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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Low-Cost Fibre Fabrication [and Discussion]

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Low-cost fibre fabrication

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Fabrication based on the vapour-phase reaction technique has proven to be the most cost-effective method for producing low-loss optical fibres. This is particularly true for silica-based materials and is now being investigated for fluoride-based glasses. The advantages accrue not only from the purity possible but from the flexibility of the process. This enables complex refractive-index structures to be fabricated that allow enhanced system performance. Advances toward low-cost fabrication have been made in all major processing techniques during the past few years. A review of the current status is presented.

Introduction

Tremendous progress has been made over the past 15–20 years in the manufacture of optical fibres. Just a few short years ago, people were gauging the amount of installed fibre in terms of circling the Earth 10 times. Today, a collection of companies has produced and installed more than 10^6 km, or enough to encircle the Earth and Moon more than 25 times. More than 90% of the long-distance traffic in North America is now carried on fibre. More than 80% of the population is within a few kilometres of an optical-fibre termination.

This roughly hundred-fold increase in manufactured fibre volume over the past five to six years has come about, in part, because of the attendant six-fold reduction in fibre price. While volume is a key ingredient to decreasing fibre price, it would not have been possible without significant advances in manufacturing technology generated by progress in research, development and engineering. Fibre use is expected to increase dramatically over the next 20 years or so. But this use may not occur if advances in technology do not continue to be made by the major manufacturers. The fibre manufacturing process is quite complex, with many separate steps. This generally does not create an efficient and low-cost process. It does, however, still leave considerable area for improvement. In this paper, we shall examine the current situation, and suggest the possible level of improvements that might be expected.

System requirements

Before examining the process situation, recall the functional properties that the fibres must possess. With the tremendous increase in fibre volume over the past few years, there also has been a significant improvement in the quality of the fibres being produced. Let us restrict the present discussion to single-mode (SM) or mono-mode (MM) fibres, as it is this class that constitute more than 85% of the world-wide installations. There are basically three classes of SM fibres being manufactured today; those optimized for operation at 1300 nm or non-dispersion-shifted, those whose dispersion has been shifted to 1550 nm or dispersion-shifted, and those whose dispersion is minimized over a broad range of wavelengths or dispersion-flattened. Figure 1 shows the refractive index profile of various designs for each of these classes

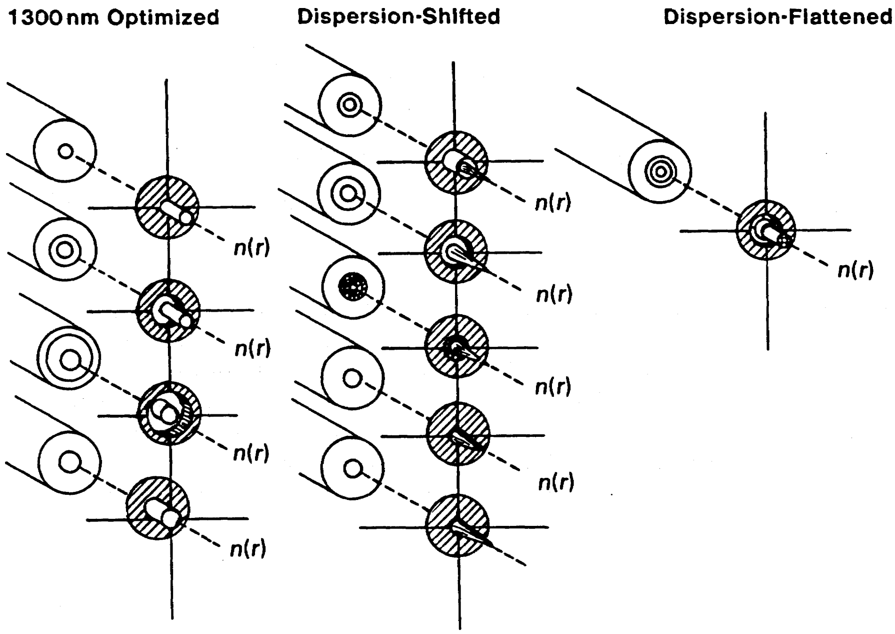

FIGURE 1. Schematic drawing of the refractive index profile of various types of single-mode fibres currently being fabricated.

of SM fibres. Not every manufacturing process is capable of fabricating each of these refractive index profiles, as may be appreciated from their relative complexity. Generally, the outside diameter of all fibres is 125 μm with a tolerance of ±2 μm. Not all of the manufacturing processes are equally capable of producing fibre to this level of precision. To reduce the cost of interconnecting fibres, it is expected that dimensional tolerances will become tighter, which probably will be reflected in the relative manufacturing cost.

Fundamentally, the fibres must perform optically. These performance levels have improved over the past few years. This is best characterized in figure 2, which shows the performance level of the two most important fibre variables, attenuation and information-carrying capacity as a function of operating wavelength. This particular graph shows the performance for a 30 km fibre length of non-dispersion-shifted optical fibre. The attenuation is a function of the various manufacturing processes, but is essentially at the Rayleigh scattering limit. The OH absorption at 1383 nm usually is less than 1 dB km^{-1} in well-made fibres, which corresponds to an impurity level of less than 10 parts per thousand million. For attenuation or bit-rate values greater than the wavy line, the intersymbol interference penalty at the detector becomes too great for low-cost system operation. In examining the attributes of the various manufacturing processes, one always must keep in mind the fact that this level of performance must be maintained because that is what the system designer has come to expect.

PROCESS DISCUSSION

We turn now to examine, in more detail, the various processes used in the manufacture of optical fibres. Out of the forest of possibilities, which includes the rod-in-tube, double-crucible, plastic-clad-silica and sol–gel, vapour deposition processing has emerged as the 'oak' of the technology.

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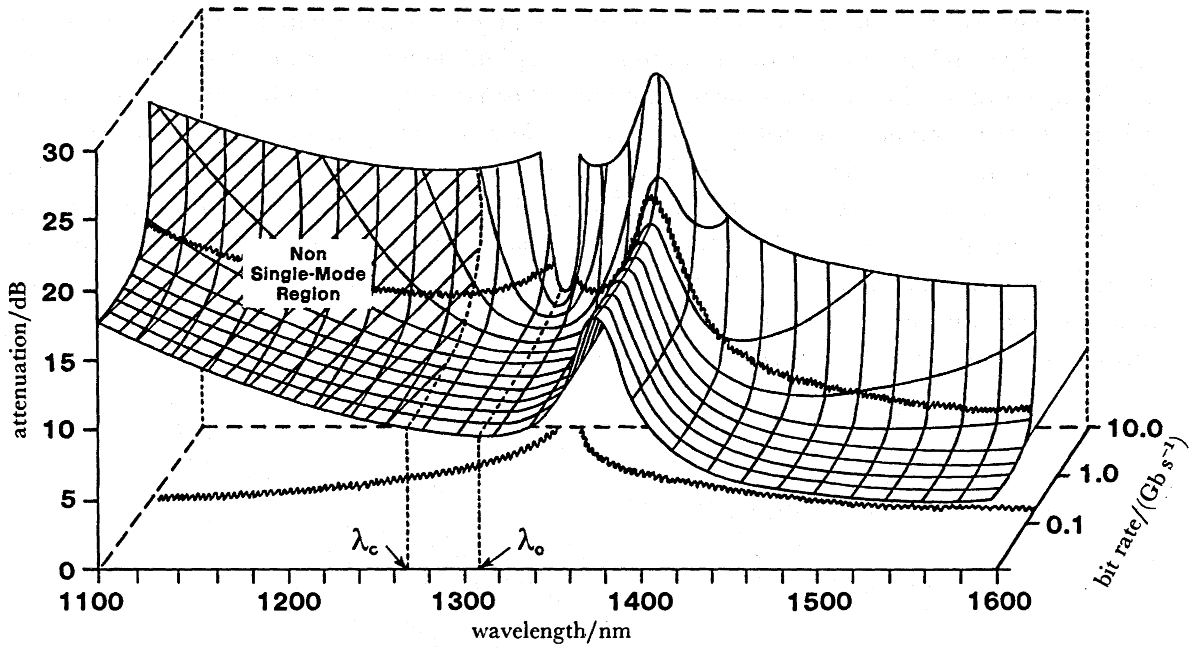

Figure 2. Single-mode optical-fibre performance trade-offs for a 30 km system. For attenuation and bit-rate levels greater than the wavy line, increased receiver complexity and therefore system cost is incurred.

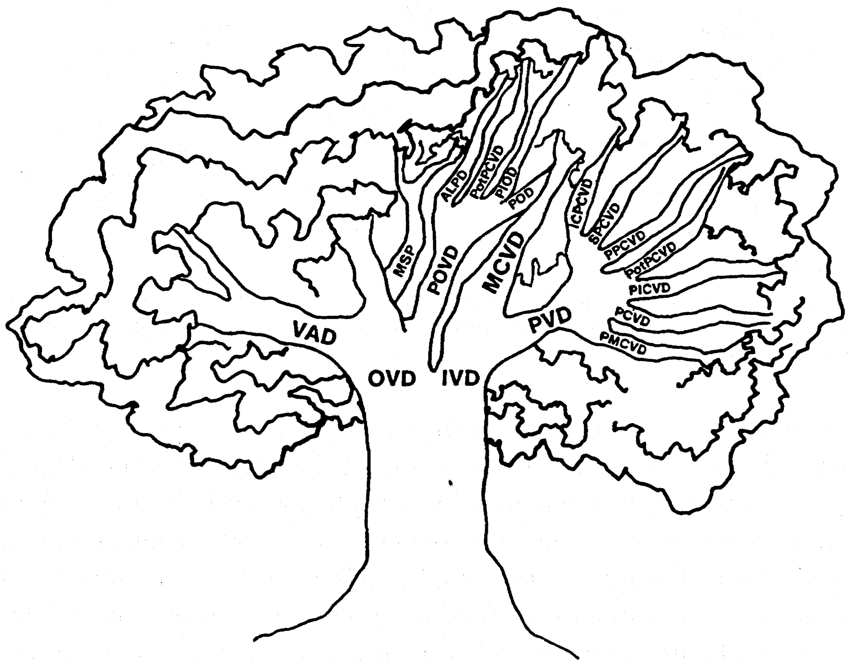

Figure 3. Evolution of optical-fibre fabrication processes.

Vapour deposition process

The schematic drawing in figure 3 depicts the evolution of the variations of this technology. Inside (Keck & Schultz 1970) and outside (VanDewoestine & Morrow 1986) vapour deposition (IVD and OVD) processes were the forerunners for the various techniques being practiced today. From the latter has sprung the vapour axial deposition (VAD) (Murata 1986) process whereas from the former has sprung the modified chemical vapour deposition (MCVD) (Nagel 1985) and plasma chemical vapour deposition (PCVD) (Lydtin 1986) processes. In addition, a host of other plasma processes also have been generated (Hunlich 1987). All of these originated in an attempt to obtain high-volume, low-cost manufacture. The OVD process is practiced primarily at Corning Glass Works and various subsidiaries. The MCVD process is practiced at AT&T, Northern Telecom and Alcatel. Plasma vapour deposition is being used at Philips. Finally, VAD is used by Japanese fabricators: NTT, Furukawa Electric, Fujikura Limited and Sumitomo Electric. All four of these processes have in common that the starting materials go through a distillation step that results in extremely pure material being incorporated into the fibre, as shown in figure 4. These pure materials are deposited on some

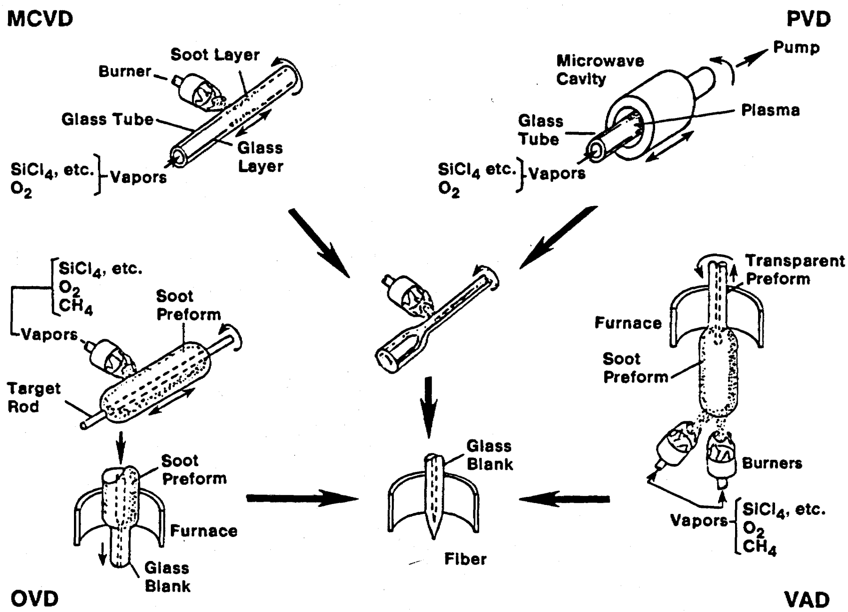

FIGURE 4. Schematic illustration of the four major vapour phase deposition processes used in optical-fibre fabrication: outside vapour deposition, modified chemical vapour deposition, plasma vapour deposition, and vapour axial deposition.

support structure such as a starting rod in the case of OVD, or in a glass tube as in the case of MCVD and PCVD. In the OVD and VAD processes, all the glass is vapour deposited. This has mechanical performance implications, and does not place a restriction on the final preform size. The deposition step in OVD, MCVD and PCVD is, of course, radially symmetric, thereby allowing the simple generation of many of the complex refractive index profiles listed in figure 1. Following the preform deposition, the resulting structure is then put into a draw furnace and heated to the glass softening point at which point a fibre may be continuously drawn.

Bulk forming techniques

Two techniques are being studied at the present time for bulk deposition of pure materials from which a fibre preform then is produced. The most recent work involving a mechanically shaped preform (MSP) (Dorn *et al.* 1988) has stemmed from the OVD process work. As shown schematically in figure 5, this process begins with the deposition of high-purity powders that are collected in a container. Both doped and undoped powders are collected, which will

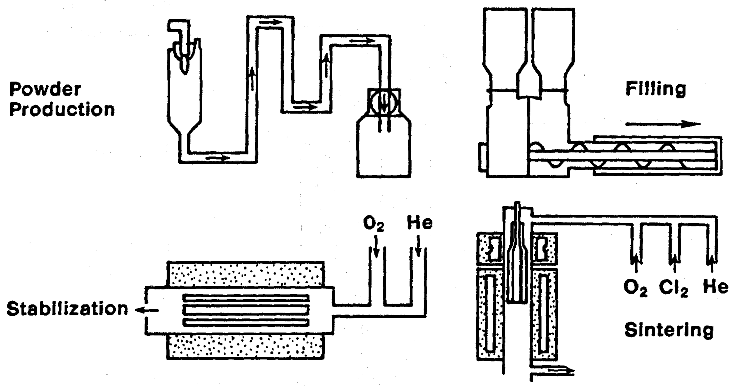

Figure 5. Schematic illustration of the 'mechanically shaped preform' (MSP) bulk forming technique for optical-fibre preform fabrication.

become the core and cladding glasses respectively. These are then placed in the feed containers from which they are packed into a reusable tube. After stabilization at a moderate temperature, the tube is removed and the resulting preform then is sintered and drawn into fibre as with the other vapour deposition processes. The features of this process are again aimed at low-cost manufacture and include virtually 100% powder collection efficiency and a relatively low-pollution process. Recently, very good loss results have been reported (Dorn *et al.* 1988), as low as 0.67 dB km^{-1}. While the SM version has still had high OH absorption, the MM version has demonstrated very low attenuation of 1383 nm. Preforms have been prepared from which up to 100 km of fibre can be produced, which puts this process in the large preform category.

The other bulk approach currently being investigated is sol-gel fabrication (MacChesney 1988). Although sol-gel has been used to make complete preforms, the technique has been used primarily to make large silica tubes for some of the other vapour deposition processes. First, small glass particles of the desired material are prepared. These are then dispersed in water or alcohol to form a colloidal suspension. After casting the material in a mold and gelling and drying it, a fibre preform is made by inserting a core cane made by one of the vapour deposition processes and drawing it into a fibre. To date the performance of SM preforms made in this way have not been as good as those of the MSP process.

Fibre drawing

As already indicated, once a fibre preform has been prepared, it is placed in a furnace, heated and drawn into a fibre. The schematic illustration of this process is shown in figure 6. The furnace for high-silica fibres operates in excess of 2000 °C. The counter-rotating drawing tractors pull the fibre from the preform at typical speeds of 10 m s^{-1}. By measuring the fibre diameter continuously, feedback can be given to the tractors to maintain a constant diameter. It is in the fibre drawing process that fibre cost begins to increase dramatically. Ideally, the process should run continuously with no breaks or diameter upsets or variations in the optical properties. The speed should be as high as possible. There are many trade-offs beginning to emerge that affect the degree to which these desires are able to be met.

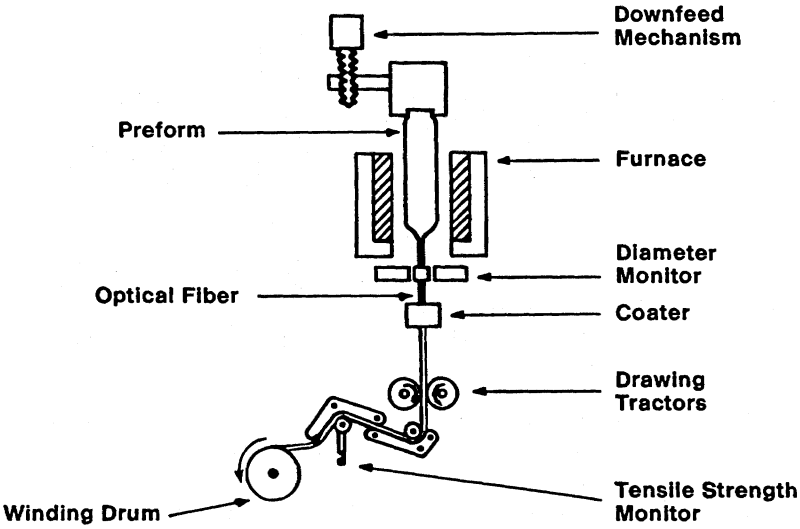

FIGURE 6. Schematic illustration of optical fibre draw apparatus.

Draw factors

Figure 7 illustrates an important set of cost-related trade-offs. Obviously, one would desire a very low materials loss. For a larger preform size at a constant draw speed, a smaller fraction of the preform is lost during start-up. For example, at a draw speed of 5 m s^{-1}, about 6 km are lost from a preform theoretically containing 30 km of fibre. Clearly, the fractional loss would be much smaller if the preform size were 200 km. While it is very desirable to draw the fibre as rapidly as possible, the end losses increase linearly with increasing speed. In fact it is possible with today's draw technology to 'lose' an entire small preform. Obviously, a large preform helps tremendously.

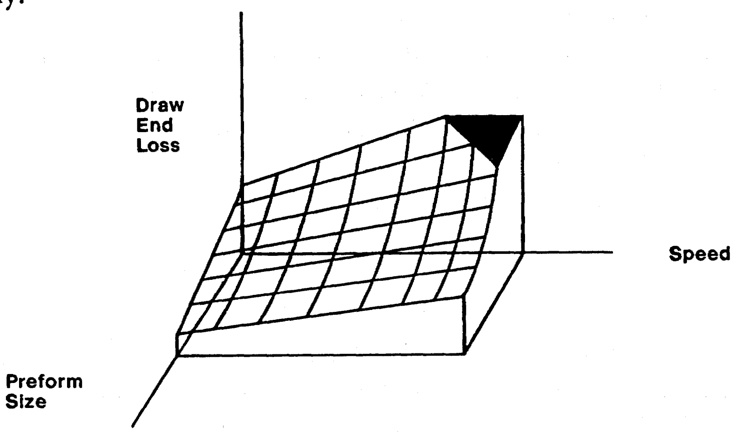

FIGURE 7. Factors affecting the economics of drawing optical fibres.

It has been the experience at Corning that larger high-quality preforms have led to progressively increasing fibre strength and decreasing fibre attenuation. Over the past six years, a 25-fold increase in standard fibre length has been recorded as shown in figure 8. This has produced cost improvement on two counts. First, the longer standard fibre lengths have enabled more efficient cable fabrication. Secondly, and perhaps less obviously, longer lengths result in reduced fibre handling during the manufacturing process, as for example, in quality

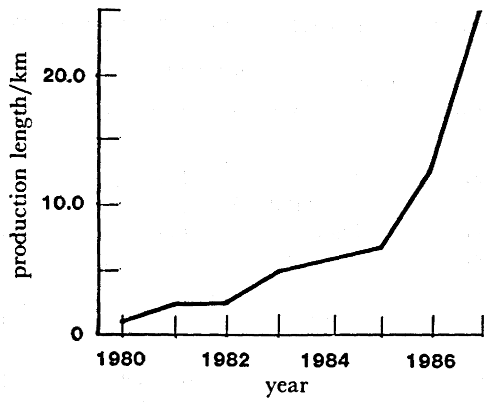

FIGURE 8. Chronology of production lengths of optical fibres commercially available.

assurance measurements. The distributed property measurements, such as attenuation, are made only once for each reel of fibre. By measuring on a longer-length piece not only are fewer measurements required but the accuracy of the measurement also is increased. The number other fixed measurements such as mode-field diameter, cut-off wavelength, zero-dispersion wavelength and core/clad dimensional properties also is decreased, bringing about an additional saving in cost.

Comparison of processes

To compare the various processes, we list the major factors in fibre fabrication in table 1. Within each major topic area – deposition, draw, and performance – there are several subfactors, some of which are obvious, and some not so obvious. For example, it is a common misconception that fibre cost is strongly influenced by the size of the core and therefore the relatively expensive germanium content. This is not true compared with such items as pollution treatment and equipment depreciation, especially for single-mode fibre. By using this format, each of the different processes will be compared for these important parameters as they have most recently been reported in the technical literature.

TABLE 1. OPTICAL-FIBRE FABRICATION: COST FACTORS

deposition	draw	performance
rate	rate	quality
efficiency	preform utilization	measurements
size	coating	optical
raw materials	raw materials	mechanical
pollution treatment	breakage rate	environmental
depreciation	depreciation	

Bulk (low temperature)

The current data for mechanically shaped preforms is given in table 2. For this early stage of research and development, relatively large preforms have been reported. The 30 g min^{-1} deposition efficiency is the highest reported for any process and the collection efficiency is of course 100%. If the losses can be reduced, this process shows some promise for simple SM designs. It will be very difficult to use for any kind of graded SM or MM profile.

Table 2. Cost factor comparison: research and development

(RIT is rod in tube.)

cost factors	MSP	MCVD	PCVD	VAD	OVD
deposition					
rate/(g min^{-1})	30	2–7 (P-MCVD)	2–3	20 (clad)	> 20
efficiency (%)	100	high	100	moderate	moderate
size/km	100	40 (RIT)	> 300 (RIT)	160	> 160
draw					
rate/(m s^{-1})	—	> 10	—	20	> 20
performance					
loss (1300/1550)/(dB km^{-1})	1/–	—	0.6/0.3	0.35/0.20	0.35/0.20
OH (1383)/(dB km^{-1})	0.5–10+	—	1.5–2.0	< 0.2	0.3–0.6
(SM – $\Delta\lambda_0$)/nm	—	—	—	—	—
(MM – BW)/(GHz km)	—	—	—	—	> 2.5
strength/(kpsi†)	—	—	—	—	400
dimensional/μm	—	—	—	—	—

† 1 kpsi ≈ 6.895 MPa.

Plasma vapour deposition

The research and development result for deposition rate is 2–3 g min^{-1} as given in table 2, which, although it is much slower than many of the processes, does exhibit very fine profile control and flexibility. The 30 km preforms in production, as listed in table 3, use two outside tubes in a rod-in-tube approach. It has been suggested that a 300 km preform is possible by extending this to 3–4 tubes. An issue will continue to be the availability of large tubes with good mechanical strength properties and low OH content. The 2.5 GHz km MM bandwidth in production attests to the excellent profile control of the plasma process.

Table 3. Vapour deposition cost factors: production

cost factors	MSP	MCVD	PCVD	VAD	OVD
deposition					
rate/(g min^{-1})	—	0.5–1.0	1 (core)	2–3 (core) 10 (clad)	9
efficiency (%)	—	high	100	moderate	moderate
size/km	—	15–30	30 (RIT)	100	90
draw					
rate/(m s^{-1})	—	> 3	—	> 3	10
performance					
loss (1300/1550)/(dB km^{-1})	—	0.35/0.21	0.38/0.21	0.35/0.21	0.35/0.20
OH (1383)/(dB km^{-1})	—	—	0.3	—	0.3–0.6
(SM – $\Delta\lambda_0$)/nm	—	±10	±5	—	10
(MM – BW)/(GHz km)	—	1.3	2.5	1.3	> 1.6
strength/(kpsi†)	—	> 50	63	> 50	> 50
dimensional/μm	—	±2	±3	±3	±2

† 1 kpsi ≈ 6.895 MPa.

Modified chemical vapour deposition

Table 3 reports the current production deposition rate for the MCVD process as 0.5–1.0 g min^{-1} although in research as high as 7 g min^{-1} has been observed in a plasma-modified-chemical-vapour process. The 40 km preform size could presumeably be increased as

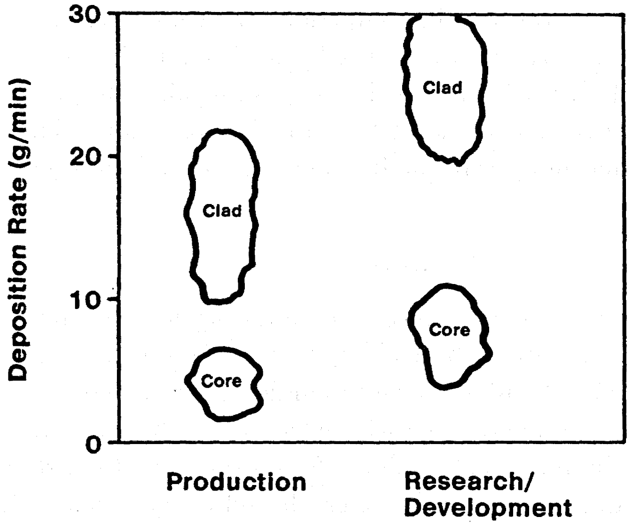

FIGURE 9. Illustration of the expected trend in deposition rate.

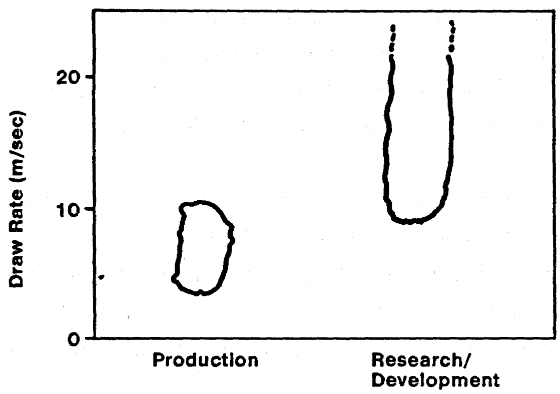

FIGURE 10. Illustration of the expected trend in draw rate.

discussed previously. Despite the relatively small blank size, the R & D draw speed at 10 m s^{-1}, given in table 2, is one of the highest reported.

Vapour axial deposition

The values reported in table 3 are for the VAD II process in which a core preform first is fabricated followed by an overcladding process. Therefore two deposition rate values are listed in the table. The 2–3 g min^{-1} for the core and 10 g min^{-1} for the cladding, are the highest reported in production. Even higher values are obtained in R & D. The largest reported preform size for production, 100 km, has been reported by Furukawa (K. Okubo, personal communication 1986). Somewhat larger preforms are reported in research and with them, a larger draw speed can be used to advantage. The value of 20 m s^{-1} is the fastest reported (Sakaguchi & Kimura 1985). State-of-the-art performance is reported both in production and research.

Outside vapour deposition

The outside vapour deposition process allows good profile control while still giving good mechanical properties because all the glass is vapour deposited. Because of the 90 km preform size listed in table 3, a 10 m s^{-1} draw rate in production can be used to advantage. Greater than 160 km and 20 m s^{-1} preform size and draw speed have been achieved in development. The extremely good mechanical properties obtained by depositing all of the glass during the process make possible the 400 kpsi screen test level for special applications. They also allow fibre lengths of 25 km whose uniform optical quality allows for a minimum measurement cost.

Summary

Although the data presented in the preceding tables depends on many factors, one can perhaps summarize the current status by looking at two of the more important cost factors: deposition rate and draw rate. By using a cloud to indicate the currently reported values, one can get a feeling for the direction and speed with which the technology still is moving. This is shown in figure 7 for deposition rate and in figure 8 for draw rate. Considering the deposition rate situation, it is noted that the values for research and development still are significantly higher than the current production values. The technology still is in a learning mode which suggests that fabrication costs and prices can still decrease. As noted in the earlier discussion, deposition rates for both core and cladding must be reported to properly account for the different processes. Similar statements can be made for draw rate, as at least a two-fold increase is still possible based on the highest reported research and development values. With increasingly larger preforms being fabricated, the technology will be able to use these higher draw speeds.

At the present time, vapour deposition processes appear to hold several advantages over bulk approaches. These include the intrinsic purity of the deposited materials, the ability to flexibly fabricate a variety of refractive index profiles, and a tremendous wealth of accumulated experience. It should be expected that persistent research on hybrid approaches, such as sol-gel tubes, which may minimize glass cost for each of the several process steps, will continue to yield promising results.

A few final points should be stated. In the future evolution of this technology, 'low-cost' and 'cheap' fibre should not be treated as synonymous. Rather, low-cost fibre is that which meets the system requirements at the lowest *installed* cost. Contained within that definition are items such as; excellent profile control to meet the information capacity requirements, superior mechanical properties to allow efficient cable fabrication, superb uniformity and product consistency, and dimensional control to facilitate fibre interconnections, all of which result in installed system advantages. To continue the current fibre economic trend, there must be a progressive increase in manufactured fibre volumes. This will encourage the major fibre manufacturers to continue to invest in and implement the technological developments necessary to optimize the installed system cost. There appears to be reason for optimism that optical communication technology will continue its noteworthy evolution.

References

Dorn, R., Baumgardner, A., Guto-Nelle, A., Koppenborg, J., Rehm, W., Schneider, R. & Schneider, S. 1988 Low-cost process for low loss single mode fibers. *Opt. Fiber Commun. Conf.*, New Orleans, paper PD6.

Hunlich, T., Bauch, H., Kersten, R. T., Paquet, V. & Weidmann, G. F. 1981 Fiber preform fabrication using plasma technology: a review. *J. Opt. Commun.* **8**, 122.

Keck, D. B. & Schultz, P. C. 1970 U.S. Patent no. 3 711 262.

Lydtin, H. 1986 A technique suitable for large-scale fabrication of optical fibers. *J. Lightwave Technol.* **4**, 1034.
MacChesney, J. B. 1988 Optical fiber fabrication by the sol-gel method: recent advances. *Opt. Fiber Commun. Conf.*, New Orleans, paper TUB1.
Murata, H. 1986 Recent developments in vapor phase axial deposition. *J. Lightwave Technol.* **4**, 1026.
Nagel, S., MacChesney, J. B. & Walker, K. L. 1985 Modified chemical vapor deposition in optical fiber communication (ed. T. Li), vol. 1, pp. 1–64. New York: Academic.
Sakaguchi, S. & Kimura, T. 1985 A 1200-m/min speed drawing of optical fibers with pressurized coating. *Opt. Fiber Commun. Conf.*, San Diego, paper MG2.
VanDewoestine, R. V. & Morrow, A. J. 1986 Developments in optical waveguide fabrication by the outside vapor deposition process. *J. Lightwave Technol.* **4**, 1020.

Discussion

J. E. Midwinter, F.Eng., F.R.S. (*UCL, London, U.K.*). Is there a strategic issue in high-volume fibre manufacture related to the availability of important materials such as GeO_2?

D. B. Keck. Many studies regarding the materials availability issue have been undertaken during the evolution of this technology. At present I know of no serious materials supply concern which exists.

M. R. Taylor (*Telephone Cables Ltd, U.K.*). Is there any technical reason for retaining a fibre cladding diameter of 125 μm and if not, are there any useful cost savings to be made by moving to a smaller diameter?

D. B. Keck. As people who have worked on fibre design know, there are a host of trade-offs which must be balanced against one another. Specifically with regard to the outside fibre diameter, there are indeed technical trade-offs. They are different for multimode and single-mode fibre; as for example with tunnelling losses. They depend upon cabling and deployment conditions as for example with microbending losses. They are impacted by the ancillary interconnecting technology. In addition, there are subjective issues surrounding the choice of fibre diameter such as ease of handling. All of these will affect the total cost-to-the-system perhaps as much or more than the fibre size impacts the direct cost of the fibre. At the present time, the technology has given the answer that there are no useful savings to be made. This question, however, really is impossible to answer in the simple way implied by its phrasing.

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