THE IMPACT OF COHERENT MPI ON FTTH NETWORKS

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1. Introduction

The phenomenon of MPI is observed when a short fiber jumper B that supports both the fundamental mode LP01 and the higher order mode LP11 is connected or spliced between two long fibers A and C with offsets in the connections, as shown in figure 1. In both connections, most power from the LP01 mode of the input fiber is coupled to the LP01 mode of the output fiber. However, at the first connection, some of the light from the LP01 mode of fiber A can be coupled into the LP11 mode of the fiber B. At the second connection, a portion of the light in the LP11 mode in fiber B can be coupled back to the LP01 mode of fiber C and interfere with the light in the LP01 mode coupled directly from fiber B to fiber C. This condition can also be applied to two macro-bends on certain non-nanostructure fiber designs as well.

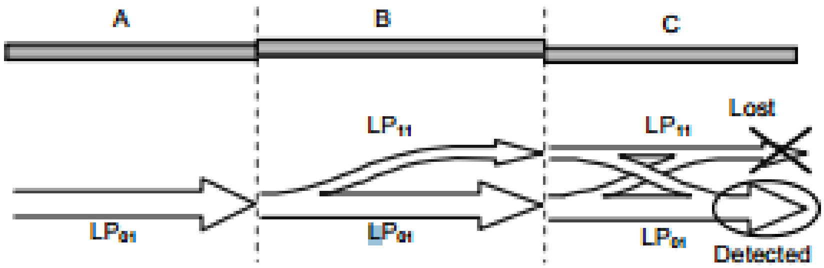

Figure 1. Schematic of MPI with a fiber jumper

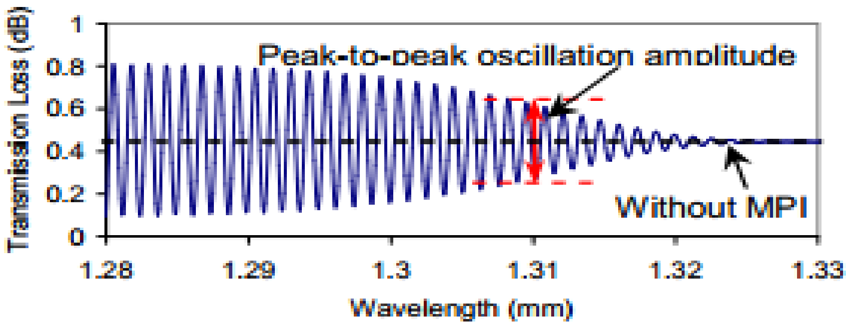

Figure 2. Fluctuation of detected power due to MPI

The MPI causes fluctuations of the detected power as the laser wavelength drifts or when there is any slow perturbation on the fiber (due to temperature change, bending, vibration, etc.). The MPI can also produce modal noise (fast fluctuation) due to chirping, mode hopping or mode partitioning in the laser. It is common to define the MPI using the following equation which is the crosstalk power relative to the coherent signal power.

$$MPI(dB) = 20\log\left[\frac{10^{PR/20} - 1}{10^{PR/20} + 1}\right]$$

This equation indicates that the MPI is determined by the peak-to-peak interference amplitude. The interference amplitude depends on the connector losses, the attenuation coefficient of the LP11 mode that depends on the cutoff wavelength and the coupling efficiencies between the LP01 and LP11 modes. The coupling efficiency between the LP01 and LP11 modes at the second connector depends on not only the magnitude of the connector offset, but also the angle between the two connector offsets.

2. Background

The issue of noise generation in short fibers was recognized in the 1980's when minimum cable repair segment lengths were restricted because of "modal noise". This effect was particularly noted in depressed clad fibers which were more bend insensitive than matched clad ones. Simple models were used to estimate the noise penalties for a given amount of propagated HOM power. [1]

This type of MPI is coherent, and is different from the incoherent MPI often of concern in long-haul systems. In the coherent case, the phase relation between the carrier light wave travelling the different paths has not been erased by the finite linewidth of the transmitter. The coherent MPI case is one where slow changes in transmitted power must be tracked. Any change in jumper refractive index, length, or position can result in changes in the resulting interference. The polarization dependence of the interference must be noted. Varying the input polarization has been suggested as a means for speeding up the MPI measurement and is critical in fully exploring the limits of noise generation.

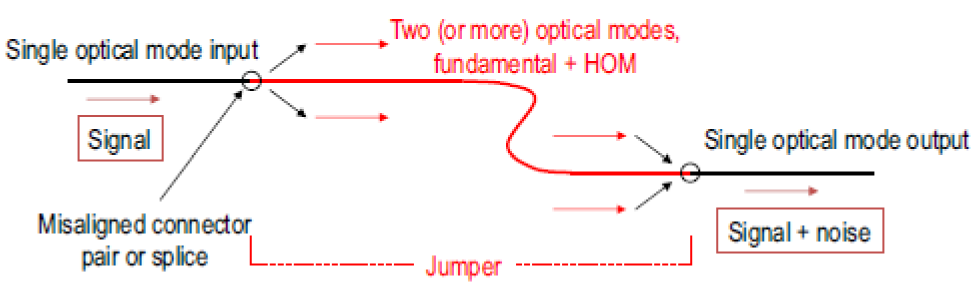

Figure 3. MPI noise generated from a short fiber jumper

The generation of MPI can be understood from the diagram shown in Figure 3. Here a short bend-insensitive jumper is depicted with poor connections at each end (due to an offset fusion splice or misaligned mechanical connector).

The incoming LP01 optical mode is partially converted to an HOM at the first connection. The LP01 mode and the HOM travel through the jumper with different group velocity. At the second connection point, some of the HOM will convert back to the LP01 mode. Any HOM propagating into the output single mode fiber is lost to radiation. Interference will occur between the LP01 which passed straight through the jumper and the LP01 which arrived by way of the HOM. This interference will manifest itself through a modification of the transmitted power through the jumper.

It is useful to think of MPI in two limits: one where the transmitter can produce a range of wavelengths (possibly as wide as the free spectral range of the "interferometer" formed by the jumper) and the second where the transmitter operates at a single wavelength. In the first case, the relevant MPI is found by including all transmitted power variations which can occur within the allowable range of operating wavelengths while varying the launch polarization. This is termed finite spectral width (FSW) MPI. The second case only has significant MPI when the polarization changes and is called zero spectral width (ZSW) MPI. This type of MPI occurs with narrow spectral width transmitters such as DFB-based ones.

3. FTTH networks

3.1 What is FTTH networks?

FTTx is an acronym that embraces a number of optical number technologies, in the case of FTTH it means Fiber To The Home. This access network, also known as the "first-mile network", connects the service provider central office to business and residential subscribers. The Bandwidth demand in the access network has been increasing rapidly over the past several years. It is estimated that there would be a bandwidth demand of 1Gbps or more, around year 2020, and 10Gbps in year 2030. [2]

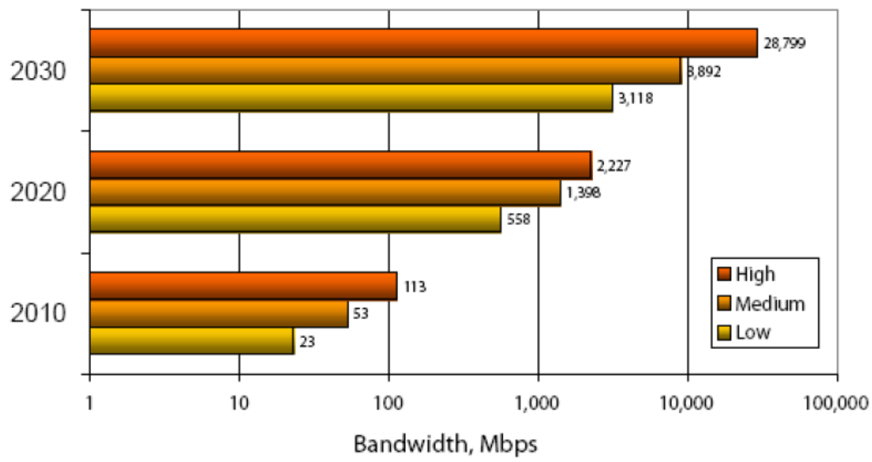

Figure 4. Projections of needed bandwidth in the future

3.2 FTTH architechtures

There are mainly two FTTH architectures that are of current interest, which are namely point-to-point architecture (P2P), and the point to multipoint (P2MP) architectures which are further classified as Active Optical Network (AON), and Passive Optical Network (PON).

3.2.1 Point-to-Point (P2P) Architecture

In this architecture, as the name suggests, individual fiber run from the Optical Line Termination (OLT) to each Optical User Unit (ONU). In other words, individual fiber runs to each home. P2P architecture has its advantages as well as certain major drawbacks. One advantage is the opportunity to provide the ultimate capacity, and satisfy each customer's requirements completely. Individual fiber pair also means greater flexibility in providing services to customers.

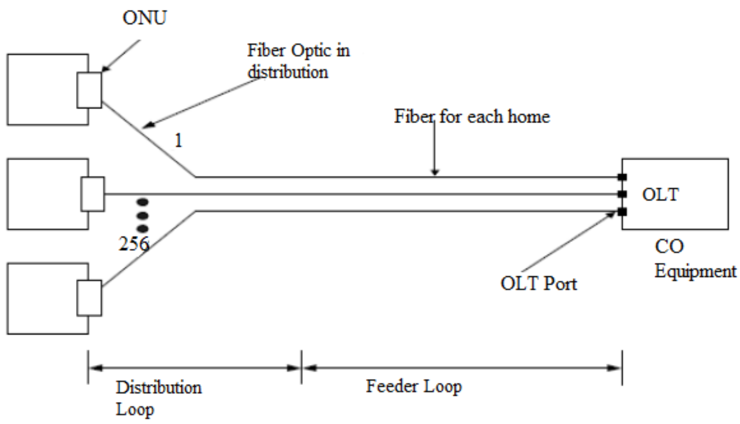

Figure 5. Point-to-Point (P2P) Architecture

There are however some major drawbacks with the P2P architecture. At the OLT, the need for hub equipment will scale with number of ONUs. Besides the cost of acquisition, these equipments may also cause problems in connection with space and power consumption. P2P solution also requires many fiber pairs, and with these all the installation and maintenance.

3.2.2 Active Optical Network (AON)

AON is characterized by a single fiber which carries all traffic to a remote node (RN)close to the end users from the central office.

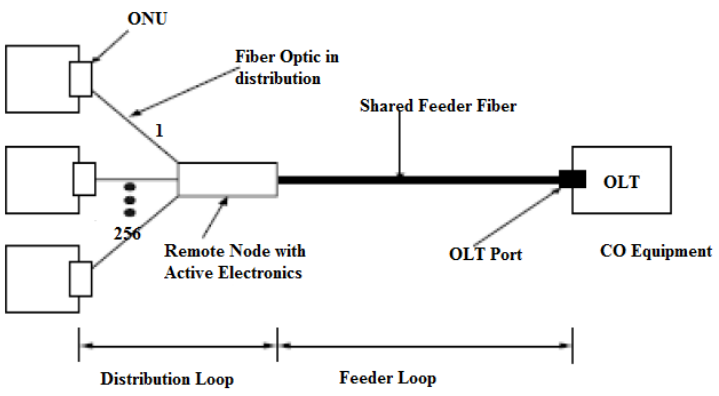

Figure 6. Active Optical Network (AON)

Compared to the P2P architecture, the AON architecture's main advantage is that it is only used a single shared fiber to cover a certain area, thus reducing the fiber cost.

3.2.3 Passive Optical Networks (PON)

In this architecture, the active node from AON is replaced with a passive optical power splitter/combiner. The splitter is denoted as passive since it just broadcasts all the data that it receives. Like the AON, there is a single shared feeder fiber from the OLT to the splitter. The task of sorting out the right packets that belongs to each subscriber lies within the network units (ONTs) in the PON model. OLT is a very important segment of PON. The most important functions that OLT perform are traffic scheduling, buffer control and bandwidth allocation.

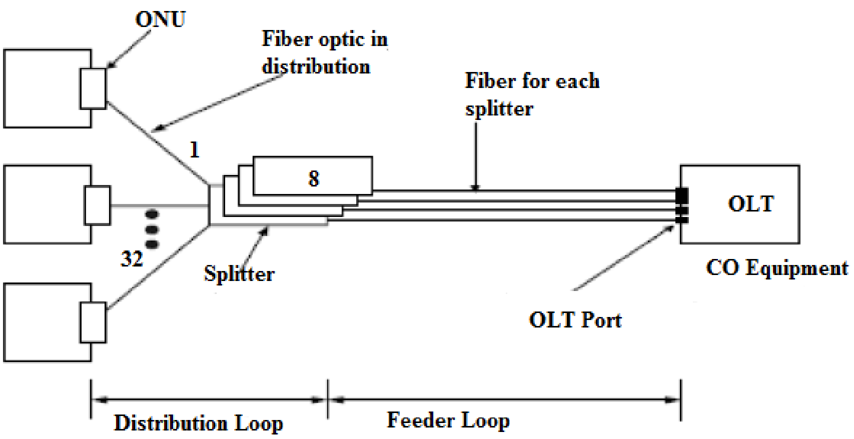

Figure 7. Passive Optical Network (PON)

Today there are two primary types of standardized passive optical network technologies, Ethernet Passive Optical Networks (EPONs), and Gigabit-capable Passive Optical Networks (GPONs).

3.3 Passive optical networks standards

The existing PON standards are the results of efforts of two different groups of network providers and equipment vendors.

3.3.1 Broadband PON Standard

The Broadband Passive Optical Network (BPON) standard was introduced first in 1999. The architecture of the BPON is very flexible and adapts well to different scenarios. The underlying ATM protocol provides support for different types of service by means of adaptation layers. The small size of ATM cells and the use of virtual channels and links allow the allocation of available bandwidth to end users with a fine granularity.
The complexity of the ATM protocol made it difficult to implement and in many cases superfluous. The much simpler, data only oriented Ethernet protocol found a widespread use in local area networks and started to replace ATM in many metropolitan areas.

3.3.2 Gigabit PON Standard

Gigabit Passive Optical Network (GPON) was released and adopted by the ITU in 2003. The GPON's functionality was heavily based on its predecessor, although it is no longer reliant on ATM as an underlying protocol. Instead a much simpler Generic Framing Procedure (GFP) is used to provide support for both voice and data oriented services. A big advantage of the GPON over other schemes is that interfaces to all main services are provided. Employing GFP guaranteed that packets belonging to different protocols could be transmitted in their native formats.
In comparison with the BPON standard much higher transmission rates are specified, the GPON being capable of supporting transfer rates of up to 2.48 Gbps in the downstream as well as the upstream direction.

3.3.3 Ethernet PON Standard

The EPON standard is the result of work in the vendor driven cooperation, the Ethernet in the First Mile Alliance (EFMA). Noticing that the majority of traffic in the network is data oriented and that efficient mechanisms enabling support for real time services were in place, the sophisticated functionality of the BPON and GPON protocols was no longer needed.
The final version of the new protocol and necessary amendments to the existing ones were accepted by the standards body and released as IEEE 802.3ah in September 2004. The main goal was to achieve a full compatibility with other Ethernet based networks. Hence, the functionality of Ethernet's Media Access Control (MAC) layer is maintained and extensions are provided to encompass the features of PONs.

3.4 Multiplexing

Multiplexing is the technique of transmitting multiple independent streams of data on the same medium. On PON this is crucial, since fibre is shared by multiple customers. Indeed in a PON there are multiple levels of multiplexing: downstream and upstream channels must also be separated. The simplest way to achieve this is to install separate downstream and upstream fibres (Space Division Multiplexing), but in order to save on fibre costs modern PONs support the transmission of data in both directions along a single fibre using light of different wavelengths (Wavelength Division Multiplexing).

Within these channels the data for multiple customers must be multiplexed together; current PONs typically place between 32 and 128 customers on the same branched fibre. Unusually due to the asymmetry inherent in a PON, it is beneficial to consider the multiplexing schemes on the upstream and downstream channels separately; they have rather different characteristics despite superficial similarity [3].

3.5 Protocols

Most FTTH systems are so-called "triple play" systems offering voice (telephone), video (TV) and data (Internet access.) To provide all three services over one fiber, signals are sent bidirectionally over a single fiber using several wavelengths of light.

BPON uses ATM as the protocol. ATM is widely used for telephone networks and the methods of transporting all data types (voice, Internet, video, etc.) are well known. BPON digital signals operate at ATM rates of 155, 622 and 1244 Mb/s.

Downstream digital signals from the CO through the splitter to the home are sent at 1490 nm. This signal carries both voice and data to the home. Video on the first systems used the same technology as CATV, an analog modulated signal, broadcast separately using a 1550 nm laser which may require a fiber amplifier to provide enough signal strength to overcome the loss of the optical splitter. Video could be upgraded to digital using IPTV, negating the need for the separate wavelength for video. Upstream digital signals for voice and data are sent back to the CO from the home using an inexpensive 1310 nm laser. WDM couplers separate the signals at both the home and the CO.

GPON uses an IP-based protocol and either ATM or GEM (GPON encapsulation method) encoding. Data rates of up to 2.5 Gb/s are specified and it is very flexible in what types of traffic it carries. GPON enables “triple play” (voice-data-video) and is the basis of most planned FTTP applications in the near future. In the diagram above, one merely drops the AM Video at the CO and carries digital video over the downstream digital link.

EPON uses packet-based transmission at 1 Gb/s with 10 Gb/s under discussion. EPON is widely deployed in Asia. The system architecture is the same as GPON but data protocols are different [4].

	BPON	GPON	EPON
Standard	ITU-T G.983	ITU-T G.984	IEEE 802.3ah (1 Gb/s) IEEE 802.3av (10Gb/s)
Downstream Bitrate	155, 622 Mb/s, 1.2 Gb/s	155, 622 Mb/s, 1.2, 2.5 Gb/s	1.25 Gb/s, 10.3 Gb/s
Upstream Bitrate	155, 622 Mb/s	155, 622 Mb/s, 1.2, 2.5 Gb/s	1.25 Gb/s, 1.25 or 10.3 Gb/s
Downstream Wavelength	1490, 1550	1490	1490, 1550
Upstream Wavelength	1310	1310	1310
Protocol	ATM	Ethernet over ATM/IP or TDM	Ethernet
Video	RF at 1550 or IP at 1490	RF at 1550 or IP at 1490	IP Video
Max PON Splits	32	64	16
Coverage	<20 km	<60 km	<20 km

Figure 8. PON system specification summary

4. Impact of MPI on FTTH networks

As the fiber reaches near or into houses for FTTH applications, it needs to have very high bend resistance. Harsh conditions like sharp turns, staples, and storage with low diameter turns are very common in indoor applications. ITU has recommended a new fiber type called G.657 for these applications and special bend insensitive fibers (BIFs) are designed for this purpose [5].

As the macro-bend loss of conventional matched clad fibers cannot be reduced beyond certain extent without disturbing mode field diameter (MFD) and dispersion, a trench in cladding design has been proposed. Fibers with trench in cladding design can achieve ultra low bend losses without compromising on MFD and dispersion. However, these fibers typically have higher cutoff wavelengths than matched clad fibers due to more confinement of optical power. Also, the existence of trench in these fibers changes the cutoff mechanism.

Because of the depressed index region in BIFs, the LP mode is bend resistant and becomes leaky around 11 cutoff wavelength and can interfere with fundamental mode. Multipath interference in a BIF is caused when signal in fundamental mode gets partially converted into higher order mode and reconverted back into fundamental mode after propagating certain distance.

MPI in FTTH networks differs from the one encountered in LH networks because the potential events causing it (splices, connections, staples, bends) are closely located on distance scales that become comparable to the laser coherent length, that is, the propagation distance from a coherent source to a point where an electromagnetic wave maintains a specified degree of coherence. The length L is given by [6]:

$$L = \frac{2\ln(2)}{\pi n}\frac{\lambda^2}{\Delta\lambda}$$

where λ is the central wavelength of the source, n is the refractive index of the medium, and $\Delta\lambda$ is the spectral width of the source.

This coherent MPI exhibits a specific spectrum whose low frequency content is not accurately captured by high-pass filtering methods used in typical incoherent-based MPI situations such as in Long haul systems.

The coherent noise differs from the incoherent MPI noise determined by double Rayleigh backscattering affecting long-haul links under distribution Raman amplification, where the typical time delay between the two scattering events is longer than the source coherence time and the field phases do not intervene in the relevant equations. It can be additionally noted that in a double backscattering , the parasitic light undergoes a backward propagation in the fundamental mode between the two events, while in the coherent MPI noise affecting bend insensitive fibers, it undergoes a forward propagation in a leaky higher order mode that ideally would be completely suppressed.

It can be observed in some bibliography that in a typical FTTH deployment operating at 10 Gb/s the maximun MPI noise level considered admissible in an optical link does not cause a significant increase of the system BER, and the associated power penalty is negligible [7].

5. Methods for measuring coherent MPI in short optical fibre cables

Modal noise is a well known phenomenon in multimode fibres arising from interference effects between propagating modes.
In the past, the effect of overmoding on system performance was studied using different single fibre cables with length L containing fibres with different cut-off wavelength ($\lambda c2$) drawn from the same depressed cladding-cladding index preform. The interconnection cables were terminated with precision biconic connectors, and were inserted between a transmitter pigtail and another single-mode jumper cable both having an effective cut-off wavelength ($\lambda c1$). The cut-off wavelength $\lambda c1$ was chosen to assure single-mode Operation in the short cable regions.
The centre wavelength of the buried-heterostructure laser used satisfied the condition:
$\lambda c1 < \lambda L < \lambda c2$

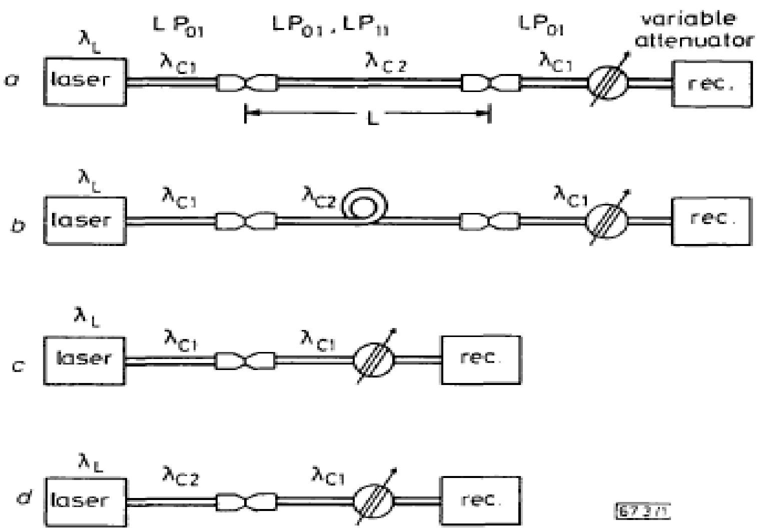

Fig 9. Different interconnection schemes to study modal noise in single mode fibre sections

The existence of modal noise in overmoded single-mode fibres could be demonstrated by this experiment [8]. Modal noise was observed for 1m-long straight cable sections when with λL=1.26 micrometers, λc1=1.24 micrometers, λc2=1.46 micrometers.

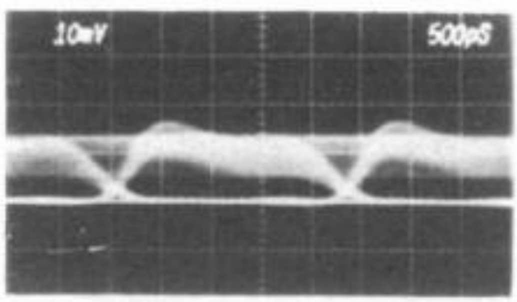

Fig 10. Eye diagram with overmoded jumper deployed straight (fig 9.a)

The figure above shows the eye diagram with the modal noise at 432 Mbit/s NRZ, obtained when the central jumper was deployed straight. The modal noise disappear when a 2.5 cm-diameter loop was introduced into the central jumper, or when the jumper is removed.

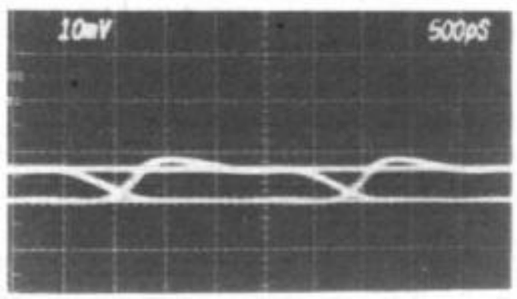

Fig 11. Eye diagram with 2.5 cm loop (Fig 9.b)

Actually there are several methods for the measurement of MPI noise, in this document it is shown some of them.
The MPI noise can be measured by using a combination of a laser and a power meter or a broadband led and an optical spectrum analyzer. The span of bend insensitive fiber can be stretched by a motorized translation stage, while a computer controls all the instruments and records the relevant data. The relative phase between the coherently co-propagating modes generated at the first splice and interfering at the second one can be varied by sweeping the wavelength or alternatively by stretching the BIF span. Splicing the BIF between two long reels of standard single mode fiber ensures that only the fundamental mode arrives at the input end of the fiber under test and into the detector, and simultaneously allows a precise measurement of the loss induced by the two misaligned fusion splices by means of a commercial optical time-domain reflectometer.

5.1. First method: The narrowband ECL/PM technique

The narrowband ECL/PM technique monitors transmitted optical power through jumper as a function of wavelength. The interference phenomenon between the fundamental, LP01, and higher-order mode (HOM) is measured by capturing the maximum and the minimum transmitted power over a range of wavelengths.

The optical source used is a tuneable external cavity laser (ECL) with recommended characteristics: linewidth less than 200 Khz, power high than -4dBm at the shortest wavelengths of interest (usually 1260 nm) and wide tunning range (-100 nm). The stability of the power should be less than 0.01 dB over the testing time and should vary less than 0.05 dB over the wavelength range required to sample the free spectral range (FSR) of the jumper interference pattern (typically 2nm). The laser RIN should be less than -145 dBm/Hz over the [10-500 Mhz] range.

Since the coupling at the connection points will be polarization dependent, power measurements must be made at many random polarizations of the incoming light. The polarization may be changed by use of a polarization controller or a scrambler. The power measurement must be made on a time scale that is short compared to the time for the polarization to change substantially. power meters usually require 0.1 - 20 ms to obtain a reading. Thus scrambling frequencies should be below the range 1 - 0.005 kHz, depending on the averaging time chosen for the power meter.

The single mode fibre in the launch line should be looped to the appropriate dimension to eliminate all but the fundamental LP01 mode propagation.

The light should be received by a power meter or a photodetector/oscilloscope combination. The power meter averaging time should be adjusted so that power measurements are made rapidly compared to the time over which the polarization scrambler changes the polarization significantly. Data is collected at each wavelength until > 100 measured power values have been captured.

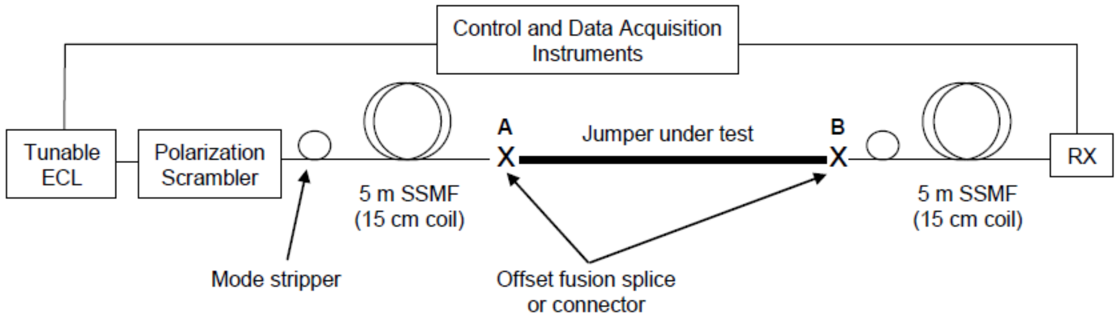

Figure 12. Schematic of set-up for narrowband ECL/PM method.

Here the "RX" receiver consists of a power meter or a photodetector/oscilloscope pair SSMF is the standard single mode ITU-T G.652 fibre.

5.2. Second method: The wideband LED/OSA technique

The same way as the first method, the wideband LED/OSA technique monitors transmitted optical power through jumper as a function of wavelength.

The optical source used is a wideband light source (typically LED based) with peak power density > -40 dBm/nm and stability less than |3| dBm/15 minutes with output in the wavelength range of interest (1260 -1625 nm). The stability of this source will not be as good as the first method, this limits the MPI which can be measured.

An scrambler is used as in the first method. The OSA power density measurement at each wavelength must be made on a time scale which is short compared to the time for the polarization to change substantially. Adjustment of the number of wavelengths tested, the sweep speed and the sensitivity allows the user to vary the acquisition time of the OSA to match the speed of the polarization scrambler.

The single mode fibre in the launch line should be looped to the appropriate as in the first method to eliminate all but the LP01 propagation mode.

The optical receiver used is an OSA that should be configured with the correct number of wavelength points and the sweep time so that the residence time at each wavelength is much shorter than the inverse of the polarization scrambling speed. This prevents polarization averaging during OSA measurement at each wavelength.

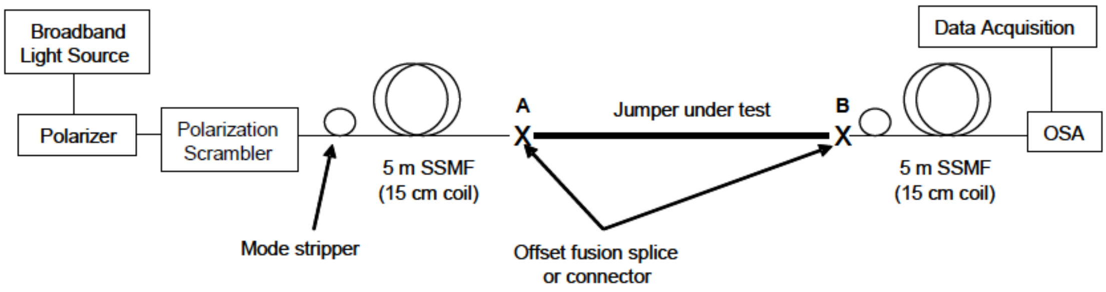

Figure 13. Schematic of set-up for the wideband LED/OSA method.

5.3. Third method: The fiber stretching technique

The fibre stretching technique utilizes the fact that the transmitted power (with interference between the LP01 and the higher order mode in the jumper) changes periodically with the optical phase difference through the jumper. This optical phase difference is dependent on wavelength but is also proportional to the jumper length. The length is most easily varied by stretching the fibre. In this case the maximum and the minimum transmitted power is measured as fibre length is varied. This method may be less easily applied in cases where the jumper is buffered and/or jacketed.

The source can be either a tuneable laser or a transceiver. Polarization changes are made by the polarization scrambler. If a tuneable laser is used, the laser performance should conform the specifications given in the first method. In the case of optical transceiver, ensure that wavelength and power output are stable over the several minutes required for the performing test.

To ensure that the worst case conditions are achieved, transmitted power measurements must be made at many random polarizations of the incoming light. The polarization must be changed by using a scrambler. The scrambling speed should be slow enough to guarantee that each power meter measurement is completed before there is a significant polarization change, the time employed by the scrambler must be longer than the power meter integration time.

The translation length must be set after the mode beating period has been determined, which should be done with the polarization scrambling turned off. The translation length should be chosen between a lower limit dictated by the periodicity of the mode beating and an upper limit corresponding to an appropriate fibre strain.

Before setting the power meter integration time, the speed of the scrambling and the translation stage velocity, the frequency of the power meter must be decided. The sampling frequency should be high enough to guarantee a clear identification of the peak/through cycle determined by the fibre stretching, with no less than 25 points collected for each oscillation period.

A reliable MPI evaluation can only be obtained only if a large enough number of power meter readings, corresponding to a different polarization state of the injected light and phase differences between the co-propagating mode. Having collected a large number of readings (2000 per example), the average and the standard deviation of collected MPI values provide a complete statistical description of the expected penalty.

The single mode fibre in the launch line should be looped to the appropriate dimension to eliminate all but the fundamental LP01 mode propagation.

The light should be received by a power meter or a photodetector/oscilloscope combination, like in the first method.

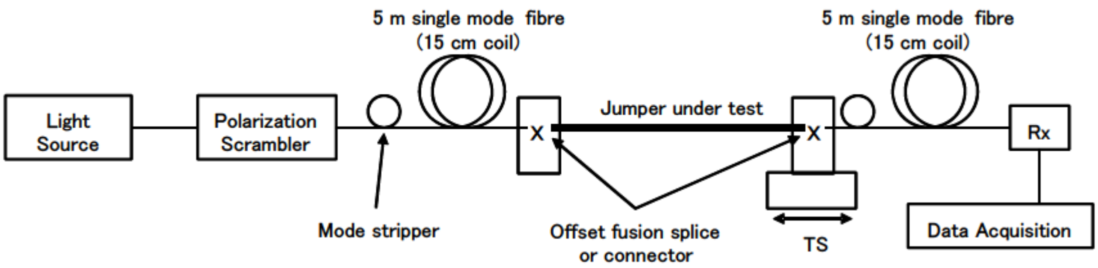

Figure 14. Schematic of set-up for the fibre stretching method. "TS" is a translation stage. Here the "RX" receiver consists of a power meter or a photodetector/oscilloscope pair

5.4. Calculations

To compute the MPI, the data is processed through a moving window of width higher or equal to Free Spectral Range (FSR). For each position of the window (denoted by his central wavelength), the maximum and the minimum power are found and used in this equation:

$$MPI(dB) = 20\log\left[\frac{10^{PR/20} - 1}{10^{PR/20} + 1}\right]$$

Where PR is the difference between the maximum and the minimum power levels detected (in dB)[9].

6. Conclusions

This chapter provides a summary of the research work done in this thesis. As an introduction, it is explained what is the effect of multipath interference, it is shown that the MPI causes fluctuations in the received power and can also produce modal noise (fast fluctuations).

This report focus on the coherent MPI, it means, the phase relation between the carrier light wave travelling the different paths has not been erased by the finite linewidth of the transmitter.

In this thesis it is also shown a comparison between the different FTTH architectures and standards, is observed that the use of passive optical networks is very advantageous in designing FTTH architectures.

It is shown that in order to minimize the impact of MPI, it is used special bend insensitive fibers (BIFs) because sharp turns, staples, and storage with low diameter turns are very common in indoor applications. With this kind of fibers in a typical FTTH deployment operating at 10 Gb/s, the maximum MPI noise level considered admissible in an optical link does not cause a significant increase of the system BER, and the associated power penalty is negligible.

Finally, it is shown a comparison between some different techniques to measure the MPI, to quantify it is necessary to have collected a large number of readings because it is computed using the maximum and the minimum detected power levels in a range of wavelengths.

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