Overview of High Energy Lasers: Past, Present, and Future?

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Overview of High Energy Lasers: Past, Present, and Future?

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The first high energy lasers were demonstrated in the mid-1960s and have made tremendous strides over the past 40+ years. This paper presents a sampling of the older work, some recent high energy laser technologies, and a discussion of what might come to be over the next 20 years.

I. Introduction

In this paper I will attempt to provide a brief historical review of the evolution of lasers with a focus on high energy laser systems. Additionally, some applications of various lasers are discussed and my personal vision of where some of the higher power systems may be headed over the next 20 years. For a paper of this magnitude I will start by saying that this will be a woefully inadequate review of the magnificent work performed by 10s of thousands of amazing scientists and engineers who have contributed in some way from conception to present over the past 60+ years to the field of lasers...I apologize ahead of time to those whom I will be unable to mention, but I have tried to reference other topical review papers, chapters, and books that have more complete information of the many high energy laser systems. This paper is intended only to provide the reader a "taste" of the many high energy laser systems, but it is far from comprehensive. Books by Perram *et al*. [Perram, 2010] and Nielsen [Nielsen, 2009] provide a more complete look at high energy laser systems and their effects, respectively.

Einstein published the concept of stimulated emission in 1916 [Einstein, 1916; Einstein, 1917]; this critical revelation was enabling for the later conception and development of the "laser" (light amplification by stimulated emission of radiation), a term coined by Gould [Gould, 1959]. The field of quantum mechanics took off in the early 1900s and went in a variety of different directions as scientists grappled with understanding this new physics (notably, we are still grappling). At the same time, significant advances in the areas of optics and electromagnetic fields allowed scientists to start merging these fields of study into a more comprehensive understanding of the world that we live in. In the 1950s the field of what is called "quantum electronics" was born. Townes led the developments in the United States and created the first "masers" (microwave amplification by stimulated emission of radiation) [Gordon, 1955], while Basov and Prokhorov led the development in Russia [Basov, 1956]. In late 1957, Gould wrote his initial notes on the concept that would later lead to a 30-year patent war. In 1958, Schawlow and Townes publicly proposed the idea of infrared and optical masers [Schawlow, 1958], and the race to create the first laser began [Hecht, 2005]. The reader is referred to the classic textbooks of Siegman [Siegman, 1986] and Verdeyen [Verdeyen, 1995] for excellent discussions of laser physics and various historical facts.

II. The Ghost of Lasers Past

Maiman [Maiman, 1960] was the first to demonstrate a pulsed laser (ruby), which was quickly followed by a continuous wave (CW) demonstration with a He-Ne gas mixture [Javan, 1961]. Following these demonstrations, the 1960's and 1970's brought in the laser with great fanfare and a lot of "Hollywood". Rapid advances were made in a number of technologies, but there was always the statement (part joke, part truth) that "the laser was a solution looking for a problem" and this needed to be addressed. Weapon-type "ray guns" were commonly envisioned (and liberally used in the movies), but practical size of such systems proved (and still proves, though less so) to be a daunting challenge, especially so for handheld weapon systems. Still, several impressive high energy laser systems were developed in this time period, many of which still have useful purposes today.

2.1 CO_2 Discharge Lasers

The CO_2 gas discharge laser was the earliest high energy laser system to develop. Patel [Patel, 1964a] was the first to recognize that one could utilize electrically excited vibrational states of N_2 to transfer their energy to CO_2 and create a laser system. The basic process is to create a discharge in an N_2-CO_2-He gas mixture [Patel, 1965], which

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produces a vibrational distribution of excited states of N_2 that subsequently transfer their energy into the lasing state of CO_2 through a much simplified reaction mechanism

$$N_2(v=0) + e^- \leftrightarrow N_2(v\geq 1) + e^- \quad (1)$$

$$N_2(v=1) + CO_2(00°0) \leftrightarrow N_2(v=0) + CO_2(00°1) \quad (2)$$

$$CO_2(00°1) \rightarrow CO_2(10°0) + h\nu\ (10.6\ \mu m) \quad (3)$$

The He in the mixture provides necessary heat conduction to the walls. Variations also exist that are designed to preferably transfer their energy to the $CO_2(02°0)$ state and subsequently lase in the 9.6 μm range, Fig. 1 [Plinski and Abramski, 2007, Fig. 6A.3] A wide variety of DC-excited and RF-excited systems have been developed, continuous wave (CW) and pulsed, along with more exotic controlled avalanche discharge systems. Excellent topical reviews of CO_2 gas discharge lasers are presented by Plinski and Abramski [Plinski, 2007] and Hill [Hill, 2007], and many of the important papers are provided in a collection edited by Eden [Eden, 1999].

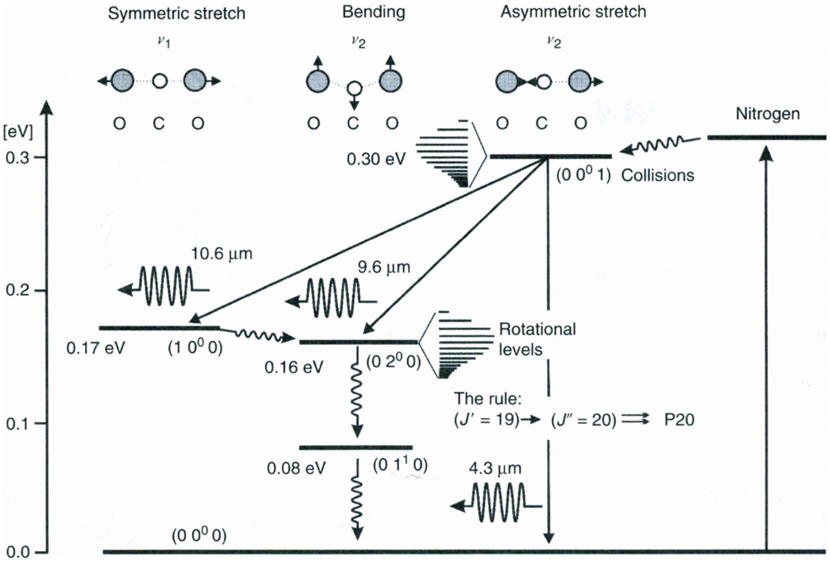

Fig. 1: Vibrational-rotational CO_2-N_2 energy level diagram showing the three quantum numbers (stretching and bending modes) of CO_2 [Plinski and Abramski, 2007, Fig. 6A.3, with permission].

The electrically driven CO_2 discharge laser has evolved into one of the more practical systems available today up to power levels of around 25 kW. These systems have exceptional reliability, stable output, and excellent beam quality. These attributes made the CO_2 laser the “gold standard” to which other laser systems are compared in terms of industrial materials processing such as laser cutting, welding, and marking. The only drawbacks to these laser systems are (1) the wavelength limits how tightly the beam can be focused, (2) the wavelength will not transmit through fiber optics and requires mirror systems to transport the beam from device to work piece, and (3) occasional maintenance that requires recharging of the gas supply and electrodes. These drawbacks have been mostly overlooked until recent years with the emergence of the solid state laser (SSL) and fiber laser systems, Sections 3.2 and 3.3; the impact of these newer systems is discussed later in Section 4.

2.2 The CO_2 Gas Dynamic Laser (GDL)

The CO_2 gas dynamic laser (GDL), a thermodynamically driven variant of the gas discharge CO_2 laser discussed in Sect. 2.1, was the earliest very high energy laser system to be developed that exceeded 100 kW. Basov et al. [1967] were the first to propose a thermally driven fluid dynamic system in which the thermal vibrational distribution of N_2 at high temperatures of > 1000 K could be frozen in a rapid supersonic expansion (typically Mach 4) and act as an energy reservoir for CO_2 lasing in the downstream resonator cavity. This system avoided some of the complications of electric discharge technology used in earlier systems (it should be noted that these issues have for the most part been resolved over the following decades). Fein et al. [Fein, 1968] were the first to publish a successful result with this concept. The basic process is to thermally heat an N_2-CO_2 gas mixture to around 1500 – 2000 K, which produces a vibrational distribution of excited states of N_2 that subsequently transfer their energy into the lasing state of CO_2, again through reaction (2) with subsequent lasing via (3) above, Fig. 1.

The GDL system is wonderfully discussed in a paper by Gerry [Gerry, 1970], as well as a more complete description in Anderson’s classic text [Anderson, 1976]. A more recent detailed mechanism for GDL kinetics can be found in Hokazono et al. [Hokazono 1991] and Ebina et al. [Ebina, 1994]. Small amounts of water vapor (typically around

1% mole fraction) were found to substantially improve laser performance by quenching the lower laser level to the CO_2 ground state and thus enhancing laser gain and power output. Many of the fluid dynamic issues in GDLs of the laser cavity and diffuser sections are comprehensively discussed in Boreysho et al. [Boreysho, 2007]. The GDL was the first high energy laser to achieve CW power levels of 100s of kW [Duffner, 1997].

Other variations of this system have included CO in the gas mixture [Belkov, 1980] or have been driven by solid combustion processes [Beletskiy, 1974]. More advanced versions were proposed by Cassady et al. [Cassady, 1979]. The GDL efforts culminated with the Airborne Laser Lab (ALL) experiment in which missiles were shot down from an airborne GDL platform [Duffner, 1997]. While GDLs were proven to be fairly reliable and relatively inexpensive to operate, the 10.6 μm wavelength presents some problems from a weapons standpoint [Horkovich, 2006]. Few GDLs are in use today; those that still are operational are used principally for laser effects testing on materials. However, GDLs may still represent a useful technology if they could be made compact enough such that raw power combined with very good beam quality could overcome other disadvantages.

2.3 CO and CO Overtone Discharge Lasers

Legay and Legay-Sommair [Legay, 1964] postulated the possibility of a CO discharge laser system, which was closely followed by a demonstration from Patel and Kerl [Patel, 1964b]. CO laser systems, while in many ways similar to CO_2 discharge laser systems, are kinetically very different. In the CO discharge lasers the electrical energy is predominantly coupled directly into the CO molecules, followed by a tremendous amount of vibrational-vibrational (V-V) energy exchange and fundamental ($\Delta v=1$) and first overtone ($\Delta v=2$) lasing [Bergman, 1977]:

$$CO(v=0) + e^- \leftrightarrow CO(v\geq1) + e^- \tag{4}$$

$$CO(v) + CO(v) \leftrightarrow CO(v-1) + CO(v+1) \tag{5}$$

$$CO(v+1) \rightarrow CO(v) + h\nu\ (\approx 4.7\text{-}8.2\ \mu m),\ \text{fundamental lasing} \tag{6}$$

$$CO(v+2) \rightarrow CO(v) + h\nu\ (\approx 2.5\text{-}4.2\ \mu m),\ \text{overtone lasing} \tag{7}$$

The detailed study of the vibrational transitions in CO by Treanor et al. [Treanor, 1968] led to a critical analytical expression and understanding of a non-Boltzmann distribution for high vibrational levels, subsequently referred to as the Treanor distribution.

The range of available wavelengths for CO is quite intriguing, Fig. 2 [Ionin, 2007a, Fig. 5.1], and covers a number of absorption lines for molecules of interest. CO lasers have demonstrated excellent electrical efficiencies (ratio of laser power output to electrical power input) of 30-50% in the fundamental and 11% in the overtone (and theoretical estimates as high as 25% for the overtone) [Ionin, 2007a].

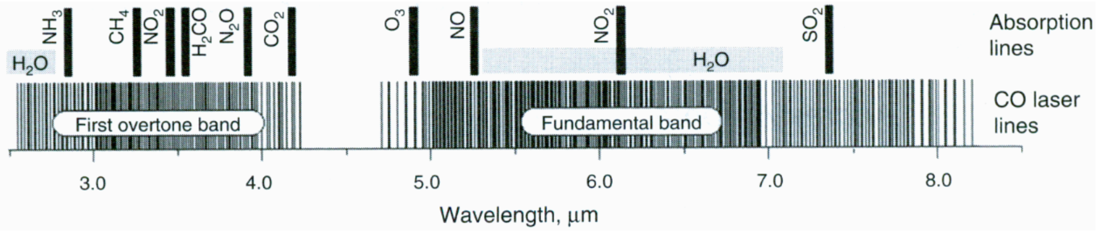

Fig. 2: Spectral lines of fundamental and overtone CO along with spectral absorption lines of some molecules [Ionin, 2007a, Fig. 5.1, with permission].

The CO discharge laser has evolved into a generally reliable system and achieved power levels > 100 kW in output power for short periods of time. An excellent topical review of the CO discharge lasers (both fundamental and overtone) is provided by Ionin [Ionin, 2007a].

Flowing fundamental CO chemical lasers that were not discharge driven were also developed. A review of these systems is presented in Bronfin and Jeffers [Bronfin, 1976]. The reaction sequence involved $CS_2 + O \rightarrow CS + SO$, followed by $CS + O \rightarrow CO(v>0) + S$, with subsequent lasing. While intriguing from an energetic standpoint as compared to HF/DF systems (Sect. 2.5), these chemically driven devices struggled to create sufficient quantities of O atoms required for high power operation. Further, the cavity pressures were also an order of magnitude larger than HF/DF, which resulted in larger density gradients and worse beam quality. As a result of these difficulties, the chemically driven CO systems never received as much attention as the discharge driven CO systems or the HF/DF chemical lasers.

2.4 Excimer and Exciplex Lasers

Ideas for "excimer" (excited dimer) or "exciplex" (excited complex) lasers have been around since the demonstration of the first laser. Houtermans [Houtermans, 1960] hypothesized a super maser working in the optical spectrum using excimer molecules as good candidates for efficient laser media. Basov *et al*. [Basov, 1970] demonstrated copious Xe_2* emission, but the first explicit and unequivocal excimer laser demonstration was performed by Hoff et al. [Hoff, 1973]. This demonstration was followed by a flurry of rare gas halide variants, including XeF [Ault, 1975] and XeBr [Searles, 1975], among many other molecular variants. Excellent topical reviews of excimer/exciplex lasers are presented in Ewing [Ewing, 2000] and Yakovlenko [Yakovlenko, 2007], and many of the important papers are provided in a collection edited by Eden [Eden, 1999]. The basic 4-level excimer/exciplex system involves a sequence of (1) pumping atoms via electron interactions, (2) excimer/exciplex formation through association reactions, (3) lasing from the excited excimer/exciplex state, followed by (4) rapid dissociation of the resulting ground state collision pair, Fig. 3, this latter step being critical.

An enormous amount of work in the excimer laser area has occurred over the past several decades. Significant efforts were made to turn these systems into high energy laser systems for military purposes, but were ultimately unsuccessful because of reliability issues of the foils necessary for the electron beams that would excite the species. However, the remarkable work with excimer/exciplex systems resulted in a stable and critical industrial role in a variety of lower energy (but still reasonably high pulsed power) commercial applications, most notably in the semiconductor industry for producing ever-faster computer microprocessors. This type of laser proved ideal for these applications due to their excellent beam quality and UV wavelengths that enable a very tightly focused beam size for the ever-shrinking size of the microprocessors.

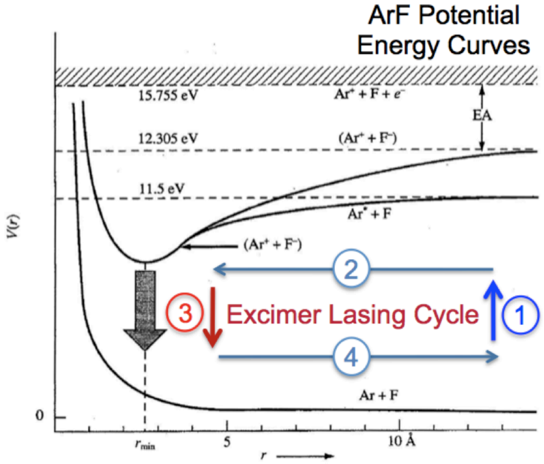

Fig. 3: Excimer/exciplex lasing cycle schematic and energy level diagram for ArF [Verdeyen, 1995, Fig. 10.33, modified with permission].

2.5 HF/DF and HF Overtone Lasers

The HF/DF chemical laser efforts represent some of the most amazing work during the first 40 years in the field of very high energy lasers, including several systems that "almost" made it to the field, but were bypassed for the "Ghost of Lasers Present" (Sect. III). The HF/DF systems were the backbone of the Reagan-era "Star Wars" program. The reader is referred to the bible of HF/DF chemical lasers by Gross and Bott [Gross, 1976] for detailed discussions of these systems, a summary paper by Sentman [Sentman, 2001], a book chapter by Behrens and Lohn [Behrens, 2007] that provides a more recent perspective, and Horkovich [Horkovich, 2006] who outlines several of the HF/DF laser systems that were envisioned, but not built and tested until after "the Handbook" [Gross, 1976] was published.

Most HF/DF chemical laser studies addressed a system characterized exclusively by what was called the "cold reaction," in which a source of F atoms would mix and react with H_2 or D_2, Eq. (8) [note that D_2 and D can replace H_2 and H in Eqs. (8-12) with different heats of reaction in Eqs. (8-10)]. The HF system was first demonstrated by Kompa and Pimentel [Kompa, 1967] in pulsed mode, and soon thereafter in CW operation by Spencer *et al.* [Spencer, 1969]. A "hot reaction" variant, Eq. (9) was originally thought to have more potential because of its higher exothermicity, but disappointing laser performance experiments with the "hot reaction" were found to be the result of a critical collisional decomposition reaction, Eq. (10), that decomposed the high vibrational levels of HF/DF into the reactants for the "cold reaction" [Detweiler, 2005]. Lasing was initially demonstrated on the fundamental Δv=1 bands, Eq. (11), and later on the first overtone Δv=2 band of HF by Jeffers [Jeffers, 1989], Eq. (12) (note that DF overtone lasing has not been demonstrated to date, but could be readily accomplished).

"Cold reaction"	$F + H_2 \rightarrow HF(v,J) + H$	$v = 1,2,3$	$-\Delta H = 31.5$ kcal/mol	(8)
"Hot reaction"	$H + F_2 \rightarrow HF(v,J) + F$	$v = 3,4,5,6$	$-\Delta H = 98.0$ kcal/mol	(9)
"Collisional Decomposition"	$H + HF(v\geq 3) \rightarrow H_2 + F$	$v \geq 3$		(10)
Fundamental lasing	$HF(v,J) \rightarrow HF(v-1,J+1) + h\nu$	≈ 2.5-3.2 μm for HF, ≈ 3.5-4.2 μm for DF		(11)
Overtone lasing	$HF(v,J) \rightarrow HF(v-2,J+1) + h\nu$	≈ 1.35-1.40 μm, ≈ 1.85-2.00 μm for DF		(12)

A far more comprehensive and recent review of HF/DF kinetics was assembled by Manke and Hager [Manke, 2001].

A schematic of a typical combustor driven HF/DF laser system is shown in Fig. 4. The more advanced systems incorporated trip injectors or ramped nozzles for mixing/performance enhancement. The trip jets and ramped nozzles create a flow distortion that stretches the reactant interface such that the reactant gases mix and react more rapidly thereby increasing the laser gain and decreasing the losses; these effects are best described in a pair of papers by Driscoll [Driscoll, 1986; Driscoll, 1987]. Other advanced mixing schemes utilized notched injector tubes to induce vortices for rapid mixing [Pannu, 1976; Solomon, 1982].

Several important lower dimensional simulation models were developed in the 1970s and 1980s [Emanuel, 1971; O'Keefe, 1979; Sentman, 1981; Sentman, 1989] for HF/DF. One of the most interesting scientific kinetic findings discovered during the intense (pardon the pun) HF/DF chemical laser era was the role of rotational non-equilibrium in describing the behavior of vibrationally pumped lasers and showed that certain observed behaviors, such as simultaneous multi-line lasing, could only be described by very fast, but measurably finite [Polanyi, 1972; Hinchen, 1975], rotational relaxation in the case of fast pumping and rapid collisional deactivation [Sentman, 1975]. Simultaneous multi-line lasing on a single v-level is not allowed by rotational equilibrium models. Sophisticated three-dimensional models were developed in the 1990s that built upon prior work, but were able to more accurately simulate the complex fluid dynamic vortex structures formed by transverse cross flow jets that would increase mixing [Lohn, 1990; Lohn, 1999].

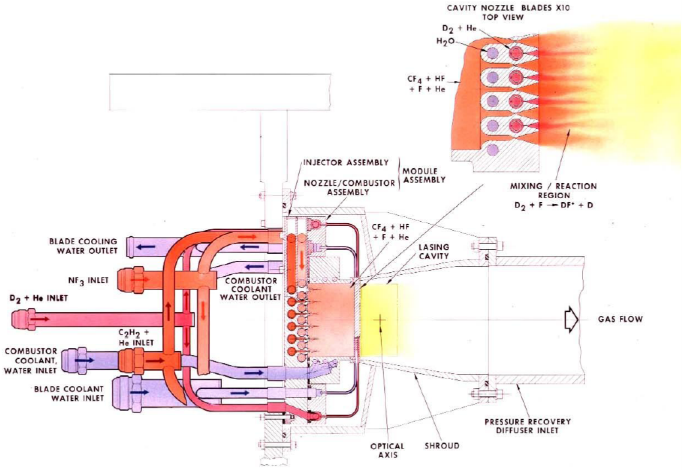

Fig. 4: Schematic of a combustion driven DF laser system, the Navy ARPA Chemical Laser (NACL) [Behrens, 2007, Fig. 7.17, with permission courtesy of Northrop Grumman Corp.].

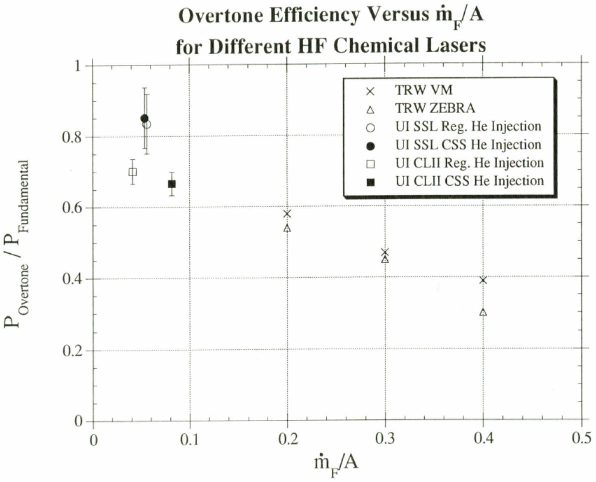

Fig. 5: Overtone efficiency as a function of the fluorine flow rate per unit of nozzle bank area [Carroll, 1993, Fig. 3, with permission].

The demonstration of the first HF Overtone laser by Jeffers [Jeffers, 1989] enabled the high energy HF laser to operate at a more attractive wavelength range of 1.35 – 1.40 μm and set off a new wave of detailed experimental and theoretical studies by different groups. The overtone wavelengths were of significant interest to the military for both atmospheric transmission and laser "brightness" reasons [Horkovich, 2006]. Overtone efficiencies of 50-70% relative to the fundamental performance were demonstrated [Duncan, 1991; Carroll, 1993], Fig. 5. This result is of particular importance because an HF overtone laser with 50% of the fundamental and having approximately half the wavelength of the fundamental would result in an increase in intensity/brightness by a factor of 2× for the overtone due to a λ^{-2} dependence [Horkovich, 2006].

The HF/DF laser programs resulted in several multi-100kW and MW-class systems including BDL, NACL, MIRACL, and Alpha [Horkovich, 2006]. MIRACL was utilized for over 25 years at White Sands Missile Range High Energy Laser Test Facility (HELSTF) for a variety of high energy laser testing including supersonic missile shoot downs. The Alpha-laser was to be the first Space Based Laser (SBL) demonstrator system, but the program was terminated in 2002 despite having developed and integrated most of the necessary technologies. The system that was closest to military in-the-field development was the ground based DF Tactical High Energy Laser (THEL);

this technology was designed for the Army to be mobilized (MTHEL) and protect against incoming rockets, artillery and mortars (RAM), and had multiple demonstrations of shooting down salvos of incoming rockets. The MTHEL program was terminated in 2006, also after having demonstrated and integrated most of the necessary elements. Despite the highest performance in terms of laser power output per unit of reactants, HF/DF lasers had met with the Ghost of Lasers Present, and high-level decisions were made to move to a next generation of laser systems.

2.6 Other Chemical and Molecular Lasers

Other hydrogen-halide lasers (HCl, HBr, and HI) also received considerable interest in the 1960s and 1970s. Kasper and Pimentel demonstrated the first pulsed hydrogen-halide chemical laser with HCl [Kasper, 1965]. While intriguing, these systems could never match the power output per unit of reactant of the HF/DF systems, principally because the HF/DF reactions are more energetic. Today they are of interest only for a limited number of wavelength specific applications.

A broad range of metal vapor lasers (MVL) were developed in the time frame of 1965-1980. These had the advantage of a very wide distribution of wavelengths ranging from the deep ultraviolet (UV) into the infrared (IR). These systems had the advantage of being able to have short pulse durations and very narrow laser linewidths, but have been progressively superseded by more modern solid state and fiber laser systems. The copper vapor laser (CVL) is one of the best known of these systems with wavelengths typically in the visible and achieved power levels in the range of several 100s of Watts. He-Cd laser systems were also very popular for their visible wavelengths. Sabotinov [Sabotinov, 2007] provides an excellent review of MVL systems, and many of the important papers are provided in a collection edited by Eden [Eden, 1999]. MVL systems still play an important role in a variety of lower energy experiments and processes requiring wavelengths in the UV and visible, but never attained power levels large enough to be of interest for military weapon systems.

III. The Ghost of Lasers Present

Several exciting lasers have evolved dramatically over the past 20 years and represent the state-of-the-art lasers of the present. These range from the most evolved chemical laser system, to solid state and fiber systems, to relatively new electrically driven gas laser systems, and to the exotic free electron laser.

3.1 The Chemical Oxygen-Iodine Laser (COIL)

The chemical oxygen-iodine laser (COIL) was first demonstrated in 1978 [McDermott, 1978]. This system operates on the electronic transition of the iodine atom at 1315 nm, $I(^2P_{1/2}) \rightarrow I(^2P_{3/2})$ [denoted hereafter as I^* and I respectively]. The lasing state I^* is produced by near resonant energy transfer with the singlet oxygen metastable $O_2(a^1\Delta)$ [also denoted as $O_2(a)$]. Since that initial demonstration, COIL technology has undergone numerous improvements [Truesdell, 1992; Zagidullin, 1998; Kodymova, 2007, Endo, 2007]; Fig. 6 illustrates a schematic of a basic supersonic COIL. Chemical efficiencies as high as 36-40% using nitrogen diluent have been demonstrated [Rybalkin, 2005]. Many of the fluid dynamic issues in COILs of the laser cavity and diffuser sections are comprehensively discussed in Boreysho *et al*. [Boreysho, 2007], and excellent overviews of COIL are given by Davis *et al.* [Davis, 2007] and Kodymova [Kodymova, 2007].

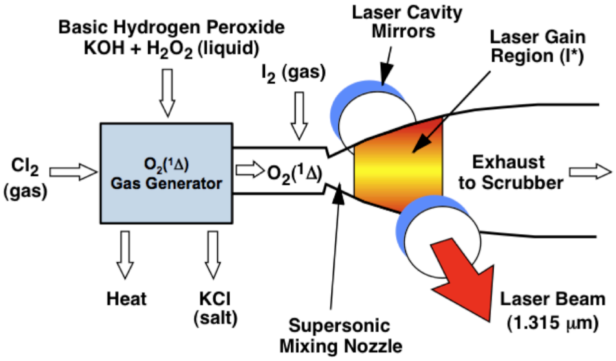

Fig. 6: Schematic of basic supersonic COIL elements [Carroll, 1998, Fig. 2, with permission].

The liquid singlet-oxygen generator (SOG) technology for relatively low pressures (20-70 Torr) has developed to a fairly mature state; a number of SOG concepts have been investigated including rotating disk [Harpole, 1992], jet-type [Zagidullin, 1991], uniform droplet-type [Thayer, 1994], and mist-type [Muto, 2002] systems. Correspondingly, a number of injection and nozzle schemes have been studied to improve mixing and performance in these lower pressure regimes [Carroll, 2000; Furman, 2001; Endo, 2006]. Elements of the COIL kinetics still remain a puzzle, but a better understanding is still of significant interest [Azyazov, 2009; Rosenwaks, 2010].

However, the major thrust in COIL technology in the past decade has been to increase the total pressure of the system for better pressure recovery by utilizing SOG designs and mixing schemes more suitable for higher pressure regimes. The ability to increase the total pressure and Mach number of the flow, while at the same time maintaining good iodine mixing, cavity kinetics, and generator pressure can have a dramatic impact on the overall system by simplifying the pressure recovery system (by reducing the amount of fluids and weight of ejector hardware) [Boreysho, 2009]. Appropriate SOG concepts that have been investigated include a twisted aerosol (TA-SOG) system [Adamenkov, 2000], a centrifugal bubble SOG [Nikolaev, 2005], a centrifugal flow SOG [Emanuel, 2004; Shi, 2008], and a centrifugal spray SOG [Kodymova, 2007]. High pressure nozzle and mixing enhancement studies by Nikolaev [Nikolaev, 2000; Nikolaev, 2002] and Yang [Yang, 2000] with ejector-mixing nozzles along with detailed modeling [Yang, 2000; Waichman, 2009; Madden, 2010] have provided important insights into the nozzle mixing issue and COIL pressure recovery performance. The ejector mixing nozzle concept put forward by the Russian Lebedev Physical Institute research group at Samara [Nikolaev, 2000] appears particularly promising and the design evolved through later work over several years [Zagidullin, 2001; Hager, 2003; Zagidullin, 2005]. Recent research evolving from the Nikolaev *et al*. [Nikolaev, 2000] design utilized vortex inducing notched ejectors [King, 2011; Vorobieff, 2011] to further enhance gain generator mixing efficiency and laser performance for systems having better pressure recovery potential.

COIL technology culminated with the Advanced Tactical Laser (ATL) demonstration of penetrating the hood of a moving truck [Skillings, 2009], and the Airborne Laser (ABL) that successfully shot down a ballistic missile in the boost phase [Skillings, 2010]. The ATL and ABL performed critically important overall systems technology demonstrations given the complexity of the overall system that includes the laser, beam control, adaptive optics, aero-optics, thermal management and flow control systems, sophisticated pressure recovery (the ATL system was notably a closed system with no exhaust), and distance tracking required to keep the beam spot on target for the necessary time for penetration. The ABL has been re-dubbed the Airborne Laser Testbed (ABLT) to perform continued technology demonstrations.

3.2 Solid State Lasers (SSL)

The first solid state laser (SSL) was in fact the very first laser demonstrated by Maiman [Maiman, 1960] using flashlamp pumping. While this was a remarkable achievement, flashlamp pumping always inhibited the electrical efficiency of these systems. The gain medium for an SSL is crystal rod or slab (sometimes very thin) that is doped with a rare-earth element such neodymium, erbium, ytterbium, etc.; the different dopants enable a range of different wavelengths. One of the most common crystalline materials used-to-date has been yttrium-aluminum-garnet (YAG). It was not until SSLs were married to diode lasers as the pump sources [Fan, 1988] that the electrical efficiency began to be improved to levels attractive to a mobile military platform. Hall *et al*. [Hall, 1962] and Nathan *et al*. [Nathan, 1962] were the first to demonstrate laser diodes. Shortly thereafter Holonyak and Bevacqua demonstrated visible laser diodes [Holonyak, 1962], often called the “light emitting diode” (LED).

At the turn of the century the diode pumped SSLs (DPSSL) were making rapid strides. Goodno et al. [Goodno, 2001] demonstrated 415 W of CW power with 30% optical conversion efficiency, followed by 19 kW in a phase-locked zigzag slab array configuration [Goodno, 2006; Goodno, 2007]. These efforts culminated in the demonstration of 105 kW “tiled” phase-locked system, Fig. 7, with a DC power-to-optical efficiency of 19.3%, an average beam quality (BQ) of 2.9, and a run time of greater than 300 seconds [McNaught, 2009] (often referred to as the Joint High Power Solid State Laser – JHPSSL – program). Seven 15 kW master oscillator-power amplifier (MOPA) laser chains were coherently combined in this system. The largest criticism of the SSL-based high energy lasers is thermal gradients that create BQ issues. The direction and application of these systems in the future will likely depend on the amount of improvement that can be achieved.

A branch of the SSL area that is showing significant promise is that of the Thin Disk Laser (TDL). This concept was proposed nearly two decades ago by Giesen *et al*. [Giesen, 1994], and an excellent summary of this version of the SSL is provided by Giesen and Speiser [Giesen, 2007]. Greater than 35 kW of CW laser output power have been obtained with this configuration with reasonable beam quality. The primary issues that still need to be resolved are to (i) further improve the output beam quality, and (ii) to push the output power levels to yet higher power.

Another area of interest is that of the ultrashort pulsed laser systems [Kremeyer, 2008; Eisenmann, 2008; Keller, 2010]. Significant advances have been made and very short pulse systems of 10s – 100s of fs pulse width are now available. Interesting applications include filament formation in the atmosphere. These systems are certainly high power and intensity during the pulse, but are not high energy (high average power) systems. It is unclear at this point how effective such systems could be for military applications.

The Navy recently utilized a Northrop Grumman-built SSL system to demonstrate shipboard defense by disabling the motor of a small boat at more than a mile distance on the Maritime Demonstration Laser (MDL) program [Keyes, 2011].

Another SSL variant is the High-Energy Liquid Laser Area Defense Systems (HELLADS) that utilizes a series of thin disk amplifiers immersed in a coolant to alleviate thermal problems that are currently a problem for the high power SSL systems [Warwick, 2009]. No public information is available on the performance of this system.

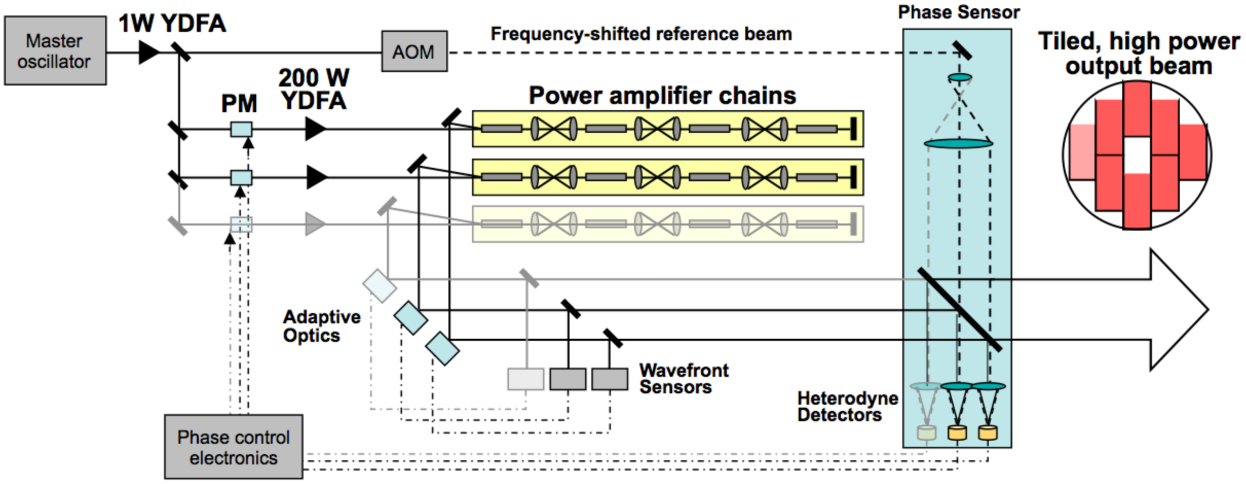

Fig. 7. Schematic of a 105 kW phase-locked SSL system [McNaught, 2009, Fig. 1, with persmission]. YDFA = Yb-doped fiber amplifier, PM = phase modulator, and AOM = acousto-optic modulator.

3.3 Fiber Lasers

The concept of a fiber maser/laser was presented by Snitzer as early as 1961 [Snitzer, 1961], and demonstrated three years later by Koester and Snitzer [Koester, 1964]. For two decades these systems evolved slowly, but with the need to feed the ever-growing demands of the internet in the 1990s, the field of fiber optics for high-speed communications and data transfer experienced explosive growth. A side-pumped 4 W fiber laser was reported by Goldberg et al. [Goldberg, 1999], and a phased 4-element fiber system producing 8 W was reported a few years later [Anderegg, 2003]. But these systems were dwarfed by a 2 kW industrial system reported by Gapontsev [Gapontsev, 2002]. A schematic of a laser diode pumped fiber laser system is shown in Fig. 8. Phase locking is seen by some as the best way to achieve very high power fiber laser systems; significant progress has been made in this area with 470 W being reported having very good beam quality [Anderegg, 2006; Goodno, 2007]. Goodno et al. [Goodno, 2007] and Rothenberg and Goodno [Rothenberg, 2010] provide excellent reviews of advances in beam combination and potential limitations. Motes and Berdine [Motes, 2009] provide a superb review of high power fiber laser systems.

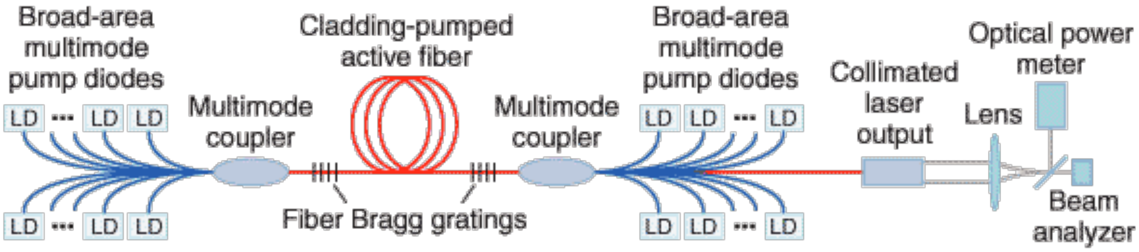

Fig. 8. Schematic of a single fiber laser system pumped by multiple laser diode (LD) sources [Gapontsev, 2002, Fig. 2, with permission].

The current state-of-the-art in high energy systems are the 10 kW single-mode fiber lasers built and sold by IPG Photonics [IPG Photonics, 2011] having wall plug efficiencies > 30%. IPG also sells systems as large as 50 kW, but with considerably worse BQ (> 30). One significant issue that will be difficult, if not impossible, to overcome in single fiber lasers is that the very high power densities will inherently initiate stimulated Brillouin scattering (SBS);

this phenomenon will limit the output power of single fiber lasers [Smith, 1972]. There are some approaches to enabling higher fluence in the fibers, e.g. doped fibers [Dragic, 2011], but there will still be limits. Intriguing work with incoherent beam combination of high power fiber lasers is also being performed [Sprangle, 2009]. A recent successful demonstration of this technique for military application was performed on the LaWS program [Schriempf, 2011].

3.3 Free Electron Lasers (FEL)

The free electron laser (FEL) was first demonstrated by Madey *et al.* [Madey, 1971; Madey, 1973; Deacon, 1977]. This is a uniquely different high energy laser system. An FEL utilizes relativistic electrons accelerated from an e-beam source that is then injected into an alternating magnetic field (sometimes called an undulator or "wiggler"). The free-electron classical interaction with the electromagnetic fields enables a laser gain region from which an optical resonator can extract useful energy in the form of a laser beam. The basics of FEL systems are expertly described in texts by Yariv [Yariv, 1989] and Freund and Antonsen [Freund, 1992].

One of the unique features of this system is that the emitted wavelength is tied to the energy of the electron beam and the magnetic field strength of the wiggler, but is not tied to any specific quantum states of any atoms or molecules. This provides the FEL the unique advantage of being able to tune the emission wavelength over a very broad range from soft-X-rays to mid-infrared. While this is a tremendous advantage, one would still have to change the mirrors to be appropriate for any particular wavelength, so once the system is tuned for one wavelength it would require some setup and realignment to change to a different wavelength, i.e., this is not an operation that can be done rapidly, almost certainly not in the heat of a battle. Another historical disadvantage of FEL systems are size, weight, and electrical efficiency. However, the Navy views these disadvantages as mostly acceptable (for large ships that can accommodate these deficiencies) in trade for advantageous wavelengths that transmit much better through the sea spray that all naval ships contend with on a constant basis.

It is theorized that MW-class FELs can be developed [Todd, 2000; Sprangle, 2004] and major advances towards this end have been accomplished in the past decade [Benson, 2007; Barletta, 2010]. To date, a 14.3 kW CW FEL demonstration was reported [Benson, 2007].

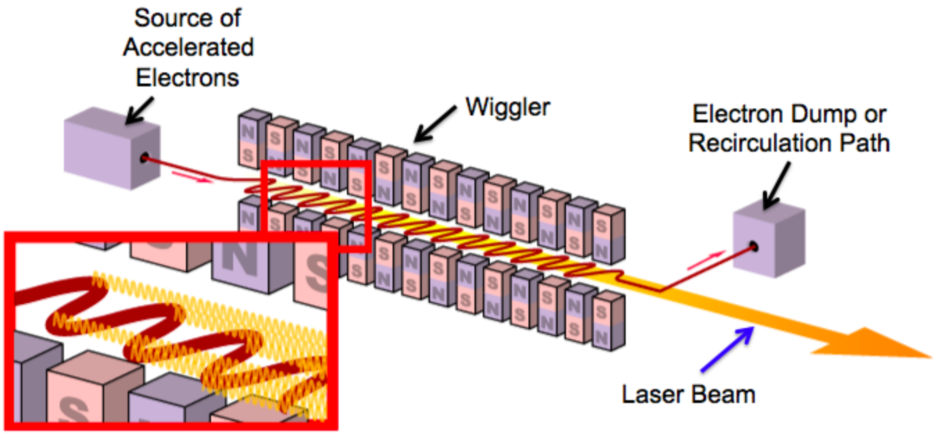

Fig. 9: Schematic of a basic free electron laser (FEL). Not shown are the optical resonator, the initial electron beam injection angle, and the electron beam recirculation loop of recent FEL devices [Modified version of a figure publicly available online].

3.4 The Electric Oxygen-Iodine Laser (ElectricOIL or EOIL)

The electrically driven oxygen-iodine laser (ElectricOIL), Fig. 10, that was first demonstrated by Carroll *et al.* [Carroll, 2005] operates on the same electronic transition of the iodine atom at 1315 nm as does COIL. The lasing state I^* is also produced by near resonant energy transfer with the singlet oxygen metastable O_2(a), however in this case the O_2(a) is generated by an "electric" discharge rather than via a "chemical" reaction (as is the case in COIL). Since the first reporting of a viable electric discharge-driven oxygen-iodine laser system (also often referred to as EOIL or DOIL in the literature), there have been a number of other successful demonstrations [Hicks, 2005; Davis, 2008]. Computational modeling of the discharge and post-discharge kinetics [Stafford, 2004; Palla, 2006; Palla, 2007; Braginsky, 2007] has been an invaluable tool in ElectricOIL development, allowing analysis of the production of various discharge species [$O_2(a^1\Delta)$, $O_2(b^1\Sigma)$, O atoms, and O_3] and determination of the influence of NO_X species on system kinetics. Ionin *et al.* [Ionin, 2007b] and Heaven [Heaven, 2010] provide comprehensive topical reviews of discharge production of O_2(a) and various EOIL studies. Motivated by work at Rakhimova *et al.* [Rakhimova, 2003], the radio frequency (rf) discharge ElectricOIL studies have focused on transverse discharge configurations [Woodard, 2011]. During the past year, the highest reported gain in an ElectricOIL device was 0.30 % cm^{-1} [Carroll, 2011], with an output power of 109 W [Zimmerman, 2010].

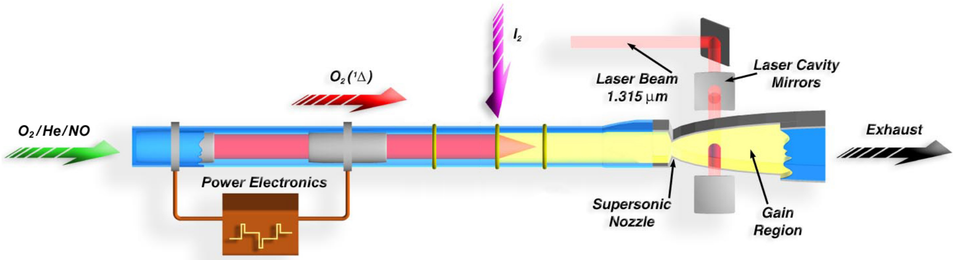

Fig. 10: Schematic of basic supersonic ElectricOIL elements.

Intriguing mysteries still remain to be solved with the ElectricOIL system, e.g., an unidentified kinetic mechanism that delays gain recovery [Zimmerman, 2009], but through systematic development and understanding, the outcoupled laser power has improved more than 600-fold since the first demonstration in 2005. As the ElectricOIL device has increased in gain length and pressure it has to date scaled in a "super linear" fashion in both power output and electrical efficiency; this provides considerable encouragement for very large systems with high quality beams. Further, very promising early results with an iodine pre-dissociator [Benavides, 2008] and a catalytic process that enhances O_2(a) downstream of the discharge [Lee, 2009] show the potential for very significant increases to the gain and laser power. This system, in my admittedly biased opinion, is one of the exciting possible high energy laser systems of the future.

3.5 The Diode Pumped Alkali Laser (DPAL)

Approximately eight years ago, Krupke *et al.* [Krupke, 2003] demonstrated an optically-pumped atomic Rb laser operating on the resonance line at 795 nm. This scheme is commonly referred to as a diode pumped alkali laser (DPAL), and an equivalent pictorial representation for the Cs version of DPAL is illustrated in Fig. 11. Several other important studies followed the initial DPAL demonstration including theoretical modeling [Beach, 2004; Hager, 2010; Komashko, 2010], demonstration of lasing with other alkalis [Beach, 2004; Zhdanov, 2007a], lasing with helium as the $^2P_{3/2} \rightarrow {}^2P_{1/2}$ relaxer gas rather than ethane [Zhdanov, 2007b; Zweiback, 2009], a multi-diode pump scheme has produced 48 W of output power at 894 nm [Zhdanov, 2008], and a high power diode stack has produced an average output power of 145 W at 794 nm [Zweiback, 2010]. The level of interest in the laser community is rising rapidly because it appears that this laser may offer a route to extremely high power levels. The primary reason for the interest is that it allows one to use high power semiconductor laser diodes as the pump source to drive a gas laser.

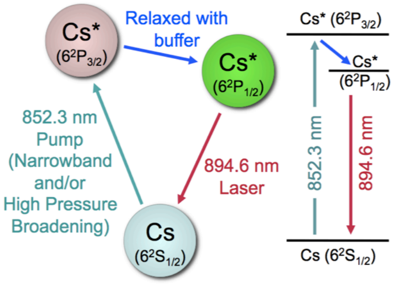

Figure 11. Pictorial representation of the DPAL scheme for pumping the cesium Cs($6^2P_{3/2}$) state, resulting in lasing on the Cs($6^2P_{1/2}$) → Cs($6^2S_{1/2}$) transition at 894.6 nm (in vacuum, 894.3 nm in air) [Palla, 2011, Fig. 1, with permission].

However the basic DPAL pumping scheme has some drawbacks. Because the atomic transition that is being pumped is spectrally very narrow (≈ 10 GHz, or equivalently ≈ 0.02 nm), only a limited portion of the semiconductor laser power will be absorbed by the alkali vapor because common semiconductor lasers typically emit with spectral widths of > 1000 GHz (roughly 2 nm). To surmount this difficulty, Krupke *et al.* [Krupke, 2004] proposed adding He gas (or other gas) to broaden the linewidth of the transition. Unfortunately, to do this with He (which has a pressure broadening coefficient of approximately 20 GHz/atm at a wavelength of 800 nm), one must add up to 25-50 atmospheres (19,000-38,000 Torr) of gas if the pump transition linewidth is to match the spectral breadth of the semiconductor laser [Krupke, 2004; Beach, 2004]. One alternative is to narrow the linewidth of the pump laser. While significant advances have been made in this area [Podvyaznyy, 2010], this approach dramatically increases the cost, and scaling of such narrow linewidth diode stacks to very high power is still uncertain. A phenomenon which appears to have some benefits for this problem is pump wave bleaching [Hager, 2010; Komashko, 2010], however it is not yet clear to what extent this phenomenon will alleviate the problem of uniform pumping of the gain medium in a DPAL system.

3.6 The Exciplex Pumped Alkali Laser (XPAL)

The XPAL approach takes a different course to this problem by invoking a molecular interaction to allow us to pump away from the atomic resonance but still obtain efficient lasing from the atom itself. Consider, for example, the CsAr molecule. It has been known for three decades [Hedges, 1972; Chen and Phelps, 1973] that the interaction of Cs and Ar atoms forms collision pairs that can absorb photons to create exciplexes (or excimers). The result is that mixtures of Cs vapors and Ar gas exhibit strong absorption tens of Å (several nm) away from the atomic resonance. An alkali-rare gas cell relying only on Lorentzian absorption will have a difficult time absorbing the pump radiation from a high-efficiency, broadband (≈ 2 nm) diode laser source, whereas absorbing the pump radiation in the exciplex wings can be easily accommodated. For conceptual clarity, Cs-Ar interaction potentials including illustrations of the two Cs-Ar XPAL system pumping pathways and the four- and five-level laser operation mechanisms are shown in Fig. 12. The four- and five-level laser operation mechanisms are further illustrated in Fig. 13. Note that the pump and lasing path of the four-level XPAL system is the reverse of the standard excimer/exciplex laser, Figs. 3 and 12. A more detailed discussion of XPAL, as well as differences and similarities to DPAL systems may be found in [Readle, 2009; Heaven, 2010; Galbally-Kinney, 2010].

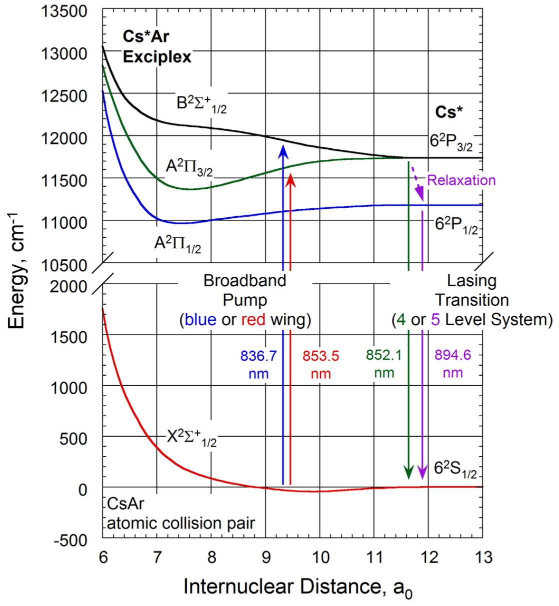

Fig. 12: Interaction potentials of Cs-Ar. The arrows indicate the various pumping pathways, with two variations of the XPAL scheme shown. Laser action at 852.1 nm and 894.3 nm correspond to four- and five-level operation respectively [Palla, 2011, Fig. 3, w/ permission].

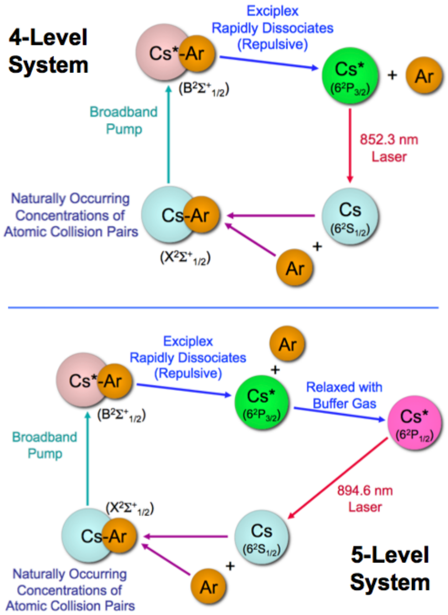

Fig. 13: Pictorial representations of four- and five-level XPAL operation respectively using either pumping pathway [Palla, 2011, Fig. 3, with permission].

The exciplex pumped alkali laser (XPAL) system was demonstrated by Readle *et. al.* [Readle, 2008; Readle, 2010] in pulsed mode in mixtures of Cs vapor, Ar, and ethane, by pumping Cs-Ar atomic collision pairs and subsequent dissociation of diatomic, electronically-excited CsAr molecules (exciplexes or excimers). The four- and five-level variations of the pulsed XPAL system have also been modeled by Palla *et. al.* [Palla, 2010], and predicts higher XPAL performance as the rare gas pressure increases, and that higher output powers are obtainable with higher temperature. A preliminary theory is in reasonable agreement with experimental data and suggests that different alkali-rare gas mixtures (other than CsAr) may be better candidates for a scaled CW XPAL system [Palla, 2011]. Regardless, quasi-CW and CW experiments need to be performed to prove out the viability of XPAL for scaling as a military weapon system.

IV. The Ghost of Lasers Yet to Come

Accurate predictions of the future have been empirically shown to be rather difficult to make. However, we note that some general visions have been intriguingly close, e.g. H.G. Wells predictions of invisible beams of heat in his classic novel *War of the Worlds* [Wells, 1898]:

> "It is still a matter of wonder how the Martians are able…to generate an intense heat…they project in a parallel beam against any object they choose by means of a polished parabolic mirror…Heat, and invisible instead of visible light. Whatever is combustible flashes into flame at its touch, lead runs like water, it softens iron, cracks and melts glass…"

Nonetheless, to identify exactly which high energy laser technologies will be the ones being used in 20 years (let alone even 10 years) is an exercise in guesswork based upon what is published today and a little bit from the surprises over the past 20 years. I am very confident that I will not be as prescient or profound as was H. G. Wells.

Keys to mission success will depend upon laser power that can be generated, the efficiency of the system (electrical or chemical), the beam quality of the outcoupled laser, the wavelength of the beam, the size of the vehicle (be it an airplane or helicopter, a ship, or a ground vehicle) carrying the laser system, and of course the requirements of the mission itself (among other factors). Just as different missile systems are used for different missions, it is highly doubtful that any single type of laser system will be best suited for all missions, and for this reason it is critical that multiple systems continue to be pursued and evolve.

The U.S. Navy's LaWS program [Horkovich, 2007; Schriempf, 2011] is a logical approach to integrating laser systems as a complement to existing more conventional defense systems, i.e., the addition of these lasers is not an effort to replace existing systems, but to add capability to existing systems that may not be able to do the job under all conditions. A laser has clear disadvantages in poor weather conditions, so this is all the more reason to make a laser a complementary defense system as opposed to a replacement in the near future. It is my general belief that in approximately 10 years (factoring in current political and national fiscal conditions) we will see major military acquisition programs for laser weapon systems in the 1 – 50 kW range to complement existing defensive systems, and it is also my belief that these systems will be primarily fiber lasers. In 15-20 years, I can also envision robust semi-portable fiber laser systems the size of current 50-caliber weapons, but with heavy additional boxes for power supply/conditioning and an electrical generator; such systems would require a small squad of soldiers.

Regardless of which laser systems are considered, they must all face important beam propagation and beam quality issues to become a "weaponized" system in a practical sense. Cook [Cook, 2005], Horkovich [Horkovich, 2006], Sprangle *et al*. [Sprangle, 2009], and Bohn [Bohn, 2010] have written excellent papers that discuss these issues.

With the dramatic emergence of the fiber laser for materials processing applications, I am of the belief that CO_2 and CO discharge lasers will be phased out almost entirely over the next 20 years. A few will still remain for niche markets, but the heavy industrial companies will adopt the fiber laser for its wavelength which couples better to most metals, and the ease of delivering the beam from device to work piece through fiber optics is a major advantage.

HF/DF laser work has stopped in the United States and Russia, but continues in China [Lei, 2008]. These systems have significant energy output-to-weight advantages because of their highly energetic chemical species, and by the same token those chemicals (reactants and products) are logistically problematic for armed forces. However, if space-based platforms are ever again seriously investigated, we will likely see an HF or HF Overtone system considered because of the tremendous power-to-weight advantage.

While the current political environment is such that the future of COIL is very unclear, COIL is the most powerful high energy laser in existence today, having excellent beam quality, and the ABL/ABLT program has demonstrated technological feats that, in my opinion, are even greater than the Apollo program that landed men on the Moon. Further, there are a number of suggested design improvements to all elements (the SOG [Emanuel, 2004; Kodymova, 2007; Shi, 2008], the gain generator [Nikolaev, 2000; King, 2011], and the diffuser/ejector [Boreysho, 2009; Noren, 2009; Madden, 2010]) of the ABLT that suggest that the sum of these enhancements could result in a factor of 2-4 enhancement in power-to-weight ratio (larger if some of the predictions are to be believed). While the logistics of COIL are still not easy, they are manageable and this potential level of enhancement may make the system a more viable weapon system. At the very least, it is my strong belief that it makes excellent sense to continue operating and enhancing the ABLT over an extended time period to evolve our understanding of how to properly evolve such weapons systems, not just from a laser use standpoint, but also from a beam control, beam propagation, and operating mobile vehicle standpoint.

It is my opinion that in 20 years, the chemical and gas lasers will remain the only Megawatt-class systems that retain excellent beam quality for long distance strategic military applications (I acknowledge my personal bias in this area as it has been my area of expertise). It is my (biased) vision that a fully scaled Megawatt-class ElectricOIL system will supplant the SOG (with the aqueous chemicals and Cl_2 gas being replaced by advanced battery systems) and gain generator of the ABLT in 15 years, and fully operational testing will begin at that time.

DPAL appears to be a very intriguing system, but based upon experimental issues at CW power levels above 50 W there are questions about how well the system will scale, i.e., the electrical-to-optical efficiency has been decreasing with power for the CW systems. The current DPAL theories that are baselined to lower power data suggest excellent scaling, but there are likely some missing factors (possibly photo-ionization at high intensity) since the experiments are not scaling linearly at higher average powers. The future of DPAL is very unclear at the moment, but there are likely some engineering solutions that will permit the system to scale into the 10-100 kW power range.

While initial pulsed XPAL experiments and modeling look intriguing, quasi-CW and CW experiments need to be performed to prove out the viability of XPAL as a military weapon system. The largest concern for XPAL is that the absorption cross-section is small enough to require very high pump intensities to drive the system; it may be possible to accommodate this through the best choice of the alkali-rare gas mixture, and optimized pump and gain volume design. Early modeling indicates that XPAL is a more efficient large system than a small system [Palla, 2010]. However, even if XPAL encounters scaling issues at very high energy, I believe that XPAL may make an excellent laser guide star system with 50-100 W output power because it can lase the sodium lines via the blue-wing pumping.

Are there any surprise gas lasers left? The bulk of atoms and molecules for gas lasers have been investigated to date, along with knowledge of the wavelengths associated with their quantum transitions. Other all gas phase iodine lasers have been created [Henshaw, 2000; Masuda, 2010], but the chemistry involved (HN_3 or NCl_3) makes these unlikely candidates for scaling. It is my opinion that we will not see any new gas laser surprises for the high energy laser field. Interesting developments in DPAL systems recently produced blue laser beams through multi-photon absorption [Pitz, 2010], but it is unclear if this process can be made efficient enough to develop into a high energy system.

Tremendous advances have been made in the SSL and fiber laser technologies, but they also face equally tremendous challenges to scale to very high power levels exceeding 100 kW with excellent beam quality. The notion of scaling SSL technology to today's power level seemed an impossible task 25 years ago. I must confess that I did not think the systems would ever get beyond 1 kW with good beam quality, which should immediately give the reader pause about any predictions that I make in this discussion! Fiber lasers were essentially unheard of 25 years ago, and are now at the forefront of the mid-range tactical laser systems (1-50 kW) and are supplanting all laser systems in the industrial cutting and welding market. There are many technical challenges for SSL and fiber systems, but the two key factors that will be critical to achieving excellent beam quality at power levels > 50 kW will be materials issues to handle the thermal stresses and optical phasing at such tremendous high energy loadings. Significant enhancement of the materials and laser systems for "eye-safer" wavelengths > 1.4 μm are almost certain to occur, so I expect that many of the high power systems will be lower efficiency, but have operational wavelengths for which scatter would have no significant effect on the human eye. It is likely that ceramic materials may be required to handle the thermal issues for SSL systems, and in 20 years I am confident that the reliability of manufacturing these materials will have improved to the point that they can be used very effectively for the high energy systems. Further work with thin-disk SSL systems and liquid cooled systems such as HELLADS will also likely play a role in improved performance of these future SSL systems. Ultra-short pulse lasers will likely find a niche in the military world due to peculiar phenomena specific to their very short pulse lengths and high intensities that are still being investigated; but I do not see them as high "energy" laser systems, just very high pulse power.

The U.S. government, the Department of the Navy in particular, has invested a great deal of money into FEL technology. From the bizarre perspective of my saying for the past 20 years that a high power FEL system would never be viable (similar to my vehement predictions at that time that the Tampa Bay Buccaneers and New Orleans Saints would never win a Super Bowl), I will conclude that I must be wrong and therefore we will see significantly powerful FELs develop in 20 years. Admittedly, these will be massive, require large volumes of hardware, be power hungry, and have a low overall electrical efficiency, but this may be acceptable on a naval ship for a system that meets particular needs for shipboard defense in a difficult sea spray environment. Through more hard work, 100 kW FELs with excellent beam quality now seem viable to me in the next 20 years, but they will require tremendous power input because of their low electrical efficiency.

V. Concluding Remarks

The demonstrations of the ALL, MIRACL, THEL, ATL, ABL, LaWS, and MDL systems provide exceptional credibility to the notion of using high energy lasers for military applications, and helps to quantify and assess system effectiveness and utility.

It is my opinion that in 20 years, the chemical and gas lasers will remain the only Megawatt-class systems that retain excellent beam quality for long distance strategic military applications (I acknowledge my personal bias in this area as it has been my area of expertise). It is my (also biased) vision that a fully scaled Megawatt-class ElectricOIL system will supplant the SOG (with the aqueous chemicals and Cl_2 gas being replaced by advanced battery systems) and gain generator of the ABLT in 15 years, and fully operational testing will begin at that time. In my estimation, and trying to factor in my own complete underestimation of where SSL technology is today, I believe that we will have SSL, fiber laser, and FEL systems of around 100 kW with excellent beam quality in 20 years; these will be perfect for tactical military situations, and fiber laser systems will almost certainly be the first fielded tactical high energy laser systems on a large scale (in terms of number of systems).

I will close this overview with a perspective: to develop any new technology into a sophisticated weapon system takes considerable time…typically well more than decades! Our species started out with clubs, spears, knives, bows and arrows, and later swords as we learned how to mold bronze and steel…we still use these technologies to a degree as the low-cost (sometimes last ditch) option, but even to get to the bronze age took thousands of years. Consider further how long it took to develop reliable canons, rifles and handguns…roughly 1000 years if you go back to the invention of gunpowder by the Chinese in around 850 C.E. (with the argument that they were relatively reliable by around 1850 C.E.). Rockets and early means of controlling/guiding them are an extension of fireworks, which also date back a rather long time. Missiles (ballistic, cruise, and space) and mortar systems are a further extension of rockets. Even attempts at flight date back over two millennia (!) to Icarus and Daedalus, or more scientifically to the likes of Leonardo da Vinci some 500 years ago. The real anomaly in weapons systems development was the nuclear bomb, but in many ways the groundwork was all laid for delivering "the bomb", it just required new and remarkably devastating physics to devise it. Lasers have been around now for 50+ years, and in fact low power versions (<10 W) have been very effectively incorporated into numerous weapons systems, e.g., ranging, laser guided bombs, etc. But large scale laser weapons are still evolving and will require patience to develop them into the next generation of weapons technology…but I am of the adamant belief that lasers are in fact the next generation weapons and it will continue to require significant and consistent funding by nations to adequately develop this relatively new area. But key to this evolution will be to exercise what I will call "Mark I" systems such as the ABLT and the LaWS concept…only through starting to deploy such systems will the warfighters learn how to use them effectively, and quite likely to discover clever ways to use them not envisioned by the scientists and engineers.

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