Investigation into
Optogalvanic Reference
Lines

Steven Knox

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Executive Summary

This report presents the results of the investigation into optogalvanic transitions for use as wavelength reference standards within the optical telecommunications band.
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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$_2$H$_2$, 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](image)

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

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.
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\(\mu\)m. 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 \(^{84}\text{Kr}\) 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 \(^{84}\text{Kr}\) 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.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wavelength / nm</th>
<th>Element</th>
<th>Wavelength / nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>1249.111 ± 0.001</td>
<td>Kr</td>
<td>1500.943 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1270.581 ± 0.001</td>
<td>Kr</td>
<td>1501.914 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1273.696 ± 0.001</td>
<td>Ar</td>
<td>1505.064 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1274.977 ± 0.001</td>
<td>Ar</td>
<td>1517.694 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1280.629 ± 0.001</td>
<td>Kr</td>
<td>1521.376 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1286.541 ± 0.001</td>
<td>Ne</td>
<td>1523.491 ± 0.001</td>
</tr>
<tr>
<td>Ne</td>
<td>1291.555 ± 0.001</td>
<td>Kr</td>
<td>1524.380 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1293.675 ± 0.001</td>
<td>Kr</td>
<td>1533.065 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1296.025 ± 0.001</td>
<td>Ar</td>
<td>1533.350 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1298.886 ± 0.001</td>
<td>Kr</td>
<td>1533.915 ± 0.001</td>
</tr>
<tr>
<td>Ar</td>
<td>1301.118 ± 0.001</td>
<td>Kr</td>
<td>1537.625 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1318.104 ± 0.001</td>
<td>Kr</td>
<td>1543.795 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1473.841 ± 0.001</td>
<td>Kr</td>
<td>1247.82599 ± 0.00010</td>
</tr>
<tr>
<td>Kr</td>
<td>1476.666 ± 0.001</td>
<td>Kr</td>
<td>1563.978 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1476.954 ± 0.001</td>
<td>Kr</td>
<td>1568.533 ± 0.001</td>
</tr>
<tr>
<td>Kr</td>
<td>1496.597 ± 0.001</td>
<td>Kr</td>
<td>1577.614 ± 0.001</td>
</tr>
</tbody>
</table>

*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.

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

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 90µA and the high current setting takes it to 2000µA. The frequency response of the amplifier is shown in figure 5.

![Figure 5: Frequency response of the power supply amplifier](image)

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](image)

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.
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 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.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wavelength, nm</th>
<th>Frequency, GHz</th>
<th>Difference from ITU 50 GHz grid, GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>1571.6128 (2)</td>
<td>190754.636(24)</td>
<td>4.636 (24)</td>
</tr>
<tr>
<td>Mg</td>
<td>1577.0147 (2)</td>
<td>190101.217(21)</td>
<td>1.217 (21)</td>
</tr>
<tr>
<td>Mg</td>
<td>1575.3294 (2)</td>
<td>190304.597(24)</td>
<td>4.597 (24)</td>
</tr>
</tbody>
</table>

*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](image)

The miniature lamps are operated at high voltages 350V-750V but at low currents (10-200) µA 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.
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
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 200µA.

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 240µA. 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.
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.
To try and improve the measurement accuracy of the Xe 1542.261nm line use of the known acetylene $v_1+v_2$ P16 line at 1542.3837125nm can be made. The system used is a double locking system in figure 24.

Using a tuneable laser source a sweep generator and modulator are used to give side bands to the laser frequency at ~7.5GHz, 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
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 ~730MHz.

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](image)

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.
2.4.2.2. Krypton

Three saturated transitions in Kr were identified at 1564, 1568 and 1582 nm. The transition at 1564 nm 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.

The line at 1582 was of particular importance as it was only –0.670 GHz away from the nearest 50 GHz 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.
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.

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).

<table>
<thead>
<tr>
<th>Element</th>
<th>Measured Wavelength of Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metal Lines</strong></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>1571.6128 (2) nm</td>
</tr>
<tr>
<td>Magnesium</td>
<td>1575.3294 (2) nm</td>
</tr>
<tr>
<td></td>
<td>1575.3294 (2) nm</td>
</tr>
<tr>
<td><strong>Unsaturated gas lines</strong></td>
<td></td>
</tr>
<tr>
<td>Xenon</td>
<td>1556.138 (1) nm</td>
</tr>
<tr>
<td></td>
<td>1598.391 (1) nm</td>
</tr>
<tr>
<td></td>
<td>1604.428 (1) nm</td>
</tr>
<tr>
<td></td>
<td>1605.767 (1) nm</td>
</tr>
<tr>
<td><strong>Saturated gas lines</strong></td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td>1599.38578(18) nm</td>
</tr>
<tr>
<td>Krypton</td>
<td>1563.97644 (14)nm</td>
</tr>
<tr>
<td></td>
<td>1568.53081(18) nm</td>
</tr>
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<td></td>
<td>1582.44137 (18) nm</td>
</tr>
<tr>
<td>Xenon</td>
<td>1542.26129 (2) nm</td>
</tr>
</tbody>
</table>

*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


