

## TUNABLE HIGH PRESSURE LASERS

R. V. Hess

Langley Research Center, NASA

SUMMARY

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Atmospheric transmission of high energy  $C^{12}O_2^{16}$  lasers can be considerably improved by high pressure operation which, due to pressure broadening, permits tuning the laser lines off atmospheric  $C^{12}O_2^{16}$  absorption lines. Pronounced improvement is shown for horizontal transmission at altitudes above several kilometers and for vertical transmission through the entire atmosphere. NASA missions for laser energy transmission through the atmosphere have important spin-offs to closely related missions in remote atmospheric sensing. Initial efforts in tuning high pressure  $CO_2$  lasers are discussed and future research is outlined which is vital to NASA missions and national goals such as isotope separation.

### INTRODUCTION

Within the last 5 years, new types of high energy gas lasers were developed which, because of operation at high pressures, have the potential of producing tunable laser radiation by tuning across pressure broadened lines. The initial efforts of these so-called Transversely Excited Atmospheric, or TEA lasers, concentrated mostly on their importance as high energy density devices, but recently efforts have been initiated at several laboratories to explore their tunability. These efforts are of great importance to diverse applications (fig. 1) such as atmospheric energy transmission, with subsequent energy conversion, as well as remote atmospheric sensing, optical radar, isotope separation, and photochemistry.

Rather than giving a broad survey of the field, I will first discuss in-house theoretical feasibility studies for applications of tunable high pressure  $CO_2$  lasers to energy transmission and, briefly, to remote sensing; the latter is discussed in more detail in an NASA publication by Hess and Seals (ref. 1). It will be shown that for these important NASA missions, the requirements for high pressure and tunability are not severe. Subsequently, I will give a brief review of the tuning characteristics and design requirements of high pressure lasers which form, respectively, part of a broad NASA basic research grant with Prof. Javan and a Langley contract with Plasma Physics Corp.

### ATMOSPHERIC TRANSMISSION OF TUNABLE HIGH PRESSURE $C^{12}O_2^{16}$ LASERS

The importance of tunable  $C^{12}O_2^{16}$  lasers for increasing atmospheric laser transmission is shown in figure 2 for the P(20) laser line centered at  $10.5911 \mu$ . As indicated by the reduction in calculated absorption coefficient, the advantage in tuning off the line center increases with altitude. Since the absorption coefficient  $k$  in  $km^{-1}$  is related to the transmittance  $\tau$  through

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$$\tau = e^{-\int_0^L k d\ell}$$

it is representative of horizontal transmittance without having to specify the length  $L$  over which the transmittance occurs. As indicated by the reduction in calculated absorption coefficient, the advantage in tuning off the line center increases with altitude due to reduction in pressure broadening with altitude.

All the calculations presented here have been performed using our line-by-line absorption and transmission computer program, including gases such as  $H_2O$ ,  $CO_2$ ,  $O_3$ ,  $N_2O$ ,  $CO$ ,  $CH_4$ ,  $SO_2$ ,  $NH_3$ ,  $NO$ ,  $HCl$  and continuum absorption for  $H_2O$  and  $N_2$  from studies by McClatchey, *et al.*

For NASA missions of energy transmission to or from space it is of special interest to plot the vertical transmittance of the tunable high pressure  $C^{12}O_2^{16}$  laser from an altitude  $h$  through the entire atmosphere vs frequency  $\nu - \nu_0$  from line center. Figure 3 indicates that the transmittance from  $h = 0$  (ground) and  $h = 2.5$  km or  $6.5$  km (mountains or aircraft) can be considerably increased by tuning  $5$  GHz off the line center. However, by positioning the laser at moderately high altitudes of  $h = 2.5$  and  $6.5$  km, even half this tuning range yields large vertical transmittance which should be useful for various applications of laser energy transmission. The reason is that at these moderate altitudes the absorption by  $H_2O$  vapor is sufficiently reduced so that great benefits are derived by tuning off the center of atmospheric  $CO_2$  lines.

The pressures required to accomplish this tuning are not very high as seen from the following. In order to tune  $5$  GHz off the line center, a  $CO_2$  laser line  $\geq 10$  GHz is required since the centers of the laser line and the atmospheric  $CO_2$  absorption line coincide. Since the line broadening per atmosphere pressure is  $\approx 3$  GHz, a laser pressure  $\geq 3$  atm would be needed; however, even half this pressure would be sufficient for a large improvement in transmittance. It is further shown in reference 1 that for vertical transmission and for transmission at moderately high altitudes, tuned  $C^{12}O_2^{16}$  lasers compare favorably with  $C^{12}O_2^{18}$ ,  $CO$ ,  $DF$ , and  $HF$ -lasers.

Since, only moderately high pressures are required to provide sufficient tuning for considerably improved transmission, the possibility of operating continuous wave (CW)  $CO_2$  lasers at pressures of  $\approx 2$  atm needs to be investigated. The feasibility of operating CW  $CO_2$  lasers at atmospheric pressures without the use of preionization is indicated in references 2 and 3. Recent discussions with Dr. George Sutton indicate that AVCO Everett has operated an E-Beam preionized CW  $CO_2$  laser at pressure of  $\approx 1$  atm and that CW operation at higher pressures may be possible.

Possible advantages of pulsed operation for control of nonlinear effects have been discussed with Dr. Gebhardt from United Aircraft and Dr. Sutton from AVCO Everett. Dr. Gebhardt indicates that thermal blooming can be reduced by multi-pulse operation instead of CW operation, using for experimental studies a TEA laser with photo-preionization. Dr. Sutton suggests improvement of vertical atmospheric transmission through bleaching of atmospheric  $CO_2$  requiring very high pulsed laser fluxes. This involves positioning the  $CO_2$  laser at moderately high altitudes, for reduction of  $H_2O$  vapor effects, as also indicated for the tuned high pressure laser transmission, discussed here in some detail.

It is concluded (fig. 4) that the development of pulsed and CW high pressure CO<sub>2</sub> lasers could be vital to NASA energy conversion missions and, of course, also to non-NASA missions requiring atmospheric transmission. It should be further pointed out that presently strong efforts are being made to resolve the comparative advantages of CW and pulsed transmission. Tuned pulsed lasers, because of low average power requirements, may also offer promise for near term evaluation of atmospheric transmission experiments into space or from space between Earth and aircraft, balloons, satellites, or shuttle. A possible cost reduction may be achieved by combining transmission experiments with related experiments in remote sensing, optical radar tracking, and communications, which may also benefit from tunable high pressure pulsed lasers. A strongly related remote sensing experiment is discussed next.

### SOME APPLICATIONS TO REMOTE SENSING

In reference 4, a variety of tunable laser applications to remote atmospheric sensing are studied. An especially strong relation exists between transmission problems of tunable C<sup>12</sup>O<sub>2</sub><sup>16</sup> lasers and a certain remote sensing technique which has been theoretically evaluated by LaRC (ref. 5) and JPL (ref. 6). This technique, shown in figure 5, is remote sensing by laser differential absorption using diffuse reflection from the Earth. The term differential implies a reference laser "on" the constituent or pollutant absorption line as well as one "off" the line, as in the transmission problem; the difference in atmospheric transmittance is a measure of the pollutant. In its simplest form this technique yields an average concentration over the entire path. Information about the vertical constituent or pollutant distribution can be obtained by tuning across the corresponding absorption lines whose collision broadened widths vary with altitude. The actual vertical distribution is obtained through a mathematical inversion technique. The differential absorption technique can also be used for ranging whereby the signal is backscattered by particulates or molecules in the atmosphere as shown, e.g., by Byer and Garbuny (ref. 7).

Four laser types are being used or proposed (fig. 6) for the IR remote atmospheric sensing techniques used in references 1, 5, and 6: (1) select frequency CW lasers operating at comparatively low pressures whose wavelength range is extended through use of various isotopes; (2) tunable CW diode lasers, that have the advantage of tunability over a wide wavelength range but operate at comparatively low power of the order of several mW; (3) tunable CW waveguide lasers, that are tuned across pressure broadened lines, but with restricted tuning range because higher pressures require increasingly narrow waveguide tubes (the CW powers of these lasers approach several watts); and (4) the high pressure tunable lasers which have the potential of overcoming these limitations. Since they can be operated at very high pressures their tuning range can be considerable for any particular lasing gas. In order to increase the tuning range over the entire infrared the alternative exists of using different lasing gases, frequency multiplication (as discussed by Dr. Billman), or nonlinear optical mixing techniques using crystals or gases. Extensive research in these areas is performed by Drs. Byer and Harris at Stanford University, Dr. Garbuny at Westinghouse Research Laboratory, and others. Another promising technique involves laser pumped lasers. The use of high energy pulses increases the signal-to-noise ratio of differential absorption techniques and also permits the use of ranging in remote sensing. These techniques for increasing the tuning range are also vital for isotope separation and photochemistry.

## RECENT PROGRESS IN TUNING OF HIGH PRESSURE TUNABLE LASERS

The key requirement for tuning of high pressure/energy pulsed lasers is the production of a uniform lasing medium. For this purpose, electron beams or uv photons from flashlamps or open arc discharges have been used for preionization. Several references to researchers pursuing these techniques are given in reference 1. The use of laser pumped lasers also shows great promise for producing a uniform lasing medium aside from its value in increasing the tuning range.

Tuning high pressure/energy pulsed CO<sub>2</sub> lasers have recently been reported by Alcock (ref. 8), Harris (ref. 9), and Bagratashvili (ref. 10). The lasers in references 8 and 9 are operated at high pressures of 15 atm (fig. 7) where line broadening is sufficient to provide overlapping (ref. 11) and continuous tuning over a wide spectral range; the lasers in reference 10 operate at  $\approx 5$  atm. Alcock performs tuning with a grating (with maximum resolution increased by beam expansion) having spectral resolution  $\geq 0.2 \text{ cm}^{-1}$  and Harris uses an etalon for tuning; personal discussions with O'Neil and Harris indicate a resolution of  $\leq 0.2 \text{ cm}^{-1}$  for the etalon. (Note:  $0.2 \text{ cm}^{-1}$  corresponds to 6 GHz.) It must be emphasized, though it is now generally recognized, that this resolution does not refer to the actual linewidth of the laser output. The reason is that, for the homogeneously broadened lines of the high pressure laser mode, competition occurs. As a result, the oscillation of one mode depletes the population and channels the energy into this single mode; thus oscillations of other modes, as shown by Goldhar (ref. 12) and Nurmikko (ref. 13), are prevented. Measurements by Nishihara (ref. 14) of line structure in a pulsed atmospheric CO<sub>2</sub> TEA laser, with a high resolution Fabry Perot interferometer, suggests single mode operation with linewidth of the order of 20 MHz. It must be emphasized that for pulsed operation the uncertainty principle,  $\Delta\nu\Delta\tau \geq 1$ , sets a lower limit for the bandwidth; for example, for the 300 nsec pulse duration in reference 14 the bandwidth  $\Delta\nu \geq 10^7/3 \approx 3 \text{ MHz}$ . As shown by Stiehl (ref. 15) chirping (frequency sweeping) in a pulsed laser may also influence the true time scale of the pulse and thus influence the bandwidth; however, it may also help in smearing out deviations from homogeneous broadening, thereby encouraging single mode operation. The importance of Stiehl's work lies partly in the fact that he uses laser heterodyning which is needed for high resolution measurements.

Our research plan with Prof. Javan and Plasma Physics Corp. is as follows. A 5-atm pulsed CO<sub>2</sub> laser is being built (fig. 8) which uses uv photo-preionization of seed material, such as propylamine (ref. 16), to produce a uniform lasing medium. Gross tuning will first be performed with a grating; however, much more extensive efforts than heretofore will be made to obtain the mode structure with heterodyning, using Prof. Javan's contact diode at M. I. T. and tunable diode lasers at Langley. Subsequently, finer tuning techniques will be used. This effort should be of great importance for improved atmospheric transmission as well as for remote sensing, optical radar, isotope separation, and photochemistry.

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- Atmospheric energy transmission and remote sensing
  - In-house theoretical feasibility studies
  - Tuning and design of high pressure CO<sub>2</sub> laser, Prof. Javan and Plasma Physics Corp.
- Optical radar
- Isotope separation, photochemistry

Figure 1.— Application of high pressure tunable lasers.

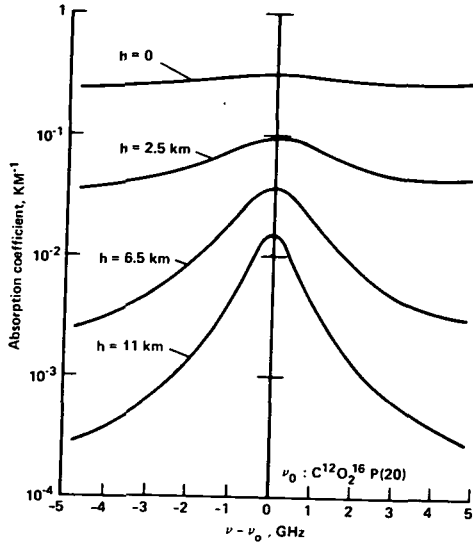


Figure 2.— Calculated frequency variation of absorption coefficient with altitude.

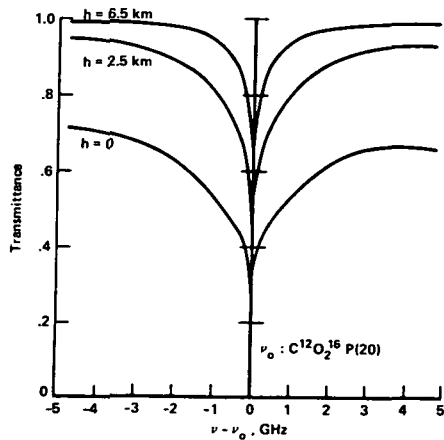


Figure 3.— Calculated frequency variation for tunable C<sup>12</sup>O<sub>2</sub><sup>16</sup> laser for vertical transmittance from various altitudes.

- Could be vital to NASA — and other agencies
- Offer promise for near term evaluation of transmission experiments between Earth/aircraft, balloons, shuttle
- Possible cost reduction by combining with related experiments
  - Remote sensing, optical radar tracking, communications

Figure 4.— High pressure/energy tunable CO<sub>2</sub> lasers for atmospheric transmission.

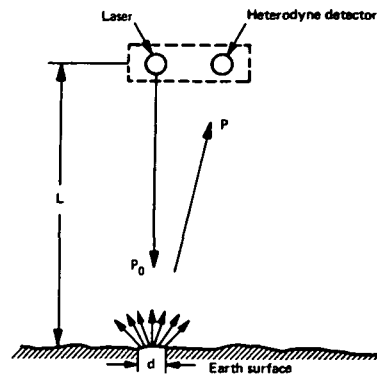


Figure 5.— Laser differential absorption with diffuse reflection from earth.

- Select frequency lasers, wavelengths extended through isotopes
- CW tunable diode lasers, wide tuning range, low mW powers
- Tunable CW waveguide lasers, tuning restricted by pressures in narrow tubes, power approach several watts
- High pressure tunable lasers, wide tuning range due to high pressures and nonlinear optical mixing

Figure 6.— Four laser types proposed for IR remote sensing.

- Experiments at  $\sim 15$  atm, line overlapping
  - Tuning with grating and etalon, resolution  $\sim 0.2 \text{ cm}^{-1} = 6 \text{ GHz}$
- Resolution does not refer to laser linewidth
  - Homogeneous broadening channels power into single mode
  - High resolution Fabry Perot suggests single mode, linewidth  $\sim 20 \text{ MHz}$
- Pulsed operation bandwidth  $\geq 1/\text{pulse duration}$  from uncertainty principle
- Heterodyning needed for high resolution

Figure 7.— Tuning of high pressure/energy pulsed laser.

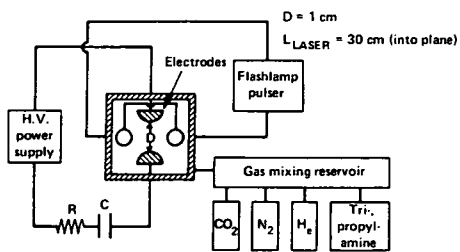


Figure 8.— High energy/pressure pulsed CO<sub>2</sub> laser with photo-preionization.

## DISCUSSION

**Charles Chackerian, NASA Ames Research Center** – If you are concerned with atmospheric transmission, why isn't it better to use an  $O^{18}-CO_2$  laser?

**Answer:** We have compared this but  $CO_2^{18}$  is more expensive, especially in military use.

**Max Garbuny, Westinghouse** – What total tuning range could you obtain with  $CO_2$ ?

**Answer:** If you use overlapping, which occurs at about 10 atmospheres, you can tune essentially from 9 to 11  $\mu$ . With doubling, tripling, and harmonic mixing with CO and HF frequencies, you can span the entire infrared range. For example, people at Los Alamos are attempting to get to 15 or 16  $\mu$ .

**Dick Pantell, Stanford University** – I don't understand why the homogeneity of the line broadening is going to discourage other modes. For example, in ruby or glass, which are essentially inhomogeneously broadened at room temperature, oscillation in one mode doesn't deplete oscillation in other modes because they occupy different spatial regions. Do you think the same thing would happen here?

**Answer:** There is some of this spatial hole burning. But that occurs when a crest of the oscillation of the laser meets with a node. By proper positioning of the laser, and proper phasing, you can reduce that.  $CO_2$  lasers have been known to work very well on a single mode. In addition, some tricks can be performed by proper positioning of the laser. Some moderate amount of chirping, for example, can smooth this out also. We are looking into all of these things. With a heterodyning detector we are going to look to see exactly what we have.

**Abe Hertzberg, University of Washington** – I would like to comment on chirping. I believe we are just beginning to understand that you cannot have a short pulse laser, with any bandwidth, without chirping. In fact, no mode-locked laser operates unchirped.