Picosecond mid-infrared amplifier for high average power

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ABSTRACT

High pressure CO_2 lasers are good candidates for amplifying picosecond mid infrared pulses. High pressure CO_2 lasers are notorious for being unreliable and difficult to operate. In this paper a high pressure CO_2 laser is presented based on well developed LC-inversion type excitation circuit. The laser contains internal room temperature catalysts allowing closed loop or rare isotope operation. The laser was designed for 300Hz operation and could achieve this for short time periods and could be operated at up to 200Hz for extended time periods. Some of the design features and experimental results are presented in this paper.

KEYWORD LIST

CO_2 laser, pulse amplification, mid-infrared, picosecond

INTRODUCTION

CO_2 lasers are good candidates to generate ultra-short high energy pulses in the mid-infrared. The vibrational spectra of many molecules fall in this region and therefore a short pulse laser would be useful for studying the photochemistry of these molecules. Short pulses in the mid to far infra-red is also suitable for studying intraband transitions in semiconductors. A short pulse mid to far infrared laser is also an attractive option for emerging applications such as laser particle acceleration. Due to the λ^2 scaling of the pondermotive potential a 1 TW 10 μm pulse is equivalent to a 100TW 1 μm pulse[1,2].

Various techniques based on CO_2 lasers have been used to generate short pulses. These methods usually start with a TEA CO_2 laser that typically produces pulses in the 50-150 ns range. One method of shortening these pulses is to use a semiconductor switch to select a section of the laser pulse. The technique consists of illuminating a semiconductor simultaneously with a TEA CO_2 laser and an ultra-short visible laser. The dense free-carrier plasma created by the visible laser acts as a reflective surface for the 10 micron radiation. A combination of two semiconductor elements, one to switch on the reflection and the other to switch off the transmission can be used to generate pulses as short as 130 fs [3]. Optical free induction decay (OFID) is an alternative method to generate picosecond 10 micron pulses. In this method a plasma shutter is used to truncate a pulse within 10ps. Due to this fast truncation large frequency sidebands are generated. Pulses of between 30 and 200ps can be generated with this method[4].

HIGH PULSE REPETITION RATE HIGH PRESSURE AMPLIFIER DESIGN AND RESULTS

The generation of high energy ultra-short pulses in the 10 micron region require an amplifier with broad enough gain bandwidth. Pressure broadening of the individual ro-vibrational lines of CO_2 causes an overlap of neighbouring lines. The result is that a large gain bandwidth can be obtained. The calculated gain of the 10 micron band of CO_2 is shown in figure 1. As can be seen the gain bandwidth of the individual P or R branches is approximately 30 wavenumbers or 1.0×10^{12}Hz (this is at half maximum). This means that if one uses the relationship

$$\Delta\upsilon\Delta t \geq K$$

and make the approximation that the laser pulse is Gaussian in time i.e. K=0.441, therefore if $\Delta\upsilon = 1.0 \times 10^{12}$ then the shortest pulse that can be amplified without gain narrowing is a pulse of approximately 500 fs. If isotopic mixtures are

XVI International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, edited by Dieter Schuöcker,
Proceedings of SPIE Vol. 6346, 63463B, (2007) 0277-786X/07/$18 doi: 10.1117/12.739382

used then the bandwidth of the amplifier can be significantly improved. A calculated gain curve showing the 9 and 10 micron P and R branches of an isotopic mixture consisting of various isotopic species is shown in figure 2. As can be seen the gain curve is considerably wider than 20 wavenumbers. In fact gain is present, although with some gaps, over a range of 220 wavenumbers. Thus if different isotopes could be found to close some of the gaps then it should in principle be possible to amplify pulses shorter than 500fs.

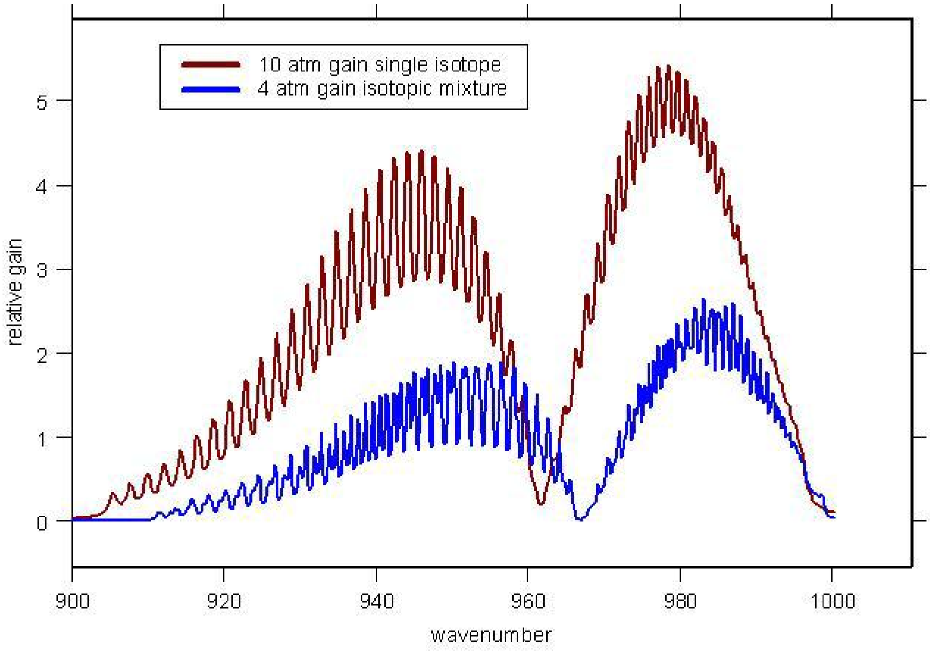

Figure 1 Calculated gain curves of both a 10 atm single isotope and a 5 atm isotopic mixture consisting of 50% $^{12}C^{16}O^{18}O$, 25% $^{12}C^{16}O_2$ and 25 % $^{12}C^{18}O_2$. As can be seen a similar gain bandwidth can be obtained with the isotopic mixture at 5 atm than with the single isotope at 10 atm.

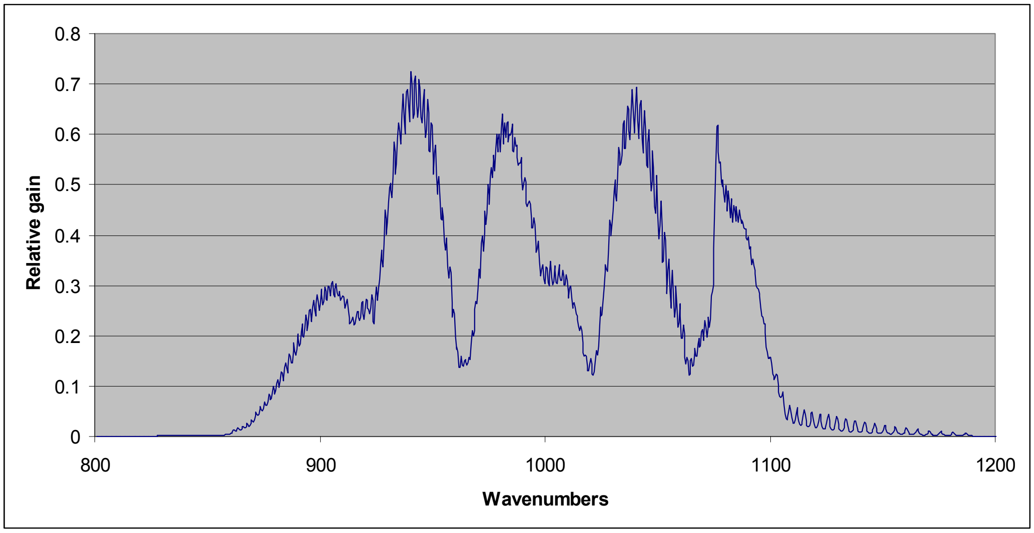

Figure 2 Gain curve of a mixture of 6 isotopes calculated using correction factors published by Freed et al[5]. Both the 9 and 10 micron bands are shown. As can be seen considerable broadening of the gain can be obtained. The following isotopes were used in the calculations $^{2}C^{16}O_2$; $^{13}C^{16}O_2$; $^{12}C^{16}O^{18}O$; $^{12}C^{18}O_2$; $^{14}C^{16}O_2$; $^{12}C^{17}O_2$

High pressure CO_2 lasers are notorious for being difficult to operate and are known to be unreliable. Most of these systems date from the early 80’s to the early 90’s and were typically based on Marx type excitation circuits and used spark gaps as switches. Our present design deviates from these in that it utilizes a standard LC inversion circuit with a pulse compressor and thyratron switching. UV spark pre-ionization is used. This laser was designed to operate at pulse repetition rates of up to 300Hz and contained internal fans and internal room temperature catalysts. This allows closed loop operation and makes the rare isotope operation a possibility.

Two centrifugal fans were installed inside the gas volume and flow modelling using a CFD package was done. An example of results obtained with the flow model is shown in figures 3 and 4. The calculated axial flow velocity is shown in figure 4. The flow velocity through the electrodes is approximately 15m/s. If a clearing ratio of 2.5 is used with a discharge width of 1cm this give a maximum pulse repetition rate of 600Hz.

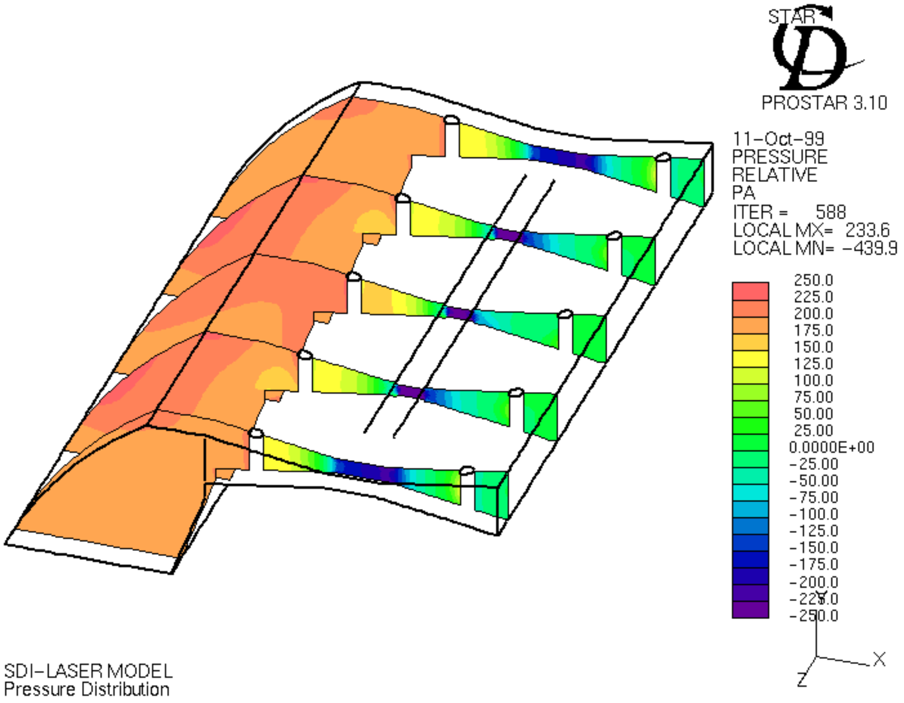

Figure 3 Pressure distribution in the high pressure electrode assembly as calculated by CFD

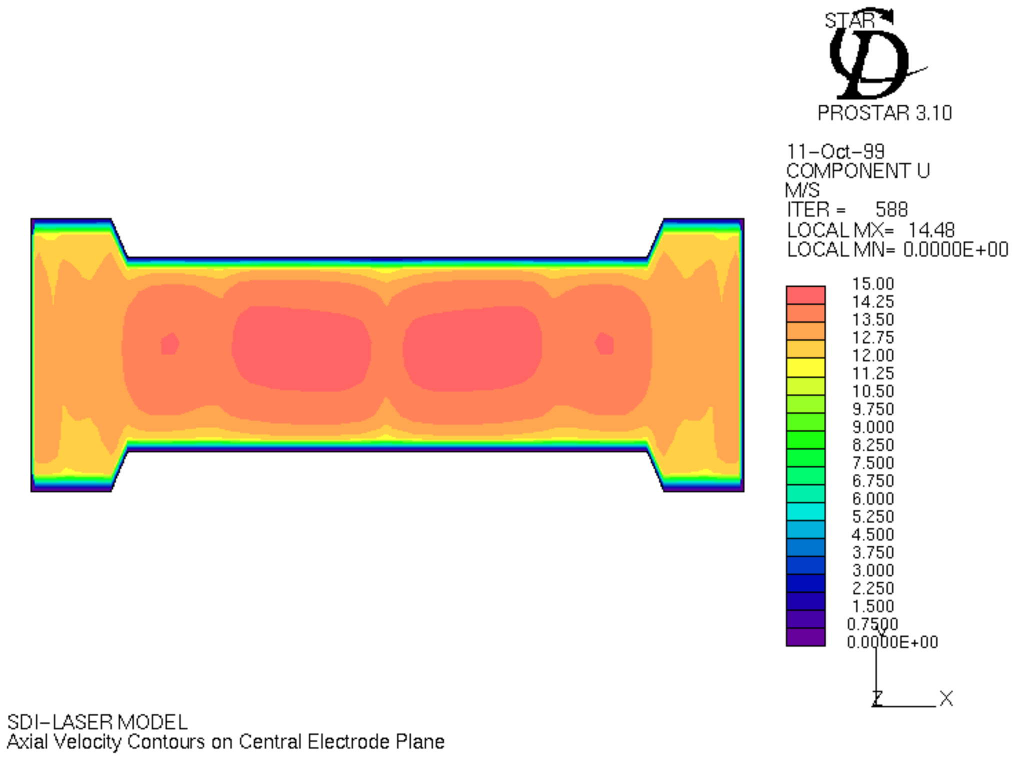

Figure 4 The axial velocity distribution through the electrodes on the centre electrode plane.

Internal room temperature catalysts were installed that allowed extended operation with a single gas mixture. A model was developed to predict the catalysts performance[6] and this was used in the design of this amplifier. A picture of the completed laser is shown in figure 5. The laser was designed to operate at a pressure of 10 atm and at a pulse repetition rate of up to 300Hz. The laser could operate for short time periods at 300Hz but due to catalysts limitations long term operation could be achieved at 200Hz. The measured small signal gain across the electrodes is shown in figure 6. The small signal gain value across the electrodes was approximately 2.2%/cm. The specific measurement shown was for a laser with a 2cm wide discharge area. The values for electrodes of 1 cm wide are similar. The saturation fluence for a multi level system can be written as

$$E_{sat} = \frac{h\upsilon P}{2\sigma z}$$

With σ the stimulated emission cross section and P the pressure of the laser. 1/z is essentially the average number of populated rotational levels. For our case z=0.07 and $\sigma = 1.54\times10^{-18}$ cm^2. Thus for a 10 atm laser the saturation fluence is:

$$E_{sat} = \frac{6.626\times10^{-34}x2.9\times10^{13}\times10}{2\times1/17\times10^{-18}\times0.07} = 1173mJ/cm^2$$

The maximum extractable energy of the laser per cm^3 is given by

$$E_{ext} = \alpha E_{sat}\ell a = 0.022*1173*1*1=26\text{mJ/cm}^3$$

The high repetition rate amplifier that was developed had an electrode length of 40 cm and 1cm^2 discharge area, thus for this specific system the maximum extractable energy is 26*1*40=1040 mJ. Thus for this amplifier operating at a pulse repetition rate of 200Hz the maximum average power that can be extracted is 208 W. This will obviously be limited by the optical damage to the laser output windows. A cooling system as well as a gas purification system was developed for cooling the optics and for blowing clean gas over them this increased the optics lifetime significantly. The use of diamond windows mounted on the Brewster angle can be used to increase the lifetime of the optics even more.

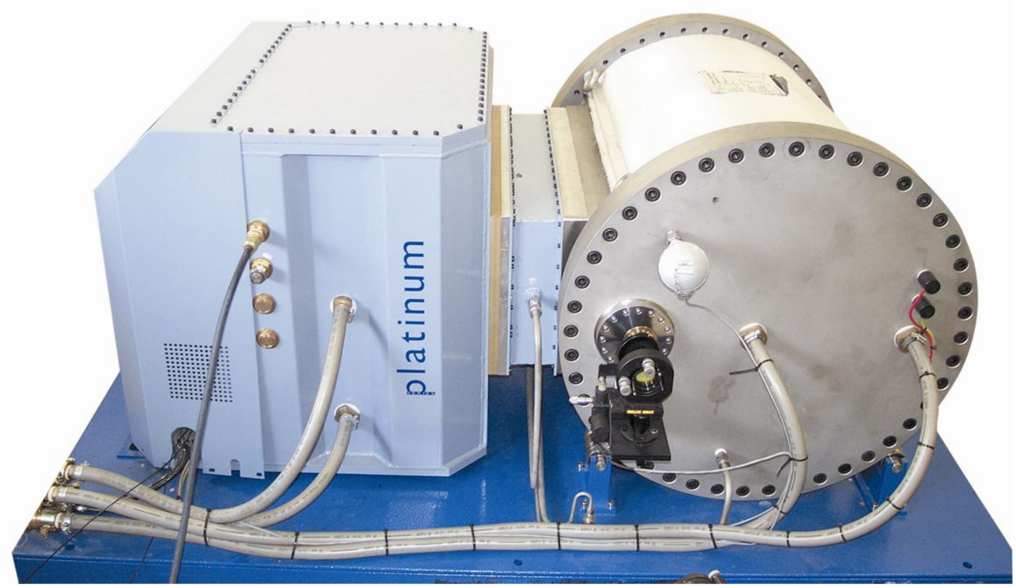

Figure 5 Picture of the completed high pulse repetition rate high pressure amplifier.

Figure 6 Small signal gain measurements of an amplifier with electrodes with a 2 cm gain width

A model was developed to predict the spatial deformation of the pulse as it propagates through the amplifier. The following set of differential and partial differential equations, based on than of Judd[7] were solved simultaneously for pulse propagation through an amplifier

$$\frac{d\delta}{dt} = -\frac{(\delta - z\Delta)}{\tau_x} - 2\sigma\frac{I}{h\upsilon}\delta$$

$$\frac{d\Delta}{dt} = -2\sigma\frac{I}{h\upsilon}\delta$$

$$\frac{\partial I}{\partial t} + c\frac{\partial I}{\partial x} = c\sigma\delta I$$

With δ the population difference of the rotational levels and Δ the population difference of the vibrational levels, τ_x is the rotational thermalization time and I is the intensity of the pulse. The above equations were solved numerically for different beam shapes. The graph in figure 7 illustrates the influence of the amplifier gain on the time shape of the beam. The input pulse shape was assumed to be Gaussian and the model predicts that the pulse will be distorted resulting in a change of the M^2.

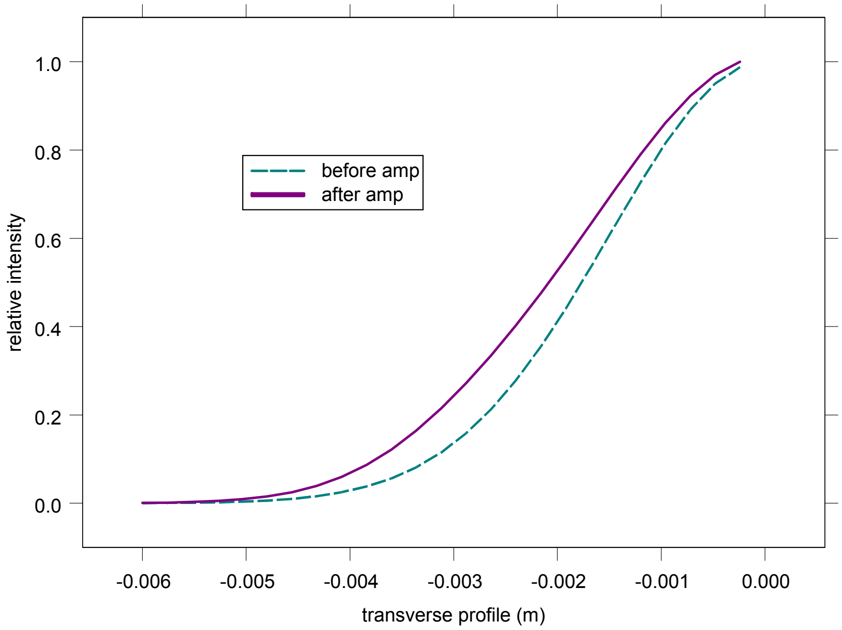

Figure 7 Change of spatial shape of laser pulse after propagation through the amplifier

CONCLUSION

A high pressure high repetition rate CO_2 amplifier was developed that is suitable for amplifying pulses as short as 750 fs. The amplifier is suitable for closed loop operation which means that isotopic gas mixtures can be used. Isotopic gas mixtures will allow shorter pulses to be amplified. The small signal gain of the laser was 2.2%/cm and the saturation fluence was 1173mJ/cm^2. The maximum energy that can be extracted from a system with 40cm electrode length with a 1cm^2 discharge area is 1070mJ and for 200Hz operation that the amplifier can achieve this results in a maximum extractable power of 206W.

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