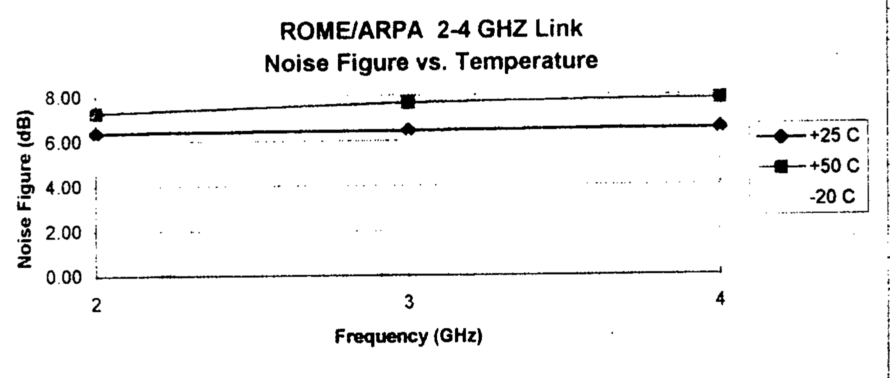
SITU /Photodiode Representative Performance


SITU RF Gain for Two Photodiodes
(HP83440C and New Focus 1014 @ 0 dBm optical Power)

SITU /SIRU Temperature Performance


Measured SITU Performance vs. Temperature

UTP
Uniphase Telecommunications Products
Transmission Systems Division

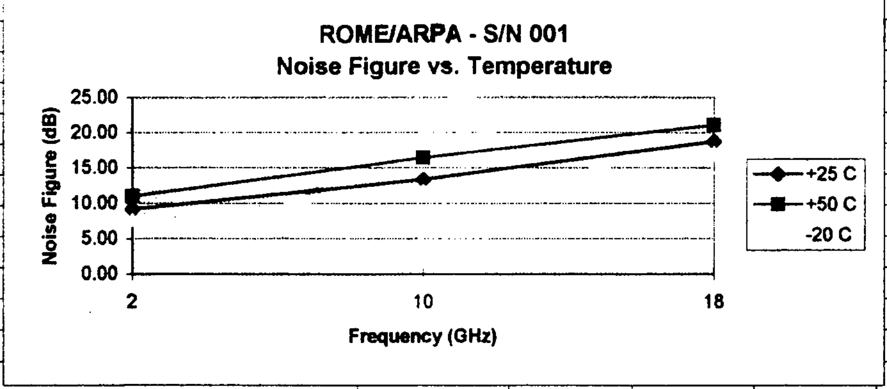


ROME/ARPA - Noise Figure over Temperature Test Results					
Engineer: S. A. Roos					
Date:5/23/97					
ADM 2.0 to 4.0 GHz Optical Link					
Total Link Gain w/post amp @ 25 degrees C:					
Measured Total Link Gain @ 2 GHz =	42.8	dB			
Measured Total Link Gain @ 3 GHz =	42.5	dB			
Measured Total Link Gain @ 4 GHz =	42.5	dB			
Total Link Gain w/post amp @ +50 degrees C:					
Measured Total Link Gain @ 2 GHz =	42.3	dB			
Measured Total Link Gain @ 3 GHz =	41.8	dB			
Measured Total Link Gain @ 4 GHz =	41.6	dB			
Total Link Gain w/post amp @ -20 degrees C:					
Measured Total Link Gain @ 2 GHz =	43.2	dB			
Measured Total Link Gain @ 3 GHz =	43.1	dB			
Measured Total Link Gain @ 4 GHz =	42.8	dB			
25 C Test Conditions:					
Optical Input to RX Photodiode =	**+ 7.6**	**dBm**			
RF Input Power Level =	**-30**	**dBm**			
Noise Figure Calculation @ 2 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-124.1	dBm/Hz	3.89E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.2	dBm/Hz	6.03E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	42.8	dB	3.29E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.63	dBm/Hz			
Noise Figure (dB)=	**6.37**	dB			

Noise Figure Calculation @ 3 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-124.4	dBm/Hz	3.63E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.9	dBm/Hz	5.13E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	42.5	dB	3.12E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.56	dBm/Hz			
Noise Figure (dB)=	**6.44**	dB			
Noise Figure Calculation @ 4 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-124.3	dBm/Hz	3.72E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.8	dBm/Hz	5.25E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	42.5	dB	3.19E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.46	dBm/Hz			
Noise Figure (dB)=	**6.54**	dB			
Noise Figure Calculation @ 2 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-123.8	dBm/Hz	4.17E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	42.3	dB	3.59E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-166.75	dBm/Hz			
Noise Figure (dB)=	**7.25**	dB			
Noise Figure Calculation @ 3 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-123.9	dBm/Hz	4.07E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.6	dBm/Hz	5.5E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	41.8	dB	3.52E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-166.33	dBm/Hz			
Noise Figure (dB)=	**7.67**	dB			
Noise Figure Calculation @ 4 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-123.9	dBm/Hz	4.07E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	41.6	dB	3.5E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-166.16	dBm/Hz			
Noise Figure (dB)=	**7.84**	dB			
Noise Figure Calculation @ 2 GHz @ -20 C					
			Test Setup correction		
Noise Output (Laser ON)=	-124.3	dBm/Hz	3.72E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.8	dBm/Hz	5.25E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	43.2	dB	3.19E-13	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-168.16	dBm/Hz			
Noise Figure (dB)=	**5.84**	dB			

NF24tem

Noise Figure Calculation @ 3 GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-124.3	dBm/Hz	3.72E-13	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-132.8	dBm/Hz	5.25E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	43.1	dB	3.19E-13	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-168.06	dBm/Hz				
Noise Figure (dB)=	**5.94**	dB				
Noise Figure Calculation @ 4 GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-124.4	dBm/Hz	3.63E-13	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-132.3	dBm/Hz	5.89E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	42.8	dB	3.04E-13	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-167.97	dBm/Hz				
Noise Figure (dB)=	**6.03**	dB				



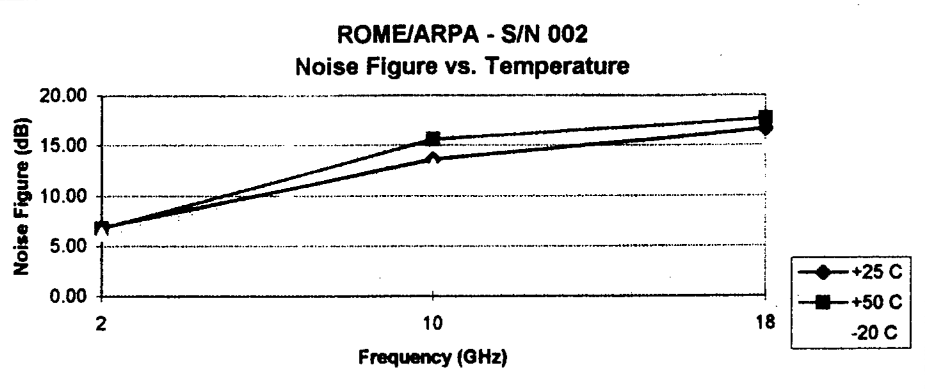
ROME/ARPA - Noise Figure over Temperature Test Results					
Engineer: S. A. Roos					
Date:5/23/97					
Serial Number 001 - (2.0 to 18.0 GHz Link)					
Total Link Gain w/post amp @ 25 degrees C:					
Measured Total Link Gain @ 2 GHz =	29.9	dB			
Measured Total Link Gain @ 10 GHz	19.08	dB			
Measured Total Link Gain @ 18 GHz	15.2	dB			
Total Link Gain w/post amp @ +50 degrees C:					
Measured Total Link Gain @ 2 GHz =	28.6	dB			
Measured Total Link Gain @ 10 GHz	17.76	dB			
Measured Total Link Gain @ 18 GHz	14.1	dB			
Total Link Gain w/post amp @ -20 degrees C:					
Measured Total Link Gain @ 2 GHz =	31.9	dB			
Measured Total Link Gain @ 10 GHz	20.58	dB			
Measured Total Link Gain @ 18 GHz	16.2	dB			
Optical Input to RX Photodiode =	**3.5**	**dBm**			
RF Input Power Level =	**-30**	**dBm**			
Noise Figure Calculation @ 2 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-129.6	dBm/Hz	1.1E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-131.1	dBm/Hz	7.76E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	29.9	dB	3.2E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-164.85	dBm/Hz			
Noise Figure (dB)=	**9.15**	dB			

NF Temp 001

Noise Figure Calculation @ 10 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.9	dBm/Hz	6.46E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	19.08	dB	7.02E-15	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-160.62	dBm/Hz			
Noise Figure (dB)=	**13.38**	dB			
Noise Figure Calculation @ 18GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-130.4	dBm/Hz	9.12E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-130.9	dBm/Hz	8.13E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	15.2	dB	9.92E-15	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-155.24	dBm/Hz			
Noise Figure (dB)=	**18.76**	dB			
Noise Figure Calculation @ 2 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-130.1	dBm/Hz	9.77E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.1	dBm/Hz	6.17E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	28.6	dB	3.61E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-163.03	dBm/Hz			
Noise Figure (dB)=	**10.97**	dB			
Noise Figure Calculation @ 10 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.5	dBm/Hz	7.08E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.2	dBm/Hz	6.03E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	17.76	dB	1.05E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-157.53	dBm/Hz			
Noise Figure (dB)=	**16.47**	dB			
Noise Figure Calculation @ 18GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.4	dBm/Hz	7.24E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	14.6	dB	1.49E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-152.87	dBm/Hz			
Noise Figure (dB)=	**21.13**	dB			
Noise Figure Calculation @ 2 GHz @ -20 C					
			Test Setup correction		
Noise Output (Laser ON)=	-130.1	dBm/Hz	9.77E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.1	dBm/Hz	6.17E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	31.9	dB	3.61E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-166.33	dBm/Hz			
Noise Figure (dB)=	**7.67**	dB			

NF Temp 001

Noise Figure Calculation @ 10 GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-132.8	dBm/Hz	5.25E-14	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-133.4	dBm/Hz	4.57E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	20.58	dB	6.77E-15	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-162.27	dBm/Hz				
Noise Figure (dB)=	**11.73**	dB				
Noise Figure Calculation @ 18GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-133.1	dBm/Hz	4.9E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	16.2	dB	8.57E-15	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-156.87	dBm/Hz				
Noise Figure (dB)=	**17.13**	dB				



ROME/ARPA - Noise Figure over Temperature Test Results					
Engineer: S. A. Roos					
Date:5/23/97					
Serial Number 002 - (2.0 to 18.0 GHz Link)					
Total Link Gain w/post amp @ 25 degrees C:					
Measured Total Link Gain @ 2 GHz =	34.1	dB			
Measured Total Link Gain @ 10 GHz =	23.9	dB			
Measured Total Link Gain @ 18 GHz =	18.2	dB			
Total Link Gain w/post amp @ +50 degrees C:					
Measured Total Link Gain @ 2 GHz =	32.8	dB			
MeasuredTotal Link Gain @ 10 GHz =	21.5	dB			
Measured Total Link Gain @ 18 GHz =	17	dB			
Total Link Gain w/post amp @ -20 degrees C:					
Measured Total Link Gain @ 2 GHz =	35.3	dB			
Measured Total Link Gain @ 10 GHz =	24.4	dB			
Measured Total Link Gain @ 18 GHz =	19.3	dB			
25 C Test Conditions:					
Optical Input to RX Photodiode =	**5.5**	**dBm**			
RF Input Power Level =	**-30**	**dBm**			
Noise Figure Calculation @ 2 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-129.6	dBm/Hz	1.1E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.2	dBm/Hz	6.03E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	34.1	dB	4.94E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.16	dBm/Hz			
Noise Figure (dB)=	**6.84**	dB			

NF Temp 002

Noise Figure Calculation @ 10 GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.8	dBm/Hz	6.61E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-133.6	dBm/Hz	4.37E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	23.9	dB	2.24E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-160.39	dBm/Hz			
Noise Figure (dB)=	**13.61**	dB			
Noise Figure Calculation @ 18GHz @ 25 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.9	dBm/Hz	6.46E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.8	dBm/Hz	5.25E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	18.2	dB	1.21E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-157.38	dBm/Hz			
Noise Figure (dB)=	**16.62**	dB			
Noise Figure Calculation @ 2 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-130.1	dBm/Hz	9.77E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.1	dBm/Hz	6.17E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	32.8	dB	3.61E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.23	dBm/Hz			
Noise Figure (dB)=	**6.77**	dB			
Noise Figure Calculation @ 10 GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.8	dBm/Hz	6.61E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-133.4	dBm/Hz	4.57E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	21.5	dB	2.04E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-158.41	dBm/Hz			
Noise Figure (dB)=	**15.59**	dB			
Noise Figure Calculation @ 18GHz @ +50 C					
			Test Setup correction		
Noise Output (Laser ON)=	-131.6	dBm/Hz	6.92E-14	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.4	dBm/Hz	5.75E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	17	dB	1.16E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-156.34	dBm/Hz			
Noise Figure (dB)=	**17.66**	dB			
Noise Figure Calculation @ 2 GHz @ -20 C					
			Test Setup correction		
Noise Output (Laser ON)=	-129.3	dBm/Hz	1.17E-13	watts/Hz	(Total Noise)
Noise Output (Laser OFF)=	-132.1	dBm/Hz	6.17E-14	watts/Hz	(Test Setup Noise)
Total Link Gain (w/post Amp)=	35.3	dB	5.58E-14	watts/Hz	(Link Noise)
EIN in dBm/Hz =	-167.83	dBm/Hz			
Noise Figure (dB)=	**6.17**	dB			

NF Temp 002

Noise Figure Calculation @ 10 GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-131.2	dBm/Hz	7.59E-14	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-132.7	dBm/Hz	5.37E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	24.4	dB	2.22E-14	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-160.95	dBm/Hz				
Noise Figure (dB)=	**13.05**	dB				
Noise Figure Calculation @ 18GHz @ -20 C						
			Test Setup correction			
Noise Output (Laser ON)=	-131.6	dBm/Hz	6.92E-14	watts/Hz	(Total Noise)	
Noise Output (Laser OFF)=	-132.3	dBm/Hz	5.89E-14	watts/Hz	(Test Setup Noise)	
Total Link Gain (w/post Amp)=	19.3	dB	1.03E-14	watts/Hz	(Link Noise)	
EIN in dBm/Hz =	-159.17	dBm/Hz				
Noise Figure (dB)=	**14.83**	dB				

APPENDIX 2 - Program Manuals

Development Program Manuals for Fiber Optic Links

Contract F30602-91-C-0050
Data Item B005

HIGH LINEARITY FIBER OTIC LINK (HIBACHI)
USERS MANUAL OUTLINE

DANGER

"INVISIBLE LASER RADIATION - AVOID EYE OR SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION"

YAG LASER
200mW MAXIMUM CW
OUTPUT
IN THE 1300 nm BAND.
CLASS IIIB LASER
PRODUCT

PREFACE
GENERAL INFORMATION
1.0 MOUNTING CONFIGURATION
    1.1 CABLE MOUNTING
    1.2 POLE MOUNTING

2.0 SUN SHIELD

3.0 INPUT/OUTPUT CONFIGURATION
    3.1 KEY SWITCH
    3.2 INPUT POWER CONNECTOR
    3.3 RF INPUT CONNECTOR
    3.4 OPTICAL OUTPUT CONNECTOR

OPERATION OF THE TRANSMITTER
GENERAL INFORMATION
4.0 POWERING UP THE OPTICAL TRANSMITTER
    4.1 OPERATING SEQUENCE

5.0 LASER TRANSMITTER INDICATOR LIGHTS
    5.1 LASER EMISSION LIGHT
    5.2 TEMPERATURE STATUS LIGHT
    5.3 OVER TEMPERATURE STATUS LIGHT
    5.4 OVER POWER STATUS LIGHT
    5.5 OVER CURRENT STATUS LIGHT

OPICAL RECEIVER
GENERAL INFORMATION
6.0 INPUT/OUTPUT CONFIGURATION
    6.1 INPUT POWER CONNECTOR
    6.2 RF OUTPUT CONNECTOR
    6.3 OPTICAL INPUT CONNECTOR
    6.4 FRONT PANEL INFORMATION

APPENDIX
INSTALLATION DRAWINGS
    A) UTP 04-1029 INTERNAL ASSEMBLY DRAWING
    B) UTP 04-1031 EXTERNAL ASSEMBLY DRAWING
    C) UTP 04-1035 SUN SHILED ASSEMBLY DRAWING

HIGH LINEARITY FIBER OPTIC LINK (HIBACHI)--*USERS MANUAL*

PREFACE

Upon receipt of the transmitter and receiver, inspect the shipping containers for gross external damage. Press the pressure relief valuve, unpack the units and inspect for damage, If any damage is found, immediately notify the shipper and UTPhotonics.

Retain the shipping containers and packaging materials. If any of the equipment requires repair, the specially designed shipping containers will ensure safe shipment to UTPhotonics. If the unit requires shipment to another destination, the provided shipping containers should be uses.

The remote Antenna fiber optic link, is an end-to-end system for conveying RF signals over a link distance of up to 5 KM. The RF signal from an antenna is connected to the transmitter, transmitted down a length of fiber, and is terminated at the receiver. The link is intended to provide a nominal 0 dB gain from RF input to RF output. No special adjustments or controls are used, except for the power input, and a key switch for turning the laser power on and off.

WARNING! LASER LIGHT FROM THIS EQUIPMENT CAN BE EXTREMELY HAZARDOUS! MAKE SURE THE FIBER CABLE IS ATTACHED BEFORE TURNING ON THE LASER. PERMANENT EYE OR OTHER INJURIES CAN RESULT IF BODILY CONTACT WITH THE OPTICAL RADIATION OCCURS!

GENERAL INFORMATION

The transmitter housing is fabricated from cast aluminum alloy 360. The housing is a modified CATV standard line product with full environmental and Rf gaskets. The transmitter has been designed to withstand exposure to outdoor, telephone mounting environments. All connectors are environmentally rugged and all dust caps should be immediately put in place when ever mating connectors are removed. Heat dissipation fins should be kept vertical and clean, allowing for good convection over the fins. An internal desiccant pack per MIL-D-3464D will keep the internal portions of the transmitter dry. An internal indicator card should be check any time the transmitter is opened to insure the desiccant is still active. If at any time the desiccant indicator card shows the desiccant is inactive, notify UTPhotonics for a replacement. The transmitter MUST be mounted with the external heat sink fins vertical. This is to insure proper cooling over the -20 to +50 degree C environment. If the transmitter is operated on a lab bench in a 22 +/-10 degree C environment, it may be rested flat.

1.0 MOUNTING CONFIGURATIONS

Due to the 30 lb. weight of the transmitter, it is recommended that the optical transmitter installation be performed by a two person team.

1.1 CABLE MOUNTING

The housing is designed to accept 0.25 max. diameter telephone type mounting cable. Two cable clamps are provided on the housing to interface with support cable. The transmitter must be mounted in a vertical orientation to provided for maximum efficiencies of the cooling fins. Care should be used when installing the device to guarantee a vertical orientation prior to bolting the transmitter to the support cable.

1.2 POLE MOUNTING

An optional direct telephone pole mounting bracket has been supplied with each unit. This bracket consists of a rectangular shaped part that must be bolted with proper lag bolts to the telephone pole. Thru bolts are preferred for this operation. The bracket should be mounted with the support ledge in the down position. The two (2) formed brackets are attached to the transmitter housing using two (2) 3/8-16 mounting fasteners. Care should be taken to not over torque these two fasteners. The transmitter then is attached to the pole bracket using four (4) #1/4-20 fasteners. The formed brackets rest in the support leg to make the installation easier. Hex head fasteners are suggested for this operation since open ended box wrenches can be used to tighten the four mounting bolts.

2.0 SUN SHIELD

2.1 SUN SHIELD

The sun shield consists of two perforated formed parts painted flat white for low solar emissivity. When using the sun shield care should be taken as to not damage the louvers.

When using the sun shield on a support cable mount, mount the transmitter to the cable, then attach the sun shield to the transmitter using the supplied stand offs. All connectors should be connected prior to the installation of the sun shield.

When using the sun shield with the pole bracket, the section of the sun shield that will be closest to the pole bracket should be attached to the transmitter prior to attaching the transmitter to the pole bracket. Once the transmitter had been mounted to the pole bracket, the other 1/2 of the shield can be attached using the appropriate supplied stand offs.

3.0 INPUT/OUTPUT CONFIGURATION

Power for the transmitter must be provided via the input power connector with the following specifications:

1.) 115/230 VAC; 50 HZ to 400 HZ power, 105 to 230 VAC, 1 amp max., single phase. EMI/RFI filtering of the transmitter is to FCC/VDE Class A power.

2.) 28 volts DC; 18 to 36 Volts DC, 4 amps max. EMI/RFI Bellcore TR-TSY-000513, FCC/VDE Class A. Surge to ICE 801-5.

3.1 KEY SWITCH

The key switch is an environmental proof switch designed for harsh environments. The key CANNOT be removed when the power to the laser is on. This is to provide a measure of safety, allowing a way to shut the laser down in the event of a problem. The key switch can only be remove in the OFF position. Spare keys have been provided with each transmitter. The key switch is part number E1, obtainable from Augat Alcoswitch, Andover Mass.

3.2 INPUT POWER CONNECTOR

The input power connector is a MIL 38999 Series I connector. The mating connector part number is MB918-E-11-F-35-S-Normal Keying, available from Matrix Science Corp. The MIL-SPEC equivalent part number is MS27467E11F35S, vendors can be found by obatining the QPL lisiting for this part number from any military agency or information systems such as VSMF. Care should be taken to insure that the connector is fully mated. Partially mated connectors will run the risk of compromising the electrical connection and environmental capability.

3.3 Rf INPUT CONNECTOR

The RF input connector is and N series MIL-SPEC connector. One source of supply is Omni Spectra Corporation part number 3084-2240-00. Care should be taken to keep the RF below 0 dBm. When the connector is not in use, the dust cap should be placed on the connector.

3.4 OPTICAL OUTPUT CONNECTOR

The optical output connector is an AT&T SIMFOCA MIL-SPEC optical connector, part number 105-544-471. Care should be taken to insure that the mating optical surfaces are clean prior to connecting any mating connectors. Since the core of the fiber is only 7um in diameter, connecting without contamination is a must. The dust cap should be installed whenever the mating connector is disconnected.

OPERATION OF THE TRANSMITTER

GENERAL INFORMATION:

The Optical Transmitter is designed to operate from -20 to +50 de C, with input power ranging from 110/220 VAC single phase 60 HZ, 115 VAC 400 HZ, or 28 VDC. The transmitter will not be effected from locally generated RF, and will support fiber length 15 M to 5 KM in length.

WARNING! LASER LIGHT FROM THIS EQUIPMENT CAN BE EXTREMELY HAZARDOUS! MAKE SURE THE FIBER CABLE IS ATTACHED BEFORE TURNING ON THE LASER. PERMANENT EYE OR OTHER INJURIES CAN RESULT IF BODILY CONTACT WITH THE OPTICAL RADIATION OCCURS!

4.0 POWERING UP THE TRANSMITTER

OPERATING SEQUENCE

4.1 Apply power to the transmitter via the input power connector. Make sure the connector is fully mated to the transmitter.

4.2 Turn the transmitter key switch to the "ON" position. The key switch will lock into this position, the key cannot be removed.

4.3 The laser will not start until the temperature control is in range. The out-of-window temperature LED will light, see figure 1. When the temperature of the laser falls within the control window, the window light will go off, and the laser emission light will turn on. The laser emission light will blink for 8 seconds prior to emissions of the laser. Under worst-case temperature conditions, it may take 15 minutes to 30 minutes for the temperature to stabilize.

AVOID EXPOSURE TO THE LASER LIGHT. APPERATURE FOR THE LASER LIGHT IS IDENIFIED ON THE TRANSMITTER HOUSING. AVOID EXPOSURE TO THIS APPERATURE WHEN THE LASER IS OPERATING!

4.4 The link should now be operating. The left set of 10 LED's indicates the level of the laser output power, which is nominally the 10th LED, indicating 100% power output.

4.5 If there are any problems during the start up procedure, one of the five fault LED's will illuminate.

5.0 LASER TRANSMITTER INDICATOR LIGHTS

Figure 1 details the function of each indicator light, viewed from the bottom of the laser transmitter.

5.1 Laser Emission: When this indicator light is lit, the laser is emitting, exposure to the emitted energy should be avoided.

5.2 Temperature Status Light: This indicator will illuminate when the laser heat sink has moved outside the design temperature limits. The laser will not shut off until the temperature has moved outside the permissible operating temperature range.

5.3 Over Temperature Status Light: This indicator will light when the laser temperature has moved outside the permissible operating temperature range. This fault condition will cause the laser to shut down, in a non latching state. The transmitter will cool down and attempt to restart in a "hickup" mode. Some time may be required for the transmitter to warm up or cool down, before the laser will restart.

5.4 Over Power Status Light: This indicator light will light when the photo detector detects excessive optical power being emitted by the laser (120%). This could cause serious damage to the transmitter. This fault condition will cause the transmitter to shut down and latch in the off state. The transmitter can only be reactivated by recycling the power via the key switch.

5.5 <u>Over Current Status Light</u>: This indicator light will light when the laser is drawing excessive electrical current (120%). This fault condition will cause the transmitter to shut down and latch in the off state. The transmitter can only be reactivated by recycling the power via the key switch.

OPTICAL RECEIVER

GENERAL INFORMATION:

The Optical Receiver is design to be rack (17in) mounted in an office/lab environment. The optical receivers will be either four (4) channel or single (1) channel, depending upon the unit purchased.

The optical receiver requires no control. The same optical, input power and RF connectors used on the transmitter, supply the inputs to the receiver. A front panel mounted power-on switch applies power to the receiver.

6.0 INPUT/OUTPUT CONFIGURATION

6.1 INPUT POWER CONNECTOR

The input power connector is a MIL 38999 Series I connector (MS27468E11F35P), identical to the connector used on the transmitter. The mating connector part number is MB918-E-11-F-35-S-Normal Keying (MS27467E11F35S). The connector is available from Matrix Science Corp., or other suppliers of MIL-SPEC connectors. Care should be taken that the connector is fully mated. A power cord and spare mating connector have been supplied with each optical receiver.

6.2 Rf OUTPUT CONNECTOR

The Rf output connector is a N series MIL-SPEC Connector, Omni Spectra Part Number 3084-2240-00. When the connector is not in use, the dust cap should be placed on the connector.

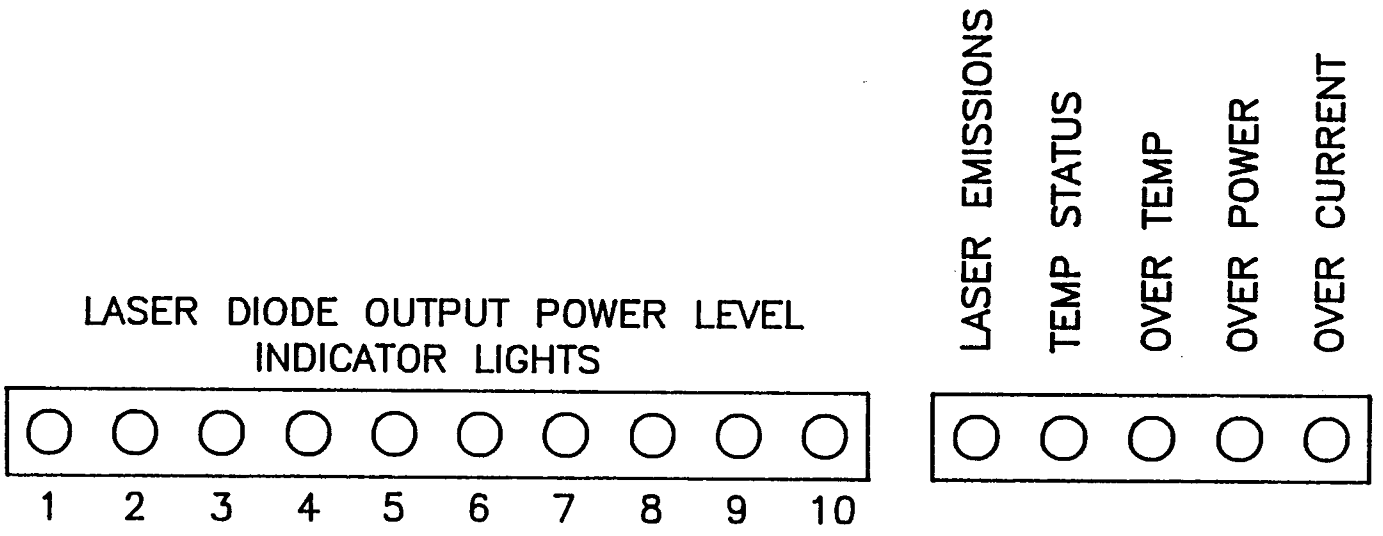
6.3 OPTICAL INPUT CONNECTOR

The optical input connector is an AT&T SIMFOCA MIL-SPEC optical connector. Care should be taken to insure that the mating optical surfaces are clean prior to connecting any mating connectors. Since the core of the optical fiber is only 7um, connecting without contamination is a must. The dust cap should be installed whenever the mating connector is disconnected.

6.4 FRONT PANEL INFORMATION

The front panel of the optical receiver is shown in figure 2. The bar-dot display indicators show the quiescent received optical power. Each dot is 1.5m watts optical power, and as long as the displayed power is in range, the system will function normally. If the power falls off the bottom, under-power LED, will light indicating insufficient, or zero optical power.

If power is applied, the power on switch thrown, and optical power is displayed on the bar dot indicators, the unit is ready to operate. Other than a few hundred milliseconds for power supply voltages to come up to operating levels, no warm up time is required for the receiver.



<u>FIGURE 1</u>—LASER TRANSMITTER INDICATOR LIGHTS

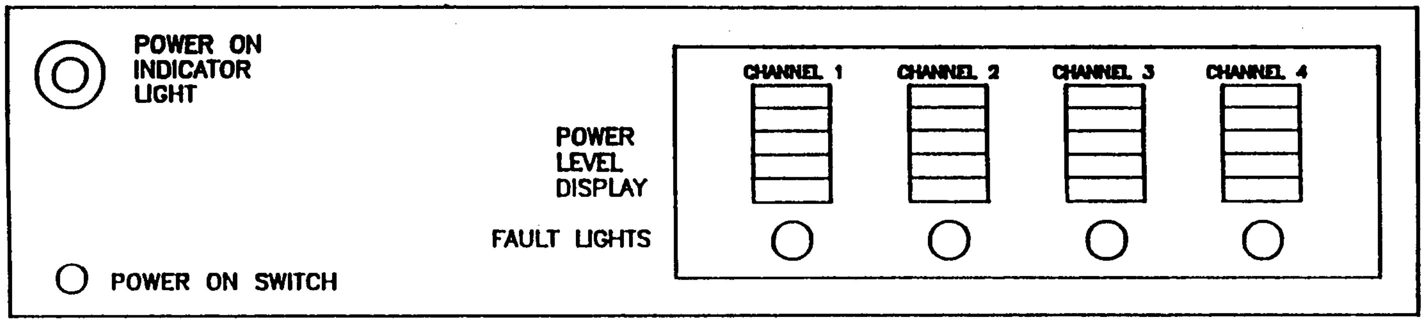
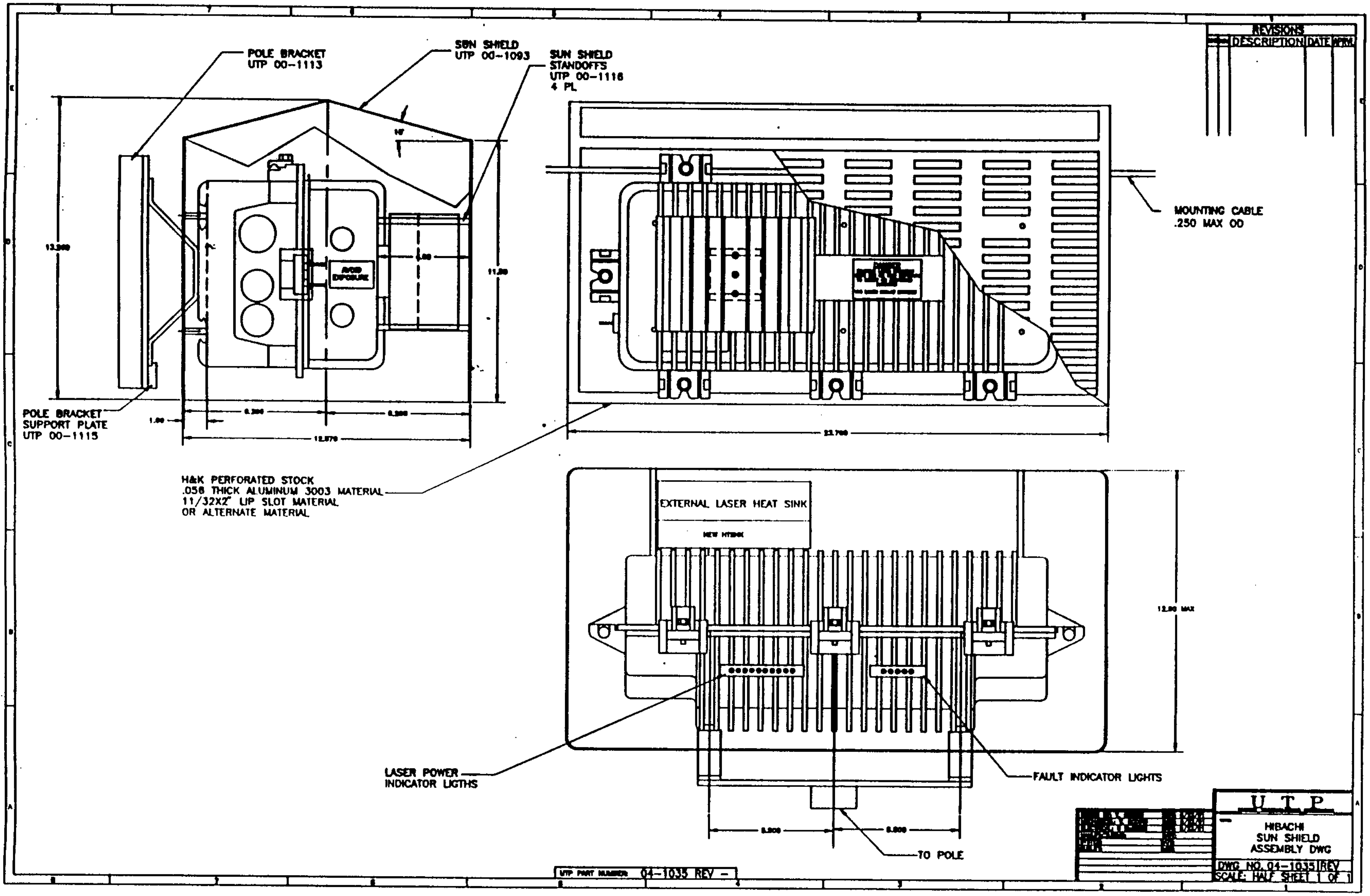
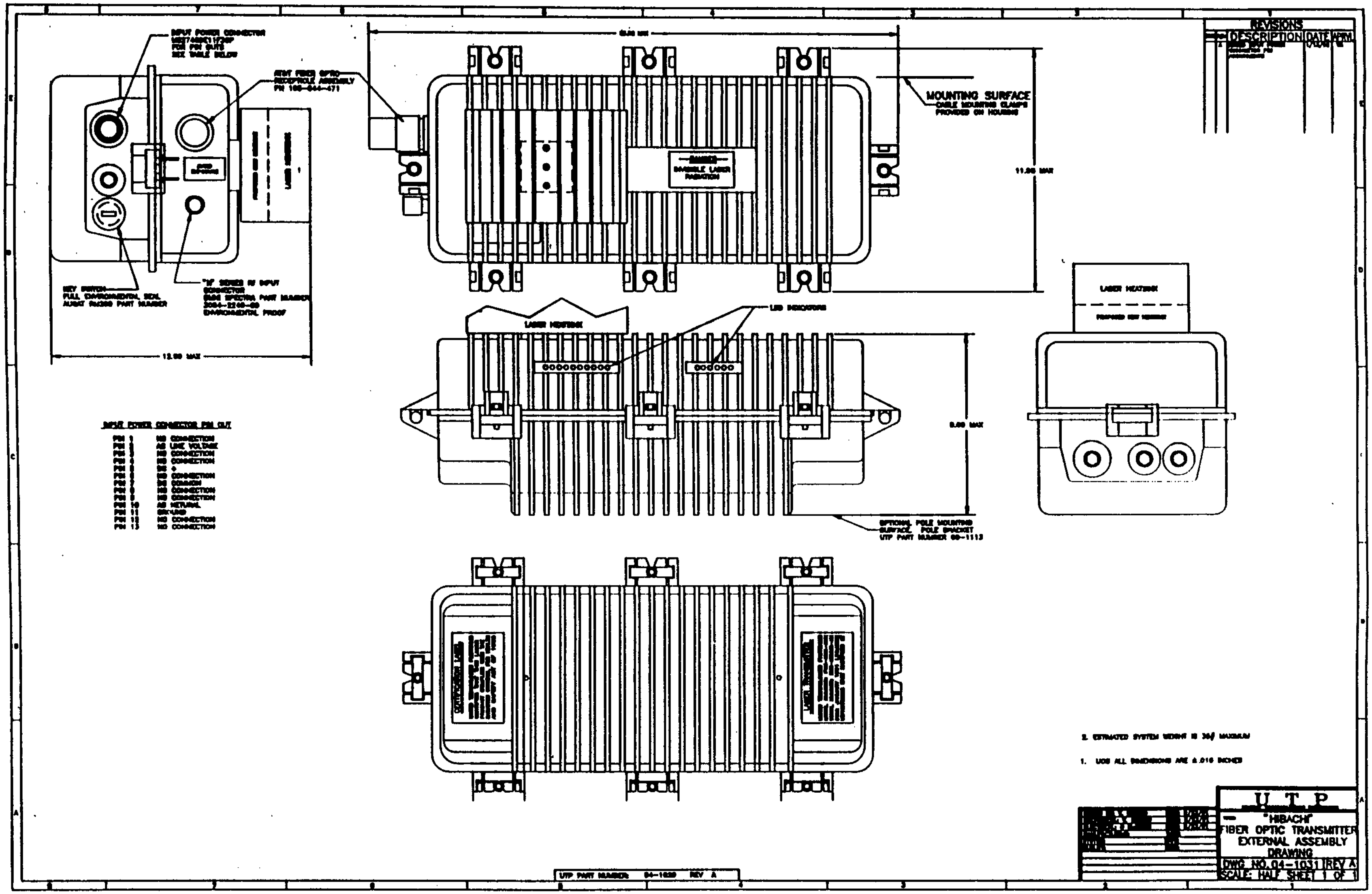


FIGURE 2--LASER RECEIVER INDICATOR LIGHTS


POLE BRACKET
UTP 00-1113
SBN SHIELD
UTP 00-1093
SUN SHIELD
STANDOFFS
UTP 00-1116
4 PL
MOUNTING CABLE
.250 MAX OD
POLE BRACKET
SUPPORT PLATE
UTP 00-1115
1.00
12.870
23.700
H&K PERFORATED STOCK
.056 THICK ALUMINUM 3003 MATERIAL
11/32X2" LIP SLOT MATERIAL
OR ALTERNATE MATERIAL
EXTERNAL LASER HEAT SINK
LASER POWER
INDICATOR LIGTHS
FAULT INDICATOR LIGHTS
TO POLE
REVISIONS
DESCRIPTION
DATE
APPR
UTP PART NUMBER 04-1035 REV -
U T P
HIBACHI
SUN SHIELD
ASSEMBLY DWG
DWG NO. 04-1035
REV
SCALE: HALF
SHEET 1 OF 1

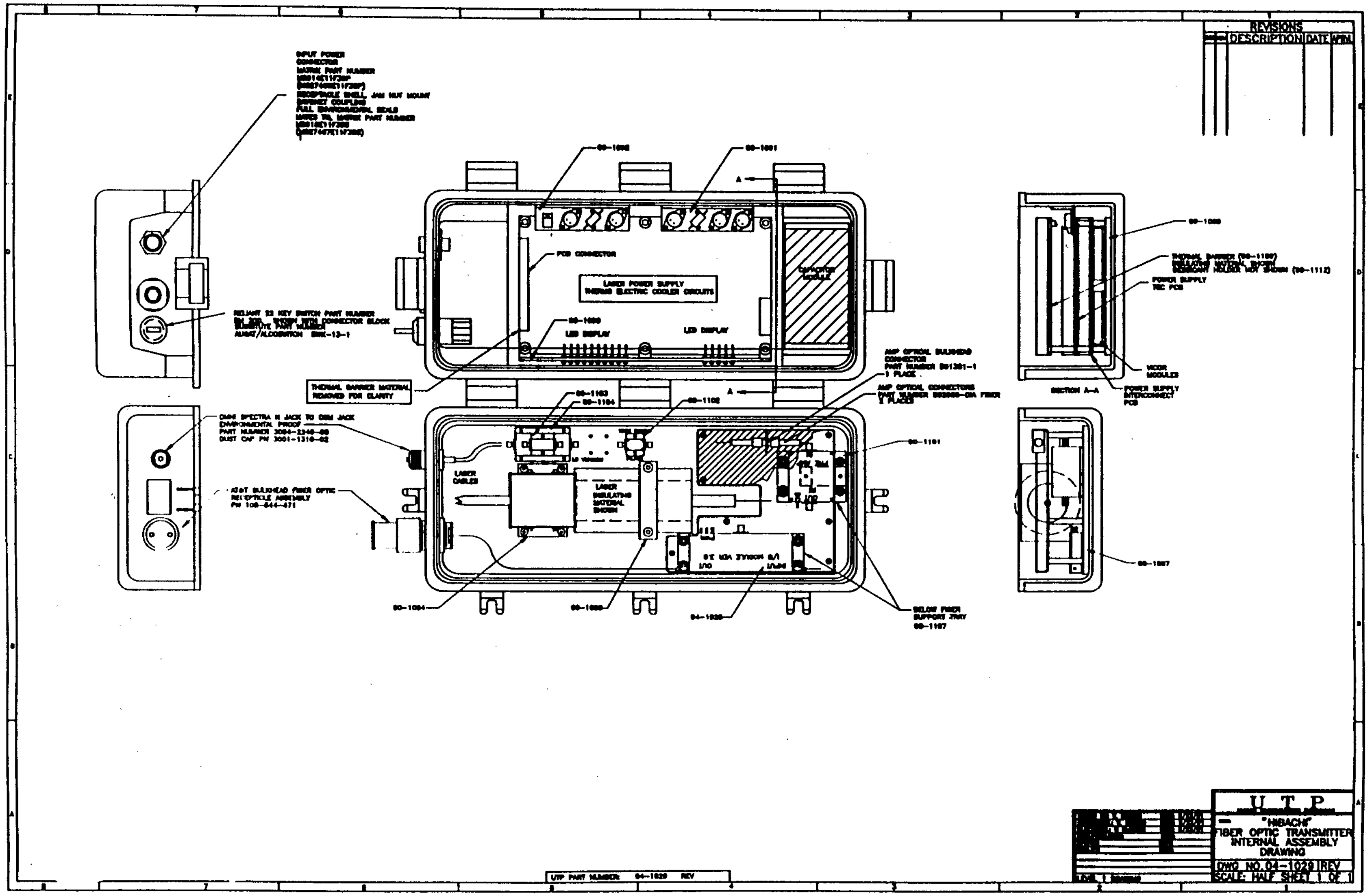


INPUT POWER CONNECTOR PIN OUT

PIN	1	NO CONNECTION
PIN	2	AC LINE VOLTAGE
PIN	3	NO CONNECTION
PIN	4	NO CONNECTION
PIN	5	DC +
PIN	6	NO CONNECTION
PIN	7	DC COMMON
PIN	8	NO CONNECTION
PIN	9	NO CONNECTION
PIN	10	AC NEUTRAL
PIN	11	GROUND
PIN	12	NO CONNECTION
PIN	13	NO CONNECTION

2. ESTIMATED SYSTEM WEIGHT IS 30# MAXIMUM

1. UOS ALL DIMENSIONS ARE ±.010 INCHES


REVISIONS
DESCRIPTION DATE APPR
INPUT POWER CONNECTOR
MATRIX PART NUMBER
(RECEPTACLE SHELL, JAM NUT MOUNT
BAYONET COUPLING
FULL ENVIRONMENTAL SEALS
MATES TO, MATRIX PART NUMBER
RELIANT 33 KEY SWITCH PART NUMBER
CONNECTOR BLOCK
SUBSTITUTE PART NUMBER
AUGAT/ALCOSWITCH SMK-13-1
THERMAL BARRIER MATERIAL REMOVED FOR CLARITY
OMNI SPECTRA N JACK TO OSM JACK
ENVIRONMENTAL PROOF
PART NUMBER 3084-2340-00
DUST CAP PN 3001-1310-02
AT&T BULKHEAD FIBER OPTIC
RECEPTACLE ASSEMBLY
PN 106-644-471
PCB CONNECTOR
LASER POWER SUPPLY
THERMO ELECTRIC COOLER CIRCUITS
CAPACITOR MODULE
LED DISPLAY
LED DISPLAY
A
A
LASER CABLES
LASER INSULATING MATERIAL SHOWN
INPUT
OUT
I/O MODULE VER 3.0
04-1029
AMP OPTICAL BULKHEAD CONNECTOR
PART NUMBER 501381-1
1 PLACE
AMP OPTICAL CONNECTORS
PART NUMBER 503660-DA FIBER
2 PLACES
BELOW FIBER SUPPORT TRAY
00-1107
00-1101
00-1102
00-1103
00-1104
SECTION A-A
THERMAL BARRIER (00-1109)
INSULATING MATERIAL SHOWN
DESSICANT HOLDER NOT SHOWN (00-1112)
POWER SUPPLY
TEC PCB
VICOR MODULES
POWER SUPPLY INTERCONNECT PCB
U T P
"HIBACHI"
FIBER OPTIC TRANSMITTER
INTERNAL ASSEMBLY
DRAWING
DWG NO. 04-1029 REV
SCALE: HALF SHEET 1 OF 1
UTP PART NUMBER 04-1029 REV

APPENDIX 3 - Addendum to Development Program Manuals

Addendum to Development Program Manuals

Information and Maintenance Instructions on Fiber Optic Cable Assemblies

Contract F30602-91-C-0050
Data Item B005

UNITED TECHNOLOGIES PHOTONICS

High Linearity, High Dynamic Range, Analog Fiber Optic Links

Addendum to
Development Program Manuals
Contract F30602–91–C–0050
Date Item B005

Information and Maintenance Instructions on Fiber Optic Cable Assemblies

Supplied by:
ATT Bell Laboratories,
Norcross, GA

ATT Contact: Bruce V. Darden
(404)447–2600

December, 1992

INTERNATIONAL WIRE & CABLE SYMPOSIUM PROCEEDINGS 1987, pg. 108 - 114

SINGLE-MODE TACTICAL FIBER OPTIC CABLE ASSEMBLIES

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V. E. Kalomiris

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U.S. Army Communications - Electronics Command, Ft. Monmouth, New Jersey 00703-5202

Abstract

The design and development of a single-mode fiber optic tactical cable assembly for use in the Single-Mode Fiber Optic Communications System (SIMFOCS) have been completed. Development effort was guided by the detailed design criteria as required by the contracting organization, the U. S. Army CECOM. A completed cable assembly consists of a 1-km cable containing two tightly-buffered single-mode optical fibers terminated with duplex, hermaphroditic connectors. Fiber utilized in the cable assembly is a standard AT&T single-mode fiber. The cable design is based on the earlier multimode Tactical Fiber Optic Cable Assembly (TFOCA) design. The connector design is also an adaptation of the multimode TFOCA design. However, due to the smaller core diameter of the single-mode fiber, further design improvements were incorporated to attain the required low loss performance.

Introduction

AT&T Bell Laboratories has completed the development of the single-mode tactical cable assembly for the Single-Mode Fiber Optic Communications System (SIMFOCS) program. This development program was funded by the U.S. Army Communications - Electronics Command (CECOM).[1] The cable assembly was designed to meet stringent specifications imposed by the contracting agency. The design is basically a single-mode adaptation of the Tactical Fiber Optic Cable Assembly (TFOCA) which uses 50/125 micron multimode fiber and was developed by AT&T for CECOM.[2] Like its multimode counterpart, the single-mode unit is ruggedized for use in tactical environments and it offers additional advantages of longer unrepeated transmission distances, higher bandwidth, and the potential for further performance improvements. This paper describes the design and development of this cable assembly and enumerates performance test results for the assembly as well as its components.

Cable Assembly Design

A completed cable assembly consists of a 1-km cable terminated with hermaphroditic connectors at both ends as illustrated in Figure 1. A cross-sectional view of the cable and an illustration of the connector are given in Figures 2 and 3, respectively.

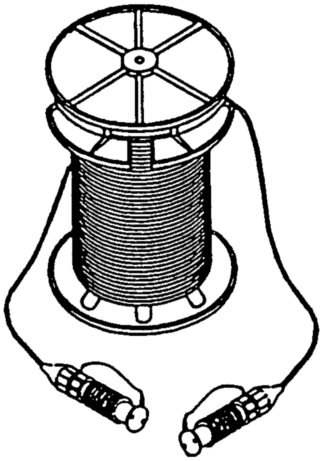

Figure 1. SIMFOCS Cable Assembly

The single-mode fiber used in the cable assembly is the standard AT&T depressed cladding design which has been shown to have exceptional microbending and macrobending performance. For this application, the fibers were prooftested to 700 MPa (100 ksi). These fibers can operate at both 1310 nm and 1550 nm wavelengths. However, tests were conducted and the results are presented only at 1310 nm wavelength. The fiber is coated with dual acrylate coatings which are mechanically strippable. These fibers are then tight-buffered to 1 mm (.039 inch) diameter with a polyester elastomer. The buffering material is also mechanically strippable in order to facilitate termination and repair in the field. The buffering material was chosen to minimize microbending losses induced by exposure of the cable to temperature extremes of -46°C to 71°C as required by the design criteria.

The core of the cable contains two buffered fibers which are color coded for identification purposes. Aramid yarns, which are the main tensile load-carrying members, are stranded around the buffered fibers in two opposing layers. The sheath over the aramid yarns is a composite of a flame-retardant polyurethane and four epoxy-glass reinforcement rods. The outer diameter of the cable is 6.0 mm (0.234 inch). The cable design is the same as the TFOCA cable design[3] except for the fiber.

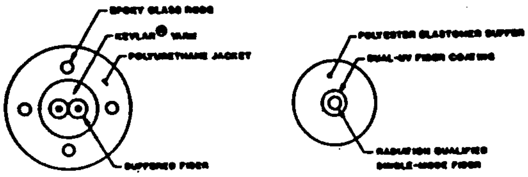

Figure 2. SIMFOCS Cable Cross Section

The connector is a single-mode adaptation of the TFOCA duplex connector.[4] It meets the mechanical and environmental requirements supplied by CECOM in the contractual statement of work. The connector, shown in Figure 3, is less than 4 cm (1.57 inch) in diameter, and a mated pair weighs under 0.6 kg (1.3 lb). A companion bulkhead receptacle was developed for the system and shares a common hermaphroditic interface.

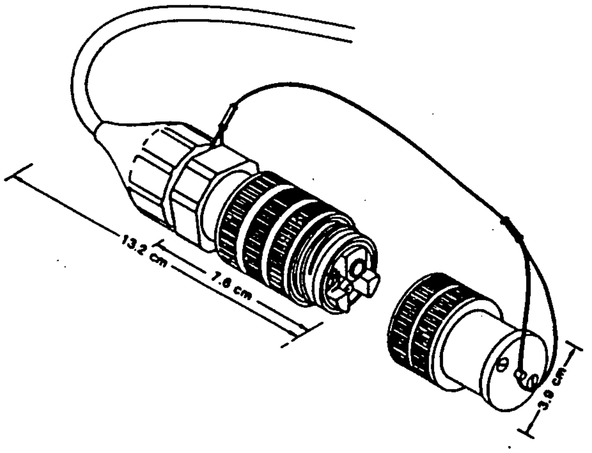

Figure 3. SIMFOCS Connector

One of the two fibers in the connector terminates with a plug and the other with a biconic sleeve. A sealed connector-insert subassembly contains the biconic components. Special features prevent water ingress and allow the plugs and sleeve to float radially and axially to properly align when two connectors are mated. The front portion of the subassembly, called the sleeve retainer, houses the sleeve and provides the connector's hermaphroditic profile.

A die-cast aluminum shell houses the connector insert and retains the cable-termination hardware. It also provides storage space for slack fiber. A threaded aluminum nut couples two connectors or a connector and bulkhead receptacle. The shell and coupling nut are designed to elastically withstand 1780N (400 lb) tension across mated connectors.

All possible water leak paths into the connector are blocked by elastomeric seals, and a hermaphroditic dust cover prevents water or dust entry into an unmated connector.

The dust-cover shell and end cap of the SIMFOCS unit are gold anodized to visually distinguish it from the all-black TFOCA connector. The SIMFOCS sleeve retainer differs intentionally from the corresponding TFOCA part to mechanically prevent the inadvertent mating of single-mode and multimode connectors.

Except for the sleeve retainer and the two gold-anodized parts mentioned above, all hardware is common between the TFOCA and SIMFOCS designs. This common parts usage reduces SIMFOCS costs by reducing the development effort, and by increasing the volume of the common parts.

Another crucial but somewhat imperceptible difference between the designs is the increased precision of the biconic components required for the single-mode application.

Performance

The whole cable assembly and individual components (fiber, buffered fiber, cable, and connector) were subjected to the required optical, environmental, and mechanical performance tests. The results for individual components and the assembly are enumerated in the following paragraphs.

Fiber Performance

All the fibers were tested for their optical and dimensional requirements before being used in the cable. These tests include attenuation, attenuation uniformity, cut-off wavelength, mode-field radius, clad and coating diameters, core eccentricity, etc. Though not required under the development program, the fibers were tested for response to environmental temperature cycling. The temperature cycle used was:

- baseline the loss measurements through multiple measurements at room temperature, 25°C,
- reduce the temperature to -46°C and dwell at least 24 hours before measurement,
- reduce the temperature to -55°C and dwell at least 12 hours before measurement,
- return to room temperature, 25°C, and dwell at least 12 hours before measurement,
- increase the temperature to 71°C and dwell at least 12 hours before measurement,
- increase the temperature to 85°C and dwell at least 24 hours before measurement,
- return to room temperature, 25°C, and dwell at least 12 hours before measurement.

The contract required that the assemblies and components be subjected to three temperature cycles described above. Instead, five cycles were run. The design requirement of temperature extremes is from -46°C to 71°C. The temperature range was extended to -55°C and 85°C to investigate the performance at these temperatures. The performance of the SIMFOCS single-mode fibers for the temperature cycles is presented in Figure 4. The fibers show excellent performance with a maximum added loss of 0.05 dB/km.

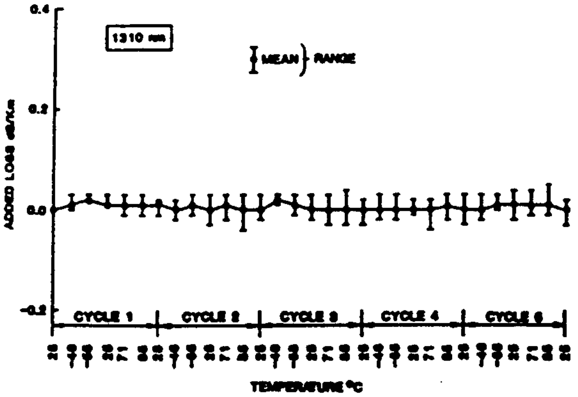

Figure 4. SIMFOCS Fiber Temperature Cycling Test Results

Buffered Fiber Performance

There were no specific requirements for buffered fibers, other than the dimensional requirements on the outer diameter and concentricity of the fiber. Every buffered fiber used in the cables was screened for these dimensional requirements. Though not required, the buffered fibers were also tested for response to temperature cycling. The results of this test, which uses the same cycle described in the fiber section, are given in Figure 5. The buffered fibers were also subjected to an accelerated-aging test which basically simulates the use of this buffered fiber (and the cable in general) at 85°C for the design life of 30 years. The accelerated aging test consists of exposure of the materials to 110°C for 10 days. This time-temperature relationship was arrived at by using viscoelastic principles. The excellent accelerated-aging performance of the buffered fibers is illustrated in Figure 6. After the completion of the accelerated-aging test, further testing was continued with temperature cycling between -75°C and 100°C. The results of this temperature cycling are also presented in Figure 6 and again show the excellent performance of the buffered fibers.

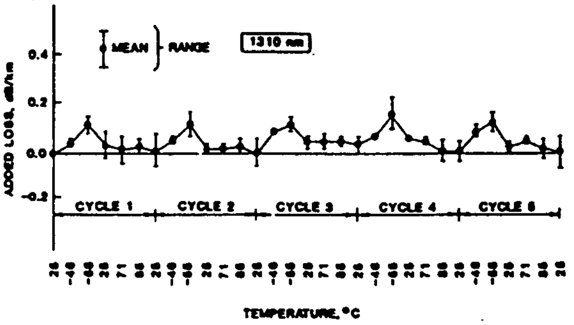

Figure 5. SIMFOCS Buffered Fiber Temperature Cycling Test Results

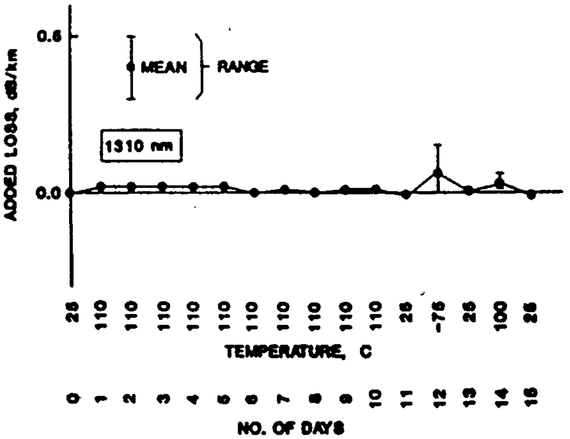

Figure 6. SIMFOCS Buffered Fiber Accelerated Aging Test Results

Cable Performance

The SIMFOCS cables, as a component of the assembly, were subjected to a battery of optical, environmental, and mechanical tests. The mean optical loss was 0.4 dB/km at 1310 nm, showing that there was basically no added loss due to the buffering and cabling processes for these cables. The cable was designed for a temperature range of -46°C to 71°C, and the evaluation was extended to -55°C and 85°C as mentioned before. The results of temperature cycling of three samples of 1-km lengths are presented in Figure 7. The stars (*) in Figure 7 are worst case data points which represent one out of six test fibers. The plotted means given also include these worst case data.

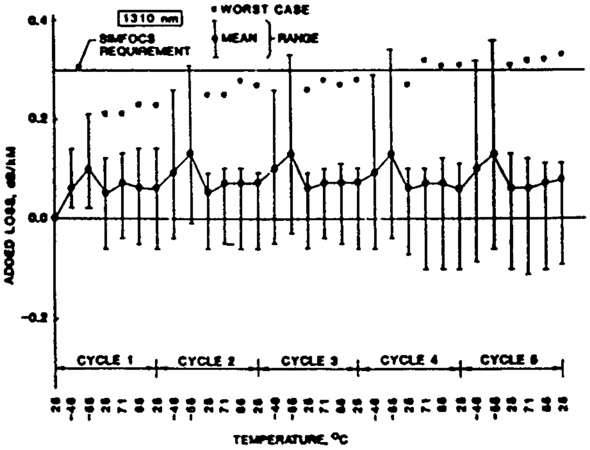

Figure 7. SIMFOCS Cable Temperature Cycling Test Results

The cables pass the requirement of 0.3 dB/km maximum added loss for three temperature cycles between -46°C and 71°C. The cable also passes the requirement for five temperature cycles between -55°C and 85°C, accounting for the accuracy of the measurement system of ± .05 dB/km. The maximum of mean added loss was at -55°C and was less than 0.15 dB/km. As a comparison, the multimode TFOCA cable had an added mean loss of less than 0.2 dB/km as opposed to the requirement of 0.5 dB/km between -55°C and 85°C. This establishes that the basic cable design is applicable for both multimode and single-mode fibers.

The results of accelerated aging testing of three 0.5 km lengths are presented in Figure 8. This figure, again, shows excellent performance of the cable not only for the accelerated aging test, but also for the unrequired temperature cycling between -75°C and 100°C. The temperature cycling between -75°C and 100°C was added to this aging test just to study the performance beyond the cable's design limits. During the temperature cycling, at -75°C, one fiber had an added loss of about 1.0 dB/km, whereas the remaining five fibers were far below the requirement.

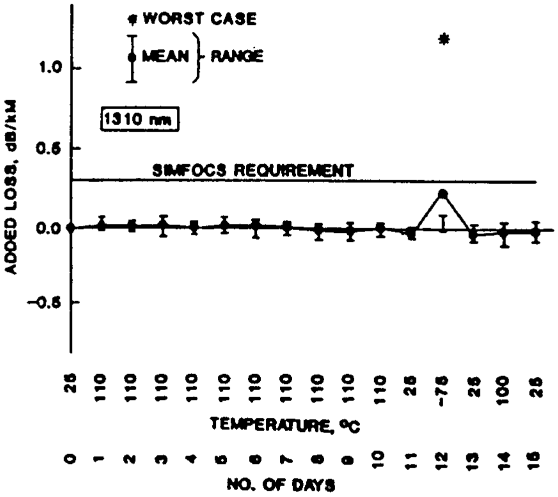

Figure 8. SIMFOCS Cable Accelerated Aging Test Results

The cables were also subjected to a long list of mechanical tests. The results of these tests are summarized in tabular form. Table I presents these tests, test procedures, test requirements, and the SIMFOCS cable's performance. Figures 7 and 8 and Table I clearly show the SIMFOCS cables meet and surpass all the optical, environmental and mechanical requirements.

TABLE 1.

SIMFOCS CABLES MECHANICAL REQUIREMENTS AND PERFORMANCE

NO.	TEST DESCRIPTION	PROCEDURE AND REQUIREMENTS	SIMFOCS CABLE PERFORMANCE
1	OPERATING TENSILE LOAD	EIA-455-FOTP-33 300N (66lbf), 5 MINS ADDED LOSS, Δ ≤ 0.2 dB	300N (66lbf), 5 MINS Δ ≤ 0.1 dB
2	TENSILE STRENGTH	EIA-455-FOTP-33 1780N (400lbf), ELONGATION ≤ 2.0% Δ -NOT SPECIFIED	1780N (400lbf). ELONGATION = 0.67% Δ ≤ 0.1
3	COLD BEND	DOD-STD-1678, 2020 MANDREL DIA. = 30mm -46°C, 10 kg, 1 TURN Δ ≤ 0.2	3 TURNS, Δ ≤ 0.1
4	IMPACT	DOD-STD-1678, 2030 1.5 kg, 15 cm, 100 CYCLES Δ ≤ 0.2	2.0kg, 15 cm, 200 CYCLES Δ ≤ 0.1
5	KNOT	AT&T BELL LABORATORIES DIAMETER = 30 mm Δ ≤ 0.2	Δ ≤ 0.2
6	COMPRESSION	DOD-STD-1678, 2040 10.1 cm DIA., 2110N (475lbf), Δ ≤ 0.2	8450N (1900lbf), Δ ≤ 0.2
7	CYCLIC FLEXING	EIA-455-FOTP-104 MANDREL DIA = 30mm 4 kg, 2000 CYCLES Δ ≤ 0.2	10 kg, 4000 CYCLES Δ ≤ 0.1
8	FREEZING WATER IMMERSION	DOD-STD-1678,4050 -10°C, 6 HOURS -2°C, 1 HOUR Δ ≤ 0.2dB	Δ ≤ 0.1
9	TWIST BEND	NOT REQUIRED	DOD-STD-1678, 2060 MANDREL DIA = 30mm 10 kg, 4000 CYCLES Δ ≤ 0.1
10	CORNER BEND	NOT REQUIRED	AT&T BELL LABORATORIES 1 mm RADIUS, 900N (200lbf) Δ ≤ 0.2
11	FLAMMABILITY	DOD-STD-1678, 5010 60 ANGLE TEST, EXTINGUISH ≤ 30 SEC	≤ 5 SEC

Connector Performance

The primary design objectives of the duplex connector are low coupling loss and field ruggedness. The unit is required to remain optically and mechanically functional under environmental and mechanical exposures typical of tactical field applications. Tests were conducted to evaluate performance with respect to the requirements listed in Table II. Some of the tests are reviewed and the results summarized in the following paragraphs.

TABLE 2.

CONNECTOR REQUIREMENTS

- INSERTION LOSS : 0.8dB MAXIMUM AVERAGE
- MATING DURABILITY : 1000 COMPLETE CYCLES
- COUPLING TORQUE : 0.75 INCH-POUND MAXIMUM
- SHOCK DROP : 10FT. DROP 6 TIMES
- SHOCK : 40G SAWTOOTH PULSE, 11ms DURATION
- VIBRATION : 5-500-5Hz, 15 MINUTE SWEEP, 4.2g
- CABLE RETENTION : 1780N (400LB.)
- FLEX LIFE : 2000 CYCLES AT 20°C, 1000 CYCLES AT -55°C
- TWIST LIFE : 1000 CYCLES AT +20°C
- HIGH TEMPERATURE : MIL-STD-810D, METHOD 501.1 (71°C)
- LOW TEMPERATURE : MIL-STD-801D, METHOD 502.1 (-57°C)
- WATER IMMERSION : 2-METER DEPTH, 24 HOURS
- HUMIDITY : MIL-STD-810D, METHOD 507.1
- SALT FOG : MIL-STD-810D, METHOD 509.1
- DUST : MIL-STD-810D, METHOD 510.1

Coupling Loss: Coupling loss measurements were made by concatenating pairs of plug-terminated 1-km cables randomly selected from a group of 16. The coupling loss was derived by subtracting the cabled-fiber attenuation from that of the measured assembly. For 60 couplings (120 channels) the mean loss and standard deviation were 0.67 and 0.24 dB, respectively, as shown in Figure 9.

Connector-loss measurements were also made using the cut-and-insert method per EIA Fiber Optic Test Procedure No. 34 on four 12-m long cables. Average loss was 0.55 dB with standard deviation of 0.11 dB.

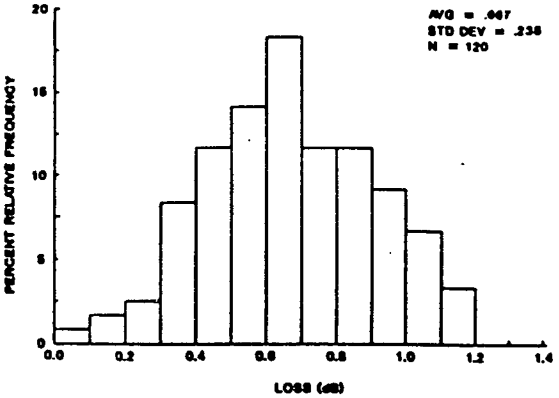

Figure 9. SIMFOCS Connector Coupling Loss

Mating Durability: This test was conducted to determine the mechanical durability of the connector assemblies as a result of 1000 coupling cycles. The failure criteria includes visible physical damage as well as optical malfunction. Loss readings were made at increments of 50 matings. At the conclusion of the test, the loss in each channel was within 0.09 dB of the initial baseline readings. The maximum loss increase observed during the test was 0.24 dB. The connectors were cleaned once after 750 matings.

Mud Immersion: The connector was designed to allow quick access to the biconic components so they can be easily cleaned after mud immersion. This aspect of the design was evaluated by subjecting a connector pair to 10 cycles of the following sequence:

a. decouple and immerse each end in a mud bath for 5 minutes;

b. water rinse, wipe clean, and air dry;

c. recouple and measure loss.

The maximum observed loss change was 0.13 dB.

Cable Assembly Performance

The 1-km long cable assemblies, including connectors, are required to be subjected to a battery of environmental and mechanical tests to insure reliable performance in the tactical field environment. Table III lists the tests. Some of the results are summarized below.

TABLE 3.

BATTERY OF CABLE ASSEMBLY TESTS

ATTENUATION
STORAGE/TRANSIT TEMPERATURE
HUMIDITY
SALT FOG
IMMERSION
TEMPERATURE CYCLING
VIBRATION
SHOCK

__Attenuation__: Attenuation measurements were made by concatenating pairs of plug-terminated 1-km cables randomly selected from a group of 16. For 64 couplings (128 channels) the mean loss and standard deviation were 1.08 and 0.23 dB, respectively, as shown in Figure 10.

__Storage and Transit Temperature__: The cable assembly was exposed to temperature extremes from -55°C to +85°C to determine whether adverse effects would result from storage and transit environments. Maximum loss increase observed was 0.09 dB.

__Immersion__: The cable assembly was immersed in a tank with one meter of water covering the unit for two hours. No evidence of leakage was observed.

Conclusions

The single-mode duplex tactical cable assembly described herein meets the requirements prescribed by the project sponsor, the U. S. Army CECOM. The average cable-assembly loss of 1.08 dB is well within the system transmission loss target of 1.4 dB for cables. Low-loss fiber, cable, and connector designs have been integrated successfully into the assembly.

By adapting the basic TFOCA design and AT&T's single-mode fiber technology, considerable development effort, time, and expense was conserved.

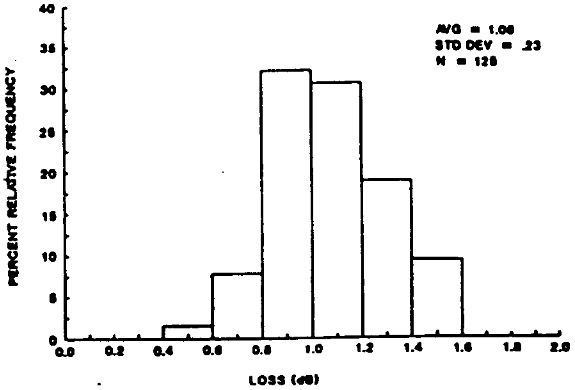

Figure 10. SIMFOCS Cable Assembly Loss

Acknowledgements

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APPENDIX 4 - Reference the ARMY SIMFOCA Maintenance Manual

Reference the ARMY SIMFOCA Maintenance Manual

Contract F30602-91-C-0050
Data Item B005

See U. S. ARMY Technical Manual
TM 11-6020-200-10

See U. S. ARMY Technical Manual

TM 11-6020-200-10

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