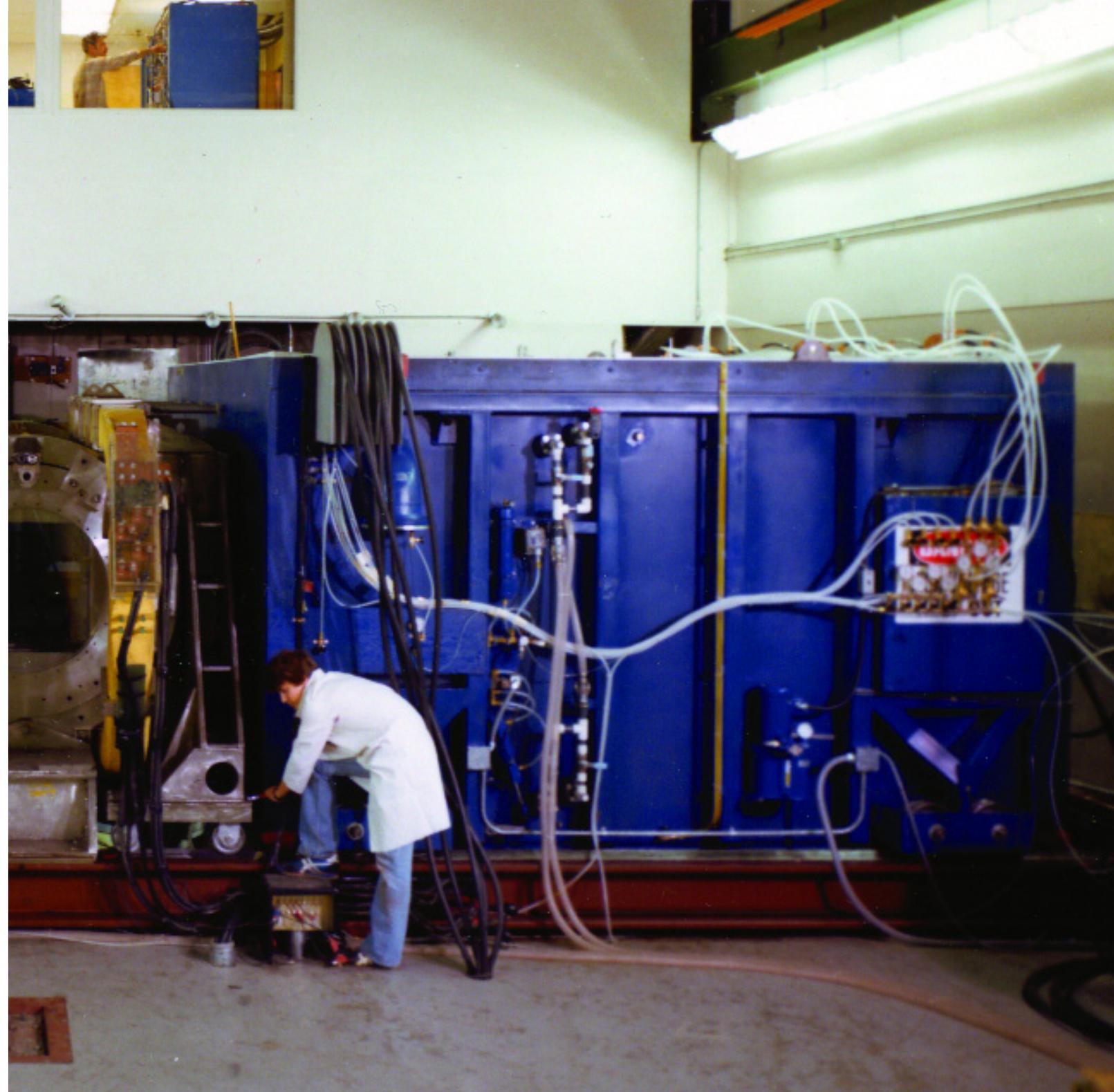




J. J. Ewing

Excimer Lasers at 30 Years



Excimer lasers have matured into an important workhorse for numerous industrial and material processing applications. They are also the key component in one of the most prevalent laser medical procedures, corneal corrective surgery. The author traces the history of excimer sources and the evolution of applications not originally envisioned by the scientists involved in their development. The case history of the excimer laser is particularly relevant to today's researchers and those who fund them, since significant applications outside the lab occurred only after years of intensive research and development.

(Above) The result of scaling up a rare-gas halide excimer laser. This single-shot laser used electron beams powered by the high-voltage generators on the left and right of the center of the photo. The total beam current was so large that an external magnetic field was used to guide the electrons into the gas through a large foil. The optical output was through a 50 cm by 65 cm window. The laser gain length was 3 m. An unstable resonator provided excellent beam quality. [Courtesy of D. Trainor of Textron Systems.]

Excimer lasers have become the laser of choice for many applications in the ultraviolet (UV) spectral region. The most commonly encountered wavelengths are shown in Table 1. The photons in this spectral range are capable of inducing photochemical reactions. The pulse energy and peak intensity are appropriate for photobleaching. The combination of UV wavelength, moderately high peak power and single-pulse energy make excimer lasers useful for materials processing. The relatively high pulse rate and average power capability offer benefits in manufacturing. From a commercial viewpoint, the most important application using photochemistry is the production of computer chips by photolithography. The most important materials ablation application is precision removal of corneal tissue in photorefractive surgery for vision correction. Although the market for the lasers themselves is significant—on the order of \$400 million annually—the systems and surgical services deriving from the excimer laser’s unique properties result in annual revenues approximately ten times higher.

It is interesting to look back over the roughly 30 years of excimer technology and see how the focus has changed compared to the initial goals of its proponents. The history of the excimer laser is particularly instructive in that it shows how long it can take a technology to

mature into real applications. Agencies that fund crucial early research may not in fact remember how the current technology evolved and how it migrated to real applications. Today’s users may not be aware of the factors behind key breakthroughs or of how far the technology has actually traveled from its roots. Finally, the time needed to develop a new technology and the corresponding new markets is generally underestimated by researchers and by those who fund them. The reticence of venture funds to embark on investments in technology that is truly new can be well understood from the case history of excimers: the time it takes to garner a return from an innovation often far exceeds the outer limits of venture capital patience.

Figure 1 provides a generic timeline of how the excimer laser as we know it came to be. Excimer research and development in the early 1970s combined excitation requirements from laser physics, kinetics and spectroscopy from the chemical physics world with the equipment and concepts of radiation effects simulators. The key concept in play was ground-state dissociation, a way to assure a population inversion at the cost of broader emission bandwidth and low intrinsic gain per excited state. The concept of ground-state dissociation is sketched in the potential energy diagram of Fig. 2.

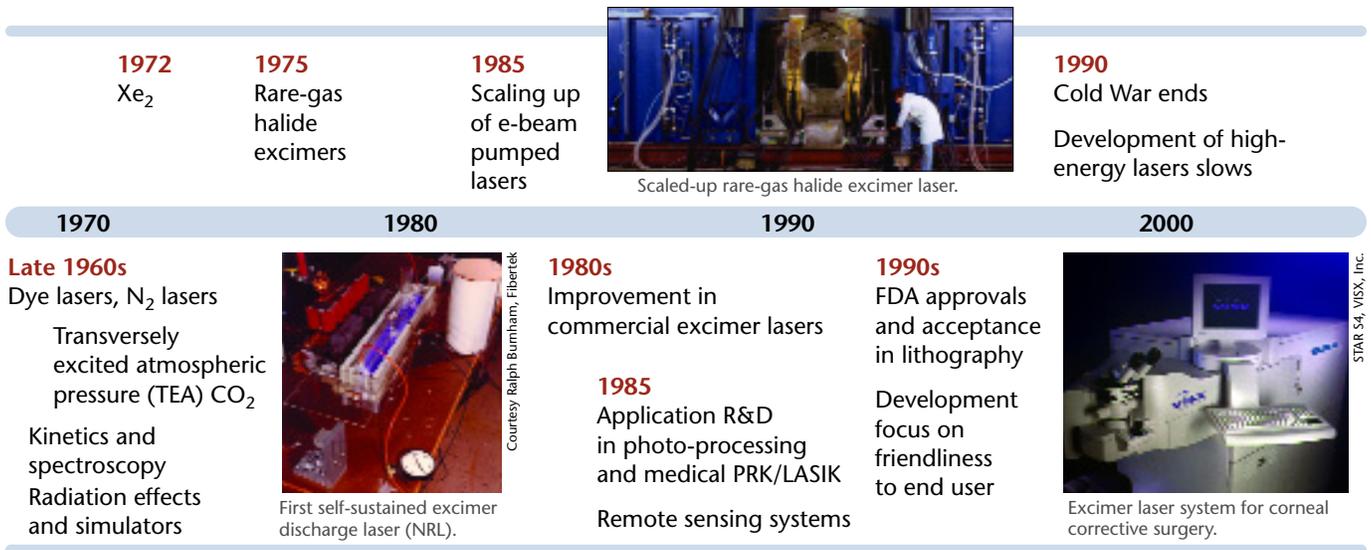
The first issue addressed was attainment of the pump power needed to bring

a laser based on excimer molecules over laser threshold. By use of very simple kinetic models or estimates, one can readily calculate the power-deposition rate required to excite an excimer laser, typically 10^5 to 10^6 W/cm³. Typical cw visible and UV lasers of the 1970s ran at power inputs a factor of 10^3 to 10^4 lower than that needed for the excimer. The transversely excited CO₂ laser, which was known by the time the pursuit of excimers began, also required high power inputs. But energy storage in the excited states of the N₂/CO₂ medium relax pump-power requirements to roughly one-tenth of that needed for laser action in an excimer. Although lamp-pumped dye lasers have a similar pump power requirement, since these lasers are optically pumped through strong absorption bands, dye-laser technology did not help in the search to develop the excimer laser. Technology provided by the simulation-physics and fast-pulsed-power community was needed.

Broad-area electron beams of the 1970s were capable of current density on the order of 10-200 A/cm² spread over areas of a few square centimeters at beam voltages on the order of 400 keV. Thus, the power incident on a gas irradiated by such an electron beam would be on the order of 4-80 MW/cm². If the range of electrons in the gas were kept to 10 cm or so, the pump requirement could be met. This would imply gas excitation at pressures in the 2-10-atm range. For gases such as xenon, this was not a major difficulty. But for promising candidates such as the mercury excimer, Hg₂, the gas pressure needed for rapid recombination to the excimer upper level (about 10 atm) led to problems in the mechanical design because of the high temperature necessary (500°C). Obtaining sufficient power input was not enough; one also had to deal with basic questions of spectroscopy. Indeed, spectroscopy almost damned excimers to a nonexistent role. Excited-state absorption in the regions of laser operation resulted in poor lasers on the xenon and other rare-gas-excited dimer transitions in the VUV, despite highly efficient energy conversion. Electrically excited Xe at high pressure can channel roughly 50 percent of the energy deposited in the gas into Xe₂ excimer

Excimer emitter	λ (nm)	Comment
XeF	353	The focus of early defense-related laser development because this wavelength propagates best of its class in the atmosphere.
XeCl	308	Optimum medium for laser discharge excitation.
XeBr	282	First rare-gas halide to be shown as a laser; inefficient laser but excellent fluorescent emitter; a choice for lamps.
XeI	254	Never a laser, excellent for a lamp.
KrF	248	Best intrinsic laser efficiency; numerous early applications but found major market in lithography.
KrCl	222	Too weak compared to KrF and not as short a wavelength as ArF.
ArF	193	Workhorse for corneal surgery and lithography.
Xe ₂	172	All rare gases can form excimer molecules such as Xe ₂ at high pressure. Excimer molecules made from lower-molecular-weight rare-gas excimers (Kr, Ar, etc.) emit at shorter wavelengths, deeper in the VUV.
F ₂	157	“Honorary” excimer; next-generation lithography.

Table 1. Key excimer wavelengths. This table omits some other laser bands and gases and analogous media.



emission in the VUV. But absorption limits laser efficiency, and VUV optics at the time experienced significant loss as well. The discovery of rare-gas halide emission in 1974 and laser action on these novel molecules in 1975 transformed excimers from an expensive R&D curiosity into lasers with real potential.

The rare-gas halide emissions were first characterized in flowing afterglow types of experiments by physical chemists examining the reactions of metastable rare-gas excited states with halogen molecules. The emission spectrum at low pressure in their work was quite broad, broader in fact than that of Xe₂. Curiously, the bands were shifted radically away from the VUV emission of the corresponding rare-gas excimer, signaling excited-state energy curves that were entirely different from those of rare-gas dimers. Based on a simple initial model, Brau and I examined the emission spectra of the rare-gas halides with high-pressure and e-beam pumping. The result was emission that was much sharper than that at low pressure and much brighter than anything we had seen up to then. In a few months, these findings were turned into laser action by competing groups at the Naval Research Lab (XeBr), Avco Everett Research Laboratory (XeF, XeCl and KrF) and Sandia National Labs (ArF). It is interesting to note that the ArF laser, important today at pulse energies on the order of 100 mJ, produced energy output on the order of 100-J the first time it lased,

indeed before it was really known that ArF was the species producing the 193 nm output.

After the initial run of rare-gas halide discovery characterization, NRL's work on discharge excitation was the true precursor to commercial excimer laser products. NRL's work—exciting excimer lasers with the hardware of a commercial transverse discharge CO₂ laser that was “sped up” to provide fast excitation—opened the door to a new regime of R&D, as well as to new products. The early commercial excimer products were brought to market by Tachisto and Lambda Physik. Tachisto was an early market entrant but the company did not survive to realize the big revenue streams of today. Lambda Physik, which had UV

Figure 1. Timeline of how the excimer laser as we know it came to be.

N₂ lasers and dye lasers as its offerings, produced a superlative excimer product, along with the dye-laser converters that the market clearly wanted. It was thus able to dominate the scientific market for excimer lasers.

Excimer R&D proceeded in several directions, typically in search of large and extremely large UV energy outputs. Several groups pursued scaling up the electron-beam pumped laser for laser fusion and defense uses. For laser fusion, techniques to pulse-compress the optical outputs of the KrF laser were explored because KrF had the highest efficiency. For Department of Defense (DOD)

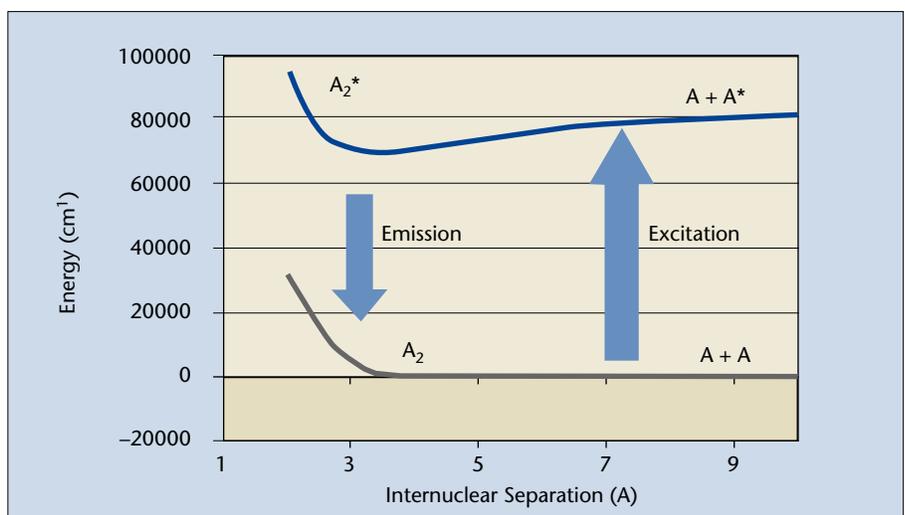


Figure 2. Simplified excimer potential energy curves.

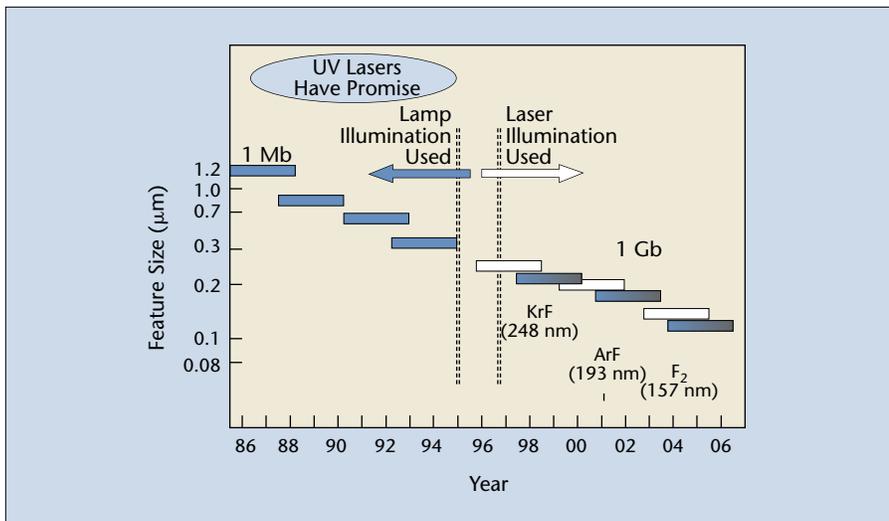


Figure 3. General progression of feature size and time leading to use of excimer lasers in photolithography. It was forecast in the early 1980s that UV lasers would be used in lithography in the early 1990s. Advances in lamp illumination methods pushed back the time when lasers were actually used in production. The fluorine-based excimer lasers KrF and ArF, along with the “honorary excimer” F₂, share a common technological development path. Key differentiation occurs in optical materials. As computers move to chips with feature densities of over 1 Gb, conventional lamp-based optical techniques have been replaced by excimer lasers.

applications, propagation in the atmosphere was and still is a key concern. For this reason, XeF was the leading candidate, though Raman shifting of XeCl could also lead to useful wavelengths. In a series of efforts, the DOD-funded teams built up a variety of large-aperture lasers. The photo on pages 26-7 shows an example of how large a laser built on this technology was. The XeF laser produced up to 5000 J per pulse. Other large-aperture lasers were built, including several that pursued the use of KrF as a laser fusion driver. To examine the potential for high power as well as high energy, researchers had to address other issues including: high-voltage-power conditioning and electron beams; beam control with large magnetic fields; ultralow perturbation gas flow to take advantage of the short wavelength; and propagation through an atmosphere that is far from static. As the timeline in Fig. 1 shows, however, the end of the Cold War put a major damper on the development of very large UV lasers.

The commercially relevant stream of excimer lasers descended from the earliest discharge-excited experiments at NRL. For some time, the government funded development of these lasers for laser-isotope separation and space-based

communications to submarines in industry and at national laboratories. The typical energy and power requirements were in the >1-J per pulse range, which was, generally speaking, outside the commercial realm. This research ultimately had derivative commercial payoff. Fast discharges require reliable pulsed power and very fast switches. Magnetic circuits were developed to provide long life. High efficiency required impedance matching, a considerably more difficult problem than in other gas-discharge lasers. The answer to this problem was the “spiker sustainer” concept, in which two separate isolated circuits were used to break down the gas and then power it in the lasing phase. XeCl UV lasers with wall-plug efficiency approaching 5 percent were developed. Discharge lasers with kilowatt power outputs and energies in the 10-J to 100-J range were built. Problems associated with gas life and materials had to be solved. The key transition from lab equipment to lasers for manufacturing required attention to materials and cleanliness in assembly of the laser chamber.

The true market, however, was always at lower energy and lower average power than in the areas driven by government-funded R&D. At first, the commercial

market centered on the academic researcher: typical R&D needs were met with lasers offering outputs of roughly 100 mJ to 500 mJ per pulse at pulse rates on the order of 30 Hz. The data acquisition systems used by early researchers were limited to low repetition rates, and therefore high pulse rates were irrelevant to them. The excimer energy requirement related to the scientific customer’s desire to pump a dye laser (and use nonlinear optics) to attain a broad range of wavelengths at an energy output on the order of 10 mJ. Successful laser vendors in the instrument market were well aware of this calculation and offered products that fit the demand. Vendors of products with pulse energy either too low or too high dropped by the wayside. With improvements to the technology, such as the use of magnetic switching for long-lived pulsed power, pulse rates could be increased as market demand required. As commercial lasers became more reliable in the mid-1980s, the technology shifted away from the chemists and physicists who had first used it.

Entry into the medical, materials processing and semiconductor manufacturing areas has opened up the most significant markets for excimer lasers. The largest current manufacturing use is in photolithography: very early on, it was recognized that the excimer would be useful in exposing photoresists and in producing finer feature sizes than possible with a mercury lamp. Lithography system developers recognized that the normal bandwidth of a lamp would lead to feature blurring caused by chromatic aberration in the lens systems. In contrast to a powerful lamp, the excimer has the valuable intrinsic property of yielding a narrow linewidth spectrum with an appropriate resonator, thus minimizing effects of chromatic aberration. To avoid speckle at narrow linewidth, multimode outputs are needed or the pulse rate should be very high, in the multi-kHz range. KrF and ArF lasers are relatively easily line narrowed, though increasing pulse rate to the multi-kHz level comes with a number of risks. To test excimer lithography, a number of purpose-built and modified commercial lasers were purchased by lithography system developers. As is often the case in technology

development, the schedule for adaptation of the new technology “slipped to the right” on the schedule charts. Lithography system vendors found ways to extend the range of utility of lamp-based systems. In time, however, excimer technology became sufficiently reliable that the laser became the “light bulb” of choice for exposing photoresists in chip manufacture. Other advanced technologies, such as x rays and soft-x rays, saw their schedules “slip to the right” as well. The KrF laser is now the workhorse for this process; ArF and F₂ lasers will ultimately drive feature sizes downward. The nominal timeline and feature sizes produced are shown in Fig. 3. One should remember that a decade ago, these same charts predicted that KrF and ArF lasers would be adapted and used in large quantities roughly five years earlier than history showed to be the case.

Laser ablation with UV-excimer lasers was well known from the very first days of research on discharge-pumped excimers. The discharge laser could be set to run at some modest pulse rate and the researcher could move around the room performing other tasks. Accidents showed the potential for ablation. The experience of having one’s belt buckle laser cleaned or some skin removed during an alignment process left no doubt that these lasers could ablate both inorganic and organic/biological material. In the 1980s, two significant applications grew out of this observation: UV-laser materials processing and corneal sculpting. Both had their initial quantitative and commercial origins in patents submitted in the 1983 timeframe. The medical procedure is far and away the one identified by the broader public with the excimer laser. This is no surprise because over 2 million laser surgeries have been performed to correct myopia, as well as other imperfections in the eye. Some market analysts project that by the year 2005, laser corneal corrective surgery will be the most common surgical procedure performed in the U.S. The differences between an ArF laser for lithography and one for eye surgery are

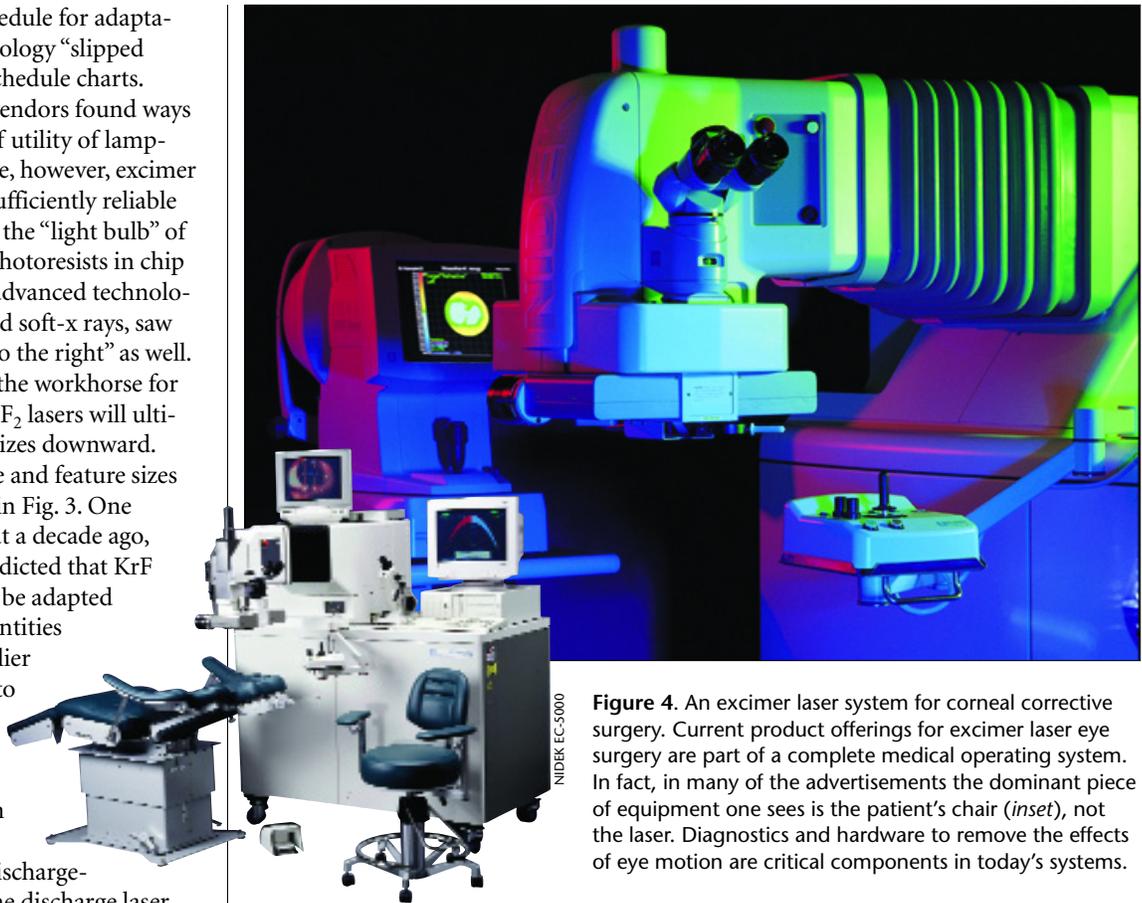


Figure 4. An excimer laser system for corneal corrective surgery. Current product offerings for excimer laser eye surgery are part of a complete medical operating system. In fact, in many of the advertisements the dominant piece of equipment one sees is the patient’s chair (*inset*), not the laser. Diagnostics and hardware to remove the effects of eye motion are critical components in today’s systems.

considerable. The requirement for laser shot life in eye surgery is orders of magnitude relaxed compared to that necessary for lithography. Linewidth is not an issue in laser eye surgery, although total integration into the medical delivery system is a requirement. The product is, in fact, a complete medical office instrument, not a laser (see Fig. 4).

As has been the case with applications in lithography, in eye surgery there have been delays in moving from concept to product to process. One of the biggest steps forward—the transition from the original photorefractive keratectomy (PRK) corrective concept to the newer laser-assisted *in situ* keratomileusis (LASIK) approach—has been based on the biology of tissue, not on optics or lasers. Both techniques achieve correction with ArF laser ablation of controlled amounts of corneal tissue. In PRK, the surface is ablated. In LASIK, a flap is cut in the cornea, the thin flap is folded out to expose internal tissue in the cornea and the correction made in the cornea.

When the flap is put back, there are apparently fewer imperfections and scattering sites in the eye’s lens when compared to a correction made by the PRK procedure. Recent improvements in the technology include active tracking of movements of the eye and optical scanning schemes and diagnostics built into the system.

Over the years, excimer technology and applications have improved and the original applications that drove development have been supplanted. Other non-laser applications, such as use of the excimer as a lamp source, have emerged. In both lithography and medicine, the time for evolution and acceptance has been longer than originally imagined. Yet the long-term payoff from defense-oriented R&D is real, despite the fact that it has occurred in ways that are totally different from those envisioned in the early days of the technology.

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