

Investigation into Optogalvanic Reference Lines

Steven Knox

April 2004

**Investigation into Optogalvanic
Reference Lines**

Steven Knox

April 2004

© Crown copyright 2004

Reproduced by permission of the Controller of HMSO

ISSN 1744-0483

National Physical Laboratory
Queens Road, Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

Approved on behalf of Managing Director, NPL
By Dr. Stuart Pollitt, Director of Enabling Metrology Division

Executive Summary

This report presents the results of the investigation into optogalvanic transitions for use as wavelength reference standards within the optical telecommunications band.

Contents

1. BACKGROUND	1
1.1. OPERATION OF AN OPTOGALVANIC CELL	1
1.2. PREVIOUS WORK.....	3
2. SURVEY OF OPTOGALVANIC MATERIALS.....	5
2.1. IDENTIFICATION OF SUITABLE TRANSITIONS.....	5
2.2. POWER SUPPLY FOR CELLS.....	6
2.3. METAL LINES.....	6
2.3.1. <i>Cadmium</i>	8
2.3.2. <i>Magnesium</i>	9
2.4. GAS TRANSITIONS	10
2.4.1. <i>Unsaturated gas transitions</i>	12
2.4.2. <i>Saturated gas transitions</i>	15
3. CONCLUSION	18
ACKNOWLEDGEMENT	19
REFERENCES	20

Figure 1: Detecting an optogalvanic transition	1
Figure 2: Unsaturated optogalvanic response	2
Figure 3: A saturated optogalvanic response	2
Figure 4: Derivatives of saturated and unsaturated responses	3
Figure 5: Frequency response of the power supply amplifier	6
Figure 6: Unsaturated Acetylene lock system.....	7
Figure 7: Unsaturated OG locking system	8
Figure 8: Measurements of the Cadmium 1571nm transition.....	8
Figure 9: Measurements of the reference wavelength of acetylene	8
Figure 10: OG response of the Cadmium 1571nm transition	9
Figure 11: OG response of the Magnesium 1575nm transition	9
Figure 12: OG response of the Magnesium 1577nm transition	9
Figure 13: A miniature OG gas cell	10
Figure 14: Voltage against pressure of Kr OG cells	11
Figure 15: Current required against pressure of Kr OG cells	11
Figure 16: Signal strength measured against pressure of Kr OG cells.....	11
Figure 17: Noise spectra for different pressure Kr gas cells up to a frequency of 100kHz.....	11
Figure 18: Noise spectra for different pressure Kr gas cells up to a frequency of 10kHz.....	12
Figure 19: OG response of Xe 1604nm transition	12
Figure 20: OG response of Xe 1598nm transition	12
Figure 21: OG response of Xe 1556 transition	13
Figure 22: OG response of Xe 1605nm transition	13
Figure 23: OG transition of Xe 1542nm transition	13
Figure 24: Double locking system used to measure Xe 1542 transition.....	14
Figure 25: Frequency difference between Xe 1542m transition and Acetylene reference.....	14
Figure 26: Configuration for saturated OG lock.....	15
Figure 27: Stability of Ar 1599 nm transition.....	16
Figure 28: OG response of Ar 1599nm transition.....	16
Figure 29: Stability of Kr 1568 transition	16
Figure 30: Lock stability of Kr 1582nm transition	17
Figure 31: Saturated OG response of Xe 1542nm transition	17

Table 1: Vacuum wavelengths of previously reported OG transitions,wavelength range (1240-1617) nm.....	4
Table 2: Survey of suitable reference materials [6]	5
Table 3: L-Band metal-vapour excited state OG transitions.....	10
Table 4: Results of the optogalvanic survey	18

1. Background

The increase in bandwidth of dense wavelength division multiplex (DWDM) systems has increased the need for accurate frequency standards. Gas absorption standards such as C_2H_2 , HCN and CO can be used as absolute reference standards and cover a large range of frequencies. Some of these gas absorption lines are closely spaced, this can cause problems in their use as the wrong line may be used. Optogalvanic excited-state transitions in noble gases have the advantages that they are well separated and can also be saturated at modest powers.

1.1. Operation of an optogalvanic cell

Optogalvanic cells consist of noble gases that produce a plasma when a high voltage is passed across the cell. The optogalvanic effect occurs when the plasma is illuminated by radiation that is resonant with an atomic or molecular transition. These transitions cause an increase or decrease in the conductivity of the discharge and can be detected as a change in the voltage across the discharge cell as shown in figure 1.

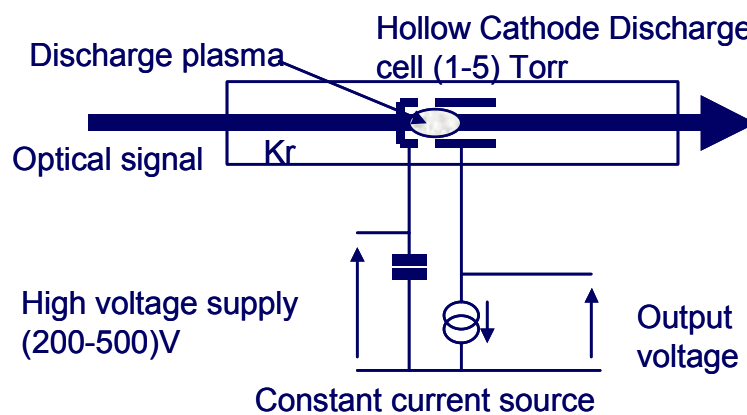


Figure 1: Detecting an optogalvanic transition

The voltage response across an unsaturated transition can be seen in figure 2.

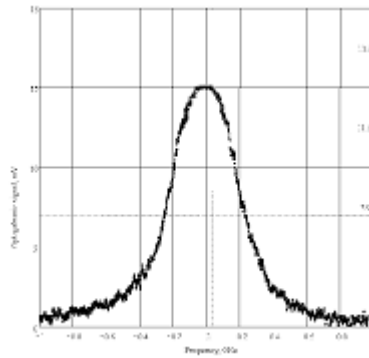


Figure 2: Unsaturated optogalvanic response

Using the derivative of the transition, figure 4, it is possible to lock between the two turning points by feeding back the signal into a tuneable laser system allowing the laser to be frequency locked to the fixed reference of the transition.

A saturated optogalvanic response can be achieved by using a mirror to reflect the light back through the plasma. This results in some of the atoms being probed by two photons, causing a resulting dip in the optogalvanic signal, figure 3.

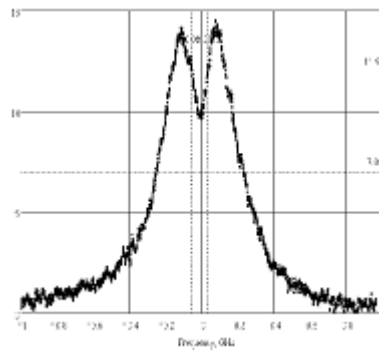


Figure 3: A saturated optogalvanic response

The derivative of the signal results in turning points that will allow for a narrower frequency width to be locked to giving higher accuracy as demonstrated in figure 4.

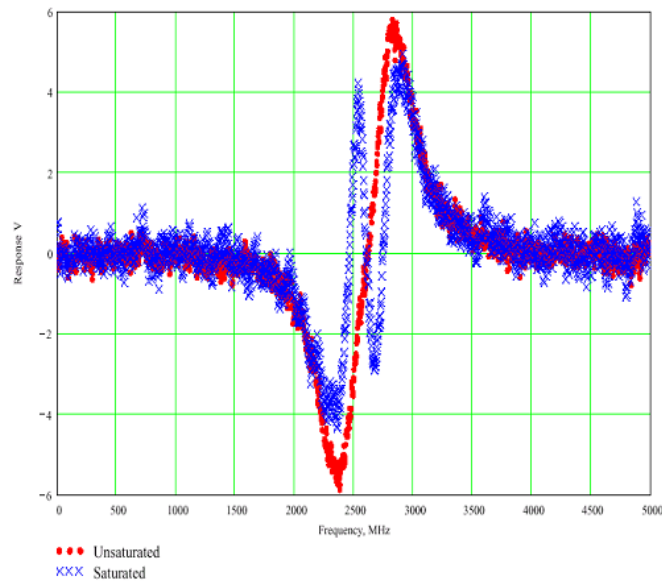


Figure 4: Derivatives of saturated and unsaturated responses

1.2. Previous Work

Some work has already been carried out on optogalvanic excited-state transitions in noble gases around wavelengths relevant to optical fibre communications.

Work carried out by A.J. Lucero [1] measured the intensities at which saturation occurred for excited states of argon, krypton, and neon of 20 transitions for wavelengths between 1.3 and 1.5 μm . The saturation intensities ranged from between 20 to 2000 mW/cm^2 . Further work [2] investigated 26 atomic transitions assigning a figure of merit to each for the comparison of the efficiency of each transition, the figure of merit was defined by the electrical signal available per photon absorbed. This gave some predictability as to the signal levels, but was more useful in comparing relative strengths of the lines since the signal levels are dependent on the experimental configuration.

Work was carried out by U. Fischer on the ^{84}Kr transition at 1547.825nm [3]. Here the Doppler-free natural linewidths of five Kr isotopes and relative intensities were measured. The study focussed on the ^{84}Kr transition at 1547.825nm, where the non-Doppler-broadened linewidth was measured at 56MHz, compared with the broadened linewidth of 400MHz.

D.A. Humphreys made the first saturated optogalvanic transition of Kr in the L-Band. [4] The optogalvanic transition at 1564nm was saturated at modest powers (<10mW). The power dependence of the saturation was found for pump powers between 1-7.8 mW. Measurement of the full width of the saturated dip was measured as (67-81) MHz at (6.7-7.8) mW, the Doppler broadened linewidths were measured as (410-427) MHz at (1-2) mW. This demonstrated the possibility for high accuracy measurements at modest power levels. The saturated transition was measured at a wavelength of

1563.97644 (14) nm @ 95% confidence measured against an unsaturated acetylene reference line. The transition was locked to for a period of time in excess of two hours.

A number of optogalvanic transitions already reported [2,5] covering the range (1240-1617)nm are shown in table 1.

Element	Wavelength / nm	Element	Wavelength / nm
Ar	1249.111 $\pm$ 0.001	Kr	1500.943 $\pm$ 0.001
Ar	1270.581 $\pm$ 0.001	Kr	1501.914 $\pm$ 0.001
Ar	1273.696 $\pm$ 0.001	Ar	1505.064 $\pm$ 0.001
Ar	1274.977 $\pm$ 0.001	Ar	1517.694 $\pm$ 0.001
Ar	1280.629 $\pm$ 0.001	Kr	1521.376 $\pm$ 0.001
Kr	1286.541 $\pm$ 0.001	Ne	1523.491 $\pm$ 0.001
Ne	1291.555 $\pm$ 0.001	Kr	1524.380 $\pm$ 0.001
Ar	1293.675 $\pm$ 0.001	Kr	1533.065 $\pm$ 0.001
Ar	1296.025 $\pm$ 0.001	Ar	1533.350 $\pm$ 0.001
Kr	1298.886 $\pm$ 0.001	Kr	1533.915 $\pm$ 0.001
Ar	1301.118 $\pm$ 0.001	Kr	1537.625 $\pm$ 0.001
Kr	1318.104 $\pm$ 0.001	Kr	1543.795 $\pm$ 0.001
Kr	1473.841 $\pm$ 0.001	Kr	1247.82599 $\pm$ 0.00010
Kr	1476.666 $\pm$ 0.001	Kr	1563.978 $\pm$ 0.001
Kr	1476.954 $\pm$ 0.001	Kr	1568.533 $\pm$ 0.001
Kr	1496.597 $\pm$ 0.001	Kr	1577.614 $\pm$ 0.001

Table 1: Vacuum wavelengths of previously reported OG transitions, wavelength range (1240-1617) nm

2. Survey of optogalvanic materials

2.1. Identification of suitable transitions

Atomic emission lines can be used as a guide to find optogalvanic transitions since the wavelength of radiation that is required to excite transitions within a plasma are near to those that are required to excite the same transition in a non-excited atom. Atomic spectra data was available from the CRC Handbook and results of work at NIST, this allowed the identification of materials that would have transitions in the telecommunications wavelength ranges. A total of 34 possible transitions were identified in the C and L bands from the elements Ar, B, Bi, Ca, Cd, Fe, Hg, Kr, Mg, P, Pb, Rb, Si, Se, Te and Xe. Elements that could be used satisfactorily within optogalvanic cells were identified with commercial lamp producers, resulting in the acquisition of gas cells containing Ar, Kr, Xe and metal cells of Bi, Cd, Mg and Se. The possible transitions are shown in table 2 with the cells acquired highlighted.

Element	Wavelength / nm	Distance from nearest ITU line / GHz	Element	Wavelength / nm	Distance from nearest ITU line / GHz
Be	1616.213	9.4	Se	1562.267	4.2
Ca	1616.177	5.2	Xe	1556.138	-1.6
Ca	1615.518	-20.5	Te	1555.048	13.3
Si	1606.442	-18.9	Se	1552.521	-0.4
Xe	1605.767	2.6	Kr	1547.825	13.8
Xe	1604.428	-3.1	Se	1547.523	-24.1
Bi	1600.587	-1.5	Te	1545.667	-6.7
Ar	1599.386	7.8	Xe	1542.261	14.9
Xe	1598.391	-8.9	Kr	1537.624	-21.3
P	1596.689	-8.8	Pb	1535.379	-6.3
Si	1589.273	15	Kr	1533.915	7.3
Kr	1582.441	0.7	Ar	1533.353	-14.3
Fe	1577.373	-8.1	Kr	1533.067	-0.8
Mg	1577.015	-1.2	Hg	1530.000	7.2
P	1571.581	-8.5	Fe	1529.876	-8.7
Cd	1571.229	-1.2	Rb	1529.366	-24
Kr	1568.53	20.5	Rb	1529.261	12.5
B	1563.335	-14.7			

Table 2: Survey of suitable reference materials [6]

2.2. Power supply for Cells

A high voltage power supply is required to operate the cells. The power supply built has connections for both +700V and +350V, a constant current input also measures the change in conductivity of the discharge and is detected as a change in voltage. The signal passes through an amplifier and is then outputted. The supply has both low and high current controls allowing for currents from 15 to 2000 μA . The low current setting takes the current from 15 to 90 μA and the high current setting takes it to 2000 μA . The frequency response of the amplifier is shown in figure 5.

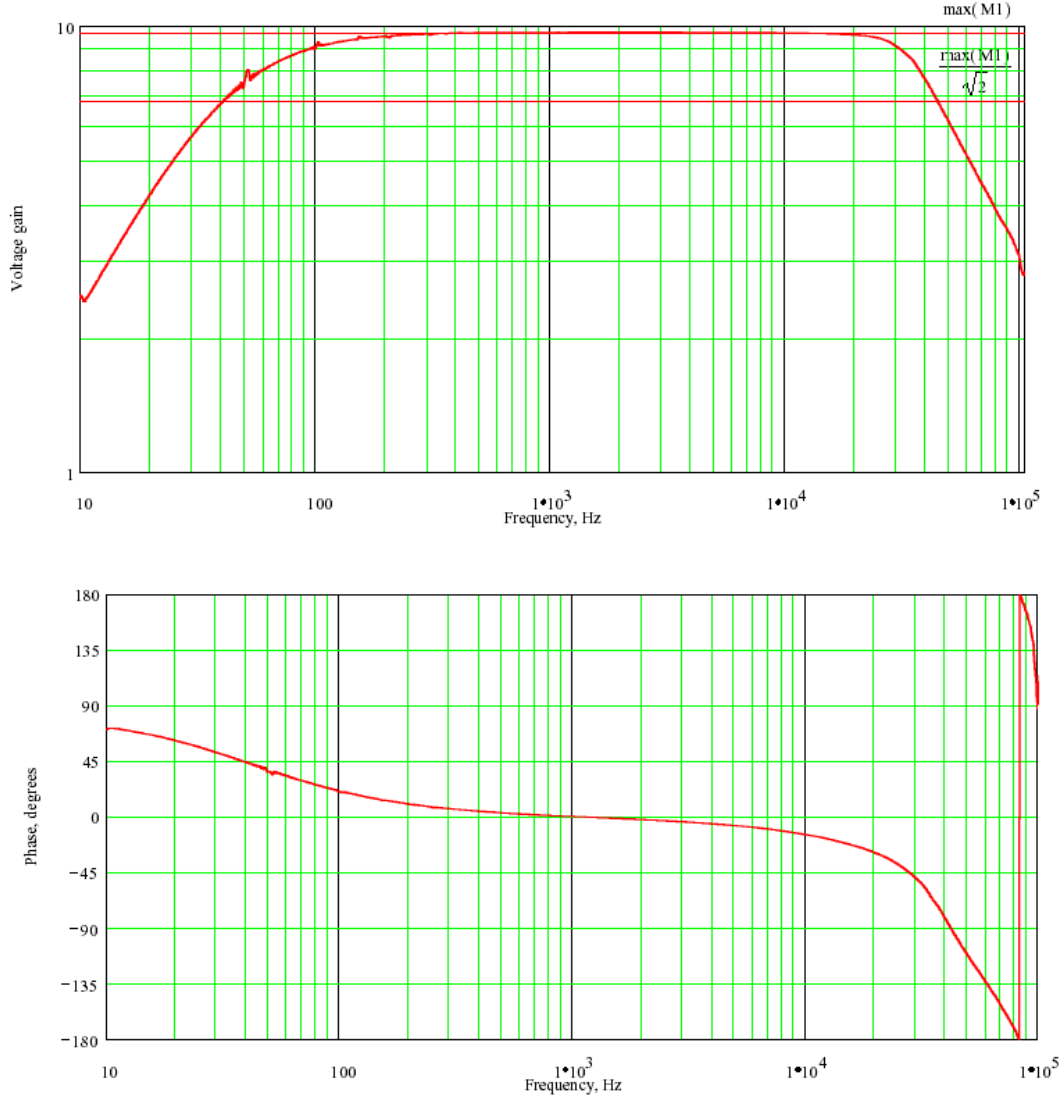


Figure 5: Frequency response of the power supply amplifier

2.3. Metal lines

Operation of the cells at high currents (5-15) mA and 700V causes sputtering of the electrodes which act as the source. This allows access to the metal vapour lines further extending the number of transitions available. The metal lines are only

accessible as unsaturated transitions due to the sputtering. The operation of the cells by sputtering limits the cell life to approximately 3000 hours due to the gradual depletion of material from the electrode. This is not too much of a problem as the lamps are a standard and relatively inexpensive product. The power supply used was unable to deliver enough current to excite any transitions in the heavy metals Bi and Se. Two cells were investigated. One with Magnesium electrodes and the other with Cadmium electrodes.

A wavelength meter measured the transitions with unsaturated acetylene lines being used as a reference, these are known and accurately characterised references. The acetylene unsaturated locking system, is shown in figure 6.

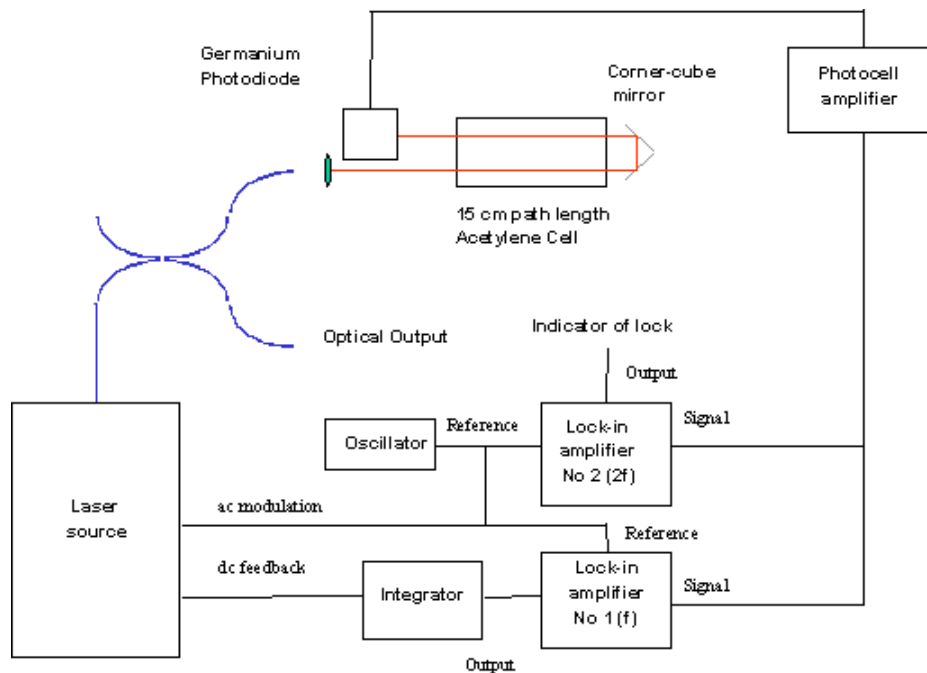


Figure 6: Unsaturated Acetylene lock system

After an OG transition has been identified the laser is locked to this transition, figure 7 shows the unsaturated locking system. The wavelength is measured over a period of time against the acetylene reference. From this the wavelength of the transition can be calculated. By scanning the wavelength across the transition the shape of the transition that is being locked to can be seen. The measurements results from the Cadmium and Magnesium cells are given.

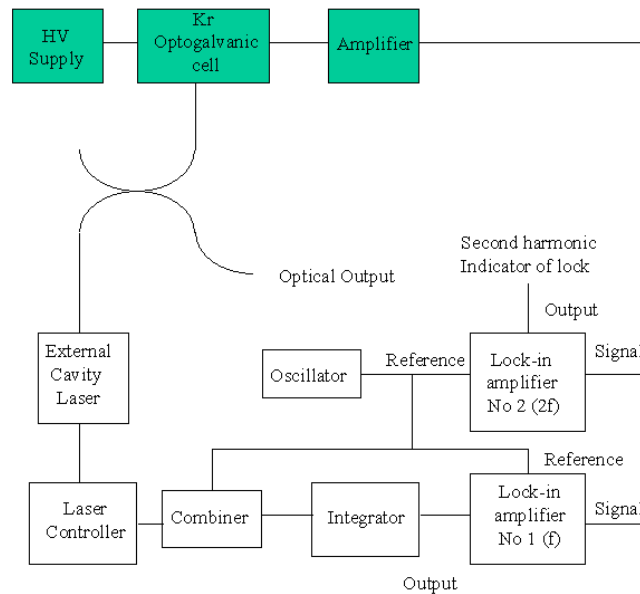


Figure 7: Unsaturated OG locking system

2.3.1. Cadmium

The wavelength could be calculated using the measurement of the Cadmium transition in figure 8, and the acetylene reference in figure 9. This allows for the measured wavelength of the Cadmium to be adjusted based on the known transition in the acetylene and so eliminates any offset in the wavelength meter readings.

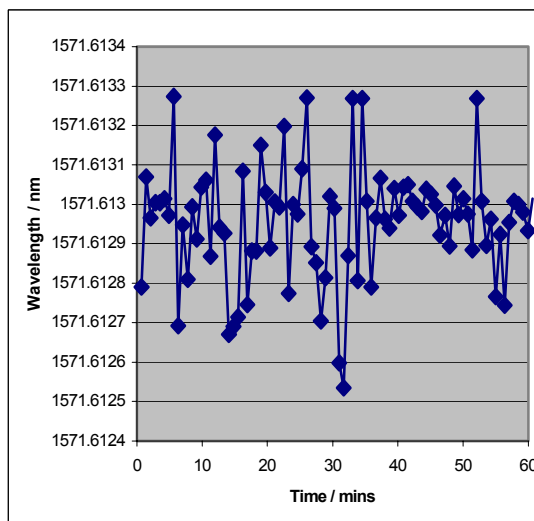


Figure 8: Measurements of the Cadmium 1571nm transition

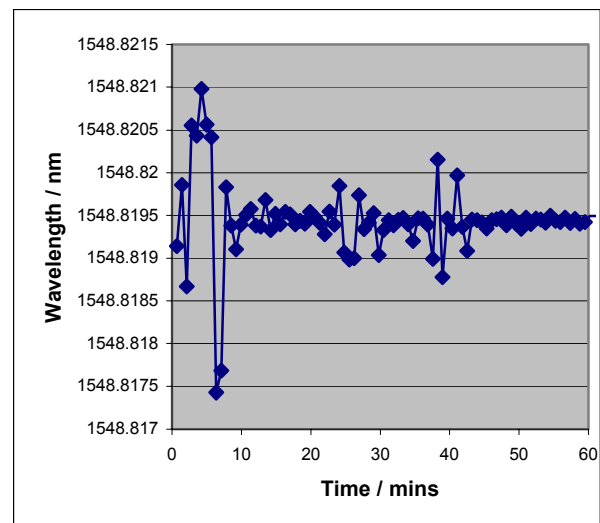


Figure 9: Measurements of the reference wavelength of acetylene

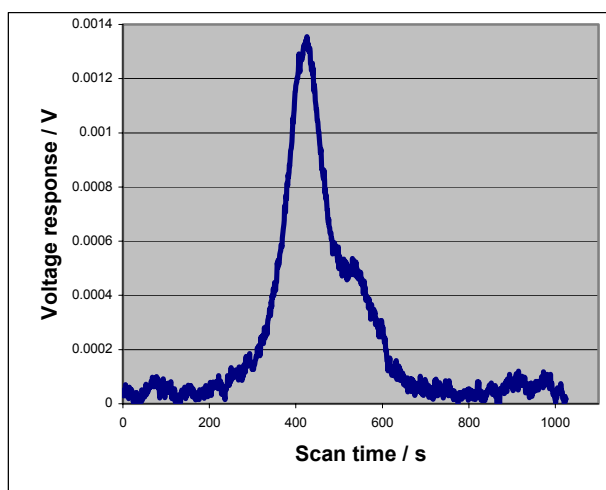


Figure 10: OG response of the Cadmium 1571nm transition

The calculated wavelength of the transition from these results was 1571.6128 (2) nm, and frequency 190754.636 (24) GHz.

2.3.2. Magnesium

Two transitions were found for magnesium, one at 1575nm and another at 1577nm. The OG response of these transitions is shown in figure 11 and figure 12.

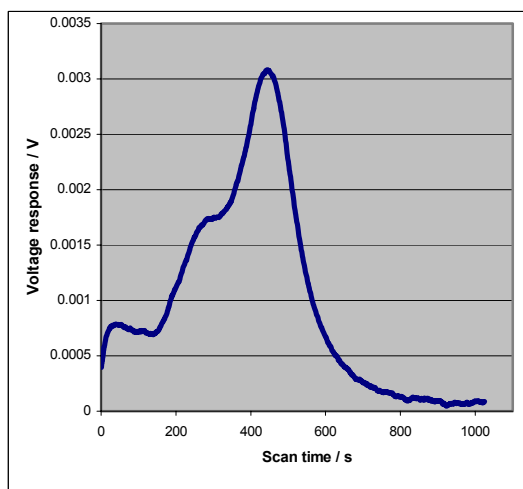


Figure 11: OG response of the Magnesium 1575nm transition

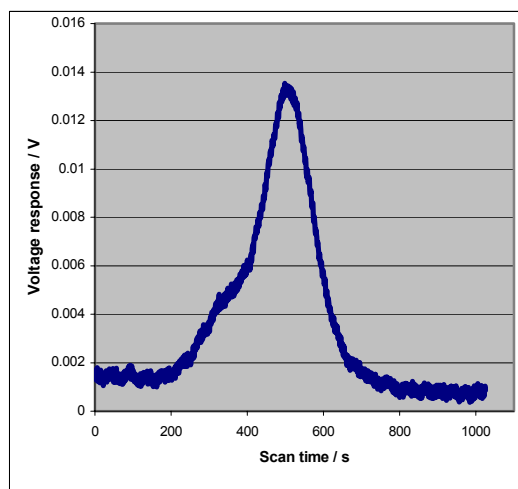


Figure 12: OG response of the Magnesium 1577nm transition

The wavelengths were again calculated accurately against acetylene transition lines. The calculated results were transitions at 1575.3294 (2) nm, frequency (190304.597 (24) GHz). And one at 1575.3294 (2) nm , (190304.597 (24) GHz).

Table 3 summarises the results and shows the distance of the transitions from the nearest 50 GHz ITU grid line.

Element	Wavelength, nm	Frequency, GHz	Difference from ITU 50 GHz grid, GHz
Cd	1571.6128 (2)	190754.636(24)	4.636 (24)
Mg	1577.0147 (2)	190101.217(21)	1.217 (21)
Mg	1575.3294 (2)	190304.597(24)	4.597 (24)

Table 3: L-Band metal-vapour excited state OG transitions

2.4. Gas Transitions

A number of miniature gas cells were used an example is shown in figure 13. The cells were filled with three different gases, Argon, Krypton and Xenon.



Figure 13: A miniature OG gas cell

The miniature lamps are operated at high voltages 350V-750V but at low currents (10-200) μ A this gives low sputtering and long cell life. The strength of transitions, saturation power, and the optical frequency difference from the excited-state transition to the nearest ITU grid line were investigated.

A number of Krypton cells were filled to different pressures. During manufacture the pressure of gas in the cell was varied while the voltage and current required to run the cell was monitored. The output signal strength was also recorded.

The results are shown graphically in figure 14, 15 and 16.

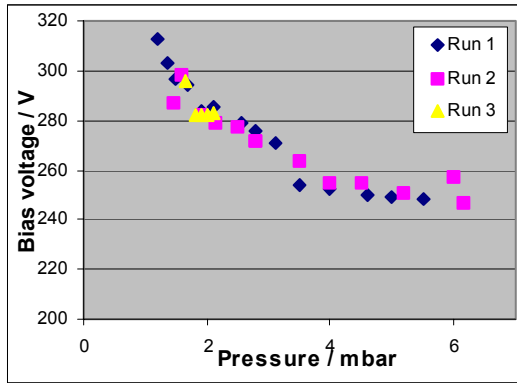


Figure 14: Voltage against pressure of Kr OG cells

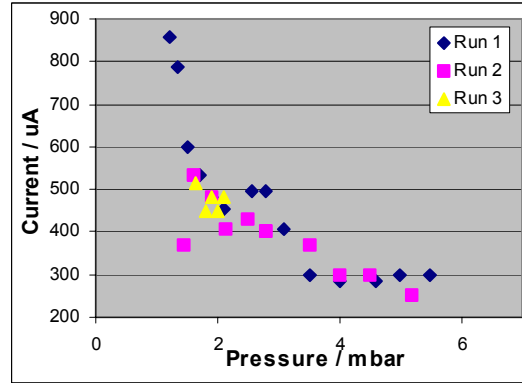


Figure 15: Current required against pressure of Kr OG cells

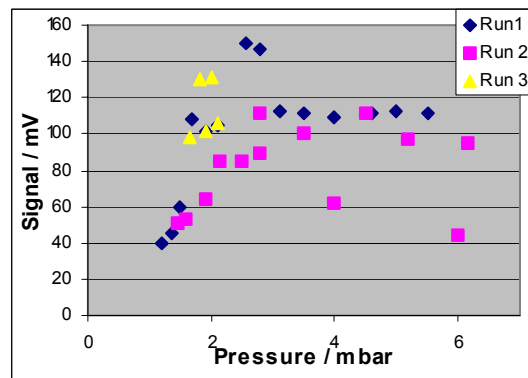


Figure 16: Signal strength measured against pressure of Kr OG cells

Based on these results the range 2-4mbar looked most optimum for general use. Cells were filled to 1.5, 1.9, 2.2 and 3.0mbar of krypton. The noise spectra for these gas cells were investigated and the results shown in figures 17 and 18.

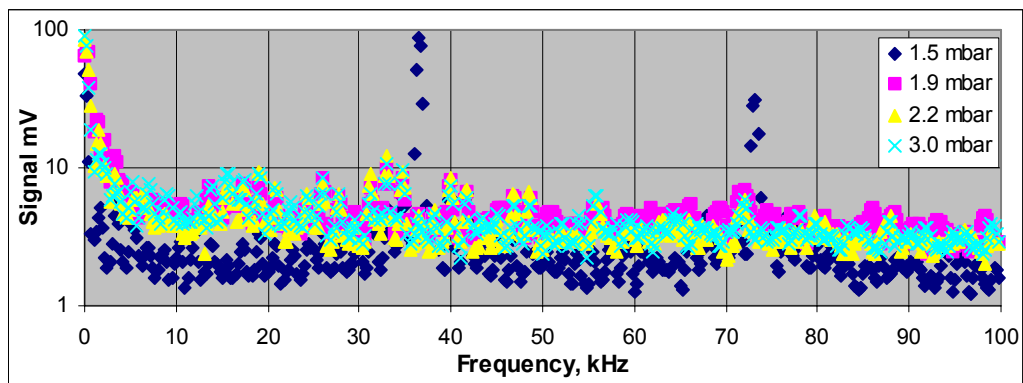


Figure 17: Noise spectra for different pressure Kr gas cells up to a frequency of 100kHz

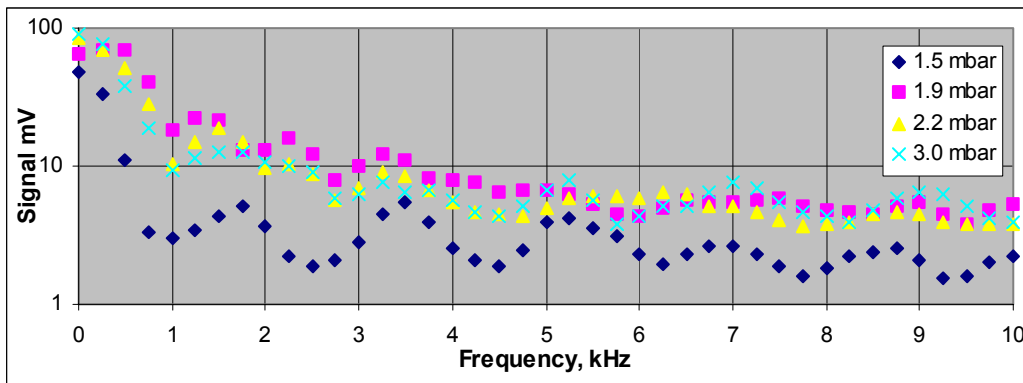


Figure 18: Noise spectra for different pressure Kr gas cells up to a frequency of 10kHz

The results of these tests showed that the low-pressure cell exhibits the most noise and is not stable below an operating current of 1.5mA so is least suitable for use. The other cells offer better signal quality and can be operated around 200 μ A.

2.4.1. Unsaturated gas transitions

Using the gas cells in single pass allows the unsaturated absorption lines to be accessed. The Xe transitions had not been verified and so were investigated further.

2.4.1.1 Xenon

The Xe miniature gas cell was filled to a pressure of 2.5mbar. The cell did not operate at 350V so the cell was run at 750V with a current of 240 μ A. Transitions at 1604.428, 1598.391 and 1556.138 were all found, but were found to be noisy and were not very clear signals. The transitions were measured using a Stanford SR850 lock-in. The transitions were scanned across and measurement of the frequency at the start and finish points of the scan recorded. The OG responses of these transitions for an input power of 8.0mW are shown in figure 19, 20 and 21.

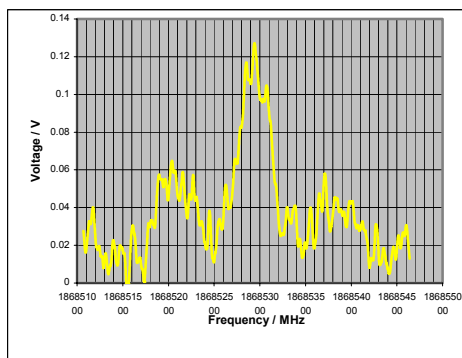


Figure 19: OG response of Xe 1604nm transition

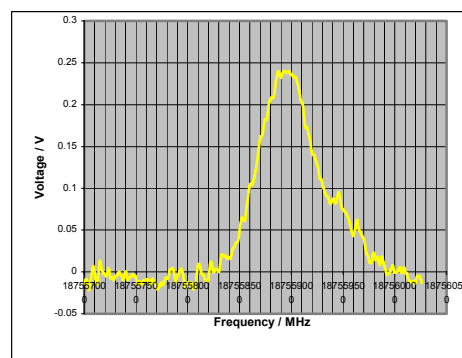


Figure 20: OG response of Xe 1598nm transition

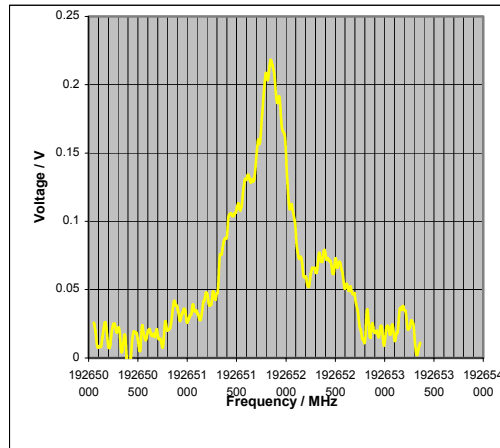


Figure 21: OG response of Xe 1556 transition

The transitions at 1605.767nm and 1542.261nm were stronger and required less optical power, a strong signal could be obtained at powers of 2.0mW. The OG responses of these transitions are shown for 6mW optical power in figure 22 and 23. The width of the doppler broadened line-widths of the transitions were found. The 1605.767nm transition was (450-500) MHz for (2-6) mW, and the 1542.261nm transition was (550-700) MHz for (2-6) mW.

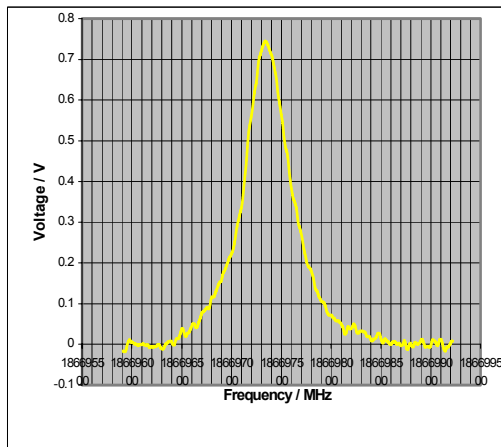


Figure 22: OG response of Xe 1605nm transition

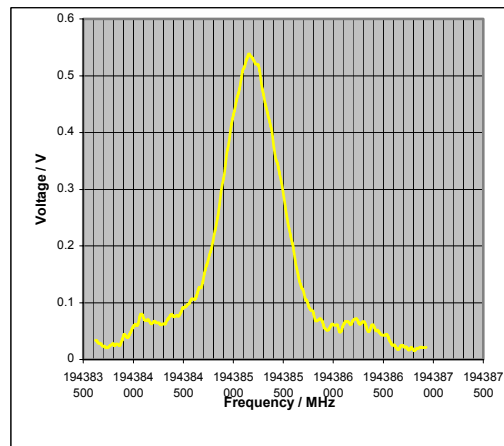


Figure 23: OG transition of Xe 1542nm transition

To try and improve the measurement accuracy of the Xe 1542.261nm line use of the known acetylene $\nu_1+\nu_2$ P16 line at 1542.3837125nm can be made. The system used is a double locking system in figure 24.

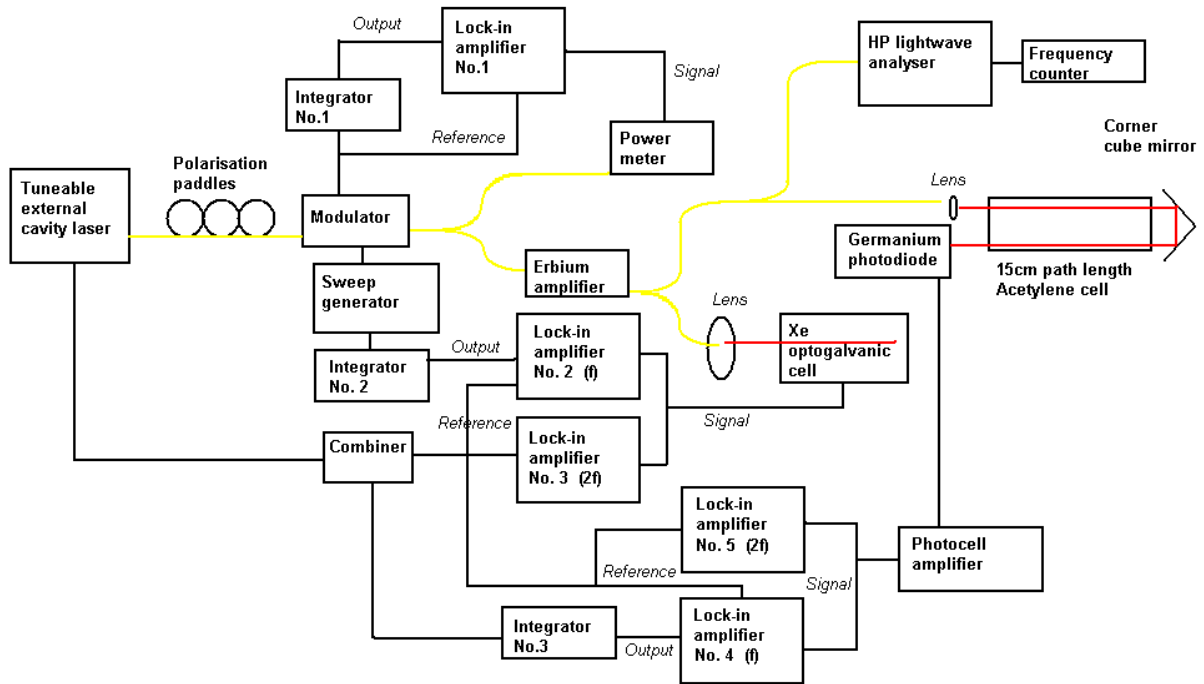


Figure 24: Double locking system used to measure Xe 1542 transition

Using a tuneable laser source a sweep generator and modulator are used to give side bands to the laser frequency at $\sim 7.5\text{GHz}$, this is approximately half the difference in frequency between the acetylene transition and the Xe transition being measured. Increasing the modulation power suppresses the central frequency and increases the sidebands. One of the side bands can then be locked to the acetylene line and the other to the Xe line. The control loop ensures locking to one side band, any movement about the transition causes the other line to move but using the second control loop the system remains locked to this transition also. The frequency counter can then measure the frequency separation over time. Figure 25 shows the frequency separation over a period of time in excess of 25hours. The frequency difference was found to be 15.4307 GHz. This gives a measured frequency of the Xe transition as 194384.9975 (25) GHz at 95% confidence, corresponding to a wavelength 1542.26129 (2) nm

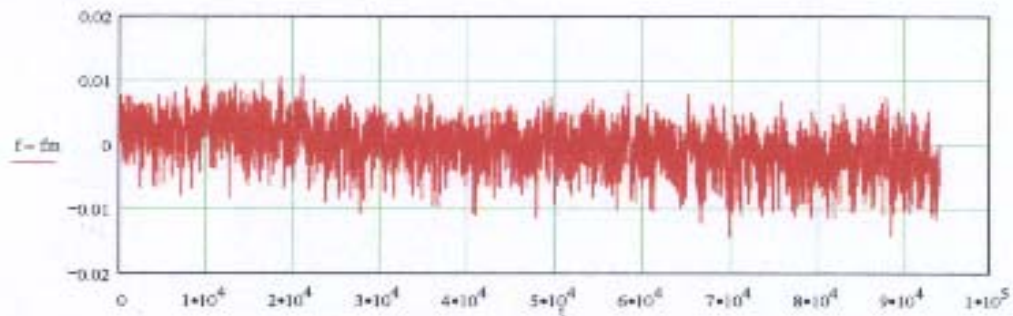


Figure 25: Frequency difference between Xe 1542m transition and Acetylene reference

The transition can also be scanned over by adjusting the modulation frequency and ensuring the acetylene transition remains locked. Using this method the width of the transition is measured at $\sim 730\text{MHz}$.

2.4.2. Saturated gas transitions

The measurement system used to lock to saturated transitions is shown in figure 26. Here two lock-in-amplifiers recover the saturated lock signal with an integrator being used to compensate for any drift. The system will only remain stable while the laser remains within the saturated dip, allowing for accurate determination of the wavelength.

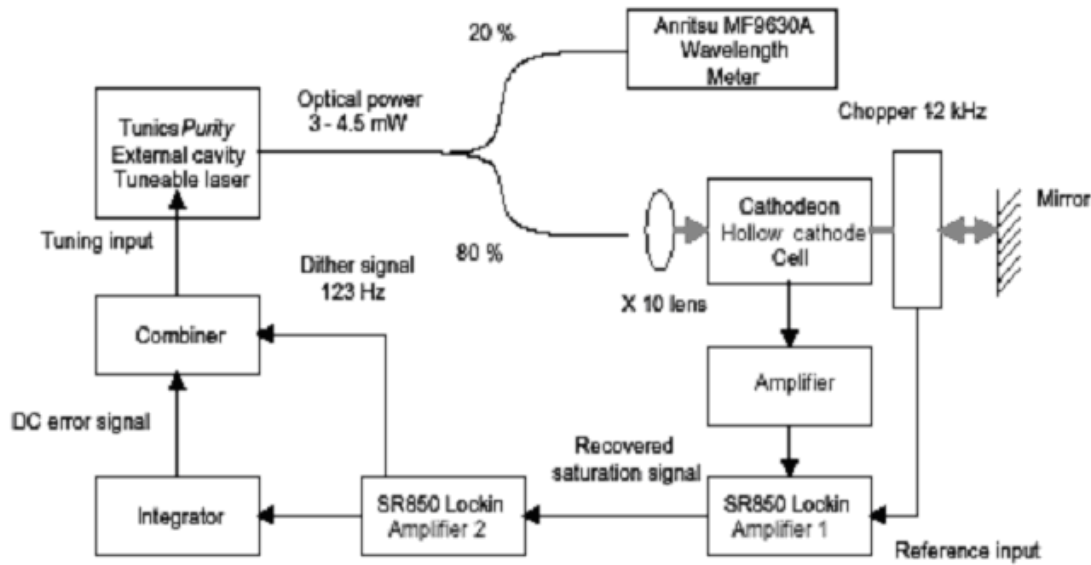


Figure 26: Configuration for saturated OG lock

2.4.2.1. Argon

The Ar transition at 1599 nm is a particularly strong transition and is able to be saturated at under 3mW. The wavelength of the transition measured against acetylene is 1599.38578(18), frequency 187442.243(21) GHz. The stability of the locked signal can be seen in figure 27, and the OG response in figure 28.

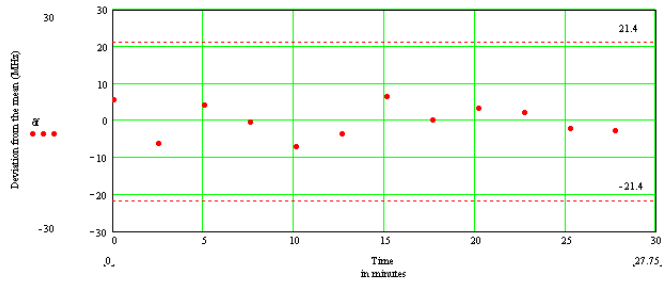


Figure 27: Stability of Ar 1599 nm transition

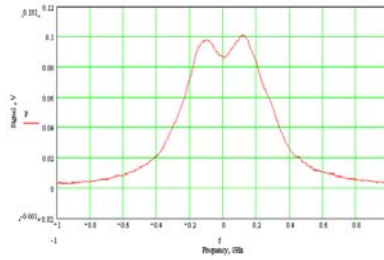


Figure 28: OG response of Ar 1599nm transition

2.4.2.2. Krypton

Three saturated transitions in Kr were identified at 1564, 1568 and 1582 nm. The transition at 1564nm had previously been saturated [5]. The wavelength measured against acetylene was 1563.97644 (14)nm at 95% confidence.

The transition at 1568 was at a wavelength of 1568.53081(18) nm, frequency 191129.467 (22) GHz the stability of the locked signal acquired is shown in figure 29.

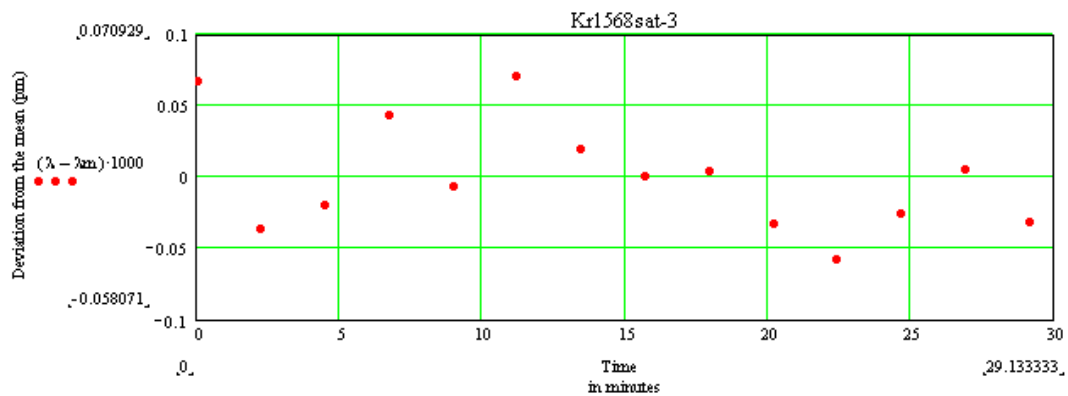


Figure 29: Stability of Kr 1568 transition

The line at 1582 was of particular importance as it was only -0.670 GHz away from the nearest 50GHz ITU grid line. The wavelength was measured at 1582.44137 (18) nm, frequency 189449.330 (22) GHz the lock stability is shown in figure 30.

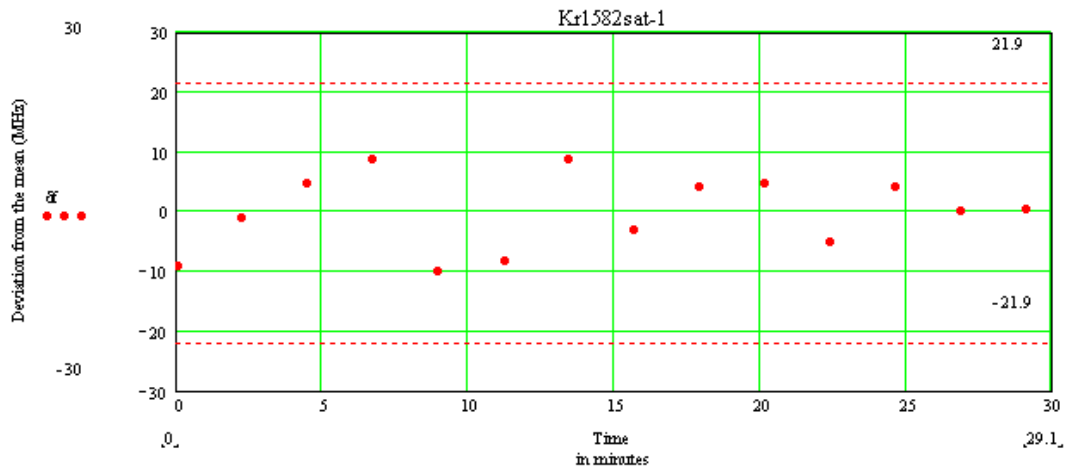


Figure 30: Lock stability of Kr 1582nm transition

2.4.2.3. Xenon

It was possible to saturate the Xenon transition at 1542nm, saturation was achieved for optical powers above 6mW. The OG response is shown in figure 32 for an optical power of 11mW.

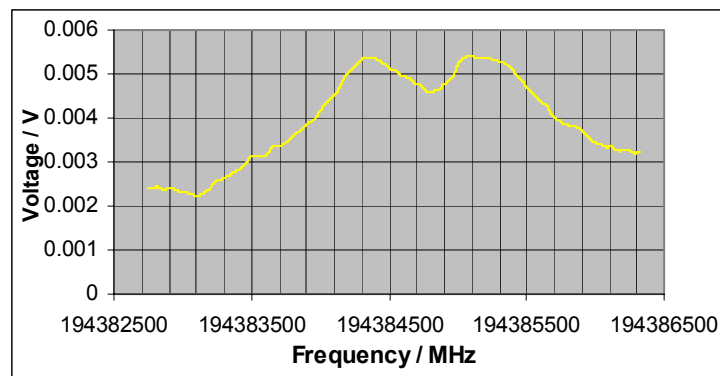


Figure 31: Saturated OG response of Xe 1542nm transition

The transition width was measured at (300-400) MHz for optical powers (8-11)mW.

3. Conclusion

Experimental investigations into further optogalvanic transitions were performed on the suitable candidates that had been identified. Table 4 summarises the results of the survey. The results increase the amount of available references that can be used as wavelength reference standards. Of particular interest are the saturated transitions that offer higher accuracy standards than the unsaturated transitions, but are still accessible at modest optical power (<10mW)

Element	Measured Wavelength of Transition
Metal Lines	
Cadmium	1571.6128 (2) nm
Magnesium	1575.3294 (2) nm
	1575.3294 (2) nm
Unsaturated gas lines	
Xenon	1556.138 (1) nm
	1598.391 (1) nm
	1604.428 (1) nm
	1605.767 (1) nm
Saturated gas lines	
Argon	1599.38578(18) nm
Krypton	1563.97644 (14)nm
	1568.53081(18) nm
	1582.44137 (18) nm
Xenon	1542.26129 (2) nm

Table 4: Results of the optogalvanic survey

Acknowledgement

This document has been produced for the Department of Trade and Industry's National Measurement System Directorate (NMSD) under contract number GBBK/C/011/00005.

References

- [1] LUCERO, A.J., CHUNG, Y.C., REILLY, S. and TKACH, R.W. Saturation measurements of excited-state transitions in noble gases using the optogalvanic effect. *Optics Lett.*, 1991, 16, 849-852
- [2] LUCERO, A.J., CHUNG, Y.C., TKACH, R.W. Survey of atomic transitions for absolute frequency locking of lasers for lightwave systems. *IEEE Photonics Tech. Lett.*, 1991, 3, (5), 484-486
- [3] FISCHER, U.H.P., HELMOLT, C.v. Saturation and Isotopic Shift of the KR 84 Excited-state Transition at 1547.825nm. *IEEE Photonics Tech. Lett.*, 1991, 1, 65-67
- [4] HUMPHREYS, D.A. Saturated Optogalvanic transition in Krypton at 1564 nm. *SOFM*, 2000, 25-28
- [5] FISCHER, U.H.P., HELMHOLT, C.v. Absorption spectra of excited Kr 84 states between 1.5 and 1.58 μm and their use for absolute frequency locking. *J. of Light wave Tech.* 1996, 14 (2), 139-143
- [6] HUMPHREYS, D.A., CAMPBELL, C. Preliminary results of L-Band excited-state optical frequency reference survey. *OFMC 2001*, 179-182