High-Brightness Ultraviolet Excimer Lasers

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Abstract. At present the performance of short-pulse rare-gas-halide excimer-laser systems is definitely below that of solid-state systems, as far as the maximum peak-power is concerned. However, short-pulse excimer lasers are expected to be the best candidates to produce the highest focused intensities (I > 10^{20} \text{W/cm}^2) provided by the shorter wavelength and less optical distortion in the gaseous active medium. This is especially feasible if the present performance of short-wavelength focusing optics is improved, and the problem of the limited extraction efficiency of excimers is solved. In this paper the results of former developments, novel methods, such as spatially-evolving chirped-pulse amplification, off-axis amplification, interferometric multiplexing, and some considerations for the achievable maximum brightness of table-top excimer systems are presented.

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In view of the recent advances in femtosecond solid-state technology, solid-state-based high-power laser systems have become an important work-horse in high-intensity experiments. Based on the well-developed high-energy amplifier technology and using the so-called Chirped-Pulse-Amplification (CPA) technique [1, 2], peak powers of several tens of TW have been reached [3–5]. These results seem to be hard to beat by other lasers. At present, the excimer-based short-pulse laser systems are operating up to a somewhat lower level [6–22]. However, in most of the high-intensity experiments, it is the focused intensity which has to be considered as the major figure of merit for the performance of the pump-laser system. This is the point, where the better focusability of short-wavelength gas lasers becomes a dominant advantage [23, 24]. This is easily seen by comparing the focusability of the different laser systems [5, 9, 17–22].

It is a general tendency that the development of lasers is striving towards ever shorter wavelengths. By frequency conversion of infrared or visible laser pulses, the wavelength range can be extended, but at the expense of energy and stability. At certain wavelengths direct generation of pulses in the UV is possible by excimers with high efficiency [25]. The bandwidth of the gain curve of excimers is significantly narrower than that of dyes, but still allows the amplification of subpicosecond pulses [23, 24, 26]. Among the various excimers XeF, XeCl, KrF and ArF are the most often used and are the main candidates for short pulse amplifiers, having their lasing wavelengths at 351, 308, 248 and 193 nm, respectively. (In spite of the great success of short-pulse amplification using the XeF (C→A) transition [27], in the present study this excimer transition is disregarded because of the longer (visible) wavelength. Also F\(_2\) has been left out because of its very low efficiency and the technical difficulties associated with the short (λ = 157 nm) wavelength [28].)

For the comparison of solid-state and excimer-based laser systems, the most important features are summarized in Table 1. It is known that the saturation energy density of solid-state materials is in the J/cm\(^2\) range, while for excimers it is ~1000 times smaller, lying in the mJ/cm\(^2\) regime [29–41]. This is roughly proportional to the maximum extractable energy from a given cross-section; that is why solid-state lasers can be much more efficiently used for high-energy application. The host material is solid-state and noble gas for solid-state and excimer lasers, respectively. The noble-gas host material with its low density and low nonlinearity results in ease of propagation of the beam in excimer amplifiers, without the danger of self-focusing, phase front distortion and self-phase modulation. Due to the different intensity level for the appearance of nonlinearities in excimers and solid-state systems and due to the very different value of their saturation energy density, direct amplification of subpicosecond pulses is only possible in excimers. In solid-state systems, saturated amplification of subpicosecond pulses corresponds to an intensity level where nonlinearities prevent any operation. The so-called Chirped-Pulse Amplification (CPA) [1, 2] scheme is devoted to overcome this problem, where the intensity of the pulse is lowered in the amplifier by temporal stretching and compression of

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The storage time for solid-state materials is in the ~ tens of nanoseconds, allowing complete extraction of the stored energy on optimum focusing. This can be explained by the different energy storage capabilities of both active media. Development of short-pulse ultraviolet excimer-laser systems or pulse duration. This makes the spatial coherence of the focused intensities reported in the literature are comparable for both systems [5, 17, 18]. It is interesting to note that one of the most important figures of merit in the development of short-pulse ultraviolet excimer-laser systems is the maximum peak power of short-pulse excimer systems. The availability of such a laser system for many laboratories would open a new strong-electric field regime of study for matter-field interaction.

The scope of this article covers the comparison of the different seed-pulse generation schemes, with special emphasis on those based on pulsed dye lasers (Sect. 1), the discussion of the amplification of short pulses in different excimers (Sect. 2) and the identification of those factors which limit the performance of short-pulse excimer-laser systems (Sect. 3). The following sections are devoted to answer the points listed in Sect. 3 for the case of KrF by introducing several new methods (spatially evolving chirped-pulse amplification (Sect. 4), off-axis amplification (Sect. 5) and interferometric multiplexing (Sect. 6), which are regarded, or already proven, to be straightforward in increasing the maximum brightness of laboratory-scale short-pulse excimer systems. In Sect. 7 considerations for the avoidance of phase and pulse front distortions for large aperture beams and preliminary focusing experiments are reported. Some historical developments of short-pulse amplification in excimers are also traced, highlighting those advances which resulted in the most significant increase in brightness while keeping the complexity of the system moderate.

### 1 Seed-Pulse Generation: General Features of Hybrid Dye/Excimer Lasers

In excimers the pulse-shortening methods used for solid-state and dye lasers are hardly applicable. Therefore, excimers are mainly used for amplification of frequency-converted short pulses which are generated by means of dye, or more recently by solid-state lasers. The schematics of such a scheme using dye lasers is indicated in Fig. 1a, incorporating a short-