NOTES ON THE PHASE STABILITY OF TRANSMISSION LINES

1. INTRODUCTION

Phase coherence of the local oscillator signals across the array is probably the single most important factor in the efficiency budget of a connected-element microwave interferometer. The temperature coefficient of time delay of the interconnecting transmission lines is, under normal circumstances, the major contributor to long-term phase instability where "long-term" is defined as averaging intervals of ten seconds or greater. It was recognized early in the planning stages of the SAO Submillimeter Array (SMA) that optical fiber would play a major role in the broadband transmission required for the IF communications between the array elements and the correlator, but the optimum transmission medium for the much more critical local oscillator reference distribution was not obvious at the beginning of the SMA design study. Unfortunately, published data on temperature stability of time delay is very limited and is scattered throughout the literature; manufacturer's data sheets typically do not include quantitative data Therefore, high priority was given to a program of measurement of the phase stability with respect to temperature of candidate transmission lines, including both coaxial cable and optical fiber. Because of the virtually unlimited variety of available microwave and optical transmission media, the measurements had to be limited to what we hope is a representative sampling of the available technologies for implementation of phase-stable transmission.

2. TRANSMISSION LINE SUMMARY

Coaxial cables were chose from those promoted as "high-stability" or "precision" and, with exceptions as noted, were purchased as connectorized assemblies. These cables are often marketed as accessories to Vector Network Analyzers or for other metrology applications. A standard semi-rigid cable, commonly used for microwave connections within modules, was included as a baseline reference. Two single-mode optical fiber types were measured; a jacketed fiber commonly used for laboratory interconnection and for patch cords, and a special, temperature-compensated fiber manufactured by Sumitomo. Temperature stability data on bare (unbuffered) fiber supplied by Corning is included for completeness.

2.1 <u>Gore 090-36</u> is an expanded-PTFE coaxial cable assembly with a velocity of propagation rating of 85%. The dielectric is a proprietary Gore development which is 70% air and 30% PTFE teflon. The first three digits of the part number specify the cable diameter in inches, the second two the length of the assembly in inches. This series is relatively inexpensive and a variety of preassembled cable lengths are available from stock with SMA connectors. The assemblies are supplied without data, but the factory has confirmed that the internal construction is identical to the much more expensive test cable sets which are shipped with complete data packages.

2.2 <u>Gore 145-36</u> is similar to Gore 090-36 described above, except that the outer diameter is 0.145 inches rather than 0.090 inches.

2.3 Flexco FC182 is a solid PTFE coaxial cable with a velocity of propagation of 67.5% which is widely used in SAO laboratories for general purpose instrumentation. The outer conductor is a 0.206" diameter strip-wound helix, contributing to a very rugged overall mechanical structure. The test cable was purchased with factory-installed SMA connectors.

2.4 Huber & Suhner Sucoflex 104P is a low-density PTFE cable with a velocity of propagation of 78%. The outer conductor is a 0.216" diameter copper braid. The test cable was procured with factory-installed SMA connectors.

2.5 Andrew FSJ1-50 is a foam polyethylene dielectric with a velocity of propagation of 78%. The 0.250" diameter corrugated copper outer conductor yields a rugged but relatively inflexible structure. The SAO Phase Monitor uses the Andrews cable for interconnection of the two antennas to the phase meter. The Andrews cable was purchased in bulk and special type "N" connectors were installed in the SMA IF Laboratory.

2.6 EZ-Form EZ 86AL is a solid PTFE dielectric semi-rigid coaxial cable with an 0.086" diameter solid aluminum outer conductor. This cable was also purchased in bulk form and standard type "SMA" connectors were installed in the SMA IF Laboratory.

2.7 Corning SMF Single-Mode Optical Fiber is the basic, workhorse optical fiber without buffer or loose tube protection. The core is approximately 9 microns, the cladding 125 microns and the acrylic coating approximately 250 microns in diameter. SMF fiber is not usable in a field environment in its unprotected form and all data shown below is taken from an unpublished Corning paper.

2.8 Siecor Jacketed Optical Cable is essentially SMF fiber with a 2.5 mm diameter PVC jacket extruded over the fiber. Jacketed fiber is widely used for patchcords and for pigtailing of fiber optic components such as couplers and sources. Unlike the protective coatings or armor applied to coaxial cables, the jacket appears to have a significant impact on the transmission performance of the cable.

2.9 Sumitomo Temperature-Compensated Delay Time (TCD) Optical Cable is a basic single-mode fiber overlaid with a proprietary organic coating which expands and contracts with temperature in a controlled fashion to exactly offset the temperature-induced refractive index variations of the glass core. The core and cladding dimensions are approximately equal to those of the Corning SMF fiber; the outside diameter, including a thin thermoplastic protective jacket, is approximately 1.0 mm.

3. MEASUREMENT PROCEDURE

Since the time resolution required for most of the tests described here is at the sub-picosecond level, it is much easier to measure phase shifts at a known frequency than to attempt direct delay measurements in the time domain. Furthermore, the data of interest to the system designer is the phase shift as a function of temperature, not the refractive index or the refractive index temperature coefficients. Therefore, all measurements were made using a synthesized signal generator at 1 or 2 GHz as the source and a Hewlett Packard 8508A Vector Voltmeter as the detector. The cable or fiber under test was enclosed in a Thermotron programmable oven; the temperature slew rate was normally set to 1 C per minute. In most cases, the temperature was ramped in both directions in an attempt to detect hysteresis effects: In general, all measured cables exhibited significant sensitivity to the sense of the temperature ramp. Additional verification runs at very slow rates of change of temperature were made to determine if the slew rate affected the test data. Small changes were noticed in the hysteresis loops at the slower rates, but no appreciable effects on the measured temperature coefficients was observed.

Figure 1 is a simplified block diagram of the microwave coaxial cable measurement system. Figure 2 shows the modifications, basically the addition of an optical laser transmitter and an optical receiver, which are required to run the same measurements on optical fiber.

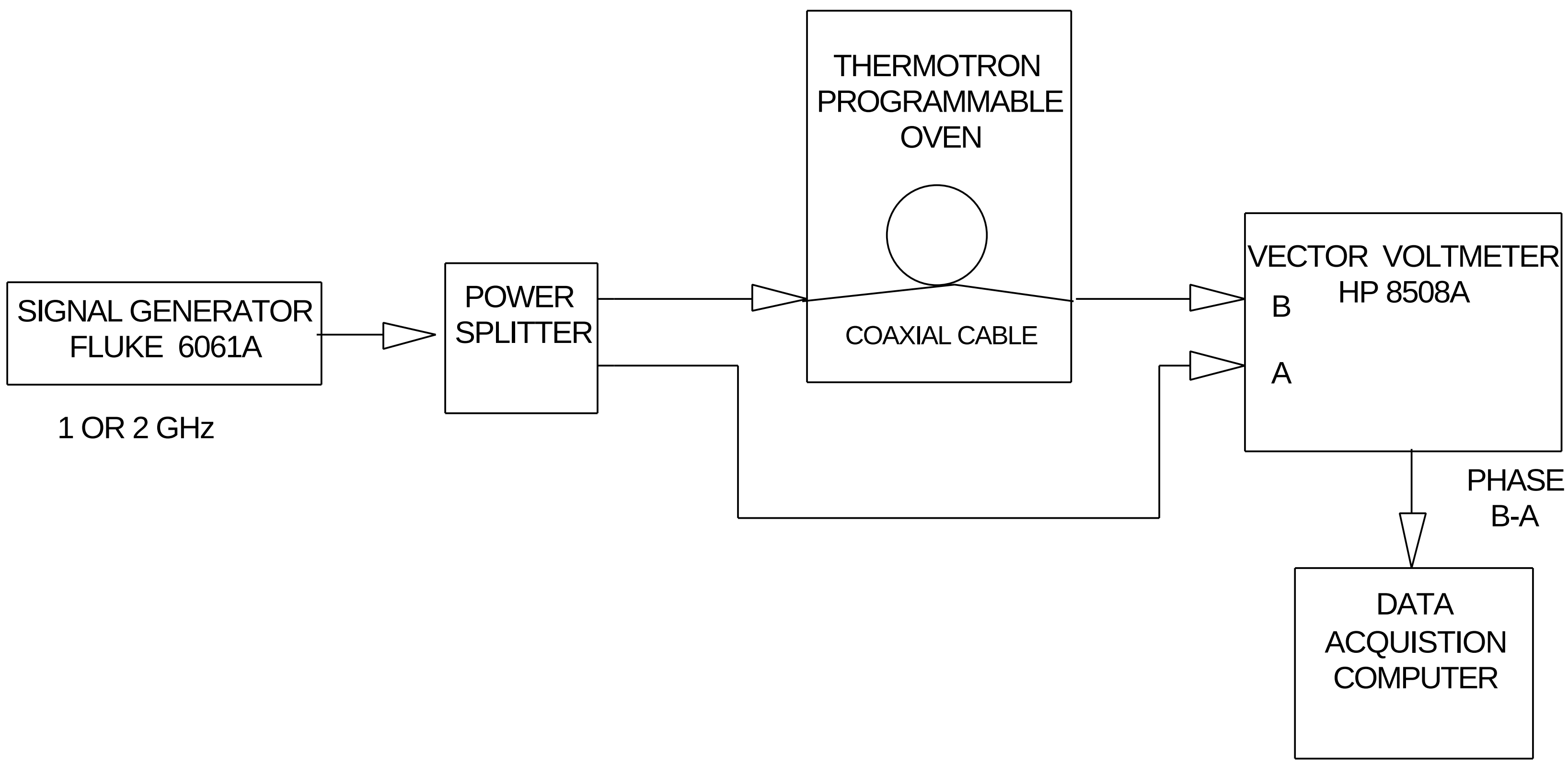
The anticipated ambient temperature for the buried cable/fiber runs on Mauna Kea is 5 to 15 C, including diurnal and seasonal variations; therefore special attention was paid to phase variations over this range. Coincidentally, PTFE teflon is known to exhibit a polymeric phase transition at approximately 10 C which is evidenced as an abrupt change in the refractive index. Also, and again by coincidence, the Sumitomo TCD fiber exhibits a point of inflection of the time delay at a temperature of approximately 10 C. In order to assure that these anomalies are captured with good fidelity, measurements were made over the -20 to +45 C temperature range, as a minimum, for all transmission lines.

4. TEST RESULTS

4.1 Individual Phase vs Temperature Measurements

There is no standardized way of expressing the time delay stability of transmission lines; most of the published data is in terms of change of electrical length as a function of temperature but temperature coefficients as a function of temperature are widely used. Within each category there is a bewildering variety of units, from a relatively straightforward <u>ppm per degree C</u> to <u>change in electrical length in degrees for ten feet of cable per degree F.</u> However, phase as function of temperature, at a specified frequency and cable length, is physically meaningful and can be readily extrapolated to a user's specific configuration. Therefore, individual plots of time delay data, normalized to read in degrees of phase at 1.0 GHz per meter of cable with temperature as the independent variable are shown Figures 3 through 13. Figures 4 and 14 are based on identical data, but expressed as temperature coefficient in ppm per degree C. In most cases the data has been fitted to a sixth-order polynomial to minimize noise and background temperature fluctuation effects.

RF CABLE PHASE STABILITY MEASUREMENT



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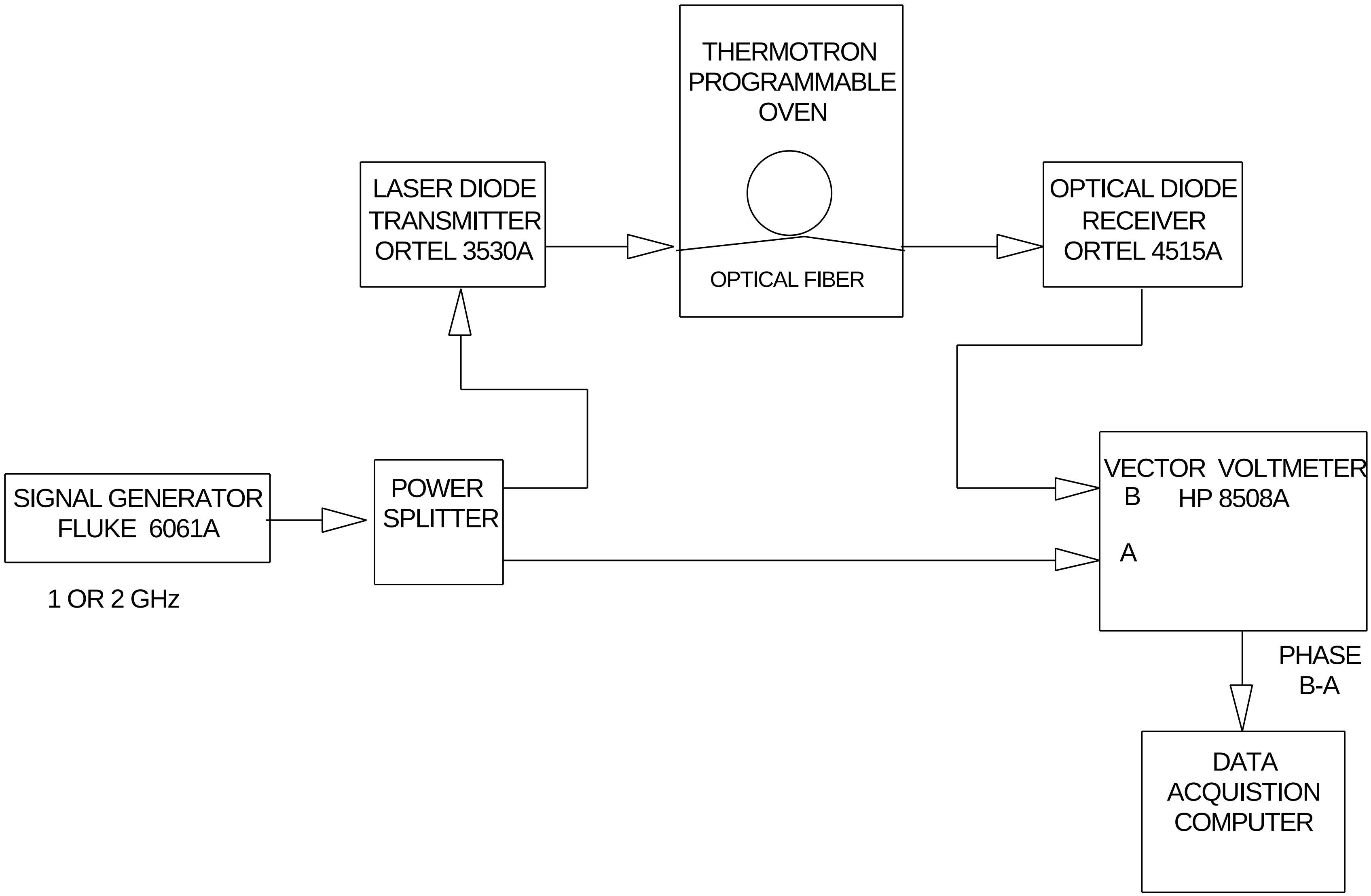
OPTICAL FIBER PHASE STABILITY MEASUREMENT



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In keeping with the system orientation of this design note, the phase vs temperature measurements are presented in a format which shows the effect of the physical changes in the transmission lines on the signal phase as measured at the receiver. It is important to note that manufacturer's data usually shows the effective change in electrical length with temperature (when it is specified at all), which has the same magnitude but the opposite sense of the phase-meter data shown here.

<u>Figure 3 Gore 090-36:</u> A measurable hysteresis is evident, although the magnitude of the loop is actually fairly small. The cable is extremely stable below the PTFE transition temperature; the phase changes are near the limit of the measurement system stability at 10 degrees C or less.

<u>Figure 4 Gore 090-36 - Temperature Coefficient:</u> The time delay performance of the Gore cable is well-behaved over the full temperature range and it is therefore useful for reference purposes to also show the temperature coefficient of phase, in ppm per degree C, as a function of temperature. The PTFE transition at about 15^{o} C is apparent in this view, as is the excellent phase stability in the -25 to +15 degree range.

<u>Figure 5 Gore 145-36:</u> The performance of this cable is, as expected, very similar to that of the 0.090" diameter Gore cable.

<u>Figure 6 Flexco FC182:</u> The solid-PTFE-insulated Flexco cable is impressively stable below the transition temperature but the electrical length changes rapidly above approximately 10^{o} C.

<u>Figure 7 Huber & Suhner Sucoflex 104P:</u> The expanded PTFE Huber & Suhner cable clearly exhibits an abrupt change in the performance of the dielectric at about 10 degrees. The effect is more marked than in any of the other cables tested and is somewhat unexpected since the higher velocity-of-propagation is normally associated with more stable performance.

<u>Figure 8 Andrew FSJ1-50:</u> The transition temperature for the polyethylene-insulated Andrews cable appears to occur at a much higher temperature that for PTFE; in the order of 25^{o} C. Note that the vertical scale is expanded and that the magnitude of the (electrical) phase change is very small even above 25^{o} C.

<u>Figure 9 EZ-Form EZ 86AL:</u> The conventional, solid PTFE semi-rigid is by far the worst performer of all cables tested. Both the absolute change in time delay and the hysteresis are substantially greater that of any other transmission line. The physical basis for these problems is fairly straightforward; a combination of a rigid copper or aluminum jacket and a solid dielectric with a much greater temperature coefficient of expansion. The forces generated by the differential expansion of the metal and the PTFE combine with the normal temperature coefficient of the dielectric to produce a time delay variation which is much greater that of either that of the PTFE or the temperature expansion of the jacket alone.

Figure 3 PHASE VS TEMPERATURE -- GORE 090-36

Figure 4 PHASE TEMPCO VS TEMPERATURE - GORE 090-36

Figure 5 PHASE VS TEMPERATURE - GORE 145-36

Figure 6 PHASE VS TEMPERATURE - FLEXCO FC182

Figure 7 PHASE VS TEMPERATURE - H&S 104P

Figure 8 PHASE VS TEMPERATURE - ANDREWS FSJ1-50

Figure 9 PHASE VS TEMPERATURE - EZ-FORM EZ 86AL

Figure 10 Corning SMF Single-Mode Optical Fiber: The data shown here is adapted from a Corning technical paper and is included for completeness. The next two figures show the profound effects of coatings and/or buffers applied over the basic fiber.

Figure 11 Siecor Jacketed Optical Cable: The general behavior of the PVC-jacketed fiber is similar to that of the basic SMF fiber, but the magnitude of the phase error is substantially increased. In this case, the size of the hysteresis effect appears to be a function of the temperature slew rate; this data in this plot, taken at the normal slew rate of 1^{o} C per minute, should be compared to that of Figure 11.

Figure 12 Siecor Jacketed Optical Cable - Reduced Slew Rate: The data shown in this figure was taken under the identical conditions as for Figure 10 above, except that the temperature slew rate was reduced to 0.3 degrees per minute. The temperature-induced phase shifts are essentially identical, but the hysteresis effect is reduced by about a factor of two. Further reductions in the temperature slew rate, not shown here, had no effect on the size of the hysteresis effect.

Figure 13 Sumitomo TCD Optical Cable: The effect of a carefully-chosen fiber coating is dramatically demonstrated in Figure 12. The temperature coefficient of phase is greatly reduced relative to the basic fiber and, in fact, actually goes to zero at a point of inflection at approximately 5^{o} C. The well-behaved and symmetrical performance of the Sumitomo cable was not observed in earlier published data, primarily because the temperature range below 20 degrees was not of major interest to users. However, by fortune coincidence, the characteristics of the Sumitomo TCD cable is well-matched to the environmental conditions at the summit of Mauna Kea . The TCD fiber does exhibit a measurable and consistent hysteresis effect which is not an artifact of the measurement process. The increasing and decreasing temperature data of Figure 12 were taken alternatively, and as can be seen from the plots, the hysteresis is highly repeatable. Additional data, not shown here, taken at lower temperature slew rates, shows a similar scale of hysteresis effects.

Figure 14 Sumitomo TCD Optical Cable - Temperature Coefficient: Because the time-delay of the Sumitomo fiber is well-behaved, it is also useful to plot the temperature coefficient of time delay, in parts per million per degree C, as a function of temperature. The precise location of the zero crossing is evident from this plot, as is the overall symmetry of the time delay characteristics. The measured temperature coefficient is clearly less than 0.25 ppm/^{o}C over the temperature range -10 to +20^{o} C, at least thirty times better than the basic SMF fiber.

Figure 10 PHASE VS TEMPERATURE - CORNING SMF OPTICAL FIBER

Figure 11 PHASE VS TEMPERATURE - SIECOR JACKETED FIBER

Figure 12 PHASE VS TEMPERATURE AT REDUCED SLEW - SIECOR FIBER

Figure 13 PHASE VS TEMPERATURE - SUMITOMO TCD FIBER

Figure 14 PHASE TEMPCO VS TEMPERATURE - SUMITOMO TCD FIBER

4.2 Phase vs Temperature Comparisons

The motivation for the measurement series described here is to provide guidelines for the design of phase-stable SMA local-oscillator reference distribution subsystems and components. Figures 15 through 17 are compilations of the temperature stability performance of candidate transmission media, presented in a format which simplifies performance comparisons.

Figure 15 RF Coaxial Cables: The temperature stability of phase of the four best performing coaxial transmission lines is shown as a function of temperature in Figure 15. The only unanticipated result is the performance of the Huber & Suhner 104P low-density PTFE cable, which is significantly worse than that of the low-velocity-of-propagation, solid PTFE Flexco cable. The Gore cables are roughly equivalent to the Andrews FSJ1 in the magnitude of the phase change over the temperature range, although the sense of the variation is reversed.

Figure 16 Fiber Optical Cables: The three curves of Figure 16 are particularly instructive. The SMF fiber shown in the center plot is similar to the basic transmission element of the jacketed Siecor cable, upper, or the Sumitomo TCD cable, lower. The impact of coating and jacketing on the performance of optical fiber is clear; the jacketed Siecor fiber is about three times worse than that of the bare fiber. Conversely, the compensating coating of the Sumitomo fiber is remarkably effective; reducing the temperature coefficient of time to a level which is not directly visible in this graph.

Figure 17 Coaxial Cable vs Fiber Comparisons: It is also useful to compare the time delay stability performance of the best coaxial cable with that of the best of the optical cables. Figure 17 shows phase as a function of temperature for Sumitomo TCD and Corning SMF optical fibers, and for Gore 145 coaxial cable. The phase change for the cable most commonly used for intra-module wiring, the 0.085" semi-rigid coaxial cable, is shown for reference purposes. It should be noted that the Gore cable exhibits a much lower temperature coefficient than SMF fiber at temperatures below about 15^{o} C. The Sumitomo fiber is, of course, vastly superior to any alternative transmission line, coaxial or optical fiber.

5. SUMMARY

A number of important practical guidelines can be drawn from the test data described above. One obvious conclusion is that certain rule-of-thumb engineering guidelines are of uncertain validity. Certainly, it has often been assumed in the past that cables with a higher velocity-of-propagation would always exhibit better time-delay performance than standard, solid-dielectric cables. This assumption is not necessarily true, as can be seen from a comparison of the Flexco FC182 and Huber & Suhner 104P cables. A second lesson is that is difficult to generalize about time delay stability without taking into account the cable operating environment. The PTFE polymer phase transition at roughly 10^{o} C is of crucial importance in this respect and various manufacturers appear to have had varying degrees of success in dealing with this complication. It is also apparent that the very common solid-dielectric semi-rigid cable should be avoided if at all possible. There are alternative semi-rigid cables

Figure 15 PHASE COMPARISON - RF COAXIAL CABLES

Figure 16 PHASE COMPARISION - FIBER OPTICAL CABLES

Figure 17 PHASE COMPARISONS - OVERALL PERFORMANCE available with foamed PTFE or polyethylene insulation, not evaluated in this study, which may be acceptable if the mechanical and electrical characteristics of a solid metallic outer conductor are essential for the application.

With respect to the optical transmission lines, the discovery that the Sumitomo TCD fiber exhibits a point of inflection of the phase versus temperature characteristic is both interesting and of significant practical importance. The extraordinary performance of the Sumitomo cable should not, however, obscure the fact that a good coaxial cable such as the Gore 145 exhibits better phase stability than the basic SMF optical fiber over the entire -25 to +50^{o} C temperature range.

This study is limited to a comparative analysis of the phase stability of transmission lines as a function of temperature. There are additional factors in the design and selection process, such as mechanical stability, attenuation, dispersion and linearity which may be of equal or greater importance in a particular application. Furthermore, the optical transmission lines require transducers for transmission and reception which are themselves temperature sensitive and which are not included in the phase stability estimates.

6. REFERENCES

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