# INVERSE PROBLEMS IN OPTICS

E. R. Pike
Chair/Editor

**Proceedings**

**SPIE Volume 808**

# Inverse Problems in Optics

**E. R. Pike**
*Chair/Editor*

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# INTRODUCTION

A number of modern problems in applied optics require a significant amount of signal processing to recover the information from the experimental data collected. The high quality of data and the virtual absence of nonphoton noise possible in many optical applications increase the need to consider carefully the potential information-transmission properties of given optical and detector arrangements so that the full benefit of these conditions may be realized. Digital photon counting is frequently employed, giving an advantageous connection with fast digital processing systems and inversion algorithms. Such information recovery in most cases necessarily suffers from the intrinsic problem of ill-conditioning, and this fact has given rise to a number of techniques designed to mitigate the problem; but such techniques are always related to questions of resolution in some general sense.

This proceedings contains papers describing recent advances and applications in these areas, including scanning microscopy, photon correlation spectroscopy, astronomy and speckle, and particle sizing by Mie scattering, Fraunhofer scattering, or extinction. The papers were presented at the Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering held in The Hague, The Netherlands, 30 March–3 April 1987.

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King's College London and Royal Signals and Radar Establishment (UK)

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*(continued)*

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**Plenary Session**

**Optical Technology in The Netherlands**

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# PLENARY SESSION INTRODUCTION

Considering that the general theme of this symposium focuses on aspects of applied optics, we thought it appropriate to devote the plenary sessions to technological developments in, or closely related to, optics. Because optical technology today is so broad a field with too many aspects to treat within the framework of the plenary sessions, we elected to highlight some major optical technologies in the host nation, The Netherlands. Although many technologies of The Netherlands, such as infrared imaging, laser vacuum deposition, integrated optics, and optical communication remain uncovered in the plenary lectures, they do address several important developments in industrial as well as in academic institutions. Two of the four plenary papers are included in this Proceedings.

In recent years, the financing of academic research in The Netherlands underwent drastic change when ongoing individual investigations were grouped into projects that required a positive judgment in order to obtain financial support ("conditional financing"). In addition, university groups gained the option to do contract research for external bodies, industry, etc. For many research groups, this both heightened their interest in technological work and widened the potential fields for their research and development activities. In addition, this new option offers new and stimulating opportunities for academic/industrial cooperation, to the benefit of both groups.

Projects of considerable size, often supported by the Ministry of Economic Affairs, are in the process of being set up to provide a national framework for technological development. On an international scale, the European Economic Community offers the possibility for similar developments within programs such as Brite, Race, Esprit, etc. There, too, cooperation between academic and industrial organizations is essential. International societies can be instrumental in encouraging these interactions and it promises well that two international bodies, SPIE and the Optics Division of the European Physical Society (EPS), agreed to cooperate with the Quantoptica Foundation in organizing these plenary sessions. We salute these societies and encourage them and their counterparts to continue their support of these activities with dynamic and exciting symposia.

**Hans J. Frankena**
Delft University of Technology, The Netherlands

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# Production of Optical Fibres for Telecommunication with the PCVD process

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## Abstract

In this paper an overview is given of the PCVD process as applied for the large scale production of optical fibres for telecommunication. The specific merits and potentials of the process, such as the profile independent high deposition rate and excellent controllability are discribed. The current state of the art of the process, as it is used in the Eindhoven production unit, is a deposition rate of 1 g/min., a preform size equivalent to 28 km of fibre and a drawing speed of 4 m/s.
Fibre characteristics are well within the requirements imposed by the telecommunication market. The PCVD process has also proven to be suited for the production of dispersion flattened singlemode fibres and high NA graded index fibres for short distance applications. For both fibre types the high refractive index differences obtained with fluorine doping are exploited. Depending upon the market demands all fibre types can be manufactured at the same productivity. Some trends are given towards further increase of productivity and reduction of fibre costs.

## Introduction

The PCVD process as a fibre manufacturing process has been applied in the Philips plant in Eindhoven for several years now. During the course of these years the productivity per lathe was increased to about 25,000 km qualified fibre per year. This increase was possible without violating the resultant fibre characteristics and without fundamental changes in production techniques. The increase in productivity, not only for the PCVD process, but also for other fibre manufacturing processes like MCVD, OVD and VAD[1], has resulted in fibre prices that make the application of optical fibre systems competitive with conventional systems on copper cables. Throughout the world this has resulted in the installation of long and medium distance optical fibre cables for telecommunication systems. To make optical systems also the optimum choice in innovative applications as in broadband subscriber networks, a further reduction of fibre prices is essential, however.

In this paper the fibre manufacturing process, based on the PCVD preform making process, will be described as it is in use now in the Eindhoven Philips plant. It must be emphasized that up to 1986 the European telecommunication market, which is the main customer for the produced fibres, primarily demanded multimode fibres. Now (1987) this market is changing rapidly into singlemode fibres. So, after a development period, the Philips plant has also changed its main product type.

## PCVD preform production

In this section the PCVD process (Plasma activated Chemical Vapour Deposition), being the heart of the manufacturing process, is briefly described. The process has been developed by Philips and first described in 1976 [2,3]. The core material and part of the cladding material are deposited on the inner wall of a silica glass substrate tube. A schematic view is given in Figure 1. In the silica glass tube a non-isothermal low-pressure plasma is generated locally by microwave energy in a resonator that traverses along the tube. The energy is coupled directly into the plasma without heat transfer through the tube wall. To compensate for small rotational asymmetries in the plasma zone the tube is rotated over a small angle each time the resonator reverses its direction of movement. The resonator operates at a frequency at 2.45 GHz and moves with a speed of about 8 m/min. over a total length of 75 cm. This allows the deposition of a great number of individual compact glass layers, each with a well controlled composition, on the interior of the tube wall without any soot formation.
Germanium and fluorine doped layers, as well as pure silica glass layers are deposited from the raw materials $SiCl_4$, $GeCl_4$, $C_2F_6$ and $O_2$ supplied by the gas delivery system.
($GeO_2$ raises the refractive index, while F lowers it compared with pure silica).

The rotary pump in the pumping section keeps the pressure inside the tube at a level of about 10 Torr. The deposition efficiences are high, i.e. about 85% for $GeO_2$ and close to 100% for $SiO_2$ and fluorine. These high and constant efficiences and the high number of layers result in a good process control and in an accurate approximation of the desired index profile. Unfortunately the efficiency for the incorporation of hydrogen containing groups and other contaminants is also high. The problems caused by these incorporations can be overcome by careful processing of the tubes, choosing raw materials of high purity and the use of fluorine doping[4]. The incorporation of chlorine, one of the resultant components of the chemical reaction, must be prevented as this causes imperfections such as cracks and bubbles in the deposited layers.
This is done by depositing the layers at 1200 °C in a furnace. This temperature is not high enough for thermally induced formation of $SiO_2$ and $GeO_2$ layers. The deposition rate at this moment is 1 g/min. This deposition rate results within a 4 hours period, in a deposition thickness of about 1.7 mm inside a 22 x 26 mm tube. As the other fabrication steps are rather independent from the process that is used for manufacturing the initial preform, these are described in the next section.

## Fibre fabrication

To be able to draw a fibre from the deposited tube, this tube must be collapsed to a solid rod. This is done on a separate lathe with a traversing oxygen-hydrogen burner. The tube is mounted horizontally and rotates slowly. The use of a separate etching treatment with $C_2F_6$ during the final stage of the collapsing eliminates the central dip in the resulting fibre refractive index profile[4]. Collapsing takes about 3 hours and is done in parallel to the deposition of the following preform tube. Because of efficiency reasons as much fibre as possible is drawn from one preform. Therefore, during the PCVD preform process more core material is deposited then necessary for the substrate tube. After collapsing, the relative shortage of cladding material is compensated for by mounting the preform rod in a 20 x 29 mm jacket tube by evacuating the intermediate airgap and fusing the ends together. No additional collapsing step is applied. This rod-in-tube (RIT) preform is brought to the drawing tower where about 28 km fibre is drawn from the preform with a drawing speed of 4 m/s. A graphite resistance furnace is applied. For cooling of the pristine fibre, a helium cooler has proved to be very effective at high drawing speeds[8]. The cooled fibre is coated-in-line with two layers UV-cured acrylate coating by leading it through two forced feed coating systems. Then the fibre is wound on a large diameter foam cushioned measuring drum. Screentesting is done with a minimum strain of 0.7% during about 0.8 sec. After that, the fibre is cut in order lengths, varying form 2.2 to 8 km. In the measuring stage all relevant geometrical and transmission parameters are measured on all fibres. For multimode fibres this is done on an automated equipment, whereas for singlemode fibres a semi-automatic equipment is used. The results are stored in the central administrative operating system.

In addition to the measurements for fibre characterisation also a number of measurements and quality checks are performed to supervise the total fabrication process. These include raw material composition, tubes, gasses, coating materials, preform index profiling, in-line outer diameter and coating diameter measurements, differential mode delay for multimode fibres and dispersion measurements for singlemode fibres. The fabrication area is controlled with respect to dust, temperature and humidity. Production occurs in 5 shifts continuous operation.

## Fibre characteristics

One of the important advantages of the PCVD process is the ability to reproduce precisely the desired index profile. For multimode fibres this is reflected in the resultant fibre bandwith, as presented in Figure 2. After splicing of these fibres a low bandwidth concatenation factor is obtained[5]. This results e.g. in bandwidths as high as 400 MHz at 1300 nm for a 37 km link, enabling 560 Mbit/s system operation[6]. Although the bandwidth decreases when the operating wavelength differs from the wavelength where the fibre is optimized, the bandwidth at 850 nm for these fibres usually is high enough to meet the current market demands.

The geometrical characteristics of the fibres are well within the ranges recommended by CCITT. Concerning the production of singlemode fibres the PCVD process offers good reproducibility of those parameters wich depend on the index profile and geometry like the spotsize diameter, the cut-off wavelengths (see Figure 3) and the zero-dispersion wavelength. In Figure 4 a histogram is given for the attenuation coefficient at 1300 nm of present production. The singlemode fibres are of a depressed cladding type with fluorine doping in the inner-cladding and a germanium-fluorine co-dope in the core. High NA and/or large core multimode fibres such as the 62.5/125, NA = 0.29 fibre, have not been transferred into full production up to now, as no significant market demand exists in Europe at this time. The capability of the PCVD process to produce such a fibre has been shown in the research laboratories. Especially the use of fluorine as doping material with a small Ge codopant concentration to reduce mechanical stresses, shows many advantages.

## Future trends

In ref. 1, the state of the art of the PCVD manufacturing process in 1982 has been described. Since then progress has been made in several areas. The deposition rate and the drawing speed doubled, the introduction of the RIT-technique further increased the size of the preform whereas longer delivery lengths reduced overall measuring time.
As these improvements hardly affected cycling time, yield and fibre quality, they reduced the cost per fibre kilometer to the current competitive level. Further increase of productivity is essential, in order to keep track with the prevailing trend towards lower market prices. As for the price calculation, machine depreciation, labour and materials are important cost factors. The first two factors are reduced mainly by increasing the productivity per machine and by an automated process control. For the preform production this results in a need for higher deposition rates and larger preforms. Those preforms have to be drawn at a higher speed in order to increase drawing tower productivity. In addition, the last steps, screentesting and measuring must be made more cost effective. With respect to these points some considerations will be given below.

Ongoing research on the PCVD process has resulted in the realisation of a deposition rate of 2.5 g/min[7]. Compared with the current process larger tubes will be necessary as the inner tube diameter at the end of the deposition phase increases with deposition rate[7]. These larger preforms will impose higher requirements on the collapsing step where more energy is needed to collapse the deposited tube in the same time. To enable higher drawing speeds for the resulting bigger preforms (50 - 80 km) new fast curing coatings and optimized processes are needed. Recent developments on these points are reported in references 8 and 9 where drawing speeds higher than 10 m/s and new ultra fast curing coating materials are reported.
As for the measurements, the productivity can be increased in several ways. Measuring longer lengths and assigning the measured values to all individual fibres coming from that length, will give a first increase. Of course, the uniformity of characteristics along the length must allow this. As a second step samplewise measurements can be considered for those parameters where fabrication tolerances are well within the allowed range. Here, a better definition of allowed tolerances in terms of statistical quantities is needed. As a third step, uniformity of measuring equipment is considered.
Although the European market demand is changing now to singlemode fibre, a continuing need for multimode fires with diverse index profiles is expected. In developing automated measuring equipment the need to characterize all fibre types on the same machine is recognized. In this way the entire manufacturing process, i.e. PCVD, drawing and measuring, can be transfered from one fibre type to another without diversification of the equipment. Thus, full-capacity operation of the expensive machinery would be provided.

On the materials side, two factors are important for costs, i.e. tubes and chemicals, $GeCl_4$ in particular. Dominating reasons for the high costs of the tubes are the tight tolerances with respect to geometry and the occurance of inclusions. For both aspects it may be expected, that these tolerances will become even tighter in the coming
years. Reasons for this are the development of new singlemode fibres types, such as the disperion flattened fibre and the trend towards the drawing of longer and stronger fibres. At this moment several new tube production techniques are considered to meet these more severe conditions. The sol-gel technique, in particular, looks promising[10]. The high costs of $GeCl_4$ can be overcome to a great extend by applying fluorine doping which has proven[4] to be very effective in the PCVD process[11].

With increasing productivity, the development of new products must be taken into account too. Fortunately, the productivity of the PCVD process is rather independent of the fibre type that has to be produced, which results in a high flexibility towards changing market demands or improvements of products. With respect to this point, our target is to exploit the capability of the PCVD process for realizing a desired index profile accurately. For the current depressed cladding singlemode fibre, this implies a further profile optimization in view of the changed insights in the cut-off phenomenon and the shift to the 1550 nm transmission window. An important further step is the development of the dispersion flattened singlemode fibres. From a first reproducibility test 12 13 it has appeared worthwhile to start the development of singlemode fibres with a low total dispersion coefficient in both wavelength regions around 1300 nm and 1550 nm. Furthermore, other profiles will be considered. By flattening the dispersion curve only regionally around 1550 nm, the possibility will be offered to operate high bit rate systems with multi-longitudinal mode lasers without the necessity of temperature stabilisation. Of course these developments are influenced strongly by system developments, especially with respect to laser sources.

The total fibre capacity at the Philips plant in Eindhoven will be doubled in 1987 compared to 1986 to a level of 200.000 km/year by increasing the number of production units. Furthermore discussions are going on for installation of other fibre plants using the PCVD proces.

## Conclusions

The PCVD process as it is applied in the Philips plant in Eindhoven results in high-quality telecommunication fibres at a competitive price. The current deposition rate of 1 g/min enabled the start of large scale production but must be increased further in view of future cost reductions. The precise control of the index profile has resulted in the manufacturing of high-bandwidth multimode fibres, asked for by the European market for application in long-distance medium bit rate digital transmission links. Now a shift towards singlemode fibres is going on. Within the recommendations made by CCITT, several index profiles are possible for 1300 and 1550 nm optimized singlemode fibres. Due to the potential of the PCVD process for high fluorine dopant concentration and precise index control, these index profiles can be transferred to production when the market demands increase. The same arguments are also valid with respect to the production of high NA fibres for application in local area networks. Further increase of productivity of each manufacturing step will be realized in the coming years by increasing the deposition rate and the drawing speed and by reduction of the number of measurements. These improvements can be obtained independent from the fibre type which guarantees optimal process flexibility.

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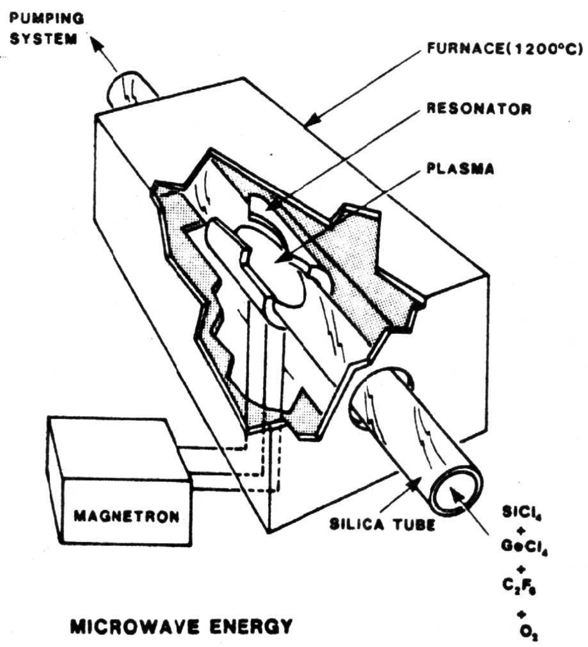


Figure 1. Schematic view of the PCVD process.

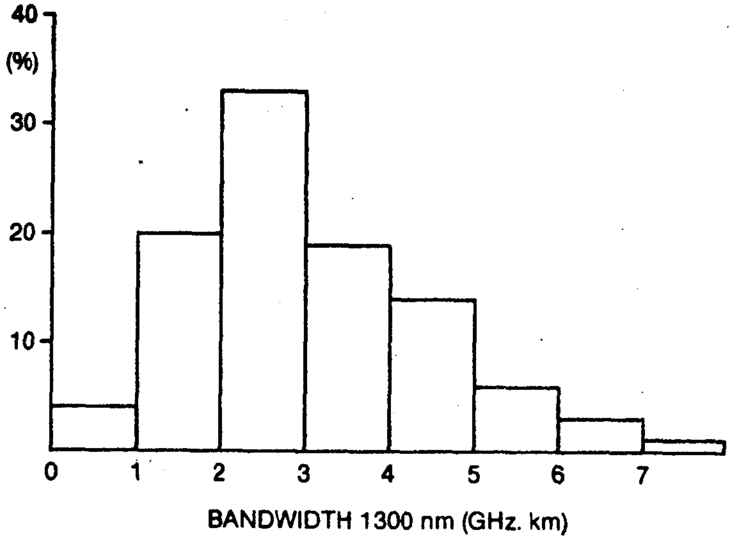


Figure 2. Bandwidth distribution at 1300 nm of present multimode fibre production (referred linearly to 1 km).

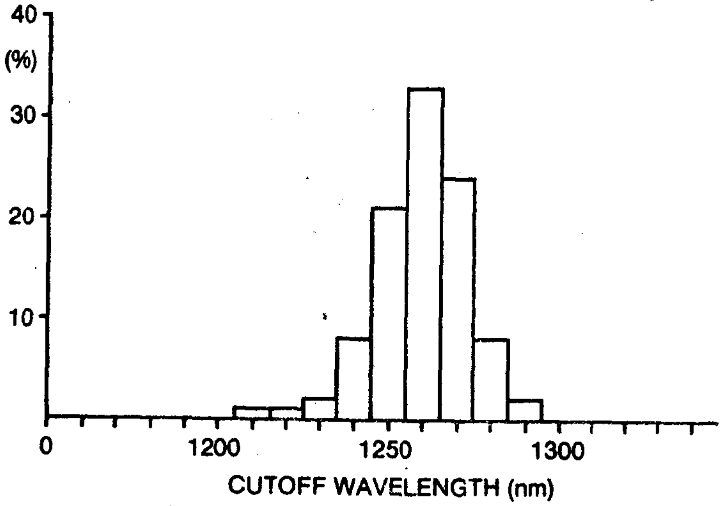


Figure 3. Cutoff wavelength distribution of present singlemode fibre production.

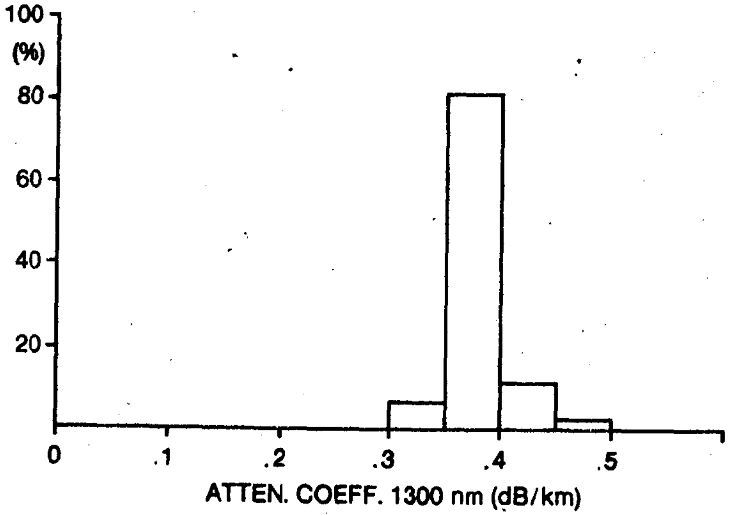


Figure 4. Attenuation coefficient distribution at 1300 nm of present singlemode fibre production.

# High power pulsed gas lasers

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Gas lasers have shown to be capable of delivering tens of terrawatt aspeak power or tens of kilowatt as average power. The efficiencies of most high power gas lasers are relatively high compared with other types of lasers. For instance molecular lasers, oscillating on low lying vibrational levels, and excimer lasers may have intrinsic efficiencies above 10%. The wavelengths of these gas lasers cover the range from the far infrared to the ultra-violet region, say from 12000 to 193 nm. The most important properties are the scalability, optical homogeneity of the excited medium, and the relatively low price per watt of output power. The disadvantages may be the large size of the systems and the relatively narrow line width with limited tunability compared with solid state systems producing the same peak power.

High power gas lasers group into three main categories depending on the waste-heat handling capacity.

## a. Diffusion cooled systems

This are the conventional CW systems using the thermal conductivity of the gas. The input energy is obtained by the glow discharge of the so called positive column in a cylindrical tube. These systems have relatively low cooling capacity. Molecular systems like CO, $CO_2$ and $NO_2$ operating by exchanging energy between low lying vibrational-rotational energy levels are very sensitive to the gas temperature. As more power goes into the gas, its temperature rises and with this the thermal population of the lower laser level. For CO and $CO_2$ systems the maximum power is in the range of 50-100 W/m.

## b. Fast flow systems

Much higher output power can be obtained by a fast flow of the active medium. The so called gas dynamic molecular lasers, where a pre-heated gas during the acceleration to supersonic velocities is cooled to low temperatures, may reach output powers in the order of 400 kW as has been extracted from a shock tube gas dynamic laser [1]. Another more practical approach for long time operation is a flow system having a transit time in the discharge region that is much faster than the characteristic time of diffusion to the wall so that the medium is cooled convectively rather than by diffusion to the wall. The input energy and consequently the output power density is much higher than by diffusion to the wall. The performance is either by fast axial parallel or by a transversal flow perpendicular to the optical beam. In both cases the radiation production is in fact dependent on the mass flow through the optical cavity. Both principles have there merits and demerits. Axial flow allows for a symmetric discharge with respect to the optical axis so that the optical quality of the beam can be high. For large diameters, say above 30 mm the stabilization of the continuous discharge may become difficult. However, recent development have shown that for larger tube diameters, even above 10 cm, the discharge can be stabilized by earodynamic turbulance in the gas flow. The injectors are used both as anode and expansion nozzles for the turbulent flow. For these large diameters the energy is extracted by means of an unstable resonator in order to get good optical quality. Stable continuous output powers up to 20 kW have been reported [2].

## c. Pulsed systems

In the case of molecular systems like CO and $CO_2$ the heat handling problem is solved by using the heat capacity of the medium. Because the heat capacity is proportional to the density the maximum output energy per pulse is also proportional to the density. Further, since the energy transfer processes of upper and lower laser levels are determined by the speed of the relaxation processes which are proportional to the density too, the peak power will then be proportional to the square of the gas density. For the CO molecular systems the pulse energy can be as high as 100 J per liter with an efficiency up to 63% [3, 4] and for $CO_2$ the output energy is up to 40 J per liter per bar pressure [5]. Excimer and recombination lasers characterized by short life times of the upper states and small cross section for stimulated emission can only reach threshold by high excitation densities, feasible in pulsed operation. For e-beam pumped KrF and ArF operating in the UV region of the spectrum the energy density is in the range of 65 to 40 J per liter comparable to the molecular systems [6, 7]. For discharge pumped excimer lasers the efficiency and output energy density are both much smaller. For instance XeCl discharge laser reaches 10 J per liter at an efficiency of about 2%. Also recombination lasers operating in the near infrared (1-3 μm) have the potential of high output energy. An energy density of 6 J per liter with an efficiency of about 5% has been reported for an e-beam discharge system [8].

Population inversion in gas lasers can also be obtained directly from a chemical reaction. energy stored in the reactants is directly converted into stimulated emission with little or . input energy. Of the various types of chemical lasers the highest energies have been found for .. operating in the 2-5 μm region. High output energies also in the order of 100 J per liter have been obtained