

## New generation of dispersion-flattened single-mode fibers

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Dedicated to Dr. H. J. Klein on the occasion of his 65th birthday

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For the first time a dispersion-flattened single-mode fiber has been manufactured which has chromatic dispersion zeros both at wavelengths of 1.3 and 1.55  $\mu\text{m}$ . Present standard-type single-mode fibers are designed for either of these wavelengths and the new fiber is compatible to both of them. In contrast to other fiber refractive index profile optimization routines a new theory for continuous profiles has been used for the fiber design. Thus, interesting and important modifications of the conventional structures of dispersion-flattened single-mode fibers have been developed. For the profile realization a method is required which allows for the continuous variation of the refractive index over the fiber cross section. With the plasma impulse chemical vapor deposition a satisfactory reproduction of the theoretical proposals is possible. Various fibers have been manufactured which showed exactly the intended chromatic dispersion. These fibers were called CP<sup>2</sup> (compatible, continuous profile).

### Neue Generation breitbandig dispersionsarmer Monomodefasern

Zum ersten Mal ist eine breitbandig dispersionsarme Faser hergestellt worden, deren chromatische Dispersion Nullstellen sowohl bei 1,3 als auch bei 1,55  $\mu\text{m}$  aufweist. Die derzeitigen Standardtypen sind für jeweils eine dieser Wellenlängen ausgelegt, und die neue Faser ist mit beiden kompatibel.

Im Gegensatz zu anderen Optimierungsverfahren der Brechzahlprofile für Glasfasern wurde bei der Konzeption dieser Faser eine neue Theorie für kontinuierliche Profile verwendet. Auf diese Weise sind interessante und wichtige Modifikationen der üblichen Strukturen breitbandig dispersionsarmer Monomodefasern entwickelt worden.

Für die Fertigung des Profils ist ein Verfahren erforderlich, das eine kontinuierliche Veränderung des Brechungsindex über den Faserquerschnitt erlaubt. Mit dem „Plasma Impulse Chemical Vapor Deposition“-Verfahren ist eine befriedigende Reproduktion der theoretischen Vorgaben möglich. Eine Reihe von Fasern ist hergestellt worden, die exakt die gewünschte chromatische Dispersion aufwies. Diese Fasern wurden CP<sup>2</sup> genannt (compatible, continuous profile).

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### 1. Introduction

After the breakthrough in the early 70's both multi-mode and single-mode fibers are now well established for applications in fiberoptic transmission systems. Besides the progress in the field of optoelectronic devices the improvement of existing as well as the development of new fiber fabrication techniques enlarged the possibilities with respect to fiber design and fiber properties. As far as the fiber is concerned the fundamental limitations for fiberoptic signal transmission systems are spectral attenuation and chromatic dispersion characteristics of the fiber used.

The measured values of spectral attenuation and chromatic dispersion of today's single-mode fibers at a wavelength of 1.3  $\mu\text{m}$  already are close to the theoretical limitations.

In comparison to that the tailoring and manufacturing of single-mode fibers for applications in the longer wavelength region between 1.3 and 1.55  $\mu\text{m}$  are much more complicated. For example in order to influence the chromatic dispersion characteristics the design and realization of an extremely complex

refractive index structure consisting of the fiber core surrounded by several claddings with varying dopants is necessary. Because of the contemporary dependence of other important fiber parameters on the refractive index profile the realization of such a fiber requires an excellent understanding of the fundamentals of waveguide propagation characteristics as well as a high-tech fabrication method with greatest flexibility.

In the present paper a numerical method is presented that takes into account the highly sophisticated possibilities of the PICVD (Plasma Impulse Chemical Vapor Deposition) technology in order to produce single-mode fibers with optimized characteristics for the wavelength region between 1.3 and 1.55  $\mu\text{m}$ . This technique – an inside-tube deposition process for preform fabrication – was developed by SCHOTT and patented world-wide. Details will be described in section 3.

### 2. Theory

Besides single-mode fibers designed for broad-band performance (i.e. chromatic dispersion zero) at 1.3  $\mu\text{m}$  there are also dispersion-shifted fibers suited

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for 1.55  $\mu\text{m}$  [1]. Recently efforts have been made to use the whole wavelength range around 1.28 to 1.6  $\mu\text{m}$  by so-called Dispersion-Flattened Single-Mode fibers (DFSM) [2].

However, no such fiber has been proposed theoretically nor realized in practice, which has dispersion zeros exactly at both 1.3 and 1.55  $\mu\text{m}$ . Such a fiber would be compatible to both standard-type fibers used today for optical transmission systems. Many attempts have been made for fiber synthesis starting with various core structures (step-index, Gaussian, triangular etc.) and a number of claddings following. However, all these designs did not meet the requirements.

Therefore, this paper starts with the most general theoretical model possible: a quasi-continuous profile of the refractive index consisting of hundreds of circular layers. The mathematical procedure has already been presented elsewhere [3]. Here, only a short summary is given. The following considerations are based on the assumption that the fiber will be a weakly guiding one [4]. Then the modes are linear-polarized (and therefore named LP modes) and both the electric and the magnetic fields are proportional to a scalar wave function  $\psi$ . For a circular fiber and a given wavelength

$$\psi(r, \varphi, z) = E(r) \cdot e^{\pm i l \varphi} \cdot e^{i \beta z} \quad (1)$$

is obtained, where  $z$  is the direction of wave propagation,  $\beta$  the longitudinal propagation constant and  $l$  an order number describing the mode's dependence from the polar angle  $\varphi$ . In the following  $n(r, \lambda)$  describes the refractive index as a function of radius  $r$  and wavelength  $\lambda$ . The radial compound  $E(r)$  obeys the scalar wave equation:

$$\left[ \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} - \frac{l^2}{r^2} + n^2(r, \lambda) \frac{4\pi^2}{\lambda^2} - \beta^2 \right] E(r) = 0. \quad (2)$$

As  $E(r)$  has to meet certain boundary conditions, special values of  $\beta$  are allowed only. The LP modes are indexed ( $\text{LP}_{lk}$ ) after the order number  $l$  and the number of radial nodes of  $E(r)$  ( $= k-1$ ).

All the physical properties discussed here are related either to  $\beta$  or  $E(r)$  (or both). The chromatic dispersion  $c(\lambda)$  is defined as the derivative of the group delay time  $d\beta/d\omega$  with respect to the wavelength  $\lambda$ .  $\omega$  is the angular frequency.

$$c(\lambda) = d/d\lambda \, d\beta/d\omega. \quad (3)$$

The leaky mode attenuation (which has to be kept below a certain level for the fundamental mode and above another one for all guided higher-order modes to make the fiber effectively single-moded) can be derived from the loss per length  $L$ . The latter is given by [5]:

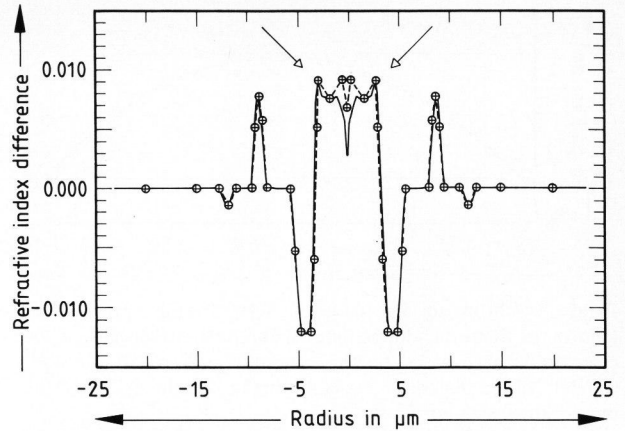


Figure 1. Refractive index profile (theoretical synthesis: solid line; profile measurements of the PICVD-manufactured preform: dashed line and crossed circles) of SCHOTT fiber profile VM 3.

$$L = (\sqrt{n_u^2 4\pi^2/\lambda^2 - \beta^2}/2\beta) E^2(R) R / \int_0^R E^2(r) r dr. \quad (4)$$

$n_u$  is the refractive index of the fiber coating and  $R$  the overall fiber radius. The fundamental mode field diameter (which must have a certain size at least in order to allow for a reasonable coupling of light into the fiber) is simply defined as twice the 1/e-radius of  $E(r)$ .

If the derivatives of these expressions with respect to the refractive index  $n_i$  of a certain layer are known, one can proceed as follows: A simple and general starting point is chosen, for instance, a step-index fiber with homogeneous core and cladding. (This is indeed the most general starting profile, as the principle structure of a central area with higher refractive index and a peripheral one with lower refractive index is due to the nature of total reflection and cannot be altered therefore.) One calculates the chromatic dispersion etc. and compares the actual with the desired values. According to the Newton method one tries to compensate the difference in first order. This is demonstrated by example of the chromatic dispersion at a certain wavelength:

$$c(\lambda)_d - c(\lambda)_a \stackrel{!}{=} \sum_i \partial c(\lambda)/\partial n_i \cdot \Delta n_i. \quad (5)$$

In equation (5) the subscript "d" means desired, the subscript "a" actual. The vector  $(\Delta n_1, \Delta n_2, \dots)$  has to fulfill corresponding equations for the mode attenuation etc. As the number of variables  $\Delta n_i$  exceeds the number of conditions [3], there is no unique solution. The vector  $(\Delta n_1, \Delta n_2, \dots)$  is chosen with the minimal Euklidian norm.

If all the physical conditions are compatible, this procedure will converge and come up with a suitable refractive index profile.

In the following two fibers will be dealt with which have been synthesized in this way and manufactured by PICVD. The first one (VM 3, figure 1) is intended

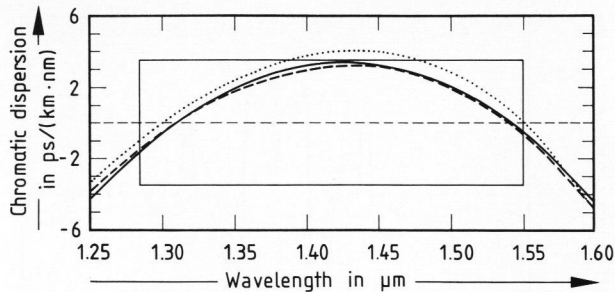


Figure 2. Chromatic dispersion of SCHOTT fiber profile VM 3 (shown in figure 1); dotted line: theoretical curve; dashed line: calculated curve based on the measured preform profile and a smaller fiber diameter than originally intended; solid line: measured dispersion of the fiber.

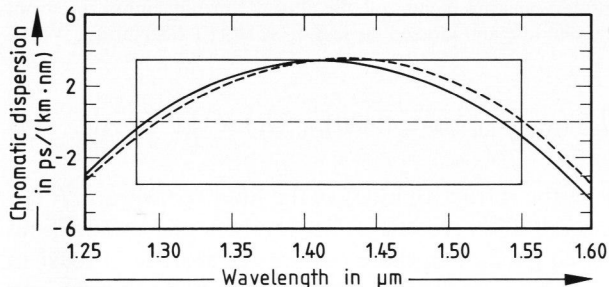


Figure 4. Chromatic dispersion of SCHOTT fiber profile VM 6 (see figure 3); dotted line: theoretical curve; solid line: measured dispersion of the fiber.

to have zero dispersion at 1.3 and 1.55  $\mu\text{m}$  and a maximal dispersion value of 4  $\text{ps}/(\text{km} \cdot \text{nm})$  between these two wavelengths. The  $1/e$ -diameter of the mode field should be 6  $\mu\text{m}$ .

The leaky mode attenuation for the first higher-order modes ( $\text{LP}_{11}$  and  $\text{LP}_{02}$ ) is chosen to be above 0.01  $\text{dB}/\text{km}$  and the one for the fundamental mode ( $\text{LP}_{01}$ ) below 0.01  $\text{dB}/\text{km}$  through the whole wavelength range. The result is a continuous profile multiple-cladding fiber with the well-known (QC (= Quadrupole Clad)-like) principle sequence of a refractive index minimum and a maximum following the central core area. However, there are interesting and essential modifications: The refractive index gap between core and first cladding has been increased by the refractive index maximum at the core edge (see arrow in figure 1). Together with a steep refractive index descent at this boundary it is responsible for shifting the chromatic dispersion to zero at 1.3  $\mu\text{m}$ . Using standard step-like QC structures this value normally is negative [2]. The synthesis has also come up with a trench surrounding the inner zone. Such a structure has already been discussed for confining the fundamental mode power to the center etc. [1]. The PICVD-manufactured preform (the measured profile of which is added to the theoretical one in figure 1) was drawn with a smaller diameter than used for the calculations to reduce the dispersion to 3.5  $\text{ps}/(\text{km} \cdot \text{nm})$  anywhere between 1.28 and 1.55  $\mu\text{m}$ . An excellent agreement between theory and

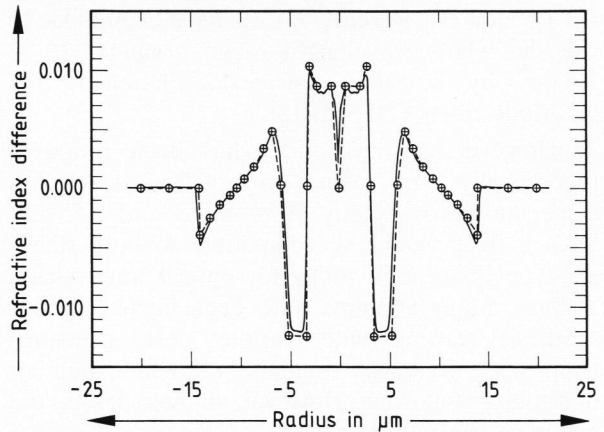


Figure 3. Refractive index profile (theoretical synthesis: solid line; profile measurements of the PICVD-manufactured preform: dashed line and crossed circles) of SCHOTT fiber profile VM 6.

experiment (figure 2) can be seen. However, the bending effect on the fundamental mode had been underestimated and the one on the higher-order modes had been overestimated. Therefore, the fiber is not effectively single-mode below 1.35  $\mu\text{m}$  and is too bending-sensitive at longer wavelengths.

Further profile optimization leads to the fiber VM 6 (figure 3: theoretically calculated and PICVD-manufactured preform profile). Its effective cut-off occurs at 1.25  $\mu\text{m}$  and a loop with a radius of 2 cm results in an excess loss of 0.05  $\text{dB}/\text{km}$  at 1.6  $\mu\text{m}$  for the fundamental mode. Its chromatic dispersion (theory and measurement: figure 4) is intended to have zeros at 1.3 and 1.55  $\mu\text{m}$  and a maximum value of 3.5  $\text{ps}/(\text{km} \cdot \text{nm})$ . From figure 4 it can be seen that the realization has almost met the theoretical result. The remaining difference can be explained by manufacturing tolerances.

Corresponding calculations have shown that the refractive index of the first minimum almost exclusively affects the chromatic dispersion at 1.3  $\mu\text{m}$ . On the other hand, a smaller drawing diameter for the preform has a stronger influence on the chromatic dispersion at 1.55  $\mu\text{m}$ . It has been made use of these antagonistic mechanisms in order to move the dispersion into the window given in figure 4.

### 3. Introduction to PICVD

Corresponding to the theoretical predictions different types of DFSM fibers with continuously shaped refractive index profiles have been prepared with PICVD. This process is a low-pressure inside deposition process. At an absolute pressure of 1 to 3 mbar a plasma discharge is generated within a silica tube. A microwave pulse of 2.45 GHz generated by a magnetron is fed to one end of the tube, building up the plasma and initiating the chemical reactions.  $\text{SiO}_2$  and dopants are deposited in molecular layers at the wall inside the tube. The repetition rate of the pulse is

approximately 100 Hz. Precursors for the process are  $\text{SiCl}_4$ ,  $\text{GeCl}_4$ ,  $\text{CCl}_2\text{F}_2$  and as reaction gas  $\text{O}_2$ . A more detailed description of the process and of the experimental setup are given in [6].

Because of the molecular thickness of the layers approximately  $2 \cdot 10^6$  layers are deposited for the fabrication of a preform. Therefore, the PICVD process especially is suited for the fabrication of smooth, continuously shaped and complex refractive index structures. Typical for the DFSM profiles developed by SCHOTT is – besides the multiple cladding structure – a fine structuring of the core.

The profiles shown in figures 1 and 3 are realized by continuous variation of the doping gases during the PICVD process. To profile the fine structure of the core the dimensions have to be chosen large enough to minimize diffusion effects during collapsing. Because of the steep gradient in the refractive index between core and first cladding especially diffusion of fluorine occurs into the core. The dip in the middle of the core is also caused by diffusion. It can be minimized by etching before the last collapse step, but it cannot be avoided completely. Both effects have the consequence that the core diameter within the preform had to be greater than 1 mm to realize the fine structure of the core. As already known from standard single-mode fibers, the ratio between deposited cladding and core diameter must be large enough to avoid bending losses for the fundamental mode.

A deposition rate of about 0.2 g/min and a deposition length of about 40 cm are achieved at the moment with the laboratory equipment. Therefore, the fiber losses have not been optimized and the core to cladding ratio has been limited to 1 : 3.5. But in spite of such restriction losses are achieved as shown in the attenuation curve (figure 5) measured at a fiber of profile VM 6.

The DFSM fiber shown in figure 3 has a profile which is continuously shaped on the whole cross-section of deposited material. Due to the low doping concentration in the outer cladding a careful design of the gas supply and control system is necessary. The realized profiles demonstrate that with the PICVD process and optimized technology parameters arbitrary complex index profiles can be produced reproducibly.

#### 4. Conclusion

It has been shown both theoretically and experimentally that dispersion-flattened single-mode fibers with

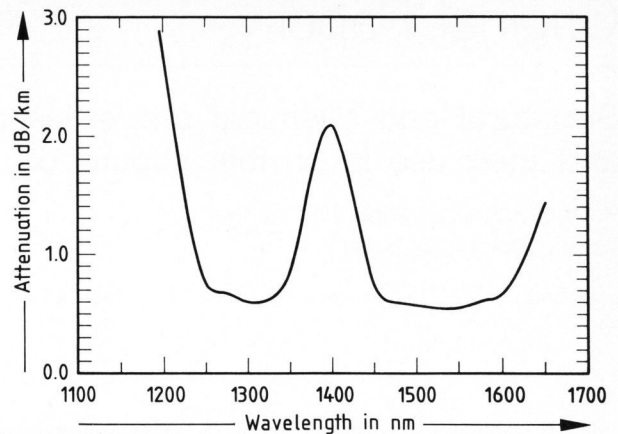


Figure 5. Attenuation measured at a SCHOTT fiber with profile VM 6 (see figure 3).

zero dispersion at 1.3 and 1.55  $\mu\text{m}$  are reality. These fibers are compatible with conventional standard (i.e., 1.3  $\mu\text{m}$ ) and dispersion-shifted (i.e., 1.55  $\mu\text{m}$ ) single-mode fibers and – because of the continuous profile – they are called CP<sup>2</sup>. These PICVD-manufactured fibers also exhibit good bending performance etc. so that they are ready for use in broad-band communication systems.

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#### 5. References

- [1] Reed, W.; Cohen, L.; Shang, H.: Tailoring optical characteristics of dispersion-shifted lightguides for applications near 1.55  $\mu\text{m}$ . *AT&T Tech. J.* **65** (1986) no. 5, p. 105–122.
- [2] Bachmann, P.; Leers, D.; Wehr, H. et al.: Dispersion-flattened single-mode fibers prepared with PCVD: performance, limitations, design optimisation. *J. Lightwave Technol.* **4** (1986) p. 858–863.
- [3] Fotheringham, U.: Dispersion-flattened single-mode fibers with minimised dopant expenditure. *Electron. Lett.* **24** (1988) no. 13, p. 801–803.
- [4] Snyder, A.; Love, J.: *Optical waveguide theory*. London, New York: Chapman and Hall 1983.
- [5] Fotheringham, U.: Attenuation of modes in multiple-cladding single-mode fibers. *J. Opt. Commun.* (In prep.)
- [6] Bauch, H.; Krause, D.; Kersten, R. et al.: Chemical vapour deposition in microwave produced plasmas for fiber preforms. *J. Opt. Commun.* **8** (1987) no. 4, p. 130–135.

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