SIDEBAR 2:

Lasers for Uranium Enrichment

Like radar and sonar, the acronym laser (light amplification by stimulated emission of radiation) has achieved the status of a familiar word. But the principles upon which lasers operate may not be so familiar. Atoms or molecules can exist only in certain definite energy levels. In the presence of a photon with an energy equal to the difference between the energies of two such levels, atoms or molecules can undergo either of two processes, absorption or stimulated emission. In absorption, the more familiar process, an atom or molecule in the lower energy level absorbs the photon and makes a transition to the upper energy level. In stimulated emission an atom or molecule in the upper level makes a transition to the lower level and emits a photon, The emitted photon and the stimulating photon are spatially and temporally coherent (that is, they have the same phase and energy) and travel in the same direction. If the upper energy level has a greater population of atoms or molecules than the lower level (a condition known as population inversion), an intense field of coherent radiation can be produced as the emitted photon in turn stimulates another atom or molecule in the upper level to emit a photon, and so on. The atoms or molecules are then said to be lasing.

Developing a working laser is not as simple as explaining its operating principle. The first requirement is a collection of atoms or molecules among whose energy levels are suitable upper and lower levels between which lasing can occur. (Suitable here refers to the ease of producing and maintaining a population inversion. That is, the upper level must be easily populated, and the lower level, as it is populated by lasing, must be easily depopulated.) Then, this active medium must be "pumped" to achieve a population inversion. Electron bombardment or exposure to an intense light source are common methods of pumping. And usually the active medium must be contained within a suitable optical cavity, such as a pair of highly reflecting mirrors. The cavity provides the feedback for lasing. To extract energy from the cavity, one of the mirrors is partially transmitting. The output of the cavity is an intense, highly monochromatic beam of light.

Compared to light from other sources, laser light can be much more intense, monochromatic, and directional. Lasers producing such light with wavelengths ranging from the ultraviolet to the far infrared are now available. In fact, some lasers can be tuned to cover a wide range of wavelengths. The many applications of laser light take advantage of one or more of its unusual properties.

Normally, a laser is developed ***before*** its applications are conceived. But our program for enriching uranium presented the reverse situation—the application was at hand, but lasers with the required properties did not exist.

The properties demanded of an infrared laser for the first step in our enrichment scheme, selective vibrational excitation of $^{235}UF_6$ molecules, were a wavelength near 16 micrometers, narrow frequency bandwidth, high energy per pulse (greater than 0.1 joule), and short pulse length (on the order of 0.1 microsecond). Another highly desirable, if not mandatory, property was tunability, either continuous or in discrete steps. Our search for such a laser began about eight years ago with suggestions from

within and without the Laboratory. Among the suggestions were the following: a 16-micrometer CO_2 laser based on different vibrational levels of the molecule than is the 10.6-micrometer $C0_2$ laser; an optical parametric oscillator based on the nonlinear crystal cadmium selenide (CdSe); nonlinear frequency mixing of carbon monoxide (CO) and CO_2 lasers in the semiconductor cadmium germanium arsenide ($CdGeAs_2$), a material referred to at the time as unobtainium; optically pumped carbon tetrafluoride (CF_4 or ammonia (NH_3) lasers; and frequency shifting of the output of the 10.6-micrometer CO_2 laser by Raman scattering.

Because of early success with the optical parametric oscillator and the frequency-mixed CO-CO_2 laser, these two lasers were the main tools for our early experiments. Later, the optically pumped CF_4 and NH_3 lasers were demonstrated experimentally and were developed as high-energy lasers. These are still used in some of our experiments. The 16-micrometer CO_2 laser was successfully demonstrated but proved to have the wrong frequency for the process,

The most powerful laser system at 16 micrometers results from Raman scattering of the 10,6-micrometer CO_2 laser's output by the second rotational energy level in parahydrogen. (Raman scattering refers to an interaction of photons with a molecule in which the scattered photons undergo a frequency change determined by the molecule's rotational or vibrational energy levels.) Suggested early in the program, this concept is covered by a patent issued to its Los Alamos originators. We did not pursue its development until it was experimentally demonstrated about three years ago at Stanford University and at Exxon Nuclear Co., Inc. A system based on this concept is now the major 16-micrometer laser under development for the program, Its energy per pulse is greater than 1 joule, its pulse length is typically 50 nanoseconds, and its frequency is variable over a sufficient range. In addition, the system is efficient, converting as much as 40 per cent of the 10.6-micrometer input energy into 16-micrometer laser light.

The second step of our enrichment scheme, dissociation of the vibrationally excited $^{23S}UF_6$ molecules into $^{235}UF_5$, required a laser with a wavelength in the ultraviolet and, like the infrared laser, with high energy per pulse, short pulse length, and tunability. The rare-gas halide lasers, which were developed in 1975, satisfied these requirements. The rare-gas halides belong to a class of diatomic molecules, referred to as excimers, that have a stable excited electronic state and an unstable ground state. This situation is ideal for a laser because a population inversion is easily produced and maintained.

The first rare-gas halide lasers yielded only millijoules of energy and were cumbersome to operate, The technology grew rapidly, however, and today these devices are relatively compact, easy to operate, and produce energies in excess of several joules at repetition rates of one to several hundred hertz.

The rare-gas halide lasers that we have used for isotope separation experiments (and their wavelengths in nanometers) are ArF (190), KrF (254), XeBr (282), XeCl (308), and XeF (354). The wavelengths of these lasers can be increased or decreased by Raman scattering involving vibrational levels of hydrogen, deuterium, or methane. These additional wavelengths provide the opportunity to study the enrichment process as a function of ultraviolet laser frequency over a very broad range.

Much of the technology of rare-gas halide lasers and their Raman shifting was pioneered at Los Alamos. In terms of intensities and repetition rates, the rare-gas halide lasers available today are suitable for use in a production plant prototype. The goals of current development include the increased reliability and longer operational life required for a full-scale plant. ■