TAPER WITH INTEGRATED MICRO LENS

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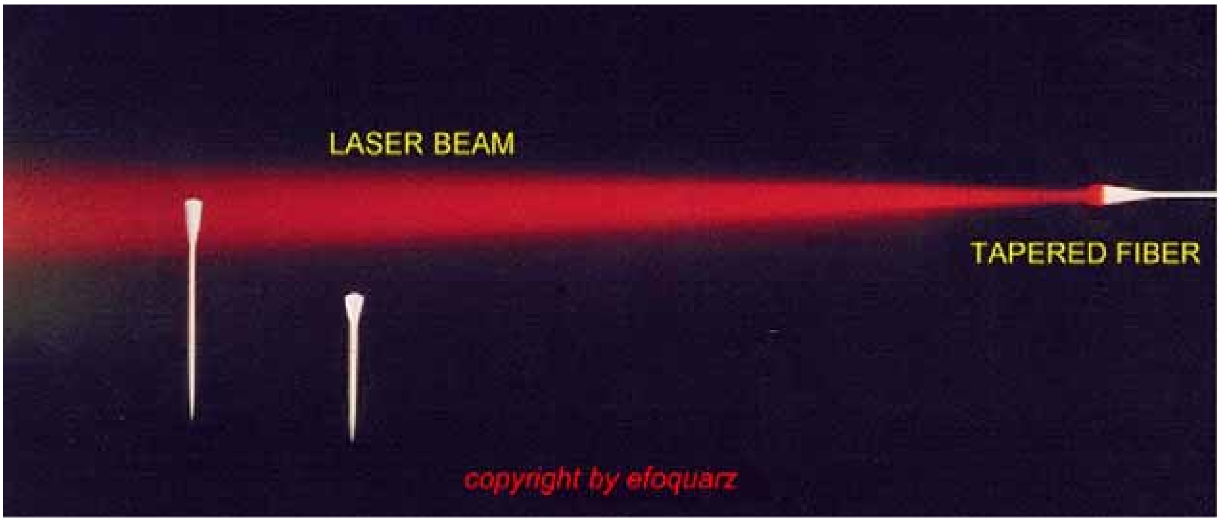


Picture 1: Focused laser beam and taper with integrated micro lens. The distance between taper and the exit point of the laser beam is 100 mm

INTRODUCTION

Light guides have become an established feature in the fields of communication, medicine and sensor technology. To interconnect multimode light guides of different cross sections or for coupling to a transmitting/receiving diode or laser beam, conical fibre optic shape-converters, so-called tapers, are generally used. Connecting a micro lens upstream from one of these tapers creates a hardwearing micro optical system capable of collimating the emerging modes at a defined distance.

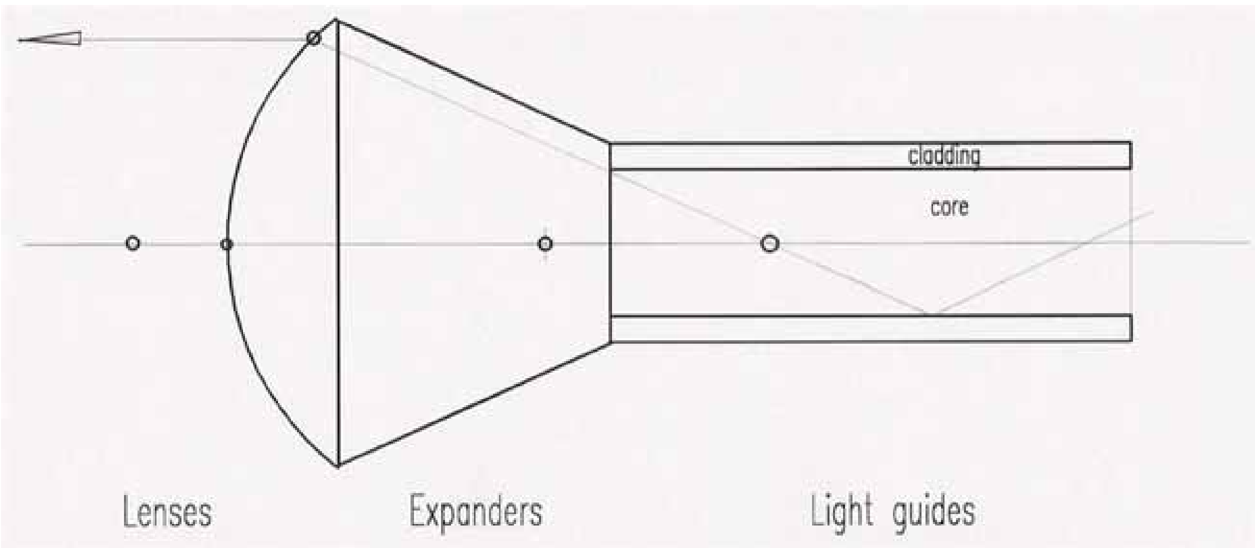
Whereas the classic taper was limited to its function as a fibre optic shape-converter between light guides, a newly developed fabrication system allows to integrate a micro lens directly within the taper. The advantage is that this allows an optical reflection of the focused rays (from transmitting diodes or lasers) into the light guide, simplifying coupling significantly, reducing losses and cost. The taper with integrated micro lens is also capable to collimate the exiting modes, after their expansion within the taper (picture 1).

STRUCTURE AND FUNCTION OF A LENS TAPER

The easiest way to illustrate the function of an optical shape-converter (taper) is by dividing it into its three parts and analysing these individually:

- **Light guides** are used to guide the light waves (modes) through total reflection.
- **Expanders** increase the cross-section of the light waves. In the reverse the conical shape-converter reduces the entry cross-section to that of the light guide; in which case the expander is more accurately referred to as a **Concentrator.**
- **Lenses** collimate or focus the light waves (modes) in the exiting light beam in a defined distance or reduce the opening angle. For the coupling of the light into a light guide the lens reflects the light beams onto the light guide.

Similar to light guides and known shape-converters the core of the lens taper is made of optically pure quartz glass. The collimator lens as is also made from the core material (picture 2) and is calculated with the refractive index η_1 in the following contemplations.



Picture 2: Lens taper consisting of a micro lens, a conical expander and the lightguide. All three optically effective components are made of pure quartz glass.

FUNCTION OF THE LENS

The optical transition from η_1 to η_2 takes place at the interface layer ***G*** along a spherical segment with the radius ***r.*** The spherical focal point ***O*** and the highest point of the spherical segment ***C*** are on the optical axis. The light beam exiting the pixel ***P*** is refracted through the highest point of the spherical segment ***A*** and reflected onto point ***P.*** The following relations are derived from Picture 3:

$$\varepsilon = \alpha + \beta$$

and

$$\varphi = \alpha' + \varepsilon'$$

This results in the relation between the angles

$$\frac{\varepsilon}{\varepsilon'} = \frac{\alpha + \varphi}{\varphi - \alpha'} \qquad \textbf{(A)}$$

According to the refractive law the following applies:

$$\frac{\eta_1}{\eta'_0} = \frac{\sin \varepsilon}{\sin \varepsilon'} \approx \frac{\varepsilon}{\varepsilon'} \qquad \textbf{(B)}$$

Assuming that the beams near the axis propagate parallel and that the angles are sufficiently small (paraxial form) the following can be stated:

$$\sin \varepsilon \approx \tan \varepsilon \approx \varepsilon \quad \text{and} \quad \cos \varepsilon \approx 1$$

for simplification the $\approx$ -sign may be changed to a =-sign with the following result:

$$\frac{\alpha + \varphi}{\varphi - \alpha} = \frac{\eta_1}{\eta_0} \qquad \textbf{(C)}$$

or

$$\eta_0 \cdot \alpha + \eta_1 \cdot \alpha' = (\eta_1 - \eta'_0) \cdot \varphi \qquad \textbf{(D)}$$

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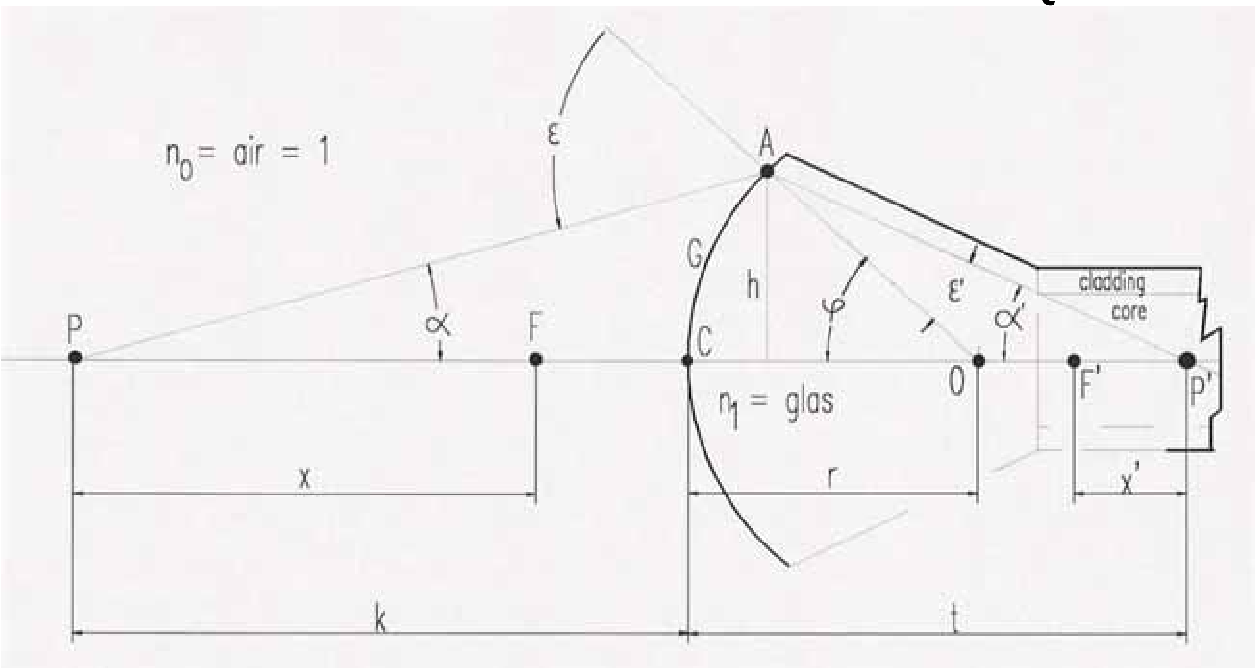


Picture 3: Beam refraction at the bended surface of the collimator lens.

Picture 3 results in the following relations:

$$\alpha = \frac{h}{k}, \qquad \alpha' = \frac{h}{t}, \qquad \varphi = \frac{h}{r}$$

The result of substitution being:

$$\frac{\eta_0}{k} + \frac{\eta_1}{t} = \frac{\eta_1 - \eta_0}{r} \qquad \text{(1)}$$

The beam hight ***h*** is not defined in (1). All beams originating in ***P*** that meet the lens are reflected to ***P'***. The correlations are shown in (1) and they are universally applicable. In the context of light guides light beams should always be referred to as modes. Since the mode dispersion is concentric in relation to the optical axis, ***P*** can adapt positive or negative values. The distance ***CF = f*** corresponds with the focal length on the object side and ***CF' = f'*** with the focal length on the image side. This relation is based on the following equation:

$$f = \frac{\eta_0}{\eta_1 - \eta} \cdot r \qquad \text{(2)}$$

$$f' = \frac{\eta_1}{\eta_1 - \eta} \cdot r \qquad \text{(3)}$$

Therefore $f' - f = r$. The signs of f and f' are always the same and positive if the signs of $\eta_1 - \eta_0$ and r are corresponding. In the other case they are always negative.
The introduction of *f* in (1) results in:

$$\frac{f}{k} = \frac{f'}{t} \qquad (4)$$

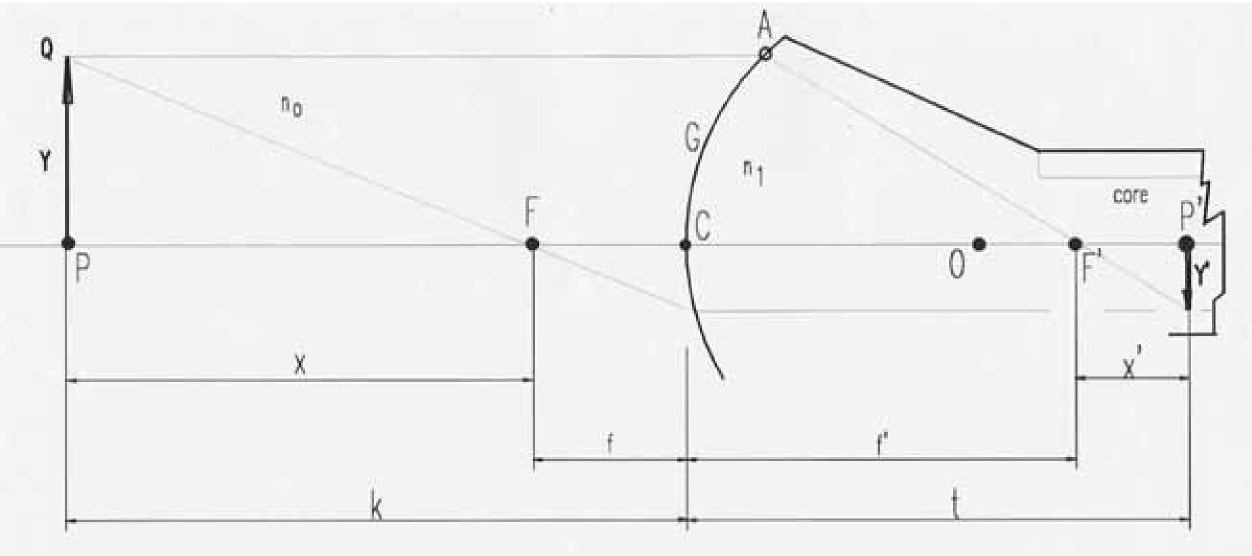
The pixel along the optical axis gains dimension and is hereafter treated as an object resulting in the construction of picture 4. Picture 4 proves that the distance measured from point ***F*** corresponds with $X = k - f$ and $X' = t - f'$ of the Newton form:

$$XX' = ff' \qquad (5)$$

For the enlargement factor ***M*** from the object to the image the following results from picture 4:

$$M = \frac{y'}{y} = -\frac{t-r}{k+r} = -\frac{\eta_0 \cdot t}{\eta_1 \cdot k} = -\frac{f}{x} = -\frac{x'}{f'} \qquad (6)$$

The object is therefore by the reflection reduced or enlarged by a certain factor ***M*** and it changes its orientation (reflection at the optical axis).



Picture 4: The object PQ is reproduced through the collimator lens onto the focal plane P Q. Expander used for Adaption

The second optically effective component of the lens taper is the expander. It is used for the adaption between lens and light guide. Its functions are entry beam coupling as well as focusing of the beam (concentrator) in exit beam coupling. In the case of entry coupling the lens serves to guide the beams into the light guide. The focussing angle of the beam α' with full illumination of the lens can be equal or smaller than the numeric aperture NA of the light guide α(picture 4).

$$\alpha \geq \alpha' \qquad (7)$$

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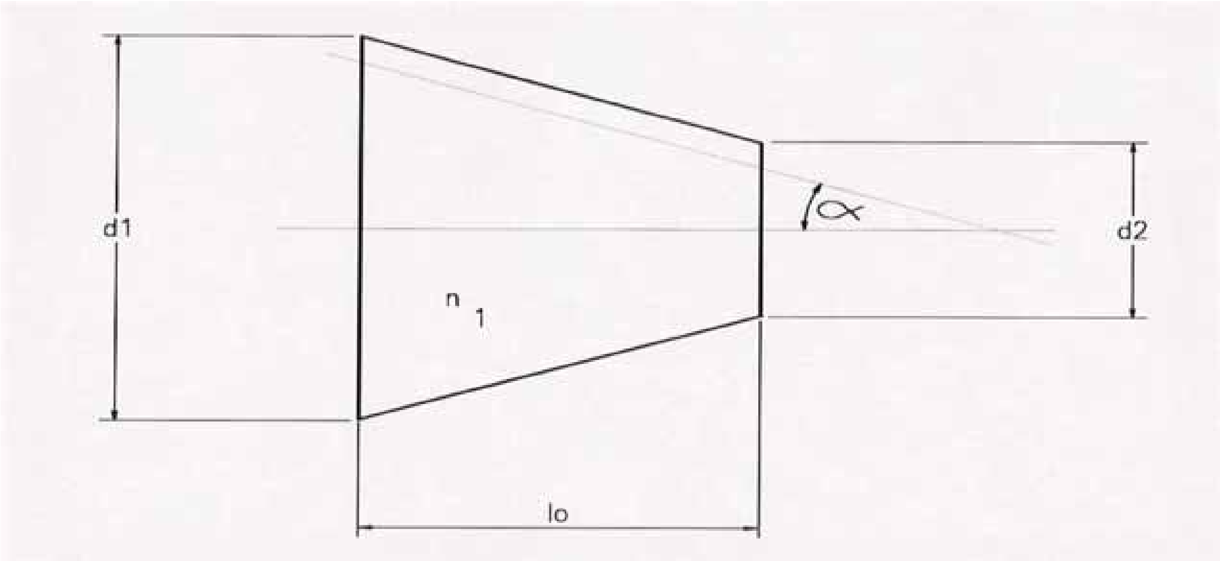
For exit coupling the modes (arriving reflected through the cladding of the light guide) have to illuminate the entire lens, without expander interface reflection. The border angle of the total reflection $\alpha_{0,}$ calculated from the core and cladding refractive indices, corresponds with the minimal angle of the expander:

$$\alpha = 90° - \alpha_0 \qquad (8)$$

Within the expander a natural beam expansion is taking place, without leaving the transmission medium (quartz glass). Particularly interesting is that the fibre core, the expander core and the lens are of the same material. Therefore there are no transitions and no reflection losses. Only during entry or exit coupling ectively losses may occur, however they can be largely eliminated by surface coating.



Picture 5: The correlation of the exit cross-section to the entry cross-section determines the beam expansion.

The expander (picture 5) has an entry diameter d_2, an exit diameter d_1, a length l_0 as well as a opening angle α. The expansion number is calculated from the quotient and the effective cross-section expansion:

$$E = \frac{d_1}{d_2} \qquad (9)$$

A collimator lens, placed on the diameter d_1 focuses the expanded beam quasi parallel. With this integrated beam expansion and collimator lens system at the end of a light guide, opening angles smaller than 1°are possible.

The exit angle σ from the expander (without lens) can be calculated as follows:

$$\sin \sigma = \sqrt{\eta_1^2 - \eta_2^2} \qquad (10)$$

The length of the expander l_0 is derived from the following equation:

$$l_0 = \frac{½d_1 - ½d_2}{\tan \alpha} \qquad (11)$$

The number of the modes reflected on the core interface is depending on the wavelength of the energy to be transmitted and the fibre core diameter. The number of modes Z_m can be calculated approximately with the equation (12):

$$Z_m \approx ½ \left(\pi . \frac{d_2}{\lambda} . \sin \sigma \right)^2 \qquad (12)$$

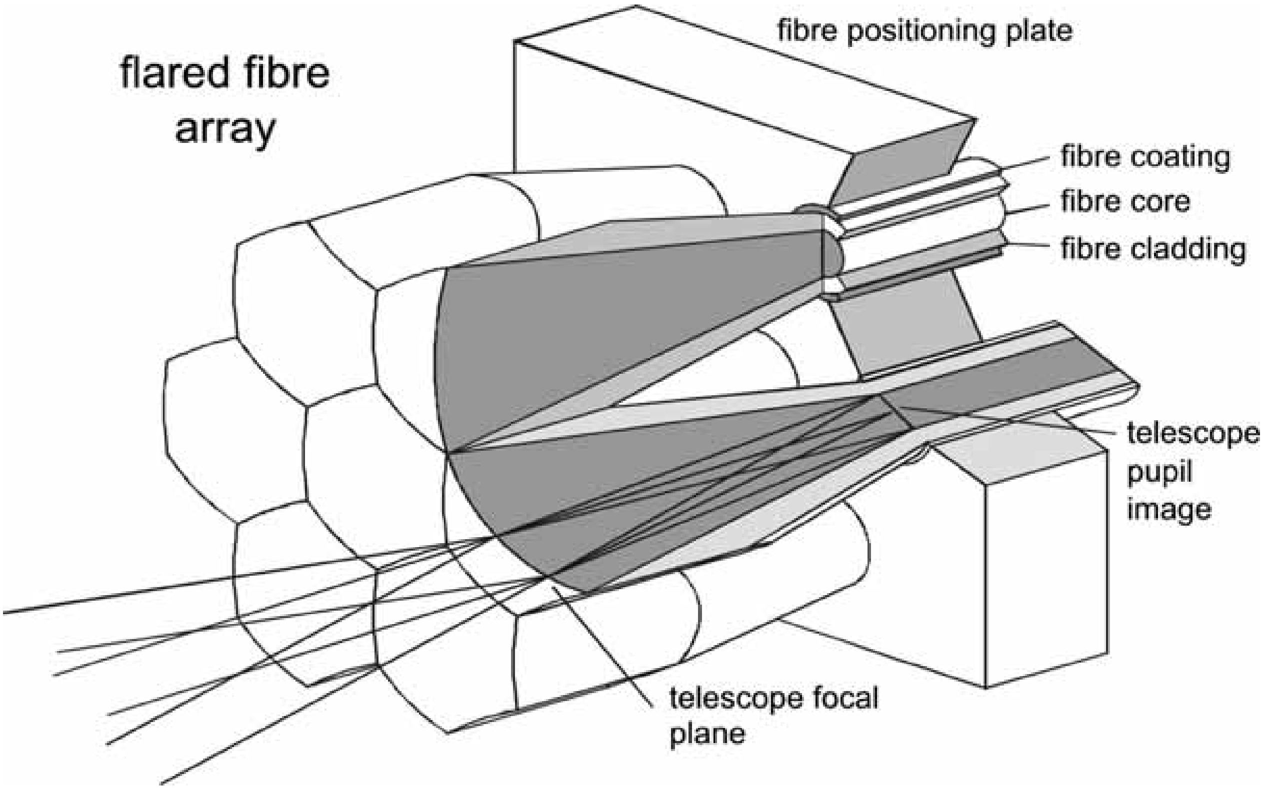
λ	=	wavelength
d_2	=	core diameter
NA	=	sin σ (numeric aperture)

Therefore a light impulse which is coupled into the fibre arrives at the end of the fibre in modes with the mode number Z_m. These modes transit the light guide (NA 0.22) with an angle of $0 \leq \alpha \leq 8°40'$ The length of the expander l_0 is derived from the following equation: **8°40'**. As the modes propagate in different reflection angles the distance travelled by each mode differs from one another, resulting in differences in propagation time.

The correlation of the propagation time dispersion is corresponding with the correlation of the refraction indices of the cladding η_2 to the core η_1. The largest reflected angle is dependent on the numeric aperture NA of the light guide.

VARIOUS INTERESTING APPLICATIONS

The future application areas of the lens taper can only be speculated on at this point in time. So far applications in the fields of sensors, endoscopy, laser technology, image conversion and laser diode coupling to light guides (pigtail) have been successful.



Picture 6: 3-D view of a tapered fiber-lens bundel

NEW POSSIBILITIES FOR SENSORIC APPLICATIONS

The use of lens taper offers advantages in the IR-spectral-pyrometry for contact free temperature measurement in the range of +400ºC to 2'600ºC on moving objects or in places with difficult access. The short measuring time allows to record very hot objects at a far distance. Contact free measurement does neither cause repercussion nor wear and tear.

There are no changes occurring at the object measured, which would be a significant factor for utilisation of lens tapers at the outlet valves of internal combustion engines or for temperature measurement at the vanes of gas turbines for instance. Another application area is in aerodynamics of gases and fluids.

Lens tapers can also be applied in laser technology for focusing and transmission of energy. For instance Nd-YAG lasers with lens tapers can be used for soldering Ball Grid Arrays. Besides the medical technology (endoscopy) image conversion opens new areas for this technology, in fields ranging from cross section conversion for Si-Arrays, image analysis to transmission and digitalisation with IR-Arrays. IR-image analysers have already been fabricated for space technology (picture 6).

CONCLUSION

Integrated lenses with expanders and light guides (with a minimum core diameter of 50 μm / step index profile) can be fabricated without problem from pure SiO_2. Usually core diameters of 100 μm, 200 μm or 300μm are used. With this new custom made lens taper for the opto-electronic field, sensor and mechanical engineering the application spectrum of light guides can be significantly enlarged.