All Weather Long-Wavelength Infrared Free Space Optical Communications

D. P. Hutchinson, R. K. Richards, J. T. Simpson, and M. L. Simpson
Engineering Science and Technology Division
Oak Ridge National Laboratory
Bethel Valley Road, Oak Ridge, TN 37831

Abstract

ORNL is developing a high-speed, full-duplex all weather communications link for ranges up to 5 kilometers. To accomplish this project, we have constructed an RF-driven waveguide CO_2 laser and a dielectric-waveguide Stark modulator. The 10-micron wavelength was selected for its ability to penetrate smoke, fog, and rain. The modulator is based on the Stark shift of NH_2D (deuterated ammonia). The laser is driven by a 60 MHz RF amplifier at a power level of approximately 50 watts. The resonator cavity of the laser is formed by a 2.4 mm internal diameter ceramic waveguide with external optics. The RF electrodes are formed from aluminum heatsink extrusions that also provide cooling for the discharge. Details of the laser design will be presented.

Laser Characteristics

One of the drawbacks to more widespread applications for long wavelength infrared communications systems is an inexpensive, compact source of 10-micron radiation. We have developed a compact CW RF-driven, air-cooled, sealed-off waveguide CO_2 laser featuring a power level of over 1 watt. The hollow Al_2O_3 ceramic waveguide has an i.d. of 2.4-mm and provides a gain length of 20-cm. Our waveguide laser is based on a design reported by Walsh[1]. A photograph of the laser is shown in Figure 1. This laser produces a power level of approximately 1.6 watts using $^{12}CO_2$ and 0.8 watts using $^{13}CO_2$, both in the EH_{11} dielectric waveguide mode. With a grating installed, our laser produces 0.4 watts on the 10.59-micron line of $^{12}CO_2$. The output mode structure of the laser, measured with a thermally sensitive liquid crystal film, appears to be a TEM_{00} Gaussian mode. Frequency measurements indicate that the laser operates in a single transverse and single longitudinal mode.

The gas mixture in the laser is $He:CO_2:N_2:CO$ in the ratio of 65:18:15:2 respectively. This is a commercial mixture purchased for a pulsed CO_2 laser and the composition has not yet been optimized for our CW waveguide laser. Walsh used a mixture of $He:CO_2:N_2:Xe$ in the mixture ratio 77:10:10:3 respectively.

One end of the laser cavity consists of a 0.5-inch diameter 3-m radius concave ZnSe 95% reflective output coupler attached to the waveguide through a brass bellows. The ceramic waveguide is attached with epoxy to a brass fitting soldered to the bellows. Epoxy is also used to attach a ZnSe Brewster window is to the other end of the ceramic tube, which was ground to the Brewster's angle. A 150 l/mm flat master grating mounted on a piezoelectric actuator in an adjustable mirror mount forms the other end of the cavity. A one-inch diameter invar rod machined flat on opposing sides serves as a temperature

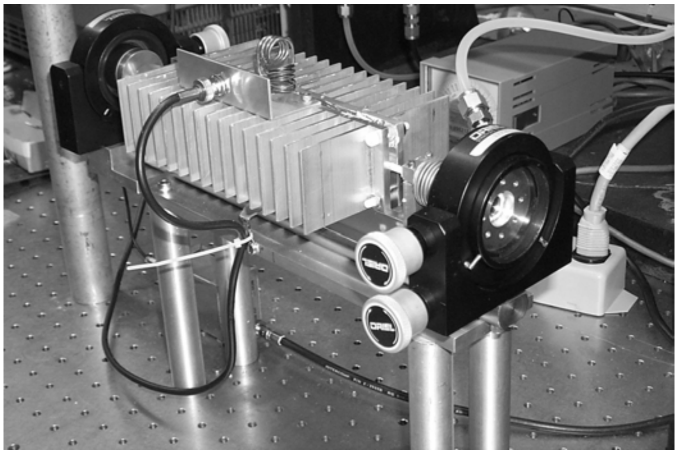


Figure 1 Air-cooled, RF-Driven CO_2 Laser.

stable mounting surface for the insulating support for the electrodes and the mirror mounts. The optimum operating pressure of the sealed-off laser is 60-65 torr. The laser is driven by a 58.5 MHz RF amplifier at a power level of approximately 50 watts. Machined aluminum heatsinks mechanically clamped to each side of the waveguide serve as RF electrodes and provide cooling for the tube. The two electrodes are shaped to conform to the round dielectric waveguide. A thin coating of heatsink compound applied to the electrodes during assembly improves thermal contact with the dielectric waveguide and enhances cooling. One side of the electrode is grounded and an air wound autotransformer couples RF power to the other electrode. The inductance of the 4-turn autotransformer resonates with the capacitance formed by the heatsinks attached to the waveguide at a frequency of 58.5 MHz. Another air-core inductor is used to connect the 50-ohm coaxial cable from the RF power supply to a tap (approximately 1-turn from the grounded end) on the autotransformer to efficiently couple power to the laser. The inductance of the coupling coil is adjusted by compressing or expanding the coil to optimize the impedance match to the 50-ohm cable. Both coils are constructed from #12 AWG copper wire.

Stark-Effect Modulator

Stark-effect modulation occurs when an electric field is applied to a gas molecule that has a substantial polarization. The applied electric field effectively changes the energy spacing of the molecular levels changing the optical frequency or wavelength that is absorbed by the gas. Also, the energy spacing is very small compared to the energy of the optical photon interacting with the gas. The modulator is filled with approximately 2 or more torr of partially deuterated ammonia (NH_2D), which has a molecular absorption resonance near the 10.59-micron wavelength line of emission of a CO_2 laser. The frequency difference between the absorption resonance and the laser line is reported to be approximately 2189-MHz[2] from the laser line. The dotted curve in Figure 2 depicts the transmission of a 30-cm cell containing 2-torr of NH_2D in the absence of an applied electric field. The laser light (located at zero difference frequency on the scale) is not strongly absorbed by the cell. The solid curve in the left graph in Figure 2 shows the transmission of the same cell in the presence of an applied electric field of 300 V/mm. The electric field causes this absorption line to split into nine Stark components classified by the designation M = 0, ±1, ±2, ±3, and ±4. The M = 0 component is roughly in the center of the plot at a difference frequency of 2189 MHz and the M = ±4 components are at the extreme left and right ends of the structure. As the electric field is increased the M

= ±4 absorption component moves closer to zero difference frequency until the peak of the absorption is in coincidence with the laser line corresponding to an electric field of approximately 380 V/mm. This situation is depicted in left graph shown in Figure 2. As the applied electric field is varied from 350 to 380 V/mm, the transmission of the 30-cm long cell varies from 90% to 75%. If the length of the cell is increased, the modulation amplitude can exceed 70%. If we impressed a steady state or d-c electric field on the electrodes half-way between 350 and 380 V/mm and apply a sinusoidal alternating or a-c voltage with an amplitude of 30-V peak-to-peak, a sinusoidal modulation of the laser beam would occur. Digital modulation can be achieved by setting the steady field at 350 V/mm and applying a 30-V digital signal to switch the transmission of the cell between the 75% and 90% states.

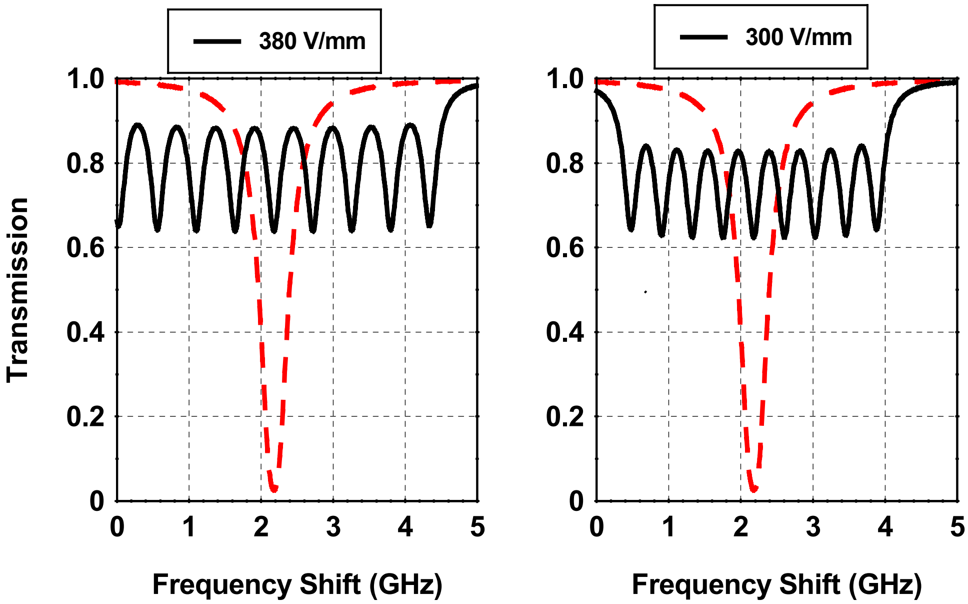


Figure 2 The application of an electric field to deuterated ammonia causes the absorption peak to split into nine components.

Dielectric Waveguide Modulator

Normally Stark modulators are constructed from two parallel electrodes separated by a distance much smaller than the width to minimize the variation of the electric field across the laser beam. The electrodes are placed inside of a dielectric tube, typically glass or ceramic, held at a pressure appropriate for the gas used for modulation, typically a few torr. A typical spacing would be on the order of 2-mm with a width of 20 or more millimeters and a length of more than 200 millimeters. One of the problems with this design is that normal expansion of the laser beam through such a structure causes a loss of laser light due to vignetting of the beam by the electrodes. To reduce this vignetting loss, we have designed a Stark modulator using a hollow glass dielectric tube to confine the optical beam with minimum loss. The laser beam is focused into the proper size by a lens to form a match to the EH_{11} waveguide mode of the dielectric tube. A lens following the waveguide collimates the beam for propagation to a detector or to other optical components. The electrodes are external to the dielectric tube that serves to confine the optical beam and provide a means to operate the modulator at the reduced pressures required for operation.

To test this concept we constructed a 0.9-mm id x 20-cm dielectric waveguide modulator. The waveguide material is borosilicate glass and is suspended between to 1-cm wide by 20-cm long flat aluminum electrodes. Lexan inserts are used to fill the gap between the electrodes outside of the waveguide. These Lexan inserts support the waveguide, align the electrodes and flatten and enhance the electric field in the waveguide. A sketch of the cross-section of the modulator is shown in Figure 3. The ends of the waveguide are sealed with ZnSe Brewster windows.

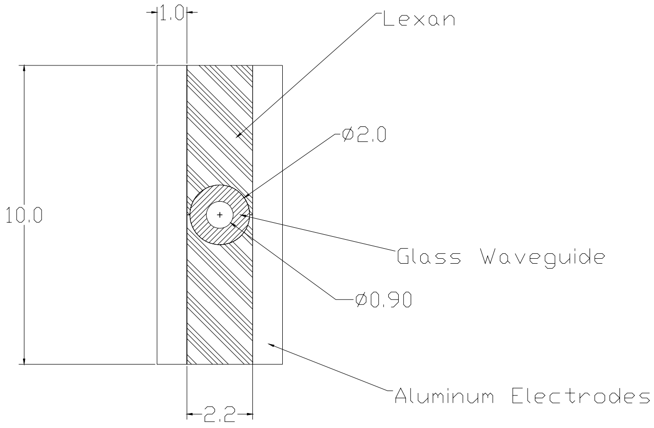


Figure 3 End view of 0.9-mm id glass modulator. All dimensions are in millimeters.

One problem that arises with this external electrode design is charge build-up from stray ions and electrons in the insulating waveguide. When an electric field is applied to the electrodes, the stray free-charge in the waveguide migrates to the sides of waveguide nearest the electrodes with electrons attracted to the most positive electrode and ions attracted to the most negative electrode. This charge migration acts to cancel the electric field inside the waveguide thereby canceling modulation. We measured the time required for this canceling charge to build-up and found that it is on the order of or less than 1 sec. Because the charge build-up requires a finite time to occur, we have developed a biasing method that negates the canceling effect of the stray charge.

A-C Biasing Method

The Stark components are created when an electric field is applied to the molecule. For the deuterated ammonia line that is in near coincidence with the 10.59 micron CO_2 laser line, the selection rules for absorption require that the electric field be applied perpendicular to the electric field of the optical beam. The polarity of the electric field is not important. For instance, if the electric field is applied with the positive electrode on the right and the negative electrode on the left or vice-versa, the absorption structure is not changed. The absorption for plus and minus M components are the same. The absorption is proportional only to the magnitude of the electric field, not direction, as long as the proper polarization relationship between the applied field and the field of the laser beam is maintained. Therefore a circuit has been developed that generates a low frequency (on the order of 100 to 1000 Hz) square wave that is applied to the electrodes. The waveform produced by the “a-c bias” circuit is shown in Figure 4. The polarity of the data waveform must match the polarity of the bias waveform to properly modulate the laser beam. This relationship is shown in Figure 5. In addition, the logic circuits buffer and temporarily store the data, and then transmit the data waveform during the constant portion of the bias signal. High voltage amplifiers such as the Apex PA-94 have slew rates of approximately 1000 V/µsec. Assuming a bias voltage level of 500 volts and a bias frequency of 100 Hz, the switching transient will cause a duty cycle loss of only 0.05 %. Using this type of biasing and data amplifiers, the waveform transmitted by the modulator should resemble the waveform shown in Figure 6. The bandwidth of the modulator is limited only by the homogeneous linewidth of the deuterated ammonia gas. Using a filling pressure of 8-torr a data rate of over 300-Mbits/sec is available.

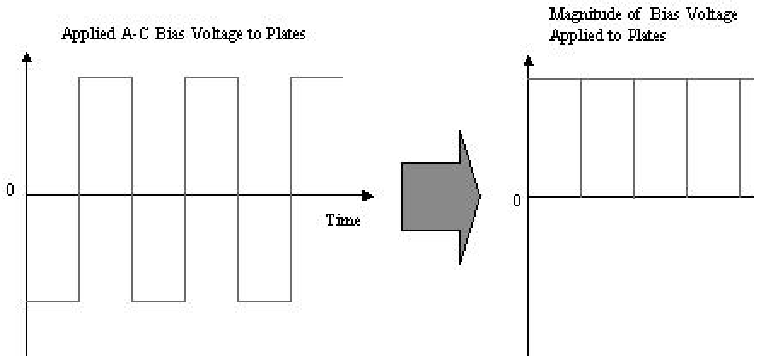


Figure 4 The applied a-c bias on the left produces the equivalent to a steady “d-c” bias as shown on the right of the diagram.

Figure 5 The polarity of the data waveform must match the polarity of the bias waveform to properly modulate the laser beam.

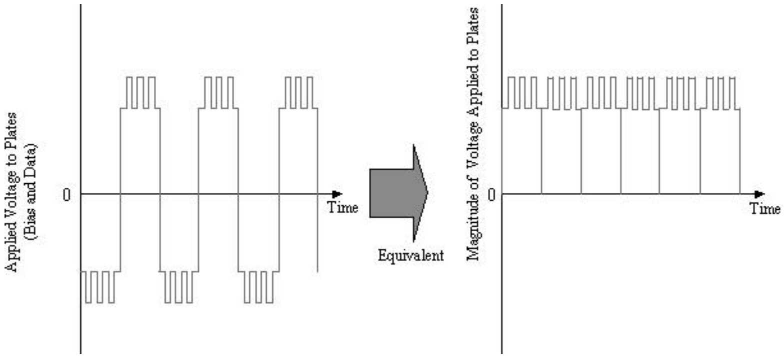
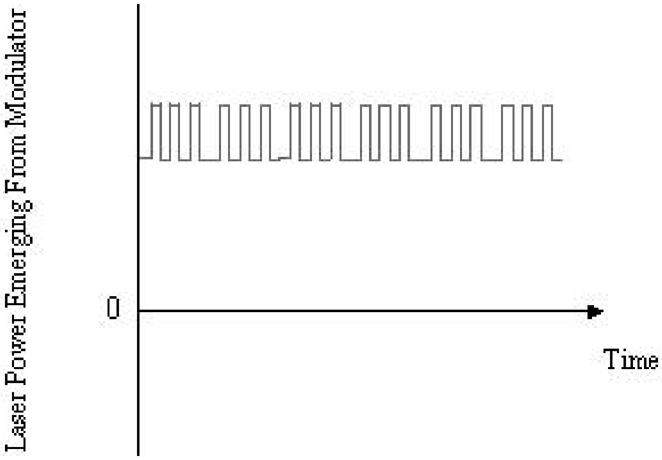


Figure 6 The total waveform produced by the a-c bias circuit combined with the data circuit appears identical to that produced using a d-c bias voltage.



Experimental Results

Using 0.9-mm id x 20-cm dielectric waveguide modulator design discussed above and shown in Figure 3, we measured the transmission of the modulator at a pressure of 8 torr as a function of the applied voltage. An "a-c bias" waveform was generated by applying a square-wave drive voltage from a signal generator to an iron-core step-up transformer (a 110 VAC to 6.3 VAC filament transformer operated in reverse). The bias was scanned from zero to 1100 volts peak and the transmitted signal was measured with a pyroelectric power meter. The "a-c bias" frequency was 3000 Hz. The resulting modulator transmission as a function of applied voltage is shown in Figure 6. The open circles are the measured data and the dashed curve is the calculated transmission based on a theoretical model taking into account the cell length, e-field enhancement and deuterated ammonia fraction. The M = 3 and M = 4 absorption peaks are clearly visible. The peak modulation index for this cell is approximately 30%. Using this information and verification of the model, we have designed and are constructing a 1-mm i.d. x 36-cm long modulator for a prototype free-space optical link for high-speed digital transmission experiments.

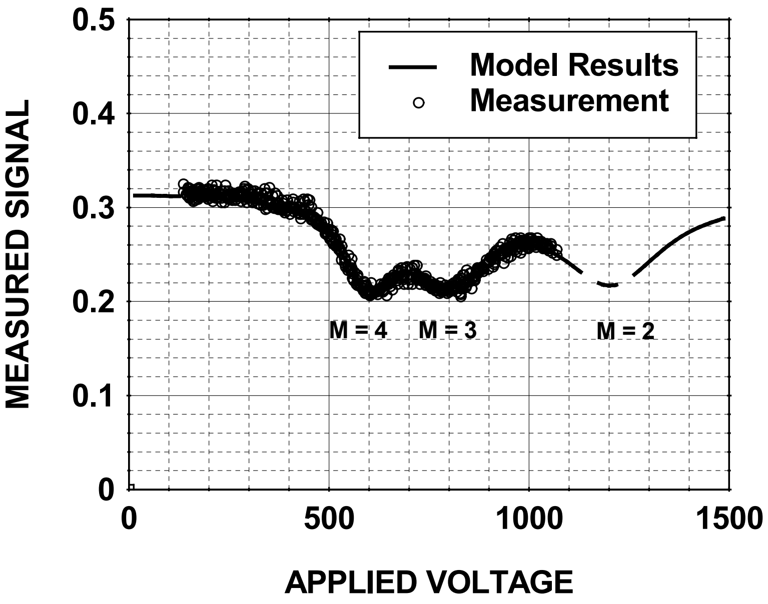


Figure 7 The measured transmission of the 20-cm long cell shows excellent agreement with theory.

---

[1] C. J. Walsh, "An rf excited circular waveguide CO_2 laser," Rev. Sci. Instrum. 61(9), Sept. 1990

[2] A. R. Johnston and R. D. S. Melville, "Stark-Effect Modulation of a CO_2 Laser by NH_2D," Applied Physics Letters, vol. 19, no. 12, 1971.