Fibre Lasers

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Introduction

One of the requirements of an optical fibre amplifier or laser is that it should have a high absorption at the pump wavelength and a very low loss at the laser wavelength. Conventionally, this has been achieved by using a high dopant concentration in a short length of neodymium-doped compound-glass[1] or silica[2] fibre. However, an attractive alternative approach is to use lower dopant levels and thus exploit the long interaction lengths and very low losses inherent in communications-grade optical fibres.

We report here a novel extension of the MCVD fabrication process which allows the fabrication of both mono- and multimode optical fibres containing rare-earth ions at concentrations of up to 0·25 wt% in the core region. The technique is unique in that it allows the use of starting materials, e.g. rareearth halides, which have a high melting point (>580°C) and hence have hitherto been unusable, since they exhibit a very low vapour pressure at the temperatures commonly encountered in reactant delivery systems for optical fibre fabrication.

Initial work has concentrated on the lanthanide series as dopants, particularly neodymium and erbium, as these are of interest for both sensors and lasers. We have produced fibres with very high-loss absorption bands (>3000 dB/km) in the visible and near infra-red regions, while maintaining the characteristic low loss (<2 dB/km) of the MCVD fabrication process in the 'second window' for optical communications (1300 nm). The technique may also be used to incorporate many other rare-earth and transition metals into optical fibres.

Fibre fabrication

The fibre preform is fabricated using the MCVD technique, with a number of important modifications to permit the incorporation of further dopants into the core glass. Prior to deposition, a conventional deposition tube is prepared by inserting the required dopant - for example, $NdCl_3 6H_2O$ (99·9% pure, melting point = 758°C) - into a dopant carrier chamber (Fig. 1), where it is dehydrated by heating under a chlorine atmosphere. This step also fuses the anhydrous $NdCl_3$ crystals to the chamber wall, thus preventing them from passing down the tube and forming bubbles in the glass subsequently deposited. The inside of the deposition tube is then cleaned by gas-phase etching using SF_6 to remove any dopant deposited during the drying process, following which the cladding glass is deposited in the usual manner. During the core deposition, however, the dopant carrier chamber is heated to around 1000°C by a stationary second burner to produce small quantities of $NdCl_3$ vapour. The vapour is carried downstream by the reactant flow, where it is oxidised to Nd_2O_3 in the hot zone formed by the deposition burner and incorporated into the core.

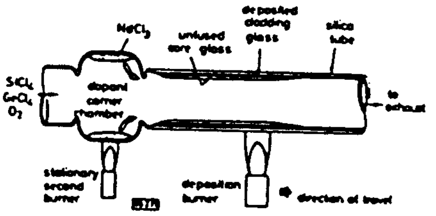

Fig. 1. MCVD process for low vapour-pressure dopanis.

Initial measurements showed that the first drying stage did not dehydrate the $NdCl_3$ sufficiently to produce low-loss fibres. Consequently, a second drying process was introduced in which the core, consisting of SiO_2, GeO_2 and a small amount of Nd_2O_3, is deposited unfused at a low temperature. The porous core layer on the inside of the deposition tube is subsequently dried by heating in a chlorine atmosphere, after which it is fused to form a clear nonporous layer. The tube is then conventionally collapsed to form a solid rod and pull into a fibre.

The process is simple to implement on existing MCVD fabrication equipment and gives reproducible fibres in terms of both refractive index profile and dopant concentration. In addition, it may be adapted to incorporate almost any dopant into the core of single- og multimode fibres.

Fibre properties

Absorption measurements on mono- and multimode fibres show that, as expected, neodymium is incorporated into the glass matrix as the trivalent Nd^{3+} ion. Fibres with absorption levels (at 590 nm) ranging from 40 dB/km to 30.000 dB/km (corresponding to dopant levels of 0·3 to 300 parts in 10^6 of Nd^{3+}) have been fabricated. The absorption spectrum for a 500 m length of neodymium-doped fibre having a dopant level of ~ 30 parts in 10^6 is shown in Fig. 2a. The very high absorption levels in the visible and near infrared regions of up to 3000 dB/km can be clearly seen. Despite this high loss, it is remarkable to observe the existence of a low-loss window between 950 and 1350 nm of <2 dB/km, a figure not very different from that observed in conventional fibres. Moreover, we believe the small excess loss is due to increased scattering in the fibre, rather than to the absorption band tails. The low OH^- absorption peak at 1390 nm indicates the success of the techniques used to dry the neodymium compounds, both before and during the deposition.

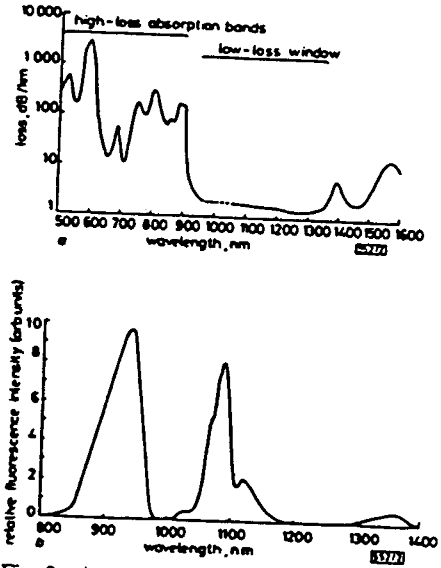

Fig. 2. a) Absorption spectrum of fibre containing ~ *30 parts in* 10^6 *Nd^{3+}. b) Fluorescense spectrum of fibre containing ~ 300 parts in* 10^6 *Nd^{3+}.*

The fluorescence spectrum of a fibre doped with 300 parts in 10^6 Nd^{3+} is shown in Fig. 2b, where broad fluorescence bands with peak wavelengths of 940, 1080 and 1370 nm can be clearly seen. As a result of the high-silica host glass, the bands are shifted to slightly longer wavelengths than the corresponding bands in compound glasses used for conventional lasers. Measurements of the 1/e fluorescence lifetime using a 590 nm pump wavelength gave a figure of 450 μs for both the 940 and 1080 transitions. This is in good agreement with previously published data for bulk silica host material[3]. In addition, the consistency of the dopant incorporation along the fibre length has been checked by measuring the local attenuation along the fibre length using an OTDR technique.

Laser raction

We present here some results on single-mode Nd^{3+}-doped fibre lasers employing low-loss fibres having very small dopant concentrations. The low Nd^{3+} content has followed the construction of long laser devices in an end-pumped configuration, using both Fabry-Perot and ring-cavity resonators. The high-reflectivity Fabry-Perot cavity has given a threshold as low as 100 μW of absorbed power from a diode laser pump. In this case, stable CW operation of a few microwatts output was observed at a wavelength of 1·088 μm, a shift of 30 nm from conventional Nd:glass lasers. Previously reported neodymium fibre lasers have either been pulsed[4] or multimode[5].

An all-fibre neodymium-doped ring cavity laser has also been constructed. To our knowledge, this is the first to be demonstrated. When pumped with a dye laser at 595 nm, the output from one port was 2mW for approximately 20 mW absorbed in the ring, with a threshold of a few milliwatts.

The fibre used in the experiments described below had a GeO_2/SiO_2 core doped with ~ 300 parts in 10^6 of Nd^{3+}, a cutoff wavelenght of 1 μm and an index difference of 1%. The loss at the lasing wavelength (1·088 μm) is less than 4 dB/km. This enables the construction of lasers up to hundreds of metres long, with a doping level selected sufficiently low to give a commensurate pump absorption length. Other parameters of the fibre were: 3·5 μm core diameter, NA of 0·21, length of 3·2 m and a total absorption at the pump wavelength of 97% (corresponding to 300 parts in 10^6 Nd^{3+} content). The fibre ends were cleaved and butted to dielectric mirrors. The input mirror had a high transmission (T = 85%) at the pump wavelength and a high reflectivity (R = 99·8%) at the lasing wavelength. In order to couple out maximum power it was found that, of the mirrors available, the optimum output mirror transmission was approximately 65%. The experimental configuration is shown in Fig. 3.

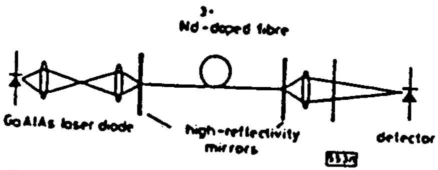

Fig. 3. Experimental arrangement for diode-pumped fibre Fabry-Perot cavity laser.

The pump source used was a single-mode GaAlAs laser (Hitachi HLP 1400), the light being launched into the fibre by microscope objectives with an efficiency of approximately 25%. The output power was measured using an InGaAs detector, and the lasing characteristic is shown in Fig. 4. The threshold for lasing action was 2·6 mW in this experiment and a slope efficiency of 33% was obtained, indicating that these devices are very efficient sources. There was no evidence of saturation at the highest pump power available (5·6 mW absorbed). This is the largest reported CW output power obtained from a single-mode silica fibre laser using a semiconductor diode pump source.

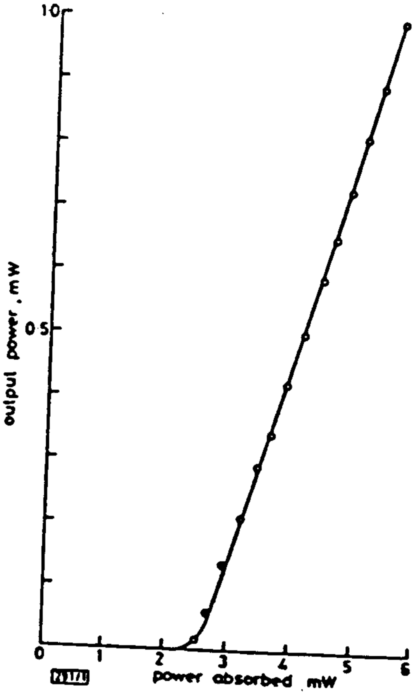

Fig. 4. CW lasing characteristic of Nd^{3+}-doped single-mode fibre laser pumped by a Ga AlAs laser diode.

In Physics Department, University of Southampton, Hanna's group[6] have performed experiments with these fibre lasers, too. In the followinghh the expelriments with q-switching and mode locking will be described.

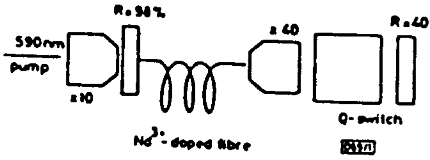

Fig. 5. Experimental arrangement used to demonstrate Q-switched operation of an Nd^{3+}-doped fibre laser.

In this case the laser system was designed to allow the insertion of a Q-switch into the cavity while maintaining low cavity losses and efficient pumping. This resulted in the arrangement shown in Fig. 5.

The active medium was an Nd^{3+}-doped single-mode optical fibre of length 2·3 m over which the continuous-wave dye laser pump light at 590 nm was totally absorbed. The high reflector (R ≈ 98%) was butted against the cleaved fibre end, and launching of the pump laser into the fibre was achieved through this reflector using a 10 x microscope objective. The very low optical losses incurred with this configuration allowed an output coupler of 40% transmission to be used with an intracavity microscope objective (40 x) to provide a collimated beam at the output mirror. The Q-switch, an Isomet 1205C-1 acousto-optic modulator, was inserted into the cavity between the miscroscope objective and output couplet, an arrangement in which the pumping rate is not affected by the Q-switch losses. The monomode fibre ensured that the output beam was a pure TEM_{00} mode.

The RF power was applied to the modulator in the form of a square wave, producing an estimated 40% modulation in the single-pass transmission. The laser output in each low-loss half-cycle consisted of a large spike followed by several smaller spikes and then continuous-wave action. During the low Q cycle of the modulator the laser was below threshold. By altering the duty cycle to shorten the high Q period relative to the low Q period, all laser output af-

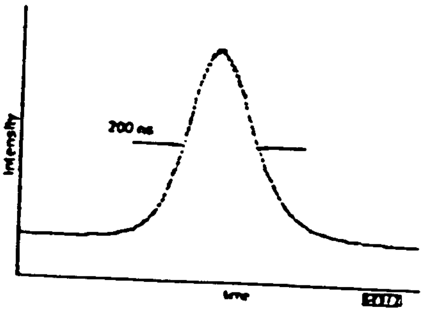

Fig. 6. Profile of 1·08 μm pulse obtained in Q-switched operation.

ter the initial large spike in each cycle could be suppressed, with a corresponding increase in peak power. Fig. 6 shows a typical output pulse obtained for a 100 Hz repetition rate and a high Q period of 5 μs. A peak power of approximately 8.8 W was achieved in a pulse of 200 ns duration. This pulse duration is in good agreement with the calculated value. The fibre laser operated in Q-switched mode for a day or more continuously with negligible long-term variation of the pulse shape.

We also investigated the effect of replacing the moculator in the cavity by an ordinary optical chopper wheel. Remarkably, we found that, in spite of the slow switch-on time of the chopper, which was 10 μs or a few hundred cavity round-trip times, peak powers approaching half those given by the acousto-optic modulator, whose switch-on time was a few nanoseconds, could be achieved. Fig. 7 shows a typical pulse of 4 W peak power and 450 ns duration obtained in this way. Multiple subsidiare pulses followed the initial pulse and could not readily be eliminated, but the experimental simplicity of this technique, which has no associated problems of alignment and cavity loss, makes it attractive.

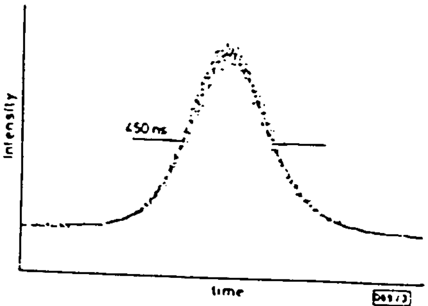

Fig. 7. Profile of 1·08 μm pulse obtained by Q-switching with optical chopper.

In the experiment with a mode locked fibre laser the active medium was a 2 m length of Nd^{3+} -doped low-loss fibre (which was monomode at about 1 μm). The pump laser was a continuous-wave rhodamine 6 G dye laser operating at 590 nm which was launched through a butted high reflector (R ≈ 98·5% at 1·08 μm). An acousto-optic rhomb mode-locker (Crystal Technology) with Brewster-angled surfaces was inserted between the intravacity 10 x microscope objective and output coupler (R ≈ 70%). Since the fibre was not polarisationpreserving, two A/4 plates were used to convert the elliptically polarised output from the fibre into vertically polarised radiation and so reduce the reflection loss of the Brewster surfaces.

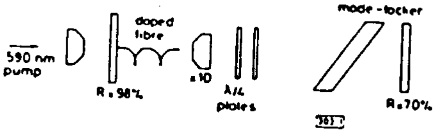

Fig. 8. Cavity arrangement.

When radio-frequency power was applied to the transducer on the mode-locker, an acoustic standing wave was set up in the rhomb. This produced a time-varying refractive index grating and caused Bragg diffraction of the incident 1·08 μm laser beam, thereby effecting cavity loss modulation. Since the resonances of the high-Q transducer were highly temperature dependent, it was found necessary to mount the mode-locker in a temperature-stabilised enclosure.

The output coupler was mounted on a translation stage so that the frequency difference between longitudinal cavity mode beats could be matched to the loss modulation frequency. Simultaneous Q-switching and mode-locking was achieved by also inserting a mechanical chopper wheel between the modulator and intracavity microscope objective.

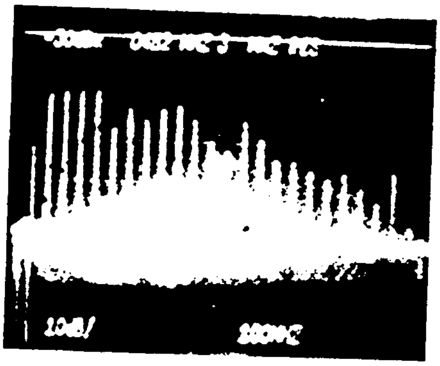

Fig. 9. Comb of modes.

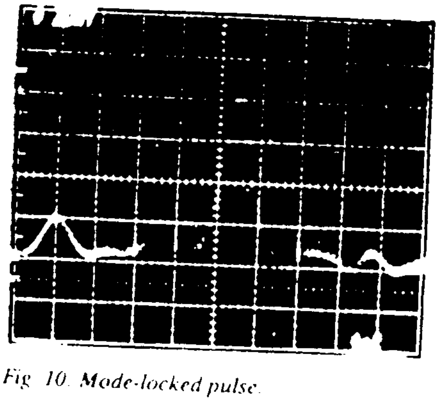

Fig. 10. Mode-locked pulse.

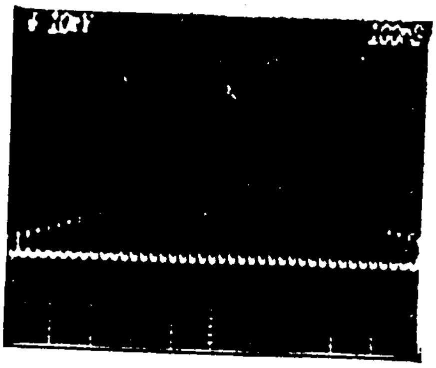

Fig. 11. Q-switched and mode-locked train of pulses.

The laser output was detected by a Ge photodiode and the amplified photocurrent fed into a Tektronix 7L14 RF spectrum analyser. With no RF power applied to the mode-locker the laser output contained weak longitudinal cavity mode beats. When RF at 20·723 MHz was applied to the modelocker and the cavity length was adjusted to match the loss modulation frequency, the beats became stronger and narrower. Eventually higher harmonics appeared and dramatically increased in intensity as the RF power was increased. The RF spectrum (Fig. 9) shows the comb of modes obtained with 250 mW of RF power applied to the mode-locker. The high frequency roll-off is due to the bandwidth of the amplifier and detector.

The laser output was then studied in the time domain using a fast detector (RCA CA309709E, FWHM resolution of ~ 60 ps) and oscilloscope (Tektronix 7A19 amplifier in a 7904 mainframe). The laser output consisted of a train of short pulses with a repetition rate corresponding to the cavity round-trip time. The pulse shown in Fig. 10 has an FWHM of less than 1 ns, limited by the 400 MHz bandwidth of the oscilloscope, and an energy of ~ 17 pJ. The structure around the pulse is believed to be due to etalon effects in the cavity.

With the laser mechanically Q-switched the output consisted of a train of pulses whose FWHM was less than 3 ns, inside a 690 ns envelope (Fig. 11). The energy of the largest pulse in the envelope was ~ 20 nJ. Structure was seen on the mode-locked pulses and is again believed to be due to etalon effects in the cavity. In addition, the build-up time for the Q-switching was not long enough for a steady state to be reached, and so the pulses would be longer than the CW case.

Conclusions

Efficient laser action in a single-mode Nd^{3+}-doped fibre laser using a GaAlAs diode source has been demonstrated. An output power in excess of 1 mW for 5·6 mW pump absorbed was obtained. In addition, both Q-switched operation and mode locking have been demonstrated. The present article is a summary of our work. More details can be found in Ref. 7 and 8.

References

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2) *J. Stone and C.A. Burrus*, Appl. Phys. Lett. *23*, 388 (1973).
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4) *C.F. Koester*, IEEE *QE-2*, 580 (1966).
5) *J. Stone* and *C.A. Burrus*, Appl. Opt. *13*, 1256 (1974).
6) *I.P. Alcock, A.C. Tropper, A.I. Ferguson* and *D.C. Hanna*, Electron. Lett. 22, 84 (1986) and Electron. Lett. 22, 268 (1986).
7) *L. Reekie, R.J. Mears, S.B. Poole* and *D.N. Payne*, to be published IEEE J. Lightwave Technol.
8) *S.B. Poole, D.N. Payne* and *M.E. Fermann*, Electron. Lett. *21*, 737 (1985) and *R.J. Mears, L. Reekie, S.B. Poole* and *D.N. Payne*, Electron. Lett. *21*, 738 (1985) and *I.M. Jauncey, J.T. Lin, L. Reekie* and *R.J. Mears*, Electron. Lett. *22*, 198 (1986).

DOPS-KURSER 1987

6. LYSKILDER/LASERE

Dato: torsdag den 5. februar
Tid: kl. 10.00-16.00
Sted: Aarhus Universitet
Fysisk Institut
8000 Aarhus C

7. ELEKTRO-OPTIK

Dato: torsdag den 26. februar
Tid: kl. 10.00-17.00
Sted: Aalborg Universitets Center
Fysisk Laboratorium
Pontoppidanstræde 103
9220 Aalborg Øst

8. INTEGRERET OPTIK

Dato: torsdag den 5. marts
Tid: kl. 15.00-17.00
Sted: Danmarks Tekniske Højskole
Bygning 101, mødelokale I
Anker Engelundsvej 1
2800 Lyngby

9. TEKNISK HOLOGRAFI

Dato: torsdag den 19. marts
Tid: kl. 9.00-16.00
Sted: Danmarks Tekniske Højskole
Bygning 101, mødelokale I
Anker Engelundsvej 1
2800 Lyngby

10. DETEKTORER

Dato: torsdag den 9. april
Tid: kl. 15.00-17.00
Sted: Danmarks Tekniske Højskole
Bygning 101, mødelokale I
Anker Engelundsvej 1
2800 Lyngby

11. INFRARØD TEKNOLOGI

Dato: torsdag den 30. april
Tid: kl. 15.00-17.00
Sted: Danmarks Tekniske Højskole
Bygning 101, mødelokale I
Anker Engelundsvej 1
2800 Lyngby

12. FLUORESCENS

Dato: torsdag den 21. maj
Tid: kl. 13.00-17.00
Sted: Carlsberg Forskningscenter
Gamle Carlsberg Vej 10
2500 Valby

Optiske kuriositeter

A. Hermansen, HCØ

Ved hjælp af moderne kopimaskiner kan man fremstille kopier på plasticark (A4) til anvendelse ved »overhead-projektionsapparater«, som findes i ethvert auditorium.

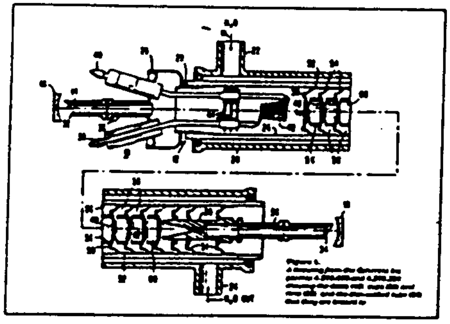
De fleste af disse plasticfolier har følgende besynderlige optiske egenskab: Lægges foliet på et vandret bord med en nogenlunde mørk baggrund og belyses foliet med diffust dagslys (fra et vindue) da vil man *for en bestemt orientering* af foliet iagttage interferensfarver, som om foliet var belagt med et tyndt gennemsigtigt olielag, hvad der imidlertid ikke kan være tilfældet, idet farverne forsvinder, når foliet drejes om sin normal (ca. 90°).

Farverne gennemløber Newtons farveskala (for to-stråleinterferens) når man flytter øjet lidt. Farvernes mætningsgrad er ringe, men forøges såfremt det diffuse dagslys passerer et dobbeltvindue og mætningen kan også forøges betydeligt, hvis himlen er blå (i stedet for overskyet).

Hvad er årsagen til disse interferensfarver?

Løsning på optisk kuriositet i DOPS-NYT 4

A. Hermansen, HCØ



Indfaldsvinklerne på »Brewstervinduerne« er på tegningen 30°, men skulle have været 55,5° (»fused quarts«). Dette vil bevirke et resonatortab fra vinduerne på ca. 20% for en dobbeltpassage, hvorimod det teoretiske vinduestab vil være nul for en indfaldsvinkel på 55,5°.

Radierne for de to resonatorhulspejle er tegnet så små, at summen af radierne er betydelig mindre end resonatorlængden d.v.s. diffraktionstabet er så stort, at laseren ikke kan virke.

Det skal dog bemærkes, at laservirkning muligvis kan finde sted med de forkerte Brewstervinkler ved anvendelse af tilstrækkelig høj strømstyrke, (og hvis resonatoren forsynes med andre hulspejle), men den stærke »udkobling« fra vinduerne, der vil finde sted i fire adskilte strålebundter vil være meget uhensigtsmæssig.

De forkert tegnede Brewstervinduer finder man iøvrigt i næsten alle afhandlinger og lærebøger om gaslasere. Det skyldes måske, at der var en forkert tegning i en af de allerførste laser-lærerbøger (B.A. Lengyel: Lasers (1962)) eller det skyldes laserfysikeres mangelfulde kendskab til Brewsters lov.

Der er ingen undskyldning for ikke at tegne Brewstervinduerne korrekt. Hvad angår de alt for korte radier for resonatorhulspejlene kan man måske undskylde sig med, at bliver radierne tegnet korrekt kan man ikke af tegningen afgøre om det er hulspejle eller planspejle.