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Review of plasma deposition applications: preparation of optical waveguides

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Abstract - This paper reviews the application of high and low pressure plasma deposition processes for the preparation of optical waveguides. First, the principles of operation of optical waveguides, the different types, and the requirements for their fabrication are briefly discussed. Next, the different routes for the manufacture of optical fibres are described. The Plasma Outside Deposition (POD) process, the Plasma Enhanced Modified Chemical Vapour Deposition (PMCVD) process and the low pressure Plasma activated Chemical Vapour Deposition (PCVD) process are described and compared in detail.

INTRODUCTION

A.G. Bell's "photophone" is an early application of light as signal carrier for telecommunication (see Fig. 1). Similar to that are the transmission experiments based on laser light propagating in the atmosphere and in hollow reflecting tubes. To circumvent atmospheric signal distortions, and the problems in installing lightguiding tubes, glass fibres were considered as transmission medium in 1966 by Kao and Hockham (ref. 1). Since then an exploding development in the field of optical transmission systems based on silica glass fibres has resulted in plants with production capacities of more than 500,000 km of fibres per year and in optical telecommunication systems operating all over the world.

The fabrication methods for optical fibres include three plasma deposition processes, the advantages and drawbacks of which will be compared and discussed. However, for a better insight, the principles of operation of optical waveguides and the competitive thermally induced methods for the preparation of waveguiding structures are briefly summarized.

OPTICAL WAVEGUIDES: PRINCIPLES OF OPERATION

A sketch of an optical transmission system is given in Fig. 2. Such a system consists of a light source - an LED or a laser -, the transmission medium - the optical glass fibre - and a photosensitive receiver - a semiconductor photodiode.

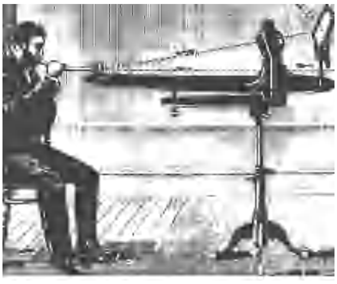


Fig. 1. A.G. Bell's "photophone". Sunlight focussed on a thin mirror fixed at the end of a speaking tube is modulated by acoustic waves. The intensity fluctuations are detected.

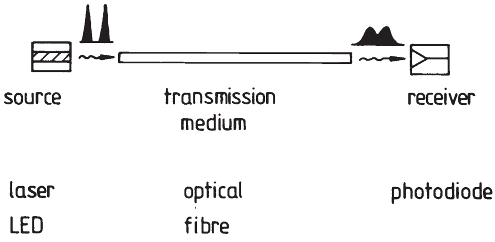


Fig. 2. Sketch of an optical transmission system.

To guide light, the optical fibre consists of a central core region surrounded by an outer region or cladding with lower refractive index. Finally, a plastic coating is applied as protective layer for the fibre surface.
The most important parameters describing the quality of the fibres are (a) optical

attenuation or losses and (b) pulse broadening or dispersion of signals propagation along a transmission line. Those parameters define the materials and structures usable for different applications as well as the requirements for the fabrication method.

a) Optical losses

While propagating along an optical transmission line, the intensity of light decreases due to absorption and scattering according to

$$I(\lambda,x) = I_o(\lambda)\, e^{-\alpha_{tot}(\lambda)\, x} \qquad (1)$$

where

α_{tot} is the attenuation per length and

x is the length of the transmission line.

More commonly eq. (1) is expressed in decibel/length

$$\alpha'_{tot} = \frac{10}{x} \log \frac{I_o}{I} \quad dB/km \qquad (2)$$

Silica was chosen as the basic material because of its intrinsically low IR and UV absorption and low Rayleigh scattering losses in the wavelength window of 0.8 to 1.6 µm. The corresponding data are given in Fig. 3 according to Osanai et al. (ref. 2). Modern optical telecommunication systems use the low loss windows of SiO_2 at 1.3 and 1.55 µm.

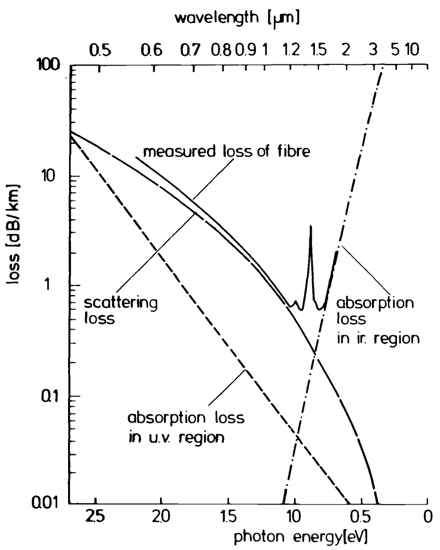


Fig. 3. Loss spectrum of a silica based optical fibre (ref. 2).

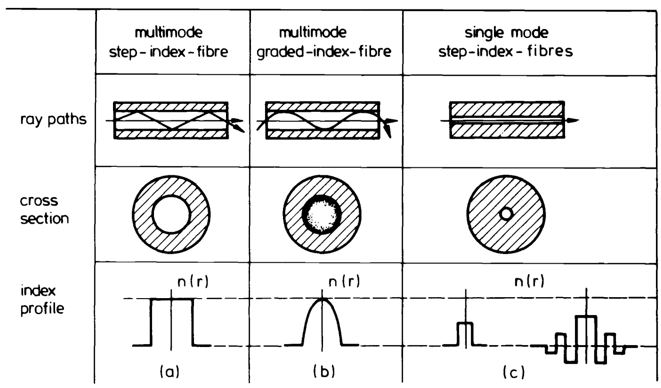


Fig. 4. Ray path, cross sections and index profiles of multimode step index (a) multimode graded index (b) and single mode (c) structures.

Unfortunately, this spectral region is extremely sensitive to both transition metal and OH-contamination of the light-guiding region. Some ppb of metals incorporated increase the fibre absorption to several dB over the whole transmission window. OH bound to SiO_2 generates absorption peaks at 0.95 µm, 1.24 µm and 1.38 µm. As a rule of thumb 1 ppm OH in the solid results in additional absorption of approx. 40 dB/km at 1.38 µm. The incorporation of metals and OH-groups has therefore carefully to be avoided during the manufacturing procedure.

To keep the Rayleigh scattering losses (which increase linearly proportional to λ^{-4}) as low as possible, inhomogeneities in the glass such as small bubbles or geometrical imperfections have to be avoided.

b) Pulse broadening

Pulse broadening determines the maximum number of individual signal pulses to be sent along a transmission line within a given time interval i.e. limits the transmission or bit rate of a telecommunication system. Three different pulse broadening mechanisms can be distinguished:

1) modal dispersion:

Assuming a steplike refractive index profile for the light-guiding core of an optical fibre (Fig. 4a), different ray paths or modes are permitted for a pulse travelling through the fibre, depending on the core diameter. Light injected at time t_o in different modes will arrive at the end of the fibre at different times $t_1 < t_2 < t_3$ depending on the order of the mode, i.e. the number of reflections at the core/cladding boundary, thus broadening the initial pulse width in the order of 50 ns km^{-1}. To improve the situation, slow high order modes can be accelerated by decreasing the refractive index from the centre to the outer region of the fibre core (Fig. 4b). In these "graded index" multimode fibres, the higher order (frequently) reflected modes travel in a region with reduced refractive index. The time of flight of high and low order modes is thus equalized. However, this requires a perfect profile over the core diameter and along the total length of the fibre. In practical systems the residual broadening is still in the order of some ns km^{-1}.

One way to avoid modal dispersion is to reduce the fibre core size to a value where only a single mode is permitted to propagate. This is schematically illustrated in Fig. 4c. However in this single mode fibre structures the ray approximation for the propagation of light is no longer valid. The fundamental mode is described as a propagating wave with a Gaussian power distribution partially penetrating into the cladding.

2) material dispersion:

Even in single mode fibres without any modal dispersion, non-monochromatic pulses will be broadened due to the different propagation speeds of its spectral components according to the wavelength dependence of the refractive index of the lightguiding material. This material specific broadening or material dispersion is proportional to the length of the fibre and the spectral width of the source and is in the order of ps nm^{-1} km^{-1}.

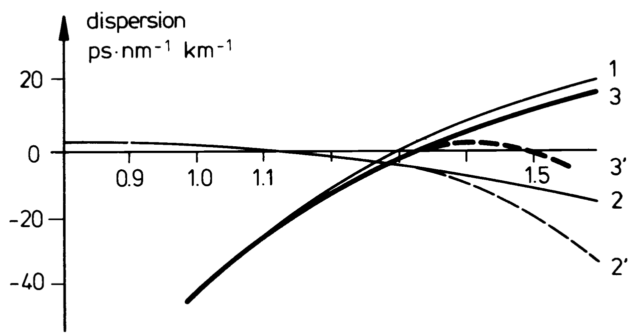


Fig. 5. Material dispersion (1), waveguide dispersion (2), and total dispersion (3) for a simple (solid) and a dispersion modificated (dashed) single mode fibre (see Fig. 4c).

In Fig. 5 a characteristic curve (1) is given. For SiO_2 the material dispersion is zero at 1.3 µm where the second derivative of the refractive index versus the wavelength is zero. Dopants for refractive index variations may shift the material dispersion zero to slightly higher or lower wavelengths depending on the dopant.

3) Waveguide dispersion:

In single mode fibres a third dispersion mechanism plays an important role. The wave front of the propagating fundamental mode is distorted due to the fact that part of the light is guided (according to the Gaussian power distribution) outside the fibre core in the cladding with lower refractive index. This so called waveguide dispersion is in the same order of magnitude as the material dispersion but has an opposite slope. It depends on the refractive index and the geometry of the waveguide. A typical curve is given in Fig. 5, (2).

Both material and waveguide dispersion are added to give the total dispersion of a single mode fibre (curve 3, Fig. 5). By proper choice and accurate manufacture of the refractive index profile, the waveguide dispersion can be adjusted to compensate the material dispersion over an extended wavelength range (ref. 3) (dashed curves in Fig. 5). This results in "dispersion flattened", more complex single mode fibres with dispersion less than 1 ps nm^{-1} km^{-1}. The manufacture of the profiles has to be extremely accurate with a geometry error of less then 0.1 µm for the fibre core. The refractive index profile of such a fibre is schematically given in Fig. 4d.

REQUIREMENTS FOR THE PREPARATION METHOD

According to the area of application the following requirements can be deduced from the basic principles mentioned above:

- For high quality telecommunication fibres the losses should be as low as possible. In addition to the optimum material composition, this requires a contamination-free fabrication method. Residual OH- and metal impurities have to be in the order of ppb. Bubbles, index and geometrical distortions have to be avoided to achieve low Rayleigh scattering.
  If only short distances e.g. in machines, cars etc. are to be bridged, higher losses can be tolerated if the fibre is cheap.

- To achieve high bit rates in systems based on "graded index" (GI) fibres, a parabolic index profile has to be closely approximated over the total length of fibre.
  For simple transmission problems step index fibres with a large core are sufficient.

- For high bit rate/long distance transmission, single mode fibres with ultra low losses are necessary. To meet the requirements of the future, broad low dispersion windows are desirable. For cheap high bit rate local area networks, the combination of LEDs and dispersionfree fibres are a possible solution. The fabrication of these dispersion flattened single mode (DFSM) fibres requires extremely accurate profiles with geometrical fluctuations of less than 0.1 µm.

In addition to the technical requirements, certain economic requirements are simultaneously to be met:

- High fabrication speed of several kilometers of fibre per hour
- High material efficiencies
- Low cost starting materials

ROUTES FOR THE PREPARATION OF OPTICAL FIBRES

a) Thermally induced CVD methods

Up to now exclusively CVD methods have proven capable of meeting the requirements for the preparation of silica based high quality optical fibres. All routes use $SiCl_4$ and O_2 as starting material to form SiO_2. The refractive index and other glass properties are varied by means of dopants. In fig. 6 the refractive index of doped SiO_2 versus the dopant concentration in the solid is given for a number of dopants applied up to now (ref. 4).

GeO_2, F, P_2O_5 and B_2O_3 are well established for the preparation of optical fibres. In Fig. 7 the different routes and the individual process steps are summarized.

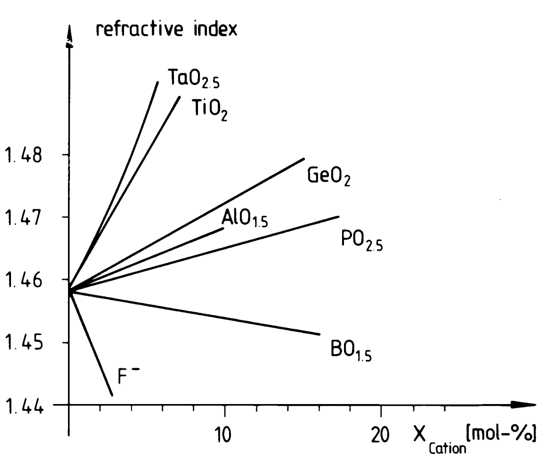


Fig. 6. Refractive index of doped SiO_2 versus the dopant concentration in the solid (ref. 4).

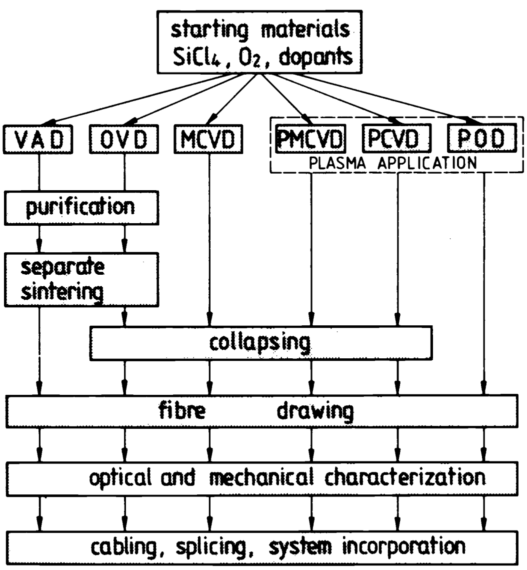


Fig. 7. Routes for the preparation of optical fibres.

In three of the methods, MCVD (Modified Chemical Vapour Deposition) (ref. 5), OVD (Outside Chemical Vapour Deposition (ref. 6)) and VAD (Vapour Axial Deposition) (ref. 7), thermal initiation of the $SiCl_4$-oxidation is applied. Small glass particles ("soot") are deposited onto rotating substrates such as the surface (OVD) or end face (VAD) of a glass rod or onto the inner surface of a tube (MCVD). In VAD, structured material is obtained by means of different burners for different materials. In OVD and MCVD, structures are built up by traversing burners, thus depositing layers of differently doped SiO_2. For VAD, OVD and MCVD, thermophoresis is the driving force for the deposition of the soot particles. In MCVD the resulting porous structure is directly purified and sintered. In OVD and VAD purification and sintering are done separately. If hollow structures are prepared, for example internally coated tubes (MCVD), these structures are collapsed into solid rods (OVD, MCVD). All manufacturing processes end up with rods consisting of a core and a cladding with lower refractive index. These rods are drawn into fibres, which are characterized optically and mechanically and then incorporated into transmission systems.

b) Plasma enhanced and plasma activated CVD methods

The three methods applying plasmas for the deposition of light guiding materials, PMCVD (Plasma enhanced MCVD) (ref. 8-10), POD (Plasma Outside Deposition) (ref. 11,12) and PCVD (Plasma Activated Chemcial Vapour Deposition) (ref. 13-18) are discussed in more detail:

From the number of process steps in Fig. 7, the POD-process looks very promising. After deposition the preform is directly drawn into fibres without purification, sintering or collapsing. This process, also known as ALPD (Axial Lateral Plasma Deposition) is applied by Heraeus, FRG and Fibres Optiques Industries, France. In Fig. 8a and 8b the experimental set-ups are given. The starting materials $SiCl_4$ and O_2 are directly fed into a 3 MHz (50-100 kW) radio frequency plasma torch at atmospheric pressure, generating a fireball at several thousand °C. In ALPD in a first step SiO_2 is deposited on the endface of a large rotating glass tub which is slowly moved away from the torch. A compact silica rod grows from the end of the stub. This rod is used as substrate in a second step where a fluorine carrier is added to the gases passing the plasma torch, thus doping the deposited SiO_2 with fluorine, reducing its refractive index (compare Fig. 6) and forming a waveguide. The second step is identical with POD as can be seen from Fig. 8b.

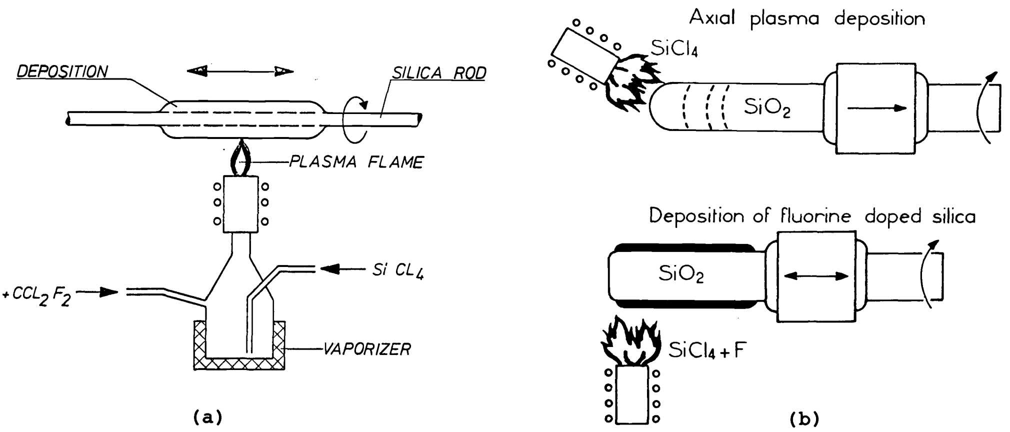
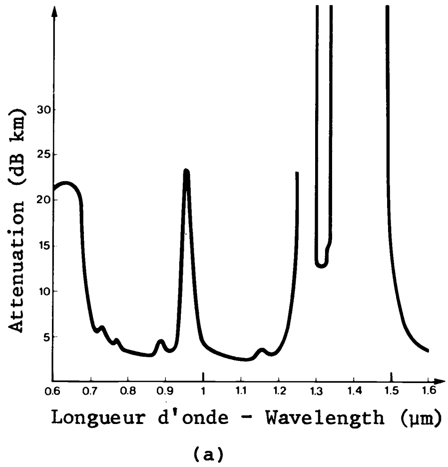


Fig. 8. Schematic views of the experimental set-ups for POD (a) and APLD (b) (ref. 11,12).

The deposition rate is approx. 1-3 g/min. SiO_2 molecules or clusters are immediately converted into compact glass layers on the surface of the substrate due to the high temperature of the plasma fireball. The surface temperature of the substrate has to be above 1800°C to generate clear glass layers and to avoid bubble formation. Subsequent sintering and collapsing is not necessary. The preforms are directly drawn into fibres. Structures can be built up by multiple pass deposition.

An advantage of POD and ALPD is the preparation of relatively large preforms sufficient for more than 100 km of fibre with standard outer diameter of 125 µm. However, low losses and high bit rates have not been reported up to now for POD or ALPD fibres. The losses are depending on both the substrate rod material and the fluorine-doped deposit. In Fig. 9a a typical loss spectrum of a corresponding fibre is given. The approximation of a desired refractive index profile is critical due to the constant index of the SiO_2 substrate rod. In Fig. 9b the corresponding profile of a multimode preform is given. In addition to the flat core, index distortions in the deposit are clearly visible. Refractive index differences of more than 1.2% ,referred to SiO_2, are difficult to prepare. The high temperatures applied during deposition limit the refractive index depression to approx. 1,2% due to fluorine etching and reduction of the deposition efficiency.



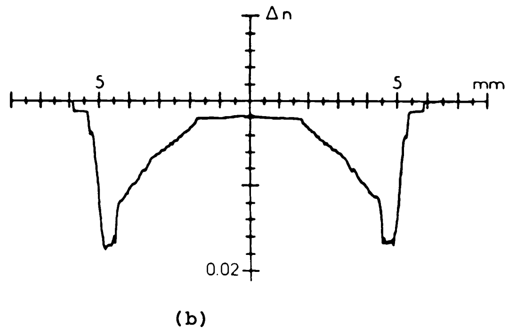


Fig. 9. Loss spectrum (a) and index profile (b) of a ALPD fibre.

Up to now the application for ALPD and POD fibres is focussed on inhouse and short distance systems, computer and machine links, measuring and medical equipment and other areas where losses and bitrates are not very important.

The second process to be discussed is the PMCVD process developed at AT&T Bell Laboratories for the preparation of optical fibres (ref. 8-10). This process is a variation of standard MCVD and the experimental set up is given in Fig. 10. In this process the oxidation reactions at atmospheric pressure are also induced by the flame of an oxy-hydrogen burner moving along the rotating silica substrate tube. This is very much the same as in standard

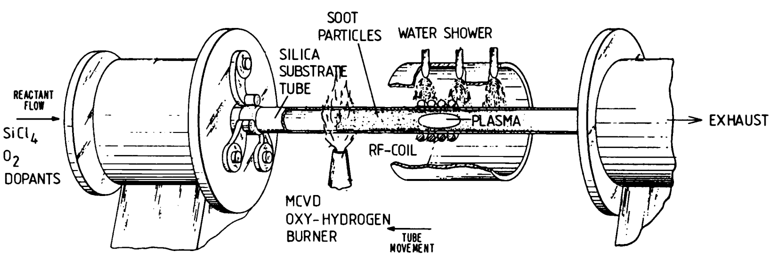


Fig. 10. Experimental set up for PMCVD (ref. 8).

MCVD (ref. 5) and therefore PMCVD is a thermal deposition method. The soot deposited downstream is sintered by means of the MCVD burner in the same pass. As already mentioned above, the temperature difference between gas and substrate is the driving force for the deposition of the glass particles onto the inner surface of the tube. However, if the gas velocity is high and the temperature differences are small,part of the soot may leave the substrate tube without being deposited. In PMCVD, the high pressure plasma is neither used to initiate the oxidation nor to sinter the deposited soot. It simply acts as hot stopper and increases the thermophoretic forces responsible for the deposition. Therefore, the rf-coil to support the 3.5 MHz plasma is mounted downstream with respect to the particle generating burner (Fig. 10). To further increase thermophoresis the substrate tube is even cooled with a water shower just behind the rf-coil. Of course, the extremely hot plasma fireball has to be carefully centered inside the substrate tube to avoid any contact with the walls. Therefore, tubes of more than 50 mm inner diameter are used in PMCVD. After deposition these tubes have to be collapsed into solid rods by means of an oxy-hydrogen-burner (see Fig. 7). Large tube diameters require more time and energy for the collapsing step thus reducing the fabrication rate and increasing the total costs of the process.

Deposition rates up to 6 g/min have been reported for PMCVD resulting in fabrication rates of 6 km fibre per hour (ref. 10). Single layers of several micron thickness are deposited in each pass. GeO_2 and fluorine are used for refractive index variation and phosphorus is applied to reduce the melting point of the deposit thus improving the sintering of the glass particles. However, phosphorus has certain disadvantages concerning the long term stability of the fibres. Again fluorine dopant levels are limited by etching effects, and index depressions of more than 0.4% are difficult to achieve. On the other hand, extremely high GeO_2 dopant concentrations have been reported for PMCVD (ref. 10). The traverse speed of the burner is limited by the heat capacity of the substrate and the growing deposit. To sinter the deposit bubble-free the burner speed has to be low (a few cm per minute). Due to the low speed the layers deposited in each pass can be clearly monitored in the refractive index profiles. In Fig. 11a and 11b the profiles of a single mode and a multimode graded index preform prepared by means of PMCVD are given. In the multimode profile the layer structure is very pronounced resulting in moderate bandwidth of the corresponding fibres. Therefore the application of PMCVD is focussed on the preparation of simple step index single mode fibres.

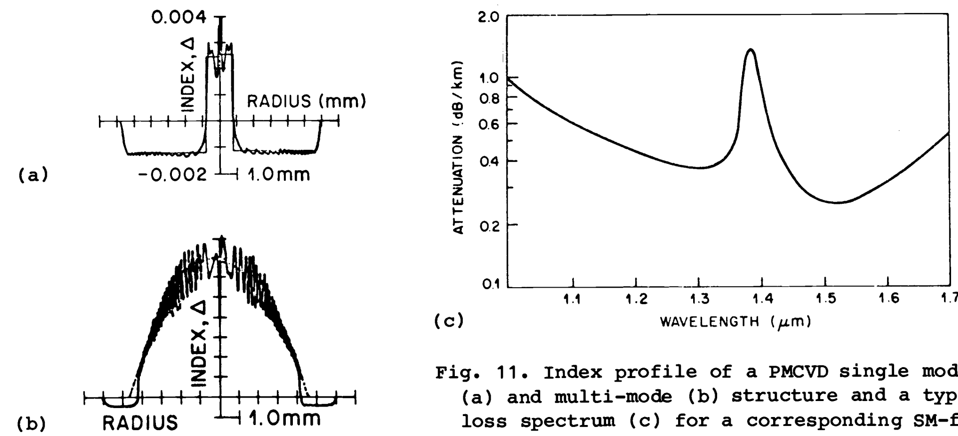


Fig. 11. Index profile of a PMCVD single mode (a) and multi-mode (b) structure and a typical loss spectrum (c) for a corresponding SM-fibre.

The optical losses of PMCVD fibres are very low. In Fig. 11c a typical loss spectrum is given. Losses of a few tenth of a dB have been achieved in the wavelength region around 1.3-1.55 μm. The OH contamination is in the order of some ppb resulting in a small OH-absorption peak of 1-3 dB/km. For SM-fibres all technical requirements for high quality telecommunication lightguides are met by PMCVD. However, up to now PMCVD has not been used for fibre preparation on a production scale.

Among the three methods applying plasmas for the preparation of optical waveguides (see Fig. 7) the PCVD process (ref. 13-18) is the only one that uses a low pressure non-isothermal plasma to induce the chemical reactions for the deposition of doped and undoped SiO_2. This process is developed at Philips Research Laboratories Aachen, FRG and is currently used for the preparation of high quality telecommunication fibres at Philips Glass Division Eindhoven, The Netherlands. Like MCVD and PMCVD, PCVD is an "inside" process, i.e. the deposition is performed inside a silica substrate tube. In Fig. 12 a sketch of a PCVD unit is given: the starting materials $SiCl_4$, O_2 and for refractive index variations, $GeCl_4$ and C_2F_6 are fed into the tube by means of a gass supply system. The gas flows are carefully controlled with mass-flow-controllers connected to a microcomputer. A low pressure 2.45 GHz microwave plasma inside the tube activates the chemical reactions. Centering of the plasma is much less important than in PMCVD and, in principle, rotation of the substrate tube is not necessary in PCVD. However, to avoid minimum profile distortions due to temperature gradients over the tube cross section, in practice the tubes are rotated. Both microwave

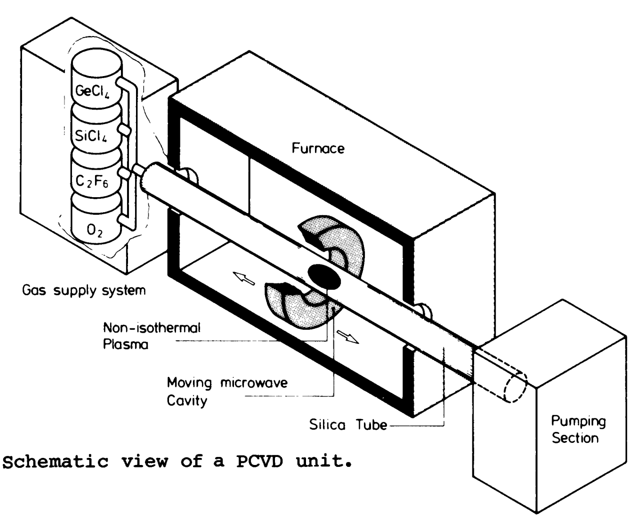


Fig. 12. Schematic view of a PCVD unit.

cavity and substrate tube are mounted inside a furnace to heat the tube to a temperature above 1150°C, thus preventing chlorine incorporation into the deposit, and avoiding bubble formation during the collapsing step. The cavity is moved to and fro along the tube and in each pass a compact glass layer is deposited on the inner wall of the substrate tube. Sooty, porous structures are not generated. Subsequent sintering is therefore not necessary in PCVD. Dopants such as P_2O_5 applied to facilitate sintering in OVD, MCVD and PMCVD can be avoided in PCVD. A pumping system downstream maintains 10-20 mbar inside the tube and removes the reaction products such as chlorine or excess oxygen.

The energy required for the chemcial reactions is directly coupled to the gases. Therefore the deposition process is independent of heat transfer through the wall of the tube or the growing deposit. Thus, the cavity can be moved at high speed yielding thin, submicron individual layers even at high deposition rates. Any desired refractive index profile can be approximated very closely with several thousands of individual layers.

The length of the axial displacement of the cavity and therefore the length of the final uniform preform is approx. 80 cm. Starting with 10 mm OD x 8 mm ID tubes microwave powers of only 200 W and deposition rates around 0.05 g/min in 1974, the tube geometry has been increased up to 29 mm OD x 26 mm ID. With microwave powers of 3 to 4 kW, deposition rates of 2-3 g/min were achieved (ref. 19).
With typical fibre lengths of 200-300 m/cm preform, the total fibre length drawn from an individual preform is approx. 15-25 km at present.

An inherent advantage of PCVD is the high deposition efficiency for both silica and dopants. For SiO_2, the efficiency is nearly 100% (even at high deposition rates (ref. 19)). This has to be compared to 40-70% efficiencies in other fibre fabrication processes.

The dependence of the GeO_2 incorporation on the deposition conditions in PCVD has been investigated in detail (ref. 20) and varies between 80% and 100% (see Fig. 13), depending on temperature, pressure and velocity of the cavity. In Fig. 14 the refractive index versus dopant concentrations in the PCVD gasphase is given for $GeCl_4$ and various fluorine carriers used in PCVD (ref. 21). The data for 100% efficiencies deduced from chemical analysis (dashed curves) are given. Fluorine incorporation depends on the fluorine carrier used (ref. 21,22) and is extremely efficient for C_2F_6. Index depressions of more than 2% have been achieved without any etching effects reducing the SiO_2 deposition efficiency. In Fig. 15a and 15b the influence of the pressure and the deposition rate on fluorine incorporation is

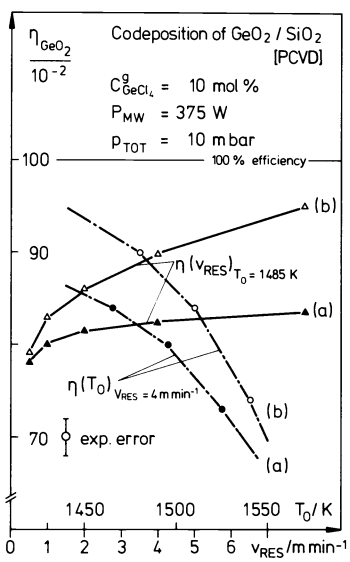


Fig. 13. Deposition of GeO_2-doped SiO_2 by means of PCVD (The local deposition efficiency η GeO_2 at different positions along the tube is plotted as a function of the velocity of the reasonator V_{RES} and the substrate temperature T_O, resp.; ((a): preform start, (b): preform end) (ref. 20).

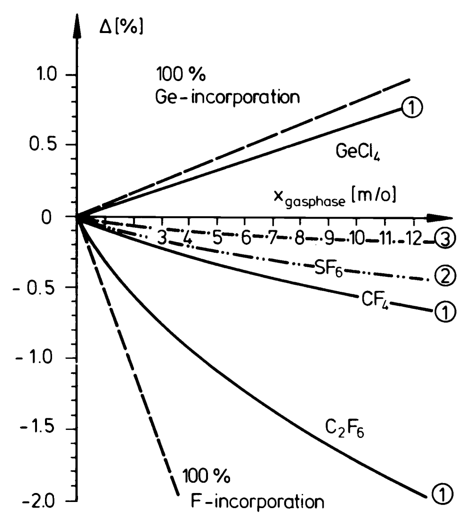


Fig. 14. Refractive index and incorporation efficiency for some dopants used in plasma processes ① PCVD ② POD ③ PMCVD

given. For increasing pressure and higher rates the efficiency approaches the 100% limit over a wide range. In PCVD any desired profile can thus be made by either using fluorine or germanium or a combination of both.

Fluorine is attractive not only as very cheap doping material but also due to its influence on the long term stability of optical fibres (ref. 23) and to its potential to reduce the OH-absorption in PCVD-glass (ref. 24).

In Fig. 16 the reduction of the OH-excess loss at 1.38 um is given versus the concentration of C_2F_6 in the PCVD gasphase. Starting with 30-40 dB/km at 1380 nm using commercially available materials the application of fluorine reduces the OH excess loss exponentially.

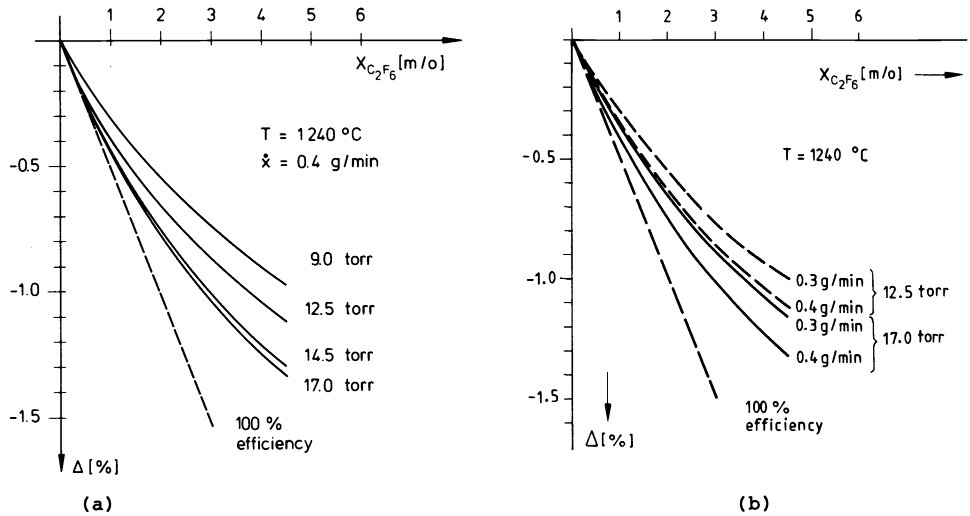


Fig. 15. Influence of pressure (a) and deposition rate (b) on fluorine incorporation in PCVD.

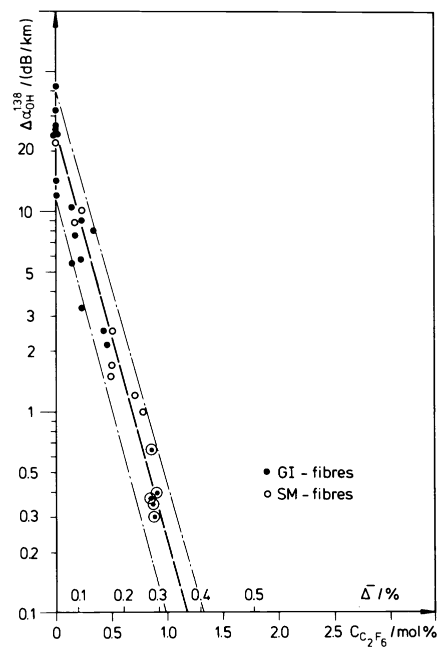


Fig. 16. Reduction of the OH-excess loss (at 1.38 µm) by means of fluorine doping in PCVD.

The lowest OH excess loss achieved so far in PCVD is 0.2 dB/km at 1380 nm. This corresponds to only a few ppb of OH bound to silica in the lightguiding region. Of course, due to the fact that PCVD is a low pressure process, the deposition unit has to be extremely leak tight (down to 10^{-8} torr l sec^{-1} helium leakage rate) to achieve these low OH-contaminations.

The deposition behaviour of PCVD can be described by relatively simple models including convection, reaction, and diffusion of molecules in the PCVD gas phase (ref. 14,25). For optimized parameters the deposition profile is localized to the plasma zone. The geometrical shape of the deposit can be well fitted assuming molecular cluster-free diffusion of SiO_2 in the plasma region resulting in a compact glass layer on the inner wall of the substrate tube. In Fig. 17 a static PCVD-deposition profile (prepared with the cavity in fixed position) is given together with the data predicted by the theory. The geometry of the final

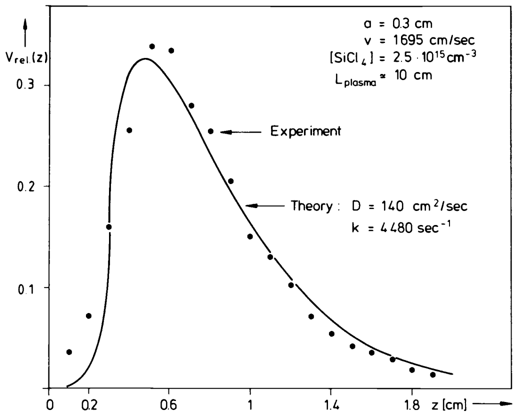


Fig. 17. Static (cavity in fixed position) silica deposition profile in PCVD (dots). Data from theoretical calculations are represented by the solid curve.

preform can be excellently predicted by a displacement of the static deposition profile over the full deposition length. Predictions and extrapolations to higher deposition rates are possible by means of model calculations. The optimization of the displacement velocity profile for maximum uniformity over the preform length resulting in nonlinear ramps for the cavity speed has also been possible by means of model calculations (ref. 26). To demonstrate the accuracy of profiling with PCVD in Fig. 18a-f a set of tomographic refractive index profiles measured at collapsed PCVD preforms are given. As an example in Fig. 19 the loss spectrum of a PCVD-single mode fibre can be seen. The quality of both "graded index" multimode and single mode fibres prepared by means of the low pressure plasma is superior. Losses close to the intrinsic limits of SiO_2 are achieved under factory conditions. PCVD multimode fibres exhibit the highest average bandwidth obtained for any fibre fabrication method and up to now "dispersion flattened" single mode fibres have been manufactured reproducibly exclusively by PCVD.

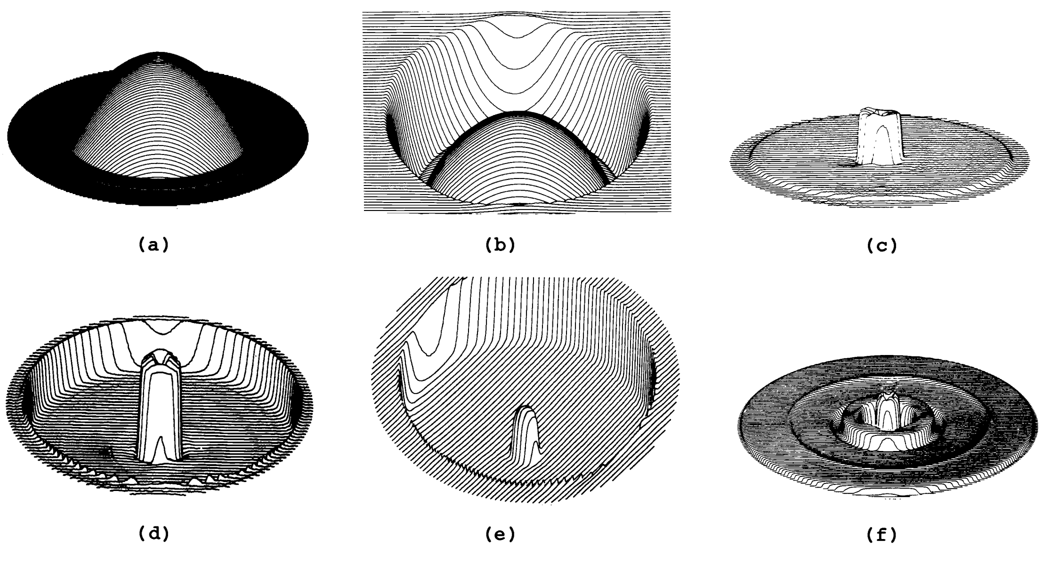


Fig. 18. Tomographic representations of measured refractive index profiles prepared by means of PCVD

(a) graded index multimode (GeO_2); (b) graded index (F)
(c) step index single mode (GeO_2); (d) "depressed cladding SM(GeO_2/F)
(e) deeply depressed cladding SM(F/GeO_2); (c) "dispersion flattened" SM(GeO_2/F)

Moreover, due to the fact that PCVD allows the deposition of well defined glassy doped silica structures at moderate temperature, this process has the potential for the preparation of integrated optical components. Microlenses suitable for laser-to-fibre coupling are an example for this application (ref. 27): The preparation steps of such lenses are described in Fig. 20.

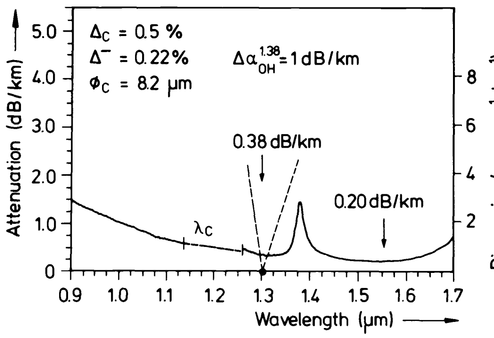


Fig. 19. Loss spectrum of a PCVD single mode fibre.

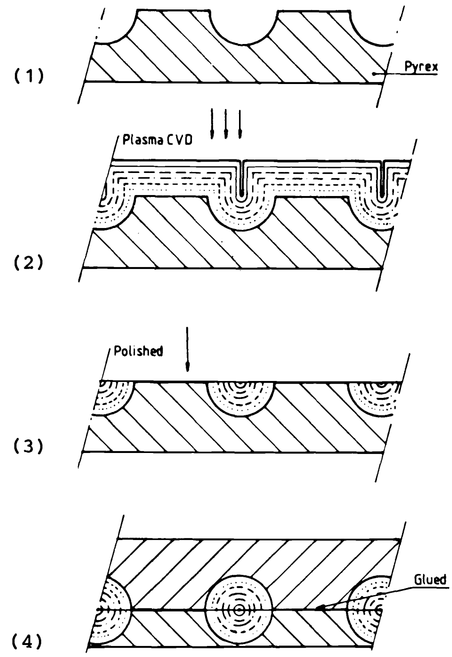


Fig. 20. Process steps for the preparation of integrated microlenses,

(1) Etching of grooves
(2) Plasma deposition of Si_3N_4/SiO_2
(3) Polishing
(4) Glueing.

In a Pyrex glass plate an array of small grooves is etched by means of photolithographic techniques. The plate is coated with a graded index Si_3N_4/SiO_2 deposit prepared from $SiH_4/NH_3/N_2O$ gas mixtures with PCVD. The deposition temperature is only a few hundred °C to avoid crack formation due to the large differences in thermal expansivity of high and low doped SiO_2. This deposit is ground down to the surface of the plate resulting in an array of graded index half sphere lenses incorporated into a flat substrate. Spherical symmetry is obtained by glueing two of these plates to each other. Si_3N_4 is used as dopant due to its high refractive index of around 2.0. With these lenses efficiencies of 80-90% were achieved for coupling of lasers to graded index multimode fibres.

SUMMARY

The applications of plasmas for the preparation of optical waveguides are well established in todays fibre optic industries. Both high and low pressure plasmas are used for the fabrication of high quality telecommunication fibres. The efficiency of plasma deposition processes is superior to conventional thermally induced deposition methods. The application of a low pressure microwave plasma allows the preparation of highly sophisticated glass structures resulting in outstanding properties of the corresponding optical fibres. Fluorine doping levels of more than 2% are exclusively achievable using a low pressure plasma deposition technique. High deposition rates of 3 to 6 g/min can be achieved by means of both high and low pressure plasmas. Due to the deposition of compact glass layers the low pressure plasma application is suitable for the preparation of integrated optical structures.

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