Chapter 2.3

Fiber loss and the measurement methods

Why it is necessary to investigate the fiber loss?

Fiber loss is a critical parameter of an optical fiber and determines how far a light can travel. Thus it can be also used to assess the performance of fiber communication system.

Fiber loss is related to the wavelength of the light in fiber, thus it determines different transmission windows in fiber communication systems.

As mentioned in the introduction, fiber loss had decreased from 20 dB/km in 1973 to 0.2 dB/km in 1993, and after that the loss level was further decreased.

The definition of fiber loss

Definition of fiber loss：loss of light power in dB between input and output

Mathematical expression： $\alpha = -10\log_{10}\left(P_{\text{out}} / P_{\text{in}}\right)/L$

Unit of fiber loss：dB/km

For example：If the P_{in} is 100 mW , the P_{out} is 1mW, L=10 km, α=2 dB/km

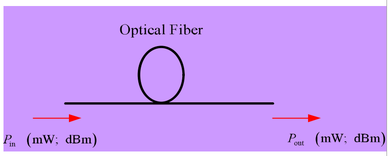
The unit of light power in fiber communication system is usually scaled in dBm since it can be simply added.

***Relationship between* dBm *and* mW：** $\text{dBm} = 10\log_{10}\left[P(\text{mW}) / 1(\text{mW})\right]$

Another expression of loss

$$\alpha = -\frac{\left[P_{\text{out}}(\text{dBm}) - P_{\text{in}}(\text{dBm})\right]}{L(\text{km})}$$

***α*=2 dB/km**



The definition of fiber loss [计算可能会用到]

$$\alpha = -10\log_{10}\left(P_{\text{out}} / P_{\text{in}}\right)/L$$

2 mW ⇨ 3 dBm

1mW ⇨ 0 dBm

0.5 mW ⇨ −3 dBm

10 mW ⇨ 10 dBm

17 dBm ⇨ 50 mW

+3 dBm对应功率乘以2 mW
-3 dBm对应功率除以2 mW
20dBm对应100mW
27dBm对应500mW
30dBm对应1000mW

The attenuation coefficient

The attenuation coefficient α_{f}

Definition： $P_{\text{out}} = P_{\text{in}} e^{-\alpha_{\text{f}} L}$

Unit： m^{-1}; km^{-1}

The relationship between the attenuation coefficient α_{f} and the loss α :

$$\alpha = 10\alpha_{\text{f}} \log_{10}(e) = 4.343\alpha_{\text{f}}$$

4.343 dB/km ~ 1 km^{-1}; 21.715 dB/km~5 km^{-1};

43.43 dB/km ~10 km^{-1}; 434.3 dB/km~100 km^{-1}

The causes of fiber loss：

① **Material absorption and scattering within fiber；光纤内材料吸收和色散**

② **Fiber microbending and macrobending**

光纤微弯和宏观折弯

③ **Splice and coupling 折断和耦合**

The causes of fiber loss：

(1) The causes of material absorption and scattering

- Loss
  - Material absorption
    - Absorption from impurity
      - Transition metal ions
      - OH^- ions
    - Intrinsic absorption
      - Ultraviolet absorption
      - Infrared absorption
  - Scattering
    - Manufacturing defect
      - Non-uniform refractive index distribution
      - Imperfect core coating surface
      - Bubble concretion
    - Intrinsic scattering and others
      - Rayleigh scattering
      - Brillouin scattering
      - Raman scattering

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Material absorption and scattering – 杂质吸收

Impurity absorption

Impurity absorption——mechanical harmonic absorption

Impure material and imperfect techniques lead to the introduction of transition metal ions (e.g., Fe, Mn, Ni, Cu, Co and Cr etc.) and OH^- ions

- In order to make the loss at the center wavelength of impurity absorption band lower than 20 dB/km, the ratio of transition metal ions are required <10^{-9}.

Three absorption peaks:1.39 μm, 1.24 μm and 0.95 μm

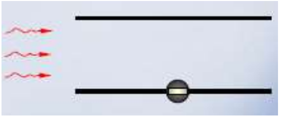
Three windows of fiber communication: 0.85 μm, 1.3 μm and 1.55 μm corresponding to the absorption valley of OH^- ions [来自氢氧焰]

Intrinsic absorption

Ultraviolet absorption：the electrons of fiber material absorbs the energy from ultraviolet and then excited to the higher levels, it results in the light energy loss and usually occurs at the short wavelength range

absorption band $\lambda \to 0.7 \sim 1.6\,\mu\text{m}$;

$\lambda \to 1.3 \sim 1.55\,\mu\text{m}, \alpha \to 0.05\,\text{dB/km}$

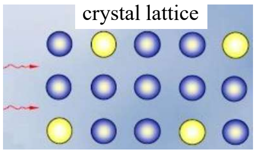


Infrared absorption：during the interaction of light wave with the crystal lattice, part of the energy was transferred to crystal lattice thus leading to a violent vibration, this also result in the loss.

absorption peak $\lambda \to 9.1\,\mu\text{m}, 12.5\,\mu\text{m}, 21\,\mu\text{m}$

peak $\alpha \to 10^{10}\,\text{dB/km}$;

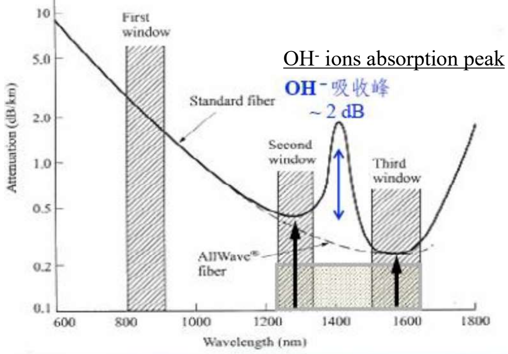
$\lambda \to 1.55\,\mu\text{m}, \alpha < 0.01\,\text{dB/km}$



Strategy：

(1)To improve to the purity of the fiber material chemically e.g., 99.9999999%

(2)To improve the fiber fabrication technique, e.g., avoid oxyhydrogen flame heating

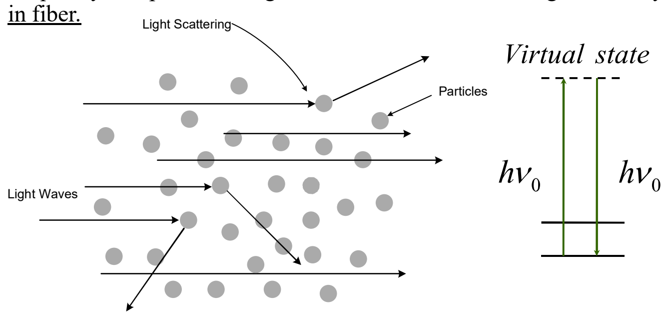


Main cause

Loss
- Material absorption
  - Absorption from impurity
    - Transition metal ions
    - OH⁻ions
  - Intrinsic absorption
    - Ultraviolet absorption
    - Infrared absorption
- Scattering
  - Manufacturing defect
    - Non-uniform refractive index distribution
    - Imperfect core coating surface
    - Bubble concretion
  - Intrinsic scattering and others
    - Rayleigh scattering
    - Brillouin scattering
    - Raman scattering

Rayleigh Scattering

Definition：It is a common optical phenomenon, named after the British physicist Lord Rayleigh. It is linear scattering of light at scattering centers which are much smaller than the wavelength of the light. The light isn't absorbed, just sent in another direction. No new frequency components are generated. It isn't related to light intensity in fiber.



$$\alpha_{SR} = \frac{A}{\lambda_0^4}(1 + B\Delta) \quad (\text{dB/km})$$

A, B are related to the material of silica and dopants;

λ_0 is the operation wavelength (μm)

Δ is refractive index difference

Fiber	Material	A	B
Multimode	GeO_2/SiO_2	0.8	100
Multimode	P_2O_5/SiO_2	0.8	42
Single mode	GeO_2/SiO_2	0.63	180±35

Taking multimode GeO_2/SiO_2 fiber as an example:

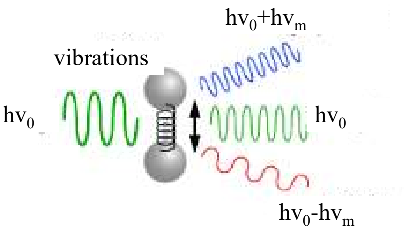
$\lambda_0 = 1.55\,\mu\text{m}, \Delta = 0.3\%$

$\alpha_{SR} = 0.18\,\text{dB/km}$

Note that the Rayleigh scattering currently cannot be removed, it determines the limitation of fiber loss.

Raman scattering

Definition：It is caused by vibrations of the crystal (or glass) lattice associated with optical phonons. One photon is converted into one lower-energy or higher-energy signal photon, and the difference of photon energies is compensated by a phonon. The new frequency components are generated. Thus the energies of initial frequency components are lost partly. It is nonlinear scattering.



•At a low power level, Raman scattering effect can occur spontaneously called as Spontaneous Raman scattering[自发].
•At a high power level, it can be changed to a stimulated effect called as Stimulated Raman scattering (SRS)[受激,带来的损耗大很多].

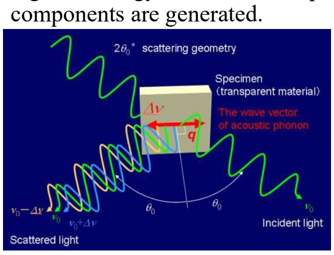
For example:
•For the multimode fiber with a core diameter of 75 μm and a loss 4 dB/km at 1.06 μm, the threshold of stimulated Raman scattering (SBS) is 500 W
•For the single mode fiber with a core diameter of 7.5 μm and a loss 0.4 dB/km at 1.06 um, the threshold of stimulated Raman scattering is decreased to 500 mW.

•Typical communication source power is at the range of 1~10 mW

It indicates that the SRS can be neglected.[可以被忽略]

Brillouin scattering

Definition：For a optical medium, the thermal motion of atoms, molecules and ions will generate acoustic phonons. An incident photon can be converted into a scattered photon with slightly lower or higher energy and a compensated phonon. New frequency components are generated.



拉曼: 原子在晶胞内的振动
布里渊: 晶体整体的振动

Main differences between Raman and Brillouin scatterings:
(1) Raman scattering is related to optical phonons (typically large, high frequency), and Brillouin scattering is related to acoustic phonons (typically small, low frequency).
(2) Raman scattering occurs in both forward and backward directions, Brillouin scattering occurs only in backward directions.

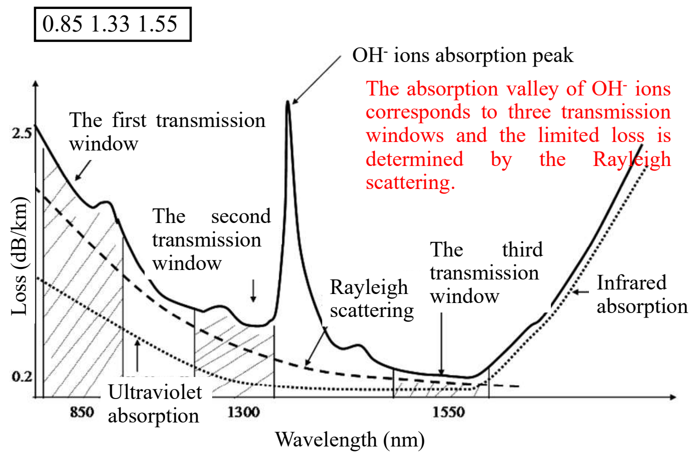
Material absorption and scattering – 布里渊散射

•At a low power level, Brillouin scattering effect can occur spontaneously called as Spontaneous Brillouin scattering.
•At a high power level, it can be changed to a stimulated effect called as Stimulated Brillouin scattering (SBS).

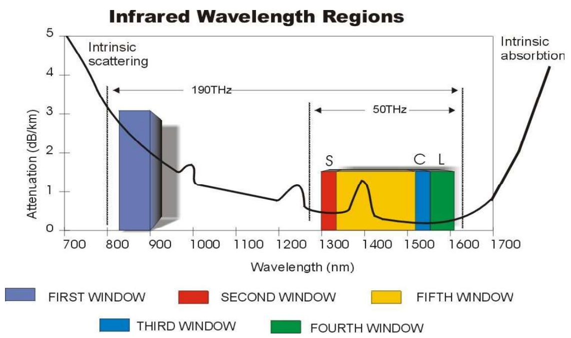
For example:
Typical communication source power is at the range of 1~10 mW
•For the multimode fiber with a core diameter of 75 μm and a loss 4 dB/km at 1.06 μm, the threshold of stimulated Brillouin scattering (SBS) is 2.5 W, thus the SBS can be neglected.
•For the single mode fiber with a core diameter of 7.5 μm and a loss 0.4 dB/km at 1.06 μm, the threshold of stimulated Brillouin scattering is decreased to 2.5 mW,

Thus the SBS can not be neglected. [不能被忽略]

The loss spectrum of fiber



In 1998, Lucent Corporation of America fabricated the all wave fiber which remove the absorption peak at 1385 nm and broadened the low loss band from 1250 nm to 1650 nm.



Transmission window: from 0.85 mm, 1.31mm,1.55 mm to S-band(1.49 mm~1.53 mm), C-band(1.53 mm~1.57 mm), L-band (1.57 mm~1.61 mm).

Available wavelength range

- O-band (Original): 1260-1360 nm
- E-band (Extended): 1360-1460 nm
- S-band (Short):, 1460-1530 nm
- C-band (Conventional): 1530-1565 nm
- L-band (Long): 1565-1625 nm
- U-band (Ultralong): 1625-1675 nm

(2) Fiber bending loss

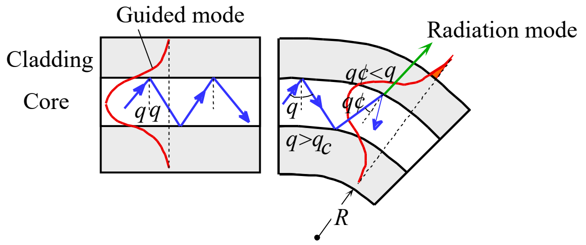
Bending loss
- **Macrobending loss**
- **Transition bending loss**
- **Microbending loss**

(2) Fiber bending loss

• Physical mechanism

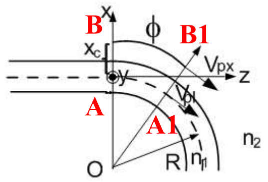
Fiber bending → The total internal reflection in fiber was broken

Waveguide mode transformed to leaky mode and even radiation mode → Bending loss



(2) Fiber bending loss

To determine the limitation of guided modes in bended fiber



The parallel equiphase surfaces intersect at O point due to the bending of the fiber. In order to keep the points at a equiphase surface have the same phase, the phase velocity should satisfy

$$\frac{V_{px}}{V_{pl}} = \frac{R+x}{R} \Rightarrow x = \frac{V_{px} - V_{pl}}{V_{pl}} R$$

In fiber core, guided modes: $V_{pl} = \frac{\omega}{n_1 k_0}$

In fiber cladding, guided modes : $\frac{\omega}{n_1 k_0} < V_{px} < \frac{\omega}{n_2 k_0}$

When $V_{px} \geq \frac{\omega}{n_2 k_0}$ **The guided modes transformed to leaky modes**

In limited case: $V_{pl} = \frac{\omega}{n_1 k_0}$ $V_{px} = \frac{\omega}{n_2 k_0}$

$x_c = \frac{n_1 - n_2}{n_2} R \approx R \bullet \Delta$ **defines the limitation.**

R↓→x_c↓→loss↑ **The bending loss is also relative to the order of guided mode. The higher the order is, the larger the bending loss is.**

(2) Fiber bending loss

1) Macrobending loss [宏观弯曲]

The causes: coiling and buckling in practical applications

$$2\alpha_e = \frac{W^2}{\beta a^2 (1+W)} \cdot \frac{U^2}{V^2} \exp\left[2W - \frac{2}{3}\left(\frac{W^3}{\beta^2 a^2}\right)\frac{R}{a}\right]$$

R is the bending radius
a is the fiber core radius
W is the normalized propagation constant

α_e is the attenuation coefficient

It can be observed $P_{out} = P_{in} e^{-\alpha_e \cdot L}$

Smaller R/a leads to larger α_e
Decreasing W can increase α_e

(2) Fiber bending loss

2) Transition bending loss

The cause: the sudden change from straight part to bended part or inconsistent bending of each section

$$\alpha = -10\lg\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right) = 8.68\frac{W_0^3 v^2}{8\Delta a^2 R_c} = 8.68\left(\frac{W_0}{a}\right)^3\left(\frac{a}{R_c}\right)\left(\frac{v^2}{8\Delta}\right)$$

$$v = \beta R_c$$

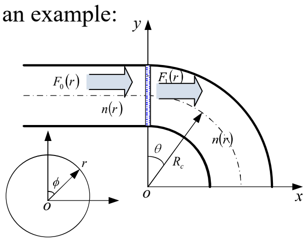
W_0 is the mode field radius

a is the core radius

Taking the standard single mode fiber as an example:

$v=2.4$, $\Delta=0.003$, $\frac{W_0}{a}=1$, $a=5\ \mu\text{m}$, $R_c=2\ \text{cm}$

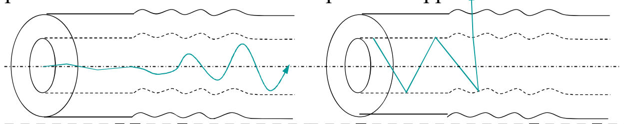
$\alpha=0.52\ \text{dB}$



3) Microbending loss

The causes:

- Nonuniformity from imperfect fiber fabrication
- Nonuniform stress from optical cable fabrication
- Different zones of a same fiber will experience different heat expansions and cold contractions in practical applications



The energies of low order modes are coupled to high order modes	The energies of high order modes escape from the fiber

$$\alpha \approx (n_2 k_0 W_2)^2 \phi_P \left(\frac{2}{n_2 k_0 W_1}\right) \text{ (dB/km)}$$

$$W_1 \approx W_0 + a\exp[3.34 - 3.28V]$$

$$W_2 \approx W_0 - a\exp[2.45 - 3.31V] \quad (1.5 < V < 2.5)$$

$$\phi_p \approx \left(\frac{2}{n_2 k_0 W_1}\right)^3 \sqrt{\pi}\sigma^2 L_c \exp\left[-\frac{1}{2}\left(L_c \frac{2}{n_2 k_0 W_1}\right)^2\right]$$

W_0 is the mode field radius,

a is the core radius,

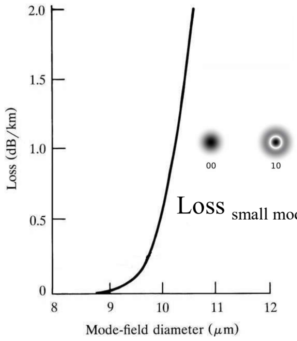
V is the normalized frequency,

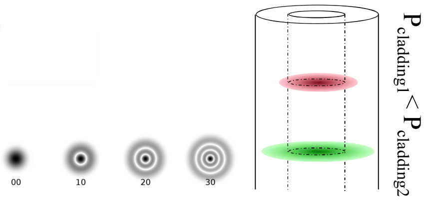
σ is the mean square root of core deviation,

L_c is the autocorrelation length.

3) Microbending loss

The relationship between bending loss and mode field diameter





$\text{Loss}_{\text{small mode field diameter}} < \text{Loss}_{\text{large mode field diameter}}$

$\text{Loss}_{\text{low order mode}} < \text{Loss}_{\text{high order mode}}$

For an 1 inch fiber ring, the measured bending loss as a function of the mode field diameter

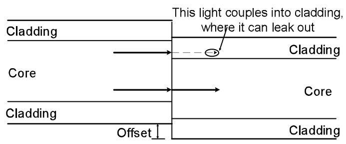
(3) Splice and coupling losses

Splice and coupling losses are caused by several factors. The major ones are listed as follows:

- Overlap of fiber cores
- Alignment of fiber axes
- Fiber numerical aperture
- Fiber spacing

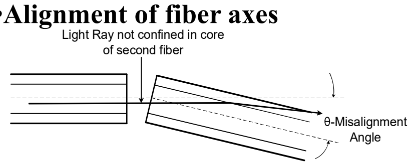
(3) Splice and coupling losses

•Overlap of fiber cores



The end of one fiber is offset from the end of the other. The loss equals the fractional of the input-fiber core area that dose not overlap with that of the output fiber.

•Alignment of fiber axes

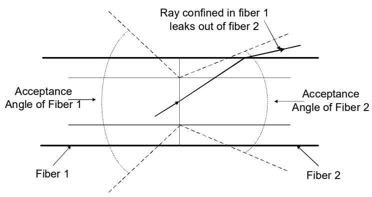


As the angle θ between fibers increase, light from the first fiber enters the second fiber at a larger angle to the axis

A good connection should align the two fibers very closely

(3) Splice and coupling losses

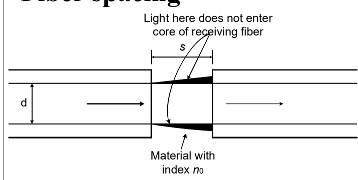
•Fiber numerical aperture



If the fiber receiving the light has a smaller *NA* than the one delivering the light, some light will enter it in modes that are not confined in the core. Then light will quickly leak out of the fiber.

$$Loss(\text{dB}) = 10\log_{10}\left(\frac{NA_2}{NA_1}\right)^2$$

•Fiber spacing



Two different mechanisms can cause loss if there is a gap between fibers:

1) Spreading of light emerging from the input fiber

2) Reflection of light passing between air and glass

(3) Splice and coupling losses

Reflection of light passing between air and glass belongs to Fresnel reflection, which occurs whenever light passes between two materials with different refractive indexes.

$$Loss(\text{dB})/\text{surface} = -10\log_{10}\left(1-\left(\frac{n_{\text{fiber}}-n_0}{n_{\text{fiber}}+n_0}\right)^2\right)$$

For the light going between glass and air, the loss is about 0.15 dB if the glass has a refractive index of 1.45 and 0.18 dB if the refractive index is 1.5.

The compensation of loss [补偿损耗]

Electrical signal amplifying

Optical signal → Electrical signal → Optical signal

Optical amplification

EDFA

Raman amplifier

$$\alpha = -10\log\left(P_{out}/P_{in}\right)/L \qquad (dB/km)$$

$$\lambda \rightarrow \alpha(\lambda)$$ Loss spectrum

(1) Cutback method [截断法]

- (Destructive measurement)

(2) Insertion loss method [插入损耗法]

- (Non-destructive measurement)

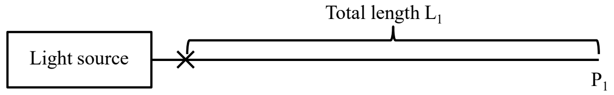
(3) Back scattering method [后向散射法]

- (Non-destructive measurement)

(1) Cutback method

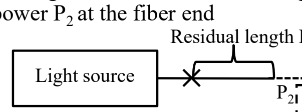
First step:

- Using a fixed light source with fixed output power. Coupling the light into the test fiber, and then measuring the output power P_1 at the fiber end



Second step:

- Cutting the fiber at a fixed length, and then measuring the output power P_2 at the fiber end



$$\alpha = -10\log_{10}\left(\frac{P_1/P_2}{L_1 - L_2}\right)(\text{dB/km})$$

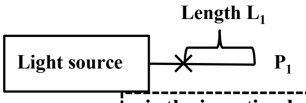
Note that P_1 and P_2 must be measured at the same initial power. Though cutback method is destructive for fiber, it has a significantly high precision [高精度], the error can be below 0.1 dB.

(2) Insertion loss method

$$\alpha = -10\log_{10}\left(\frac{P_2/(P_1\times(1-10^{-0.1x}))}{L_2}\right)(\text{dB/km})$$

First step:

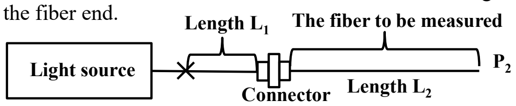
Using a light source with fixed output power. Coupling the light into a short fiber with length of L_1 same as the test fiber, measuring the output power P_1 at the fiber end.



Second step:

x is the insertion loss of the connector

Connecting the test fiber via a mobilizable connector, measuring the output power P_2 at the fiber end.



It is convenient to use a mobilizable connector to connect two fibers. But it should be noted that the loss (0.2~0.5 dB) introduced by the connector should be removed in calculation. Though the method is non-destructive, it has a low precision [精度较低].

(3) Back scattering method

Comparison：Compared to previous methods which can be only used to measure the fiber average loss, back scattering method can give the detailed loss information along fiber.

Advantages：1) the loss at any positions of the fiber can be measured；2) the position can be determined.

Mechanism：The loss at one point is obtained by measuring the scattering signal.

Steps: Injecting pulsed signal into the test fiber, setting the power at input end (z=0) as P_i , when the light signal reaches the point with a distance z from the input end , the power attenuates to

$$P(z) = P_i \exp\left[-\int_0^z \alpha_i(x)\mathrm{d}x\right]$$

If setting the reflection coefficient as $R(z)$, the signal that is reflected at the position z to the input end can be expressed as

(3) Back scattering method

$$P_s = R(z)P(z)\exp\left[-\int_0^z \alpha_s(x)\mathrm{d}x\right]$$

$$= R(z)P_i\exp\{-\int_0^z[\alpha_i(x)+\alpha_s(x)]\mathrm{d}x\}$$

If defining the average loss as:

$$\bar{\alpha} = \frac{1}{2(z_2 - z_1)}\int_{z_1}^{z_2}[\alpha_i(x)+\alpha_s(x)]dx$$

Setting $R(z)$ as a constant, we can obtain:

$$\ln\frac{P_s(z)}{R(z)P_i} = -\int_0^z[\alpha_i(x)+\alpha_s(x)]\mathrm{d}x$$

The method of measuring return loss can be used to fabricate Optical Time Domain Reflectometer（OTDR）！

$$\ln\frac{P_s(z_1)}{R(z)P_i} = -\int_0^{z_1}[\alpha_i(x)+\alpha_s(x)]\mathrm{d}x \qquad \ln\frac{P_s(z_2)}{R(z)P_i} = -\int_0^{z_2}[\alpha_i(x)+\alpha_s(x)]\mathrm{d}x$$

$$\ln P_s(z_1) - \ln P_s(z_2) = \int_{z_1}^{z_2}[\alpha_i(x)+\alpha_s(x)]dx$$

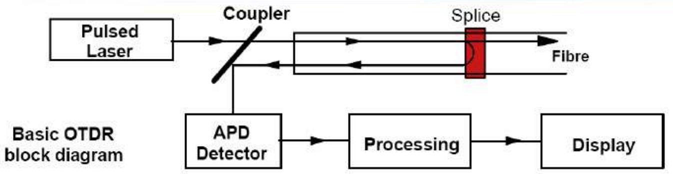
$$\bar{\alpha}_{1\rightarrow 2} = \frac{1}{2(z_2 - z_1)}[\ln P_s(z_1) - \ln P_s(z_2)]$$

The position z can be determined by

△t is the time delay between input pulse and echo pulse

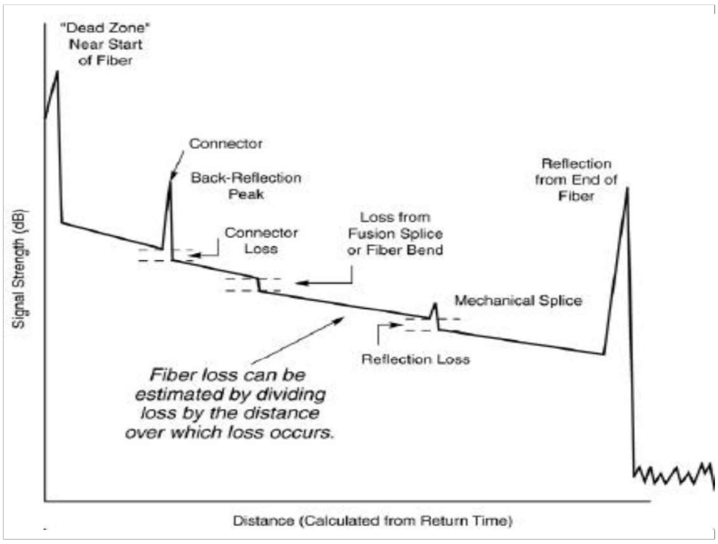
$$z = \frac{c}{2n}\Delta t$$

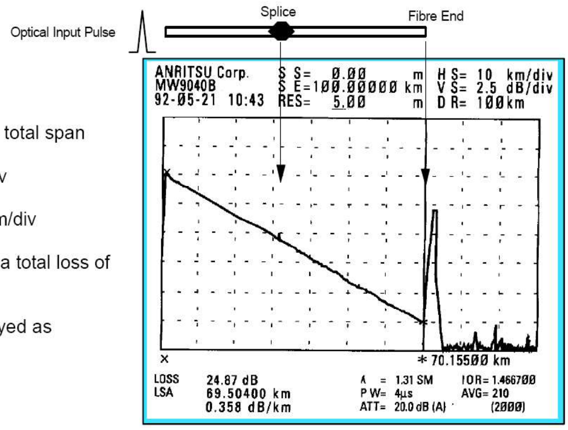
Optical Time Domain Reflectometer（OTDR）



The functions of OTDR

- **Measuring fiber total loss**
- **Measuring fiber loss per unit**
- **Measuring splice loss of fiber**
- **Measuring return loss of fiber connector**
- **Measuring fiber length**
- **Measuring fiber macrobending and microbending**
- **Finding the positions of defect and breakpoint of fiber**





- Display shows total span
- Loss 2.5 dB/div
- Distance 10 km/div
- Markers show a total loss of 24.87 dB
- Span is displayed as 70.155 km
- Anritsu OTDR