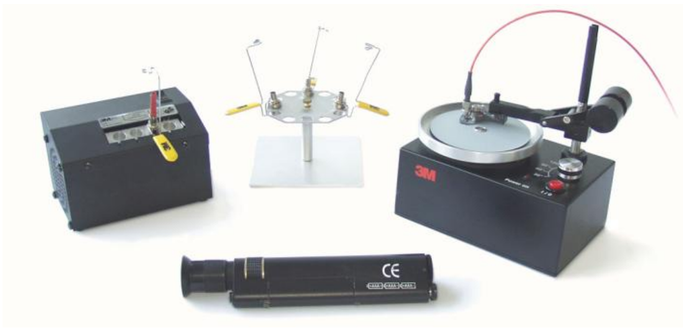
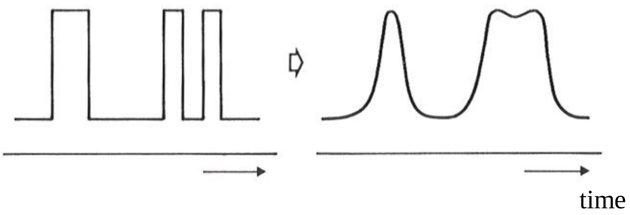


Experiment 24

Fibre Workshop



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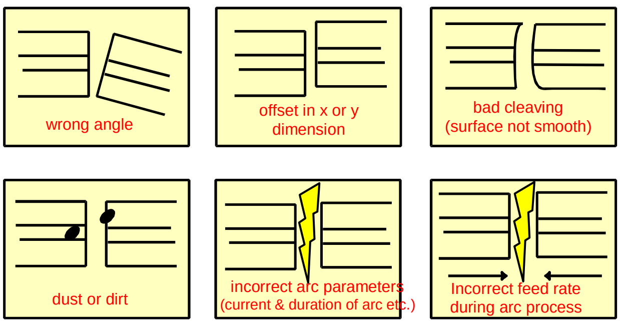

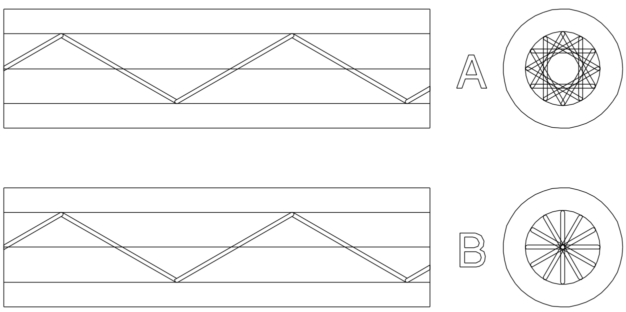

1 Introduction

In the near future twisted pair cable will be not able to sustain the big demands of the Ethernet network any more. The Gigabit Ethernet technology brings copper lines to their physical limits, and – Gigabit Ethernet is not standard yet – 10 Gigabit Ethernet is launched already, which is feasible with glass fibre technology only.

Besides such requirements concerning capacity, a glass fibre based telecommunication network is able to serve further advantages. Glass fibre cables have a very compact construction (up to 144 fibres in a 15 mm thick cable), are light and can be easily handled in pieces of several kilometers of length. Optical fibres show chemical robustness and insensibility to electrical flashes and induction. But probably most important in telecommunication is another property of glass fibre: it is tap-proof.

Today the transmission of signals using optical fibres has become an indispensable technology and the on-going development in this area is one of the most important within this century.

The idea of using light guided along a light conducting material for data transmission reaches back to H. Buchholz ("Die Quasioptik der Ultrakurzwellenleiter", 1939). But only with the development of the semiconductor laser in 1962 Buchholz' idea could be realized by using just these lasers and fibres as light transmitting medium. Suddenly simple and powerful light sources for the generation and modulation of light were available. Laser diodes can transform short electrical signals into optical pulses. Their emitted light in the near infrared range matches ideally the window of high transmission of the most glasses. Nevertheless, there are great demands made on the glass itself, especially on its purity.

The technology of communication via optical fibre is based on well known fundamentals in a way that no new understanding has to be created. Still, there is a challenge with respect to the technical realisation keeping in mind that the light has to be guided within fibres of 9 µm diameter only. Appropriate fibres had to be developed and mechanical components of high precision had to be disposed for coupling the light to the conductor (fibre) and for the installation of the fibres. Further goals are the reduction of transmission losses, optical amplification within the fibre as replacement of the electronic amplifiers and laser diodes of small band width to increase the transmission speed of signals. For practical application and daily operation a plug-play technology had to be developed to handle optical fibre lines as easy as conventional electrical equipment.

In this workshop we focus on a training of the preparation of the fibre ends in a way that the light signal can be easily fed in the fibre and the losses of the signal are as little as possible. Connectors for simple plug in electro optical transmitter and receiver units are commercially available. Here we learn how to fix them to the glass fibre and how to achieve the high optical requirements for the connector surface.

In a second part we get acquainted with the splicing of two fibres. First, the fibre ends have to be prepared in a proper way. Then the splicing process can be performed, and finally, the splice is covered by a protection shield.

2 Basics

There is hardly any book in optics which does not contain the experiment of Colladan (1861) on total reflection of light. Most of us may have enjoyed it during the basic physics course.

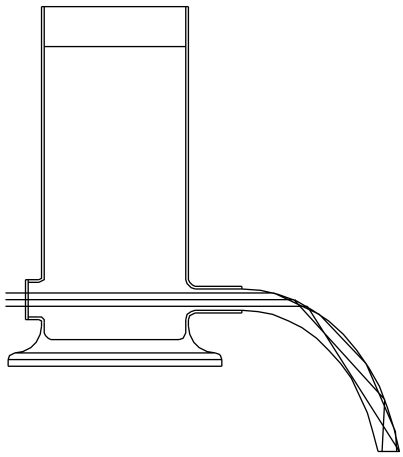

Fig. 1: Colladan's (1861) experiment for the demonstration of the total reflection of light

An intensive light beam is introduced into the axis of an out flowing water jet. Because of repeated total reflections the light can not leave the jet and it is forced to follow the water jet. It is expected that the jet remains completely darken unless the surface contains small disturbances. This leads to a certain loss of light and it appears illuminated all along its way. Effects of light created in this way are also known as „Fontaines lumineuses". They please generally the onlookers of water games. This historical experiment already shows the physical phenomena which are basic in fibre optics. The difference of this light conductor to modern fibres is the dimension which for a fibre is in the order of magnitude of the wavelength of light. If we designate the diameter of a light guide with d we can state:

„Fontaines lumineuses"	$d >> \lambda$
Multimode fibres	$d > \lambda$
Monomode fibres	$d \approx \lambda$

For the fibres manufactured these days this leads to further effects which can not be described exclusively by total reflection. Their understanding is of special importance for optical communication technology. These effects can be derived by a formalism basing on Maxwell's equations (the interested student can find a comprehensive deduction in Exp. 12, Fibre Optics). However, for our aim it is not compulsory to know this formalism.

2.1 Fibres as light wave conductors

To avoid losses by emerging of the light through the wall of the fibre the light is kept within the core by total reflection. Therefore the core of the fibres has diameters down to µm, only a few wavelengths of the transmitted light, what makes the coupling of the beam to the fibre not easy.

Glass fibres as wave conductors have a circular cross section. They consist of a core of refractive index n_k. The core is surrounded by a glass cladding of refractive index n_m slightly lower than n_k. Generally the refractive index of the core as well as the refractive index of the cladding is considered homogeneously distributed. The final direction of the beam is defined by the angle Θ_e under which the beam enters the fibre. Unintended but not always avoidable radiation and cladding waves are generated in this way. For reasons of mechanical protection and absorption of the radiation waves the fibre is surrounded by a protective layer.

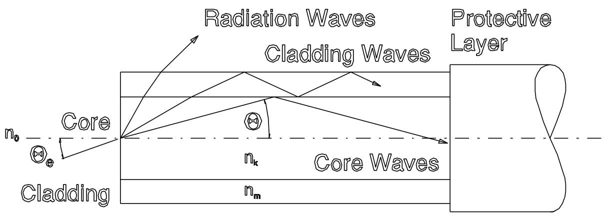

Fig. 2: Step index fibre

Fig. 2 reveals some basic facts which can be seen without having solved Maxwell's equations. Taking off from geometrical considerations we can state that there must be a limiting angle Θ_c for total reflection at the boundary between cladding and core.

$$\cos(\Theta_c) = \frac{n_m}{n_k} \qquad (2.1.1)$$

For the angle of incidence of the fibre we use the law of refraction:

$$\frac{\sin(\Theta_{ec})}{\sin(\Theta_c)} = \frac{n_k}{n_0}$$

and receive:

$$\Theta_{ec} = \arcsin\left(\frac{n_k}{n_0} \cdot \sin\Theta_c\right).$$

Using equation (2.1.1) and with $n_o = 1$ for air we finally get:

$$\Theta_{ec} = \arcsin\left(\sqrt{n_k^2 - n_m^2}\right)$$

The limiting angle Θ_{ec} represents half the opening angle of a cone. All beams entering within this cone will be guided in the core by total reflection. As usual in optics here, too, we can define a numerical aperture A:

$$A = \sin\Theta_{ec} = \sqrt{n_k^2 - n_m^2} \qquad (2.1.2)$$

Depending under which angle the beams enter the cylindrical core through the cone they propagate screwlike or helix like. This becomes evident if we project the beam displacements onto the XY-plane of the fibre. The direction along the fibre is considered as the direction of the z-axis. A periodical pattern is recognised. It can be interpreted as standing waves in the XY-plane. In this context the standing waves are called oscillating modes or simply modes. Since these modes are built up in the XY-plane, e.g. perpendicularly to the z-axis, they are also called transversal modes. Modes built up along the z-axis are called longitudinal modes.

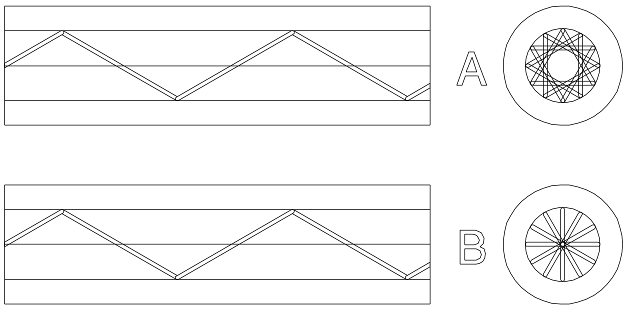

Fig. 3: Helix (A) and Meridional beam (B)

2.2 Types of fibres

Assuming a bunch of light rays entering the fibre, it is obvious that the rays with a bigger angle Θ are more often reflected on the cladding, what causes a longer pathway within the fibre, and finally, they exit the fibre later than rays with small Θ. If light is applied in short pulses this behaviour leads to a temporal smear out of the pulse: the pulse becomes longer (so called mode dispersion). Fig. 4 illustrates that this effect limits the pulse frequency. The maximal possible bandwidth of the transmitted signals is restricted by the fibre, not by the repetition rate of the laser diode. The steep rising and trailing edges of the pulses are smoothened and in the case of short distances of pulses the modulation depth is decreased drastically.

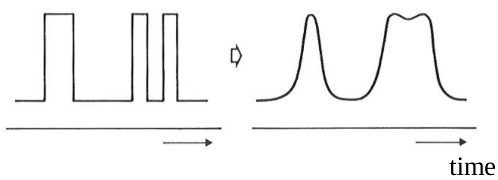

Fig. 4: Mode dispersion in an optical fibre

To increase the bandwidth fibres with graded index profile were developed, i. e. the index continuously rather than stepwise decreases from the axis of the fibre to the cladding. Here the light beam is not reflected but bent back to the centre (Fig. 5). The fibre works like a lens and induces so called self focusing of the beam. Such a fibre is more difficult in manufacturing and therefore more expensive, but the broadening of the pulses can be reduced from about 30-50 ns/km for step index fibres to 0.1-1 ns/km.

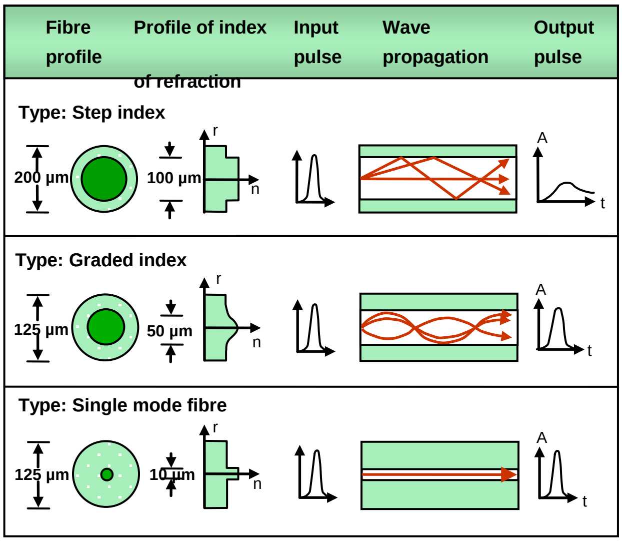

Fig. 5: Different types of glass fibres

A further step is to allow only one longitudinal mode travelling within the fibre. As a result such single mode fibres have a core with a diameter of only a few nanometres. Now the bandwidth is limited not by the dimensions of the fibre but only by the dispersion of the material.

2.3 Coupling of light

We are facing the problem to couple a beam of light to a fibre, respectively to introduce it into a fibre, the diameter of which is in the order of magnitude of 4-10 µm and in so far comparable to the wavelength of light. To get a sufficient high excitation of the fundamental mode of the fibre, the beam of the light source has to be focused to a diameter of this order of magnitude. Under these circumstances the laws of geometrical optics fail because they anticipate parallel light beams or plane light waves which in reality exist only in approximation.

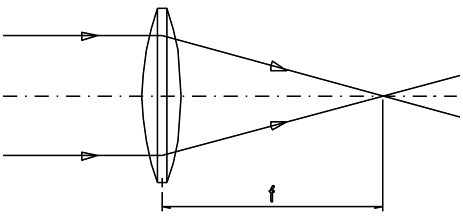

Fig. 6: Focusing two beams in geometrical optics

Real parallel light beams do not exist in reality and plane wave fronts exist only at a particular point. The reason for the failure of geometrical optics is the fact that it has been defined at a time where the wave character of light was still as unknown as the possibility to describe its behaviour by Maxwell's equations.

To describe the propagation of light one has to solve the wave equation. With the condition of spherical waves propagating in z-direction within a small solid angle, the solution of the wave equation provides fields which have a Gaussian intensity distribution over the cross section of the beam. Therefore they are called Gaussian beams. Similar to light in a fibre the Gaussian beams exist in different modes depending on the actual boundary conditions. Such beams, especially the Gaussian fundamental mode (TEM_{00}) are generated with preference by lasers. But the light of any light source can be considered as the superposition of many such Gaussian modes. Still, the intensity of a particular mode is small with respect to the total intensity of the light source.

The situation is different for the laser. Here the total light power can be concentrated in the fundamental mode. This is the most outstanding difference with respect to ordinary light sources next to the monochromasy of laser radiation. Gaussian beams behave differently from geometrical beams.

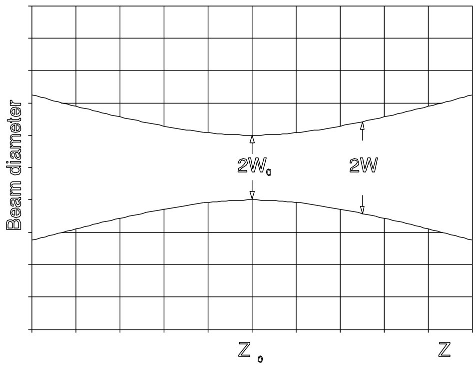

Fig. 7: Beam diameter of a Gaussian beam as fundamental mode TEM_{00} and function of z.

A Gaussian beam always has a waist. The beam radius w results out of the wave equation as follows:

$$w(z) = w_0 \cdot \sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

w_0 is the smallest beam radius at the waist and z_r is the Rayleigh length

$$z_R = w_0^2 \frac{\pi}{\lambda}$$

In Fig. 8 the course of the beam diameter as a function of z is represented. The beam propagates within the direction of z. At the position $z = z_0$ the beam has the smallest radius. The beam radius increases linearly with increasing distance. Since Gaussian beams are spherical waves we can attribute a radius of curvature of the wave field to each point z. The radius of curvature R can be calculated using the following relation:

$$R(z) = z + \frac{z_r^2}{z}$$

This context is reflected by Fig. 8. At $z = z_r$ the radius of curvature has a minimum. Then R increases with 1/z if z tends to $z = 0$. For $z=0$ the radius of curvature is infinite.

Here the wave front is plane. Above the Rayleigh length z_r the radius of curvature increases linearly. This is a very essential statement. Due to this statement there exists a parallel beam only in one point of the light wave, to be precise only in its focus. Within the range

$$-z_r \leq z \leq z_r$$

a beam can be considered as parallel or collimated in good approximation. In Fig. 9 the Rayleigh range has been marked as well as the divergence Θ in the distant field, that means for $z >> z_0$. The graphical representations do not well inform about the extremely small divergence of laser beams another outstanding property of lasers.

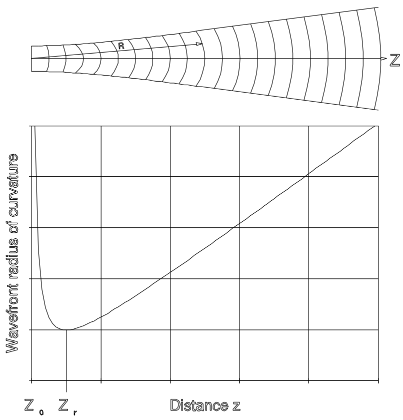

Fig. 8: Course of the radius of curvature of the wave front as a function of the distance from the waist at z=0

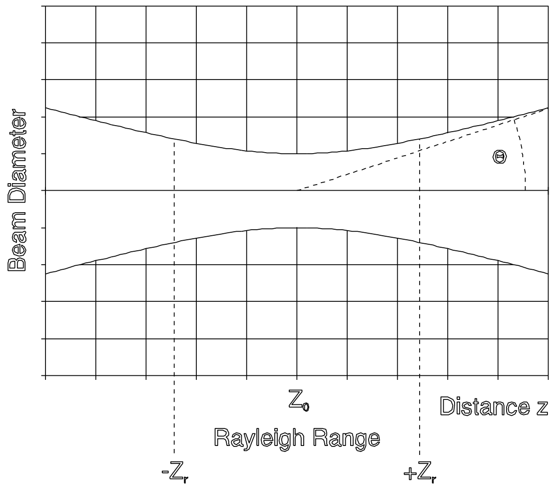

Fig. 9: Rayleigh range z_R and divergence Θ for the far field $z>>z_R$

The reason for this is that the ration of the beam diameter with respect to z has not been normalised. Let's consider, for example, a HeNe-Laser (632 nm) with a beam radius of w_o*=1mm* at the exit of the laser. For the Rayleigh range 2 z_r we get:

$$2 \cdot z_R = 2w_0^2 \frac{\pi}{\lambda} = 2 \cdot 10^{-6} \frac{3.14}{623 \cdot 10^{-9}} = 9{,}9 \text{ m}$$

To get a maximum of power into the fibre a coupling optic of focal distance f is required assuring the coupling of a Gaussian beam into a weak guiding step index fibre in the LP_{01} fundamental mode.

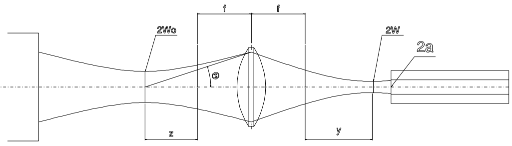

Fig. 10: For the calculation of the coupling optic

The radius at the waist is

$$w = \frac{w_0 \cdot f \cdot \theta \cdot}{\sqrt{w_0^2 + \theta^2 \cdot z^2}}$$

The position of the waist is:

$$y = \frac{z \cdot f^2}{z^2 + \left(\frac{w_0}{\theta}\right)^2}$$

Example: The beam of a HeNe laser of 0.5 mm diameter and of 1.5 mrad divergence is to focus by means of a lens. The focal distance is 50 mm and the lens is at a distance of 2 m from the laser. We find:

$$w = \frac{0{,}5 \cdot 10^{-3} \cdot 0{,}05 \cdot 1{,}5 \cdot 10^{-3}}{\sqrt{0{,}25 \cdot 10^{-6} + 2{,}25 \cdot 10^{-6} \cdot \; 2 - 0{,}05 \;^2}} = 12{,}6 \mu\text{m}$$

$$y = \frac{2 - 0{,}05 \; \cdot 2{,}5 \cdot 10^{-6}}{2 - 0{,}05 \;^2 + \left(\frac{0{,}5}{1{,}5}\right)^2} = 1{,}25 \mu\text{m}$$

For this example the position y of the waist coincides with the focus in good approximation and the radius of the waist is here 12.6 µm. To get the fibre under consideration adapted in an optimal way the focal distance f has to be chosen in a way that the radius of the beam is equal to the radius of the core. When laser diodes are used the preparation of the beam becomes more complicated.

3 Technical Bases

3.1 Mounting Connectors

The straight tip (ST) connector specified by AT&T is suited for multi- as well as single mode fibres. Due to its easy handling the ST connection is the most favourite and most widespread plug connection nowadays. This series connector is a high performance connector based on the ceramic technology.

Basically, the ST connector consists of a rigid spike of ceramic with a small duct where the glass fibre is fed in and fixed by glue or molten in cement (so called hot melt connector). A convenient bayonet locking system enables quick and easy installation. A sheath on the fibre side of the connector avoids too strong bending of the fibre close to the connector.

The mounting procedure of a connector consists of three steps: First the fibre protection coating has to be stripped off. Then the connector is heated in an oven to melt the cement. In the liquid cement the stripped fibre end is inserted. After cooling down the connector's ceramic spike with the fibre tip in it is polished down until the ceramic-glass body builds a smooth flat surface. The high quality of this surface is important for coupling light in the fibre with a minimum of losses.

Fig. 11: mounted ST connector

3.2 Splicing Fibres

Usually optical fibres are available up to a length of 6 km. For longer distances the fibres have to be pieced together either by plug connections or mechanical splicing or arc splicing.

Plug connections can be easily detached and have the distinction of a high flexibility. Their drawbacks are high values of attenuation and reflections on the surfaces. Further, the preparation of connectors in the field is not quick and easy.

Mechanical splicing, also called crimp splicing, is a mechanical connection of fibres, where the two fibre ends are cramped in an aluminium jaw. Optical contact between the fibre surfaces is provided by a liquid. This splicing technique is mainly used for reparation of optical fibres because its realisation is faster and cheaper. But also here the high attenuation and reflections are adversarial. Additionally, long term stability is not proven yet.

Lower values of attenuation and almost no reflections exhibit arc splices. Here the two fibre ends are molten together by an electric arc. The long term stability of such arc splices is high and the cost of the splice is low, however, the prime cost is higher compared to other splicing techniques.

Because we will perform arc splicing in this workshop we have to discuss the influence of the quality of the splice on the attenuation behaviour of the fibre: the losses.

3.3 Losses

Besides the inherent attenuation of the fibre due to light scattering there are losses appearing on each transition from one to another medium, e. g. by changing physical parameters like the index of refraction or just by changing the geometrical conditions. Here we will discuss about losses which appear on a splice of two fibres.

The main difficulty in splicing is to merge the two fibre ends together in such a way that the losses are kept as low as possible. Therefore it is necessary to know what causes the losses and how these influences can be minimized. Losses introduced by splicing in principle depend on

- the fibre itself
- the splicing device
- the operator performing the splicing

3.3.1 Losses introduced by fibre

Typical sources for losses caused by improper fibres used for the fibre splicing process are depicted in Fig. 12. One has to expect disproportionately higher losses, when

- fibres have different core diameter
- fibres have different numerical aperture or different index of refraction values
- core of the fibre is eccentric
- core profile is not circular

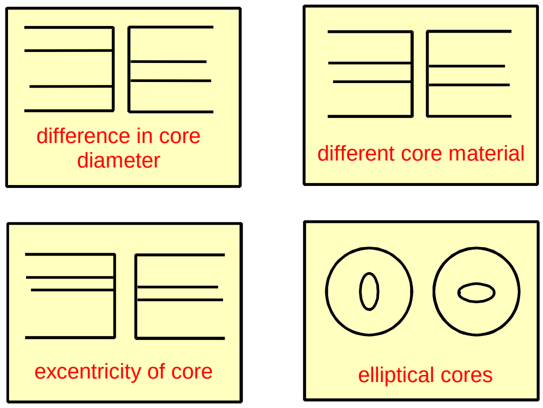

Fig. 12: fibre causes for bad splices

3.3.2 Losses introduced by operator and instrument

Fig. 13 shows typical mistakes of the splicing process which cause high losses, namely

- improper alignment, either in angle or in an xy-offset
- badly cleaved fibre ends
- dirt or dust particles on fibre ends
- incorrect settings for arc parameters
- incorrect feed rate in fibre direction during the arc process

A modern splicing device is able to recognize such mistakes and automatically correct them or gives an error message in case.

Since air pressure, humidity and temperature influence the arc characteristics some instruments are able to control these parameters and compensate the arc process for optimal performance. Finally, the attenuation of the splice can be measured and the tensile strength can be proved by a traction test.

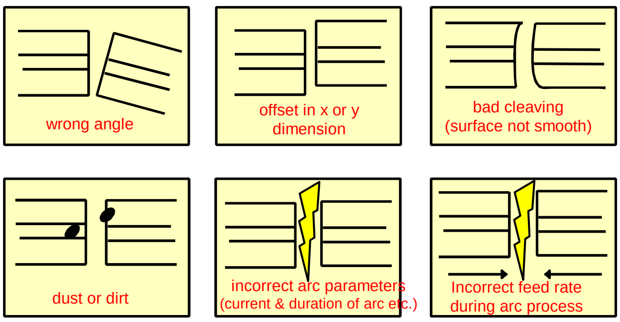

Fig. 13: possible mistakes of splicing