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A High Power Microwave Frequency Modulated KrF Laser

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Abstract

We report on the development of a 260mJ 248 nm KrF laser with 98.7% depth of modulation at 1.3 GHz and 77% depth of modulation at 2.6 GHz using a 1.3 GHz microwave source driving a Pockel's cell. Subsequent single-pass amplification of the modulated KrF source to the 1/4-joule level is shown to be straight forward with no noticeable degradation of the modulation depth.

Introduction

An amplitude modulated intense ultraviolet source has applications in the areas of low level signal detection without narrow band optical filters such as in laser induced fluorescence LIDAR, underwater communications and in laser materials interaction studies. One technique is to develop a two wavelength narrow-band source separated by a certain difference frequency. The two laser fields propagating colinearly will give a resultant field which is amplitude modulated at this difference frequency as the two fields go in and out of phase. An alternate approach is to take an oscillator field of a given pulse length and subsequently actively amplitude modulate this field. Finally, both techniques then require passing the oscillator field through an amplifier or amplifier chain to bring the laser source to usable energies. It is not clear that the amplified field will be able to keep the fidelity of the source field. Degradation of this fidelity will result from the gain characteristics of the amplifying medium. We anticipate that amplified spontaneous emission as well as gain recovery times may play important roles in the degradation of the initially achieved depth of modulation. We will describe our efforts in achieving high energy amplitude modulated sources using both these techniques.

Two-Frequency Narrow-Band Laser Source

The initial work on a two-frequency narrow-band laser source concentrated on obtaining narrow linewidth oscillators. Using intra-cavity etalons to obtain two wavelengths equally spaced about the gain line center proved to be unsatisfactory with the available etalons in our possession. In the gigahertz separation regime the etalons are fairly thick and angle tuning of these devices proved problematic.

Our final set-up for two wavelength operation is shown in Fig.1. The oscillator was line narrowed using a grazing incidence grating. A 3290 g/mm holographic grating resulted in linewidths of 5 GHz when the feedback was tuned to first order and of 1 GHz when the feedback was tuned to second order of the grating. The linewidth was measured with a 0.5 cm^{-1} etalon (or a free spectral range of 15 GHz). Ring patterns obtained through the etalon are shown in Fig.2. A more accurate measurement of the linewidth was performed looking at the coherence length of the source with the use of a Michelson interferometer. Interference fringes are obtained up to a path length difference of greater than 30 cm or a coherence time of 1 ns. This translates to a 1 GHz linewidth.

Figure 1. Schematic of experimental set-up for two line operation at 6.67 GHz separation

Figure 2. One GHz linewidth lasing from oscillator seen through 15 GHz free spectral range etalon.

The line narrowed oscillator is then passed through a solid etalon of 6.67 GHz free spectral range with 90% reflectivity on the mirror faces. Thus, we use this etalon to select two frequencies on the wings of the oscillator source as shown in Fig.3. The output from the etalon is then sent through a gain medium and amplified. In single pass gain configuration we obtain output energies of 50 mJ per pulse.

Figure 3. Selection of two frequency output from line-narrowed oscillator laser field.

The ring patterns obtained when we analyzed the output with a 0.5 cm^{-1} etalon is given in Fig. 4. The patterns show that we need to tune the external etalon carefully so that its modes are evenly distributed about the center of the oscillating wavelength. Due to the very large gain bandwidth of the KrF medium, we found that it was not important to place the oscillator lasing wavelength on the peak of the gain curve. To all intensive purposes any two wavelengths separated by 6.67 GHz see approximately the same gain through the amplifier. Thus, the relative intensity of the two lasing lines is determined by the proper tuning of the external etalon. Figure 4a gives the field output from the etalon when the etalon modes are tuned unevenly about the central lasing frequency and Fig. 4b gives the situation when the etalon modes are tuned symmetrically about the peak lasing frequency.

It is seen that the spaces between the rings are fairly light indicating that a substantial amount of light at other frequencies is exiting the amplifier. This actually is not too surprising as the etalon is trying to filter out the most intense part of the lasing spectrum. Further, as the field input of this source is very weak, amplified spontaneous emission effects are more important. This lack of pureness of the two frequencies show up in the depth of modulation that is obtainable. The 6.67 GHz frequency separation source gave depth of modulation measured at only 20%. Using a 3.75 GHz free spectral range etalon we were able to improve the depth of modulation but the best results were no better than 25%.

Pockel's Cell Amplitude Modulated Laser Source

Of course, one can directly amplitude modulate a laser field. Our approach is shown in the experimental set-up given in Figure 5. The oscillator output is sent through a pair of cross polarizers with extinction ratios better than 500 to one. Between the polarizers is a fast Pockel's cell to provide the polarization rotation. In this situation the oscillator output can be broadband. Thus, the only reason to aperture the oscillator is for beam quality requirements. As our experiments do not require near diffraction limited beam quality, we enlarged our intra-cavity apertures to 4 mm diameters. This increase in oscillator intensity eliminates any fidelity degradation effects due to amplified spontaneous emission in the amplifier. The gain recovery time in discharge KrF laser devices is of the order of a few nanoseconds. We amplitude modulate the laser field at much higher frequencies and, therefore, the laser field sees a steady-state gain in the amplifier. At modulation frequencies close to the gain recovery time

(a)

(b)

Figure 4 Amplifier output of a two-frequency source 6.67GHz apart. (a) uneven tuning and (b) even tuning about oscillating line center.

we will expect to see some distortion to the modulating sine wave of the laser field. Figure 5 shows the amplitude modulated laser field exiting the Pockel's cell-polarizer pair is then expanded to utilize the full gain cross-section of the amplifier. Since we used only spherical lenses, the beam expansion only accessed the smaller dimension of the gain cross-section which generally has an aspect ratio of 3 to one. Thus, using cylindrical lenses to properly match the amplifier gain cross-section we can expect a gain of a factor of three in output energy from that obtained in these experiments (260mJ).

Figure 6. Pockel's cell amplitude modulated experimental set-up

The high speed Pockel's cell is driven by a ± 750 volt microwave source driven at 1.3 GHz frequency for duration of 5 ms. The turn-on of the voltage source is synchronized with the laser pulses. The polarization need only a small component in the opposite polarization direction to provide sufficient amplitude modulation signal for subsequent amplification. If we align the Pockel's cell to show a perfect Multese-Cross, we are in the condition where the polarization vectors move symmetrically up and down about the original polarization when driven by the oscillating voltage as shown in Fig. 6a. This results in an amplitude modulated signal at twice the frequency of the microwave driver. We can d-c voltage offset the Pockel's cell to obtain the condition in Fig. 6b. This will result in an amplitude modulated signal at the drive frequency. In practice it is much easier to obtain this second condition by simply misaligning the Pockel's cell and simultaneously watch the laser output. Angular misalignment of the cell is equivalent to applying a d-c off-set field. In this manner we obtain amplitude modulated signals at both the 1.3 GHz and 2.6 GHz frequencies.

Figure 6 Laser polarization rotation directions for twice the driving frequency case (a) and the driving frequency case (b).

Comparison of the laser signals before and after amplification shows no decrease in fidelity after amplification at both 1.3 and 2.6 GHz. frequencies. It is also evident that for case (b) it is possible to control the depth of modulation by tuning the angle such that the field vector never reaches the original polarization, for example. Thus, we can arbitrarily control the depth of modulation for the case of AM modulation at the driving frequency. At the doubled driving frequency, case (a), it is impossible to change the depth of modulation. This DOM is controlled by the ability of the Pockel's cell to respond to the driving voltage. Misalignments cause every other half sine wave to have different amplitudes.

Figure 7 shows the AM modulated signal at 1.3 GHz as measured on a 1 GHz Textronix 7104 scope (Fig 7a). With the Pockel's cell and polarizers taken out the unmodulated laser intensity is shown in Fig. 7b. We see that there is no observable energy loss out of the amplifier due to the Pockel's cell set-up.

Figure 7 Comparison between amplitude modulated and unmodulated amplifier output.

The depth of modulation of the AM laser at the two frequencies can be viewed in expanded scale with a Textronix 7250 6GHz scope. A portion of the modulated output laser waveform is shown in Fig.8.

Figure 8. A portion of 1.3GHz modulated amplitude waveform as viewed by a Textronix 7250 scope.

Using a tunable microwave source we can calibrate the instrumental distortions of the experimental set-up as shown in Fig.9

Figure 9 Signal response through experimental system when driven by a constant voltage variable frequency microwave generator.

Using these results we can plot the actual depth of modulation versus the apparent depth of modulation as shown in Fig. 10. From these studies we measure a depth of modulation (DOM) of the 1.3 GHz AM laser to be 98.7% and that of the 2.6 GHz AM laser to be 77%. The decrease in DOM at the higher modulation frequency is due to the response time limits of the Pockel's cell.

Figure 10. Comparison of apparent depth of modulation (DOM) versus actual DOM.

Conclusions

We have shown that in the case of high gain, fast radiative lifetime systems such as the rare-gas halide lasers the better technique to achieve a microwave amplitude modulated field is through the direct modulation and subsequent amplification of a pulsed oscillator field. The use of Pockel's cell modulation of this field is straight forward and the AM laser output is steady and robust.

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