A RAPIDLY-TUNED, SHORT-PULSE-LENGTH, HIGH-REPETITION-RATE CO₂ LASER FOR IR DIAL

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A rapidly-tuned, short-pulse-length, high-repetition-rate CO₂ laser

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Abstract.
Analysis of noise sources in Differential Absorption LIDAR in the infrared region of the spectrum indicates that the signal-to-noise ratio for direct detection can be improved if multiple-wavelength, short-pulse-length beams are transmitted and received at high repetition rates. Atmospheric effects can be minimized, albedo can be rapidly scanned, and uncorrelated speckle can be acquired at the maximum possible rate. A compact, rugged, RF-excited waveguide laser can produce 15 nanosecond pulses at a 100 kHz rate with sufficient energy per pulse to reach the speckle limit of the signal-to-noise ratio. A high-repetition-rate laser has been procured and will be used to verify these signal and noise scaling relationships at high repetition rates. Current line-tuning devices are mechanical and are capable of switching lines at a rate up to a few hundred Hertz. Acousto-optic modulators, deflectors or tunable filters can be substituted for these mechanical devices in the resonator of a CO₂ laser and used to rapidly line-tune the laser across the 9 and 10 micron bands at a rate as high as 100 kHz. Several configurations for line tuning using acousto-optic and electro-optic devices with and without gratings are presented. The merits of and constraints on each design are also discussed. A pair of large aperture, acousto-optic deflectors has been purchased and the various line-tuning designs will be evaluated in a conventional, glass tube, CO₂ laser, with a view to incorporation into the high-repetition-rate, waveguide laser. A computer model of the dynamics of an RF-excited, short-pulse-length, high-repetition-rate waveguide laser has been developed. The model will be used to test the consequences of various line-tuning designs.

Introduction
Analysis of noise sources in Differential Absorption LIDAR in the infrared region of the spectrum indicates that the signal-to-noise ratio can be improved if multi-wavelength, short-pulse-length beams are transmitted at a high repetition rate. A high-repetition-rate produces more information in a given time: more laser lines, more spatial positions, and more uncorrelated speckles. The short pulse with its narrow (in time) sampling window more effectively uses the available pulse energy and reduces the noise-equivalent-energy due to thermal background noise and other white noise sources by the square root of the pulse length. Rapid line-tuning gives more speckles due to wavelength decorrelation of speckle, more lines for chemical analysis and albedo separation and more measurements before the atmosphere changes. The multiple wavelengths and high repetition rate provide uncorrelated data at the fastest rate it can be generated.

We are developing a high-repetition-rate, short-pulse-length, rapidly-tuned CO₂ laser. The wavelength range will span the 9 and 10 μm bands, the pulse width will be 15 nanoseconds, the pulse repetition rate will be up to 100 kHz with a line-tuning rate of up to 100 kHz, and the pulse energy will be approximately 80 μJoules. The laser is an RF-excited, low-pressure, sealed-off, waveguide laser. This compact, rugged laser was chosen because of its high energy efficiency. The CO₂ linewidth is approximately 400 MHz and the free spectral range of the laser resonator is 200 MHz. The short pulse length is obtained by Q switching and cavity dumping the waveguide resonator.

We have recently procured two RF-excited, waveguide lasers from DEOS Corp. Figure 1 shows the z-fold lasers combined in a single beamline using thin-film polarizers and electro-optic modulators placed external to the laser cavities as combining elements. The p-polarized beam from the first laser is transmitted through the thin-film polarizer without modification. The s-polarized beam from the second laser reflects at the turning mirror and the thin-film polarizer. The electro-optic modulator, in the half wave mode, rotates the polarization of the 2nd beam to the p-plane. Wavelength selection is accomplished by a closely-coupled grating. This laser system meets the pulse-repetition-rate (100 kHz) and pulse-length (15 nsec) requirements that have been specified. The number of wavelengths can be increased by combining beams from additional lasers at the rightmost thin-film polarizer. To maintain linear polarization for the expanded system, a second electro-optic modulator would be placed at the output.

The two-wavelength laser system will be used to demonstrate and confirm the signal-to-noise scaling relationships for speckle, albedo and atmospheric effects. The short pulse length will require significant increase in detector electronics bandwidth and the repetition rate will impact the data rate for the computer control system. Line tuning will initially be accomplished by mechanical rotation of the gratings. The lasers will eventually be
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modified by Los Alamos National Laboratory to effect rapid line tuning.

Background information

In one type of approach that has been used in the past to achieve rapid wavelength selection and tuning, motor-driven, rotating mirror, is employed intracavity in the laser to direct the beam onto a stationary grating\(^\text{2,3}\) (also Scott Thomas, 1968) in a Littrow mount. The mirror is sometimes multi-faceted and the laser is either pumped cw or pulsed excitation is synchronized to the mirror rotation. The resulting laser output is a burst of pulses sequentially tuned to adjacent rotational lines in the CO\(_2\) spectrum, over a period of a few hundred microseconds, at rates of a few hundred macro pulses a second. The laser produces all possible lines and there is no convenient way to select a set of preferred wavelengths.

Another common line selection scheme, of relatively recent vintage, uses a mirror driven by a galvanometer to direct the beam onto a fixed grating\(^4\). This design can randomly access and resolve individual CO\(_2\) lines, but the tuning rate is limited to approximately 100 Hz. The lasers presently used in the LANL DIAL trailer employ this method of line tuning and Figure 2 is a schematic representation of the trailer-based system. The

limiting elements for the tuning rates of these conventional line-tuners is the mechanical deflector. Since the CO\(_2\) waveguide laser can be pulsed at rates up to 100 kHz without substantial reduction in pulse energy, it may be possible to increase line-tuning rates by up to three orders of magnitude if we can substitute acousto-optic devices for the galvanometer driven mirror.

* Within this report, three different isotropic, germanium, acousto-optic devices are proposed as solutions to various line-tuning designs. All three of these different devices diffract an incident optical beam when the beam interacts at the Bragg angle with a traveling, longitudinal, acoustic wave generated by an RF field and a piezoelectric transducer. An acoustic absorber, opposite to the RF transducer, absorbs the acoustic energy and
Line-tuning by deflecting directly onto a grating

The rotating mirror of figure 2 has been replaced in figure 3 with two acousto-optic deflectors. Deflector #1 is tilted at the nominal Bragg angle for a particular optical wavelength, \( \lambda_0 \), and a particular acoustic wavelength, \( \Lambda_0 \). (The nominal wavelengths are assumed to be in the middle of the acoustic frequency bandwidth and the optical wavelength range.) The 2nd deflector is tilted at two times the nominal Bragg angle. A particular line in the CO2 spectrum of the gain cell is selected for Littrow condition by correct deflection onto the grating. Both the grating and the deflectors contribute to dispersion of unwanted lines. The portion of the incident beam that isn't deflected or absorbed passes through the device as a loss term for the resonator and is represented by the dotted lines in figure 3. (The undiffracted beams on the return path from the grating are not shown in the sketch to avoid complicating the drawing.) In its interaction with the acoustic wave, the optical wave is Doppler shifted up or down in frequency by an amount equal to the RF frequency. If not accounted for, this frequency shift will accumulate and rapidly force the optical wave outside the pass band of the resonator. By approaching the acoustic wave from opposite directions on successive transits through the AOD's, the optical wave will be shifted alternately up and down in frequency with no net wavelength change.

\[ \beta = \arcsin \frac{\lambda}{2d} = \pm \left( \frac{2\Lambda_0}{\Lambda} - \frac{2\lambda_0}{\Lambda} \right) + \arcsin \frac{\lambda_0}{2d} \tag{1} \]

where \( \lambda \) is an optical wavelength, \( \Lambda \) is the acoustic wavelength, \( d \) is the line spacing for the Littrow-mounted grating, and \( \lambda_0 \) and \( \Lambda_0 \) are the previously described nominal optical and acoustic wavelengths. The plus-and-minus sign is a recognition that the grating can be approached from either side of its normal with a different tuning result for each case. Using numerical analysis, the tuning curve for a particular device (Isomet LS-600) can be found and prevents acoustic reflections. (A standing wave version of this device can be used in a resonator to mode-lock a laser.) The diffraction angle is set by the optical and acoustic wavelength in these well known devices. The device performs as a transmission phase grating with the Bragg angle condition being equivalent to a blaze angle of a plane reflectance grating. The three acousto-optic devices are: 1.) The acousto-optic modulator is a bulk-crystal device with a single RF transducer. It has a narrow angular acceptance and a narrow deflection range. 2.) The acousto-optic deflector has a number of smaller transducers arranged on a planar surface. The RF phase for succeeding transducers is advanced or delayed by an appropriate length of coax cable so as to produce an effective tilt to the acoustic wave as the RF frequency is changed. This has the effect of maintaining the device diffraction efficiency across a wider RF bandwidth. However, the acousto-optic deflection angle is a linear function of RF frequency and the simple phase control produces an acoustic tilt proportional to \( 1/\ell \), thus producing only an approximation to perfect tilt. 3.) The phase-controlled acousto-optic deflector uses electronic phase shifters to produce an acoustic tilt that exactly matches the deflection angle. This technique produces a wide bandwidth device with near-perfect deflector efficiency. We have selected a deflector (Isomet LS-600) that can serve for all three devices. Its aperture is 4 mm x 75 mm, and the single pass efficiency is 80 %. The Isomet device can operate throughout the RF frequency range of 50 to 90 MHz.
is shown in figure 4 for various values of grating line spacing. It can be seen that a grating with a line spacing greater than 8 μm obtains complete coverage of the 9 to 11 μm optical range.

![Tuning curves for the Isomet acousto-optic deflectors when used in the direct deflection configuration.](image)

Figure 4. Tuning curves for the Isomet acousto-optic deflectors when used in the direct deflection configuration.

The size of the deflection angles and the resultant incidence angle errors, particularly in the 2nd deflector, require that phase-controlled, acousto-optic deflectors be used in this design.

The dispersion of the grating and deflectors provides a loss factor for all lines competing with the selected line. This dispersion can be modeled as a tilt of the plane mirror in a hemispherical resonator. A first-order description\(^5\) of the loss term is:

\[
V(\alpha) = 1 + 2 \left[ \frac{g_2 L_{\text{eff}}}{1 - g_1 g_2} \right] \left[ \frac{a}{w_1} \right]^2 \exp \left[ -2 \left( \frac{a}{w_1} \right)^2 \right]
\]

where \(\alpha\) is the angle of tilt in radians, \(L_{\text{eff}}\) is the effective gain length, \(R_1\) and \(R_2\) are the radii of curvature of the mirrors, \(w_1\) is the beam diameter at an aperture and \(a\) is the aperture radius. By including this loss in an expression for output power from the cavity\(^8\,9\)

\[
P_o = \frac{T}{2(T+V)} \left[ 2\gamma L_{\text{eff}} + \ln(1 - T - V) \right]
\]
where \( T \) is the output coupler transmission and \( \gamma_0 \) is the unsaturated small signal gain, we can estimate the effects of dispersive losses. Experiments in our laboratory have demonstrated the validity of these equations and they indicate that a tilt of 300 \( \mu \text{rad} \) is sufficient to reduce lowest-order-mode output power by 50%. The solid curve in figure 5 is a normalized plot of Eq. 3, the theoretical output power from a hemispherical resonator as the plane mirror on one end of the cavity is tilted through an angle. Normalized experimental results are also plotted in the graph using a dashed line marked with x's.

The theoretical and experimental laser output power as a function of mirror tilt.

The 50% reduction in output power for 300 \( \mu \text{rad} \) of tilt is well within the dispersive capacity of any of the deflection schemes that are considered in this paper. The apparent required resolution, \( \lambda/\Delta\lambda_{\text{min}} = 1000 \), is often reduced in actual practice but that resolution number has been used in this paper for computational purposes. The total dispersion for the tuning scheme shown in figure 3 is:

\[
D = \frac{4f}{v} \pm \frac{1}{d \cos \theta_g}
\] (4)

where \( f \) is the RF frequency, \( v \) is the acoustic velocity and \( \theta_g \) is the grating diffraction angle. The first term on the right represents the dispersion contributed by the four passes through the deflectors. The second term is dispersion from the Littrow-mounted grating. The tuning range can be calculated as:

\[
\Delta \lambda_{\text{total}} = \frac{4 \lambda \Delta f_{\text{total}}}{vD}
\] (5)

The minimum size of the beam is given by:

\[
d_{\text{beam}} = \frac{1}{D \Delta \lambda_{\text{min}}} \frac{\lambda}{D}
\] (6)
producing a minimum beam size of 7 mm when the resolution equals one thousand. In summary, the high dispersion gives a high resolution for a given beam size. The relatively simple optical system is balanced by a requirement for linear phase control for the RF.

**Plane-mirror system**

Figure 6 shows a design that promises to provide the most efficient line-tuning with the fewest resonator components. The grating has been replaced with a plane mirror and wavelength discrimination is performed solely by the acousto-optic modulators. The beam, at every selected wavelength, remains at a constant angle. Photons that are not selected experience a dispersion that is cumulative through all passes through the modulators. The selected wavelength is always at the correct Bragg incidence angle in the modulators and should always experience the maximum possible diffraction efficiency.

![Plane Mirror](image.png)

Displacement for this system is:

\[
D = \frac{4f}{\nu}
\]  
(7)

The lower dispersion requires a larger beam size than the previously discussed line-tuning method. The tuning range is defined by:

\[
\Delta\lambda_{\text{total}} = \lambda \frac{\Delta f_{\text{total}}}{f}
\]  
(8)

The minimum required beam size as given by Eq. (6) is approximately 17 mm. The wavelength tuning curve is linear with frequency and the selectivity is improved for higher RF frequencies. (Thus, the nominal frequency would be at the upper end of the 50 to 90 MHz bandwidth of the Isomet device.) The fixed angle allows use of moderate device apertures and simpler devices and electronics. The mirror provides improved efficiency and the design is optically simple. However, the requirement for a large beam in the modulators may complicate the simple optical system.

**Line-tuning with a negative lens**

An example of a line-tuning configuration using a grating, two standard deflectors and a negative lens is shown in figure 7. This line selection method has been previously discussed in the literature. In the cited paper, a tuning range of 10 nm was reported at a wavelength of 850 nm for a relative tuning range of 1.2%. The tuning range for the CO₂ laser will need to be 2 μm with a relative tuning range of 20%.
The beams exit the left-most deflector without any angular difference as a function of wavelength; the angular change has been undone by the second deflector. However, the vertical translation at the aperture is proportional to the optical wavelength and the RF frequency. The negative lens converts this translation to an wavelength-dependent incidence angle with respect to the grating normal. The dispersion for the system is given by:

$$D = \frac{2f}{v} \frac{L_{sep}}{f_{neg}} + \frac{1}{d \cos \theta_g}$$  \hspace{1cm} (9)$$

where \(L_{sep}\) is the translation separation of the beams, \(f_{neg}\) is the focal length of the negative lens, and the other variables are as previously noted. The tuning range is defined by:

$$f_{neg} \geq 3 \frac{d_{beam}}{\Delta \theta_{AOD}} = \frac{\sqrt{3} f}{v} L * d_{beam}$$  \hspace{1cm} (10)$$

The spotsize of the beam at the lens produces a divergence at the grating and a loss in efficiency for the deflector. If a 10% mismatch is acceptable, then the divergence at the deflector is characterized by:

$$f_{neg} \geq \frac{\sqrt{3} f}{v} \frac{\Delta \lambda_{total}}{2} L * d_{beam} = 40 * d_{beam}$$  \hspace{1cm} (11)$$

for a grating spacing of 10 \(\mu\)m. Therefore, we require either a very large acousto-optic device and lens or a very small beam with attendant potential damage issues.

**Ring laser configurations**

Figure 8 is an example of line tuning in a ring laser configuration. The solution for the ring requires that the acousto-optic deflectors place the beam at the same spot on the top mirror for all selected optical wavelengths. The dispersion from the two gratings and the standard acousto-optic deflectors is cumulative and the aperture requirements for the deflectors is reduced. However, the gain cell length must be increased by an approximate factor of two as compared to the two-pass resonator. In addition, the ring cavity is more difficult to align.
An alternative ring laser tuning scheme would replace the top mirror with two plane mirrors. The ring tuning would be complete when the diffraction angle from the gratings was a constant for all selected wavelengths.

**Line tuning with an Acousto-Optic Tunable Filter**

Figure 9 shows a line-tuning scheme designed and built by Westinghouse Science & Technology Center.11 This design features an acousto-optic tunable filter (AOTF) made of Thallium-Arsenic-Selenide (TAS), a proprietary material that is birefringent. A shear wave transducer on the left end of the crystal launches an acoustic wave into the material. P-polarized light traveling to the left (ASE (p) in the sketch) is split off by the polarizing beam splitter. S-polarized light from the gain cell continues through the AOTF and is collinear with the acoustic wave. Phase matching in the material selectively converts a narrow range of wavelengths into p-polarized photons. Upon reflection at the 43.4° surface, these photons are ordinary rays and exit the crystal at normal incidence; they are reflected by the mirror; and then travel back down the crystal where they are reconverted to s-polarized light. Any light that is not converted (upshifted p) is discarded at the beam splitter. Unselected light at the reflecting surface is angularly separated from the selected light and discarded.

The resolution is given by Eq. (13):

$$\frac{\Delta \lambda}{\lambda} = \frac{5\lambda}{2\pi L \sin \theta_0 - n_0 l} \quad (13)$$

where $n_0$ and $n_e$ are the are the ordinary and extraordinary indexes of refraction. The Westinghouse authors indicated that wavelength selection within a line is possible. A typical interaction length of the TAS crystal is 7 cm and losses can be high. The resolution of the AOTF was 1645. Some development effort would be required to produce a tunable filter from this proprietary material. The collinear, two-pass design means that the Doppler frequency shift of the optical wave is cancelled. These filters can have a large acceptance angle and may have use as a narrow-band filter in a LIDAR receiver.

Non-collinear, acousto-optic tunable filters have also been produced from TAS by the Westinghouse Science and Technology Center. This device separates an unpolarized wave into three beams, a selected p-polarized wave, a selected s-polarized wave, and the remaining unselected wavelengths. The beams are relatively insensitive.
to angle and the acceptance angle of the device is high. This type of device (in the reported case using a TeO2 crystal) has been used in the visible spectrum to tune an argon-ion laser.\(^{12}\)

**Line tuning with electro-optic modulators**

Figure 10 shows a scheme for rapidly line tuning a single laser resonator and producing two different wavelengths of light using a half-wave-mode, electro-optic modulator and a thin-film polarizer. In the absence of a voltage on the modulator, p-polarized light from the cell will travel through the thin-film polarizer to the grating at the end of the resonator. Upon the application of the half-wave voltage, the p-polarized light is converted to s-polarized light and is reflected at the thin-film polarizer onto the second grating.

![Figure 10. A two-line laser using an electro-optic modulator and a thin-film polarizer.](image)

An extension to this idea is shown in Figure 11. If the insertion losses for the acousto-optic devices become too large for lines with low gain, the electro-optic modulator can be used to switch out the acousto-optic deflector section when the cavity field has crossed threshold. The deflectors will select the desired wavelength and discriminate against unwanted lines. With the field above threshold and the EO modulator on, the normal competition among lines for energy should ensure that the selected line continues to propagate in the resonator.

![Figure 11. An electro-optic modulator can reduce losses in the resonator.](image)

**Laser Modeling**

In the early days of CO2 laser development, it was considered necessary to expend some effort developing a computer model of the laser that was being examined in the laboratory. As the laser became more and more a tool provided by industry, this computer modeling effort dropped off. However, the short-pulse-length, high-repetition-rate lasers that we are developing are sufficiently ahead of the typical laser in the detail of the laser and its complex application that a computer modeling effort is useful and necessary. To develop a model that includes the sealed-off, waveguide effects of thermal and molecular diffusion and CO production, an existing three-temperature, flowing gas, large volume resonator model was modified to account for the additional losses. Figure 12 is a diagram of the energy elements for the CO2 waveguide laser model. The input energy source is RF and the energy exchange
mechanism is electrons ionized as a small percentage of the gas density. Using Boltzman statistics and measured cross sections for collisions, a set of rate constants is developed for the gas mixture under consideration. The rate constants describe the energy exchange mechanisms. The upper state, asymmetric, vibrational mode pumped by the electrons and the nitrogen molecules relaxes to the symmetric and bending modes and produces the selected 9 or 10 micron radiation.

Figure 12. Energy flow elements in the laser model

The input to the model includes amplifier length, cavity length, mirror reflectances, gas pressure, gas mixture proportions, electric field and the E/N ratio. An example of some of the useful output data from the model is shown in figure 13. At time zero, the RF is applied and pumps the CO\textsubscript{2} to the inverted state. The small-signal gain and gas temperature increase and the temperature approaches a maximum. At an appropriate time, after 800 microseconds as seen in the figure, the cavity Q is increased and a pulse builds up from the noise in the resonator. (The x-axis scale length has been changed to emphasize data resolution for the Q-switched portion of the plots.) A pulse is formed and the cavity is dumped. The large decrease in gain and small rise in temperature during the high-Q period can be seen. The model can predict the effect of line-switching and rapid pulsing on the output beam.
Figure 13. Model results of the small signal gain, gas temperature and output power for a specific set of input parameters.

Summary

This paper has described the efforts that are being made to develop a rapidly-tuned, high-repetition-rate, short-pulse laser. We have purchased a two-wavelength laser that will be used to test the proposal that a short-pulse laser running at a fast repetition rate is the preferred method for Differential Absorption LIDAR. We have discussed some designs for rapid line tuning using acousto-optic and electro-optic devices.

We are preparing to test three of the line-tuning schemes using Isomet acousto-optic deflectors: deflection onto a grating, deflection onto a mirror, and deflection with a negative lens. After evaluation of these designs we intend to adapt one of the schemes to our waveguide laser.

Finally, we have developed a computer model of the kinetics of a CO₂ waveguide laser and will use the model to predict the effects of rapid switching between weak and strong lines and other laser development issues.

Bibliography: