Excimer lasers and their applications in industrial technology and in medicine

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1. Introduction

Many applications have been found for laser radiation both in industrial processes and medicine. Most lasers used in technology and medicine generate radiation within the infrared range (neodymium glass, YAG crystals, CO_2 lasers etc.) or the visible region (argon, krypton, ruby crystal etc.). The radiation of such a laser interacts with the material thermally. The penetration depth into the material depends directly on the wavelength of the laser beam. The precision of the laser machining, efficiency and resolution also depend on the wavelength.

The range of industrial and medical applications underwent great expansion as a result of the introduction and mastery of the production of UV radiation in highly efficient excimer lasers. Excimer lasers operate in pulse mode only. They generate nanosecond UV radiation pulses within a range of 126 nm to 351 nm. In practice, ArF (193 nm), KrF (248 nm), XeCl (308 nm) and XeF (351 nm) lasers are most frequently used. Many laser applications are determined by the energy of a single photon, which is 6.4 eV for an ArF laser, 1.2 eV for YAG:Nd and 0.1 eV for a CO_2 laser. In this paper we will explore the properties of excimer lasers, looking specifically at their use in micromachining and medical applications.

2. The properties of excimer lasers

In contrast with the properties of UV radiation, the design of excimer lasers is relatively scarce in contemporary literature. Therefore, let us devote a few lines to describe the specific properties of such lasers.

What are excimer lasers? The word "excimer" is an abbreviation of EXCIted diMER, meaning a compound of two atoms or molecules, which only produce chemical bonds in an excited state. Such molecules satisfy one of the fundamental conditions to generate laser radiation: the domination of excited molecules over non-excited ones. For excimer molecules, the inversion of level population is a normal state. A typical example of excimer molecules is found in such inert gases as He_2^*, Ne_2^*, Xe_2^*, and $NeAr^*$ or excimer composed of one atom of an inert gas and one atom belonging to the halogen group, such as ArF^*, $XeCl^*$, KrF^* or XeF^*.

The first excimer laser in the world was operated in 1970 [1]. It was an Xe_2^* laser pumped by an intense electron beam. An effective generation of UV radiation with halogenides of inert gases (KrF, XeCl) was obtained in 1975 [2]. This was achieved with a laser excited by electrical discharge. The excitation threshold was much lower than in systems based on molecules of inert gases. Since 1976, much work has gone into the development of excimer lasers. In Poland, the first succesful attempt to generate UV radiation (308 nm) from the $XeCl^*$ molecule excited by a transverse electrical discharge were made in 1985 by Professor A. Kopystyńska and, also by the present author [3].

Presently, the emitted light beam in a typical excimer laser structure transmits an energy up to a few joules in a single pulse. The duration of the pulse is about 10 ns, the peak power reaches a value of several megawatts (10^6 W). The average power reaches a value of several kilowatts (10^3 W). The repetition rate exceeds 1 kHz. One filling of the discharge chamber with mixture of working gases is enough for more than 10^{10} useful discharges. Relatively easy exchange of gas mixture in the discharge chamber of the laser ensures a possibility to generate radiation of various wavelengths. The stability of the radiation parameters is ensured by microprocessor-controlled systems [4, 5]. The remarkable similarity between the excimer laser and earlier gas lasers with electrical discharge ensures their complementary character and, therefore, easy replacement of another lasers in particular applications.

For many users in the industry, the efficiency, or the coefficiency, of transformation of electric power into laser light power is essential. The efficiency of excimer lasers is the second best among all comercial pulse systems now in use. Typical efficiency for various commercial lasers are given in Table 1.

Other important faetures of UV radiation of excimer lasers are high radiation intensity, small width of spectrum lines, low price per photon, insignificant divergence of the radiation beam and very high focusing ability. These parameters are much better than those usually obtained in classical xenon lamps. They are also higher than those obtained after multiplying the frequency of other lasers (i.e. reducing the wavelength) in non-linear crystals. Thus, in the ultraviolet region, excimer lasers are now the most efficient sources of radiation.

The following characteristics are of particular importance concerning the interaction of laser radiation:

- generated wavelength λ,
- divergence of laser beam θ,
- radiation intensity within the beam cross-section $A(r, t)$,
- polarization P,
- pulse duration τ,
- repetition rate f,
- pulse energy E_L,
- energy density E_L/S.

Let us now discuss, in brief, the most essential problems linking the above characteristics to the results from principal applications.

The wavelength of the laser radiation implies the size of diffraction spot d at the focus of the optical system is $d \sim \lambda$. The theoretical resolving power of the optical system is described by the expression $d = 0.6\lambda/NA$, where "NA" denotes the size of the numerical aperture of the optical system.

The radiation wavelength λ is closely connected with the spectral purity of the spectrum line $\Delta\lambda$. Thus, for instance, a conventional KrF^* laser [6] is characterized by spectrum line of a breadth of 0.3 nm (FWHM). An XeCl [6] laser typically generates two lines: 307.96 ± 0.017 nm and 308.21 ± 0.0335 nm. This parameter is essential for many industrial applications. For example, laser photo-litography requires radiation with a line of a width $\Delta\lambda \approx 3$ pm and a wavelength stability $\delta\lambda \approx \pm 1$ pm.

Table 1. **Energetic efficiency of different lasers**

Laser	Emission wavelength [nm]	Efficiency [%]
CO_2	10600	5.0
Excimer	248	2.9
Nd:YAG (ω_o)	1064	0.6
Nd:YAG ($2\omega_o$)	532	0.2
Nd:YAG ($3\omega_o$)	355	0.1
Ar	488/514	0.006

The efficiency of interaction of laser radiation on a material is dependent directly to the wavelength. One of the parameters characterizing the efficiency of such an action is the coefficient of absorption of the laser light by the material. Thus, for instance, for metal acted on by a light with a wavelength of 248 nm (a KrF laser) falling perpendicularly to the material surface, the coefficient of absorption is many times higher as at higher wavelengths. The coefficients of absorption of laser light for KrF, YAG:Nd and CO_2 lasers by the most popular metals are shown in Table 2.

From data contained in Table 2 we can see the differences in efficiency in the interaction with metals for typical industrial lasers with predominance of UV radiation. Similar differences in the coefficient of absorption for various wavelength appear, if the light acts on a biological tissue and water. An illustration of the differences for the most commonly used medical lasers is given in Table 3. In this case UV lasers appear to be less advantageous, particularly with the YAG:Er laser.

Of all medical applications, the most important is referred to as a cold process of action in biological tissue, which is an effect of photo-decomposition ablation [9] occuring in organic materials as a result of the absorption of high-energy photons. Typical photo-ablation is a three-stage process shown schematically in Fig. 1. In the first stage, laser radiation is absorbed in the material. Second, bonds break in large molecules in organic chains, formatting a volatile molecular fragments. In the third stage we see total absorption of the incident radiative energy in the thin ablation layer, which is thus produced. The process of photo-decomposition ablation is a threshold process, and the threshold values of the radiation energy density will be discussed in the next chapter of this paper. To end the present discussion, let us now compare the action of photons resulting in photo-ablation and the typical effects of interaction of radiation of other wavelengths with the material. This is illustrated in Fig. 2.

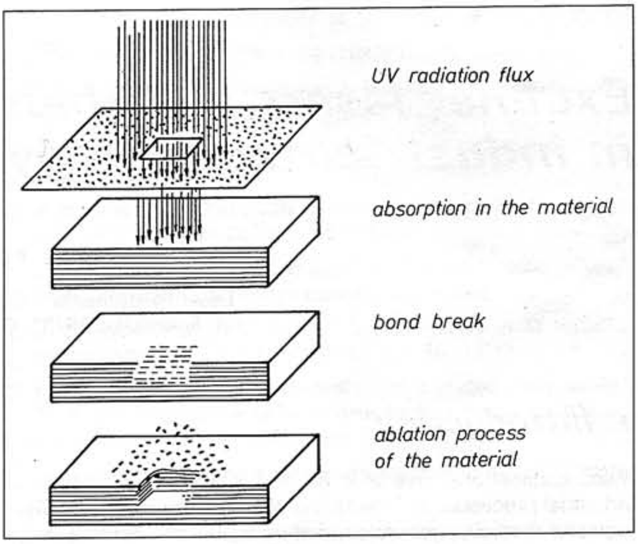


Fig. 1. Illustration of the three-stage process of laser photo-decomposition ablation

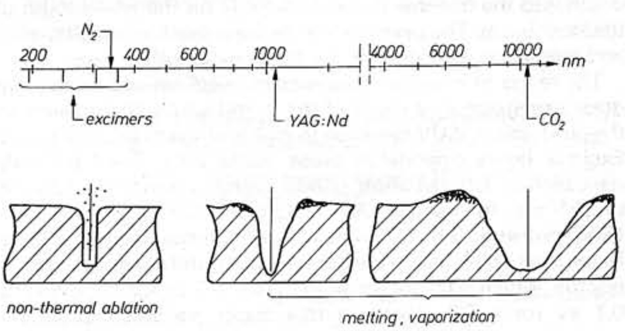


Fig. 2. Illustration of the fundamental mechanisms of interaction of the light of typical lasers [10]

The divergence of an UV radiation beam from an excimer laser depends chiefly on the optical resonator used. In the case of parallel plane mirrors of the resonator in a laser excited by transverse electrical discharge, the divergence of the laser beam is (usually) between 1 and 3 milliradians in the vertical plane, and 4 and 6 milliradians in the horizontal plane. If an unstable resonator is used with an excimer laser, the divergence may be as small as one-tenth of that of a classical resonator, and the difference between "horizontal" and "vertical" values decays. It should be stressed that if the divergence of the laser beam is the same for both resonators, the radiation energy is much higher in that laser which operates with an unstable resonator. In lasers built by Lambda Physik [8], the divergence of radiation of the beams is approximately 1 mrad. The divergence of radiation of the laser with the unstable resonator approaches one-third of a conventional laser resonator. The divergence of the radiation beam θ is important for the focusing ability d of the optical system, bearing in mind the relation $d \sim \theta$.

Table 2. **Coefficients of absorption of laser radiation. Perpendicular beam incidence on metal surface [7]**

Material	Coefficient of light absorption A [%]		
	KrF* laser (248 nm)	YAG:Nd laser (1064 nm)	CO_2 laser (10600 nm)
Aluminium	18	10	2
Iron	60	35	4
Copper	70	8	1
Molybdenum	60	42	4
Nickel	58	25	5
Silver	77	3	1

Table 3. **Coefficients of absorption of biological tissue and for various wavelengths of medical lasers**

Laser	Wavelength [nm]	Coefficient of absorption [cm^{-1}]	
		tissue	water
CO_2	10600	600	950
YAG:Er	2940	2700	4500
HF	2700	1000	1700
YAG:Nd	1320	8	1.2
YAG:Nd	1064	4	0.1
He-Ne	633	4	
YAG:Nd (2ω)	530	12	
Ar	514	14	
	488	20	
XeF	351	40	0.01
XeCl	308	200	0.1
KrF	248	600	>10.0
ArF	193	>400	>100

On the other hand, the divergence of the radiation beam and the width of the spectral generation line $\Delta\lambda$ have a very strong influence on what is termed spectral brightness (SB) of laser radiation [8] which is described by the relation:

$$SB \sim 1/(\theta \cdot \Delta\lambda)$$

The distribution of the intensity of the laser beam $A\ (r, t)$ can, in most cases, be made to approach the form of a rectangle. If there are no focusing systems, such a profile is suitable for the laser machining of material surfaces. The asymmetry of distribution of the beam in the vertical and horizontal plane makes symmetric laser machining by a focused beam impossible. Such a machining is possible only when a special beam forming system is used.

Polarization P of laser radiation is essential to the process of interaction with materials [11, 12]. In particular, a polarized beam is very important in cutting materials. In classical gas lasers, with transverse electrical discharge, the beam is not polarized, so the required polarization is forced by an external optical system [13].

The duration τ of a laser pulse of a typical excimer laser is 5 to 50 ns. The pulse width is decisive for the type of action and essentially influences the ability to guide the laser beam through an optical fiber. Detailed classification of the processes of laser interaction with material as a function of the pulse duration is given by Kreutz and Treush [14]. The results of research on the transmission of UV radiation through optical fibers for various densities of energy are presented by Sovada, Kahlert and Basting [15]. Thus, for $\lambda = 308$ nm and with a pulse of $\tau = 20$ ns, 0.6 mm diameter optical fiber can transmit no more than 10 mJ. For shorter wavelengths, the values are still lower. The dependence of the energy transmitted through the optical fiber on the width of laser pulse is expressed by the empirical formulae:

$$E_L(\lambda = 308 \text{ nm}) \sim \tau^{1/2}$$

$$E_L(\lambda = 248 \text{ nm}) \sim \tau^{1/3}$$

From these relations it follows that if the optical fiber must transmit a greater quantity of energy, lasers of longer pulse should be built. Special lasers with a pulse duration of up to 1 μs already exists [16]. However, to prolong the pulse width in an existing laser structures one must reduce the radiation energy output [17].

It has already been mentioned that the pulse repetition rate f of excimer lasers currently reaches 1 kHz. However, most of these lasers operate within an interval of 1 Hz to 1 kHz. Each structure has an optimum frequency, at which the radiation energy reaches its maximum. It should also be stressed, that for excimer lasers with the same repetition rate the radiation energy is higher in a system with X-ray preionization than it is in a system with UV preionization.

The process of interaction of laser light on a material depends, above all, on the energy E_L and the energy density E_L/S. Excimer lasers now available on the market can produce pulses of an energy from 1 mJ to 2 J. The energy density in a non-focused beam varies from a fraction of a mJ/cm² to 500 mJ/cm² (depending on the model). The focusing of the radiation from such a laser can ensure energy densities reaching a value of 10^6 J/cm² and power densities above 10^{13} W/cm². Such an energy density range satisfies the requirements for most micromachining processes. Examples of threshold values of the radiation energy density E_L/S of an ArF laser ($\lambda = 193$ nm) for photo-ablation of typical materials used in electronics [19] are presented in Table 4.

Table 4. Threshold values of the energy density of photo-ablation for a few typical materials ($\lambda = 193$ nm, $E_{h\nu} = 6.4$ eV)

Material	$(E_L/S)_{th}$ [mJ/cm²]
Nitrocellulose	<20
Photoresist	30
Polyamide	45
Polycrystalline silicon	100
Silicon oxide	350
Silicon	>1000

Table 5. Comparison of principal parameters of UV and IR lasers [14]

Characteristics (parameter)	Laser		
	excimer	YAG:Nd	CO_2
Wavelength [nm]	193–351	1060	10600
Average power [W]	500	$2 \cdot 10^3$	up to $2.5 \cdot 10^5$
Type of operation:			
pulse	×	×	×
continous	–	×	×
Frequency of repetition [Hz]	up to 10^3	up to 10^6	up to $5 \cdot 10^3$
Resonator:			
stable	×	×	×
unstable	×	–	×
Beam distribution:			
single mode	–	×	×
multimode	×	×	×
Minimum dimension of the beam at the focus [μm]	1–10	10–100	50–500
Fiber optics guiding of the beam	difficult	easy	difficult

Further, the thickness l of the material layer to be removed depends on the value of the energy density of the incident laser radiation. The thickness l is a logarithmic function of the density of the laser radiation flux:

$$l = m \cdot \ln\left(\frac{E_L/S}{(E_L/S)_{th}}\right)$$

and the value of the coefficient m depends (as with threshold $(E_L/S)_{th}$) on the kind of material and the lasers wavelength. For example, let us say that the typical thickness of organic material removed by a single pulse is, for $E_L/S = 0.5$ J/cm², approximately 0.5 μm. This value is rather small, but the high accuracy and high repeatibility of the parameters are difficult to obtain through other methods.

Summing up the above remarks, one could say that excimer lasers provide a new tool for precision machining of materials. In particular, they can be applied in processing of semiconductors, composites and also to interact with biological tissue. The advantages of machining operations with this type of laser over machining with YAG:Nd and CO_2 lasers include minimum action in the boundary region (cold machining), sub-micron resolving power, and the uniform machining of large, plane surfaces. The principal features of UV and IR lasers used to study the effects on materials are compared in Table 5.

The next two sections will be devoted to examples of applications in industry and medicine.

3. Examples of excimer laser industrial applications

Typically the UV radiation emitted by excimer lasers is used in applications concerning the photo-ablation of organic material, high-accuracy cutting and scribing of various materials (mainly metals, ceramics and semiconductors) and for laser micro-photochemistry.

The photo-ablation effect is most clearly illustrated by piercing micro-holes in organic materials. Polyamide is commonly used in industry and its threshold energy for ablation is about 45 mJ/cm² (see Table 4). Fig. 3 shows two examples of micro-holes made in polyamide by a KrF* laser (248 nm). The first hole (photo 1) was made in the thin protecting layer of the optical fibre [19], with the linear dimension of the hole being about 20 μm. The second hole (photo 2) was 300 μm in diameter and made in a 75 μm thick polyamide layer. Photos 3 and 4 show micro-holes made in the same material by a CO_2 and YAG:Nd laser, respectively. The photographs clearly show that the precision and quality of the holes made by KrF laser are higher than the quality of the holes made using infrared radiation. The difficulties in making micro-holes by CO_2 and YAG:Nd lasers are even more evident, if we look at making a miro-hole in 4 mm thick collagen. Such tests were made by Dickman [8] and are illustrated by the photos in Fig. 4. Here, one can see that the edge of a 1.5 mm diameter hole is decidedly sharp, even when the value of energy density of UV radiation emitted by an ArF laser (1.4 J/cm², 20 Hz) is rather low. Drilling such a hole with a CO_2 laser required a radiation power of about 500 W. The quality of the hole was then much lower, it was similar to that in the case of classical drilling. Photo 3 shows that, in reality, it is not possible to drill holes in collagen type materials with 1.06 μm radiation emitted by an YAG:Nd laser operating at approximately 1.2 J and 1 Hz.

Similar differences between interaction of high-power IR and UV radiation of on metals are observed. In such case metals are machined by means of high-power CO_2 and YAG:Nd lasers to balance low values of the absorption coefficient (see Table 2). In contrast with macro-machining where this process is usually economically justified, when micro-machining of thin layers it is highly uneconomical. In particular, micro-machining materials such as gold, copper or nickel with CO_2 and YAG:Nd lasers on a base which cannot be heated during machining is unjustified.

Now, micro-machining of such metal layers is most effectively done with UV radiation. Examples of such machining are presented in the photographs in Fig. 5. Photos A and B show cuts in 1 μm thick aluminium and copper foil, made by a XeCl laser [21]. Photo C shows an example of micro-machining of gold foil with a KrF laser (energy density of 10 J/cm²). Some selected examples of present authors works on the application of UV excimer laser radiation for micro-machining nickel, copper and silver layers are discussed among other papers in Ref. [22].

The method described above to cut thin silver layers is also applied to precision cutting silvered ceramic plates, used to manufacture of capacitors. Direct cutting and scribing in ceramic materials is also more effective and more accurate than with YAG:Nd and CO_2 lasers. Examples of cutting ceramic plates of zirconium [23] are shown in Fig. 6. Comparison of the results obtained for approximately 1 mm thick plates is more advantageous for an XeCl laser than a YAG:Nd laser. The quality of the edge of the cut and the machining rate are better if a UV excimer laser used. It is also observed that the UV radiation power is about 1/6 of that in the other case with the same cutting effect.

The action of UV radiation on metals and synthetic materials is also effective for marking operations of materials, elements and subassemblies. Such applications are simple and common but very important. Typical marking system are based on the method of template projection or the contour (spot by spot) method. The mask method is usually accomplished with CO_2 pulse lasers. The other common method uses a YAG:Nd pulse laser with a radiation beam scanning system. Projected infrared radiation makes marks which do not contrast with many materials. In this case UV excimer lasers prove to be competitive. In the contour method, the radiation emitted from a YAG:Nd laser often produces craters which are too wide and too deep. In this case, UV radiation should be applied to give contrasting craters with minimum size and minimum slag. As a result, the marks are readable and small. This makes it possible to make use of a greater active area of the material. Excimer lasers were first used to mark silicon plates in the Lumonics works [24] in 1981. The integrated production system there enabled 400 silicon plates to be marked per hour, with 18 different symbols. The fact that the laser marking methods are contactless is very important when dealing with brittle materials such as silicon plates, glass, ceramics, cables and light pipes in particular. The present authors works on remote, contactless marking using UV radiation, on some selected elements and materials are illustrated in the photos in Fig. 7. Marking with UV radiation excimer lasers using the mask projection method is increasingly important and is becoming competitive with the CO_2 TEA type laser marking systems which are currently very popular. This statement is confirmed by the fact that a special firm, Spectrum Technology Ltd., has been organized [25] to manufacture automatic systems that will incorporate excimer lasers, to mark cables to be used in aviation.

The photo-ablation effect and the ability to focus UV radiation on a small area prove to be very useful in the production of large and very large scale integration (LSI and VLSI) electronic structures.

By applying UV radiation from excimer lasers to the production of integrated circuits we can reject a number of complicated and laborious photoresist production processes. Chemical processes such as oxidizing, depositing, doping or etching can be conducted in a remote, dry manner with laser radiation. The resolution may be as high as 0.2 μm [24]. This new type of production process is referred to as laser microphotochemistry.

The two most typical examples of such processes are laser depositing and laser etching. The next two figures diagrammatically illustrate those processes and show examples of the results. Fig. 8 is a diagramm representing of the process of chemical deposition [26]. The process produces a chemical reaction (pyrolysis) on the locally heated substrate surface. The pyrolysis process is of a threshold type that requires a critical temperature to occur. The parameters of the process can be adjusted so that the size of the dump obtained may be smaller than the wavelength of the laser used. In practice there are two fundamental groups of laser-induced pyrolytic processes. The first group is surface-catalysed, single particle reaction of thermal decomposition, of the type:

$$SiH_4 \xrightarrow{\text{Temp.}} Si\downarrow + 2\,H_2\uparrow$$

The other group of reactions is made up of reductions of haloids of metals:

$$WF_3 + 3\,H_2 \xrightarrow{\text{Temp.}} W\downarrow + 6\,HF\uparrow$$

These processes, which begin in the gas phase, depend on the energy density of the laser light, the pressure of the working gas and the number of laser pulses irradiating the substrate. A measurable effect the processes, in addition to the size of the dump, is seen in the resistance of the layer. An example of such characteristics, obtained by Gerasimov et al. [26] is shown in Fig. 8b. According to the results, the rate of laser deposition is several orders of magnitude higher than that of conventional chemical vapour deposition (CVD).

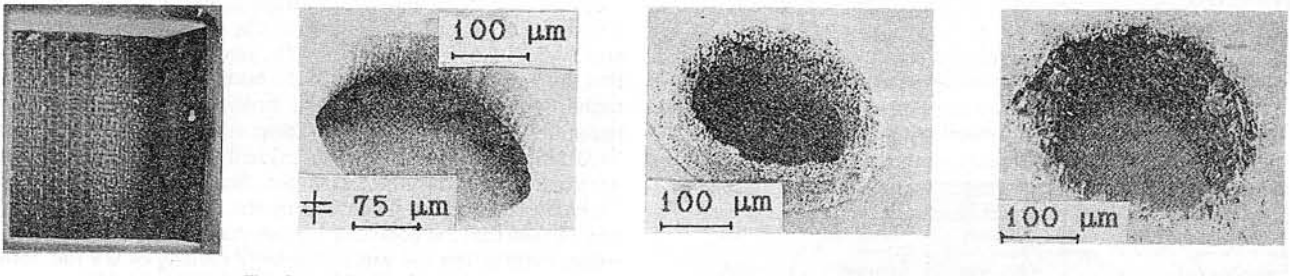


Fig. 3. Micro-holes made in polyamide by means of three different pulse lasers [19, 20]

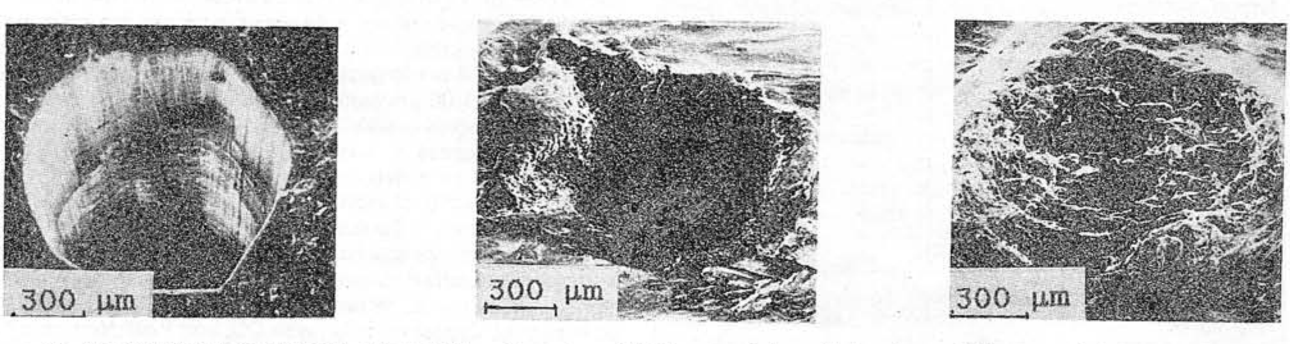


Fig. 4. Laser micro-hole drilling in a 4 mm thick collagen layer [8]. The rate of photoablation for an ArF laser was 0.4 μm per pulse

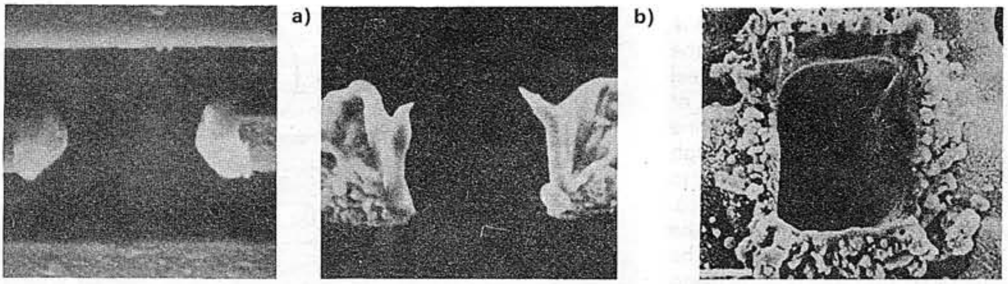


Fig. 5. Examples of cutting of metal layers by means of the radiation of an UV excimer laser: a) cutting of 1 μm aluminium foil on a silicon foundation [21], b) cutting of 1 μm copper foil on a polymer base [21], c) a 10 × 10 μm hole in gold foil [19]

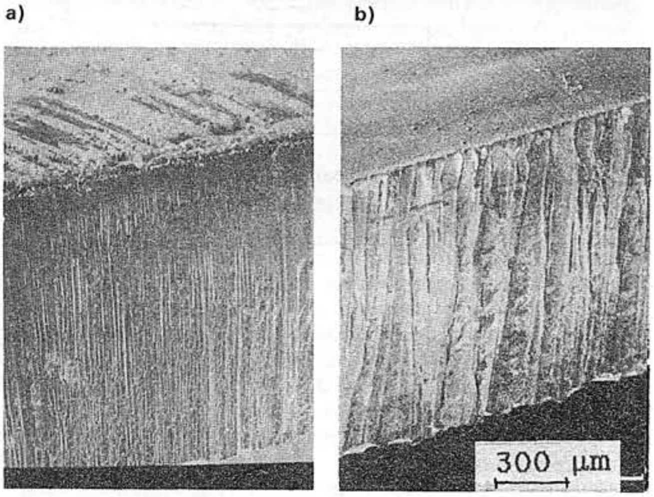


Fig. 6. A laser cut of a 1 mm thick ZrO_2 ceramic plate [23]: a) by UV radiation, v = 15 mm/min, b) by IR radiation, v = 10 mm/min

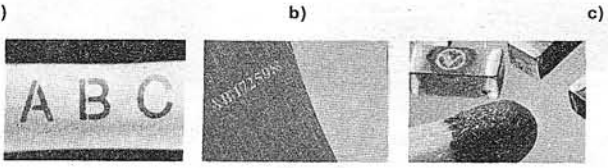


Fig. 7. Examples of the excimer laser marking of materials: a) kapton wire, 2.2 mm o.d., b) aluminium, c) ceramic capsulated SMDs

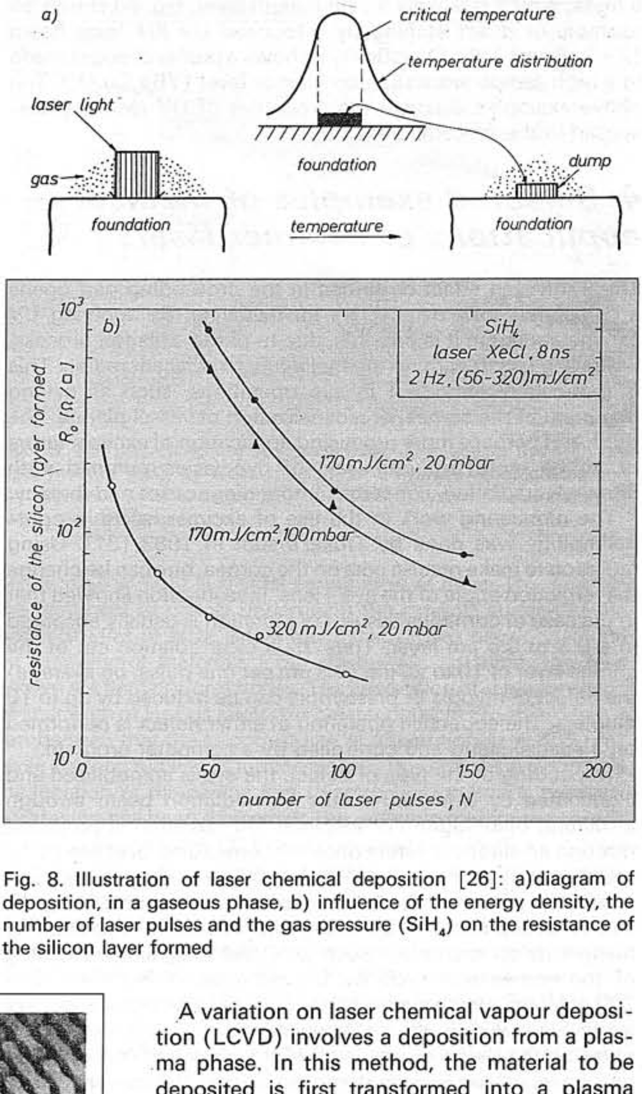
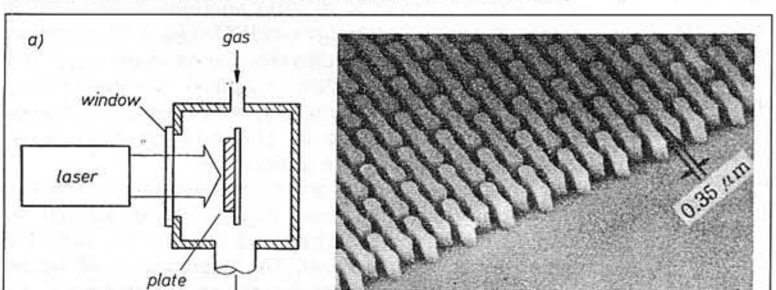


Fig. 8. Illustration of laser chemical deposition [26]: a) diagram of deposition, in a gaseous phase, b) influence of the energy density, the number of laser pulses and the gas pressure (SiH_4) on the resistance of the silicon layer formed

Fig. 9. Illustration of the process and the results of etching materials with a KrF [29, 30] excimer laser: a) schematic diagram of the experimental installation, b) pictorial diagram of the mechanism of laser etching [29], c) example of a structure of a resolution of 0.35 μm etched in PMMA [29] by KrF laser of a power density of 0.6 W/cm², d) profile of a superconductor layer ($YBa_2Cu_3O_7$) after direct etching by nine pulses of a KrF laser operating at energy density of 0.68 mJ/cm² [30]



A variation on laser chemical vapour deposition (LCVD) involves a deposition from a plasma phase. In this method, the material to be deposited is first transformed into a plasma state, which expands, and is thus deposited on the base, which has already been heated. This process can be successfully used to produce thin layers and foils of high temperature superconductors [27] or multilayer mirrors for X-radiation [28].

Let us now move to another important process involving laser photochemistry, namely etching. Direct and indirect laser etching are distinguished. Direct etching involves the local removal (by evaporation or ablation) of the material. The etching process is illustrated in Fig. 9 This figure show s a typical test stand for indirect etching. Fig. 9b illustrates the etching process in a chlorine atmosphere [29]. An example of the structure of a resolution of 0.35 µm etched in a 1 µm thick PMMA photoresist is shown in Fig. 9c. Indirect etching, as illustrated in Fig. 9b, is made up of three stages: dissociation of particles in the neighbourhood of the surface; reaction with surface atoms; and desorption of the reaction products. Horike and Nayasaka [29] describe the process of laser etching in a halogen gas atmosphere. They feel that indirect etching can be described by the following set of events. Particles of Cl_2 undergo photodissociation. Chlorine atoms are adsorbed into a silicon surface. As a result of high electronegativity, chlorine electrons in the base are transfered to adsorbed atoms. Cl ions may then penetrate the crystal lattice. The volatile products of the reaction occuring during the penetration process of $SiCl_x$ ($x = 1$ to 4) are desorbed to the gaseous phase. The etching of required structure is done using a mask, which is usually an aluminium layer. Fig. 9d shows an example of direct etching by a focused UV KrF laser beam ($\lambda = 248$ nm) [30]. Specifically it shows a profile of edges made in a high-temperature superconductor layer ($YBa_2Cu_3O_7$). The above examples illustrate the properties of UV radiation discused in the preceding section.

4. Selected examples of medical applications of excimer lasers

The Srinivasan effect described in the proceeding part opens a completely new perspective for medicine. By applying UV excimer radiation it is possible, due to photo-ablation process, tissue can be cut with no thermal injury to adjacent region. This is particularly important in eye operations, such as milling treatment of the cornea, or recanalization of vessel plaque. The third, and perhaps more promising application of excimer lasers or, to be more accurate, sets of dye lasers pumped with ultraviolet radiation, concerns tumour diagnostics and therapy.

The pioneering work in the use of excimer lasers in ophthallmology was done by Trokel's staff in 1983 [31]. Using radiation to make precise cuts on the cornea, one can be change the refraction angle of the eye's lens. Investigation showed that in the case of corneous tissue, UV radiation is usually absorbed in a 0.3 to 0.5 μm layer. Thus, by a clear ablation cut of the cornea layer of 10 to 20 μm (0.3 μm per one pulse, on average) the defect of myopia or presbyopia can be reduced by up to 10 diopters. The corrective operation of either defect is performed on a special stand and controlled by a computer program.

Depending of the type of defect, the eye is immobilized and illuminated by a homogeneous UV radiation beam through a rotating diaphragm. For instance, UV radiation is projected through an elliptic aperture onto the cornea and, because of the rotating motion, a thin layer of the cornea is removed in such a way that a new parabolic-spherical cornea is formed. Fig. 10 shows this process [32], using the corrective operation of myopia as an example . Such cuts and programmed milling of the cornea are made by UV radiation of no more than 200 mJ/cm² . Using such a level of radiation energy density we avoid thermal side effects. Nanosecond interaction of a laser pulse on the tissue results in all of the absorbed energy being taken away along with the removed layer of the cornea. One of the most important problems in correctly forming the cornea is that of uniform illumination of the treatment slit and very careful checking of the energy of a radiation pulse repeatability. Problems with eye cornea operations using an excimer laser are now being studied by more than ten groups of medical scientists all over the world [32].

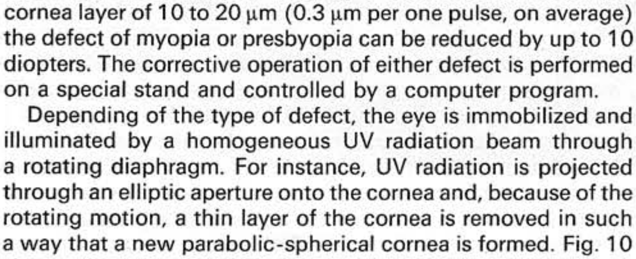


Fig. 10. Diagramatic representation of the reduction process of myspia by means of an excimer laser and a rotating automtically controlled diaphragm with variable hole diameter [32]

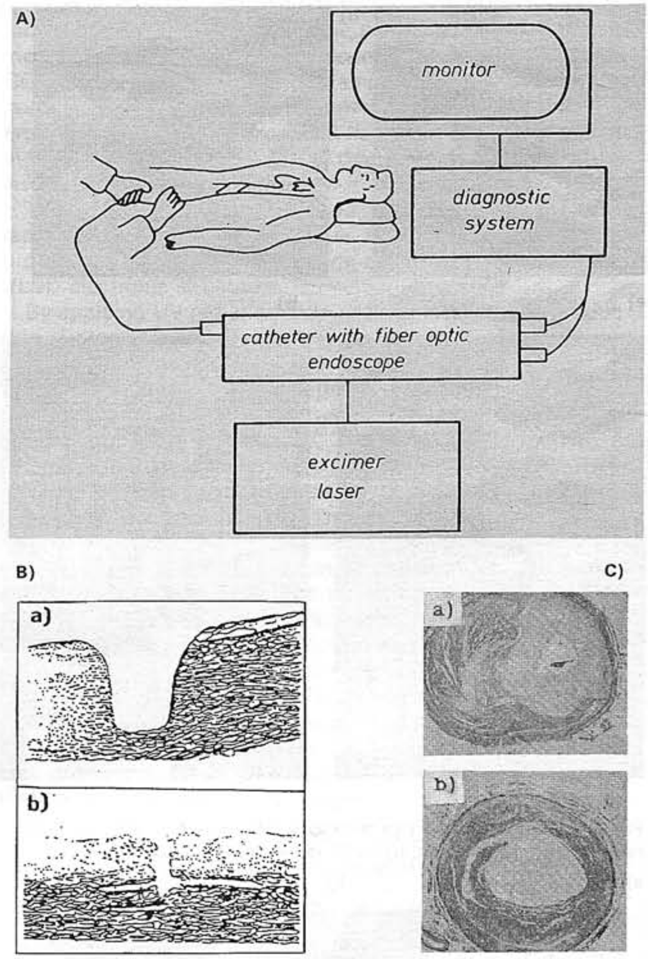


Fig. 11. Illustration of laser operation of recanalization of an plague in a blood vessel:

A) Schematic diagram of a laser set for diagnosis and photoablation removal of embolias [33];

B) Comparison of the results of ablation if human aorta performed by two different lasers of identical pulse width (7 ns): a) ablation by an excimer laser, b) ablation by a YAG:Nd laser, b) ablation by a YAG:Nd laser;

C) Example of removal of calcification in the aorta [34]: a) a photograph of the embolia, b) a photograph of the completely cleaned aorta

The second application of UV excimer lasers in terms of scale and popularity is referred to as laser angioplasty or in other words recanalization. The energy needed for such an operation amounts to some 40 mJ per pulse (several nanoseconds), and can be transmitted through flexible optical fiber larger than 0.6 mm in diameter. The laser angioplasty operation involves photo-ablation of the plaque by UV radiation illumination introduced into the rein by the optical fiber.

Fig. 11 illustrates the laser angioplasty operation. The ablation monitoring system shown in Fig. 11a is realized by observing the fluorescence of the tissue which is forced by UV illumination by an excimer laser. The fluorescence of sound tissue is different than the fluorescence of arteriosclerotic plaque. Fig. 11B shows the difference in the character and the results of ultraviolet (UV) and infrared (IR) radiation on a biological tissue. The fact that the UV radiation method of plaque removal does not involve scorching effects should also be mentioned. If a YAG:Nd laser is used, typical injuries by acoustic waves are observed [33]. An example of rein cleaning by excimer laser are seen in Fig. 11C. The estimated value of the efficiency of angioplastic operations by means of UV excimer lasers is now 70%.

The third important group of applications for excimer lasers is what is phototherapy of tumours. Laser therapy of tumouric diseases can be explained as follows. The problem is treated by using compounds (photosensitizers) previously introduced into the organism. As a result of irradiation of the cancerous region by light of a specific colour, the photosensitizer is transformed into a compound which selects and destroys cancer cells, leaving the sound tissue undamaged. Correct selection of the photosensitizer is essential, as it should be deposited in the cancer foci only, without producing harmful side effects. As an example of such preparations let us mention substances known as porphirines and, in particular hematoporphyrin derivatives (HpD) also known as photodynamic therapy (PDT) in medical literature.

Photodestruction of cancerous tissue in the presence of a photosensitizer is a complex process and will not be explained here. A description of the process can be found in papers dedicated to the topics (Refs. [35] to [37]). Here we shall only show in greater detail the role and the way of selecting a laser for succesful application of the method considered.

The essential features in the correct selection of a laser are illustrated in the diagrams in Fig. 12. Fig 12a illustrates both the ability for absorption of various photosensitizers and the optical permeability of human tissue. It is seen that, accomplish the PDT method, a middle course must be taken between the ability of the photosensitizer absorb and the penetration depth into the tissue by radiation at a given wavelength. As regards porphirines it can be seen in Fig. 12a that their absorption is greatest in the 400 to 410 nm band and the penetration depth of the radiation is greatest for one of the weakest maxima of absorption (i.e. for 630 nm). 630 nm radiation penetrates only a few millimeters into the tissue and may be applied to surface tumours or in the early stages of cancer. It may also be used to treat post-operation tumours.

Most research in this area now aimed at finding a biologically active and safe substance with maximum absorption for $\lambda = 750$ to 800 nm. In the diagram in Fig.12a we see that the depth of penetration of light is several centimeters at most. This enables the treatment of cancer underneath the external surface of the body. Studies of new, active biochemical dyes now concetrate on tetraphyrrol materials [39]. At the present time, the best known are hematoporphyrines. The absorption and luminescence spectrum of HpD is shown in greater detail in Fig. 12b. Here it can be seen that the strongest line of absorption ($\lambda = 405$ nm) gives a strong red line of luminescence. This effect is used to find the location of the cancer foci (diagnostics) in which hematoporphyrine has been deposited. The requirements for the source of laser radiation in the PDT (HpD) method are as follows. A laser emitting 405 nm radiation is needed to localize the tumour. Photodestruction of cancerous cells at the possible greatest depth requires red radiation of 630 nm. Both wavelengths can be obtained either by using two different lasers or by using a tuned or two-wave dye laser. The dye laser can be pumped by continuous or a pulse UV laser (excimer or harmonic of YAG:Nd laser). Investigation that has been conducted to date shows that the efficiency of the therapy with pulse laser is many times (above 170) more efficient than using a continuous action laser. As a result, the interest in excimer dye laser sets is very great. Their application in therapy and diagnostics of tumour diseases is very important. Let us mention here the great achievements of the Japanese center [35].

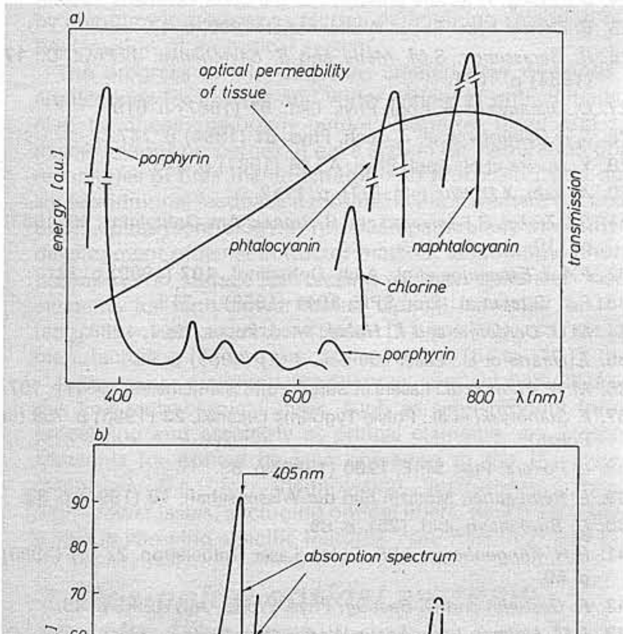


Fig. 12. Spectrum characteristies of sensitizers used with the PDT method [37]: a) ability for absorption of typical photosensitizers and the optical permeability of the biological tissue, b) the spectrum of absorption and fluorescence of hematoporphyrin derivative (HpD)

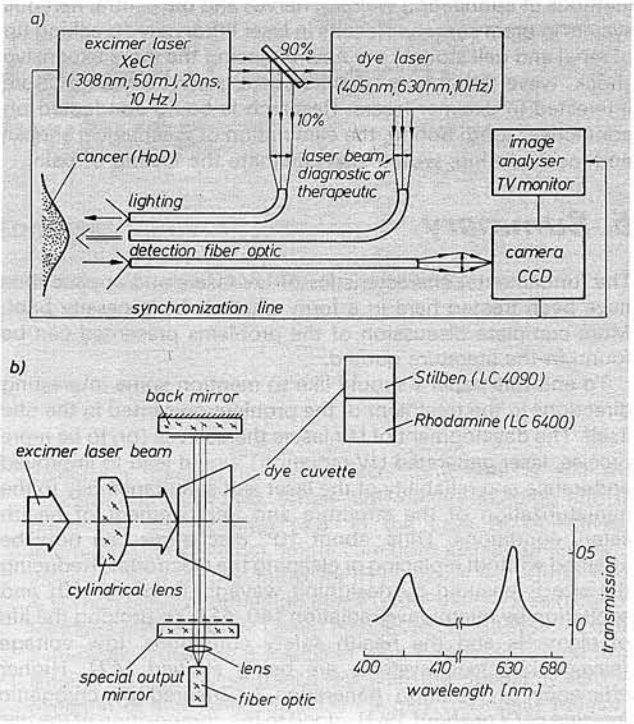


Fig. 13. The present author's „excimer-dye" laser set for use with the HpD method [38]: a) block diagram of a system for diagnosis and therapy system with an optical observation system, b) diagram of two-wave dye laser

The Japanese-like, but simpler, laser system presented in Fig. 13, is now being constructed by the author's group. Illumination of the tumourus region is ensured by a fraction (approx. 10%) of the UV radiation emitted by an excimer laser. Two waves (of 405 nm and 630 nm) will be generated [39] by a single dye laser with a two-compartment tray inserted in either end into the region of a plano-plano resonator. Alternate generation of the two wavelengths is achieved, in addition to the automatic exchange of the two-compartment tray by special outlet mirror for the resonator. Fig. 13b shows the structure of the dye laser itself in greater detail. Such a simplified structure enables us to introduce radiation from the dye laser into the tissue using a single optical fiber system.

Finally, let us mention briefly the research work on the applications of eximer lasers in other domain of medicine. Very promising results have been obtained in neurosurgery, in methods of connecting welding nerves and the central nervous system in brain surgery. Results in laser lithorypsy (breaking up of renal and gall stones) are now replacing the more expensive shock wave lithotripsy. Dentists are also becoming more interested in excimer lasers. Research is being conducted on contactless tooth boring, the elimination of mechanical shocks and local heating, would also eliminate the feeling of pain.

5. Summary

The fundamental characteristics of UV lasers and applications have been treated here in a form which is by necessity brief. More complete discussion of the problems presented can be found in the literature quoted.

To end this paper I should like to mention some interesting directions in the treatment of the problem presented in the title itself. The development of UV lasers themselves (or, to be more precise, laser generated UV radiation) would lead to improved endurance and reliability of the laser and simultaneously to the miniaturization of the structure and improvement of health safety conditions. Thus, about 10^{10} discharges can now be attained without replacing or cleaning the electrodes. Reducing the size is ensured by designing waveguide lasers [40] and excitation by microwave radiation [40, 41]. To prolong the life of elements and the health safety conditions, low voltage (several kV) feed systems are being studied [42]. Higher efficiency of radiation generation is ensured by cryogenic freezing of Cl or about 1% H added to the composition of the gas of the XeCl laser. For better UV radiation guidance of in optical fiber [15] the duration of the laser pulse should be increased to as much as 1 μs. The stability of the parameters generated at a given level requires control and inspection of the laser by a microcomputer [10]. Another trend in research is to devise a method to generate intense pulse radiation in the visible range of the spectrum [43].

The prospects for the development of excimer laser are well illustrated by the fact that a construction program of the EU 205 laser of 1 to 3 kW mean power is financed, within the framework of the well known EUREKA program, by about 60 millions US dollars [10]. This program should be finished in 1994 and 11 countries of Western Europe are participating. A similar program, AMMTA (Advanced Material-Processing and Machining Technology Association), is being conducted in Japan, with investment of more than 100 milion US dollars, by more than 20 firms and institutions. Both programs are presented, in greater detail, in Table 6.

Table 6. **European and Japanese development program for high power excimer lasers [10]**

Name of the program	EUREKA (EU 205)	AMMTA
Fundamental parameters of the laser	(1–3) kW (248 nm, 308 nm) >0.5 kW (193 nm)	2 kW, % kHz (258 nm, 308 nm) 1 kW (193 nm)
Number of realizing institutions	>11 countries	20
Investment	58 million USD	≈100 million USD

Regarding applications of UV radiation (Refs. [44] to [46]) in other interesting directions, one can sight projects investigating:

- micro-photochemistry,
- production of high resolution diffraction gratings with a single pulse of an excimer laser [45, 46],
- laser microscopy,
- source of intense X-radiation for studies of X-lasers and X-ray litography,
- generation of ultrashort radiation pulses and femtosecond pulses,
- diagnostics and therapy of tumourous diseases and tuberculosis of the lungs.

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