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EFFECTS OF RESTRICTED LAUNCH CONDITIONS FOR THE ENHANCEMENT OF BANDWIDTH-DISTANCE PRODUCT OF MULTIMODE FIBER LINKS

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ABSTRACT

Several techniques had been proposed to enhance multimode fiber bandwidth-distance product. Single mode-to-multimode offset launch condition technique had been experimented at Kennedy Space Center. Significant enhancement in multimode fiber link bandwidth is achieved using this technique. It is found that close to three-fold bandwidth enhancement can be achieved compared to standard zero offset launch technique. Moreover, significant reduction in modal noise has been observed as a function of offset launch displacement. However, significant reduction in the overall signal-to-noise ratio is also observed due to signal attenuation due to mode radiation from fiber core to its cladding.

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1. INTRODUCTION

The introduction of digital television and the increase popularity for Internet services are continually increasing the demand for higher data rate transmission on local area networks (LANs). LAN standards have been recently upgraded to rates up to 622 Mb/s and the standardization of a gigabit per second is currently under consideration. Such high-speed networks are expected to be essential for the Kennedy Space Center (KSC) backbone networks. Since the dominant fiber base currently in KSC is multimode fiber (MMF), its modal bandwidth imposes an upper limit on the achievable transmission speed and link distance. For such fiber, the maximum bandwidth distance product is limited to 500 MHz.km for over-filled-launch (OFL) conditions. Transmission rates greater than 1 Gb/s over distances beyond 1 km is not feasible on the basis of this specification. Although alternatives, such as using single mode fiber (SMF) links exist, it would be more economically feasible to develop high speed links using the installed MMF LAN.

There have been several attempts to overcome the OFL bandwidth limit by selective excitation of limited number of modes extending the bandwidth distance product [1-4].

This project is to explore the possibility of selective excitation of limited number of modes using a technique simpler than the ones reported in literature. This technique consists of SMF-to-MMF offset launch conditions such that only few modes are selectively excited resulting in extending the bandwidth distance product. Single mode fiber patch cord (10 meter long) terminated with a standard FC connector is coupled to a standard ST connector of the multimode fiber link. The offset is in the connector-to-connector coupling. This technique is expected to be more rugged than reported attempts and hence it may be more suitable for KSC applications.

2. PARAMETERS UNDER INVESTIGATION

The offset launch relies on exciting only a subset of all propagating modes of the MMF at the launch, so that the pulse broadening due to modal dispersion is lower and hence the bandwidth is larger. However, offset connector coupling loss increases due to the change in refractive index profile of the graded index fiber core. Furthermore, offset launch excites higher order modes. Higher order modes radiate off fiber adding to the nominal attenuation of the fiber. This effect will decrease signal's power at the receiving end. Another side effect of selective mode excitation is reducing modal noise [5].

The combination of reduction of, signal's power and modal noise results in changing the over all signal-to-noise ratio (S/N) affecting the quality of service (QoS) of the LAN. This change could be reducing or improving the overall S/N depending on other noise sources in the link.

Detailed performance studies for overall noise floor, modal noise, signal-to-noise ratio, connector and fiber attenuation, and bandwidth all as function of offset displacement are investigated. Optimum connector offset position can then be determined for a desired application according to signal-to-noise or/and fiber attenuation.

3. EXPERIMENTAL SET-UPS

Offset launch condition is accomplished in the laboratory using connectors lateral misalignment. Single mode fiber terminated with a standard FC connector is coupled to a standard ST connector of the multimode fiber link under consideration. The offset is in the connector-to-connector coupling. Three experimental set-ups are shown in Figure 1. Short description for each of the three experiments is given in the following sections.

3.1. Noise Measurement Set-up

This experiment, as shown in Figure 1 (a), is to measure overall system noise and to calculate modal noise. The lightwave component analyzer is used to generate 100 MHz sinusoidal signal. The Over all signal-to-noise ratio (S/N) is initially measured for 8 spools of Corning graded index fiber. Each spool is ~1 km long (LDF 50/125, BW 3-dB= ~1214 MHz-km, and NA= ~ 0.2). The measured S/N includes noise due to laser, modal, shot, thermal, and amplifier. The measurement is repeated for five SMF-to-MMF connector lateral offsets: 0 μm, 5 μm, 10 μm, 15 μm, 20 μm, and 25 μm. The experiment is then repeated without the 8 spools of MMF and the offset connector. An optical attenuator (Anritsu MN934F) is then inserted instead, using two SMF patch cords. The attenuator is used to attain the same received optical powers as in the previous parts. The measured S/N in this case does not include modal noise however, it includes all other noise sources laser + receiver). The S/N due only to modal noise is then calculated by substituting in the equation:

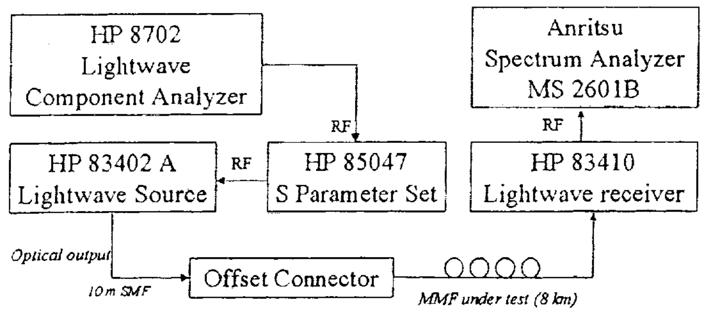
$$\left(\frac{S}{N}\right)^{-1}_{Modal} = \left(\frac{S}{N}\right)^{-1}_{Total} - \left(\frac{S}{N}\right)^{-1}_{Laser+Receiver}.$$

3.2. Attenuation Measurement Set-up

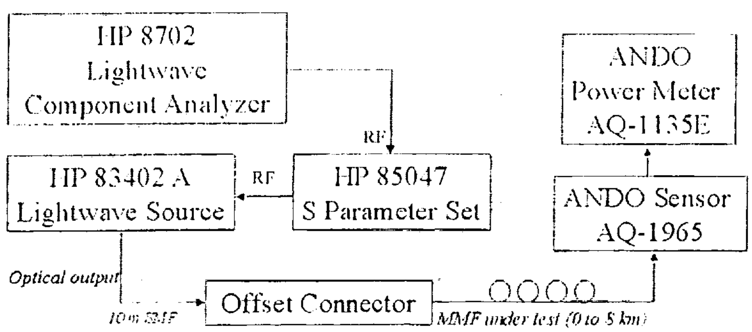
This experiment, as shown in Figure 1 (b), is to measure offset connector attenuation as well as the attenuation of the fiber as function of the length. Similar to the previous experiment, the lightwave component analyzer is used to generate 100 MHz sinusoidal signal. The signal emitted by the lightwave source (HP 83402 A) has a wavelength of 1.3 μm and optical power equal to 0.0 dBm. The optical power is then measured immediately after the offset connector and after each one of the eight spools of fiber.

3.3. Bandwidth Measurement Set-up

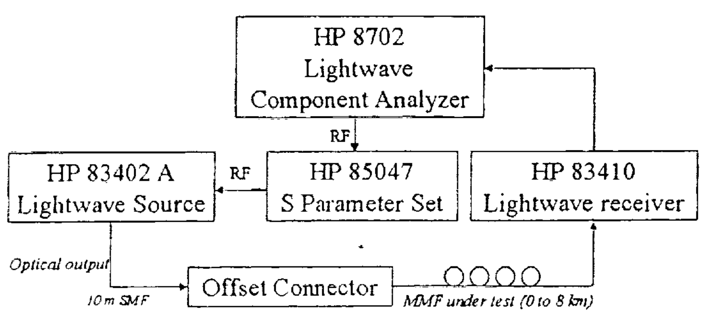
This experiment, as shown in Figure 1 (c), is to measure the bandwidth of the MMF after each connector. The HP S-Parameter set sweeps the spectrum starting at 300 kHz and ending at 3 GHz. The lightwave component analyzer is then used to measure the electrical 3-dB bandwidth.



(a) Noise Measurement Set-up

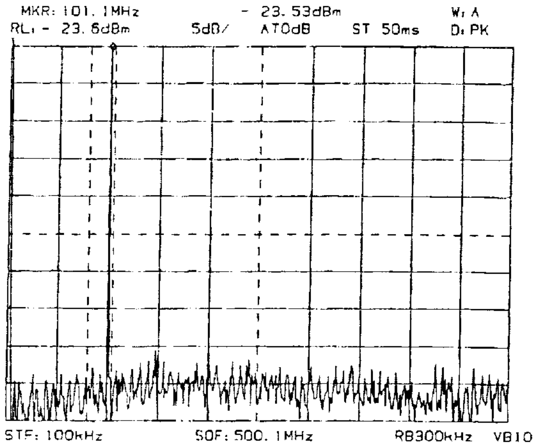


(b) Attenuation Measurement Set-up

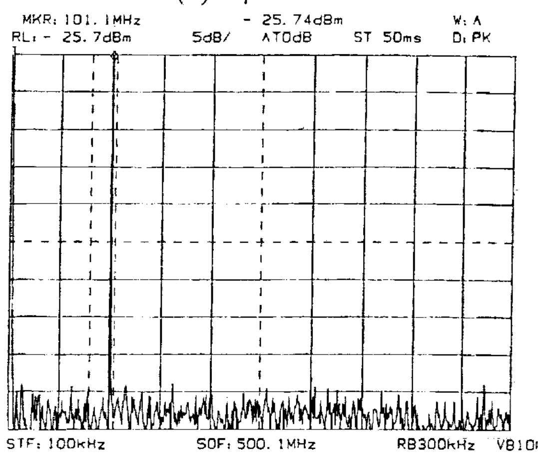


(c) Bandwidth Measurement Set-up

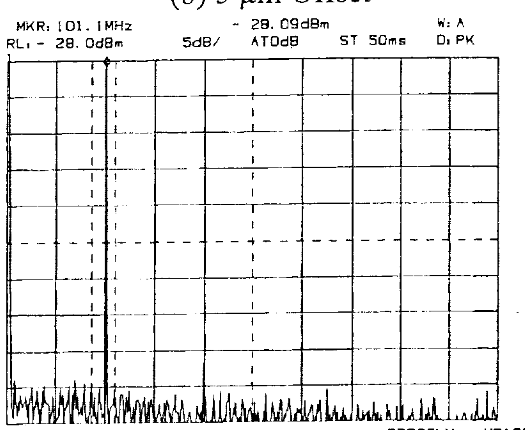
Figure 1: Experiments Set-up



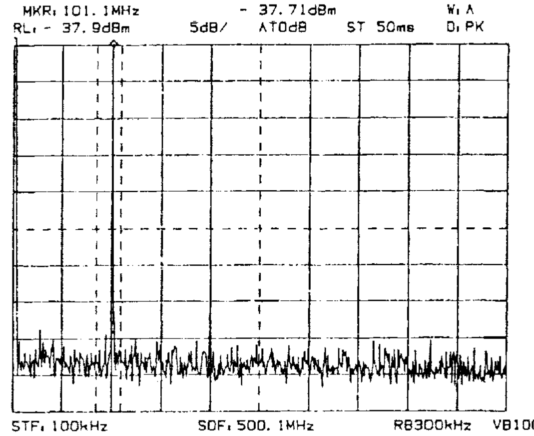
(a) 0 μm Offset



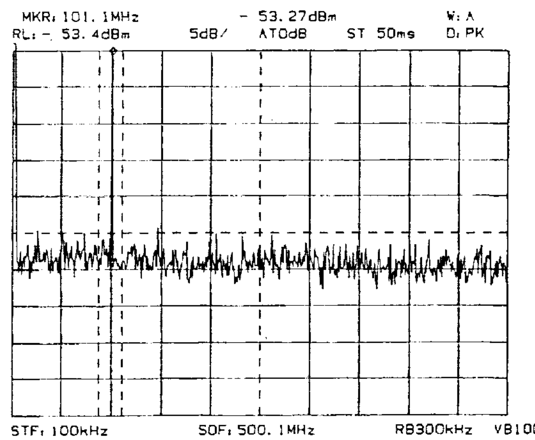
(b) 5 μm Offset



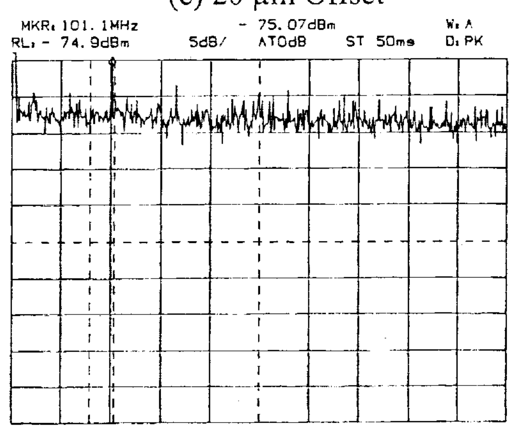
(c) 10 μm Offset



(d) 15 μm Offset



(e) 20 μm Offset



(f) 25 μm Offset

Figure 2: Signal-to-noise measurements for 8 km of MMF for different connector offsets. Signal frequency is 100 MHz for all six cases

4. RESULTS

4.1. Noise Measurement Results:

Output signal spectra for different offset connectors are shown in Figure 2. Similar measurements are repeated without including the 8 km MMF. Using spread sheet, the S/N due to modal noise is calculated as shown in Table 1.

Offset (μm)	0	5	10	15	20	25
Noise MMF (measured in mW)	-64.5	-73.0	-78.0	-81.0	-82.0	-82.9
Noise SMF (measured in mW)	-73.0	-76.0	-78.0	-82.0	-83.0	-83.2
P_{signal} (measured in mW)	-23.4	-25.6	-28.2	-38.0	-53.4	-74.0
$(S/N)_{laser + receiver}$ (calculated in dB)	49.6	50.4	49.8	44.0	29.6	9.2
$(S/N)_{total}$ (calculated in dB)	41.1	47.4	46.8	43.0	28.6	8.9
$(S/N)_{modal}$ (calculated in dB)	41.7	50.4	49.8	49.8	35.4	20.6
Modal Noise (calculated in dBm)	-65.1	-76.0	-78.0	-87.8	-88.8	-94.6
Modal Noise (calculated in μW)	3.5×10^{-4}	2.5×10^{-5}	1.5×10^{-5}	1.6×10^{-6}	1.3×10^{-6}	3.4×10^{-7}

Table 1: Calculations for modal noise and $(S/N)_{modal}$

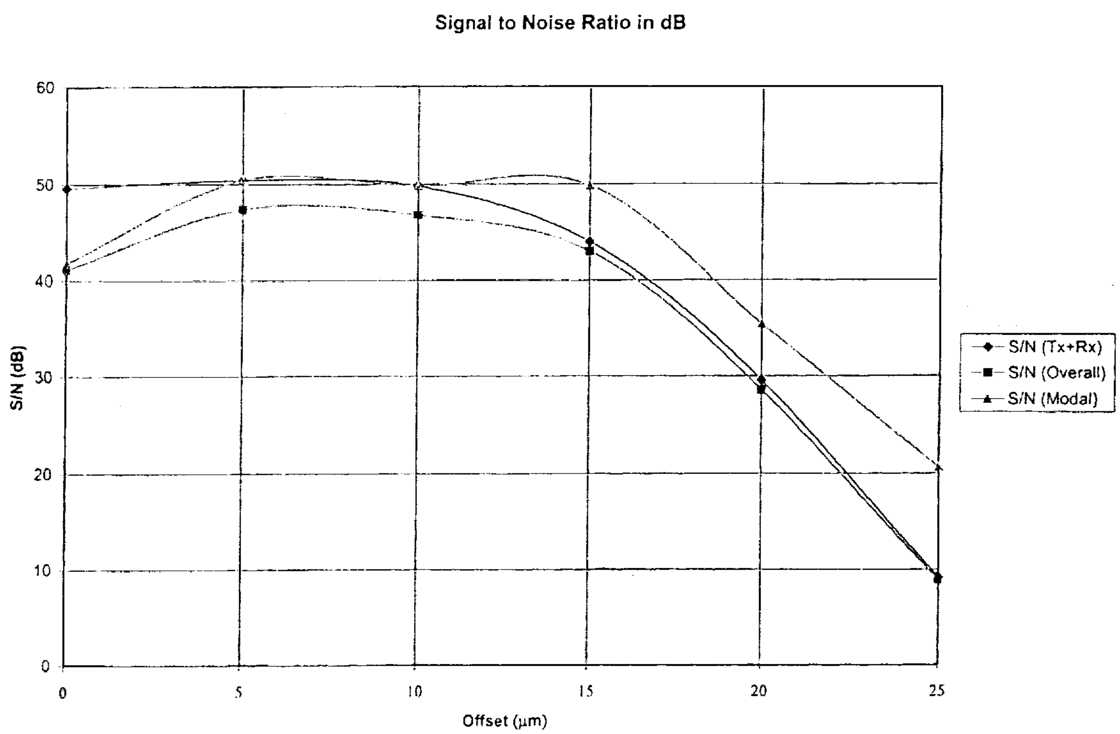


Figure 3: $(S/N)_{dB}$ vs. lateral offset in μm due to: laser + receiver, shot, and total noise.

We conclude from Table 1 and Figure 3, that shot noise decreases with increasing connector lateral offset. However, connector lateral offset increases signal attenuation as well. The combination of the two effects gives the curve shown with the symbol $\triangle$. For 0 μm offset, we notice that the dominant noise is modal noise. For offsets larger than 15 μm the dominant noise is due to laser + receiver. Between 5 and 10 μm, modal noise is in the same order of magnitude of the sum of other noises. Hence, based only on S/N, the optimum operating point should be between 5 and 10 μm. However, there are other factors to be put into consideration such as attenuation and bandwidth.

4.2. Attenuation Measurements

Optical power P_o is measured immediately after the offset connector and after each segment (each segment is 1 km) up to 8 segments. The measured values are shown in Table 2.

Offset (μm)	**0**	**5**	**10**	**15**	**20**	**25**
P_o @ 0 km (dBm)	-0.4	-1.0	-1.0	-2.4	-2.4	-15.5
P_o @ 1 km (dBm)	-1.1	-1.5	-1.6	-4.3	-10.0	-20.5
P_o @ 2 km (dBm)	-2.0	-2.2	-2.8	-6.6	-13.5	-23.1
P_o @ 3 km (dBm)	-2.7	-3.2	-3.9	-8.0	-15.1	-24.6
P_o @ 4 km (dBm)	-3.4	-4.0	-5.2	-9.7	-17.0	-26.7
P_o @ 5 km (dBm)	-4.1	-4.6	-6.1	-10.7	-18.3	-27.9
P_o @ 6 km (dBm)	-5.1	-5.8	-7.4	-12.0	-19.7	-29.4
P_o @ 7 km (dBm)	-5.8	-6.5	-8.2	-12.8	-20.6	-30.1
P_o @ 8 km (dBm)	-6.7	-7.4	-9.2	-13.8	-21.7	-31.2

Table 2: Optical power P_o in dBm as function of connector lateral offset at different lengths of MMF.

Table 2 is graphed in Figure 4 from which we notice that for 0 μm offset the attenuation is linear vs length i.e. the attenuation of the first km of fiber is equal to the attenuation of the 8th km of the fiber. However, for large connector (such as 25 μm) offsets the attenuation at the beginning of the fiber is much larger than the attenuation at the end of the fiber (more than five folds). This is because most of the modes excited by lateral offset launch are "radiation modes," these are the modes that are **not** confined in the core [6]. However, zero connector-to-connector offset mainly excites "meridional and helical modes". These modes are guided inside the core. We Also notice that connector loss jumps suddenly from 2.4 dB to 15.5 dB when offset is incremented from 20 μm to 25 μm. This is due to the high radiation loss occurring at the first 10 m of MMF connecting the offset connector with the Optical Power Meter.

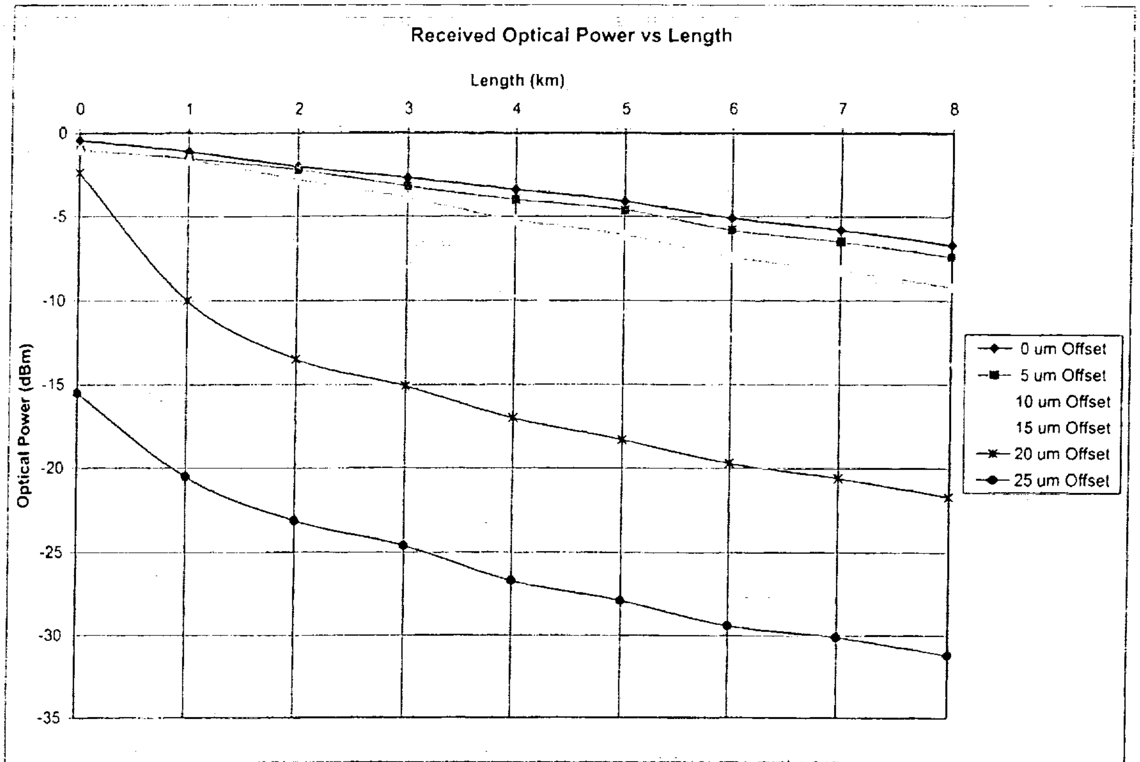


Figure 4: Received optical power in dBm vs. MMF length in km for different connector offsets.

4.3. Bandwidth Measurements

Electrical bandwidth is measured after each segment (each segment is 1 km) up to 8 segments. The measured values are shown in Table 3.

Offset (μm)	0	5	10	15	20	25
BW @ 1 km (MHz)	694	890	1100	1200	1300	1500
BW @ 2 km (MHz)	400	536	675	676	715	810
BW @ 3 km (MHz)	382	450	580	630	665	675
BW @ 4 km (MHz)	346	370	441	520	535	540
BW @ 5 km (MHz)	308	330	406	428	440	510
BW @ 6 km (MHz)	279	309	389	396	405	460
BW @ 7 km (MHz)	193	238	328	346	375	395
BW @ 8 km (MHz)	189	225	300	310	335	360

Table 3: Bandwidth in MHz as function of connector lateral offset at different lengths of MMF.

The plot of this table is shown in Figure 5.

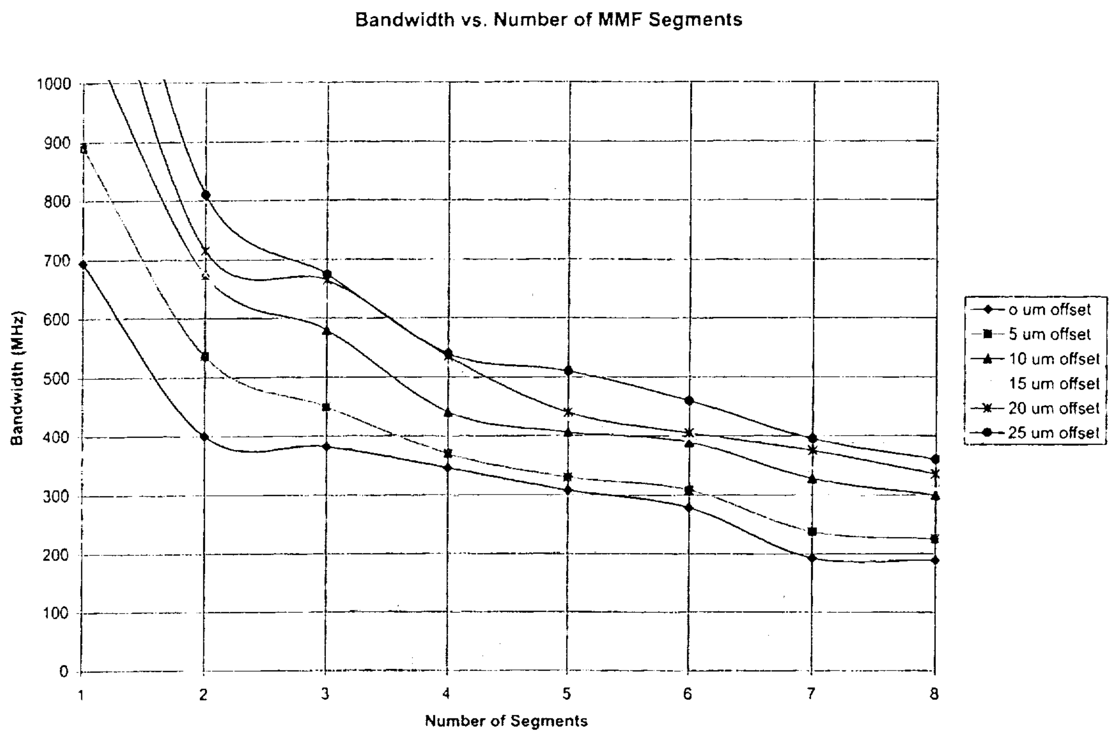


Figure 5: Bandwidth in MHz vs. MMF number of segments (1 km each) for different connector offsets.

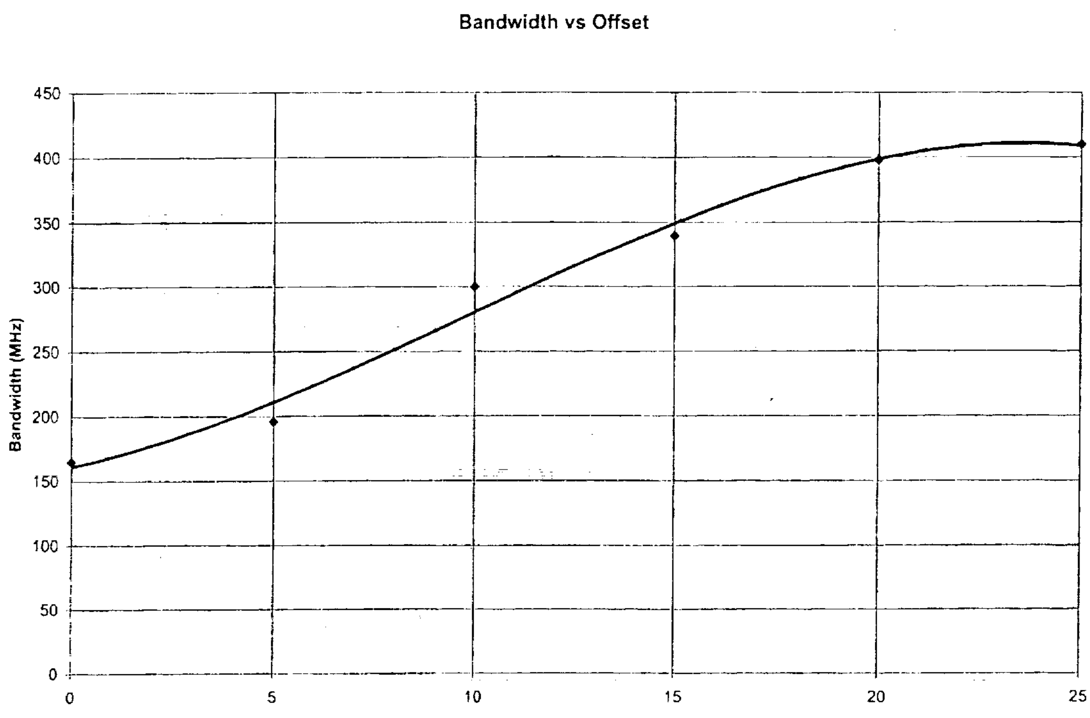


Figure 6: Bandwidth in MHz vs. lateral offset in μm for an 8 km MMF link.

We observe here that the dispersion is large at the beginning of the MMF link and it level off after few segments. This could be explained by the fact that modal dispersion, which is dominant in MMF, is proportional to the number of modes. The number of modes is larger at the beginning of the fiber link than at the end of the fiber link. Propagating modes at the beginning of the fiber include radiation modes as well as meridional and helical modes. After couple of kilometers, radiation modes radiate off the core leaving only meridional and helical modes in the fiber core.
We obtain Figure 6 when the length is fixed to 8 km and the experiment is repeated. We notice that bandwidth improvement for 25 μm offset is almost three fold better that the bandwidth at on-line SMF-to-MMF coupling. Explanation of this phenomenon is well studied previously [1-6]

5. CONCLUSION

It is evident that extending the bandwidth-distance product of a MMF is possible. A simple lateral offset connector could be used to selectively excite higher order modes to extend the bandwidth-distance product. However, the optimum lateral offset depends on signal modulation, and transmission distance. Depending on the minimum required S/N, the optimum connector offset is initially estimated from Figure 3. Receiver's sensitivity and maximum bit rate could then be found from Figure 4 and Figure 5. For binary digital, transmission is achievable with S/N as low as ~20 dB. From Figure 3 we find that the offset could be as large as 22 μm for a link of 8 km. Receiver's sensitivity is then estimated from Figure 4 for an 8 km link to be equal to ~ -23 dBm (for an 8 km link). Depending on the distance, the maximum bit rate transmission could then be determined from Figure 5 (maximum bit rate $\approx 2 \times$ bandwidth). Following the same procedure for analog transmission, connector offset is estimated to be 15 μm. However, a significant enhancement in S/N (more than 5 dB) is achievable with a SMF-to-MMF 5-10 μm offset.

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