Off-Axis Amplification Scheme for Short-Pulse Amplifiers

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Abstract. A novel geometry is presented for transversally pumped, short-pulse dye and discharge-pumped excimer amplifiers. Significant increase of the homogeneity and of the cross-section of the active medium seen by the short pulses is accomplished by proper choice of the incident angle of the beam to be amplified. The proposed scheme makes it possible to substitute the sophisticated wide aperture, homogeneously pumped amplifiers by standard devices.

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Dye amplifiers are often classified as longitudinally or transversally pumped amplifiers. Longitudinal pumping is a commonly used technique in dye amplifiers, where the pump beam and the signal beam have practically the same direction [1–4]. This imposes strict requirements for the homogeneity of the pump beam and strong limitations for the achievable small-signal gain, especially in the presence of strong excited-state absorption. The former requirement can significantly be decreased by using a small angle between the pump and the signal beam. This results in a certain kind of averaging and homogenizes the active medium seen by the pulse to be amplified (as shown for longitudinally pumped Raman amplifiers in [5]). In order to overcome the second problem transversal pumping for dye amplifiers can be used [1, 2, 6]. In this pumping scheme the direction of the signal pulse is generally determined by the geometry of the dye cell (generally parallel to the front surface) and the direction of pumping is close to perpendicular. The transversally pumped dye amplifiers generally suffer from very poor beam quality. This is due to the one-dimensional, near-exponential decrease of the pump intensity in the active medium and due to the diffraction of the beam at the interface between the active volume and the front window. The exponential feature of pumping introduces an amplitude variation across the beam, and a deviation of the beam through dynamic refractive index changes [7].

These problems were considerably diminished by the introduction of special pumping schemes, like the Bethune cell [8] and optical cones [9, 10], allowing four-fold or rotational symmetry. However, more recent investigations showed [11, 12] that it is difficult to avoid significant destruction of the beam quality, due to thermally and flow-induced refractive index changes. Even using special designs, optimized for optimum flow conditions [12] the achievable beam quality and the highest repetition rate is still much below the value allowed by the standard transversally pumped transversal-flow dye cells [11]. This means that simple transversally pumped amplifiers would give good results if the inhomogeneous distribution of the deposited pump energy seen by the short pulse could be avoided. Some efforts have been made to homogenize the distribution by placing a flat mirror or a saw-tooth shaped reflecting surface behind the front window [13]. However, these partial improvements are only useful for a given beam diameter.

Transversally discharge-pumped excimer amplifiers are similar to transversal dye amplifiers from the point of view of homogeneity of the gain medium seen by the signal pulse. Here the inhomogeneity is caused by the inhomogeneous power deposition in the plane perpendicular to the electrodes. The inhomogeneity is strongly pronounced in the direction perpendicular to the electric field lines. In case of discharge-pumped short-pulse excimer amplifiers there is another problem when using them in the conventional geometry: the limited cross-
sections of the discharge. In short-pulse amplification experiments the achievable output energy is roughly a linear function of the cross-section, due to saturation of the amplification [14, 15] and the influence of nonsaturable absorption [15, 16]. It is shown in [16, 17] that the achievable maximum normalized energy density \( e_{\text{max}} \) – normalized to the saturation energy density \( e_{\text{sat}} \) – is strictly limited in the presence of nonsaturable absorption to \( e_{\text{sat}} = g_0/\alpha \), where \( g_0 \) is the gain coefficient and \( \alpha \) is the absorption coefficient. An energy density, which is several times the saturation energy density, can only be reached with significant loss of gain. For this reason, in excimer amplifiers, having non-negligible absorption, the output energy density has an optimum value regarding efficiency. This value for KrF amplifiers, where \( g_0/\alpha \approx 10 \), is roughly three times the saturation energy density [18].

This is why the availability of wide-aperture homogeneously pumped excimer amplifiers was regarded as the key point to reach high powers in short-pulse excimer-amplification experiments. However, the fabrication of such amplifiers is complicated and can only be done with increased cost, compared to the narrow discharge, unpreionized, standard amplifiers having similar stored energy. From the point of view of wall-plug efficiency, compactness, case of operation and even of maximum stored energy, commercial medium aperture KrF lasers are close to ideal as free-running oscillators. However, their applicability for short-pulse amplification experiments has been limited, due to the limited homogeneous cross-section of the discharge seen by the short pulse in the standard amplification geometry.

In this paper a novel geometry is presented which makes it possible to increase the homogeneous cross-section and/or improve the homogeneity of the active medium, seen by the input pulse, for transversally pumped dye and excimer amplifiers.

1. The Off-Axis Amplification Geometry

The desired increase of the homogeneity and the cross-section can be achieved simply by tilting the amplifier with respect to the input pulse, as displayed in Fig. 1. The plane of the figure contains the conventional optical axis \( (z) \) (on-axis amplification) and that axis which points in the direction where the homogeneously excited active medium has its minimum dimension \( (x) \). This is actually a plane perpendicular to the front surface of the dye cell and to the plane of the two electrodes in side-pumped dye amplifiers and transversally discharge-pumped excimer amplifiers, respectively.

It is seen from Fig. 1 that significant increase of the cross-section is expected for pencil-like \( (z/x \gg 1) \) amplifying media when using them in the off-axis geometry. The homogeneity of the amplified beam is improved, if the active volume has better longitudinal than transversal uniformity (the homogeneity of pumping is better along the axis \( z \) than axis \( x \) in Fig. 1). These are just the conditions which generally occur in dye and excimer amplifiers. In both cases the longitudinal homogeneity is generally good, while the homogeneity along the axis \( x \) is poor. This is due to the exponential decrease of pumping and due to the inhomogeneous energy deposition in the discharge in the case of dye and excimer amplifiers, respectively.

Quantitative comparison of the on-axis and the off-axis amplification scheme have been performed by calculating the line-integral proportional to the excited molecules \( C = \int g_0 d'z' \) across the beam (along \( x' \)) seen by the pulse to be amplified, for different angles \( (\beta) \), where \( x' \) and \( z' \) are the new coordinates in a coordinate system fixed to the input beam (Fig. 1). In these calculations homogeneous (flat-topped) distribution was assumed along the axis \( z \), for \( L = 85 \) cm length and the spatial dependence of the excited molecules along \( x \) was varied.

Figure 2a shows the line integral proportional to the excited molecules across the beam seen by the short pulse for different angles \( \beta \), when a Gaussian distribution, described by \( B = \exp\left(-x/2 \text{mm}\right)^2 \), is assumed along \( x \). The plots were made for angles starting at \( \beta = 0^\circ \) and increasing in \( 0.4^\circ \) steps until \( \beta = 2.4^\circ \). One sees that the peak of the line-integral decreases with increasing angles, but the widths of the distribution increases. This increase is less pronounced for small angles (around \( 0^\circ \)). A homogeneous flat-topped distribution is obtained for angles larger than \( 0.6^\circ \). In this region by proper choice of \( \beta \) one has a