A LAB REPORT ON

OPTICAL FIBER CHARACTERIZATION

PSE60A: PHOTONICS LAB TECHNIQUES

Submitted by

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INDEX

Experiment -I

Objective:

Following are the objectives of the experiment:

1. Optical Fiber Coupling Loss for Single Mode Fiber
2. Bending loss for single mode optical fiber
3. NA determination of single mode optical fiber at two different positions.
4. Misalignement loss determination for single mode optical fiber:
   a. Longitudinal misalignment
   b. Transverse misalignment
   c. Angular misalignment

Apparatus Required

1. He-Ne Laser
2. Focusing objective (20X)
3. Optical fiber with alignment with (x, y, z & angular) mounts (quantity 2)
4. Translation stage
5. Photo-detector with mount
6. Digital multi-meter

Theory:

Optical fibers, which are made by drawing glass (silica), are flexible and transparent fibers widely utilized for transmitting light between two endpoints in fiber-optic communications. Apart from this, specially designed optical fibers are also utilized for various other purposes such as fiber optic sensors and fiber lasers.

The structure of an optical fiber consists of a transparent core surrounded by a transparent cladding material that has a lower index of refraction than the core. This design allows light to be confined within the core through the phenomenon of total internal reflection, causing the fiber to act as a waveguide. As light enters the fiber at a particular angle, it propagates along the length of the fiber until it emerges from the other end. To ensure effective propagation, the incident angle of light on the fiber's end surface can be easily determined using the ray model of light.

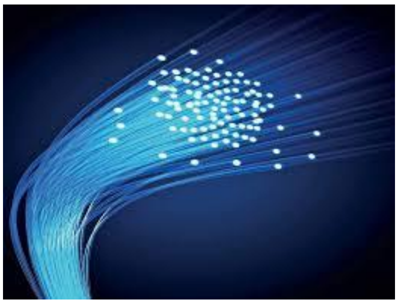


Fig 1: Representative picture of optical fibers

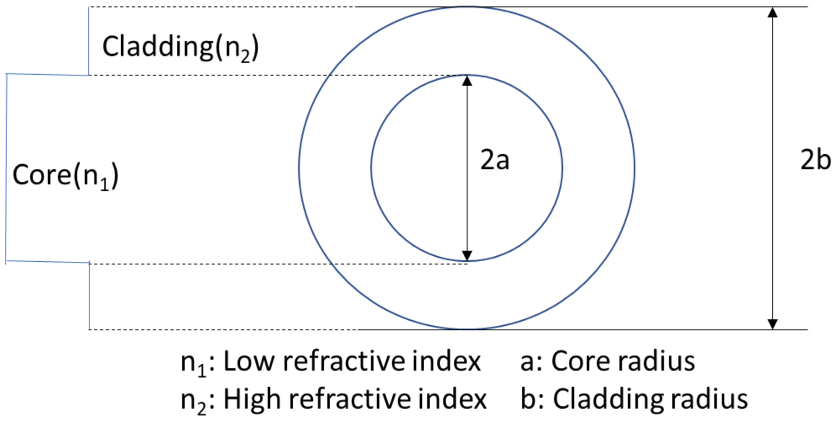


Fig 2: Optical fiber (single clad-step index): refractive index profile & cross section

Working principle

Snell's law is a principle that explains how light bends when it passes through two transparent materials with uniform indices of refraction. If a ray of light travels from a medium with a refractive index of n_1 to a medium with a refractive index of n_2, and the angle of incidence and refraction are θ_1 and θ_2, respectively, then Snell's law states that:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

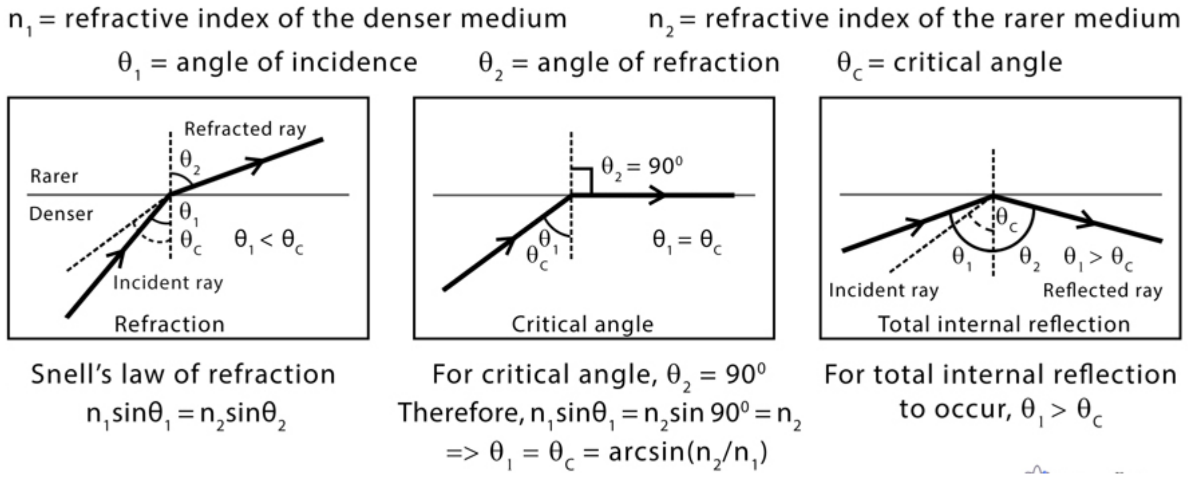


Fig 3: Principles of fiber optics

When n1 is greater than n2, if the angle of refraction θ_1 is increased, the angle of refraction θ_2 will continue to increase until it reaches a critical point. At this critical angle ($\theta_1 = \theta_c$), the refracted angle θ_2 becomes $\pi/2$, and the refracted ray follows the interface. The angle $\theta_1 = \theta_c$ is known as the critical angle. Consequently, Snell's law can be expressed as:

$$n_1 \sin \theta_1 = n_2 \sin \pi/2$$

$$\sin \theta_1 = n_2 / n_1$$

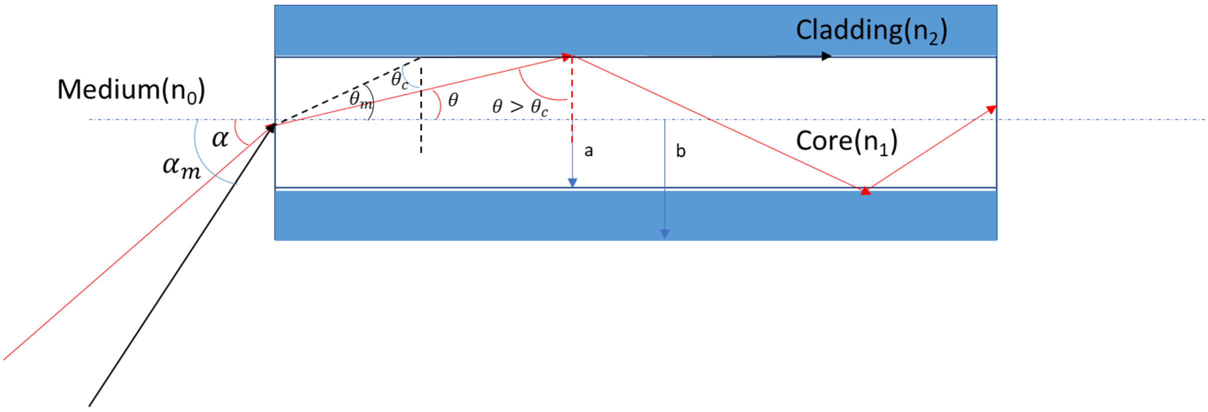


Figure 4: Ray propagation in optical fiber (step index side view)

The principle of Snell's law also applies to the propagation of light in optical fibers. In the case of a step index fiber, the refractive index is a function of radial distance, with a step change at the core-cladding interface.

Suppose a step index fiber is immersed in a medium with a refractive index of n_a, and the refractive indices of the core and cladding are n_1 and n_2, respectively, with $n_1 > n_2 > n_a$. If a light ray enters the flat end of the fiber at an angle α, it will bend towards the axis, creating an angle θ. This bent ray will strike the interface between the core and cladding at an angle θ. If the angle of incidence θ equals the critical angle θ_c, the light ray will undergo total internal reflection and continue to propagate through the fiber until it emerges from the other end.

The propagation of light through the above phenomenon requires an angle of incidence θ that is greater than the critical angle θ_c, and thus the bending angle θ must be less than a certain angle $\theta_m = \pi/2 - \theta_c$. Therefore, the angle of incidence α must be within a certain range, which corresponds to the limiting value of $\theta_m = \pi/2 - \theta_c$. This maximum value of α is known as the angle of acceptance, which is the cone angle within which all the light will be collected and transmitted through the fiber. Using Snell's law, it can be observed that:

$$n_\alpha \sin(\alpha_m) = n_1 \sin(\theta_m) = n_1 \cos(\theta_c)$$

$$n_\alpha \sin(\alpha_m) = \sqrt{(n_1^2 - n_2^2)} = N.A.$$

The numerical aperture (N.A.) of a fiber determines its light-gathering ability, also known as the light-gathering capacity. When the emitted power of the fiber decreases to 5% (or $1/e^2$) of its original power, the angle of acceptance is achieved, as per the definition.

2. Bending loss in Single mode optical fiber:

Bend losses pose a common challenge in waveguides, especially in fiber optics, as fibers can be bent with ease. When fibers are bent, they suffer from additional propagation losses, as light is coupled from core modes (guided modes) to cladding modes. Once a critical bend radius is reached, these losses increase rapidly. For fibers with strong guiding properties (high numerical aperture), the critical radius can be very small (a few millimeters). On the other hand, for single-mode fibers with large mode areas, the critical radius tends to be much larger (often tens of centimeters).

3. Misalignment Losses

Whenever two optical fiber ends are brought together to form a joint, be it temporary or permanent, there is always a chance of mechanical errors causing the fibers to become misaligned. The following image illustrates some examples of these misalignments.

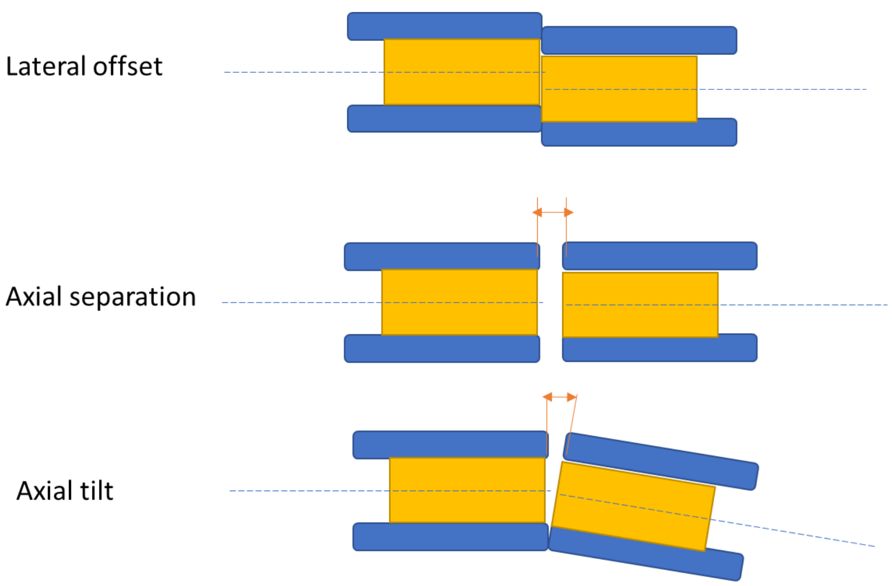


Figure 8: Various misalignment losses in an optical fiber coupling

The axes of the two fibers get misaligned as shown in the above figure is called transverse misalignment. Thus, the loss in dB is given as:

$$\alpha_t(dB) = 4.34(\frac{u}{w})$$

Where, u is the transverse misalignment and w is the spot size.

In longitudinal misalignment there is gap between two fibers ends in the final joint as shown in figure 8(axial separation). For this misalignment loss is given as

$$\alpha_t = 10 \log (1 + \check{D}^2)$$

Where,

$$\check{D} = \frac{D\lambda_0}{2\,\pi\, n_1 w^2}$$

Where

λ_0 = free space wavelength,

n_l= refractive index between fiber ends

w = spot size,

D = longitudinal misalignment

In axial tilt where two fiber axes are not parallel to each other. The loss is given by:

$$\alpha_0 = \frac{4.34(\pi n_l w\theta)}{\lambda}$$

Here, λ_0 is the free space wavelength, n_l is the refractive index between of the medium between the fiber ends, θ is angular misalignment between the axes of two single mode fibers with the spot size w.

Experiment Setup and Procedure:

To conduct fiber characterization, a specific setup and procedure must be followed. One essential step in the process is the cleaving of the fiber end to ensure that it is free of any dust particles and has a flat surface. The cleaving process involves three steps: first, the fiber acrylic coating must be stripped; second, any residual dust on the fiber should be gently cleaned with acetone; and finally, the fiber should be cleaved using a fiber cleaver. It's important to note that the angle mount has a least count of 0.01660 and the transverse mount has a least count of 10µm.

a) To determine Optical Fiber Coupling Loss for single mode fiber (SMF):

1. Make the arrangement as shown in figure 9.
2. Turn on the He-Ne laser source and wait for 5 minutes so that the laser gets stabilized.
3. Place an objective lens (20X) in front of the source. Align it in such that laser light is passing through it and then adjust the focus of the lens and the horizontal and vertical axis such that back reflection should fall at the center of the source in a circular symmetry.
4. Observe the power value on the photo-detector.
5. Place a fiber cable on a mount as shown in figure 9.
6. Adjust the height and position of the fiber with the help of alignment screws in the mount so that maximum light propagates in the fiber (see in multi-meter).
7. Measure the light intensity at the laser input right after the lens and also at the output end of fiber.
8. Note down the readings and then calculate the coupling loss.

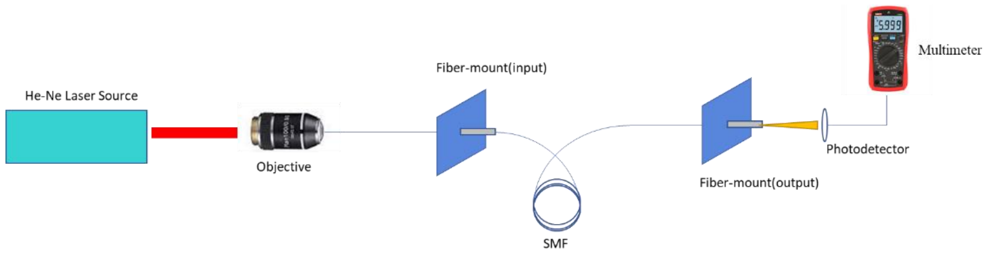


Figure 9: Optical fiber coupling loss measurement

b) To determine bending loss in Single mode optical fiber:

1. Align all the components as shown in figure 10 as explained.
2. Bend the fiber for different radius of curvatures using a mandrel.
3. Measure the variation of the output intensity falling at the photodiode for these curvatures.
4. Calculate the loss for each reading.

5. Curve fit the loss with respect to the radius of curvature.
6. Calculate the value of critical radius.

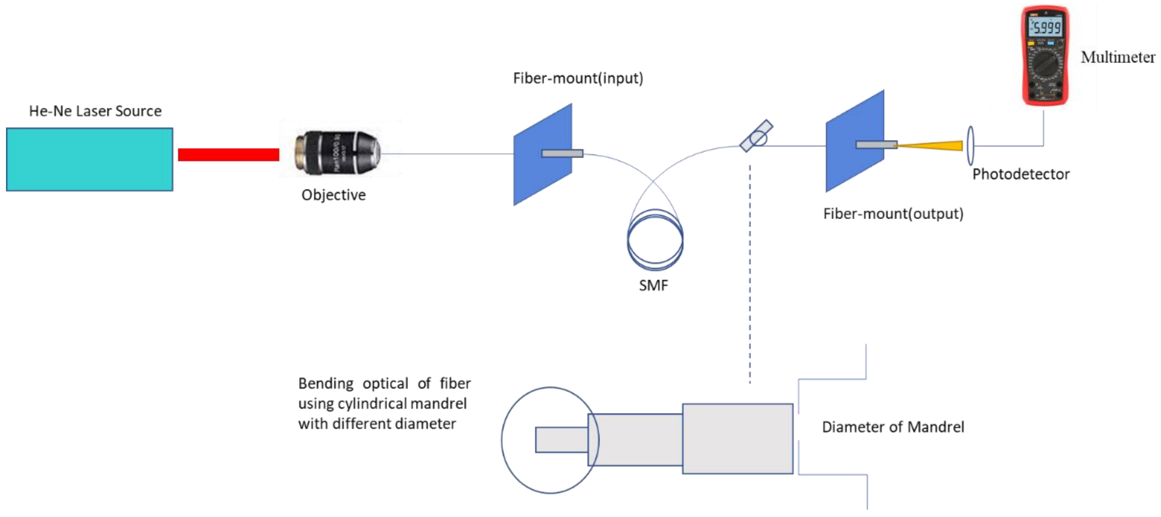


Figure 10: Optical fiber bending loss measurement

<u>c) To measure NA of Single Mode Optical fiber:</u>

1. Make the arrangement as shown in figure 11.
2. This time place the output end of fiber over an angular stage.
3. Measure the output power of the fiber with a photo-detector and read it on a multi-meter.
4. Vary the angle of the stage to find the output power variation from minimum to maximum then to minimum.
5. Plot these readings and find the data points at which the maximum power goes $1/e^2$ of its value.

   These two angles would be $\emptyset_1$ and $\emptyset_2$.

6. Calculate the acceptance angle with following formula

$$2\emptyset_a=\emptyset_2-\emptyset_1$$

7. Calculate the numerical aperture by using measured acceptance angle as follows:

$$NA=n_0*\sin\emptyset_a$$

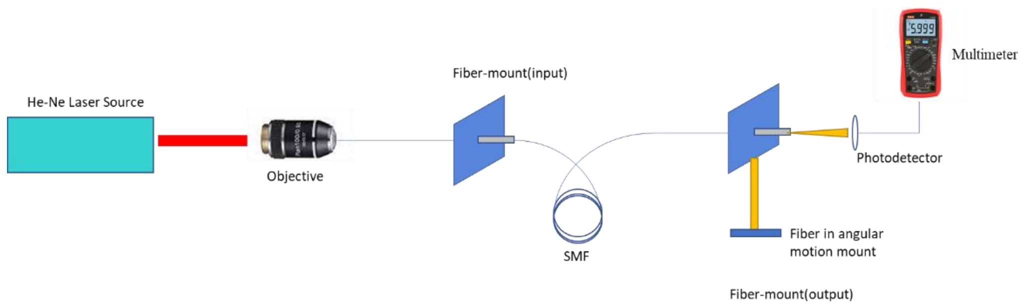


Figure 11: Optical fiber Numerical aperture measurement

d) Misalignment loss in Single mode optical fiber:

1. Align the components as shown in figure 12.
2. Place another SMF near the end of the input SMF as shown in figure 12.
3. Couple the output intensity coming out from the Input SMF to the output SMF.
4. Align two of the fiber edges until the maximum power starts coupling between them.
5. Place a detector at the end of second SMF.
6. Measure the intensity with the help of a multi-meter.
7. Move output SMF with the help of an angular stage as used in figure 11 but mounting second SMF.
8. Take the readings for very small steps of angular movement. Curve fit the plot.
9. For the observation of transverse misalignment loss, we repeat 1 to 4 steps and then mount the second SMF on a linear stage and then take the readings in a very small steps in transverse direction until the two fibers cross each other completely.
10. For observing the longitudinal misalignment loss after step 4 we mount the second SMF on a linear stage and then move this fiber in longitudinal direction. Start taking the reading from where are getting maximum intensity up to the point where we get minimum value of intensity.

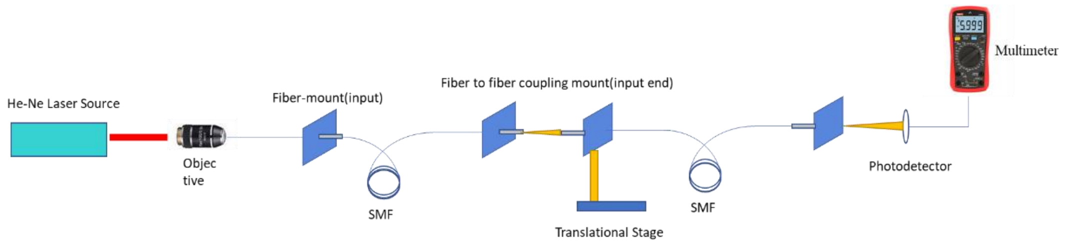


Figure 12: Optical fiber misalignment loss measurement

Observations & Results:

We determine NA and observe the variation of coupling power from He-Ne laser to the optical fiber with various losses due to misalignment, observed as a function of the voltage.

a) Coupling Loss in single mode fiber:

Coupling loss is calculated using following formula

$$Loss(in\ dB) = -10log\frac{V_0}{V_i}$$

V_0 = Power at Second Fiber output

V_i = Power at first fiber output

V_0, V_i =33 mV, 307 mV

Coupling loss for single-mode fiber comes to be **9.68dB**

Explain a bit --- Here one voltage is calculated in one fiber end and another voltage is calculated in the second fiber end. When one fiber is coupled with another fiber, there is always a loss in power. Here it is calculated as 9.68 dB.

b) Bending loss measurement

The table below shows how the output power varies with respect to the mandrel diameter, while the loss has been determined using the corresponding loss equation.

S.No.	Diameter(mm)	Output(mV)	Loss(dB)
1	8.58	305	0.0565864
2	7.33	302	0.0995154
3	6.14	299	0.1428729
4	5.02	273	0.5379583
5	4.49	228	1.3202363
6	4.07	232	1.2447049
7	3.59	214	1.5954471
8	3.07	208	1.7189514

Graph

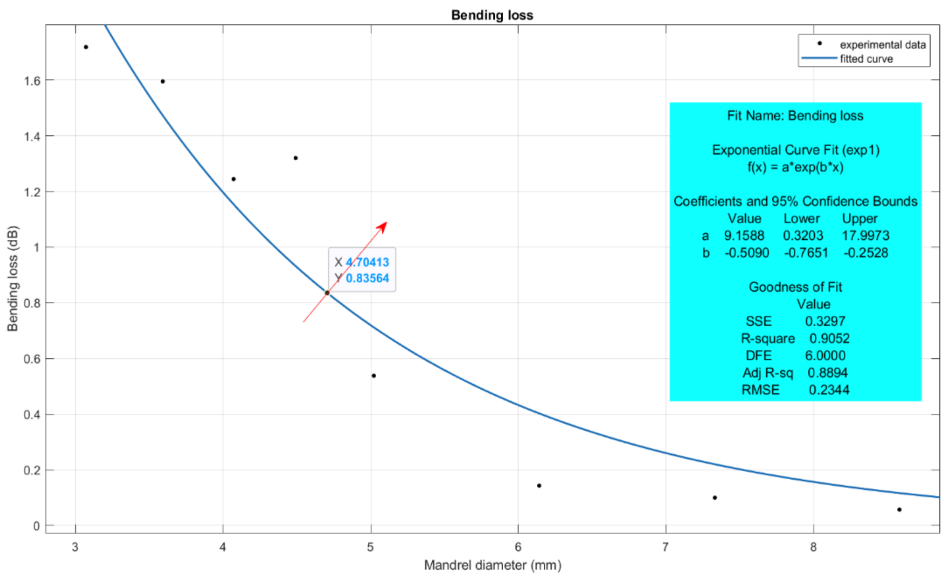


Fig13:Bending loss plot with change in diameter of mandrel

So, the calculated bend radius is 4.7 mm.

b) Numerical aperture measurement

Numerical Aperture measurement has been done for one position with photo-detector at around 10cm distance from the fiber end tip; laser power observed at the detector is ~166 mV. The following observation is given in table below. The least count is 0.0166 (i.e. 1/60, as one small rotation of main scale is 20 and circular scale rotates 120 marks for complete 20 angular change).

i) For the distance of 10 cm:

Table

Division	Angle	Voltage(mV)	Loss(dB)
0	0	25.1	10.95870616
5	0.083335	28.1	10.46838018
10	0.16667	29.1	10.31651349
15	1	31	10.04182644
20	0.083335	32.3	9.863418152
25	0.16667	27	10.64180573
30	2	39	9.044797305
35	0.083335	45	8.423318238
40	0.16667	38	9.157607409
45	3	59	7.246923259
50	0.083335	62.4	7.003597479
55	0.16667	88.7	5.476207177
60	4	96	5.132731045
65	0.083335	108	4.621205821
70	0.16667	120	4.163630915
75	5	134	3.684395392
80	0.083335	143	3.402083001
85	0.16667	155	3.052126394
90	6	146	3.311914818
95	0.083335	160	2.914243549
100	0.16667	172	2.600158906
105	7	171	2.625482272
110	0.083335	177	2.475710712
115	0.16667	183	2.330932478
120	8	191	2.145109703
125	0.083335	194	2.077426076

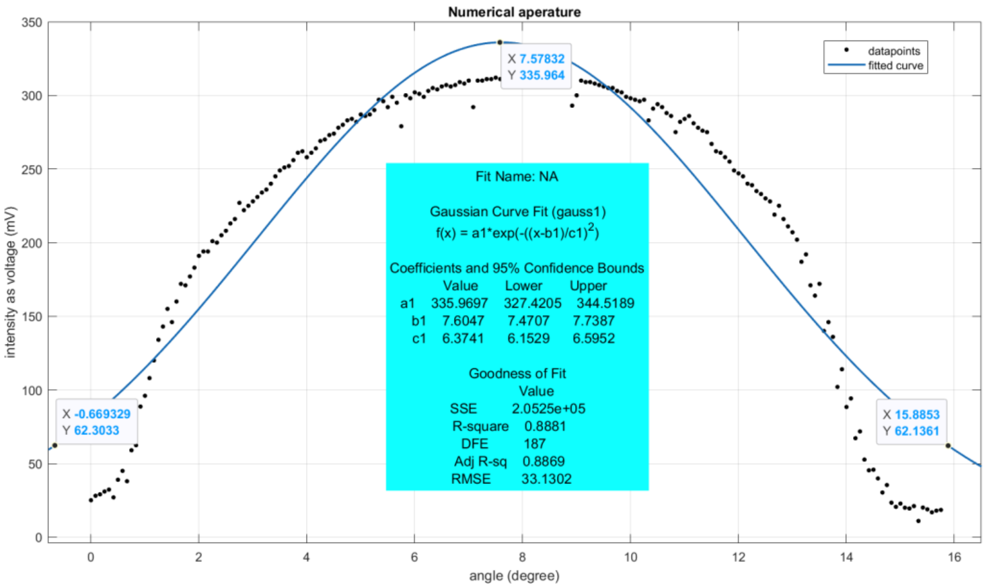
130	0.16667	194	2.077426076
135	9	201	1.923482801
140	0.083335	200	1.945143419
145	0.16667	205	1.837904765
150	10	208	1.774810026
155	0.083335	213	1.671647341
160	0.16667	216	1.610905864
165	11	227	1.395184804
170	0.083335	222	1.491913631
175	0.16667	225	1.433618194
180	12	228	1.376094905
185	0.083335	231	1.319323577
190	0.16667	234	1.263284801
195	13	236	1.226323346
200	0.083335	240	1.153330958
205	0.16667	245	1.063782532
210	14	249	0.993449905
215	0.083335	251	0.958706161
220	0.16667	252	0.941437968
225	15	256	0.873043722
230	0.083335	261	0.789038302
235	0.16667	262	0.772430462
240	16	258	0.839246316
245	0.083335	261	0.789038302
250	0.16667	264	0.739404107
255	17	269	0.657920575
260	0.083335	270	0.641805734
265	0.16667	273	0.593816905
270	18	274	0.577937747
275	0.083335	278	0.514995416
280	0.16667	280	0.483863062
285	19	283	0.43757902
290	0.083335	284	0.422259975
295	0.16667	282	0.452952292
300	20	287	0.376624408
305	0.083335	286	0.391783044
310	0.16667	287	0.376624408
315	21	290	0.331463396
320	0.083335	297	0.227878882
325	0.16667	296	0.242526265
330	22	292	0.301614861
335	0.083335	299	0.198731492
340	0.16667	295	0.257223216
345	23	279	0.499401343
350	0.083335	300	0.184230828
355	0.16667	298	0.213280735

360	24	302	0.155373946
365	0.083335	301	0.16977842
370	0.16667	299	0.198731492
375	25	303	0.14101709
380	0.083335	305	0.112444982
385	0.16667	304	0.126707539
390	26	306	0.098229111
395	0.083335	307	0.084059621
400	0.16667	306	0.098229111
405	27	307	0.084059621
410	0.083335	309	0.055858581
415	0.16667	308	0.06993621
420	28	310	0.041826437
425	0.083335	292	0.301614861
430	0.16667	310	0.041826437
435	29	310	0.041826437
440	0.083335	311	0.027839485
445	0.16667	311	0.027839485
450	30	312	0.013897435
455	0.083335	311	0.027839485
460	0.16667	312	0.013897435
465	31	311	0.027839485
470	0.083335	307	0.084059621
475	0.16667	312	0.013897435
480	32	311	0.027839485
485	0.083335	312	0.013897435
490	0.16667	313	0
495	33	313	0
500	0.083335	312	0.013897435
505	0.16667	311	0.027839485
510	34	312	0.013897435
515	0.083335	312	0.013897435
520	0.16667	313	0
525	35	312	0.013897435
530	0.083335	311	0.027839485
535	0.16667	293	0.286767172
540	36	300	0.184230828
545	0.083335	310	0.041826437
550	0.16667	309	0.055858581
555	37	309	0.055858581
560	0.083335	308	0.06993621
565	0.16667	307	0.084059621
570	38	306	0.098229111
575	0.083335	305	0.112444982
580	0.16667	305	0.112444982
585	39	303	0.14101709

590	0.083335	302	0.155373946
595	0.16667	299	0.198731492
600	40	298	0.213280735
605	0.083335	297	0.227878882
610	0.16667	296	0.242526265
615	41	297	0.227878882
620	0.083335	283	0.43757902
625	0.16667	291	0.316513486
630	42	294	0.271970071
635	0.083335	292	0.301614861
640	0.16667	288	0.361518498
645	43	286	0.391783044
650	0.083335	275	0.562116437
655	0.16667	282	0.452952292
660	44	284	0.422259975
665	0.083335	286	0.391783044
670	0.16667	281	0.468380176
675	45	278	0.514995416
680	0.083335	276	0.546352555
685	0.16667	275	0.562116437
690	46	267	0.690330762
695	0.083335	262	0.772430462
700	0.16667	261	0.789038302
705	47	258	0.839246316
710	0.083335	255	0.890041571
715	0.16667	249	0.993449905
720	48	247	1.028473843
725	0.083335	245	1.063782532
730	0.16667	240	1.153330958
735	49	239	1.171464366
740	0.083335	235	1.244764753
745	0.16667	233	1.281884165
750	50	230	1.338165015
755	0.083335	228	1.376094905
760	0.16667	219	1.551002227
765	51	225	1.433618194
770	0.083335	216	1.610905864
775	0.16667	211	1.712618822
780	52	207	1.795739921
785	0.083335	202	1.901929681
790	0.16667	187	2.23702731
795	53	192	2.122431088
800	0.083335	171	2.625482272
805	0.16667	164	2.807004895
810	54	172	2.600158906
815	0.083335	140	3.494163019

820	0.16667	146	3.311914818
825	55	136	3.620054292
830	0.083335	102	4.869441658
835	0.16667	114	4.386394862
840	56	88.4	5.490920725
845	0.083335	94.2	5.214934348
850	0.16667	67.2	6.681750645
855	57	71.8	6.394198933
860	0.083335	52.7	7.737337223
865	0.16667	45.4	8.384884847
870	58	45.8	8.346788595
875	0.083335	39.9	8.945714419
880	0.16667	30.3	10.14101709
885	59	35.4	9.465410755
890	0.083335	23.4	11.2632848
895	0.16667	20.6	11.81677117
900	60	22.8	11.37609491
905	0.083335	20	11.94514342
910	0.16667	19.5	12.05509726
915	61	21.1	11.71261882
920	0.083335	11	14.54151652
925	0.16667	20.1	11.9234828
930	62	18.9	12.19082533
935	0.083335	16.9	12.67657633
940	0.16667	18	12.40271832
945	63	18.5	12.28372609

Graph:



Numerical Aperture of Optical Fibre is calculated as: For 10 cm Distance, we got 2θ =16.5546 from fig 8 at $1/e^2$ of the maximum value, hence θ = 8.2773.

Numerical Aperture = n∗ sin θ = 1 * sin (8.2773) = 0.14396.

Here n = refractive index of air = 1

c.) Misalignment Measurement

i) Angular Misalignment

Division	Angle	Voltage (mV)	Loss(dB)
0	0	9.3	10.092407
1	0.016667	11.2	9.2850558
2	0.033334	9.75	9.8871899
3	0.050001	10.2	9.6912343
4	0.066668	14.4	8.1936111
5	0.083335	10	9.7772361
6	0.100002	12	8.9854236
7	0.116669	16.7	7.5500713
8	0.133336	25	5.797836
9	0.150003	35.5	4.2749525
10	0.16667	67	1.516488
11	0.183337	95	0
12	0.200004	88	0.3324093

13	0.216671	52.3	2.5922192
14	0.233338	24.8	5.8327192
15	0.250005	13.9	8.3470881
16	0.266672	10.9	9.4029711
17	0.283339	8.7	10.382044
18	0.300006	7.17	11.222044
19	0.316673	6.4	11.715436
20	0.33334	9.7	9.9095187
21	0.350007	7.4	11.084919
22	0.366674	6.8	11.452147

Graph:

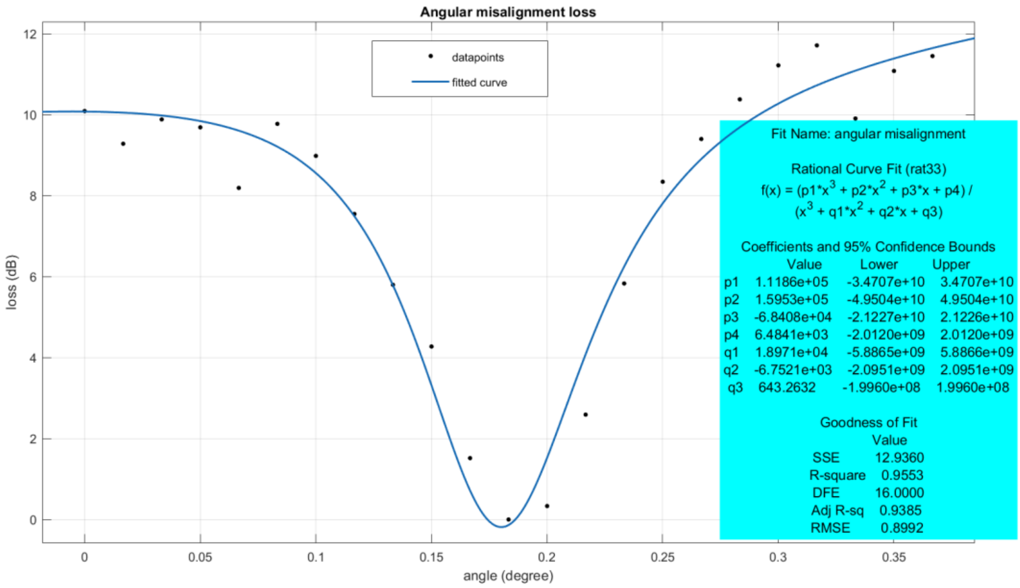


Fig : Angular Loss variation at the output end of the 2nd SMF with angular deviation from O0with respect to 1st SMF fiber input tip

ii) **Longitudinal Misalignment:**

Division	Measurement(mm)	Voltage(mV)	Loss(dB)
0	0	88	0
1	0.01	82	0.306688198
2	0.02	79	0.468555809
3	0.03	79	0.468555809
4	0.04	75	0.694214088
5	0.05	74.1	0.746644642
6	0.06	76	0.636690799
7	0.07	73.8	0.764263103

8	0.08	71.8	0.883582279
9	0.09	68.7	1.075259351
10	0.1	67.7	1.138940035
11	0.11	68.9	1.062634502
12	0.12	77	0.57991947
13	0.13	70.7	0.950632584
14	0.14	56.9	1.893704058
15	0.15	51.2	2.352127112
16	0.16	65.4	1.289049238
17	0.17	50.7	2.394747128
18	0.18	57.1	1.878465639
19	0.19	53.5	2.161288901
20	0.2	55.5	2.00189689
21	0.21	54.8	2.057021137
22	0.22	45.4	2.874268193
23	0.23	47.7	2.659642931
24	0.24	57.3	1.863280502
25	0.25	58.2	1.795596875
26	0.26	58.6	1.765850561
27	0.27	53.7	2.145083865
28	0.28	60.2	1.648861809
29	0.29	45.2	2.893442373
30	0.3	54.4	2.088837725
31	0.31	57.1	1.878465639
32	0.32	62.3	1.499946255
33	0.33	50.6	2.403321553
34	0.34	47.1	2.71461765
35	0.35	57.5	1.848148275
36	0.36	51.8	2.301529124
37	0.37	41.2	3.295854561
38	0.38	44.3	2.980789459
39	0.39	51.3	2.34365307
40	0.4	50.4	2.420521357
41	0.41	50.3	2.429146871
42	0.42	45	2.912701584
43	0.43	48	2.632414348
44	0.44	56	1.962946451
45	0.45	48	2.632414348
46	0.46	35	4.004146278
47	0.47	46	2.817248405
48	0.48	44	3.010299957
49	0.49	42	3.212333818
50	0.5	30	4.673614174
51	0.51	33	4.259687323
52	0.52	42	3.212333818
53	0.53	41	3.316988154

54	0.54	33	4.259687323
55	0.55	41	3.316988154
56	0.56	43	3.110142166
57	0.57	40	3.424226808
58	0.58	27	5.13118908
59	0.59	38	3.646990755
60	0.6	39	3.534180651
61	0.61	25	5.465426635
62	0.62	24	5.642714304
63	0.63	39	3.534180651
64	0.64	38	3.646990755
65	0.65	18	6.89210167
66	0.66	38	3.646990755
67	0.67	37	3.762809481

Graph:

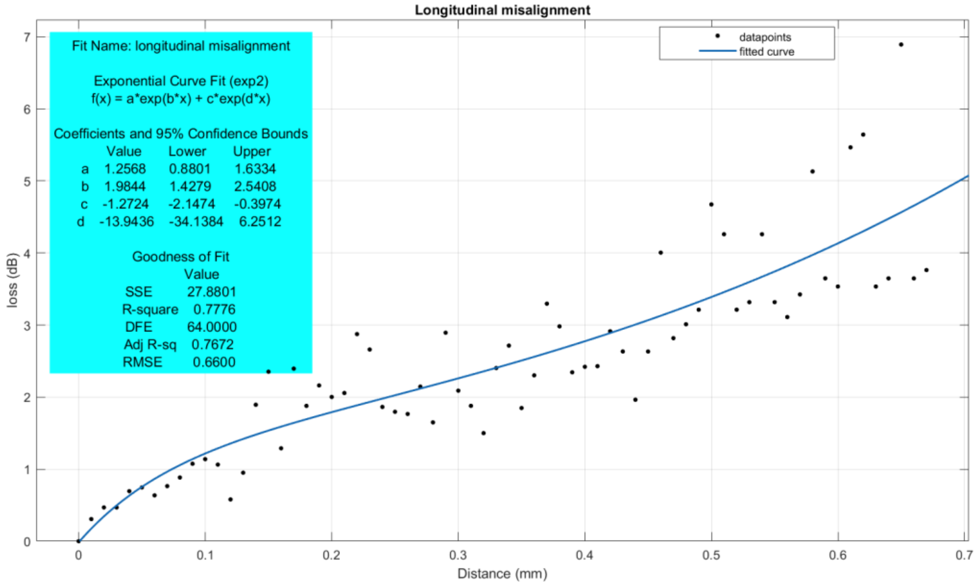


Fig: Longitudinal loss variation at the output end of the 2nd SMF with angular deviation from zero position with respect to 1st SMF fiber input tip.

iii) Transverse Misalignment

Division	Measurement(mm)	Voltage(mV)	Loss(dB)
0	0	16	6.4097806
1	0.01	13	7.3115469
2	0.02	17	6.1464912
3	0.03	13	7.3115469
4	0.04	15	6.6900678
5	0.05	17	6.1464912
6	0.06	22	5.0267536
7	0.07	16	6.4097806
8	0.08	14	6.9897
9	0.09	15	6.6900678
10	0.1	18	5.8982553
11	0.11	20	5.4406804
12	0.12	23	4.833702
13	0.13	22	5.0267536
14	0.14	24	4.648868
15	0.15	17	6.1464912
16	0.16	21	5.2287875
17	0.17	16	6.4097806
18	0.18	18	5.8982553
19	0.19	20	5.4406804
20	0.2	18	5.8982553
21	0.21	18	5.8982553
22	0.22	20	5.4406804
23	0.23	38	2.6531444
24	0.24	47	1.7300018
25	0.25	53	1.2082217
26	0.26	36	2.8879554
27	0.27	37	2.7689632
28	0.28	59	0.7424603
29	0.29	24	4.648868
30	0.3	68	0.1258913
31	0.31	70	0
32	0.32	14	6.9897
33	0.33	23	4.833702
34	0.34	18	5.8982553
35	0.35	16	6.4097806
36	0.36	22	5.0267536
37	0.37	15	6.6900678
38	0.38	16	6.4097806
39	0.39	14	6.9897

Graph

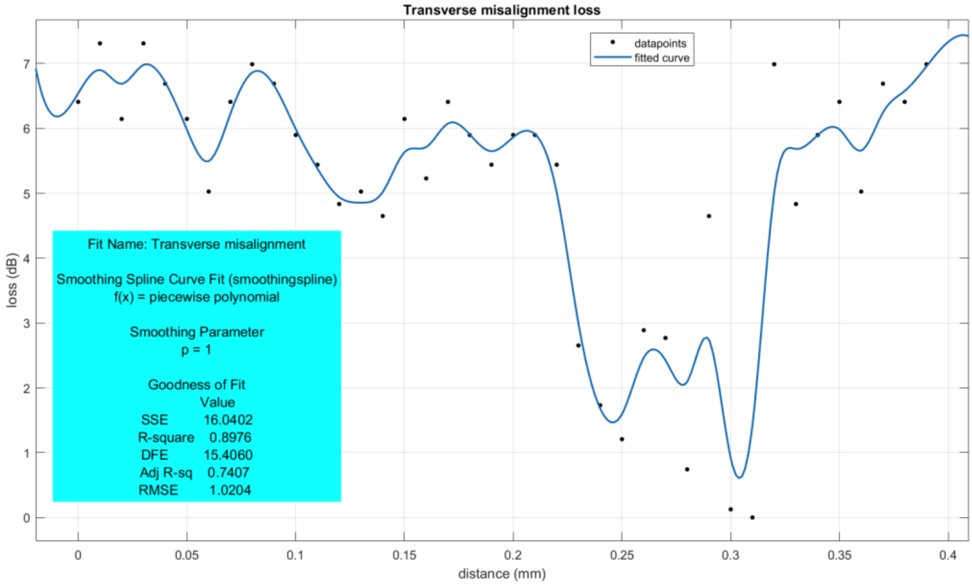


Fig: Transverse Loss variation at the output end of the 2nd SMF with angular deviation from center position with respect to 1st SMF fiber input tip.

Calculations:

1) V number:

   a = radius of core = 2.15 µm

   λ = 632.8 × 10−9 m

   V = ($\mathbf{2}\pi$/ $\boldsymbol{\lambda}$)× a × NA =($\mathbf{2}\pi$/632.8 × 10−9)× 2.15 × 10^{-6} × 0.14396= 3.0732

2) Mode field diameter:

$$\frac{w}{a} = 0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6}$$

$$w = 2.15 * 10^{-6} * \left(0.65 + \frac{1.619}{V^{\frac{3}{2}}} + \frac{2.879}{V^6}\right)$$

$$w = 2.0509 * 10^{-06}$$

Mode field diameter = 2w= $4.1018 * 10^{-06}$m

3.) Longitudinal Misalignment Loss:

λ = 632.8 × 10−9 m

say for D = 0.05 mm and n =1

$$D^{\sim} = \frac{D\lambda}{2 * \pi * n_i * w^2}$$

$$D^{\sim} = \frac{0.05 * 10^{-3} * 632.8 * 10^{-9}}{2 * \pi * 1 * (2.0509 * 10^{-6})^2}$$

$D^{\sim} =$ 1.1972

$\alpha_1(dB) = 10 * \log_{10}(1 + D^2)$ =3.862 dB

4.) Transverse Misalignment Loss:

Say u = 0.05 mm

$\boldsymbol{\alpha}_t(\mathbf{dB}) = \mathbf{4.34}\ (u/w)^2 = 4.34\ (0.05*10^{-3}/375.90*10^{-6})^2 =$ 0.0768 dB

Error Analysis:

1) Numerical Aperture
   Theoretical Value = 0.12
   Experimental Value = 0.14396
   Relative Error = ((|0.12 – 0.14396)|/0.12)*100 = 19.97%

2) V Number:
   Theoretical Value = 2.5617
   Experimental Value = 3.0732
   Relative Error = |3.0732– 2.5617|/2.5617 = 19.97%
3) Longitudinal Misalignment Loss:
   Theoretical Loss = 2.9178 dB
   Experimental Loss = 3.862 dB
   Relative Error = (|2.9178-3.862|/2.9178)*100 = 32.36 %

Discussion and Conclusion

From the above observation the coupling loss calculated is **9.68 dB.** It comes from scattering at the joining point . And also, some guided modes in the first fiber become radiation modes in the second fiber. It also can be reason for coupling loss.

There are significant errors in calculating NA, V number and misalignment loss. It might be due to fluctuations and others reasons.

Sources of Error & Precautions:

1. It is crucial to avoid touching the sensitive surfaces of the optical components with
2. Proper alignment of optical components is vital in any optical experiment, as inaccurate placement can lead to significant errors in the results.
3. The translational and rotational stages used in the experiment have a least count, which can contribute to errors.
4. Ensure proper coupling between the source and the fiber

References:

1. Introduction to Optics 2nd ed - F. Pedrotti, L. Pedrotti (Prentice-Hall, 1993)

2. Optics by Hecht & Ganeshan

3. “Introduction to fiber optics” by A. Ghatak and K. Thyagarajan, Cambridge university press, 1st edition (2000). 4. K P Zetie et al, 2000,Phys. Educ. 35,4

Experiment No. 12-b

Objective:

1. To measure the Attenuation and Dispersion in an optical fiber

Theory:

An optical fiber is a type of cylindrical waveguide that is made of low-loss materials such as silica glass. Its structure consists of a central core that guides the light and is surrounded by an outer cladding layer with a slightly lower refractive index, as depicted in Figure 1. When light rays enter the boundary between the core and cladding at an angle greater than the critical angle, they undergo total internal reflection and are guided through the core without experiencing any refraction. However, rays with larger inclinations to the fiber axis lose some of their power to the cladding layer at each reflection and are not guided. The optical fiber's specific characteristics are defined by the refractive indices of the core and cladding layers (n1 and n2, respectively), as well as their radii (a and b). Attenuation is defined as reduction in intensity of light as it propagates along the fiber. Attenuation is caused by various factors, such as absorption, scattering, and bending losses. Absorption refers to the loss of optical power due to the conversion of the signal into another form of energy, such as heat. This type of attenuation can be caused by impurities in the fiber material, such as water or metallic ions. Scattering occurs when the light signal is scattered by microscopic irregularities in the fiber, causing some of the light to travel in a different direction or be absorbed. There are two types of scattering: Rayleigh scattering, which is caused by variations in the density of the fiber material, and Mie scattering, which is caused by impurities or defects in the fiber. Bending losses occur when the fiber is bent or curved beyond a certain angle, causing some of the light to escape from the fiber core. This type of attenuation can be minimized by using fibers with a larger core diameter, or by carefully designing the fiber path to avoid sharp bends. Attenuation is a major factor in determining the maximum transmission distance and data rate of optical fiber systems. To minimize the effects of attenuation, various techniques can be used, such as using high-purity fiber materials, optimizing the fiber geometry, and using optical amplifiers to boost the signal strength.

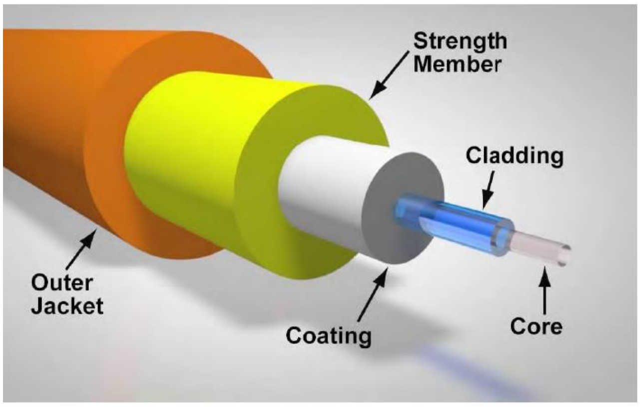


Fig: Structure of a fiber optic cable

Calculations:

Light travelling through an optical fiber exhibits a power that decreases exponentially with the distance. The overall optical throughput (transmission) of an optical fiber can be quantified in terms of the input optical power, P_0, and the output power, P(z) observed after light propagates a distance, z, along the fiber length:

$$P(z) = P_0 e^{-\alpha z} \qquad (1)$$

where α is attenuation coefficient. The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses. Optical losses of a fiber are usually expressed in decibels per kilometer (dB/km). The expression is called the fiber's attenuation coefficient α and the expression is:

$$\alpha = -10 \log \left(\frac{P(z)}{P_0} \right)$$

where P(z) is the optical power at a position z from the origin, P(0) is the power at the origin. For a given fiber, these losses are wavelength-dependent. The value of the attenuation factor depends greatly on the fiber material and the manufacturing tolerances.

Setup:

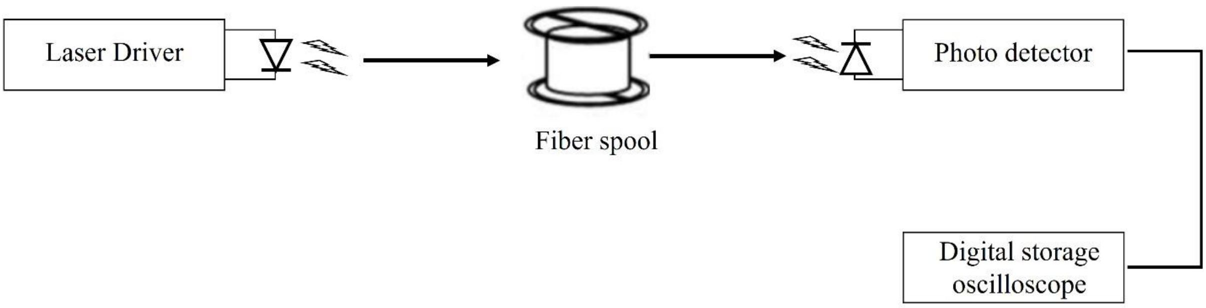


Fig. 3: Measurement of attenuation in optical fiber

Procedure:

1. Switch ON the LIGHT RUNNER kit.
2. Help>Attenuation in optical fiber>Enter
3. Connect 1550 laser source to the photodetector PD1 with the help of a patch cord.
4. Connect BNC connector adjacent to PD1 to any channel (CH1) of the digital storage oscilloscope (DSO).
5. Enable the 1550 laser and set the following parameters:

   (a) frequency = continuous, 5 KHz

   (b) duty cycle = 50%

   (c) laser power= 50%

6. Click on the START button, waveform will appear CH1 on the DSO screen.

7. In case of detector saturation, reduce the laser power level below the saturation level by using software control.

8. **NOTE:** while operating LIGHT RUNNER, if the detector is fed with high optical power it will be saturated and will not give correct readings and waveforms (on DSO). For reliable results, users are expected to keep optical power fed to detector below the saturation limit by adjusting source power through variable optical attenuator

9. Note down the power level at PD1 as P_1.

10. Click on the STOP button.

11. Disconnect the patch chord from PD1 and connect it to a fiber spool of known length (L).

12. Connect the other end to PD1.

13. Click on the START button.

14. Note down the power level at PD1 as P_2.

15. Calculate the attenuation loss using Eqn. (2).

16. Repeat the experiments with various length of fiber by combining the individual spools.

17. Each time a patch cord is connected to a spool, an extra connector loss (□$_C$) would appear in Eqn. (2). So, the actual attenuation loss in all the configurations can be computed by subtracting CL from ‘□’.

18. Repeat the procedure 3−16 for the other wavelength 850 nm. Here, the patch cord needs to be connected to the other photodetector PD2 which would be connected to the other channel (say CH2) via a BNC connector.

Observation

i) Determination of the connector loss

Input frequency = 5kHz, duty cycle = 50%, laser power = 50%

- Input power from LD @ 1550 nm = 142 μ W
- Power observed after connector = 136 μ W
- Decrease in power due to connector = 6 μ W
- Connector loss = 0.187 dB

ii) Determination the fiber attenuation

Input frequency = 5kHz,

Duty cycle = 50%

Laser power = 50%

λ (nm)	L (km)	P_1 (μW)	P_2 (μW)	Attenuation (A) in dB = 10log(P_1/P_2)	No. of connectors (n)	Connector loss (α_C) (dB)	A'= $A-n\alpha_C$	Attenuation loss (α) in dB/km= A'/L
1550	1	142	94	1.791605	2	0.374	1.043605	1.043605
	2	142	98	1.610623	2	0.374	0.862623	0.431311
	3	142	99	1.566531	2	0.374	0.818531	0.272844
850	1	224	82	4.364342	2	0.374	3.616342	3.616342
	2	224	74	4.810163	2	0.374	4.062163	2.031081
	3	224	38	7.704644	2	0.374	6.956644	2.318881
	5	224	14	12.0412	3	0.561	10.3582	2.07164

Concluding Remark

We can see from the table, attenuation for 850 nm is greater than for 1550 nm. We can also see that, with increasing length, the losses become increase. It might be due the intrinsic properties.

Experimental demonstration-II

Objective: To measure the dispersion in an optical fiber

Components required: 1550 nm and 850 nm Laser, Optical fiber spools (1 km, 2 km, 3 km, 4 km, 5 km, 6 km), Fiber connectors, Patch cords, BNC Cable, Digital Storage Oscilloscope, 3 dB Coupler, WDM (980/15XX) Coupler.

Theory:

Dispersion in optical fiber refers to the phenomenon where different wavelengths of light travel at different speeds through the fiber, causing the pulse of light to spread out over time. In other words, dispersion is the distortion of a signal as it propagates through a fiber optic cable. There are two main types of dispersion in optical fiber: chromatic dispersion and modal dispersion. Chromatic dispersion occurs because different wavelengths of light travel at slightly different speeds through the fiber. This type of dispersion can cause the pulse of light to broaden over time, which can limit the data transmission rate of the fiber. Modal dispersion, on the other hand, occurs when the light pulse takes multiple paths (modes) through the fiber, and these different paths have different lengths. Modal dispersion can also cause the pulse of light to spread out over time, limiting the maximum data transmission rate of the fiber.

To minimize the effects of dispersion, various techniques can be used, such as using dispersion-shifted or dispersion-compensating fibers, or using wavelength division multiplexing (WDM) to transmit multiple signals at different wavelengths.

Setup:

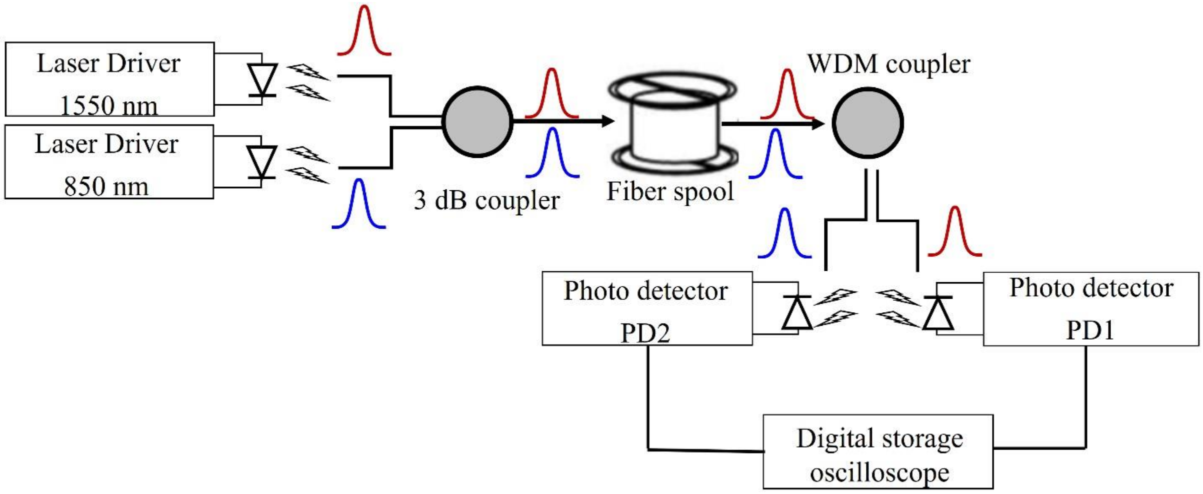


Fig. 4: Measurement of dispersion in optical fiber

Here are the steps for conducting the experiment:

1. Turn ON the LIGHT RUNNER kit.
2. Click on Help and select Dispersion in Optical Fiber, then enter.
3. Connect the 850 nm laser to the port of the 3 dB coupler that delivers more power than the other port. Connect both ports of the 3 dB coupler to the laser and connect the 'COM' port of the coupler to the power meter using a patch cord.
4. Connect the 1550 nm laser to the other port of the 3 dB coupler using a patch cord.
5. Connect the 'COM' port of the coupler to the 'COM' of the WDM coupler using a patch cord.
6. Connect the photodetector PD1 to the 1550 port and PD2 to the 980 port of the WDM coupler.
7. Connect BNC connectors adjacent to PD1 and PD2 to CH1 and CH2 of the DSO.
8. Enable the 1550 nm laser using a stylus and set the frequency to 50 KHz, duty cycle to 50%, and laser power to 60%.
9. Click on the START button, and a waveform will appear at CH1 on the DSO screen.
10. Enable the 850 nm laser using a stylus and set the frequency to 50 KHz, duty cycle to 50%, and laser power to 60%.
11. Click on the START button, and a waveform will appear at CH2 on the DSO screen.
12. If the detector is saturated, reduce the laser power level using software control below the saturation level.
13. With the power level of both lasers fixed, enable both lasers and run the experiment.
14. Measure the time delay between the rising edges of both pulses at CH1 and CH2.
15. Connect a fiber spool of known length between the 'COM' of the coupler and the 'WDM' coupler using a patch cord, and measure the time delay.
16. Repeat the experiment with various fiber lengths.

Note: The laser output at 850 nm is collected from the 980 port of the WDM coupler, so there will be some loss since the coupler response depends on the wavelength. To ensure reliable results, keep the optical power fed to the detector below the saturation limit by adjusting the source power through a variable optical attenuator.

Observation:

Rise time when no-fiber (only patch chords) was connected in between source and PDs

For 1550 nm = ~ 28 ns

For 850   nm = ~ 588 ns

Rise time when following fibers lengths were connected:
Here dispersion(coefficient) is calculated using following formula:

$$D = \frac{\Delta\tau}{L * \Delta\lambda}$$

Fiber length (km)	Delay between positions of 850 nm and 1550 nm pulses (ns) $\Delta\tau$	Dispersion (ps/km-nm)
3	0.041605	19.81190476
2	0.023774	16.98142857
5	0.071322	20.37771429

Average of Dispersion ~ 19.057 ps/km-nm

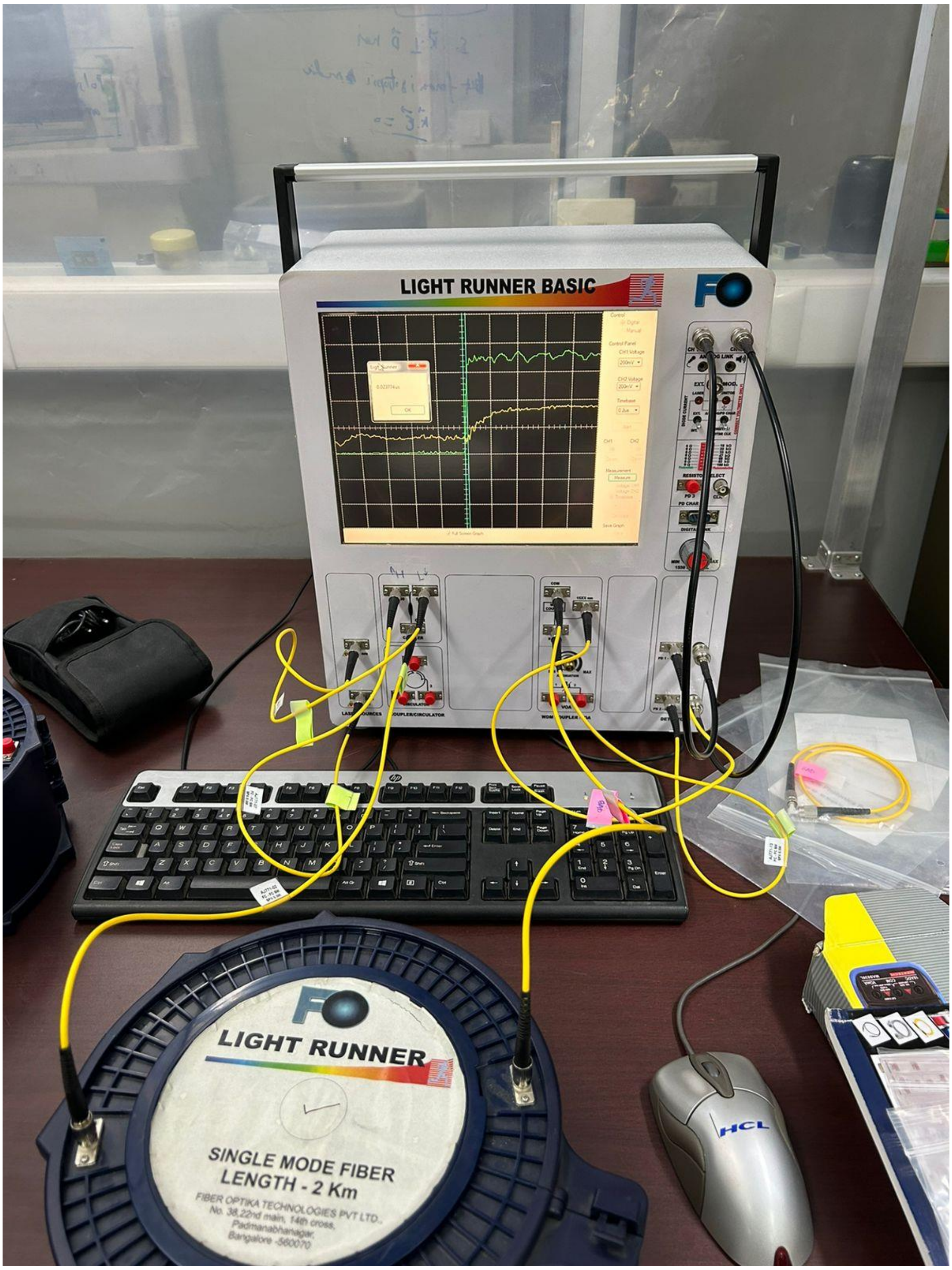


Fig: Rise time when 1 km fiber is connected

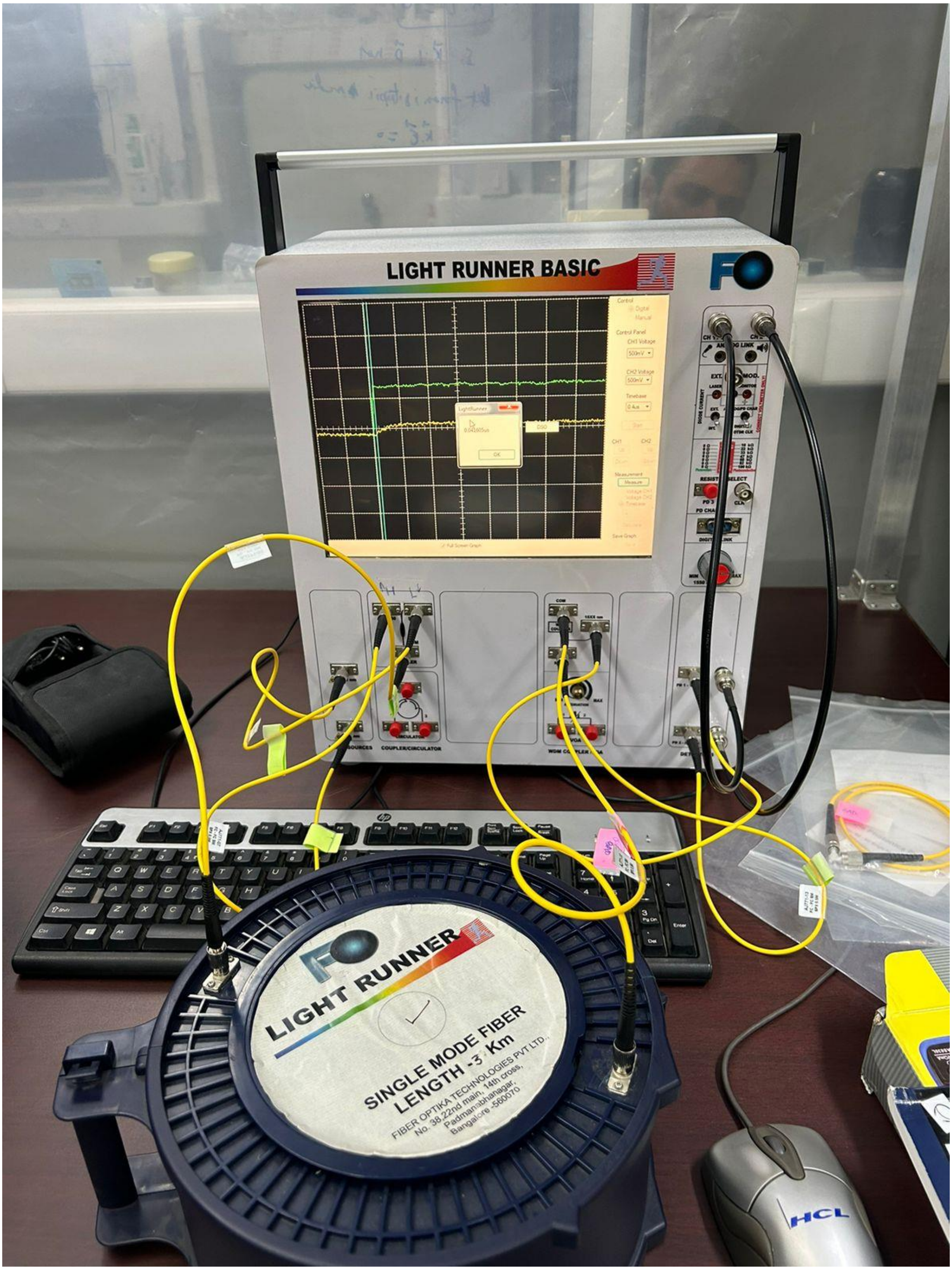


Fig: Rise time when 2 km fiber is connected

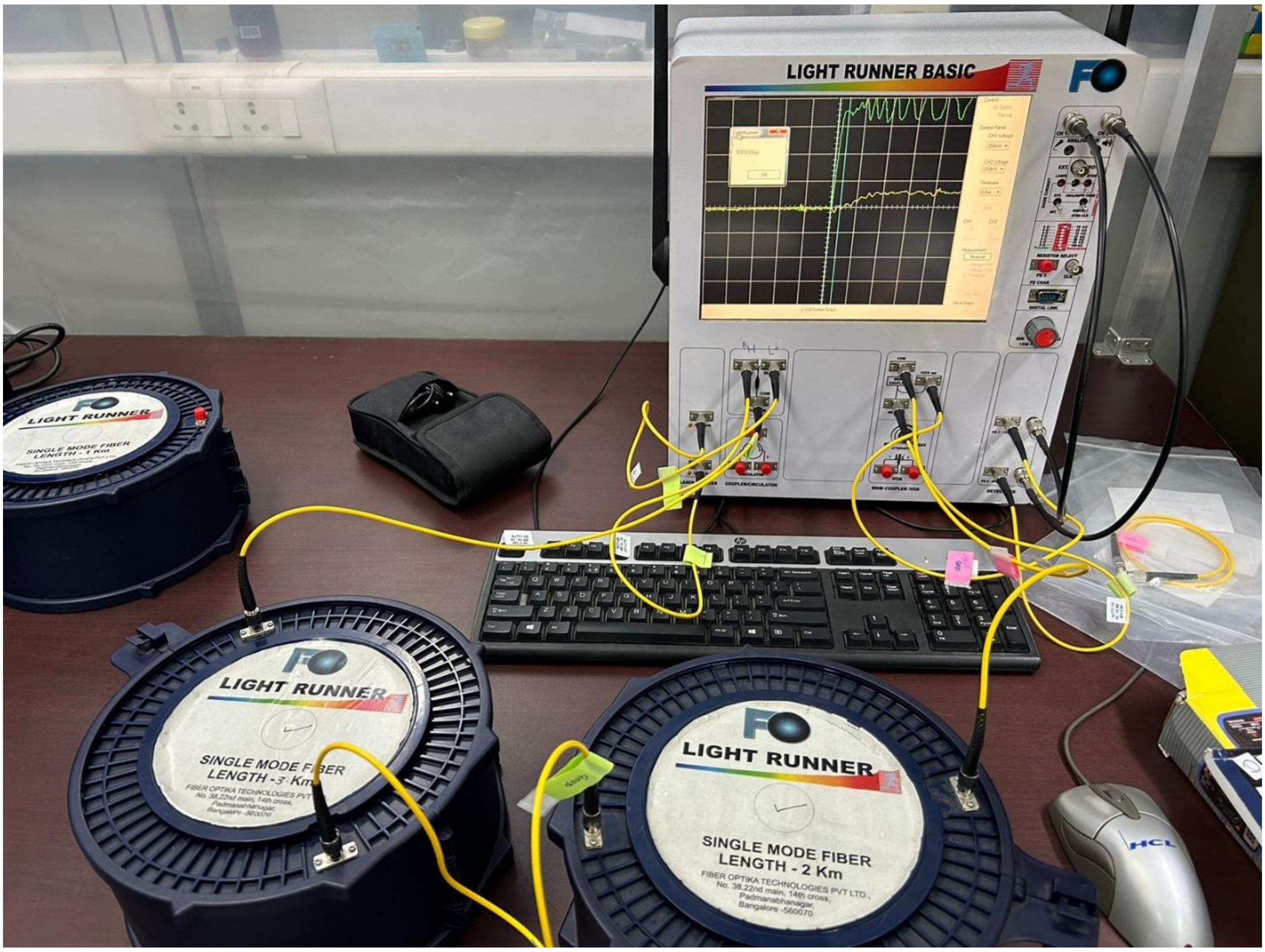


Fig: Rise time when 5 km fiber is connected

Conclusion: From these, we can see the material dispersion in fiber. The group velocity of the light at different wavelength is different. We can see from the table the dispersion increases with the length of the fiber. That’s why we get the broadening pulses.

Experimental demonstration-III

Objective: To determine the position of the fault in a fiber optic link using OTDR method

Components required: 850 nm Laser, Optical fiber, Fiber connectors, Patch cords, BNC Cable, Digital Storage Oscilloscope, Optical circulator

Theory: OTDR (Optical Time Domain Reflectometer) is a test instrument that uses optical pulses to measure the loss and attenuation of fiber optic cables.

Here are some of the factors and parameters that can be used in OTDR calculations:

- Pulse width: The pulse width determines the resolution of the OTDR measurement. A shorter pulse width provides better resolution, but a longer pulse width can provide better sensitivity for longer fiber lengths.
- Refractive index: The refractive index of the fiber core affects the speed of the optical pulse, and therefore the distance measurement.
- Fiber length: The length of the fiber affects the attenuation of the optical signal.
- Attenuation coefficient: The attenuation coefficient of the fiber is a measure of how much the signal is attenuated per unit length of fiber.
- Backscattering coefficient: The backscattering coefficient of the fiber is a measure of the amount of light that is scattered back towards the OTDR by imperfections in the fiber.

Using these parameters and factors, an OTDR can calculate the attenuation and loss of a fiber optic cable. The exact calculation method may vary depending on the specific OTDR instrument and the manufacturer's instructions.

The delay between the input pulse and the reflected pulse can be calculated from the following:

$$\Delta\tau = \frac{2L}{v_g}$$

Here, L is the fiber length, v_g is the group velocity of the input pulse in the medium. Typical group velocity of a 850 nm laser pulse in a silica fiber by using the is ~ 236,000 km/s

Observation:

Fiber length (in km)	Approx. time delay between the pulses, t (in μs)	Fiber length, L = v_g. t/2 (in km)
2	20.802376	2.454680368
3	30.906389	3.646953902
1	11.292719	1.332540842

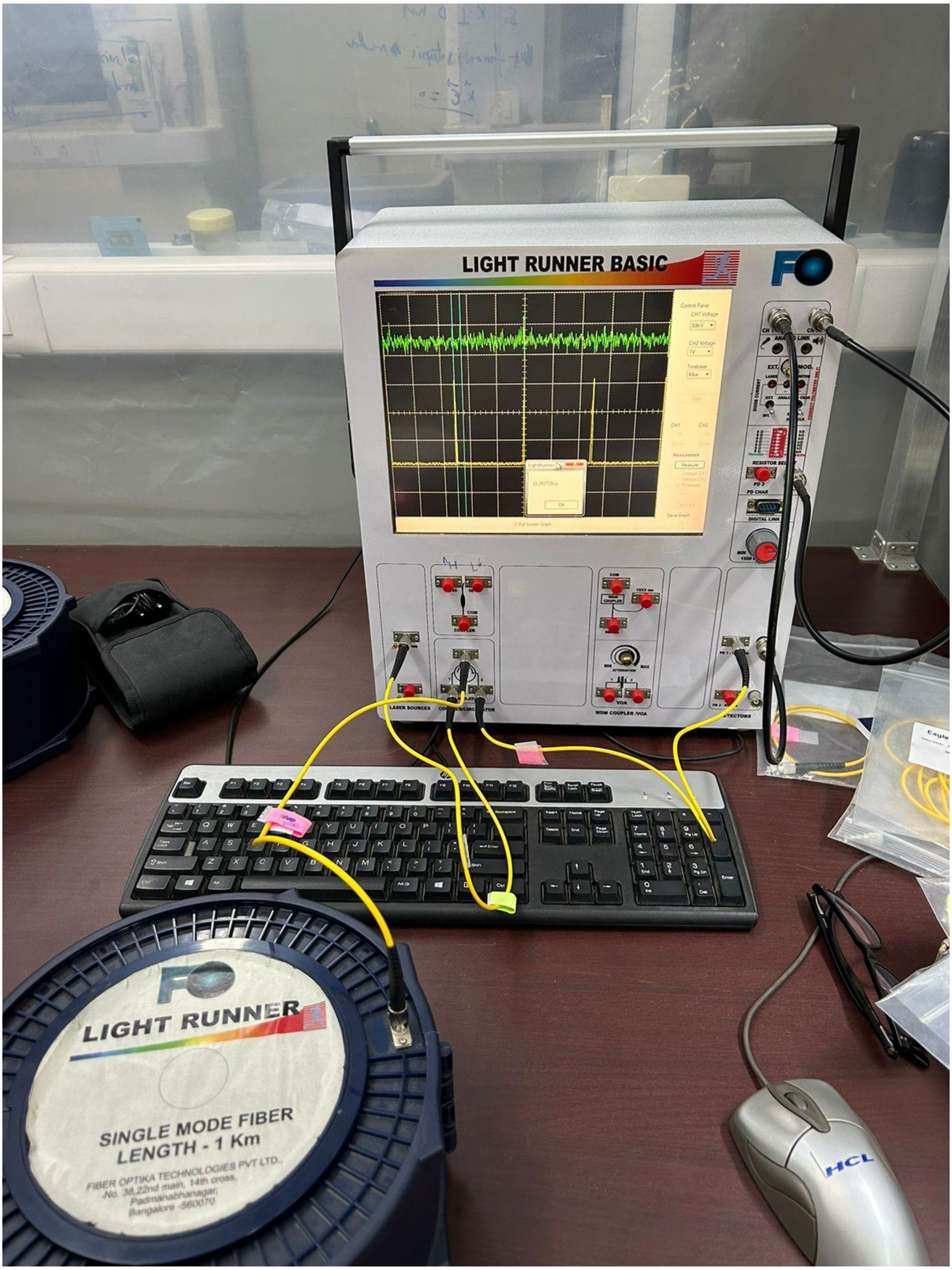
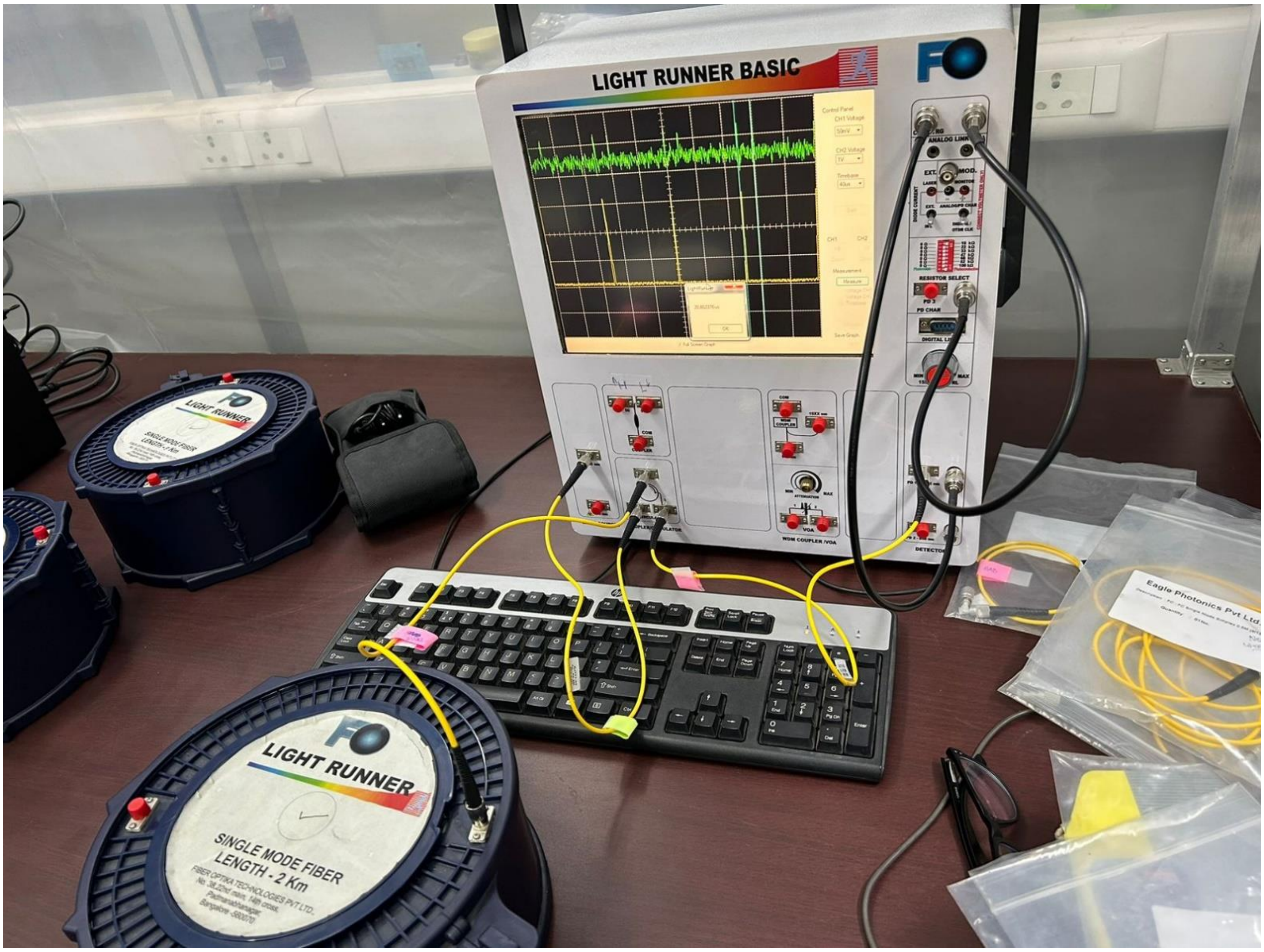
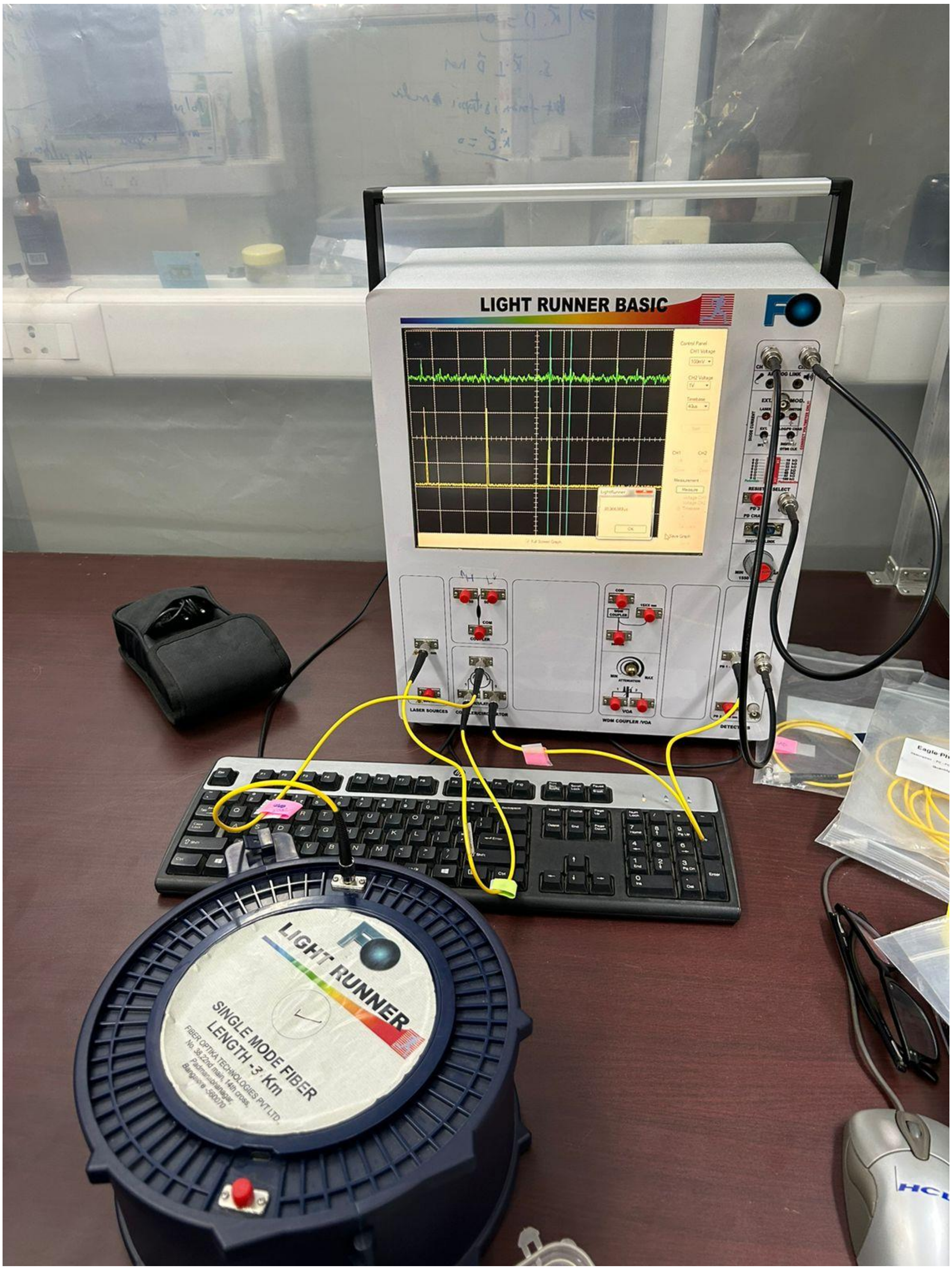


Fig : Photograph of the OTDR experiment for 1 km fiber length where the reflected pulse delayed by ~11.29 μs



Example Graph: Photograph of the OTDR experiment for 2 km fiber length where the reflected pulse delayed by ~ 20.8 μs



Example Graph: Photograph of the OTDR experiment for 3 km fiber length where the reflected pulse delayed by ~ 30.9 μs

Setup:

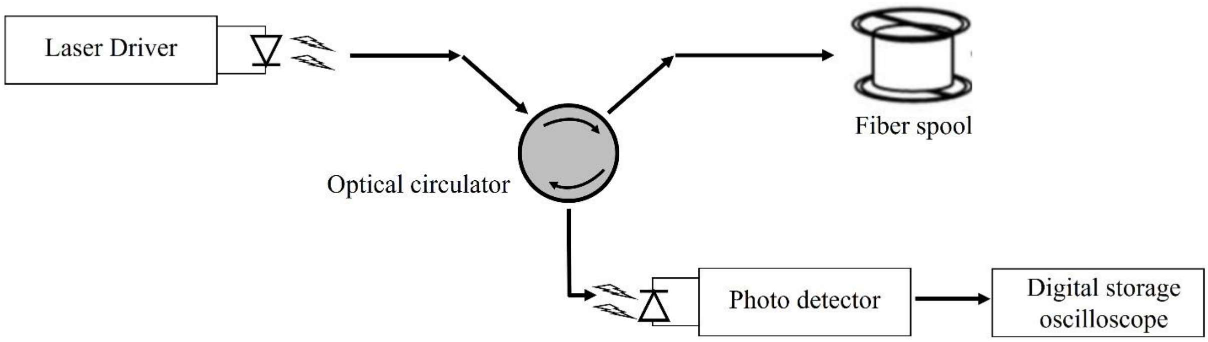


Fig. OTDR SETUP

Procedure:

Procedure:

1. Turn on the LIGHT RUNNER kit.

2. Access the Optical Time Domain section of the Help menu and enter it.

3. Use a patch cord to connect the 1550 nm laser source to port 1 of the optical circulator.

4. Connect a patch cord to port 2 of the circulator and leave the other end of the patch cord free (assuming the patch cord has a break at the free end).

5. Use a patch cord to connect port 3 of the circulator to the photodetector PD1.

6. Connect the BNC connector adjacent to PD1 to CH2 of the DSO using a BNC cable.

7. Use the stylus to set the pulse width to 1 microsecond (which corresponds to a minimum fiber detection length of approximately 206 meters given vg~ 2.06x108 m/s), and then click the START button to start the experiment.

8. Decrease the detection voltage of DSO CH2 to display the low power reflected signal on the DSO.

9. Use a BNC cable to connect the OTDR clock to CH1/TRG of the DSO for the input reference clock. NOTE: Ensure that the toggle switch under INT MOD is set to DIGITAL/OTDR clock.

10. Measure the time delay between the rising edge of the reference clock pulse at CH1 and the rising edge of the reflected pulse.

11. Repeat the experiment with fiber spools of varying lengths.

    NOTE: If multiple spools are connected by patch cords, you may observe multiple reflected pulses by leaving the patch cord ends slightly loose.

Calculations

1. OTDR:

   Fiber Length, L = $V_{g(t/2)}$ (km)

   T = Time gap between pulses (μs)\

   v = speed of the pulse = 2.36*10^5 km/s,

   L = $2.36*10^5*(11.29/2)*10\text{-}6$ = 1.332 km.

2. Error in length L = ((1.322 – 1)/1)*100 = 32.2%

Conclusion:

From our result we can see that there is a significant error in calculating the length. Actually this experiment tells the fault in the fiber. So, our connector should be fixed properly. Otherwise, there will be huge loss in fiber.