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ABSTRACT

A general method is described for selecting and optimizing a gas mixture which serves to isolate the amplifier stages of a CO_2-laser chain. Such isolation increases the useful energy extracted by eliminating self oscillation. The performance of an optimized non-saturating gas mixture in a laser working on the 9P(32) line is reported.

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INTRODUCTION

The efficiency of energy extraction from a multi-amplifier TEA CO_2-laser chain is often limited by self oscillation and parasitic feedback.[1,2] This is particularly so if the laser is operated on a line which has a significantly lower gain than that of the P20 line of the 10 μm band [10P(20)line]. One way of overcoming this problem is to use an absorbing medium as isolator between the amplifier stages.

In this paper, we report the selection, optimization and use of a multi-component gas mixture as an isolator to achieve efficient energy extraction from a CO_2-laser chain operating on the 9P(32) line; used to optically pump a far-infrared D_2O laser emitting at 66 μm. Unlike previous work using gas cells as isolators,[1,3] we have achieved high values of small-signal transmission ($\gtrsim 93$ %) at the operating wavelength, 9.66 μm, by a judicious selection and optimization of the gas mixture. Saturation of the absorber is not a prerequisite to efficient energy extraction.

APPARATUS

The laser chain used is shown schematically in figure 1 and comprises 5 identical TEA laser modules,[4] each of excited cross-section 5x5 cm and length L=100 cm. The oscillator comprises a diffraction grating (150 grooves per mm and blazed for 8 μm) and a ZnSe meniscus output coupler coated to give a reflectivity of 55%. A single transverse mode is produced from the

half-symmetric resonator through the use of an aperture adjacent to the grating. An intra-cavity Fabry-Perot etalon may be used to produce a single longitudinal mode - in the work reported herein it was not used. To maintain a constant cavity length, the resonator end reflectors are mounted on a temperature-compensated frame made of invar and stainless steel.[5]

From the oscillator, the 8 mm diameter, 0.3 J output beam passes via a beam steerer into the triple-pass preamplifier. An off-axis Cassegrainian telescope is used to expand the beam as it is being amplified. On leaving the preamplifier, the 45 mm diameter beam makes a single pass through the final three modules. In the work reported in this paper four gas cells are used for isolation: one in the preamplifier, one at the beginning of the amplifier chain and two to separate the three modules.

The oscillator, preamplifier and amplifiers were operated at charging voltages of 38 kV, 46 kV and 50 kV, respectively - the voltage appearing on each of the two 0.22 μF capacitors in the two-stage Marx bank of a module. For a gas mixture of CO_2, N_2 and He in the ratio 1 : 1 : 2, from previous work,[4,6] on the 10 P(20) line the average small-signal gain coefficients g_o were estimated as being 2.75, 3.25 and 3.75% cm^{-1} for the oscillator, preamplifier and amplifiers, respectively.

The selection and optimization of the absorber gas mixture was performed in four stages. Firstly, a number of gases was selected which had known strong absorption bands in the wavelength range 9 to 11 μm. Secondly, the small-signal absorption spectrum of each of these gases was determined accurately over this range, using a Perkin-Elmer Model 521 infrared spectrometer of resolution 0.3 cm^{-1} at 1000 cm^{-1}. Subsequently, each spectrum was reduced to digital form. Thirdly, using a computer, a non-linear least-squares best fit to an idealized spectrum was performed, with the measured spectra as input data and the concentrations of the gases as variables, to give the optimal ratio of the component gases. Gases with negligible working pressure in the mixture were elimated after inspection. Finally, the best pressure for the mixture was determined experimentally using the laser chain already described.

The small-signal absorption spectrum of each of the following gases was measured: CH_3F, $CHF_2C\ell$, $CF_2C\ell_2$, $CF_3C\ell$, $C_2F_3C\ell$, $C_2F_5C\ell$, C_2F_6, C_3F_8, C_4F_8 (cyclic), NH_3, OCS, SiF_4 and SF_6.

The best mixture for the present purposes was determined to be a combination of SF_6, $CF_2C\ell_2$ and C_4F_8 in the ratio 50 : 100 : 5, respectively. In figure 2 the small-signal absorption spectrum for this mixture is shown. We see that for the 10P, 10R and 9R bands the absorption is strong, whilst for the 9P band it is relatively weak; the mixture acts as a filter with an approximately-rectangular pass band. In particular, for a pressure of 155 torr and a cell length of 10 cm, the transmission for the 10P(20) and 9R(22) lines is less than 0.5%, that for the 10R(20) line is 22%, while the transmission for the 9P(22) line is 90%. Since

the intensity transmitted, I_t, is related to the incident intensity, I_i, by $I_t = I_i \exp(-\alpha pL')$, we may calculate the effective absorption coefficient as a function of wavelength.

To identify the contribution of each component gas to the absorption spectrum of the mixture, in figure 3 the individual spectra for $CF_2C\ell_2$, C_4F_8 and SF_6 are given. It can be seen that $CF_2C\ell_2$ will suppress the 9R band and the short-wavelength part of the 9P band. The combination of C_4F_8 and SF_6 will suppress the 10R and 10P bands. Finally, C_4F_8 may also be used to give controlled absorption over the 9P band.

EXPERIMENT

Final optimization involving tests of the gas mixture at high laser intensities cannot be avoided as the procedure described above only optimizes the gas mixture with respect to its small-signal isolation characteristics. Processes such as power broadening[7] and bleaching[2] of the equilibrium rotational population can, in principle, significantly change the low-level absorption characteristics. However, the optimization procedure described proved to be adequate in determining the optimal ratio for the gas mixture.

To optimize the working pressure of the mixture, the amplifier chain alone was fired at the standard voltage and the presence of parasitics was detected by burn marks on Polaroid film and by using a grating spectrometer (Optical Engineering Spectrum Analyser) to monitor

the emission. Without any gas in the cells, the emission occurred on the 10P(20) line. Shot by shot, gas was introduced into cells 3 and 4 until all parasitic emission ceased. The pressure at which this occurred was about 35 torr. At pressures over 10 torr, it was seen that the parasitic emission occurred on the 9P(22) line; that in other bands having been prevented by the strong absorption. The process was repeated for the preamplifier, firing it alone, until at a pressure of 10 torr in cell 1 all parasitic emission ceased. Finally, the whole system was fired together, upon which parasitic emission was once more detected. To suppress this, gas was admitted into cell 2. However, more efficient energy extraction was obtained by increasing the pressure in cells 3 and 4 by 50%, to about 50 torr, and then admitting sufficient of the gas mixture into cell 2 to suppress parasitic emission - this required a pressure of 20 torr.

Using the appropriate amounts of gas in the cells, 17J of energy have been extracted from the laser system on the 9P(32) line, in a beam of diameter 4.5 cm. There was no detectable parasitic emission at other wavelengths. In contrast, without gas in the cells about 20 J of parasitic emission were produced on the 10P(20) line from the preamplifier and amplifier chain, in the absence of an oscillator output.

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DISCUSSION AND CONCLUSIONS

Taking the ratios of the small-signal gain coefficients for the 10P(20), 10R(20), 9P(22) and 9R(22) lines as 1.0 : 0.9 : 0.7 : 0.65, knowing the working pressure in each cell and having calulated the absorption coefficient of the gas mixture for each of these lines, we tabulate the sums of the gain-length product $\Sigma g_o L$ and the absorption-length product $\Sigma \alpha p L'$ for each line, in table 1.

TABLE 1

line	$\Sigma g_o L$	$\Sigma \alpha p L'$	$\Sigma g_o L - \Sigma \alpha p L'$
10P(20)	21.0	12.3 *	8.7 *
10R(20)	18.9	7.7	11.2
9P(22)	14.9	0.3	14.6
9R(22)	13.7	12.3	1.4

In practice, because the preamplifier is separated from the amplifier modules by about 200 cm, a certain amount of decoupling occurs between the two due to the reduced solid angle. This reduces the small-signal gain sufficiently for all the lines, in the presence of the isolator gas, to ensure complete stability against self oscillation; i.e. $\Sigma g_o L - \Sigma \alpha p L' \lesssim 10\text{-}12$.

* These figures pertain to a transmission of 0.5% for the 10P(20) line, derived from figure 2. This is an upper bound; in reality the transmission is much lower but its true value cannot be determined from the trace. Using a published value[2], 0.32 cm^{-1} $torr^{-1}$, for the absorption coefficient of SF_6 at 10.6 μm we obtain $\Sigma \alpha p L' = 640$ and $\Sigma g_o L - \Sigma \alpha p L' = -619$.

The small-signal transmission, for the 9P(32) line, of cells 3 and 4 is calculated as being 80%, including reflective losses from the salt windows, that of cell 2 as 90% and that of cell 1 as 92%. Subtracting the reflective losses, the transmissions become 93 %, 98 % and 99.5 %, respectively. Under high CO_2-laser irradiation it is possible that the absorption saturates and the losses become even smaller.

The performance of the system was not found to depend sensitively on the gas mix ratios nor on the absolute pressure of the mixture. At normal working pressures in the gas cells, the amount of SF_6 could be increased or decreased by over 50%, keeping the partial pressures of the other gases constant, without any change in the energy or spectral purity of the laser output. The concentration of $CF_2C\ell_2$ could likewise be varied with no detectable effect. However, a change of $\sim$ 20% in the concentration of C_4F_8 was found to be significant - decreasing the concentration by 20% permitted parasitic emission on the 9P(22) line while increasing it by the same amount lead to a decrease in laser output. Using the standard mixture, with 50 torr pressure in cells 3 and 4, a change of $\sim$ 5 torr in one of the cells was the minimum pressure increment that affected the laser output. Increasing the pressure reduced the output, while a decrease permitted emission on the 9P(22) line - presumably due to the change in concentration of C_4F_8.

Since the laser system was only operated on the 9P(32) line, no attempts were made to find a suitable isolator gas for other lines. However, the technique for selecting and optimising a gas mixture is quite general and could easily be applied to operation on lines in bands

other than the 9P band. Two additonal gases which would be useful for this purpose are $C_2F_3C\ell$ and $C_2F_5C\ell$. The transmission through a cell of length 10 cm, filled to a pressure of 100 torr, is less than 5% over the ranges 1045 - 1090 cm^{-1} and 960 - 1010 cm^{-1} for $C_2F_3C\ell$ and $C_2F_5C\ell$, respectively.

Because in the present system the gas pressure in the cells was adjusted to eliminate parasitic emission, from figure 2 it can be seen that output is achievable on any line in the 9P band, from about the P(18) line to longer wavelengths, simply by tuning the oscillator to that line. For operation of the system at shorter wavelengths in this band, the effect of the cut-off edge of the $CF_2C\ell_2$ - see figure 3 - becomes important. It would be necessary to reduce the concentration of this gas in the mixture to achieve reliable operation of the system on the shorter-wavelength lines. Operation of the system on the 9R band could be achieved by eliminating, or drastically reducing the concentration of, the $CF_2C\ell_2$. Parasitic hold-off could be maintained by increasing the concentration of C_4F_8, although the gas mixture would no longer be optimised.

New gas mixtures would be required for operation on the 10R and 10P bands. A suitable mixture for operation of the system on the 10R band would be $CF_2C\ell_2$ and $C_2F_3C\ell$, to suppress the 9R and 9P bands, and SF_6 and C_4F_8, to suppress the 10P band. The effect of spontaneous emission on the 10R band could be controlled by adjusting the concentration of C_4F_8. For

operation on the 10P band a suitable mixture would be CF_2Cl_2, C_2F_3Cl, C_2F_5Cl and SF_6. The SF_6 would be used to give controlled absorption on the 10P band, while the C_2F_5Cl would suppress the 10R band.

In conclusion, we have demonstrated the selection, optimization and use of a gas mixture as an isolator between the amplifier stages of a CO_2-laser chain to suppress parasitic emission and to yield efficient energy extraction. The mixture suppresses all bands, with the exception of the 9P band, by strong absorption while permitting a small-signal transmission of greater than 93% at the working wavelength , 9.66 μm, corresponding to the 9P(32) line. Efficiency in energy extraction is not dependent on the isolator gas bleaching at working CO_2-laser intensities.

From an effective gain length of 600 cm for amplification, 17 J of energy have been extracted in a beam of diameter 4.5 cm, at 9.66 μm, without any detectable parasitic emission at other wavelengths.

ACKNOWLEDGEMENTS

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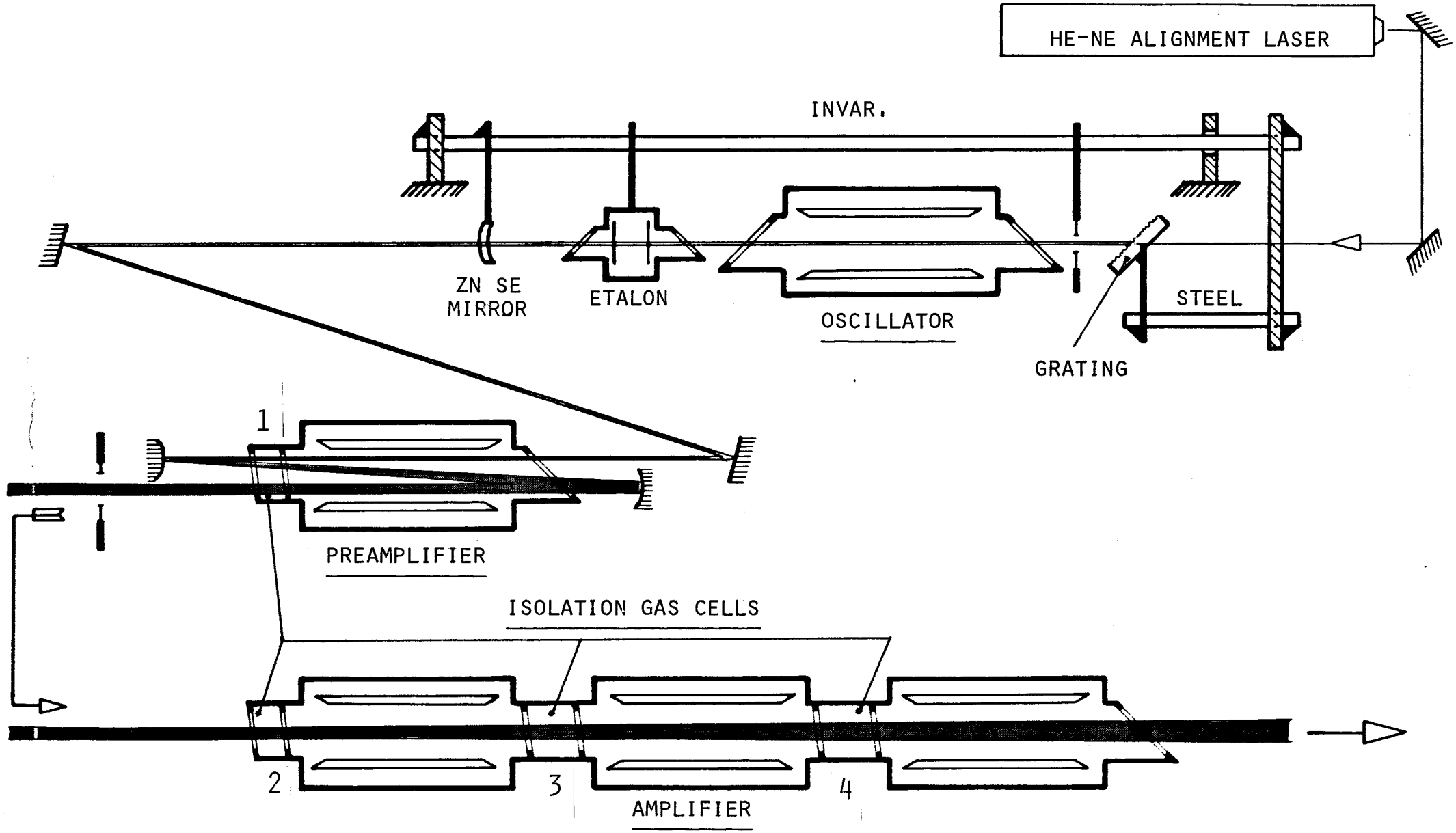
FIGURE CAPTIONS

Figure 1 : Layout of the CO_2-laser chain used for optical pumping. The lengths of the isolation gas cells were as follows: cell (1) 10 cm, cell (2) 20 cm and cells (3) and (4) 55 cm.

Figure 2 : A small-signal transmission spectrum of the optimized gas mixture from 910 to 1100 cm^{-1}. Also shown are the relative gains of the P and R branches of the CO_2-laser transitions.

Figure 3 : Small-signal transmission spectra for the individual gases of the isolation mixture. Cell length 10 cm. Gas pressures : C_4F_8 50 torr, SF_6 50 torr and $CF_2C\ell_2$ 100 torr.


HE-NE ALIGNMENT LASER
INVAR.
ZN SE
MIRROR
ETALON
OSCILLATOR
STEEL
GRATING
1
PREAMPLIFIER
ISOLATION GAS CELLS
2
3
4
AMPLIFIER

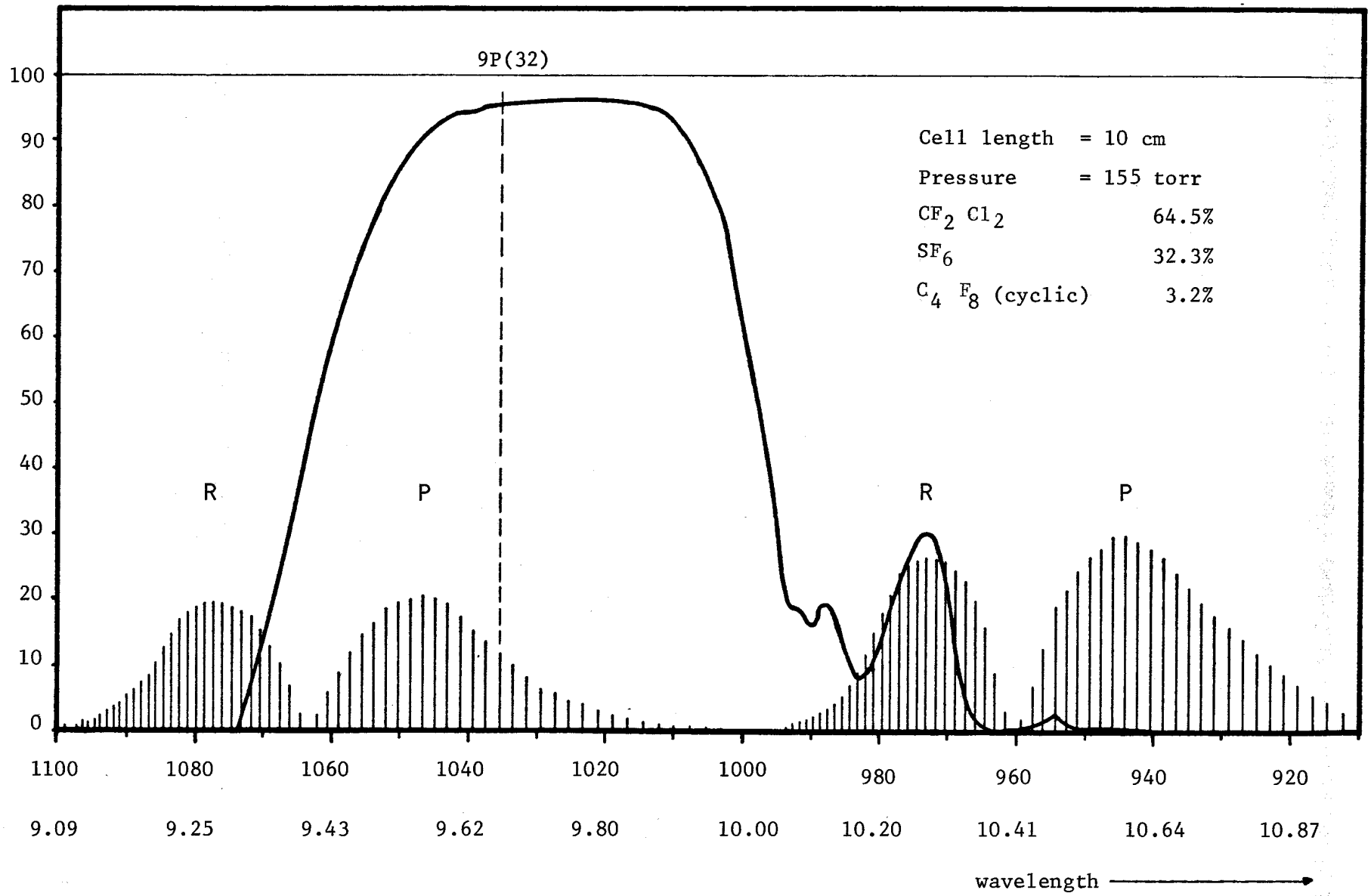

9P(32)
100
90
80
70
60
50
40
30
20
10
0
transmission in %
Cell length = 10 cm
Pressure = 155 torr
$CF_2 Cl_2$ 64.5%
SF_6 32.3%
$C_4 F_8$ (cyclic) 3.2%
R
P
R
P
1100
1080
1060
1040
1020
1000
980
960
940
920
cm-1
9.09
9.25
9.43
9.62
9.80
10.00
10.20
10.41
10.64
10.87
µm
wavelength

Figure 2

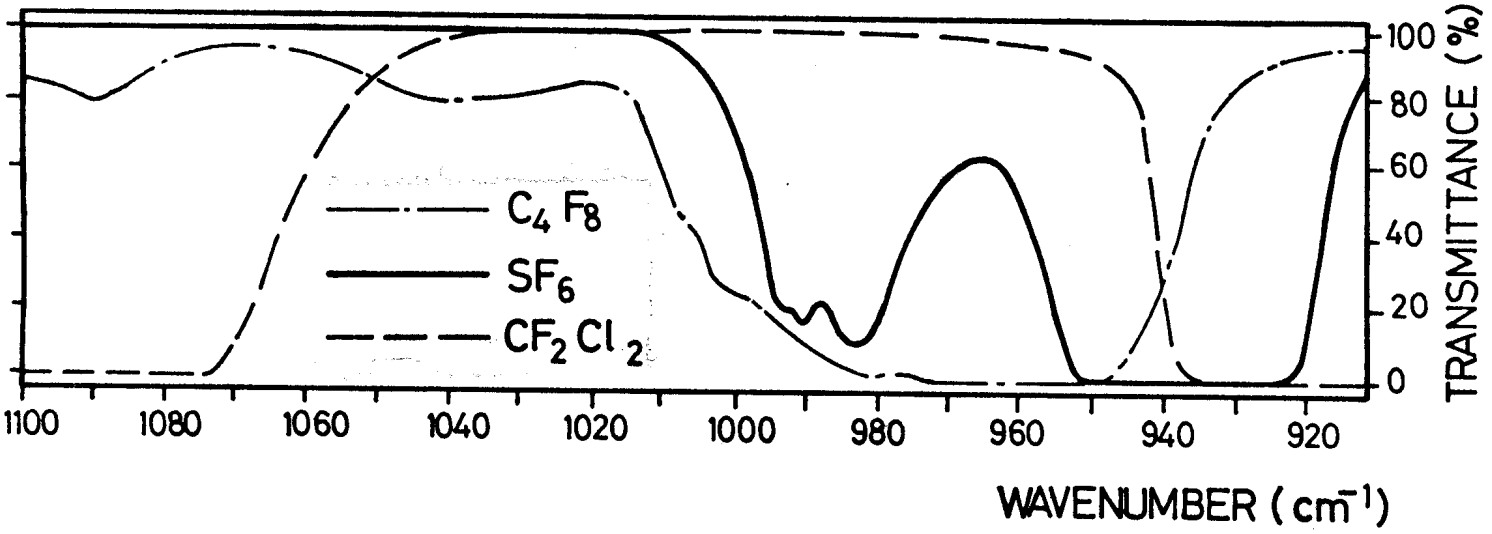

C4 F8
SF6
CF2 Cl 2
100
80
60
40
20
0
TRANSMITTANCE (%)
1100
1080
1060
1040
1020
1000
980
960
940
920
WAVENUMBER (cm-1)

Figure 3