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GALILEO ELECTRO-OPTICS CORP STURBRIDGE MA H J HOAR
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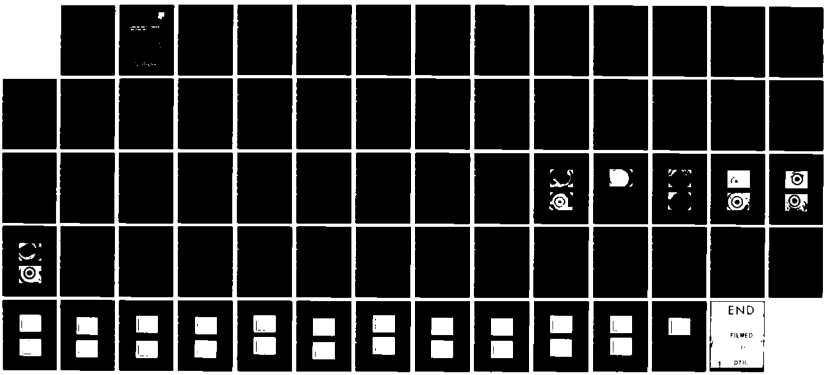

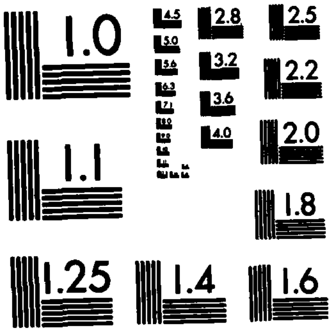

RADC-TR-82-88
Final Technical Report
November 1982

DESIGN AND DEVELOP A CONCENTRIC CORE OPTICAL FIBER

Galileo Electro-Optics Corp.

Henry J. Hoar Jr.

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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Concentric core optical fibers were developed for operation at 0.85 μm and 1.3 μm. The fibers were characterized for cross-sectional geometry, numerical aperture, attenuation, crosstalk and dispersion.

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PREFACE

Galileo Electro-Optics Corporation is pleased to submit to Electronic Systems Division, Hanscom Air Force Base, this final report on the "Design and Development of Concentric Core Optical Fibers."

The material in this report summarizes all aspects of research and development conducted by Galileo, as Contractor, under Government Contract No. F19628-80-C-0200.

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1.0 INTRODUCTION/SUMMARY

The objective of this program was to develop and characterize concentric core optical fibers for secure communications. The configuration of the concentric core fiber was to have a central core of high refractive index glass, surrounded by a ring clad area of lower refractive index, surrounded again by an annular or ring core, and totally surrounded by an outer clad, again of lower refractive index. (See Figure 1 for refractive index profile). Two fabrication techniques were to be investigated. These were rod and tube, and an "All Chemical Vapor Deposition"(CVD) process. The latter technique proved to be the more effective technique in producing fiber of required characteristics. The "All CVD" technique was used to produce twenty (20) preforms. Twelve (12) of these preforms were actually drawn into fiber. Eight (8) preforms were lost in fabrication. The geometrical properties were measured using a microscope, and photographic recording device. The optical characteristics (Table 1, Concentric Core Design Goals), spectral attenuation, numerical aperture, and pulse broadening, were measured by standard inspection methods. Optical cross talk, and the amount of signal that is leaked from the central core to the annular core, was a more difficult measurement. A new technique was developed under this contract to test the actual levels of cross talk between the central and ring cores. The design goals of this program were achieved to a relatively high degree. The physical geometries of the concentric core fiber were achieved with little difficulty in fabrication or

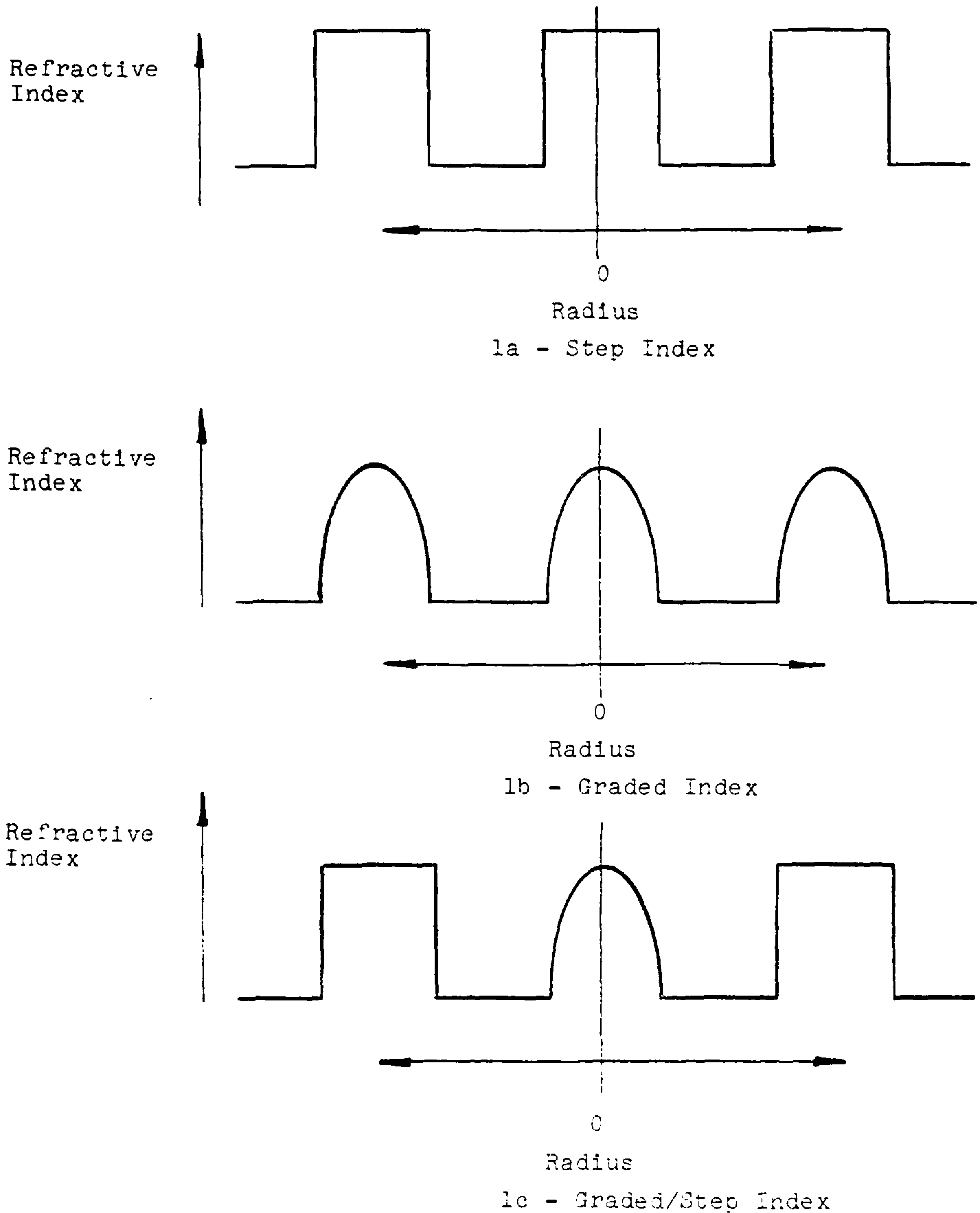


FIGURE 1. CONCENTRIC CORE OPTICAL FIBER REFRACTIVE INDEX PROFILES

TABLE 1. CONCENTRIC CORE DESIGN GOALS

GEOMETRICAL	
Central Core Diameter	≥ 25μm
Width of Ring (Annular Core)	≥ 15μm
Outside Diameter	≤ 180μms
Ellipticity	≤ 95%
Concentricity	≥ 2μm
OPTICAL	
• Numerical Aperture	
Central Core	≥ .2
Ring Core	≥ .2
• Attentuation	
.82 μm	≤ 4.0 db
1.2 - 1.3 μm	≤ 2.0 db
• Inter-Channel Cross Talk	-30 db (1 kilometer)
• Bandwidth Central Core	100 MHz, kilometer

characterization. The desired levels of attenuation, bandwidth, numerical aperture, and cross talk were achieved, although not all in the same fiber.

2.0 TECHNICAL OBJECTIVES

The objectives addressed are those set forth in Contract Number F19628-80-C-0200. The intent of the program was to design and to develop a concentric core optical fiber. To accomplish this end, the following tasks were undertaken:

1) To design and develop a concentric core opti l fiber with a refractive index profile simila) that shown in Figure 1.

2) To design and develop new test methods to characterize the concentric core fiber for the following parameters:

   (a) Geometrical evaluation including:
   Central Core Diameter
   Width of Ring (Annular) Core
   Outside Diameter
   Ellipticity
   Concentricity

   (b) Optical evaluation including:
   Numerical Aperture
   Ring Core Attenuation
   (0.82 μm and 1.2 - 1.3 μm)
   Central Core Attenuation
   (0.82 μm and 1.2 - 1.3 μm)

(c) Inter-Channel Cross Talk

(d) Bandwidth (central core)

3) To fabricate, draw, characterize, and deliver three (3) lengths (1 kilometer each) to meet design goals set forth in contract (see Table 1 for specifications).

3.0 TECHNICAL ACCOMPLISHMENTS

3.1 The first objective in this contract involved a comparison of two (2) fabrication techniques (i.e., Rod and Tube versus "All CVD"). Both techniques will be summarized as to feasibility versus yield and quantity.

3.1.1 Rod and Tube Technique:

A graded index preform was fabricated by standard techniques and inserted into a silica tube whose inside surface consisted of several layers of sintered glass core composition. The core glass was deposited on the inside surface of the tube by passing a gaseous mixture of O_2, $SiCl_4$, $GeCl_4$, and $POCl_4$ through the rotary tube while at the same time, traversing a H_2/O_2 flame over the outside surface of the tube. A chemical reaction occurs with oxides of silica, germanium, and phosphorus, allowing deposition to occur on the inside surface of the tube. Multiple layers of glass soot are deposited in this manner, and built up to a suitable thickness. For preforms 1-A and 2-A, the volume of $GeCl_4$ gas was kept constant, thereby, producing a core layer of uniform refractive index (step index). After inserting the graded index rod into the core glass deposited tube, one end of the tube was thermally sealed to the preform and the entire tube was collapsed. Two collapsing techniques were attempted: preform 1-A was collapsed under a partial vacuum, while preform 2-A was collapsed under ambient pressure. Neither technique produced a useful preform, due to bubbles, seed formation, and interfacial cracking. Bubble formation occurred at the interface between the graded index preform and the tube containing the deposited ring core, due to surface irregularities (scratches or localized variations in the preform/tube diameter) which resulted in air entrapment and the formation of seeds. In addition, localized cracking of the ring core occurred due to the abrupt thermal mismatch between the pure silica clad of the graded index preform (low expansion), and the deposited glass of the ring core (high expansion). Interfacial cracking was most apparent in areas exhibiting many bubbles or seeds. Due to these collapsing problems, and general mechanical difficulty associated with properly aligning the preform within the tube, the rod and tube approach was terminated, and the "All CVD" technique was pursued.

3.1.2 "All CVD" Technique:

The "All CVD" preforms were fabricated in the following general manner. An acid etched and methanol degreased 15 x 17 (Amersil) waveguide tube was inserted into the lathe. A boron containing barrier layer was deposited using $SiCl_4$, BCl_3, and O_2 in the gas stream. The ring core was then deposited using O_2, $POCl_3$, $SiCl_4$, and $GeCl_4$ in the gas stream. For preform Number 1, the flow rate of $GeCl_4$ was kept constant during each pass to create a step index profile (10 passes), while for preform Number 2, the flow rate of $GeCl_4$ was incrementally increased in a linear fashion for one-half of the total number of ring core passes, and then decreased in a similar manner to create a graded index profile. There were thirteen (13) total passes in this core deposition. The ring clad was subsequently formed from oxides of silica and boron. The central core was deposited using the same gases that we used for deposition in the ring core. The $GeCl_4$ was incrementally increased in a linear fashion for each consecutive pass. Five (5) central core passes were deposited in preform Number 1 and preform Number 2.

Seeds were formed during the collapse of preform Number 1, which resulted in the preform being scrapped. No problems were encountered during the collapse of preform Number 2. This preform was drawn into fiber, and a primary buffer of ultraviolet curable resin was applied. The fiber was then characterized for geometrical and optical properties. The data, shown in Table 2, indicates that the "All CVD" technique produced fiber that nearly met the design goals of the program. It was decided that the technique was well suited to producing concentric core fibers. However, some modifications to the fabrication technique, gas flow rates, and number of deposition passes must be explored. A total of twenty (20) preforms were made using the "All CVD" technique. Twelve (12) preforms were successfully fabricated, drawn into fiber, and characterized (see Table 2 for fabrication information). It was possible to change gas flow rates and number of deposition passes to meet all geometric specifications. All the design goals were not met in any one fiber, however, Galileo did manufacture concentric core fibers which exhibited acceptable levels of performance in all specified areas.

3.2 The second objective set forth in this contract was to characterize the manufactured fiber for the following parameters: geometry, attenuation, numerical aperture, bandwidth, and inter-channel cross talk.

a) Geometrical data is summarized in Table 3. A microscope with photographic recording device was utilized to determine the physical characteristics.

TABLE 2. FABRICATION INFORMATION

Gas Flows (cc/m)		RADC PREFORM NUMBER					
		2	5	6	7	8	9
Cleaning (# Passes)		5	5	5	5	5	5
He		120	120	120	120	120	120
Clad #1 (# Passes)		3	3	3	3	3	3
O_2		1200	1200	1200	1200	1200	1200
$SiCl_4$		200	150	150	150	150	150
BCl_3		50	50	50	50	50	50
Ring Core (# Passes)		13	19	19	19	29	29
O_2		1200	1200	1200	1200	1200	1200
$SiCl_4$		280	180	180	180	180	180
$GeCl_4$	Start	300	220	220	220	220	220
	Middle	370	310	310	310	360	360
	End	300	220	220	220	220	220
$POCl_3$		20	20	20	20	20	20
Ring Clad (# Passes)		5	6	6	6	8	8
O_2		1200	1200	1200	1200	1200	1200
$SiCl_4$		280	150	150	150	150	150
BCl_4		75	75	75	75	80	80
Central Core (# Passes)		5	6	6	6	8	8
O_2		1200	1200	1200	1200	1200	1200
$SiCl_4$		280	150	150	150	150	150
$GeCl_4$	Start	600	300	300	300	350	350
	Middle	600	350	350	350	420	420
$POCl_3$		20	20	20	20	20	20
Fabrication Date		11/24	4/14	4/15	4/16	4/23	4/27

TABLE 2. FABRICATION INFORAMTION (continued)

	RADC PREFORM NUMBER					
Gas Flows (cc/m)	10	12	13	14	16	17
Cleaning (# Passes)	5	5	5	5	5	5
He	120	120	120	120	120	120
Clad #1 (# Passes)	3	3	3	3	3	3
O_2	1200	1200	1200	1200	1200	1200
$SiCl_4$	150	150	150	140	150	150
BCl_3	50	50	60	60	60	60
Ring Core (# Passes)	29	19	19	19	19	25
O_2	1200	1200	1200	1200	1200	1200
$SiCl_4$	180	180	180	180	180	180
$GeCl_4$ Start	220	220	220	220	210	220
Middle	360	310	310	310	310	340
End	220	220	220	220	210	220
$POCl_3$	20	10	10	10	10	10
Ring Clad (# Passes)	8	12	12	12	12	12
O_2	1200	1200	1200	1200	1200	1200
$SiCl_4$	150	150	150	150	150	150
BCl_4	80	85	85	85	85	85
Central Core (# Passes)	8	12	12	12	12	12
O_2	1200	1200	1200	1200	1200	1200
$SiCl_4$	150	150	150	150	150	150
$GeCl_4$ Start	350	300	300	300	300	300
Middle	420	410	410	410	410	410
$POCl_3$	20	10	10	10	10	10
Fabrication Date	4/28	6/10	6/11	6/12	6/16	6/17

TABLE 3. CONCENTRIC CORE FIBER: DRAW & GEOMETRIC DATA SUMMARY

	RADC FIBER NUMBER						Desired Concentric Core Dimensions
	2	5	6	7	8	9	
DRAW DATA							
Draw Date	12/2	4/15	4/16	4/16	4/29	4/29	
Draw Temp. (^{o}C)	2100	2130	2130	2130	2130	2130	
Fiber Dia. (μm)							
$\bar{x}$	-	180.10	-	180.10	-	-	
σ	-	0.66	-	0.71	-	-	
Maximum	-	182.80	-	182.70	-	-	
Minimum	-	178.00	-	177.50	-	-	
Length (meters)	-	1430	503	1058	325	1370	
GEOMETRICAL DATA							
Radius (μm)							
Central Core	21	15	17.50	17.50	10	10.30	15
Ring Clad	46	40	37.50	41.25	27.50	30	45
Ring Core	56	52.50	52.50	57.50	57.50	59	60
Outer Clad	89	90	90	3.70	94.00	94	90
Thickness (μm)							
Central Core (Dia)	42	30	35	35	20	22.60	≥ 25
Ring Clad	25	25	20	24	7.50	9.40	30
Ring Core	10	12.50	15	16	30	30.60	≥ 15
Outer Clad	33	37.50	37.50	36	36	38.40	30
Ellipticity (%)	97.50	98	98	99	99	99	≥ 95
Concentricity (μm)	0.50	0.50	0.20	0	0.50	0.20	≤ 2

TABLE 3. CONCENTRIC CORE FIBER: DRAW & GEOMETRIC DATA SUMMARY (CONTINUED)

	RADC FIBER NUMBER						Desired Concentric Core Dimensions
	10	12	13	14	16	17	
DRAW DATA							
Draw Date	4/28	6/18	6/18	6/23	6/23	6/23	
Draw Temp. (°C)	2130	2130	2130	2130	2130	2130	
Fiber Dia. (μm)	-	178.30	177.40	178.30	177.90	178.40	
$\bar{x}$	180.10	177.72	178.02	178.05	177.97	178.09	
σ	1.42	1.01	0.81	0.83	0.78	0.89	
Maximum	182.50	181.20	181.40	182.00	181.20	181.10	
Minimum	171.90	175.40	173.80	174.50	174.50	175.70	
Length (meters)	861	932	1255	1120	960	1338	
GEOMETRICAL DATA							
Radius (μm)							
Central Core	12.15	25	23.80	26.90	25	27.50	15
Ring Clad	30	50	46.90	48.10	46.30	46.30	45
Ring Core	60	61.30	52.50	60.60	57.50	62.50	60
Outer Clad	91.50	90	87.50	90.60	93.10	90	90
Thickness (μm)							
Central Core (Dia)	24.30	50	47.50	53.80	50	55	≥ 25
Ring Clad	7.50	25	21.3	21.3	20	18.80	30
Ring Core	30	10	12.50	13.80	11.30	15	≥ 15
Outer Clad	32.50	28.80	27.50	30	33.80	27.50	30
Ellipticity (%)	99						≥ 95
Concentricity (μm)	0.50						≤ 2

It became apparent that by varying the gas flows and deposition rates, one could attain the design goals set forth in this contract with relatively little trouble, and that the majority of the research would involve meeting the other design goals. (See Appendix A for photographic results).

b) N.A. - defined as the sine of the half angle of the emission cone.

Attempts were made to measure the numerical aperture of the central and ring cores using a 10 mW helium neon laser as a source. The operative laser was focused onto the input end of the fiber using a 10X, 0.25 N.A. microscope objective and launch probe. The output end of the test fiber was positioned about the axis of rotation of a rotary stage. A small area detector was used to detect relative intensity emitted from the fiber, as a function of angular displacement of the fiber end. This technique did not produce useful results, due to large intensity variations in the output radiation pattern. This is a common problem associated with laser emission, and is known as "laser speckle". A filtered, incoherent source, must be used for this purpose. Even after utilization of said source, intensity was the limiting factor. Galileo was unable to characterize the fiber via intensity scan.

The technique which eventually was employed involved "enclosed power". This procedure requires a large active area detector, which is butted to the output end of the test fiber, and captures all the emitted power. It is backed off until only 90 percent of the power is captured by the detector (See Figure 2). The formula applied to calculate N.A. is as follows:

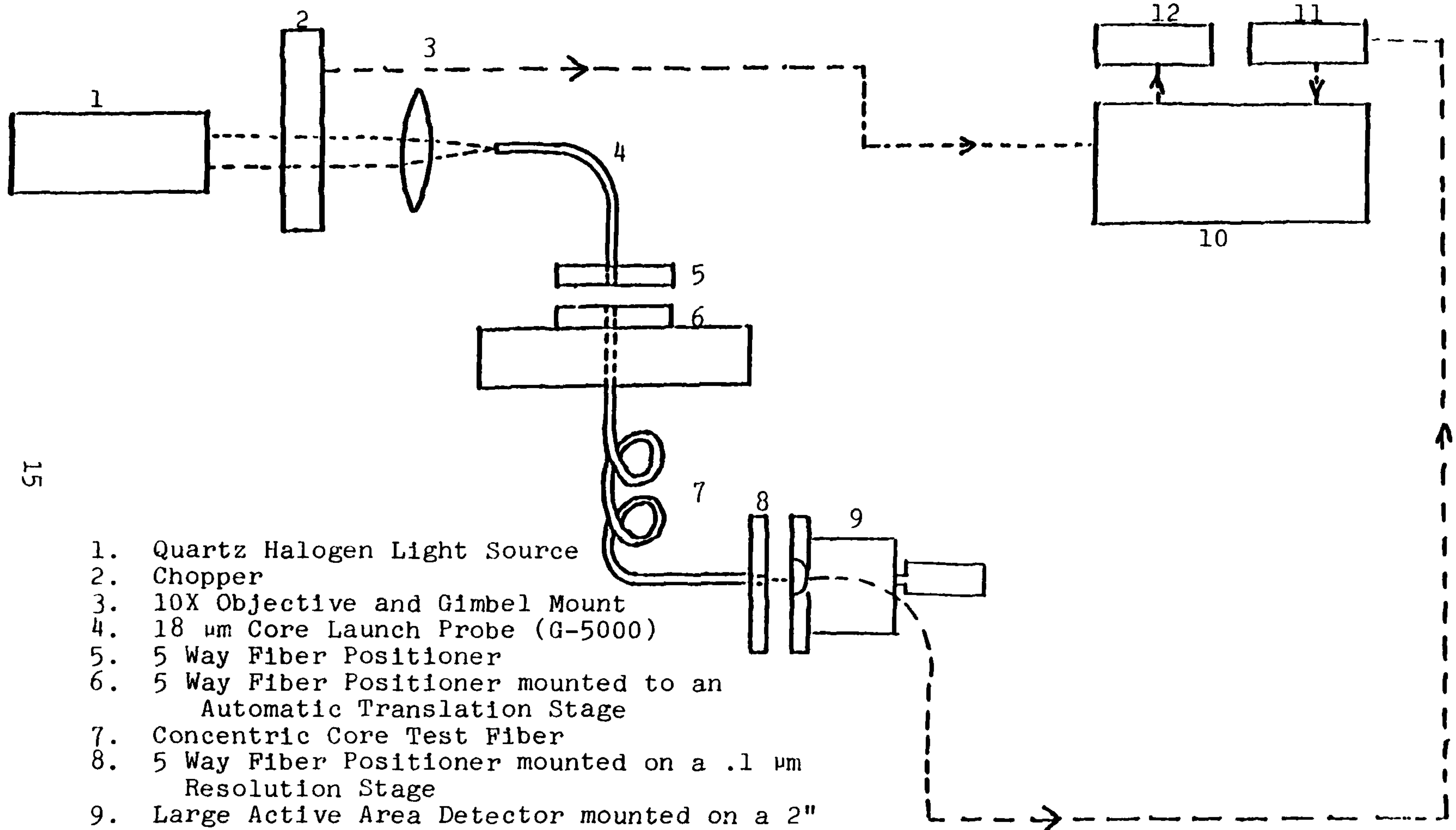
$$N.A. = \text{sine}\left[\arctan\left(\frac{d+d'}{r}\right)\right] \qquad (1)$$

Where d = The displacement distance from the detector required to capture 90 percent transmission.

d' = The distance from the active area of the detector to the front surface of its faceplate.

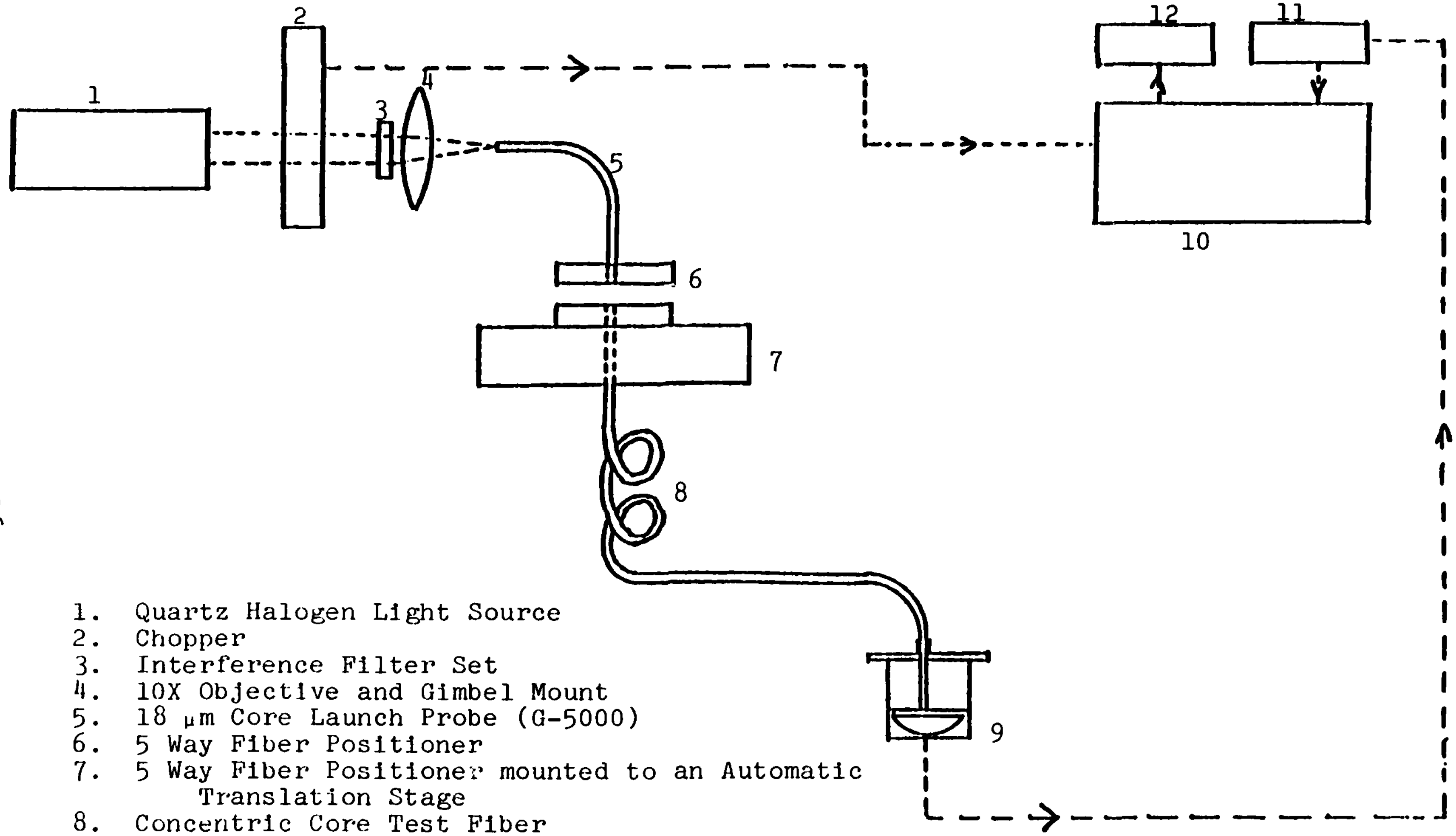
r = Radius of the detector's active area.

c) Attenuation was measured on both the ring and central cores of all the preforms that were drawn into fiber (See Figure 3 for test apparatus). The description of the measurement technique is as follows: A 100 watt tungsten flat filament light source was mechanically chopped, and the frequency referenced to a lock-in amplifier. The light emission from the source was focused down with a 10X microscope objective onto a 18 μm core ϕ step index fiber. When properly aligned, this technique allows for selective core excitation. The standard "cut-back" technique was then utilized. Attenuation was calculated using the following formula:



1. Quartz Halogen Light Source
2. Chopper
3. 10X Objective and Gimbel Mount
4. 18 μm Core Launch Probe (G-5000)
5. 5 Way Fiber Positioner
6. 5 Way Fiber Positioner mounted to an Automatic Translation Stage
7. Concentric Core Test Fiber
8. 5 Way Fiber Positioner mounted on a .1 μm Resolution Stage
9. Large Active Area Detector mounted on a 2" Travel Translation Stage
10. Lock-in Amp
11. Current Sensitive Pre-Amp
12. Digital Volt Meter

FIGURE 2. NUMERICAL APERTURE MEASUREMENT SYSTEM



1. Quartz Halogen Light Source
2. Chopper
3. Interference Filter Set
4. 10X Objective and Gimbel Mount
5. 18 μm Core Launch Probe (G-5000)
6. 5 Way Fiber Positioner
7. 5 Way Fiber Positioner mounted to an Automatic Translation Stage
8. Concentric Core Test Fiber
9. GE Detector
10. Lock-in Amp
11. Current Sensitive Pre-Amp
12. Digital Volt Meter

FIGURE 3. ATTENUATION MEASUREMENT SYSTEM

$$db/km = \frac{10 \log \frac{P_2}{P_1}}{L1-L2} \qquad (2)$$

Where P_1 = Voltage detected in the long length.

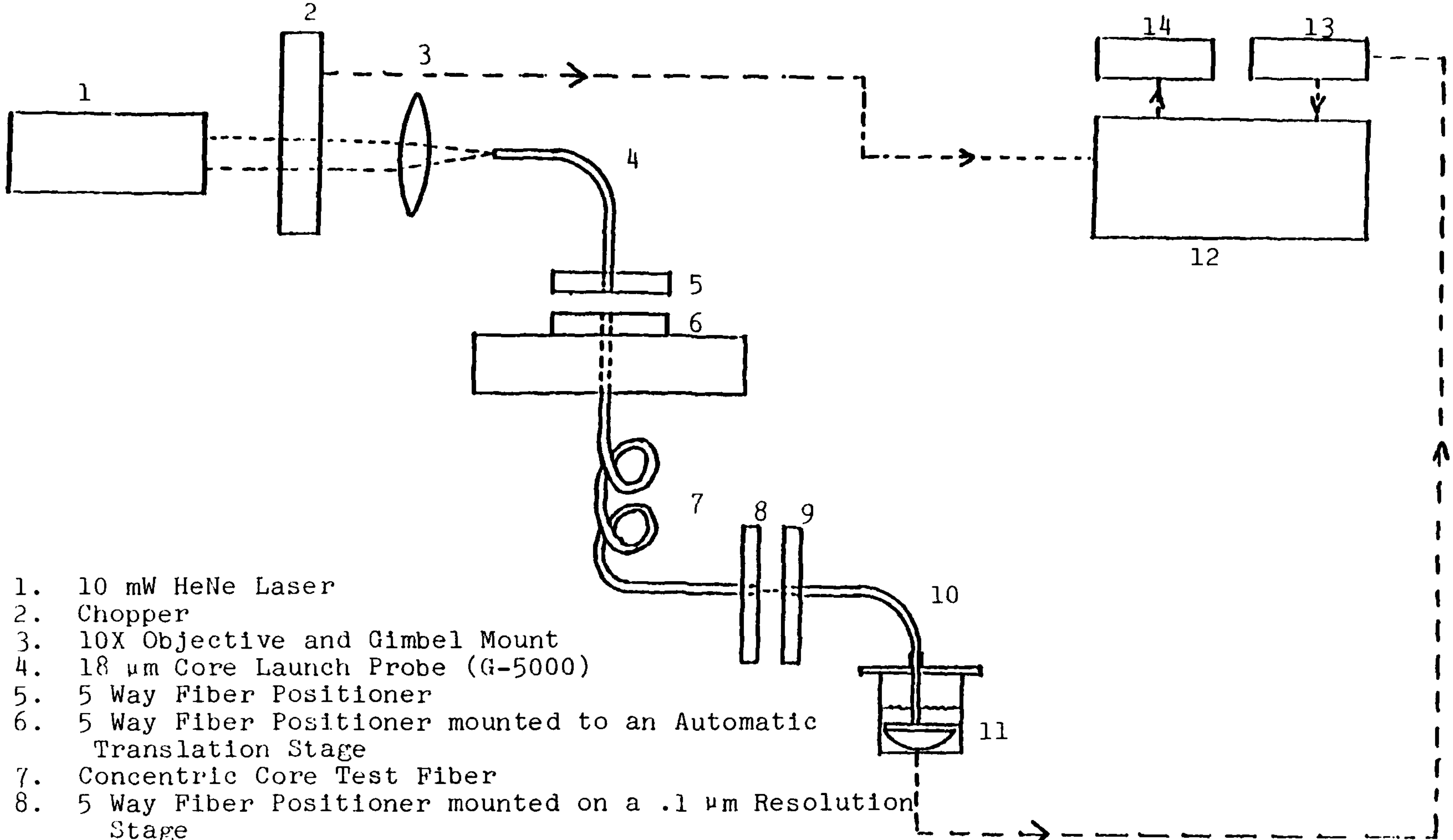
P_2 = Voltage detected in the reference length.

L1 = The sampled length (long length).

L2 = The reference length (2 meters).

d) The successful application of a concentric core fiber is based in part upon the requirement that interchannel cross talk (specifically from the central core to the ring core) be minimized. A novel technique to measure cross talk was developed at Galileo and is illustrated in Figure 4. The procedure for the cross talk measurement is detailed in the following paragraph. The numbers in parenthesis refer to the various components listed in Figure 4.

A 10 mW helium-neon (HeNe) laser (1) was mechanically chopped (2), referenced to a lock-in amplifier (12), and focused with a 10X microscope objective (3) onto an 18 μm core diameter step index fiber (4) mounted in a five-axis positioner (5). The concentric core test fiber (7) was mounted on a five-axis positioner, which was mounted on an automated translation stage (6),



1. 10 mW HeNe Laser
2. Chopper
3. 10X Objective and Gimbel Mount
4. 18 μm Core Launch Probe (G-5000)
5. 5 Way Fiber Positioner
6. 5 Way Fiber Positioner mounted to an Automatic Translation Stage
7. Concentric Core Test Fiber
8. 5 Way Fiber Positioner mounted on a .1 μm Resolution Stage
9. Same as Number 8
10. Single Mode Fiber Detection Probe
11. Oil Immersion Detector
12. Lock-In Amp
13. Current Sensitive Pre-Amp
14. Digital Volt Meter

FIGURE 4. CROSS TALK MEASUREMENT SYSTEM

(with an accuracy of ± 0.1 μm travel in a direction perpendicular to the test fiber axis). The two fibers were air-butted. The output end of the concentric core test fiber (7) was observed with a microscope. The input end of the test fiber was aligned to the output end of the step index fiber using the five-axis positioner, so that only the ring core was excited. The output end of the test fiber was then placed in another five-axis positioner (8), and mounted on a translation stage (with ± 0.1 μm accuracy of travel). The detection probe (a single mode fiber (10) with an approximately 5 μm diameter core), also mounted in a five-axis positioner and a ± 0.1 μm resolution translation stage (9), was butted to the output end of the test fiber, aligned for maximum throughput and locked into position. This procedure assured that the measurement of excitation of the ring core was optimized. The input end of the test fiber was then translated to a position whereby only the central core was excited. The signal from the ring core was monitored and recorded. This signal is representative of the cross talk level.

e) Bandwidth relates the information carrying capacity of the fiber. The central core of the fiber was measured using the standard technique, which involves properly aligning the laser emission (λ820 nm) onto the central core ϕ (laser emission is ≈ 50 μm in length by 15 m in width). This is accomplished by utilizing a hand held infrared (IR) viewer and actually viewing the emission, which is superimposed on the fiber face. Alignment onto the active area of the avalanche photodiode (APD) is accomplished in much the same manner. The root-mean-square (RMS) value of the sampled length is recorded and photographed. After carefully cutting back from the launch, leaving ∿ 2 meters for the reference length, the above procedure is repeated. Pulse broadening of the sampled length is calculated by the following:

$$PB = \frac{\sqrt{S1^2 - S2^2}}{L} \qquad (3)$$

Where S1 = RMS value for the sampled length.

S2 = RMS value for the reference length.

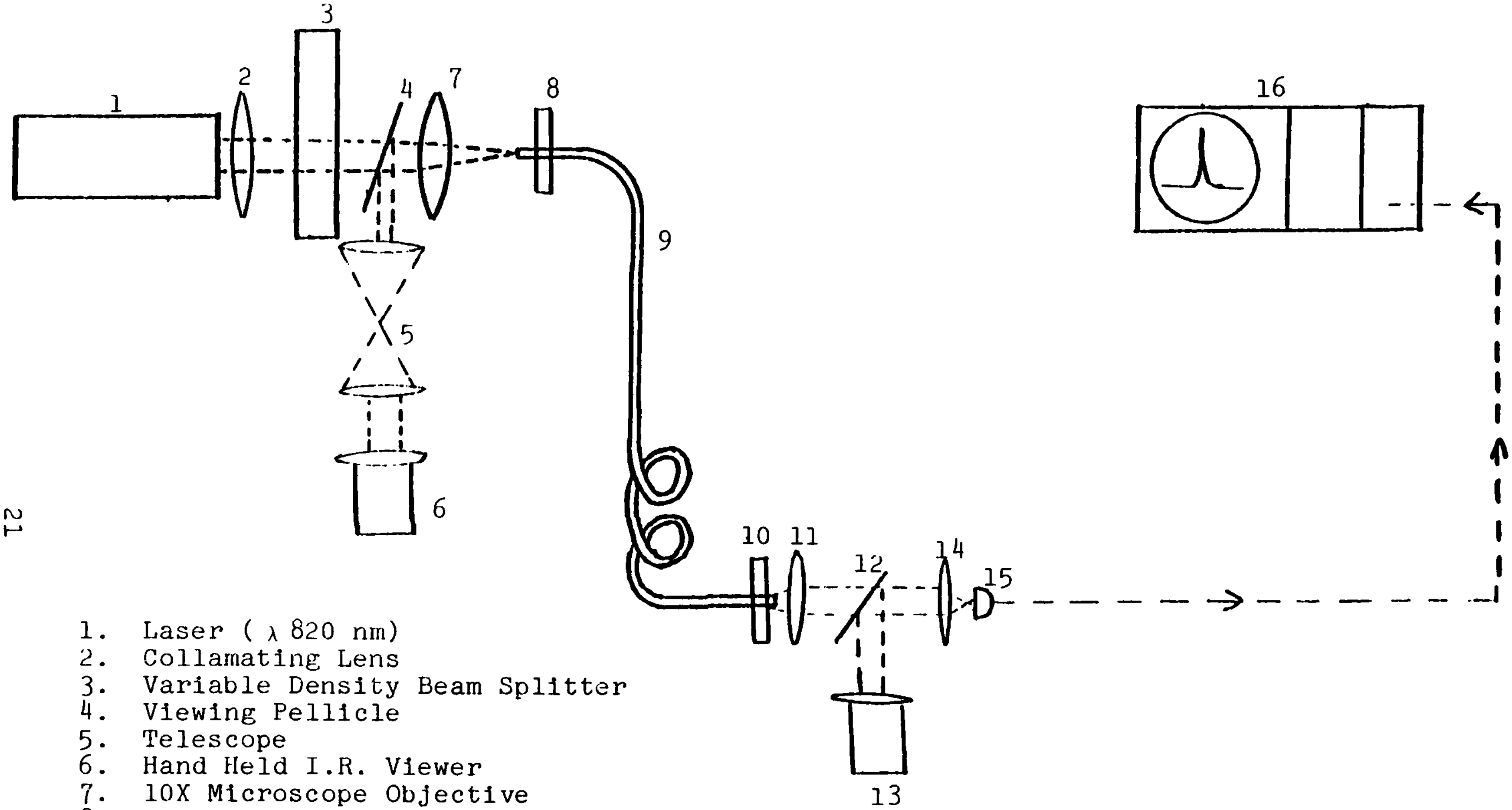
L = Sampled length.

To convert from the time domain (TD) to the frequency domain (FD), the following equation is employed:

$$\frac{1}{PB} \times .22 = fn\ (FD) \qquad (4)$$

Where PB = The pulse broadening.

.22 = The factor employed to convert to the frequency domain. (See Figure 5 for test apparatus).



1. Laser (λ 820 nm)
2. Collamating Lens
3. Variable Density Beam Splitter
4. Viewing Pellicle
5. Telescope
6. Hand Held I.R. Viewer
7. 10X Microscope Objective
8. Multiple Axis Fiber Holder
9. CC Fiber Under Test
10. Multiple Axis Fiber Holder
11. Collamating Lens
12. Viewing Pellicle
13. Hand Held I.R. Viewer
14. 10X Microscope Objective
15. APD
16. O-Scope

FIGURE 5. PULSE DISPERSION (BANDWIDTH) MEASUREMENT SYSTEM

All fiber measurements employed the 37 μm launch probe. The N.A. was characterized (Figure 6) and it was assumed that proper launch conditions were used. (See Table 4 for Optical Summary on all Fibers).

3.3 The third objective was to deliver three (3) kilometers of fiber for evaluation. This was completed, and the fiber submitted exhibited the best of various design goals. (See Table 5 for Delivered Fiber Summary).

4.0 CONCLUSIONS

A concentric core optical fiber for secure communications was designed and developed through an (interactive) approach to fabrication and characterization. The method that was developed is a modified version of a CVD technique. The method produced concentric core fibers with excellent geometrical properties, good cross talk levels, relatively low attenuation, and acceptable numerical aperture. The bandwidth of the central core met the specification goal on only one of the twelve fibers drawn; however, the failure of the later preforms to reach this specified goal was due to problems with the gas delivery system, and should not be a problem in any further production.

The difficult task of accessing cross talk between the central and ring cores was accomplished through the development of a technique which employs a small diameter step index fiber as a launch probe, and a single mode fiber as a detection probe. This method produced repeatable results, and is clearly superior to techniques reported in prior development efforts.

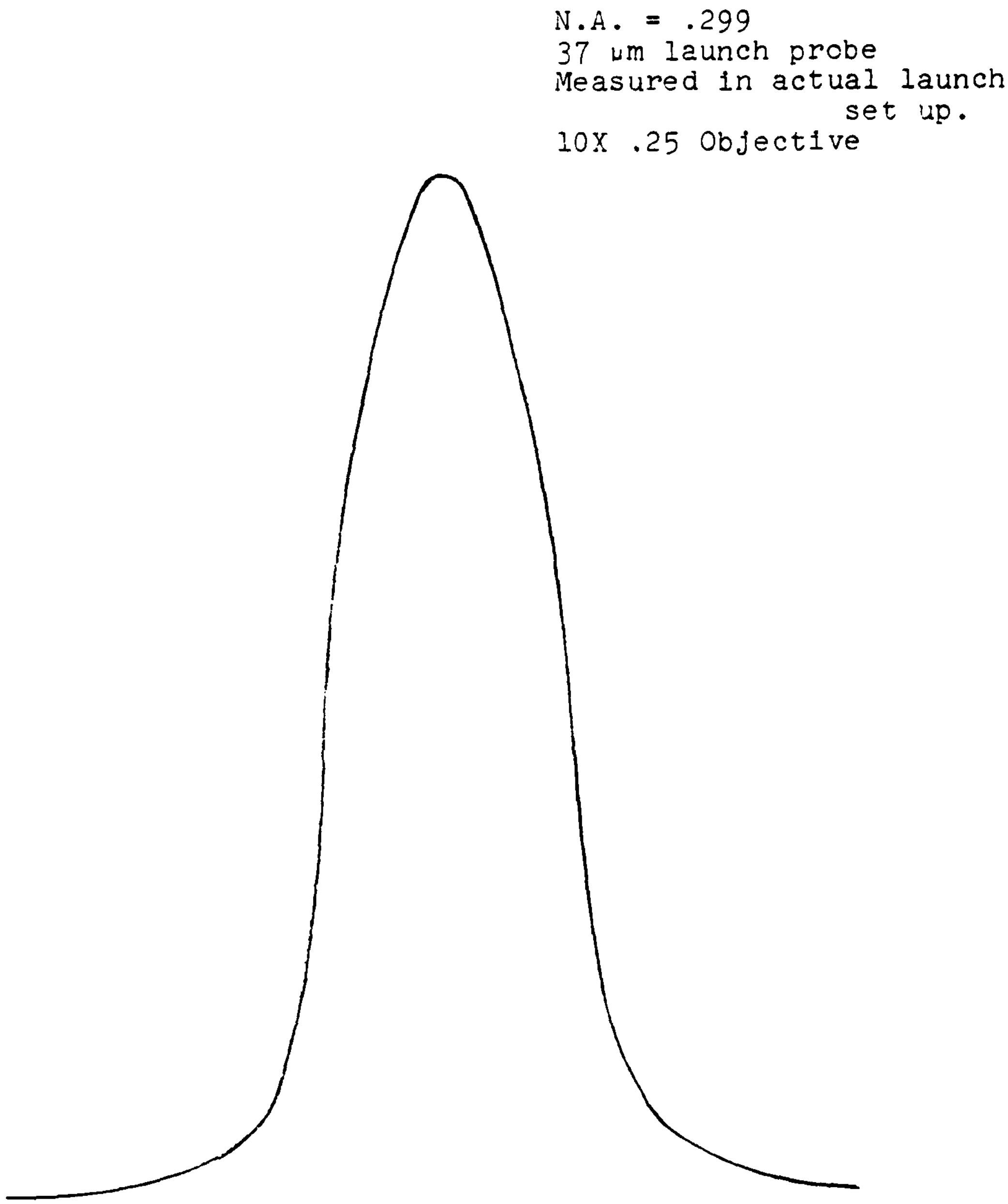


FIGURE 6. W.A. LAUNCH CONDITIONS

TABLE 4. OPTICAL SUMMARY FOR ALL FIBERS

	RADC NUMBER						
	2	5	6	7*	8	9	Desired Properties
N.A. Central Core	.208	.204	.247		.255	.230	>.2
Ring Core	.187	.225	.238		.249	.218	>.2
Sample Length	2m	2m	2m		2m	2m	Not Specified
Attenuation db/km							
Central Core							
@ 850 nm	10.93	15.45	10.84		11.58	17.05	≤ 6 @ 850 nm
@ 1300 nm	18.32	21.20	14.19		18.00	22.46	≤ 2 @ 1300 nm
Ring Core							
@ 850 nm	11.4	6.85	5.10		12.57	12.33	Not specified
@ 1300 nm	13.8	16.87	11.40		12.62	8.07	
Sample Length(m)	560	133	271	1055	325	300	
3 db/km Bandwidth							
Central Core	40	23	17	85	107	28	> 100
Ring Core							
Sample Length(m)	560	133	271	1055	325	1369	
Crosstalk	-33	-41.3	-24.8	-31.8	-48.7	-49.4	> -30 db
(db)	-39	-41.6	-23.4	-30.4	-50.2	-51.7	Core to Ring
Sample Length(m)	2500	2	2	2	2	2	
Final Length(m)	193 115	133 296	501 166 271 266		318	1069 296	> 1000

* Fiber was given to RADC for testing.

TABLE 4. OPTICAL SUMMARY FOR ALL FIBERS (CONTINUED)

	RADC NUMBER						
	10	12	13	14	16	17	Desired Properties
N.A. Central Core	.224	.226	.246	.232	.241	.232	>.2
Ring Core	.213	.219	.248	.226	.230	.211	>.2
Sample Length	2m	2m	2m	2m	2m	2m	Not specified
Attenuation db/km							
Central Core							
@ 850 nm	13.38	9.74	5.46	11.33	12.36	11.83	≤6 @ 850 nm
@ 1300 nm	11.38	21.37	21.82	7.14	17,84	17.85	≤2 @ 1300 nm
Ring Core							
@ 850 nm	10.63	9.70	6.96	8.37	13.59	8.80	Not specified
@ 1300 nm	14.27	25.61	14.06	25.15	24.08	13.85	
Sample Length(m)	300	290	300	300	300	300	
3 db/km Bandwidth							
Central Core	35	28	21	17	21	25	> 100
Ring Core							
Sample Length(m)	859	632	300	300	300	300	
Crosstalk	-39	-40	-30.4	-42.05	-25.3	-36.2	> -30 db
(db)	-37.5	-42.05	-30.3	-41.99	-26.7	-38.9	Core to Ring
Sample Length(m)	2	2	2	2	2	2	
Final Length(m)	559	296	296	817	660	1038	> 1000
	296	632	655	298	291	296	

* Fiber was given to RADC for testing.

TABLE 5. DELIVERED FIBER SUMMARY

Test Description	Delivered Fiber Test Summary #12	#13	#17	Desired Properties
N/A. Central Core	.226	.246	.232	>.2
Ring Core	.219	.248	.211	>.2
Sample Length(m)	2m	2m	2m	Not specified
Attenuation db/km				
Central Core @ 850 nm	9.74	5.46	11.83	≤ 6
@ 1300 nm	21.37	21.82	17.85	≤ 2
Ring Core @ 850 nm	9.70	6.96	8.80	Not specified
@ 1300 nm	25.61	14.06	13.85	
Sample Length	290	300	300	
3 db Bandwidth Central Core	28 MHz	21 MHz	25 MHz	>100
Sample Length(m)	632	300	300	
Crosstalk (-db)	-40 -42.05 2m	-30.4 -30.3 2m	-36.2 -38.9 2m	< - 30 db Core to Ring
Final Length(m)	296m 632m	296m 655m	1038m 296m	

Finally, several lengths of concentric core optical fiber were drawn and characterized for geometrical and optical properties, and delivered for evaluation.

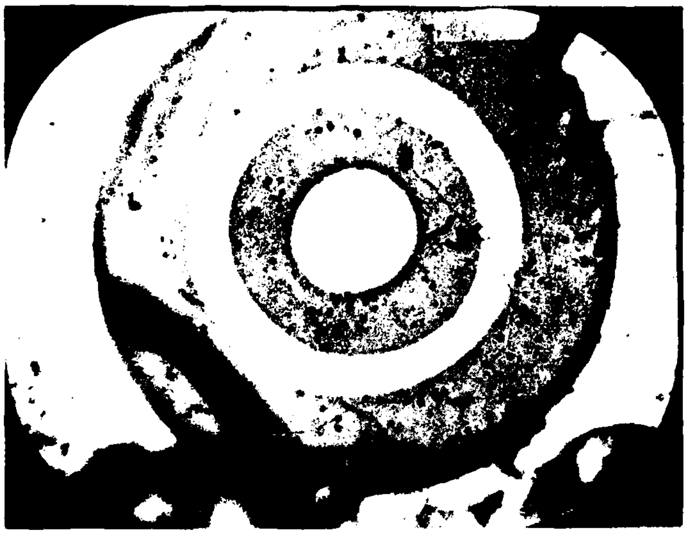
5.0 RECOMMENDATIONS

It is recommended that a relatively large number of concentric core preforms be fabricated using identical gas flow rates, and number of deposition passes. This would establish the repeatability of the fabrication process in regard to the geometrical properties in the drawn fiber. It would also allow for further testing of the repeatability in the optical characterization, i.e. numerical aperture, bandwidth, attenuation, and optical cross talk. The gas flow rates and number of deposition passes that produced the highest bandwidth characteristics should be chosen for this initial production phase, because additional correlation needs to be made between the number of deposition passes and the bandwidth of the central core. Another point to be addressed involves the high attenuation at the 1.3 micron wavelength region. It should be noted that this is near a water absorption peak and that care should be exercised to minimize the water content in the optical preforms.

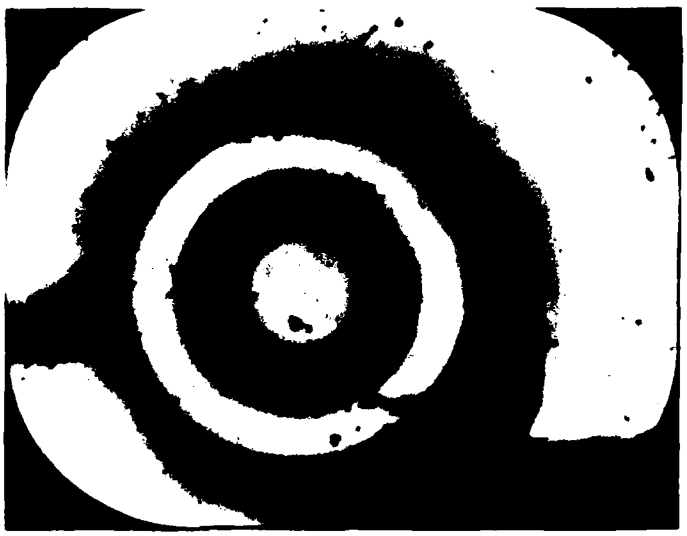
APPENDIX A

PHOTOGRAPHIC RECORDS OF FIBER GEOMETRY

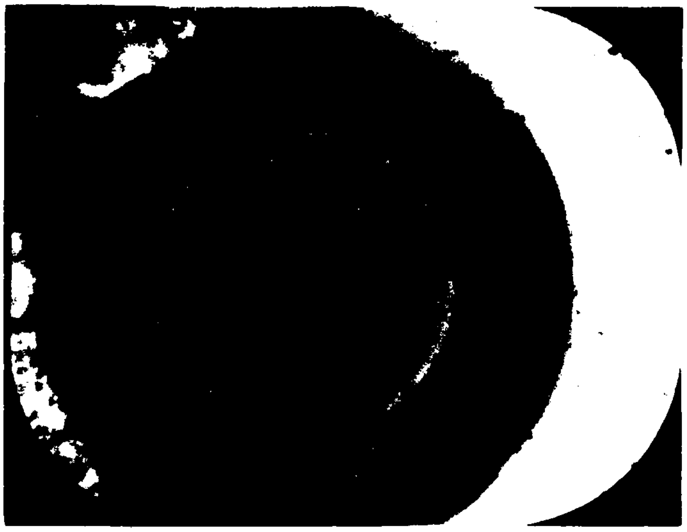
RADC #2 Concentric Core



RADC #5 Concentric Core



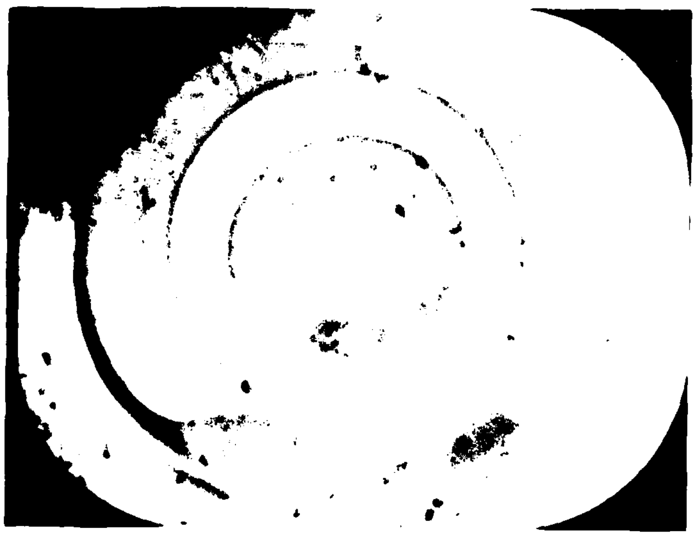
RADC #6 Concentric Core



RADC #7 C.C.
was given to RADC for characterization

RADC #8 Concentric Core

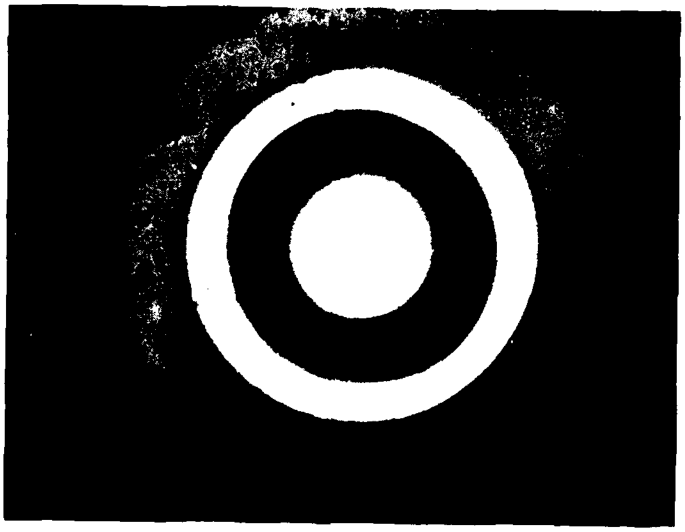
RADC #9 Concentric Core



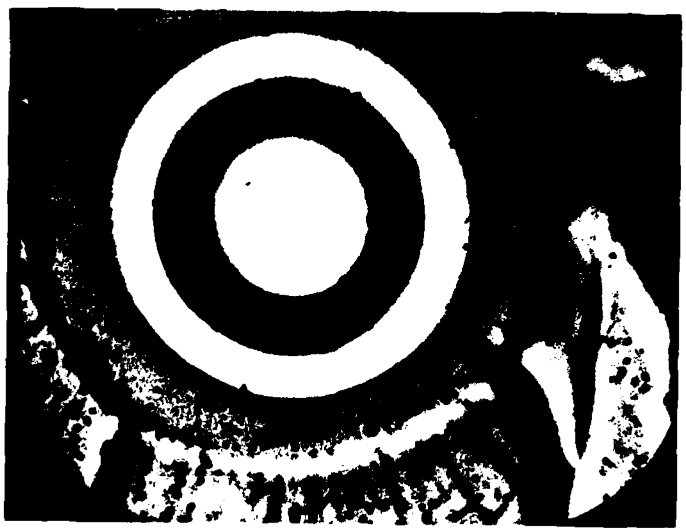
RADC #10 Concentric Core

RADC #12 Concentric Core

RADC #13 Concentric Core

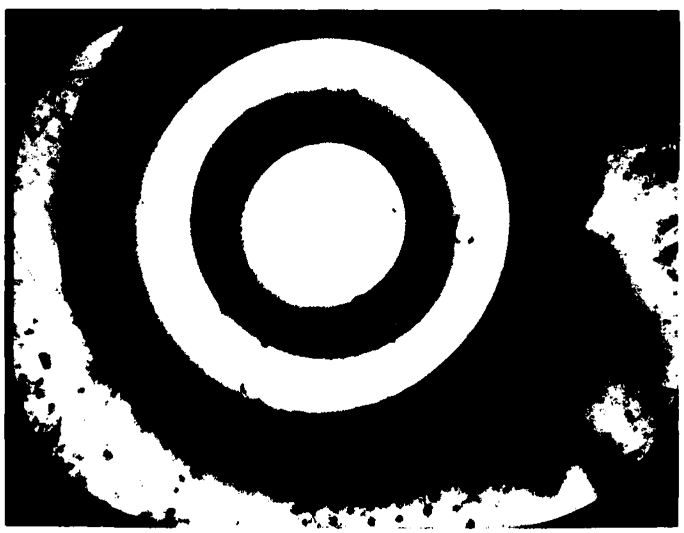


RADC #14 Concentric Core



RADC #16 Concentric Core

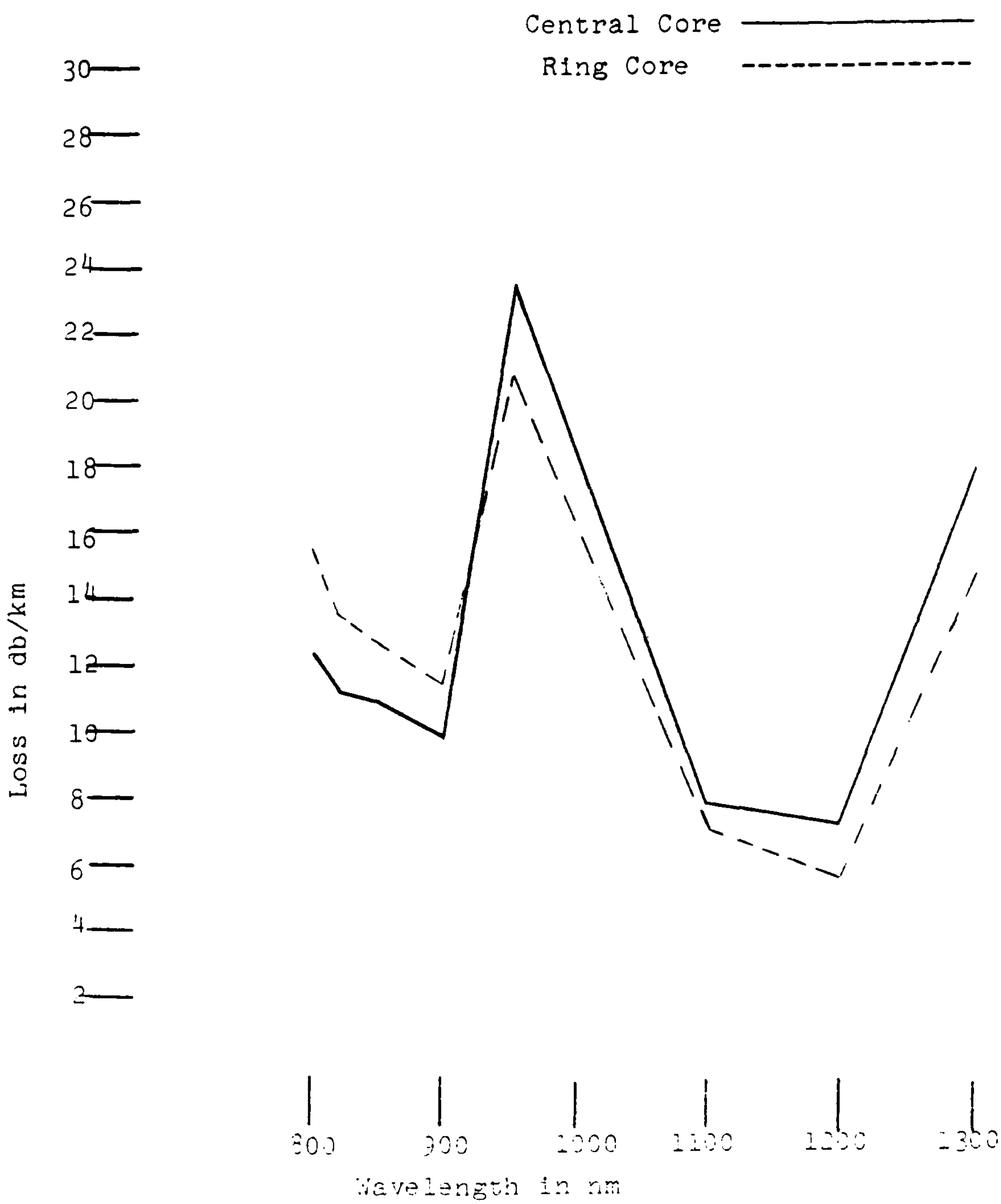
RADC #17 Concentric Core



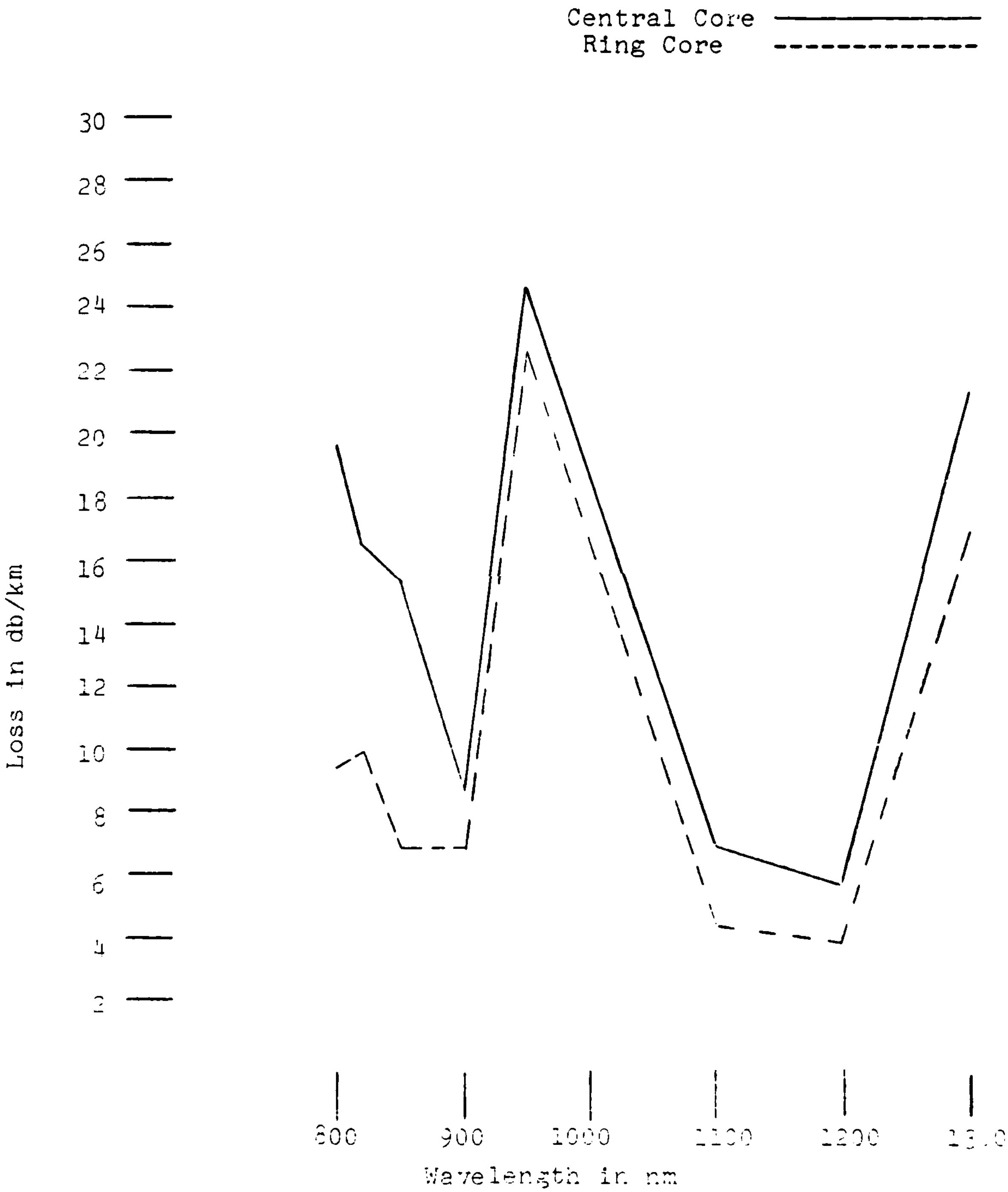
APPENDIX B

ATTENUATION GRAPHS

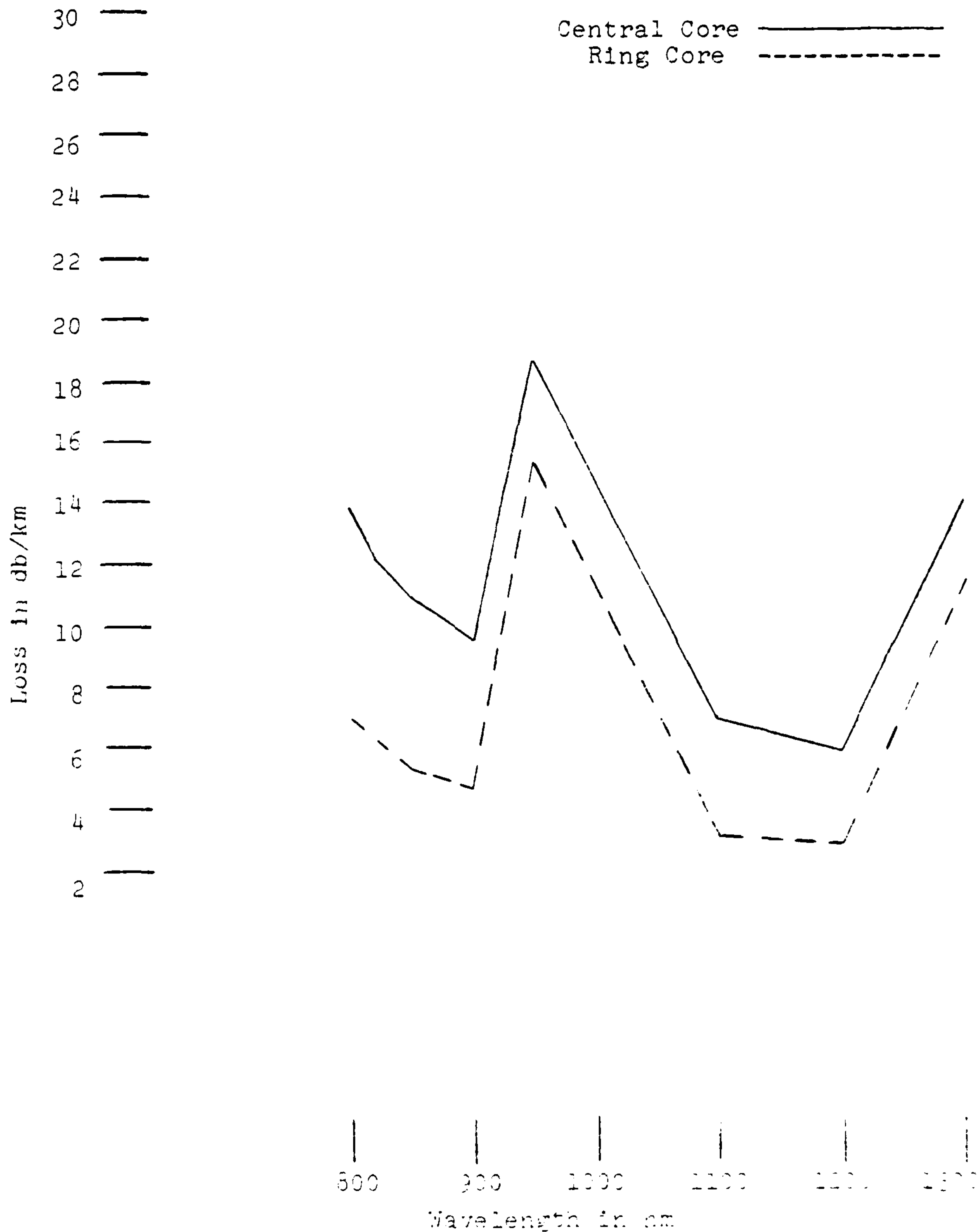
CC #2 Attenuation



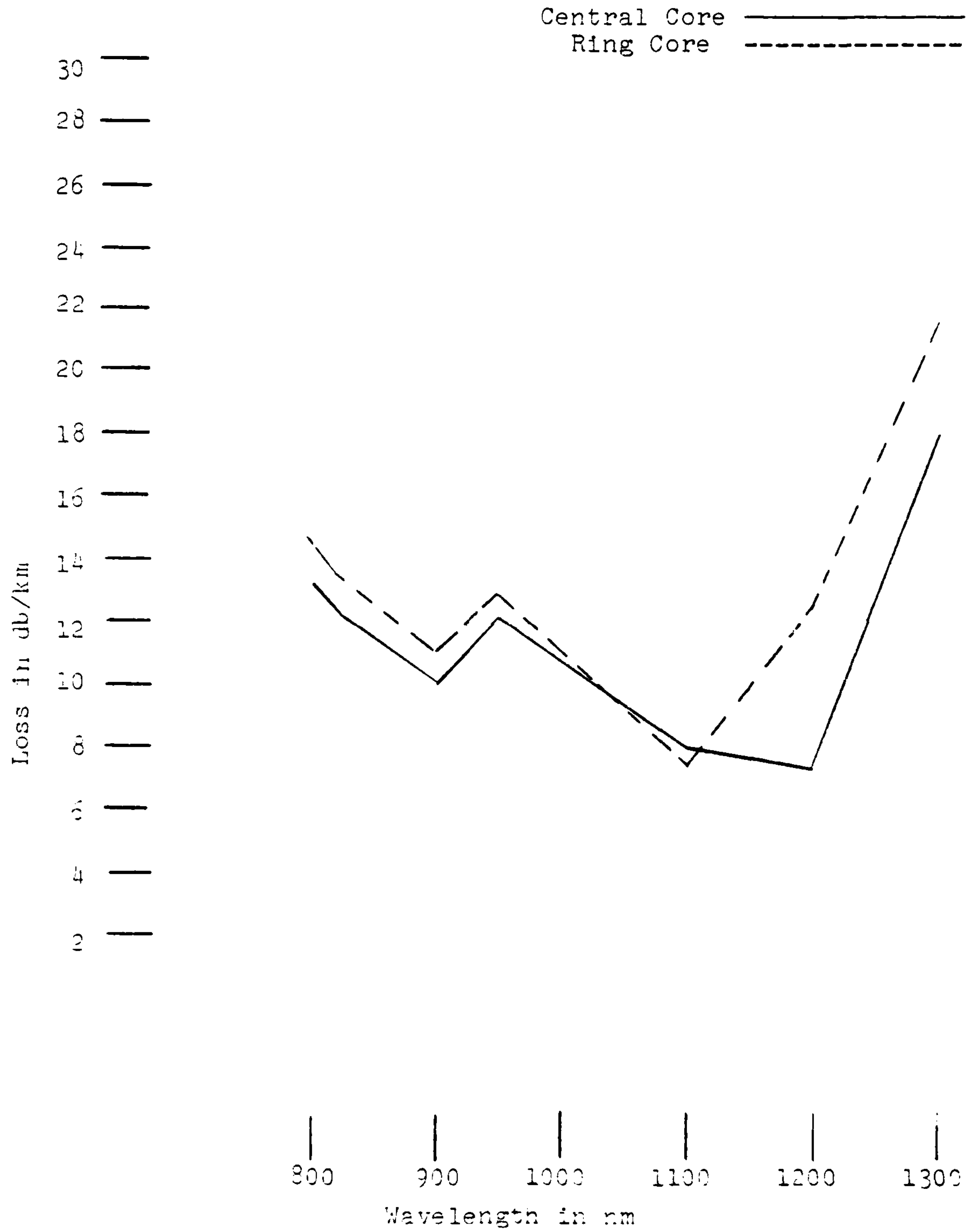
CC #5 Attenuation Plot

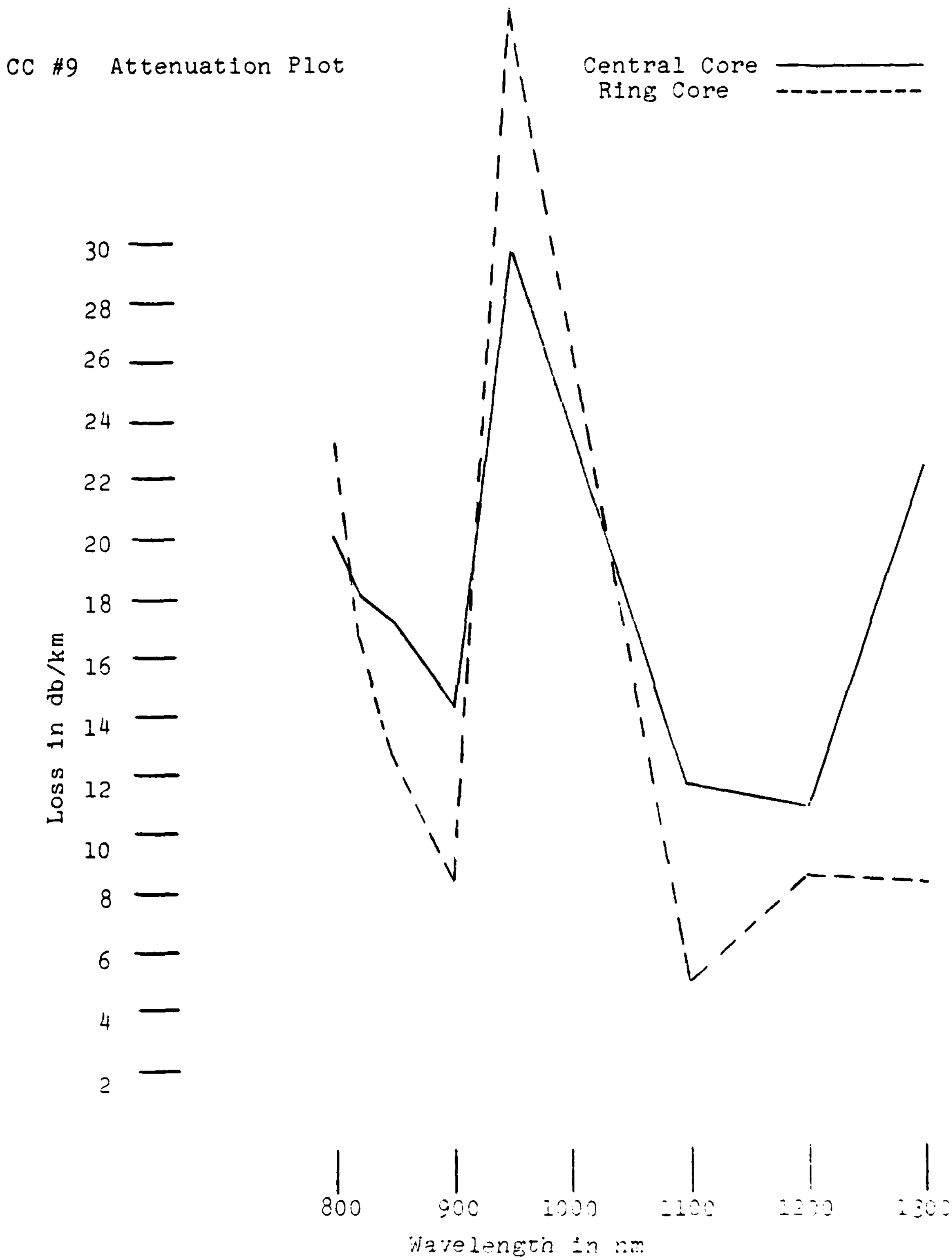


CC #6 Attenuation Plot



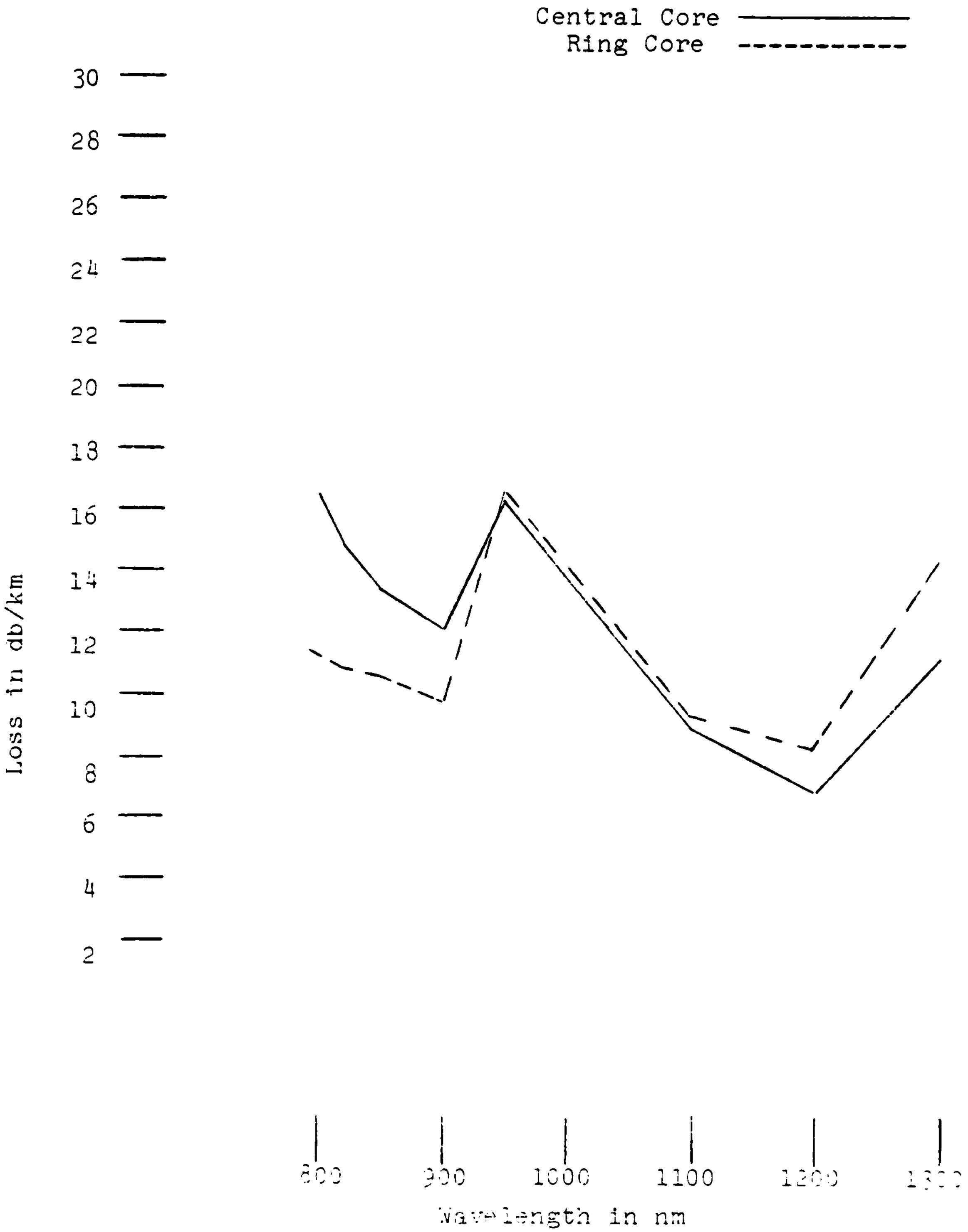
CC #8 Attenuation Plot



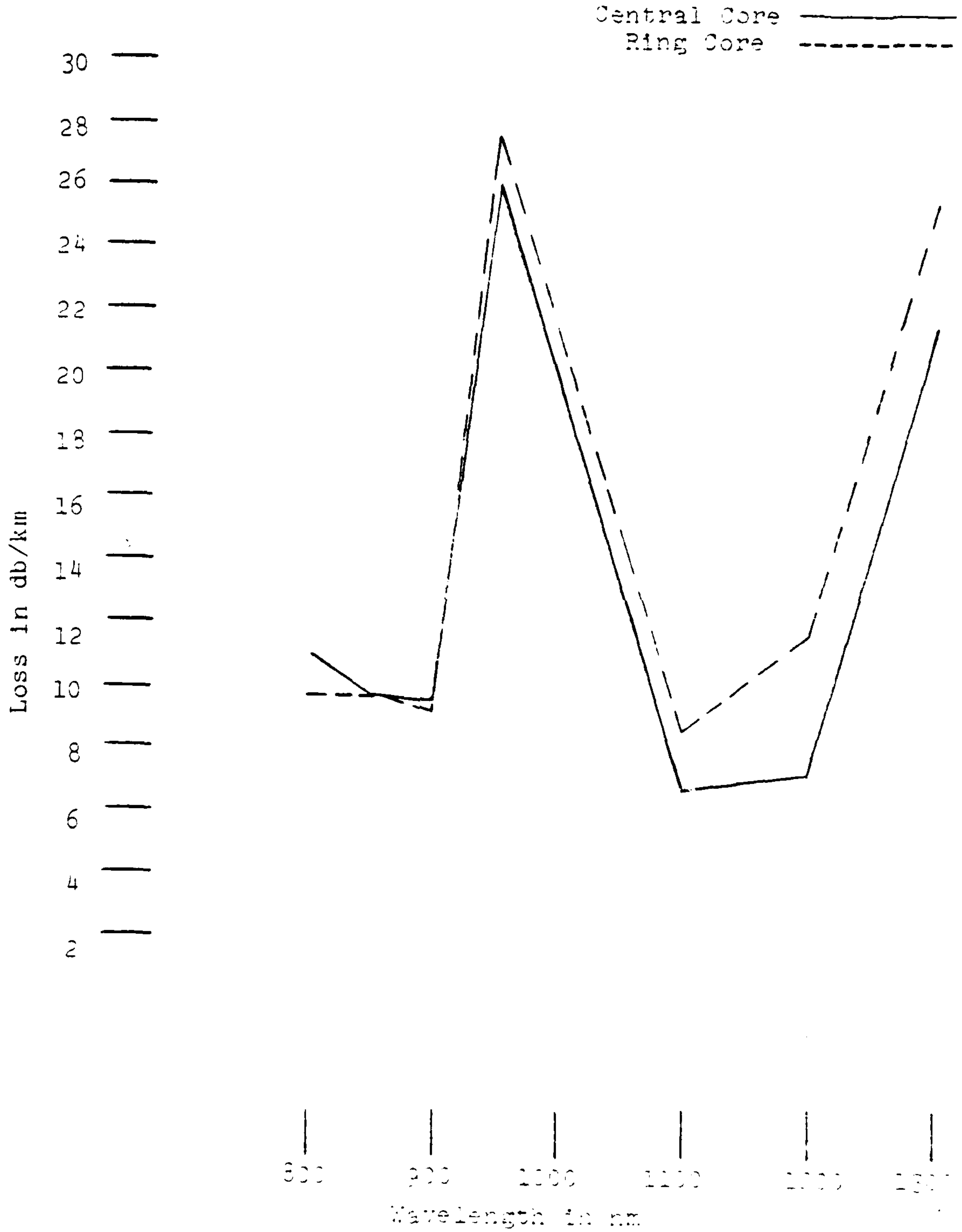


CC #9 Attenuation Plot
Central Core
Ring Core
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
Loss in db/km
800
900
1000
1100
1200
1300
Wavelength in nm

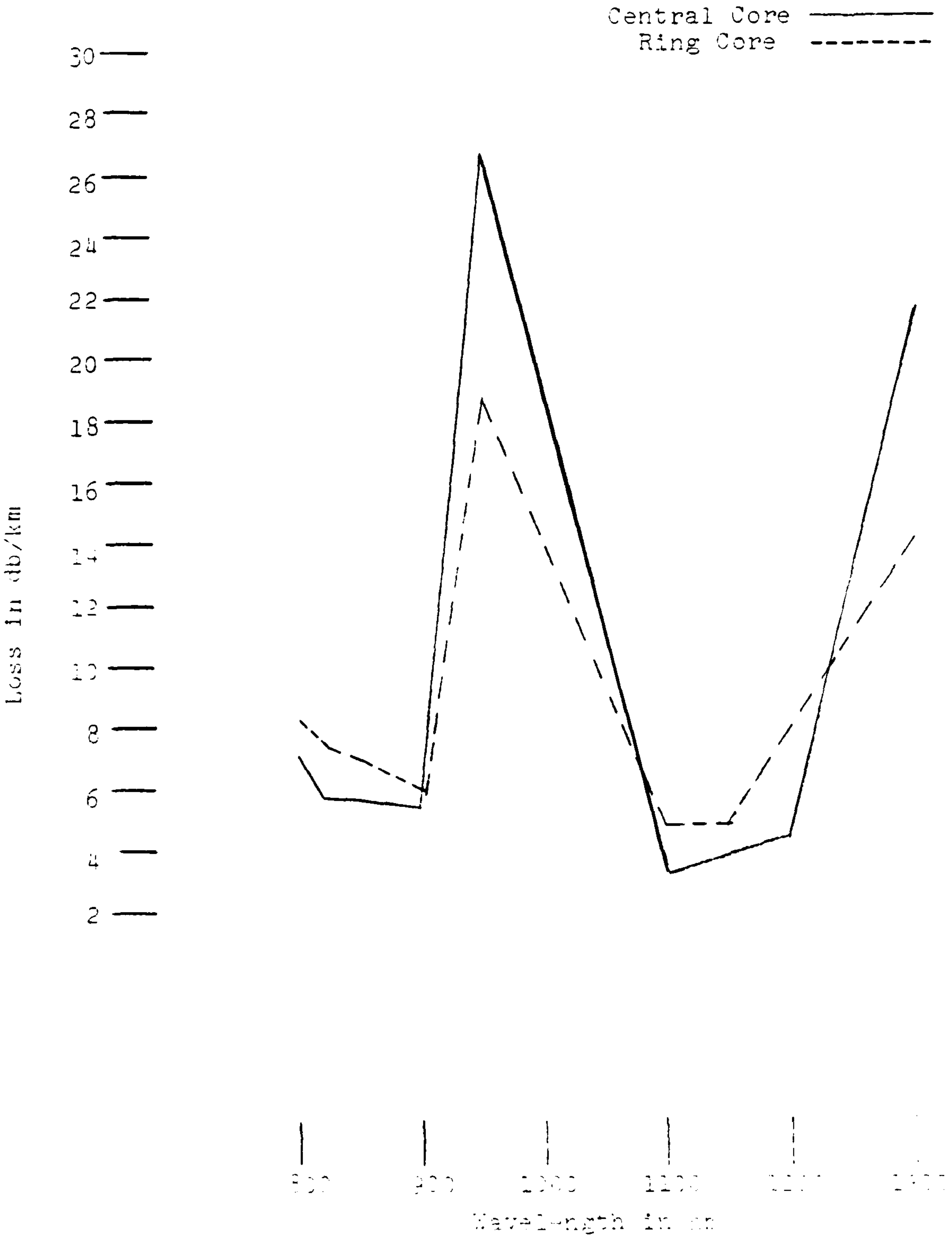
CC #10 Attenuation Plot



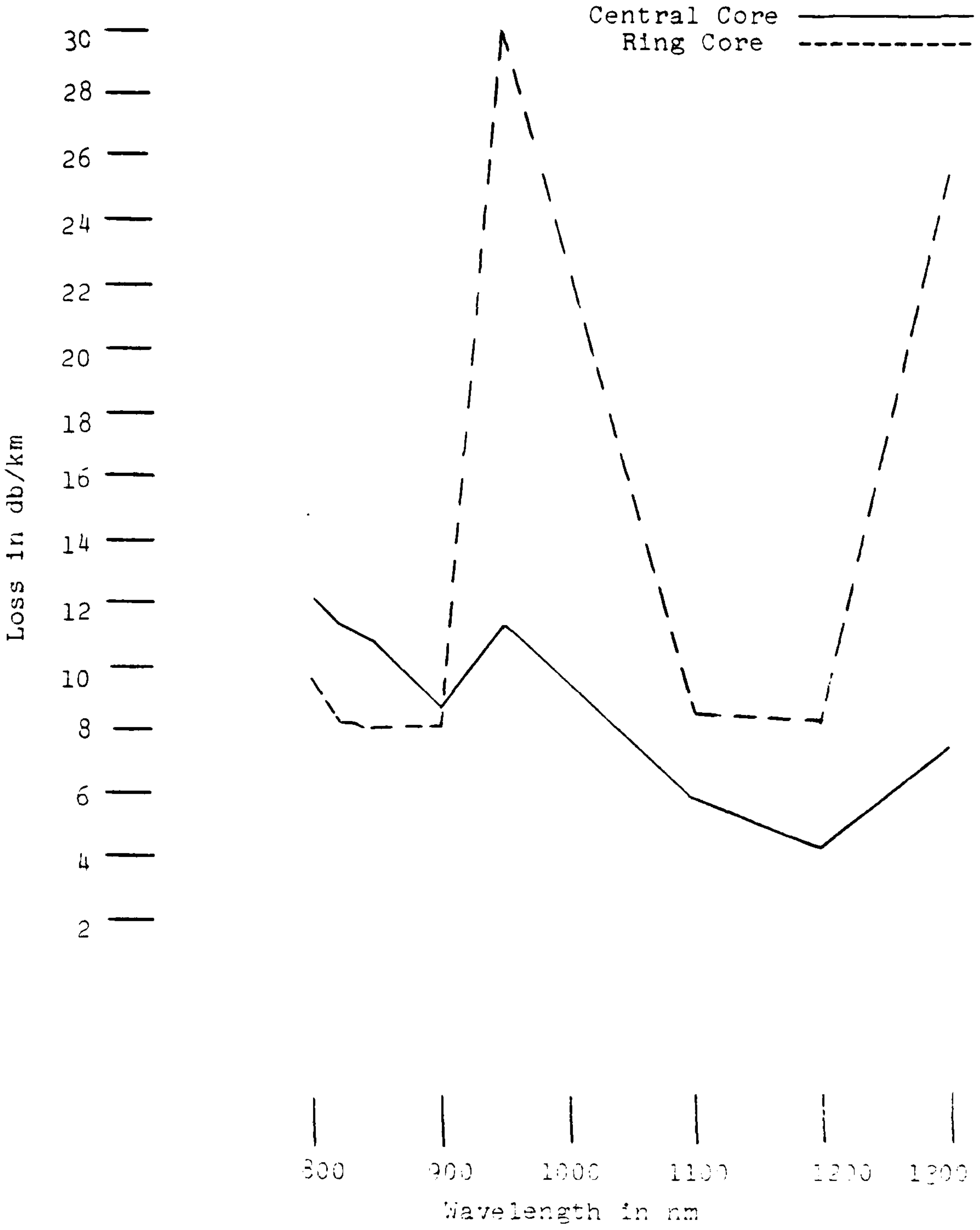
CC #12 Attenuation Plot



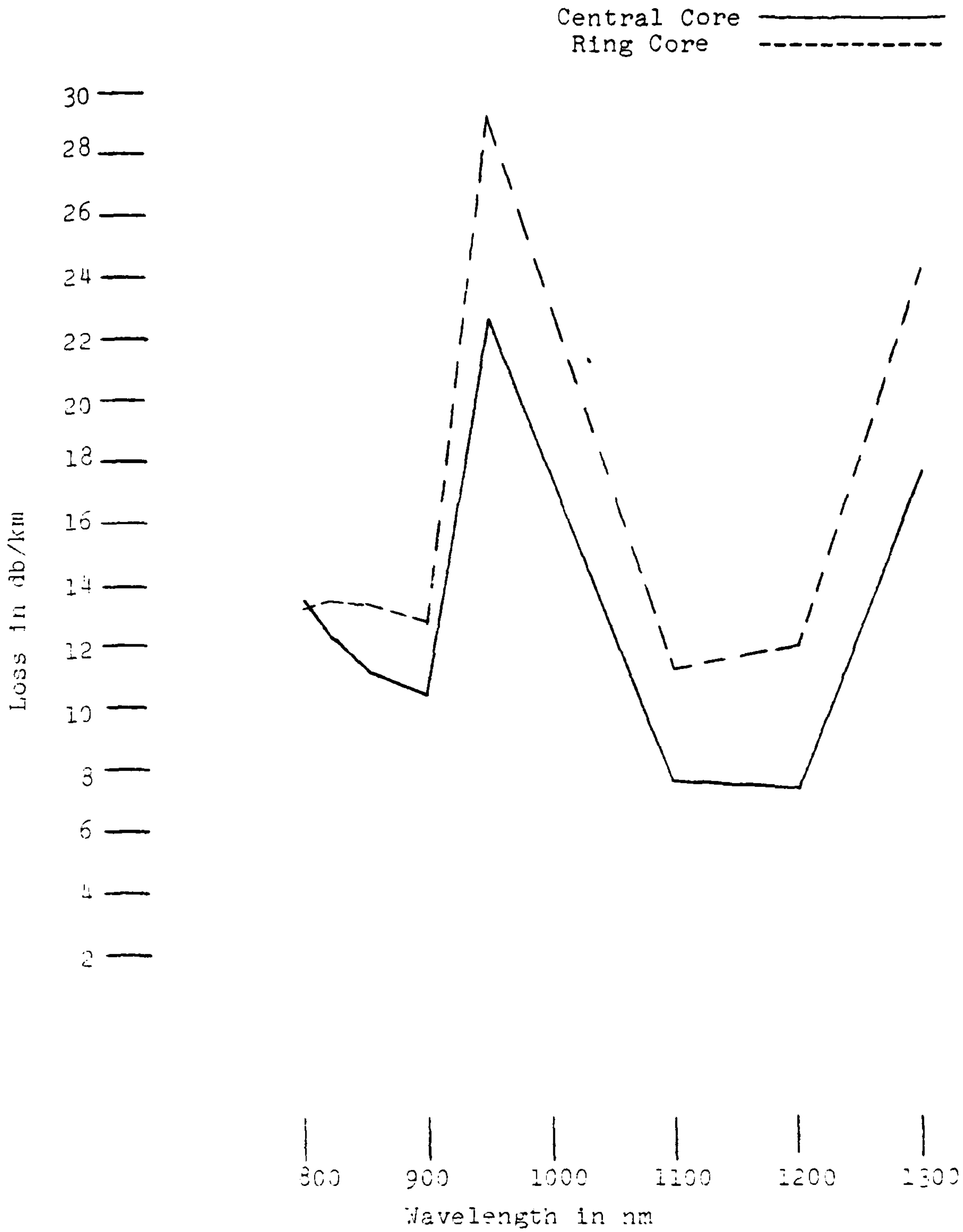
CC #13 Attenuation Plot



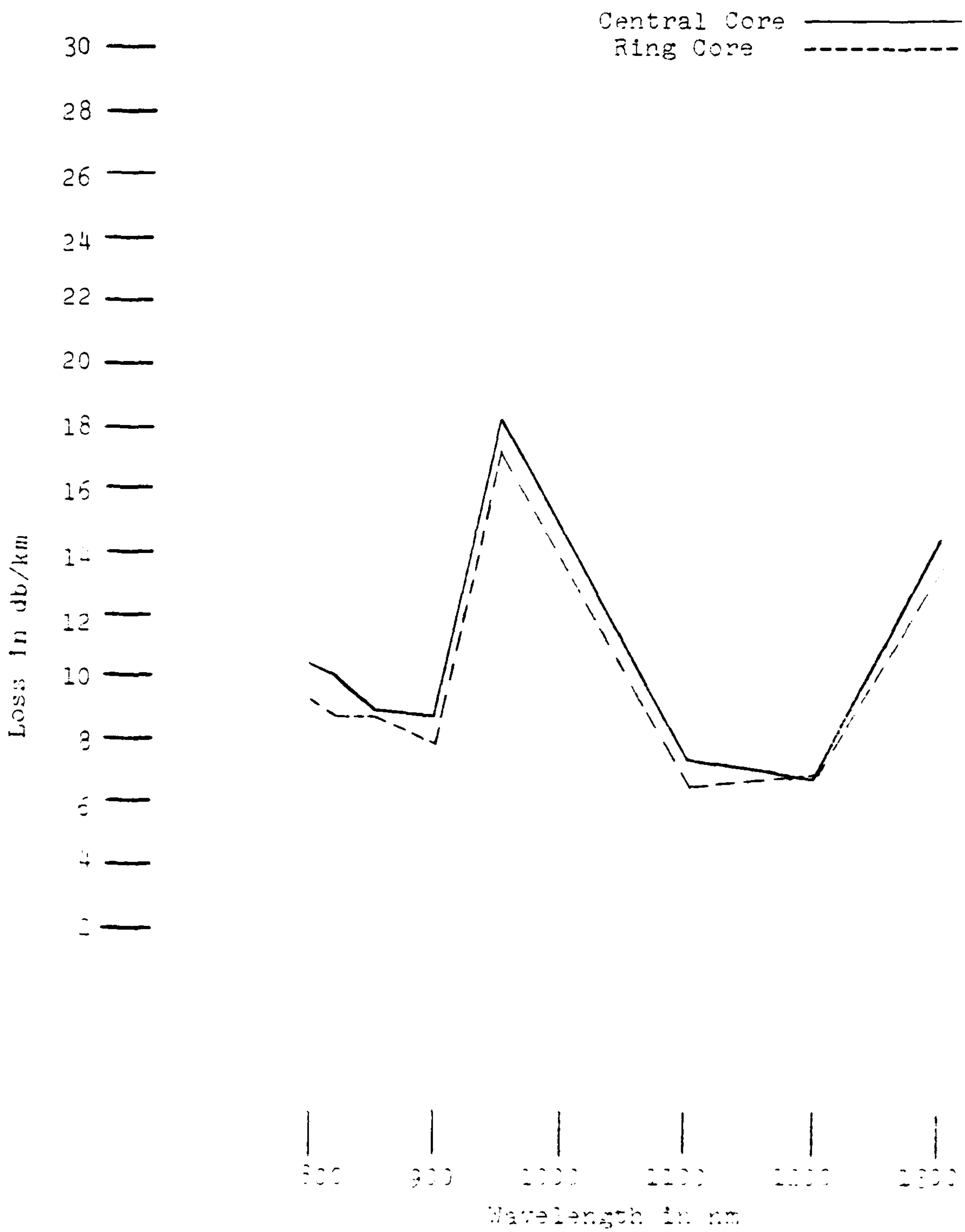
CC #14 Attenuation Plot



CC #16 Attenuation Plot



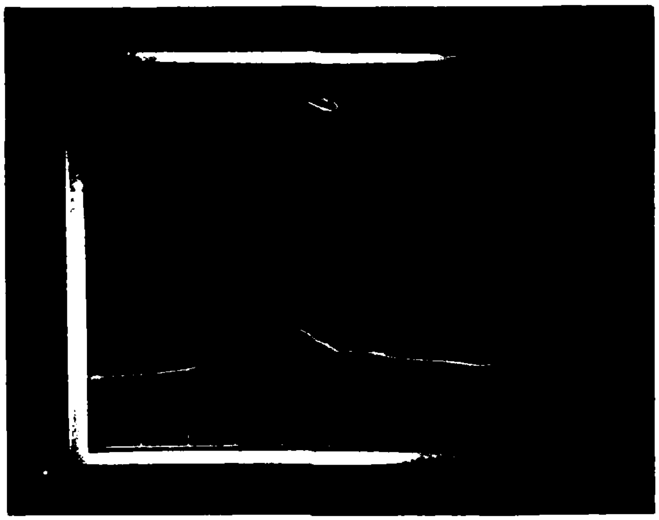
CC #17 Attenuation Plot



APPENDIX C

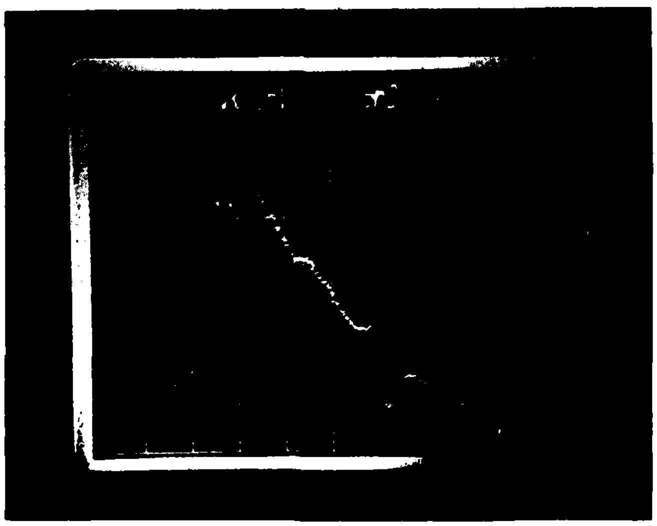
PULSE DISPERSION RESULTS

Concentric Core #2



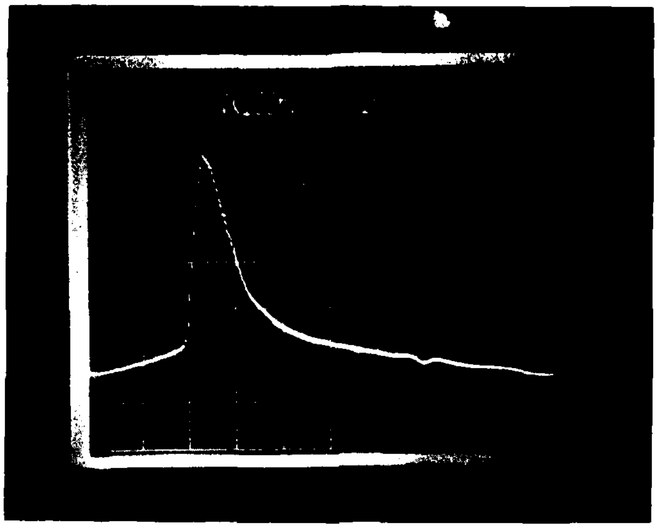
Ref.

Concentric Core #2

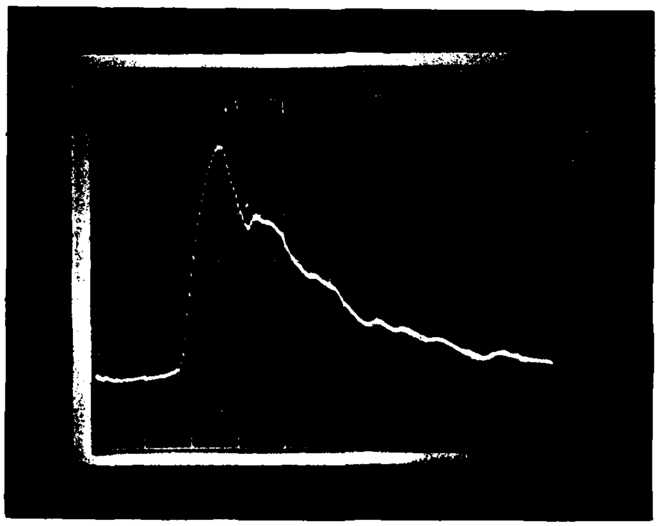


Sample

Concentric Core #6   Ref. 1 ns

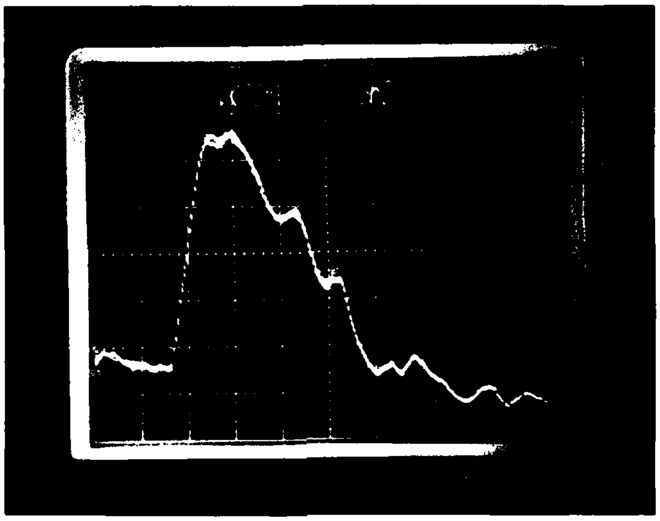


Concentric Core #6   4.4 ns   ℓ 325m

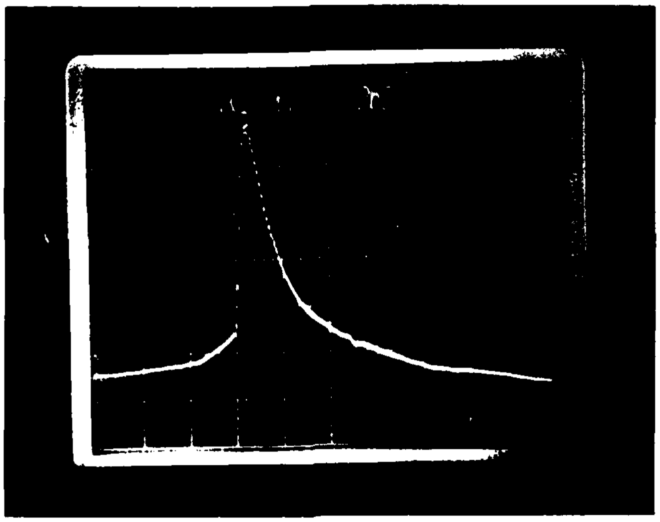


13.2 ns/km   17 mHZ

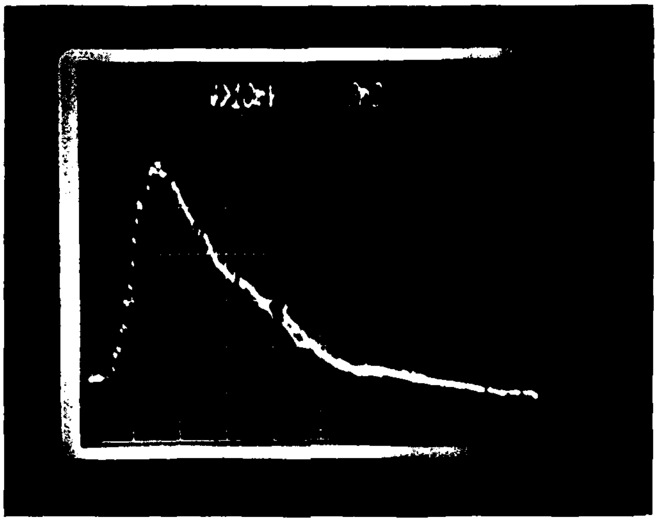
Concentric Core #5 ℓ - 1300μ 13 ns



9.8 ns/km 17 mHZ

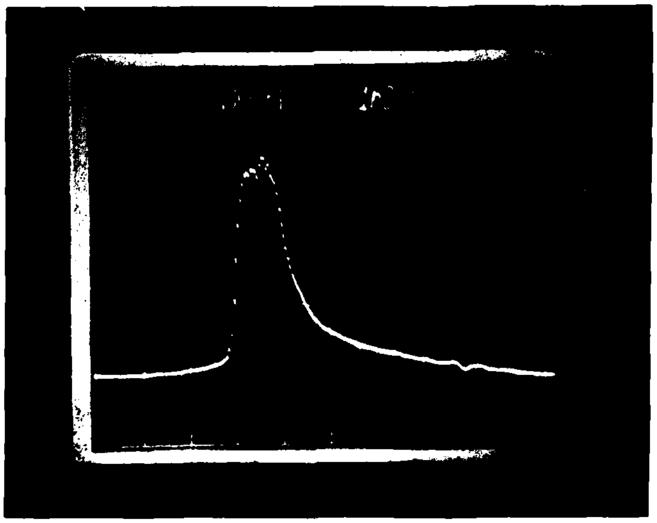


Concentric Core #7 3 ns

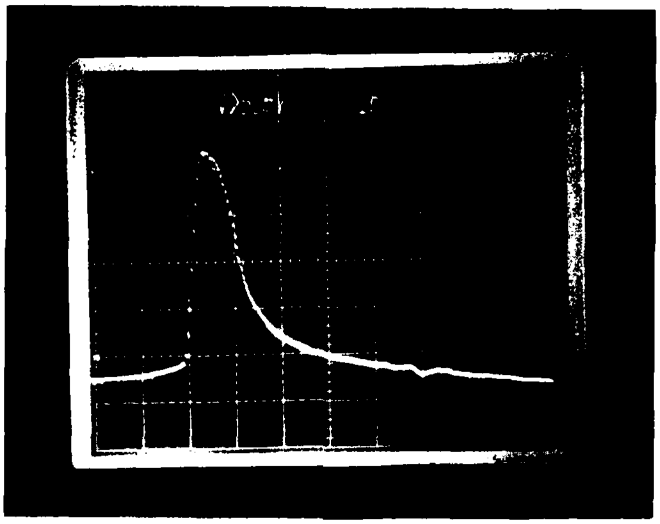


2.6 ns/km = 85 mHZ

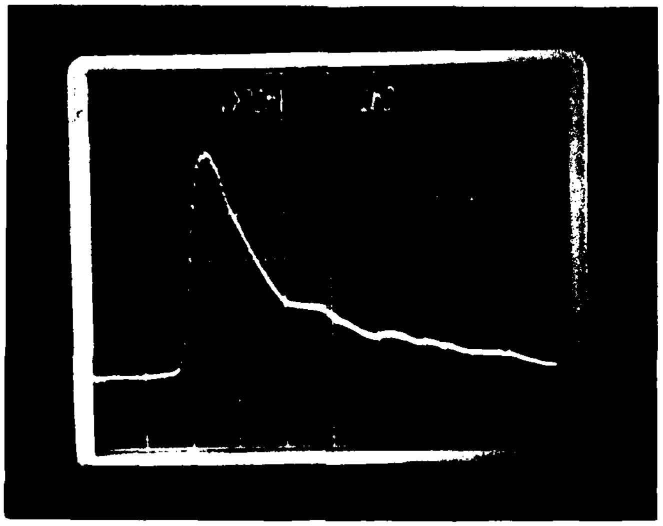
Ref. Concentric Core #7 1 ns



Ref. Concentric Core #8 1 ns

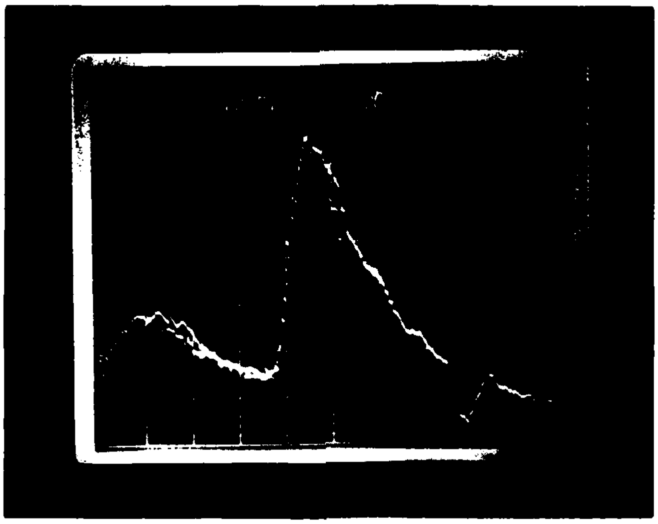


Concentric Core #8 ℓ-325m



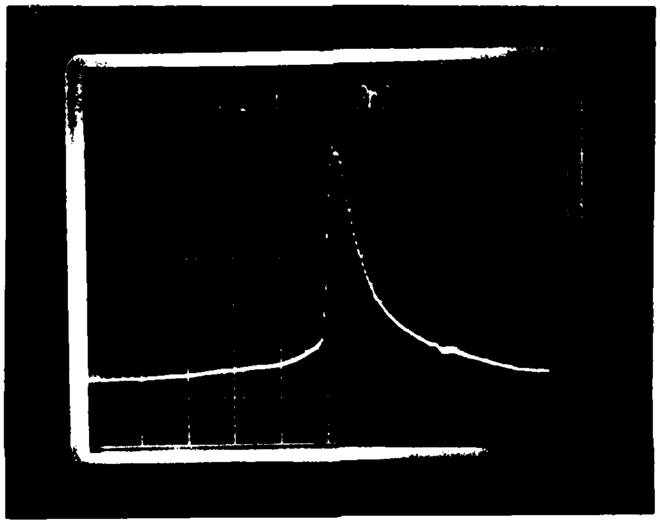
2.04 ns/km 107 mHZ

Concentric Core #9   8.5 ns   ℓ-1069m

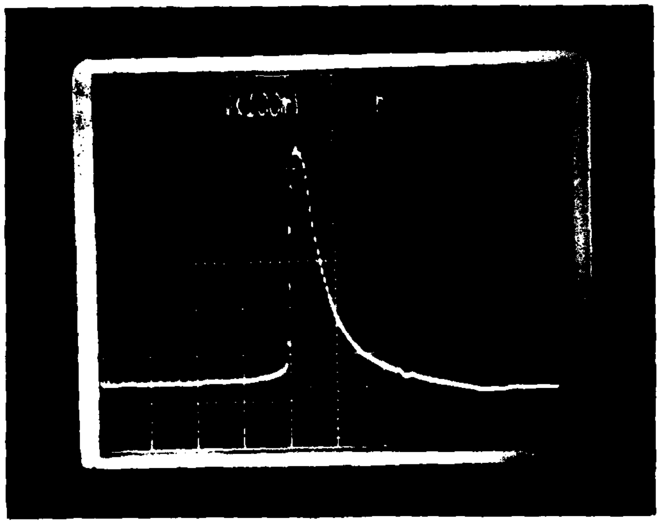


7.7 ns/km   28 mHZ

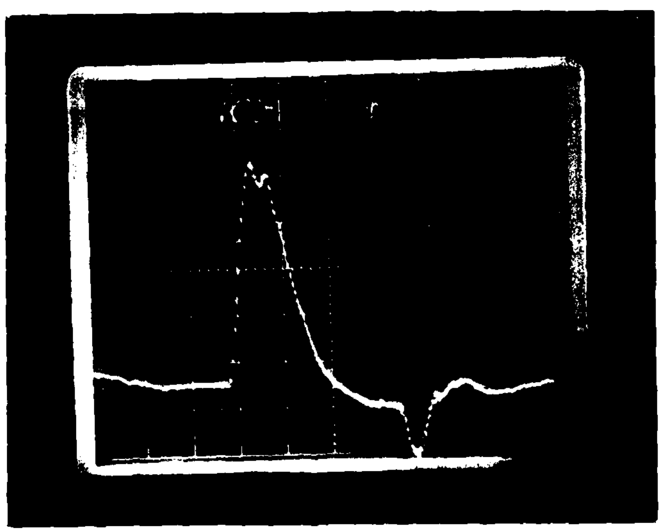
Concentric Core #9 Ref. 1.7 ns



Ref. Concentric Core #10   1.7 ns

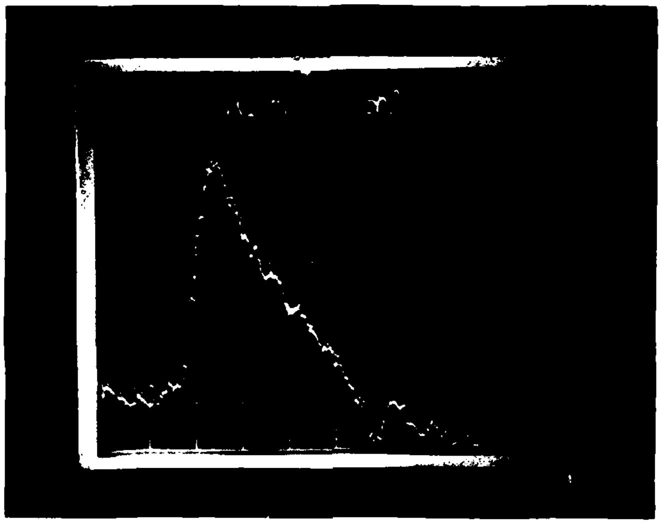


Concentric Core #10   5.7 ns   ℓ-859-4



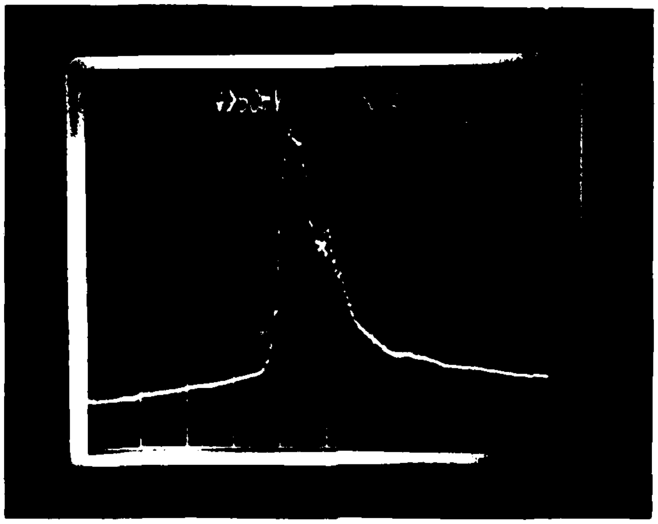
6.3 ns/km   35 mHZ

Concentric Core #12 ℓ-632m 7.5 ns

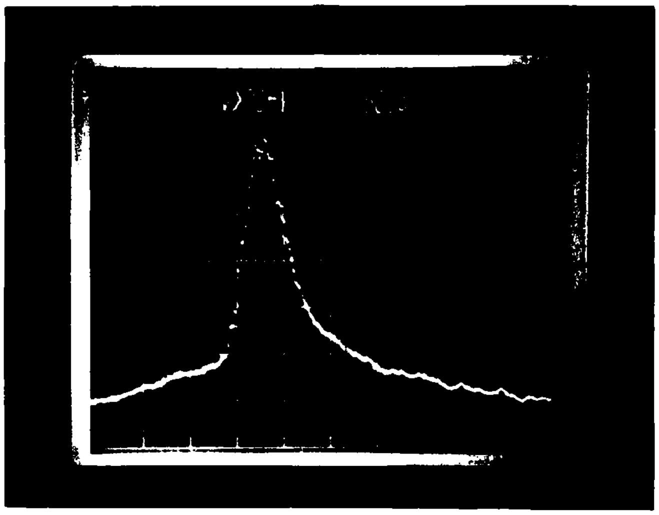


11.82 ns/km 28 mHZ

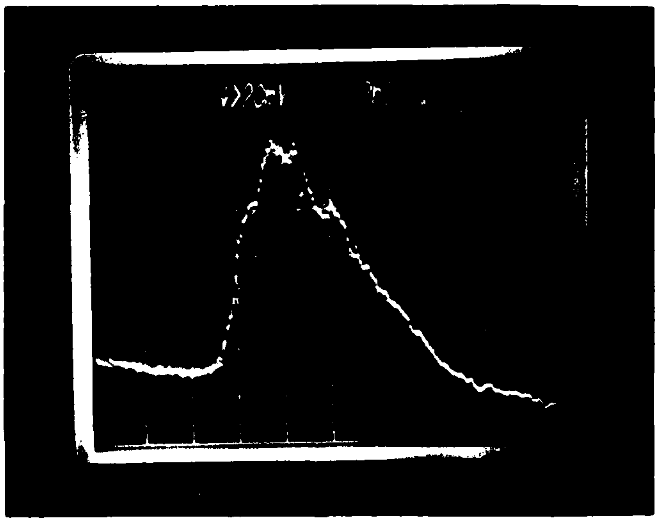
Ref. Concentric Core #12 600 ps



Ref. Concentric Core #13   600 ps

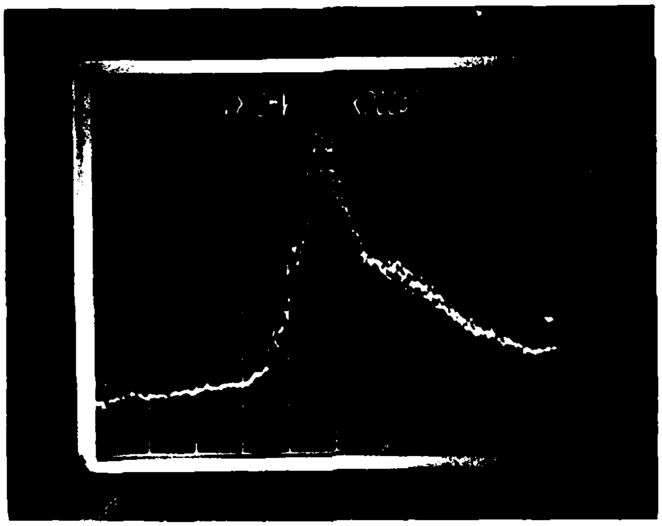


Concentric Core #13 ℓ-300m   5 ns



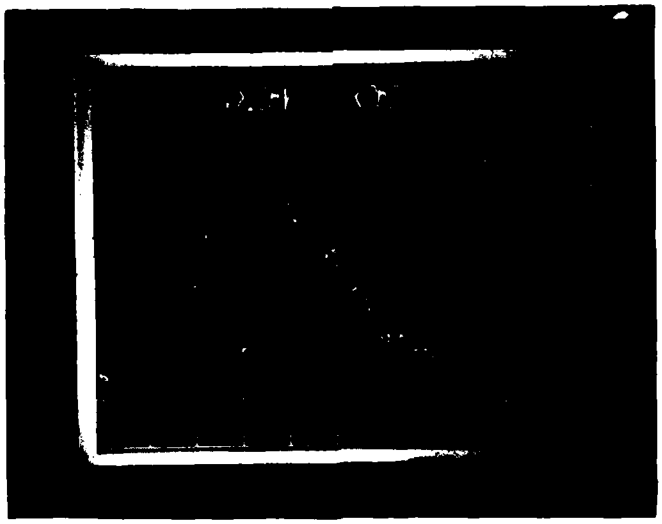
16 ns/km   21 mHZ

Concentric Core #14



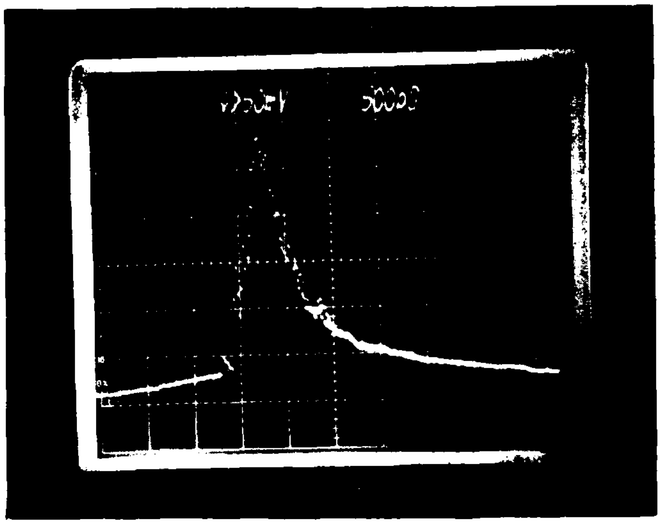
Ref. 400 ps

Concentric Core #14 5.8 ns

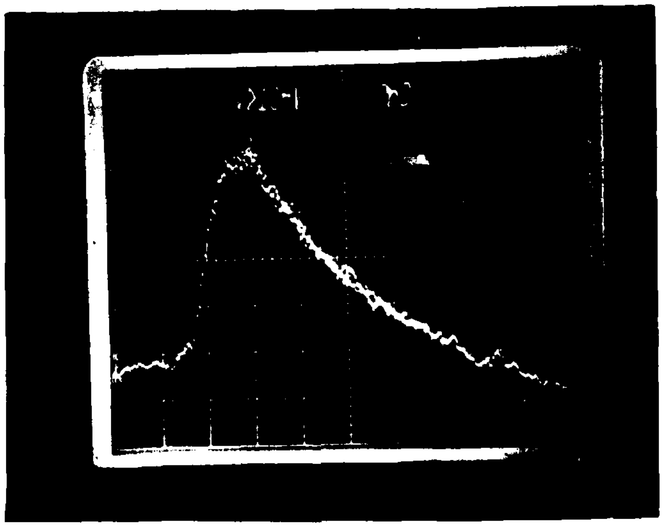


ℓ-300m 17 mHZ 19 ns/km

Concentric Core #16   600 ps

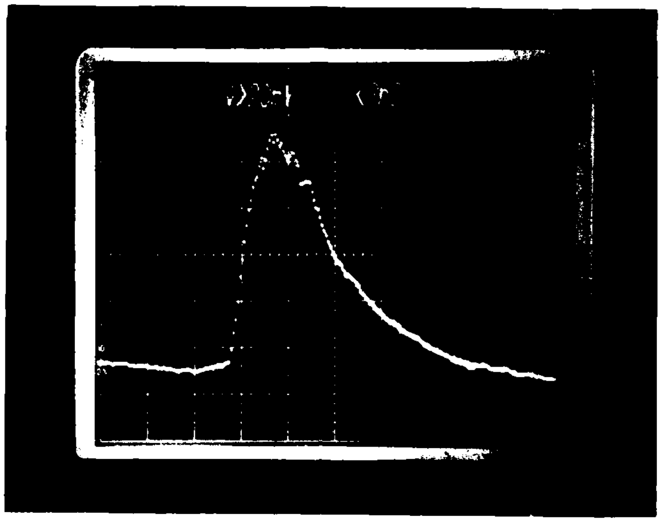


Concentric Core #16 ℓ-300m 5 ns



16 ns/km   21 mHZ

Concentric Core #17   4.0 ns



13.18 ns/km   25 mHZ (.33 factor)

NOTE: Reference for C.C. #17 is the same as C.C. #16.

2-8

DT