

The Synthesis of L-Band Wavelength References Via Four-Wave Mixing

Helen White, Colin Campbell

April 2003

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Approved on behalf of Managing Director, NPL
by Dr Stuart Pollitt, Head of Centre for Electromagnetic and Time Metrology

Summary

The work presented in this report sort to investigate the production of wavelength reference standards for the L-Band, via four-wave mixing products locked to known gas absorption lines. The work was two-fold:

- To investigate experimentally the production of frequency combs, via four-wave mixing, using “off the shelf” single mode fibre. To lock the combs to known gas standard absorption lines and identify the extent to which such a system could provide wavelengths standards for the L-Band region.
- To simulate dual fibre systems (two different fibres in series), to ascertain if any advantage would be gained over a single fibre system, in maximising the wavelengths range over which the first four-wave mixing product could be maintained.

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1. Introduction

Non-linear effects are caused within dielectric materials when a non-linear relationship exists between the induced polarisation (redistribution of charges) and the amplitude of the incident electromagnetic field. Single mode optical fibres are susceptible to non-linear effects because the small core diameters can create high optical intensities, which are then maintained over long distances. When multiple optical waves are propagating, interactions will occur between those waves due to the non-linear response of the propagating medium. Such interactions are called “parametric processes” as they result from the light-induced modulation of a medium parameter (such as refractive index). Some examples of processes that fall into this category are: harmonic generation, four-wave mixing and parametric amplification¹.

The result of four-wave mixing (FWM) within an optical fibre is the creation, or amplification, of signals at new frequencies via the transfer of power from the original incident signals. This can be a disadvantage in systems where multiple frequencies are co-propagating but must remain independent of each other. However, since the new signals are at well-defined frequencies, the four-wave mixing effect can be used to synthesise optical frequencies for use as references.

Previous work conducted at NPL investigated the use of FWM in optical fibres to extend the range of wavelengths available from gas-cell based reference standards^{2,3}. It was shown that it was possible to lock to known Acetylene frequencies, and then create new frequencies that spanned the gap between the Acetylene and Carbon Monoxide absorption spectra. The demonstrated efficiency of conversion was such that an overlap into the CO absorption regime was possible. It was proposed that the CO absorption spectra could be mapped with greater accuracy, via the use of FWM products locked to the Acetylene absorption spectra. The possibility of creating wavelength references close to ITU grid lines, from known gas standard absorption lines, was discussed.

The work presented in this report expands on the above by focusing on the production of frequency combs (via FWM) within “off the shelf” single mode fibre, and their possible use as L-Band wavelength references. Theoretical calculations are also presented, which investigate the use of dual fibre systems.

1.1 Frequencies Generated via Four-Wave Mixing

The frequencies of the signals generated (or amplified) via four-wave mixing can be calculated via a simple combination of the initial incident frequencies:

Equation 1.1

$$f_{ijk} = f_i + f_j - f_k$$

where f_i , f_j and f_k are the frequencies of the input waves and f_{ijk} is the frequency of the FWM product.

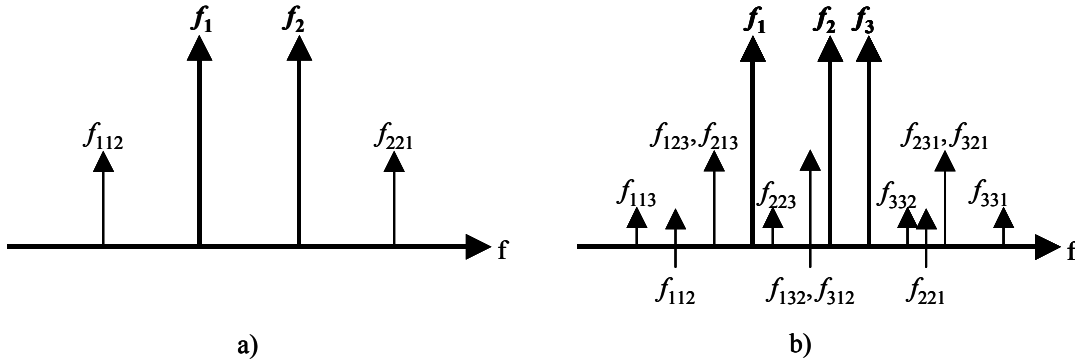


Figure 1.1: Additional frequencies generated through FWM in a) the partially degenerate and b) the non-degenerate case.

Figure 1 demonstrates the possible frequency combinations that can be produced. In the partially degenerate case only two distinct frequencies are incident, and one of the incident signals assumes the role of both f_i and f_j . In the non-degenerate case three unique frequencies are incident with the result of a large number possible four-wave mixing products.

Equation 1.1 is arrived at via the consideration of conservation of energy within the system before and after the interaction. Although this equation indicates the position of potential four-wave mixing products it provides no information as to whether the product will be viable, i.e. if the process will be efficient enough for the product to have significant power. The efficiency of the four-wave mixing process is determined by the *phase matching condition*.

1.2 Phase Matching and FWM Efficiency

1.2.1 Phase Matching

The position of the four-wave mixing products comes from a consideration of the conservation of energy; phase matching (and hence efficiency) is arrived at via the consideration of the conservation of momentum before and after the

interaction. The transit time of a group of wavelengths through a fibre is determined by their group velocity, which, in turn, is dictated by the chromatic dispersion of the fibre, D_c . The contributing mechanisms to chromatic dispersion are material dispersion and waveguide dispersion, which results in a frequency dependence to the velocity of a signal through a fibre. Appendix A gives values for chromatic dispersion for selected fibre types.

Phase matching, therefore, depends on the frequencies of the incident and resultant signals, and the chromatic dispersion of the fibre. By considering the difference between the modal propagation constants, β , within the fibre,

Equation 1.2

$$\Delta\beta = \beta_1 + \beta_2 - \beta_3 - \beta_4$$

and then expanding 1.2, the Phase Mismatch, $\Delta\beta$, can be expressed as^{5,6}:

Equation 1.3

$$\Delta\beta := \left[\frac{2 \cdot \pi \cdot (\lambda_k)^2}{c} \right] \cdot (\Delta f)^2 \cdot \left[D_c + \left[\frac{\Delta f \cdot (\lambda_k)^2}{c} \cdot \frac{d}{d\lambda} D_c (\lambda_k) \right] \right]$$

Equation 1.3 is for the partially degenerate case where $\Delta f = |f_{ij} - f_k|$. Equation 1.3 is not complete because it does not take into account the effect of power levels within the fibre. In the non-linear regime, medium parameters, such as refractive index, become dependant on the intensity of the signals travelling within the material. Consequences of this are non-linear effects such as self-phase modulation and cross-phase modulation, which will tend to modulate the phase of the signals. The Phase Mismatch parameter, for the partially degenerate case, can be expanded to include intensity dependant effects as follows⁶:

Equation 1.4

$$\Delta\beta_{\text{spm}} := \Delta\beta - \left[\gamma \cdot P_0 \cdot \frac{(1 - \exp(-\alpha \cdot L_{\text{eff}}))}{(\alpha \cdot L_{\text{eff}})} \right]$$

Where γ is the non-linear coefficient, L_{eff} is the effective length, α is the attenuation (neper/km) and P_0 is the incident power.

The effective length is defined as the length of lossless fibre that would generate the same amount of non-linearity, as the lossy fibre under consideration:

Equation 1.5

$$L_{\text{eff}} := \frac{(1 - \exp(-\alpha \cdot L))}{\alpha}$$

The non-linear coefficient is related to the second-order refractive index, n_2 , (and, therefore, the third-order susceptibility) and the effective area, A_{eff} , of the fibre core¹:

Equation 1.6

$$\gamma := \frac{2 \cdot \pi \cdot n_2}{\lambda \cdot A_{\text{eff}}}$$

From equation 1.3 it can be seen that $\Delta\beta$ will be minimised when $\Delta f = 0$. However, equation 1.4 shows that the effect of the intensity dependence of four-wave mixing will move this minimum away from $\Delta f = 0$ (the greater the power the greater the move).

Another way of looking at equation 1.4 is to consider the intensity dependant phase mismatch as a summation of components due to material dispersion ($\Delta\beta_m$), waveguide dispersion ($\Delta\beta_w$) and non-linearity ($\Delta\beta_{nl}$)¹.

Equation 1.7

$$\Delta\beta_{\text{spm}} = \Delta\beta_m + \Delta\beta_w + \Delta\beta_{nl}$$

For single mode fibres, the waveguide contribution tends to be very small compared with the material dispersion contribution (for identically polarised signals), except near zero dispersion wavelengths where they become comparable¹. From this it can be seen that the following conditions will lead to minimisation of $\Delta\beta_{\text{spm}}$ ¹:

1. The use of small frequency differences and low pump powers to reduce the material and non-linear components.¹
2. Operation near the zero dispersion wavelength: here the waveguide component is comparable to the material component and can be used to balance $\Delta\beta_m$ and $\Delta\beta_{nl}$.^{1,5,7}
3. Operation in the anomalous dispersion regime ($D_c > 0$). Here the material contribution becomes negative and can be balanced by the non-linear component.^{1,6}

1.2.2 Four-Wave Mixing Efficiency – Single Fibre System

The four-wave mixing efficiency, η , generated as a result of the phase mismatch can be expressed as^{5,6,7}:

Equation 1.8

$$\eta := \frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2} \cdot \left[1 + \frac{4 \cdot \exp(-\alpha \cdot L) \cdot \left(\sin\left(\frac{\Delta\beta \cdot L}{2}\right) \right)^2}{(1 - \exp(-\alpha \cdot L))^2} \right]$$

Where L is the length of the fibre, $\Delta\beta$ could be from equation 1.3 or $\Delta\beta_{\text{spm}}$ from equation 1.4 (if intensity dependence needs to be considered), and η has been normalised to a value of 1 at $\Delta\beta = 0$. As the four-wave mixing efficiency will oscillate as the signals proceed along the fibre, a sinusoidal term is included within equation 1.8 which is dependent on the length of the fibre and the phase matching condition².

1.2.3 Time-Averaged Optical Power – Single Fibre System

The time-averaged optical power generated within a four-wave mixing product, produced via co-polarised input signals f_i , f_j and f_k , is given by:^{5,6,7}

Equation 1.9

$$P_{i,j,k}(L) := \frac{\eta}{9} \cdot D^2 \cdot \gamma^2 \cdot P_i \cdot P_j \cdot P_k \cdot \exp(-\alpha \cdot L) \cdot \left[\frac{(1 - \exp(-\alpha \cdot L))^2}{\alpha^2} \right]$$

Where D is the degeneracy factor, which takes a value of 1,3 or 6 depending on whether all, two or none of the incident frequencies are the same.

For the purposes of this report, the Relative Power was considered, which is proportional to $P_{i,k,j}(L)$.

Equation 1.20

$$\text{RelativePower} := \eta \cdot (L_{\text{eff}})^2 \cdot \exp(-\alpha \cdot L)$$

Note:

$$P_{i,j,k}(L) := \frac{1}{9} \cdot D^2 \cdot \gamma^2 \cdot P_i \cdot P_j \cdot P_k \cdot \text{RelativePower}$$

1.2.4 Four-Wave Mixing Efficiency – Dual Fibre System

When two fibres of differing dispersion characteristics (lengths L_1 and L_2), are used in series, the resulting four-wave mixing efficiency is not a simple summation of the values for each fibre segment⁷:

Equation 1.21

$$\eta_{1,2} := \left[\left[\frac{\exp\left[\left[-\alpha + (\Delta\beta_1 \cdot i)\right] \cdot L_1\right] - 1}{(\Delta\beta_1 \cdot i) - \alpha} \right] + \left[\exp\left[\left[-\alpha + (\Delta\beta_1 \cdot i)\right] \cdot L_1\right] \cdot \frac{\exp\left[\left[-\alpha + (\Delta\beta_2 \cdot i)\right] \cdot L_2\right] - 1}{(\Delta\beta_2 \cdot i) - \alpha} \right] \right]^2$$

Normalising $\eta_{1,2}$ to $\Delta\beta_1 = \Delta\beta_2 = 0$ gives the normalised efficiency, η_{nor} :

Equation 1.22

When $\Delta\beta_1 = \Delta\beta_2 = 0$

$$\eta_{1,2} := (\eta_{1,2})^0$$

Equation 1.23

$$\eta_{\text{nor}} := \frac{\eta_{1,2}}{(\eta_{1,2})^0}$$

The cross component within equation 1.22 means that signals generated within each fibre segment interfere with each other at the output of the fibre, generating interference patterns⁷.

1.2.5 Time-Averaged Optical Power – Dual Fibre System

The time-averaged optical power generated within a four-wave mixing product, produced via co-polarised input signals f_i , f_j and f_k , is given by:⁷

Equation 1.24

$$P_{i,j,k}(L_1 + L_2) := \frac{\eta_{1,2}}{9} \cdot D^2 \cdot \gamma^2 \cdot P_i \cdot P_j \cdot P_k \cdot \exp\left[-\alpha \cdot (L_1 + L_2)\right]$$

Where D is the degeneracy factor which takes a value of 1,3 or 6 depending on whether all, two or none of the incident frequencies are the same.

For the purposes of this report, the Relative Power was considered, which is proportional to $P_{i,k,j}(L_1 + L_2)$.

Equation 1.25

$$\text{RelativePower}_{1,2} := \eta_{1,2} \cdot \exp[-\alpha \cdot (L_1 + L_2)]$$

1.3 Frequency Comb Generation

Multiple four-wave mixing products can be produced providing sufficient launch power is applied, and the chromatic dispersion of the fibre is low and positive⁸. The conservation of energy condition that dictates the position of the four-wave mixing products (see section 1.1) creates a defined comb spacing. If the initial incident signals are locked to known wavelengths from gas cell standards then a large number of frequency standards are subsequently produced.

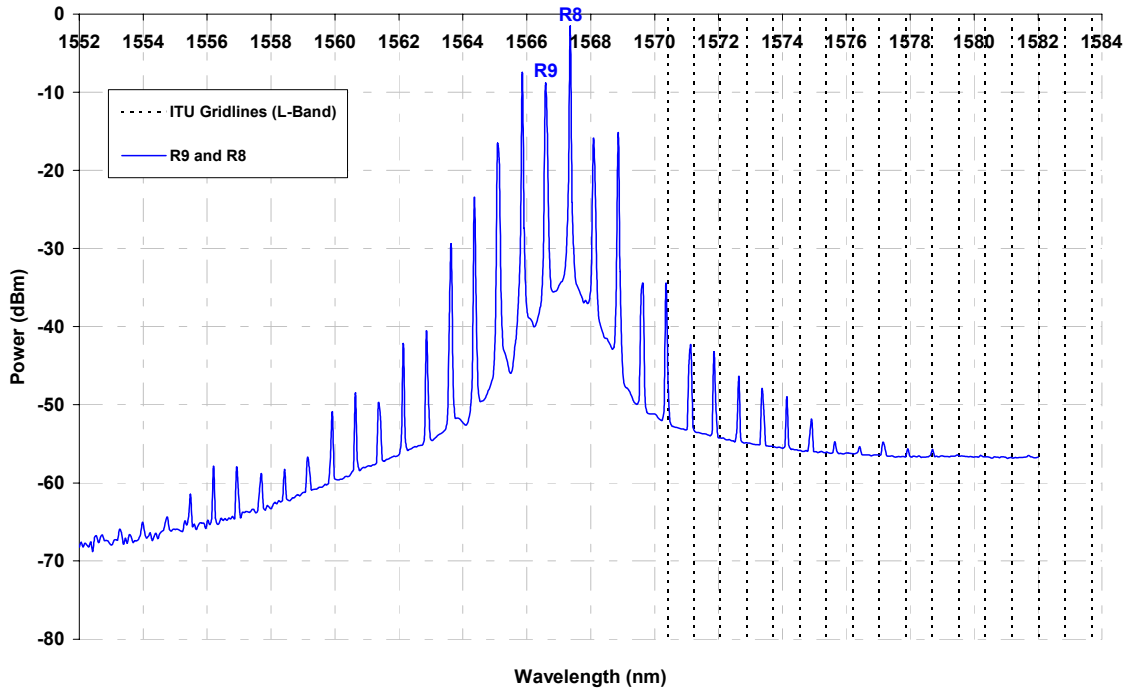


Figure 1.2: An example of an extended frequency comb produced via four-wave mixing, using 2 wavelengths close to CO absorption lines R8 and R9.

1.3.1 Frequency Combs Matched to L-Band ITU Grid-Lines

The tables in Appendix F show the potential use of frequency combs to lock to L-Band ITU grid lines, using combinations of CO absorption lines (Appendix D) to provide the incident frequencies for the comb. CO absorption lines are not the ideal starting point for this exercise due to the fact that the uncertainties associated with them are higher than for Acetylene (Appendix

E). However, the CO lines are closer to the L-Band frequencies and so the generated comb would, in theory, cover more of the L-Band range.

2. Experimental Investigation Into Frequency Comb Generation

This section presents the experimental work carried out to investigate the production of frequency combs from an “off the shelf” single mode fibre. It then discusses the possible use of these frequency combs as wavelength standards for the L-Band ITU grid by locking said combs to known gas absorption lines (see section 1.3).

2.1 Experimental

Several experimental designs were investigated in an attempt to maximise the breadth of comb generated. Figures 2.1 – 2.4 summarise the systems used.

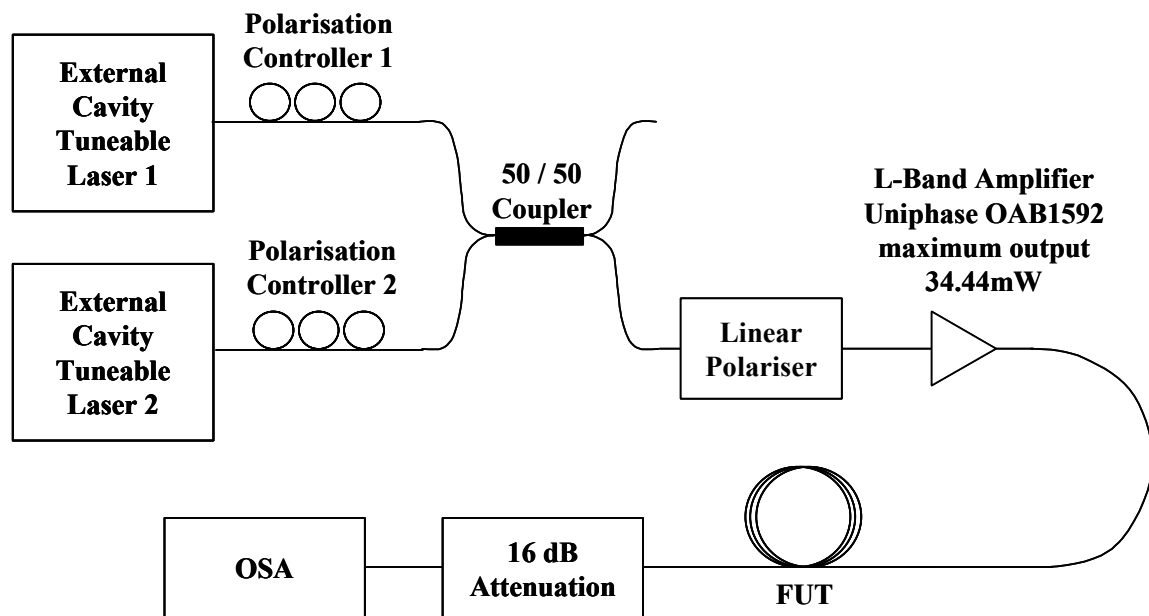


Figure 2.1: Experiment A

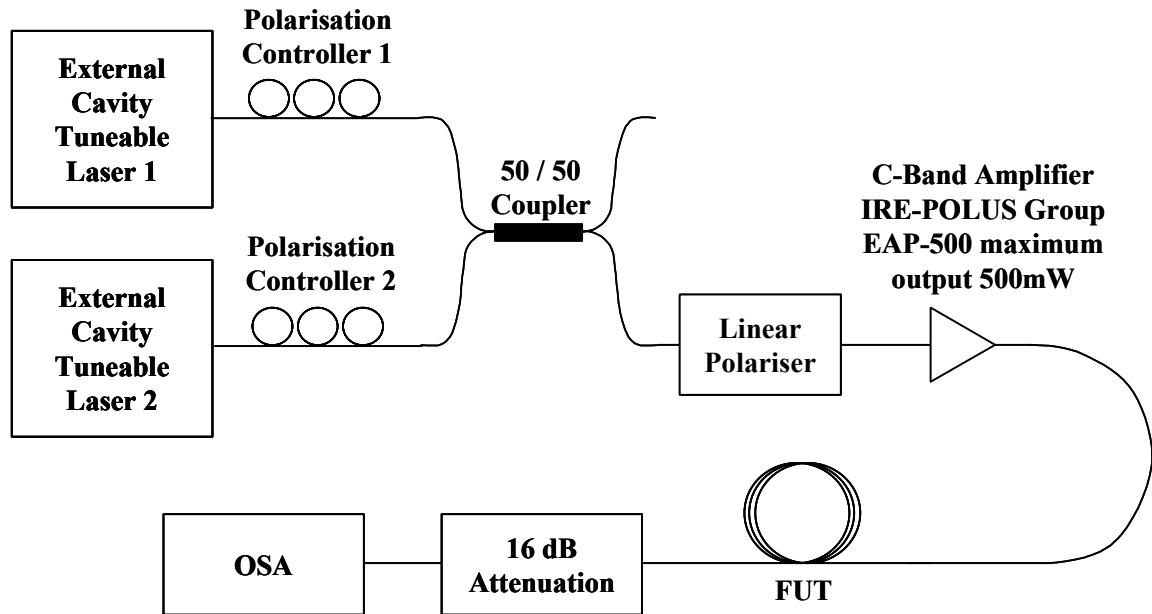


Figure 2.2: Experiment B

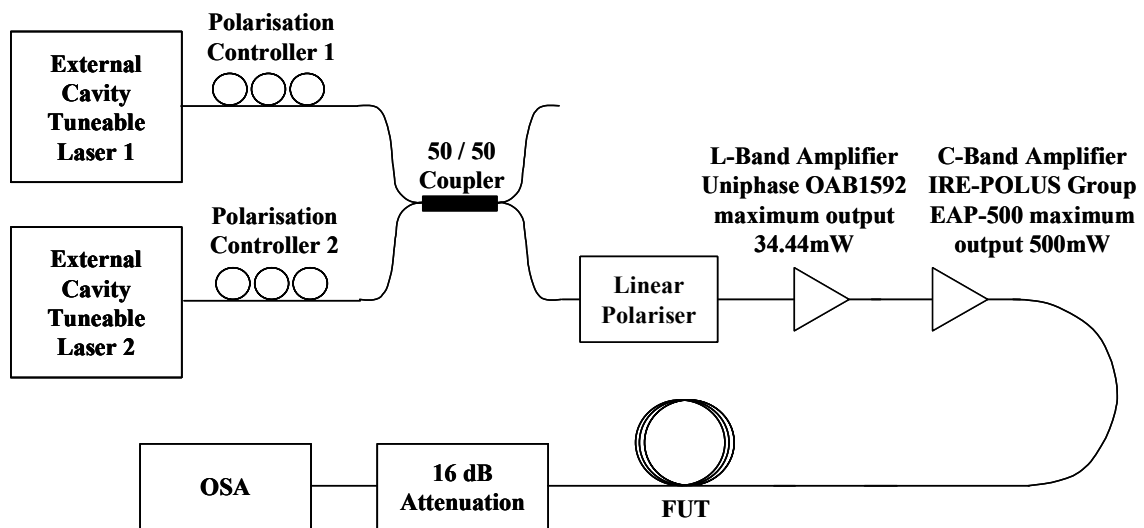


Figure 2.3: Experiment C

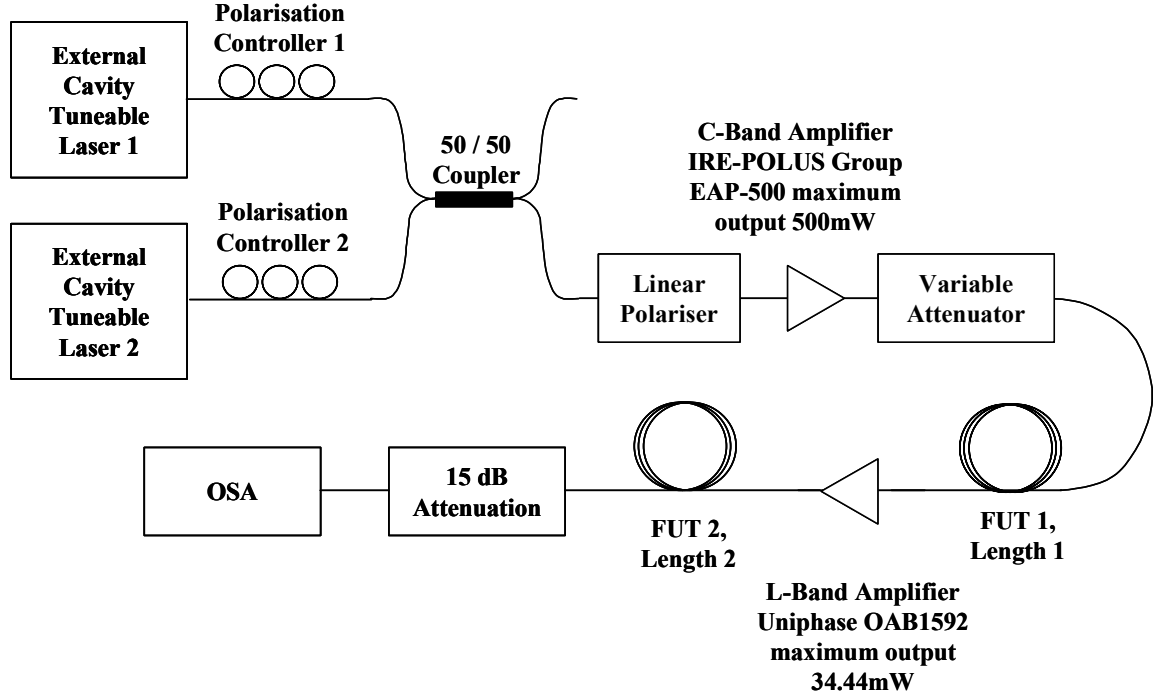


Figure 2.4: Experiment D

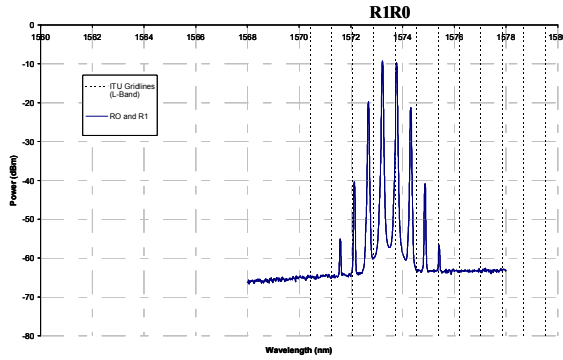
All four experiments involved the production of continuous wave (CW) four-wave mixing. The two Tunics lasers were tuned to match the two gas absorption wavelengths of interest. A slight amplitude modulation was applied to the lasers (16kHz, 4V peak to peak) to defeat the effects of Stimulated Brillouin Scattering (SBS), which would otherwise limit the amount of power entering the system under test. The laser outputs were combined via a 50/50 coupler and passed through a linear polariser. The output at this point was maximised by adjusting the polarisation controllers, thereby ensuring that the incident signals were co-polarised. In experiments A and B the signals were passed through either the L or C band amplifiers, which were adjusted to give the desired launch power into the fibre under test, the results were then displayed on an Optical Spectrum Analyser (Figures 2.1 and 2.2). Experiments C and D differed slightly, as the combination of the L and C-Band amplifiers in series was investigated (Figures 2.3 and 2.4).

A pre-experiment was carried out to decide on the appropriate fibre for the main experiments, given that the higher CO absorption lines ($\sim 1573\text{nm}$) were to be the main target of the experiments. Three fibre types were tested on experimental system A: Sumitomo Dispersion Shifted (61-2000-7590), Corning Submarine Leaf (321736069705) and Lucent Truwave RS (991444960001). The Sumitomo Dispersion Shifted fibre ($\lambda_0 = 1555.09\text{nm}$) gave the best initial results and was therefore chosen as the fibre to be tested under the main set of experiments (see appendices A and B for details of chromatic dispersion and A_{eff}). The fibre length employed in experiments A, B and C was $\sim 12.8\text{km}$. For experiment D the same fibre was used for both loops: FUT 1 employed a length of $\sim 12.8\text{km}$ and FUT 2 employed a length of $\sim 10\text{m}$.

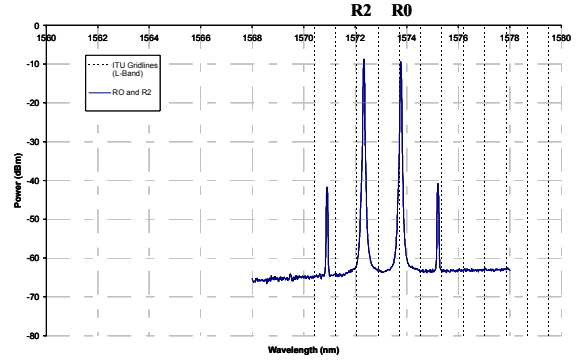
2.2 Results and Discussion

Figure 2.5 shows the effect on the four-wave mixing products as the separation between the incident wavelengths was increased. The upper incident wavelength was set at the highest CO absorption line, RO (1573.767nm). The wavelength of the second incident signal was decreased progressively through the CO absorption spectrum. Experimental system A was used with the L-Band amplifier set at its maximum output of 34.44mW. Note that this power level was not sufficient to produce a broad comb of frequencies. As the separation increased the power in the first four-wave mixing product decreased. The product remained visible out to a wavelength of 1578.76nm, which equates to an incident wavelength separation of 4.993nm. This approach would provide wavelength reference to a limited region at the lower wavelength range of the L-Band Grid.

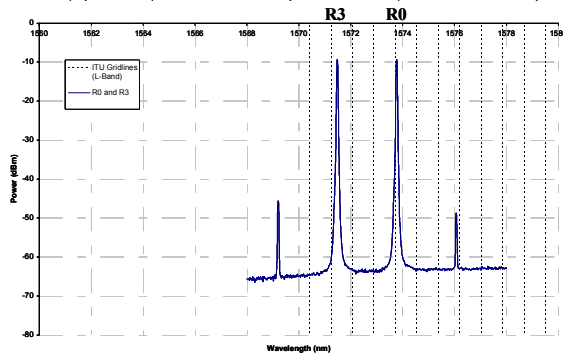
This experiment is analogous to those performed in previous experimental work at NPL^{2,3}. A fixed wavelength of ~1553.05 was employed and the secondary wavelength was then scanned downwards, increasing the separation of the incident signals, whilst the first four-wave mixing product was monitored. The efficiency of the mixing product in that case was maintained out to separations of over 20nm because of the closer proximity of the incident wavelengths to the zero dispersion wavelength of the fibre under test.



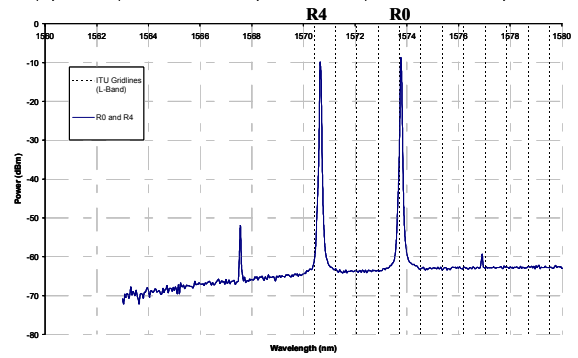
(a) RO (1573.767nm) and R1 (1572.867nm)



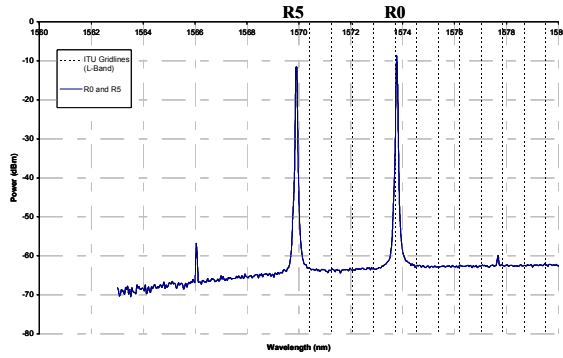
(b) RO (1573.767nm) and R2 (1571.995nm)



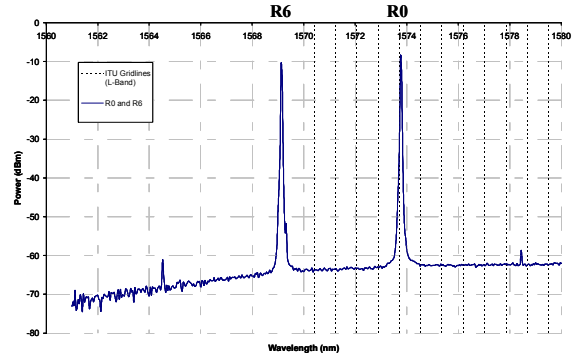
(c) RO (1573.767nm) and R3 (1571.149nm)



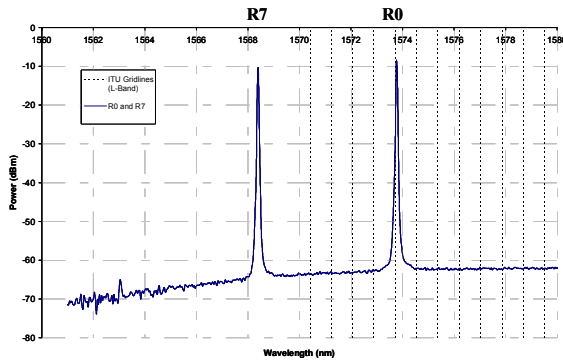
(d) RO (1573.767nm) and R4 (1570.331nm)



(e) RO (1573.767nm) and R5 (1569.539nm)



(f) RO (1573.767nm) and R6 (1568.774nm)



(g) RO (1573.767nm) and R7 (1568.036nm)

Figure 2.5: Experiment system A (L-Band amplifier output = maximum). Increasing wavelength separation between CO absorption lines.

In order to create frequency combs of larger extent, a greater incident power was required than could be provided by experiment system A with the L-Band Amplifier alone. Figure 2.6 demonstrates the development of a frequency comb using experimental system B with the more powerful C-Band Amplifier.

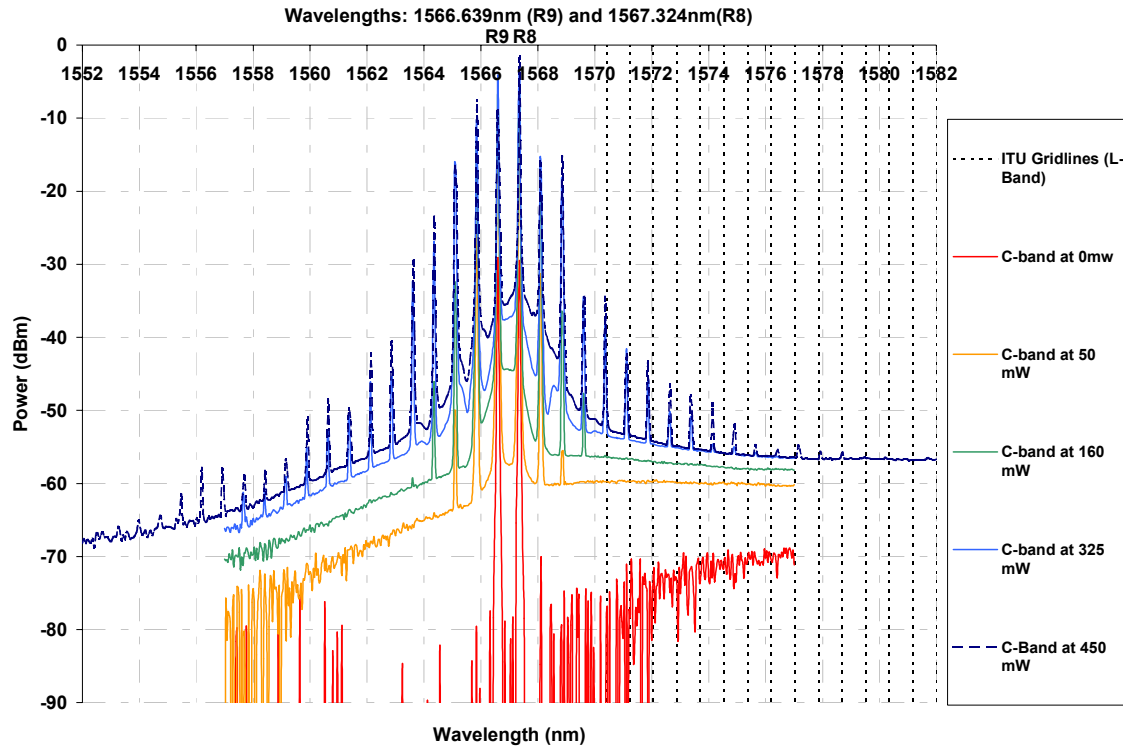


Figure 2.6: The development of a frequency comb using experimental system B with increasing incident power.

Out of the four experimental systems investigated it was found that the best results in terms of the breath of the frequency comb produced, came from experimental system D (Figure 2.4), with an attenuation of 3dB set at the variable attenuator. Experimental system C (Figure 2.3) also performed well. A comparison between these various experiments is presented in Figure 2.7.

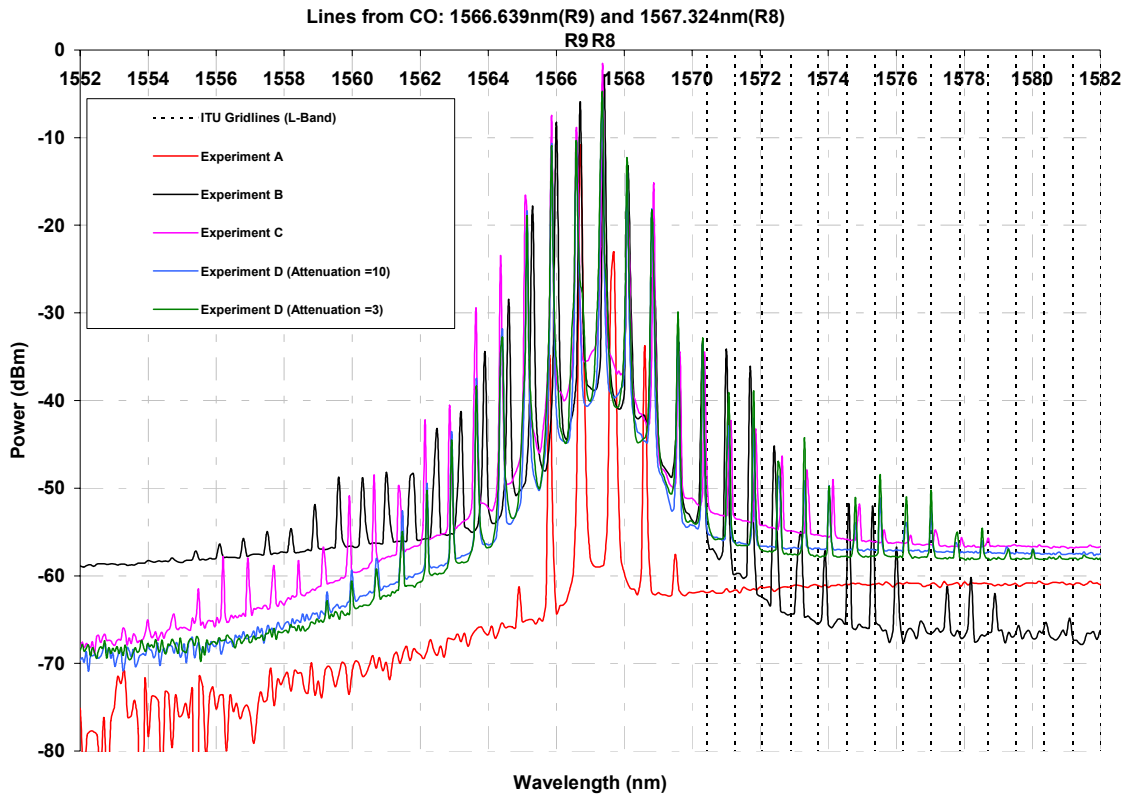


Figure 2.7: A comparison between experimental systems A – D.

A series of experiments was then carried out looking at the extent of frequency combs created for various pairs of absorption lines – the results are shown in Figure 2.8. Despite using the highest pair of absorption lines available, R0 and R1 from the CO absorption spectrum, the highest four-wave mixing product produced was only 1580.967nm (Figure 2.8(a)). Although this is 7.2nm higher than the highest available CO absorption line (R0 at 1573.767nm), it still only gives coverage for the lower 25% of the L-Band ITU grid.

The above discussion assumes that the accuracy by which the CO absorption spectrum is known is sufficient to make the experiment viable for use as a wavelength reference. The highest two acetylene lines, P39 (1558.082nm) and P38 (1557.332nm) were also used as locking points for a frequency comb (Figure 2.8(j)). The highest products of that comb only overlapped with the lowest 2 L-Band ITU lines. This comb does, however, lend further evidence to the conclusions of the previous work carried out at NPL in this area^{2,3}. That work showed that it was possible to span the gap between the acetylene and CO absorption spectra using four-wave mixing products. It also showed that the efficiency was such that products overlapped into the CO absorption spectrum, leading to the possibility of mapping the CO lines using the acetylene spectrum as a basis (the comb in Figure 2.8(j) demonstrates this overlap). This could potentially lead to a more accurate knowledge of the position of the CO absorption lines.

A second consideration for a practical version of the above experiment is the power of the four-wave mixing product required for measurement. It is possible that some of the outermost products are too weak to be used as wavelength standards.

It was interesting to note the increased width of the frequency combs as the incident wavelengths decreased towards the zero dispersion wavelength of the Sumitomo Dispersion Shifted Fibre (1555.09nm). The reasons for this are twofold: the increased ease of phase matching closer to the zero dispersion wavelength (see section 1.2.1) and the fact the chromatic dispersion lowers towards λ_0 whilst remaining positive. Intuitively it might be expected that the Submarine Leaf fibre, with its higher zero-dispersion wavelength of 1574.68nm might give better result for the higher CO lines. This was shown not to be the case for comb production. This could be because of the higher gradient to the dispersion curve in the λ_0 region for the Submarine leaf fibre, but also that the chromatic dispersion is negative for all the wavelengths discussed. It has been shown that a positive chromatic dispersion is more conducive to the production of wide frequency combs⁸. It should also be noted that A effective for the

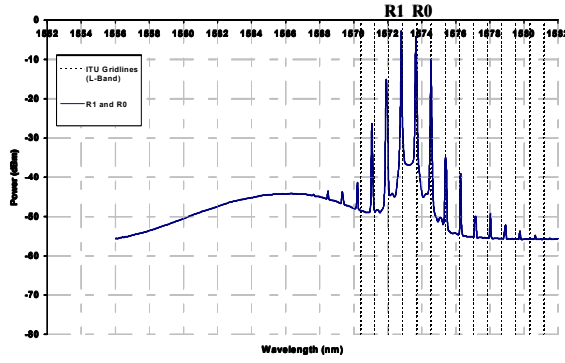
+Submarine Leaf Fibre is greater than that for the Sumitomo Dispersion Shifted fibre – this will lead to an overall decrease in the resultant non-linear effects.

2.3 Conclusions

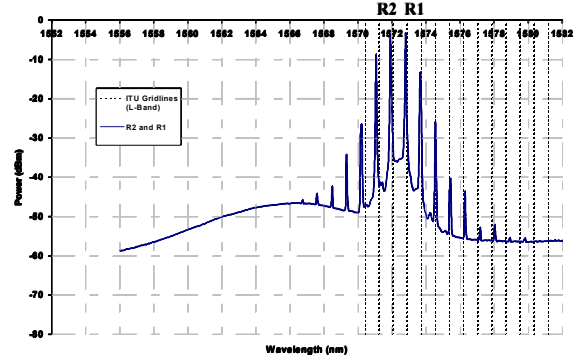
This section presented the experimental work carried out to investigate the production of frequency combs from an “off the shelf” single mode fibre, for use as wavelength standards in the L-Band ITU grid. The following conclusions were reached:

- The calculations in Appendix F showed that if a frequency comb could be produced, for a particular combination of CO absorption lines, then a large number of L-Band ITU grid lines could be matched with a corresponding wavelength standard. The smaller the wavelength difference between the pair of CO absorption lines, the greater the number of ITU gridlines covered by the subsequent comb.
- The Sumitomo Dispersion Shifted (61-2000-7590) fibre was determined to be the best for frequency comb production out of the fibre types available. This was due to its positive chromatic dispersion values and low dispersion gradient over the wavelength range of interest.
- For amplification it was found that a combination of the L and C-Band amplifiers in series resulted in the largest width of frequency comb (see Figures 2.3 and 2.4).

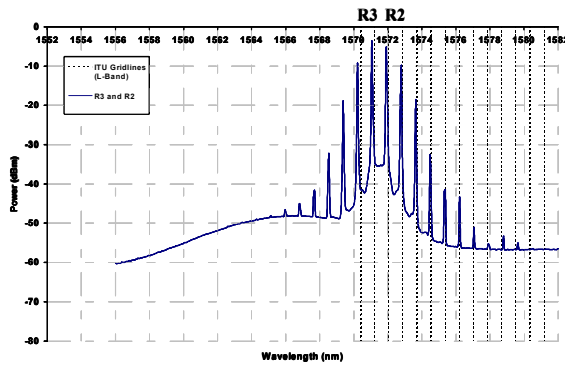
- The highest four-wave mixing product produced (at 1580.967nm) came from a comb locked to the highest pair of CO absorption lines available, R0 (1573.767nm) and RI (1572.868nm) (Figure 2.8(a)). Although this is 7.2nm greater than the highest available CO absorption line (RO at 1573.767nm), it still only gives coverage for the lower 25% of the L-Band ITU grid.
- Although the combs did not cover the whole of the L-Band region they did provide some gains over the current CO lines available. However, issues were raised over the practicality of the above scheme. The wavelengths of the higher accuracy acetylene absorption lines were not of high enough to cover the L-Band region to the same degree as combs produced from the CO absorption lines. The lower accuracy of the CO lines could mean that this method is not viable, but, previous work in this area^{2,3} has suggested ways of improving the accuracy of the CO lines, so this may not be a problem in the future. The power of some of the outmost products may not be sufficient for practical use as wavelength standards – this further decreases the wavelength range covered.



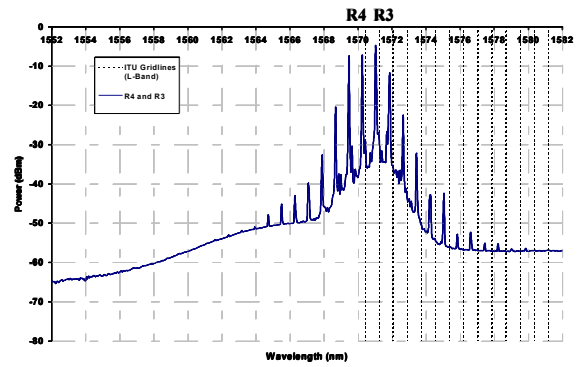
(a) CO lines: R0 (1573.767nm) and R1 (1572.867nm). Experiment C: L-Band 34mW, C-Band 450mW.



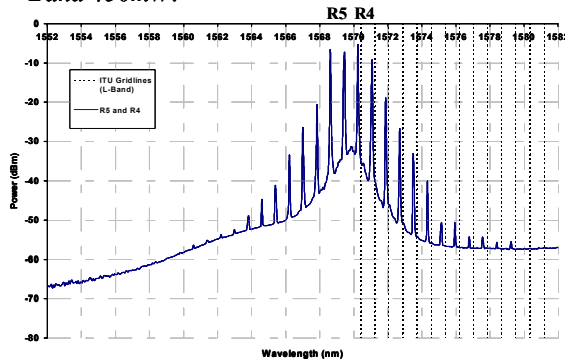
(b) CO lines: R2 (1571.995nm) and R1 (1572.867nm). Experiment C: L-Band 34mW, C-Band 450mW.



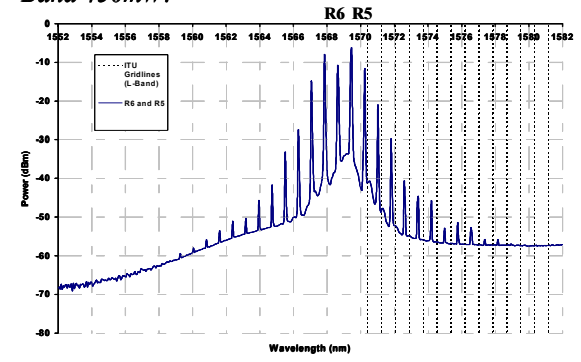
(c) CO lines: R3 (1571.149nm) and R2 (1571.995nm). Experiment C: L-Band 34mW, C-Band 450mW.



(d) CO lines: R4 (1570.331nm) and R3 (1571.149nm). Experiment C: L-Band 34mW, C-Band 450mW.

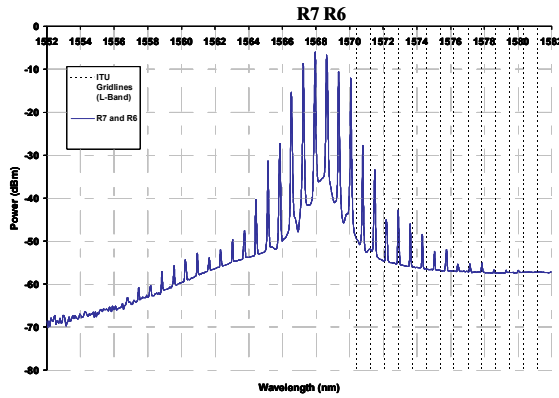


(e) CO lines: R5 (1569.539nm) and R4 (1570.331nm). Experiment C: L-Band 34mW, C-Band 450mW.

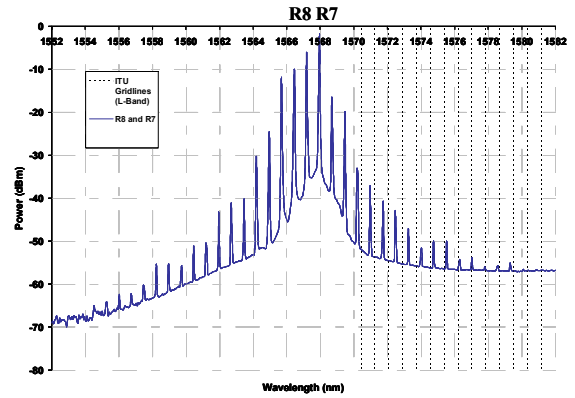


(f) CO lines: R6 (1568.774nm) and R5 (1569.539nm). Experiment C: L-Band 34mW, C-Band 450mW.

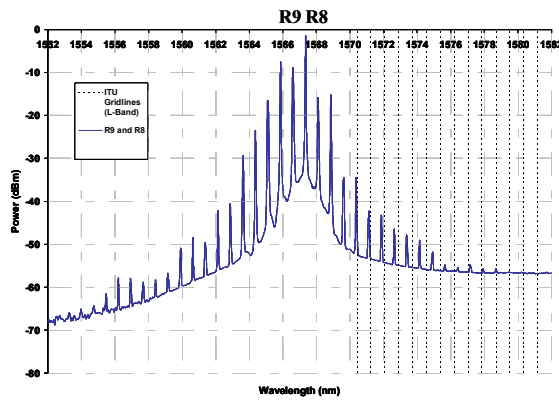
Figure 2.8: Frequency combs produced by locking to various pairs of adjacent gas absorption lines.



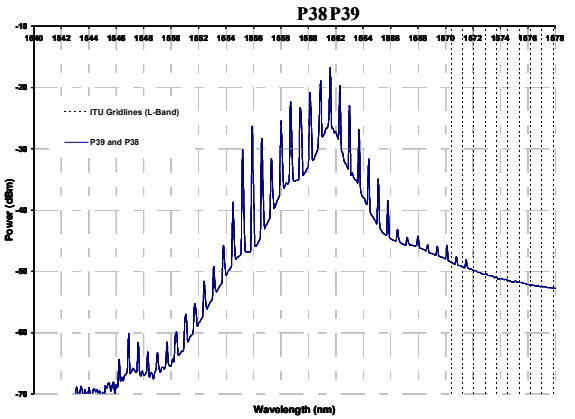
(g) CO lines: R7 (1568.036nm) and R6 (1568.774nm). Experiment C: L-Band 34mW, C-Band 450mW.



(h) CO lines: R8 (1567.324nm) and R7 (1568.036nm). Experiment C: L-Band 34mW, C-Band 450mW.



(i) CO lines: R9 (1566.639nm) and R8 (1567.324nm). Experiment C: L-Band 34mW, C-Band 450mW.



(j) Acetylene lines: P39 (1558.082nm) and P38 (1557.332nm). Experiment D: L-Band 34mW, C-Band 225mW.

Figure 2.8: Frequency combs produced by locking to various pairs of adjacent gas absorption lines.

3. Simulation of Four-Wave Mixing Products in Dual Fibre Systems

The experimental work carried out in section 2, and in previous investigations undertaken at NPL^{2,3}, employed a single test fibre type. The work in this section uses the theory discussed in section 1 to simulate the use of a dual fibre system (two different fibres in series), to indicate if this would improve the wavelength range over which a four-wave mixing product could be maintained. The ultimate aim, as in previous work, would be to provide wavelength standards for the whole of the L-Band ITU grid, from four-wave mixing products locked to known gas absorption lines. In section 2, the maximum coverage achieved was for the lower 25% of the L-Band range.

3.1 The Simulated Experiment

The experiment chosen for this exercise mimics the type of experiment demonstrated in Figure 2.5 (and used in previous work packages^{2,3}). Figure 3.1 shows the principle: incident wavelength λ_1 is fixed whilst incident wavelength λ_2 is decreased, creating an increasing wavelength separation $\Delta\lambda$. The efficiency and relative power (see section 1) of the four-wave mixing product λ_{112} , is monitored as a function of $\Delta\lambda$. The position of λ_{112} at a particular wavelength separation is given by $(\Delta\lambda + \lambda_1)$.

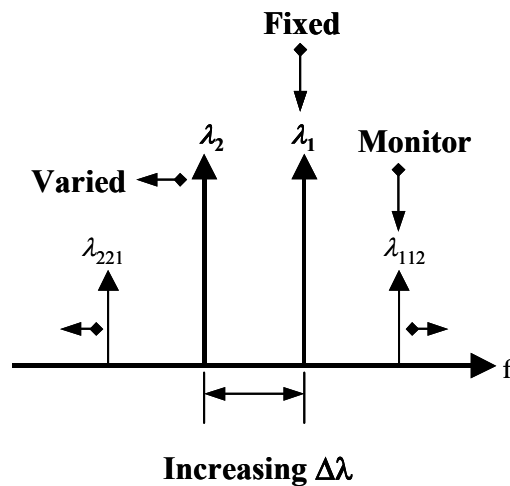


Figure 3.1: The simulated experiment.

3.2 Fibre Types and Parameters

The fibre types included within the simulated experiment are listed in Figure 3.2.

Type	I.D	λ_0
Matched Cladding - Standard Dispersion	081216706305	1313.07
RDS Truewave	991444960001	1448.76
Corning Dispersion Shifted	392154322304	1546.5
Sumitomo Dispersion Shifted	61-2000-7590	1555.09
Submarine Leaf	321736069705	1574.68
Lucent Dispersion Compensating	974844640001	

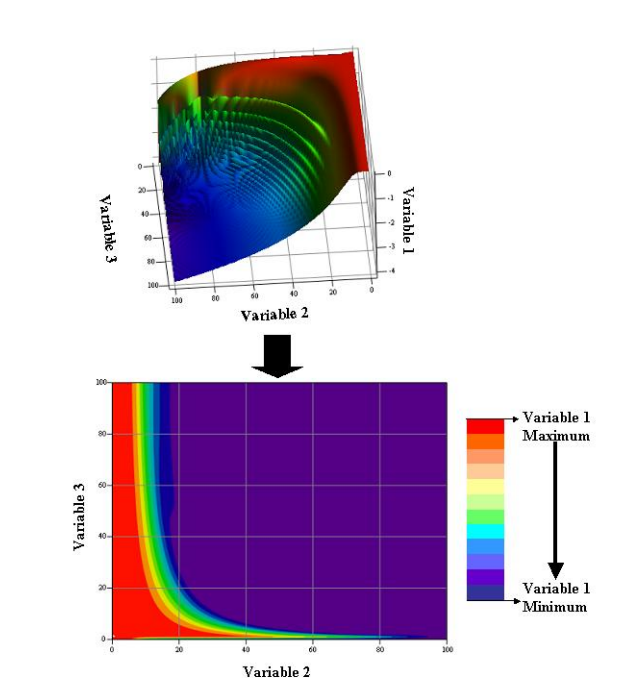
Figure 3.2: The fibre types.

Data for the chromatic dispersion and A_{eff} of the above fibre types are included in Appendices A and B. A_{eff} data for the Corning Dispersion shifted fibre was not available, so the values for the Sumitomo fibre were used. A simple linear interpolation was used to obtain values over the wavelength range of interest. An attenuation value of $\alpha = 0.046$ neper/km, and a second order refractive $n_2 = 3 \times 10^{-20} \text{ m}^2 \text{W}^{-1}$, were employed for all fibre types¹.

3.3 The Interpretation of the Contour Plots

The calculations involved the investigation of either the efficiency, or the relative power, of the λ_{112} (FWM(112)) product as a function of two other variables. This involved the plotting of 3D plots in order to view the resulting data, however, it was found that contour plots presented a clearer view of the subsequent data. Figure 3.3 clarifies the interpretation of the plots presented within section 3.

Figure 3.3: The interpretation of the contour plots.



3.4 A Single Fibre Under Test

Initially, each fibre type was tested using two different values of λ_1 : 1573.767nm to correspond to the highest CO absorption line, R0, and 1553.05nm to simulate a region within the lower acetylene absorption lines^{2,3}.

For a single fibre system, equation 1.8 was used for the four-wave mixing efficiency, η (maximum value = 1, minimum value = 0), and equation 1.20 for the Relative Power (which is proportional to the time-averaged optical power, equation 1.9). These parameters were plotted as a function of $\Delta\lambda$ and fibre length, for the four-wave mixing product λ_{112} (FWM(112)).

Firstly, the phase matching condition described via equation 1.3 was utilized, which takes into account the effects of chromatic dispersion alone. As discussed in section 1.2.1, operating near the zero dispersion wavelength of the fibre is one of the ways to achieve the phase matching condition^{1,5,7}. As a result, the fibres that sustained the four-wave mixing efficiency/power over the greatest wavelength range were:

- The Sumitomo Dispersion Shifted fibre ($\lambda_0 = 1555.09\text{nm}$) for $\lambda_1 = 1553.05\text{nm}$ (Figure 3.4).
- The Submarine Leaf fibre ($\lambda_0 = 1574.68\text{nm}$) for $\lambda_1 = 1573.767\text{nm}$ (Figure 3.5).

Note that the phase matching condition for the experiment in question, and for frequency comb generation, differ slightly. When considering a single four-wave mixing product the above is correct. When considering multiple products, as produced in a comb, a low positive dispersion is advantageous⁸ which meant that the Sumitomo Dispersion Shifted fibre performed better at $\lambda_1 = 1573.767\text{nm}$ than the Submarine Leaf fibre (see section 2.2).

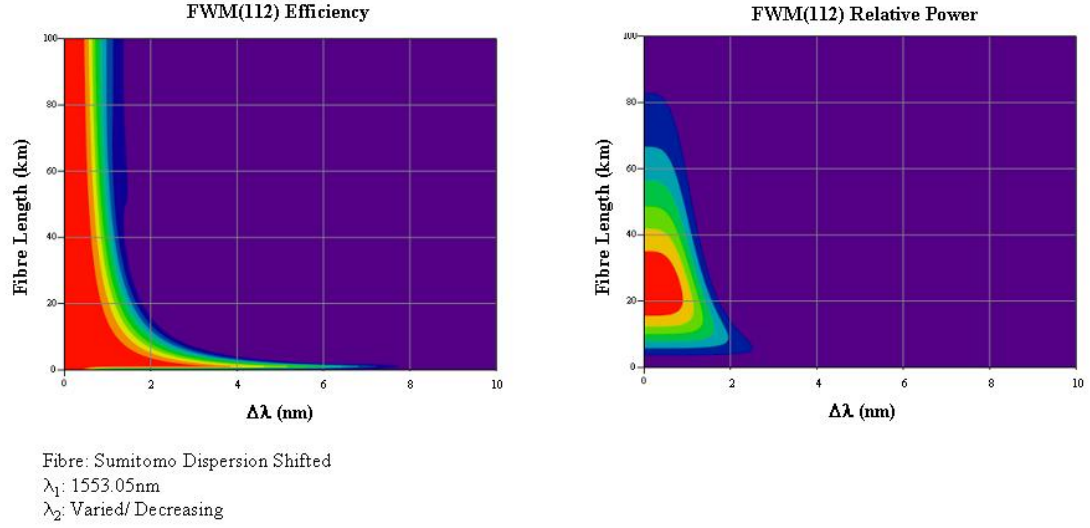


Figure 3.4: Sumitomo Dispersion Shifted fibre ($\lambda_0 = 1555.09\text{nm}$) for $\lambda_1 = 1553.05\text{nm}$.

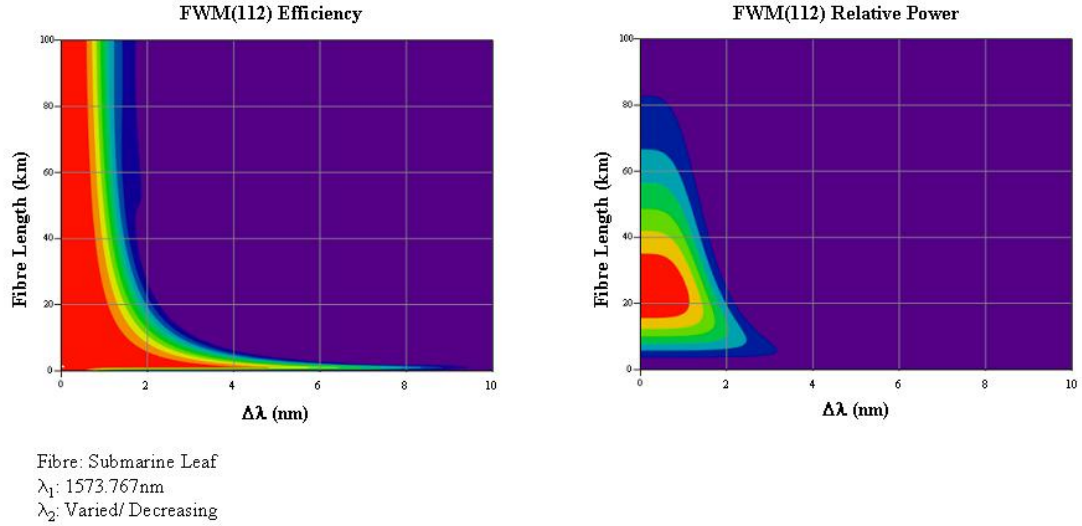


Figure 3.5: Submarine Leaf fibre ($\lambda_0 = 1574.68\text{nm}$) for $\lambda_1 = 1573.767\text{nm}$.

A second way to achieve the phase matching condition is to move to the anomalous dispersion regime ($D_c > 0$) and utilize non-linear effects such as self phase modulation (refer to discussion in section 1.2.1)^{1,6}. Equation 1.4 governs the phase matching condition when intensity dependant effects are included. Figure 3.6 shows the effect of increasing the incident power level on the output from the Sumitomo Dispersion Shifted fibre for $\lambda_1 = 1567.324\text{nm}$. Note that the maximum for the efficiency, and hence the Relative Power, shifts away from $\Delta\lambda = 0$, as described in section 1.2.1.

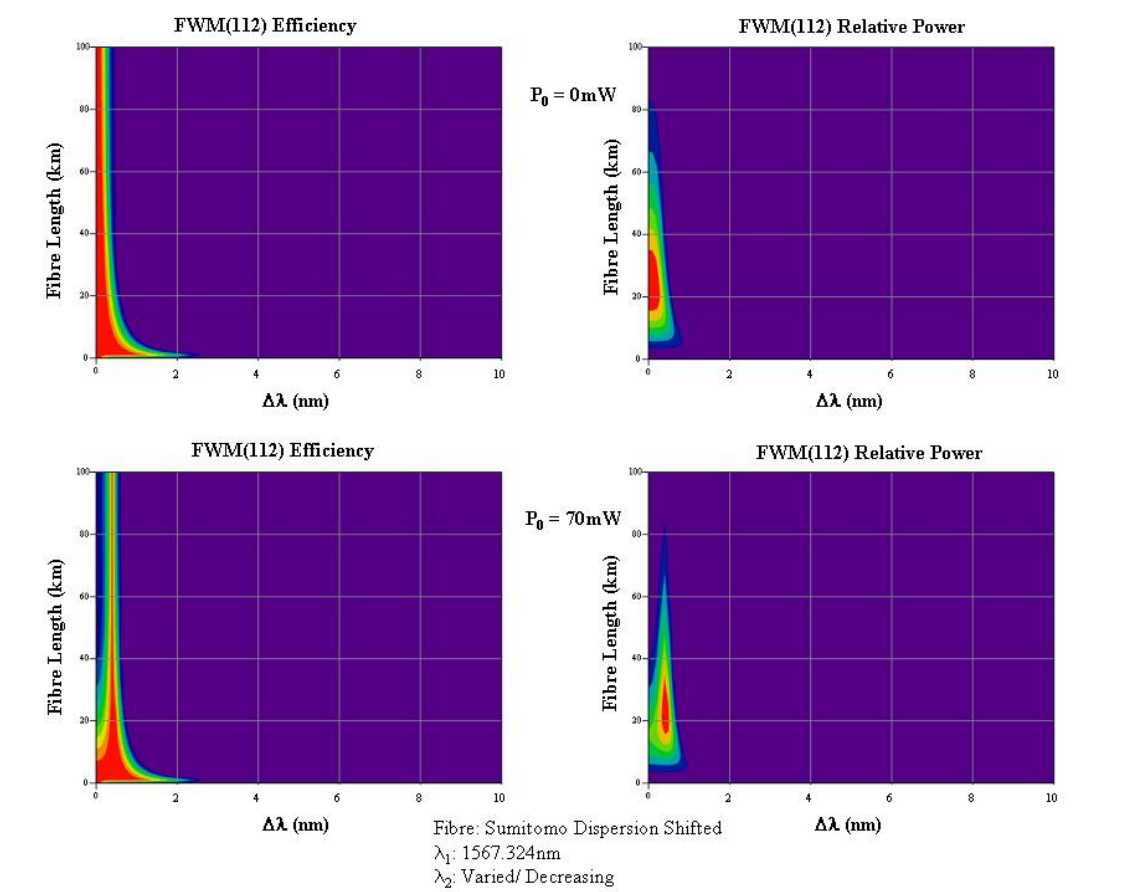


Figure 3.6: Sumitomo Dispersion Shifted fibre ($\lambda_0 = 1555.09\text{nm}$) for $\lambda_1 = 1567.324\text{nm}$ – increasing power levels.

3.5 Dual Fibre System – Phase Matching Via Chromatic Dispersion

The experiment now assumes that the “fibre under test” consists of two fibres in series, of differing fibre types. All combinations of the list of fibres presented in Figure 3.2 were tested. Initially, a fixed wavelength separation ($\Delta\lambda$) of 0.9nm was used (to simulate a typical distance between adjacent absorption lines) for two different values of λ_1 : 1573.767nm and 1553.05nm .

For a dual fibre system, equation 1.23 is used for the four-wave mixing efficiency, η_{nor} (maximum value = 1, minimum value = 0), and equation 1.25

for the Relative Power (which is proportional to the time-averaged optical power, equation 1.24). The phase matching condition described via equation 1.3 was utilized, which takes into account the effects of chromatic dispersion alone. The Relative Power was plotted as a function of the lengths of both fibres – to ascertain the optimum lengths for the experiment. An example of one of these plots is displayed in Figure 3.7 – note the interference pattern superimposed on the output as predicted by Inoue⁷ (refer to section 1.2.4).

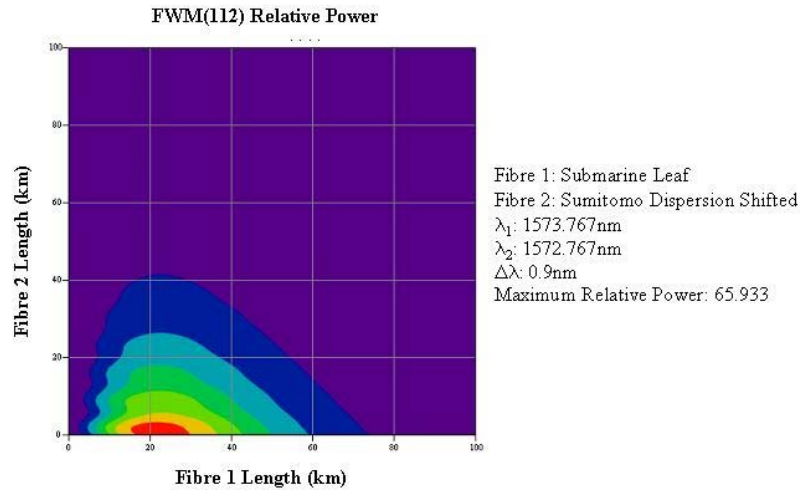


Figure 3.7: Dual system – Submarine Leaf and Sumitomo Dispersion Shifted fibre.

Looking at the values of the maximum Relative Power it could be seen that the most promising combinations of fibres were:

- At $\lambda_1 = 1553.05\text{nm}$ – Sumitomo Dispersion Shifted (20km) + another fibre type (1.5km).
- At $\lambda_1 = 1573.767\text{nm}$ – Submarine Leaf (22km) + another fibre type (1.5km).

The length of the first fibre was then fixed at the optimum length, as above, and the efficiency / relative power plotted as a function of $\Delta\lambda$ and the length of the second fibre. This was done for all combinations from the bullet points above. The aim of this work was to see if a dual fibre system would improve the wavelength range over which a four-wave mixing product could be maintained. It was found that the dual fibre system did not give any significant advantage over the single fibre system. Figure 3.8 shows two examples of the typical plot obtained – in this case, two combinations of Sumitomo Dispersion Shifted fibre and Submarine Leaf fibre at $\lambda_1 = 1573.767\text{nm}$. The efficiency of the four-wave mixing product is curtailed by

the interference between the signals from the two differing segments of fibre – refer to Figure 3.5 for comparison with the optimum single fibre equivalent.

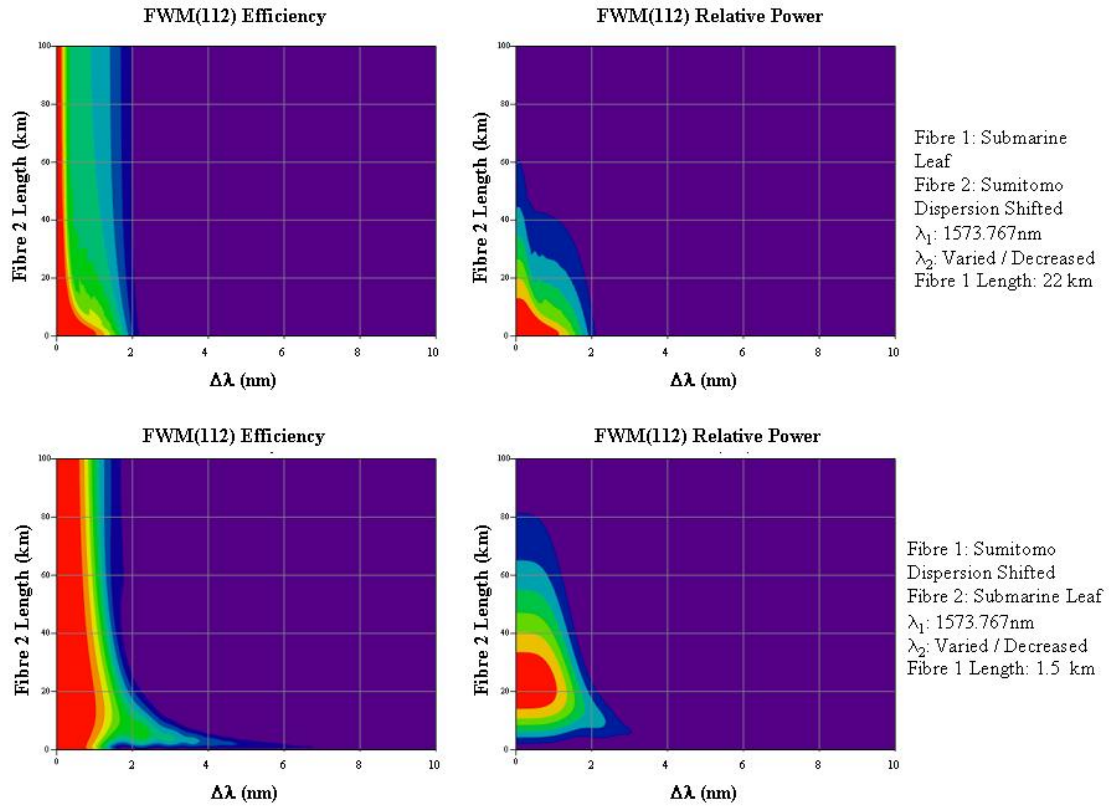


Figure 3.8: Dual system – Submarine Leaf and Sumitomo Dispersion Shifted fibre.

3.6 Dual Fibre System – Phase Matching Including Intensity Dependant Effects

Taking the combination of Submarine Leaf and Sumitomo Dispersion shifted fibre discussed above, intensity dependant effects were added to the calculation to investigate any possible improvements in performance.

Initially, a fixed wavelength separation ($\Delta\lambda$) was used $\lambda_1 = 1573.767\text{nm}$ (R0 CO absorption line) and $\lambda_2 = 1572.868\text{nm}$ (R1 CO absorption line). The efficiency and relative power of λ_{112} (FWM(112)) was calculated as a function of incident power, and fibre length, for each of the fibres separately (equations 1.4, 1.8 and 1.20) and then in combination (equations 1.4, 1.21 and 1.25). The results are displayed in Figure 3.9 (a) and (b).

In the case of the single fibre systems, the optimum power levels were then used, and the relative power of λ_{112} (FWM(112)) plotted as a function of $\Delta\lambda$ and the length of the fibre. In the dual fibre system, the optimum power levels were then used, and the relative power of λ_{112} (FWM(112)) plotted as a function of $\Delta\lambda$ and the length of the second fibre (the length of the first fibre being fixed). The results are displayed in Figure 3.10 (a) and (b).

Figure 3.9(a): Consideration of intensity dependant effects in a Submarine Leaf and Sumitomo Dispersion Shifted fibre single fibre system.

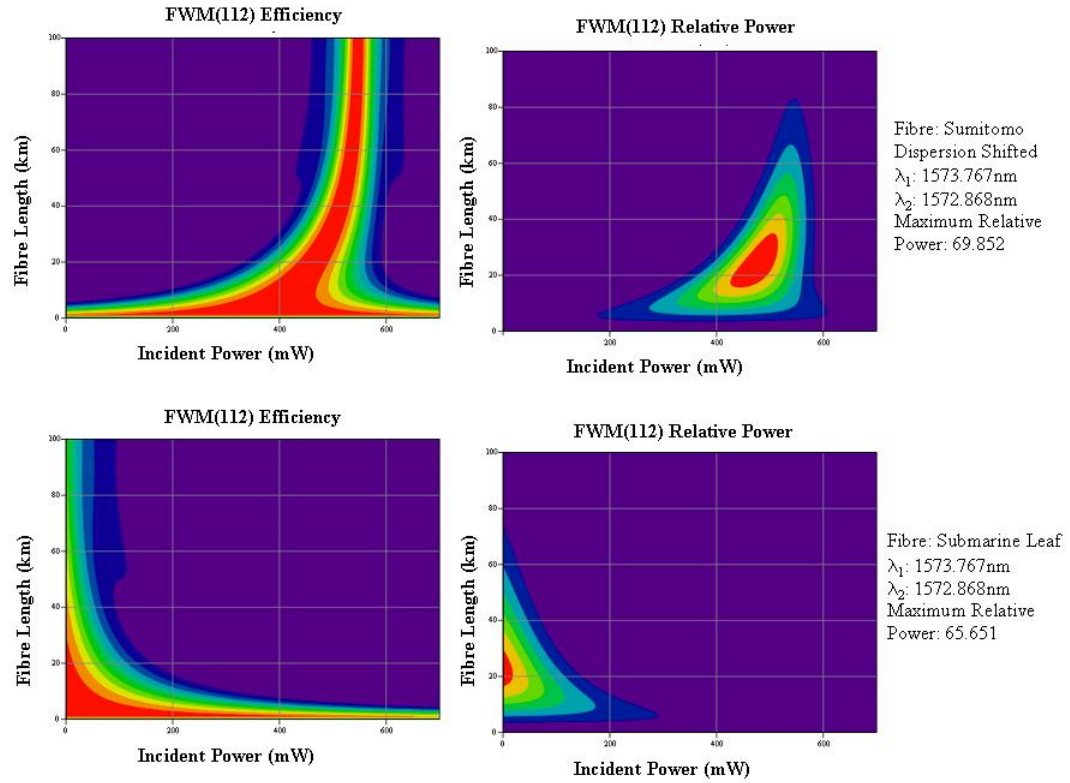
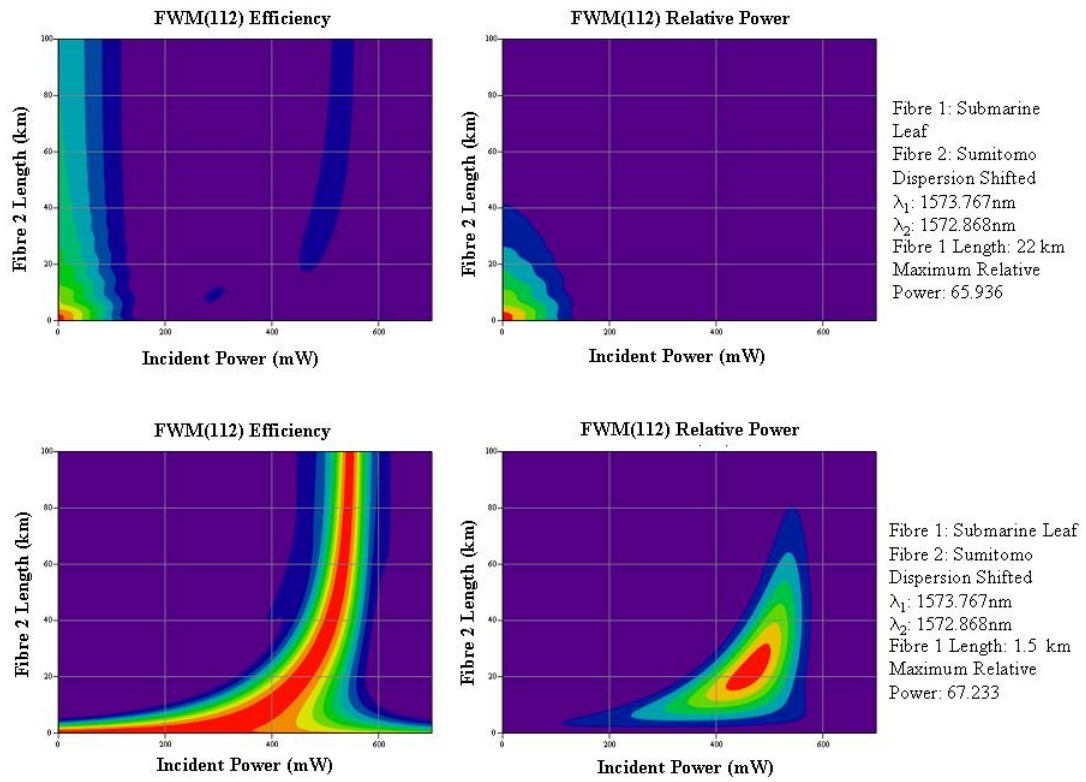


Figure 3.9(b): Consideration of intensity dependant effects in a Submarine Leaf and



Sumitomo Dispersion Shifted fibre dual fibre system.

Figure 3.10(a): Consideration of intensity dependant effects in a Submarine Leaf and Sumitomo Dispersion Shifted fibre single fibre system. For the Sumitomo Dispersion Shifted Fibre, $P_0 = 0\text{mW}$ has been included for comparison.

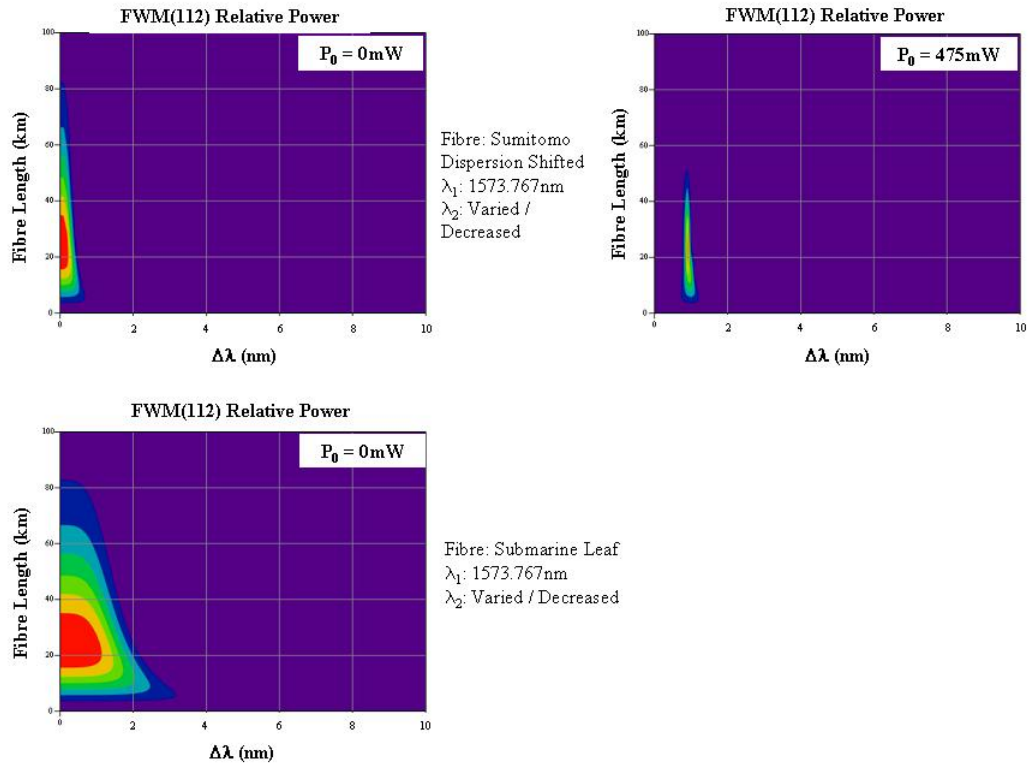
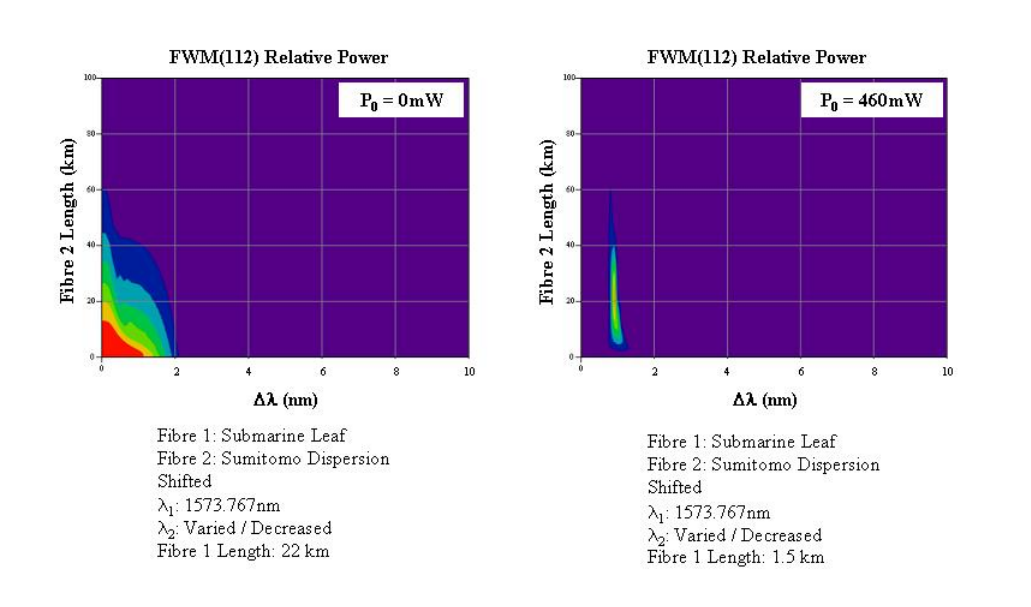


Figure 3.10(b): Consideration of intensity dependant effects in a Submarine Leaf and Sumitomo Dispersion Shifted fibre dual fibre system.



Looking once again at the objective of maximising the wavelengths range over which the four-wave mixing product could be maintained, Figure 3.9 and 3.10 showed that no added advantage was gained over the single fibre examples. As with the experiment in section 3.5 the efficiency of the dual fibre system is curtailed by the interference between the products from each fibre section.

3.7 Conclusions

This section presented simulations of the creation of four-wave mixing products via the use of a dual fibre system, created by two different “off the shelf” fibres in series. Focusing on the first four-wave mixing product alone, λ_{112} , virtual experiments were carried out to see if a fibre combination could maintain the efficiency of the product over a larger wavelength range than the single fibre alone. The ultimate aim would be to provide wavelength standards for the whole of the L-Band ITU grid, from four-wave mixing products locked to known gas absorption lines. In section 2, the maximum coverage achieved experimentally was for the lower 25% of the L-Band range. Although several combinations of fibre types, fibre lengths, incident powers were investigated the dual fibre systems showed no discernable advantage over the single fibre version. The interaction between signals generated between within each segment of the dual system created interference at the fibre output, which curtailed the performance of the system as a whole.

Of course the fibres used as part of this simulation differ widely in zero dispersion wavelength, chromatic dispersion characteristics etc.. A second version of this type of experiment has been reported¹⁴. A single fibre was cut into a series of short segments and the segments arranged considering the zero dispersion wavelength of each piece. The wavelength range over which the four wave mixing product was maintained was improved compared with that of the original fibre. This method could be tried experimentally with the fibres selected as optimum for the wavelength ranges identified, to see if any further improvements could be made.

4. Conclusions

The work presented in this report sort to investigate the production of wavelength reference standards for the L-Band, via four-wave mixing products locked to known gas absorption lines. The work was two-fold:

- To investigate experimentally the production of frequency combs, via four-wave mixing, using “off the shelf” single mode fibre. To lock the combs to known gas standard absorption lines, and identify the extent to which such a system could provide wavelengths standards for the L-Band region.
- To simulate dual fibre systems (two different fibres in series) to ascertain if any advantage would be gained over a single fibre system, in maximising the wavelengths range over which the first four-wave mixing product could be maintained.

It was shown that frequency combs locked to gas absorption lines would be ideal for matching to a large number of ITU grid wavelengths in the L-band. Experimental results showed that the highest four-wave mixing comb product produced, from the single mode fibre available, was at a wavelength of 1580.967nm (7.2nm greater than the highest available absorption line). This provided potential coverage of the lower 25% of the L-Band range. The disadvantages of this method were also discussed: the overall accuracy of using CO absorption lines as the lock for potential combs, and the power of the four-wave mixing products in question.

The second way of approaching the problem is to work with the first mixing product only, and increase the wavelength separation of the two incident signals. This was tried experimentally but was found not to cover the same range as the comb described above. Simulations of this particular experiment showed that some gains may be made if a fibre of higher zero dispersion wavelength was employed - this highlighted the slightly difference phase matching requirements between this and frequency comb production. Simulations of dual fibre systems indicated that no advantage could be gained over using a single fibre, due to the interference within the system. The re-arrangement, and management, of the zero dispersion distribution along a single fibre, was suggested as a possible way of increasing the overall wavelength range available. By using a re-arranged fibre, Inoue¹⁴ showed a 50% improvement in the frequency range covered. However, this result will depend on how non-uniform the zero dispersion wavelength distribution along the fibre was in the first place.

5. Appendix A – Values of Chromatic Dispersion for Selected Fibre Types⁴

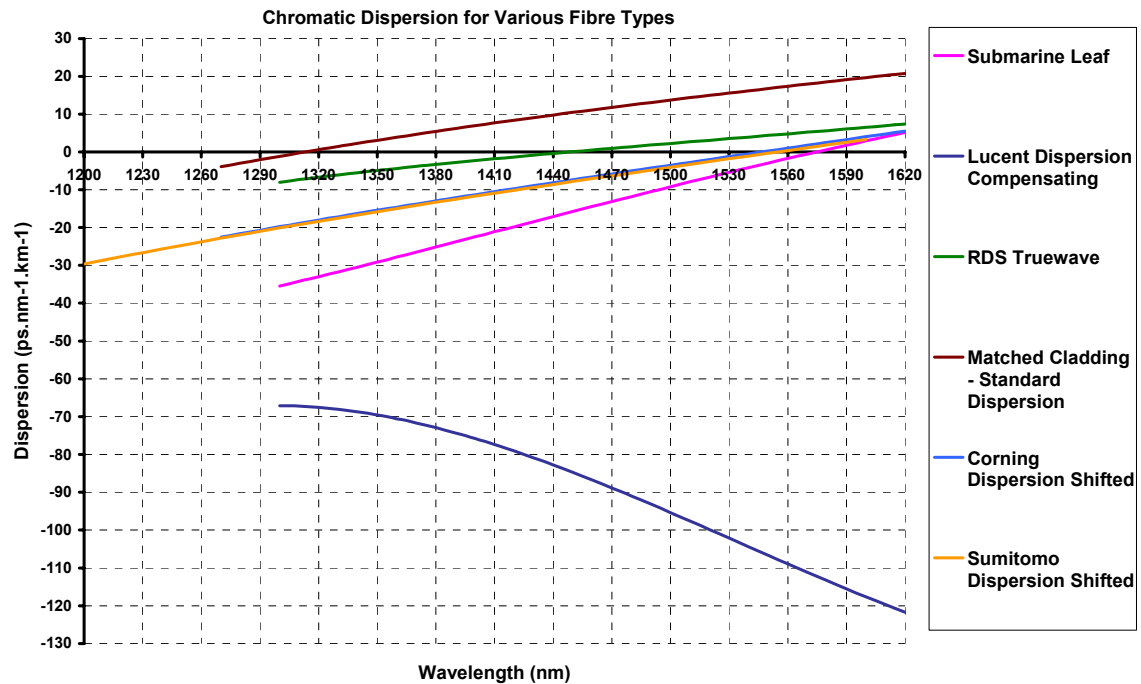


Figure A1: Values of chromatic dispersion for selected fibre types.

Type	I.D	λ_0
Matched Cladding - Standard Dispersion	081216706305	1313.07
RDS Truwave	991444960001	1448.76
Corning Dispersion Shifted	392154322304	1546.5
Sumitomo Dispersion Shifted	61-2000-7590	1555.09
Submarine Leaf	321736069705	1574.68
Lucent Dispersion Compensating	974844640001	

Table A1: Values of zero chromatic dispersion for selected fibre types.

6. Appendix B – Values of Effective Area for Selected Fibre Types⁴

		Fibre	1310nm	1550nm	Reference
All Wave	004V 1959 7D2 CLD	Attenuation Flattened	66.385	80.936	11
True Wave	991 444 960 001	Dispersion Flattened	38.467	53.835	11
	223 13006411/A1	Matched Cladding	67.786	83.391	11
Sumitomo	61-2000-7590	Dispersion Shifted	29.747	46.05	11
Submarine LEAF	3217 360 6970 SA	LEAF -'ve Dispersion	34.107	67.25	11
Terrestrial LEAF	621 758 938 807	LEAF +'ve Dispersion	38.841	68.399	11
SMF28	D0816 4540 6305	NPL Standard	65.7	81.7	12
Lucent Dispersion Compensating	974844640001	DK-SM	11.5	22.5	13

Table B1: Values of effective area for selected fibre types.

7. Appendix C - The L-Band ITU Grid-Lines⁹

100 GHz Grid		50 GHz Offset	
THz	nm	THz	nm
186	1611.79	186.05	1611.35
186.1	1610.92	186.15	1610.49
186.2	1610.06	186.25	1609.62
186.3	1609.19	186.35	1608.76
186.4	1608.33	186.45	1607.9
186.5	1607.47	186.55	1607.04
186.6	1606.6	186.65	1606.17
186.7	1605.74	186.75	1605.31
186.8	1604.88	186.85	1604.46
186.9	1604.03	186.95	1603.6
187	1603.17	187.05	1602.74
187.1	1602.31	187.15	1601.88
187.2	1601.46	187.25	1601.03
187.3	1600.6	187.35	1600.17
187.4	1599.75	187.45	1599.32
187.5	1598.89	187.55	1598.47
187.6	1598.04	187.65	1597.62
187.7	1597.19	187.75	1596.76
187.8	1596.34	187.85	1595.91
187.9	1595.49	187.95	1595.06
188	1594.64	188.05	1594.22
188.1	1593.79	188.15	1593.37
188.2	1592.95	188.25	1592.52
188.3	1592.1	188.35	1591.68
188.4	1591.26	188.45	1590.83
188.5	1590.41	188.55	1589.99
188.6	1589.57	188.65	1589.15
188.7	1588.73	188.75	1588.3
188.8	1587.88	188.85	1587.46
188.9	1587.04	188.95	1586.62
189	1586.2	189.05	1585.78
189.1	1585.36	189.15	1584.95
189.2	1584.53	189.25	1584.11
189.3	1583.69	189.35	1583.27
189.4	1582.85	189.45	1582.44
189.5	1582.02	189.55	1581.6
189.6	1581.18	189.65	1580.77
189.7	1580.35	189.75	1579.93
189.8	1579.52	189.85	1579.1
189.9	1578.69	189.95	1578.27
190	1577.86	190.05	1577.44
190.1	1577.03	190.15	1576.61
190.2	1576.2	190.25	1575.78
190.3	1575.37	190.35	1574.95
190.4	1574.54	190.45	1574.13
190.5	1573.71	190.55	1573.3
190.6	1572.89	190.65	1572.48
190.7	1572.06	190.75	1571.65
190.8	1571.24	190.85	1570.83
190.9	1570.42	190.95	1570.01

8. Appendix D – List of CO Transitions¹⁰

The carbon monoxide absorptions are given in the CRC Handbook of Chemistry and Physics, 79th edition (1998), pages 10-236 to 10-240. This consolidated information provided in previous publications. The R21 line has been verified by frequency doubling against ⁸⁷Rb at 780 nm. These values are reproduced in the table below. The pressure shift measured for the R19 transition is (2.95±1) fm.

Transition	Wavenumbers	uncertainty	Wavelength	uncertainty	Frequency	uncertainty
R	cm ⁻¹	cm ⁻¹ x 10 ⁶	nm	pm	GHz	MHz
0	6354.179057	13	1573.767423	0.003220	190493.496	0.39
1	6357.813923	13	1572.867675	0.003216	190602.466	0.39
2	6361.343487	13	1571.994976	0.003213	190708.280	0.39
3	6364.767599	13	1571.149275	0.003209	190810.932	0.39
4	6368.086115	13	1570.330523	0.003206	190910.419	0.39
5	6371.298887	13	1569.538673	0.003202	191006.735	0.39
6	6374.405768	12	1568.773681	0.002953	191099.877	0.36
7	6377.406611	12	1568.035506	0.002950	191189.840	0.36
8	6380.301271	12	1567.324108	0.002948	191276.620	0.36
9	6383.089600	12	1566.639453	0.002945	191360.212	0.36
10	6385.771452	12	1565.981507	0.002943	191440.612	0.36
11	6388.346680	13	1565.350239	0.003185	191517.815	0.39
12	6390.815139	13	1564.745620	0.003183	191591.818	0.39
13	6393.176681	13	1564.167627	0.003181	191662.615	0.39
14	6395.431160	13	1563.616236	0.003178	191730.203	0.39
15	6397.578430	13	1563.091427	0.003176	191794.576	0.39
16	6399.618344	13	1562.593183	0.003174	191855.731	0.39
17	6401.550757	13	1562.121489	0.003172	191913.664	0.39
18	6403.375523	13	1561.676332	0.003170	191968.369	0.39
19	6405.092495	14	1561.257704	0.003413	192019.842	0.42
20	6406.701527	14	1560.865596	0.003411	192068.080	0.42
21	6408.202474	14	1560.500006	0.003409	192113.077	0.42
22	6409.595189	15	1560.160931	0.003651	192154.830	0.45
23	6410.879527	15	1559.848373	0.003650	192193.333	0.45
24	6412.055343	16	1559.562335	0.003892	192228.583	0.48
25	6413.122491	17	1559.302822	0.004133	192260.576	0.51
26	6414.080825	19	1559.069845	0.004618	192289.306	0.57
27	6414.930201	90	1558.863415	0.021870	192314.769	2.70
28	6415.670474	23	1558.683545	0.005588	192336.962	0.69
29	6416.301500	37	1558.530253	0.008987	192355.880	1.11
30	6416.823133	50	1558.403558	0.012143	192371.518	1.50
31	6417.235231	67	1558.303481	0.016270	192383.872	2.01
32	6417.537649	90	1558.230048	0.021853	192392.939	2.70

9. Appendix E – List of $^{13}\text{C}_2\text{H}_2$ transitions¹⁰

The table below lists the first 15 vacuum wavelengths (nm) for the $\nu_1 + \nu_3$ band of acetylene ($^{13}\text{C}_2\text{H}_2$) absorption lines. The lines with even numbers are the stronger lines.

Transition ($\nu_1 + \nu_3$)	Wavenumber s cm^{-1}	uncertainty y cm^{-1}	Wavelength nm	uncertainty pm	Frequency GHz	uncertainty y MHz
P39	6418.147451	0.00412	1558.082	0.1	192411.22	12
P38	6421.237922	0.00412	1557.332	0.1	192503.87	12
P37	6424.301708	0.00413	1556.589	0.1	192595.72	12
P36	6427.341144	0.00413	1555.853	0.1	192686.84	12
P35	6430.362568	0.00413	1555.122	0.1	192777.42	12
P34	6433.360308	0.00414	1554.398	0.1	192867.29	12
P33	6436.335033	0.00414	1553.679	0.1	192956.47	12
P32	6439.28272	0.004146	1552.968	1	193044.84	124
P31	6442.218103	0.000415	1552.260	0.1	193132.84	12
P30	6445.125605	0.000004	1551.5601422	0.0010	193220.00472	0.12
P29	6448.009587	0.000004	1550.8661805	0.0010	193306.46433	0.12
P28	6450.873591	0.000004	1550.1776401	0.0010	193392.32501	0.12
P27	6453.713518	0.000004	1549.4954916	0.0010	193477.46388	0.12
P26	6456.531045	0.000004	1548.8193165	0.0010	193561.93121	0.12
P25	6459.326013	0.000004	1548.1491381	0.0010	193645.72225	0.12

10. Appendix F – Frequency Comb Match to L-Band Grid Lines

Locking the proposed frequency comb to CO absorption lines, the tables below show whether the subsequent four-wave mixing comb products would match to the L-Band grid lines. The matching criteria are: to within 40 GHz for heterodyne measurements with commercially available equipment; to within 26GHz for the reduced RF detection requirement².

Transition 1		Transition 2		Difference		L-Band Grid Lines (Frequency (THz))											
Transition n	Frequency (THz)	Transition n	Frequency (THz)	Difference	THz												
						190.9	190.8	190.7	190.6	190.5	190.4	190.3	190.2	190.1	190	189.9	189.8
R1	190.602	R0	190.493	R1 and R0	0.10897												
R2	190.708	R1	190.602	R2 and R1	0.10581												
R3	190.811	R2	190.708	R3 and R2	0.10265												
R4	190.91	R3	190.811	R4 and R3	0.09949												
R5	191.007	R4	190.91	R5 and R4	0.09632												
R6	191.1	R5	191.007	R6 and R5	0.09314												
R7	191.19	R6	191.1	R7 and R6	0.08996												
R8	191.277	R7	191.19	R8 and R7	0.08678												
R9	191.36	R8	191.277	R9 and R8	0.08359												
R2	190.708	R0	190.493	R2 and R0	0.21478												
R3	190.811	R0	190.493	R3 and R0	0.31744												
R4	190.91	R0	190.493	R4 and R0	0.41692												
R5	191.007	R0	190.493	R5 and R0	0.51324												
R6	191.1	R0	190.493	R6 and R0	0.60638												
R7	191.19	R0	190.493	R7 and R0	0.69634												

Within 40GHz

Within 26GHz

Transition 1		Transition 2		Difference		L-Band Grid Lines (Frequency (THz))											
Transitio n	Frequen cy (THz)	Transitio n	Frequen cy (THz)	Differen ce	THz												
						189.2	189.1	189	188.9	188.8	188.7	188.6	188.5	188.4	188.3	188.2	188.1
R1	190.602	R0	190.493	R1 and R0	0.10897												
R2	190.708	R1	190.602	R2 and R1	0.10581												
R3	190.811	R2	190.708	R3 and R2	0.10265												
R4	190.91	R3	190.811	R4 and R3	0.09949												
R5	191.007	R4	190.91	R5 and R4	0.09632												
R6	191.1	R5	191.007	R6 and R5	0.09314												
R7	191.19	R6	191.1	R7 and R6	0.08996												
R8	191.277	R7	191.19	R8 and R7	0.08678												
R9	191.36	R8	191.277	R9 and R8	0.08359												
R2	190.708	R0	190.493	R2 and R0	0.21478												
R3	190.811	R0	190.493	R3 and R0	0.31744												
R4	190.91	R0	190.493	R4 and R0	0.41692												
R5	191.007	R0	190.493	R5 and R0	0.51324												
R6	191.1	R0	190.493	R6 and R0	0.60638												
R7	191.19	R0	190.493	R7 and R0	0.69634												

Transition 1		Transition 2		Difference		L-Band Grid Lines (Frequency (THz))											
Transitio n	Frequen cy (THz)	Transitio n	Frequen cy (THz)	Differen ce	THz												
						187.5	187.4	187.3	187.2	187.1	187	186.9	186.8	186.7	186.6	186.5	186.4
R1	190.602	R0	190.493	R1 and R0	0.10897												
R2	190.708	R1	190.602	R2 and R1	0.10581												
R3	190.811	R2	190.708	R3 and R2	0.10265												
R4	190.91	R3	190.811	R4 and R3	0.09949												
R5	191.007	R4	190.91	R5 and R4	0.09632												
R6	191.1	R5	191.007	R6 and R5	0.09314												
R7	191.19	R6	191.1	R7 and R6	0.08996												
R8	191.277	R7	191.19	R8 and R7	0.08678												
R9	191.36	R8	191.277	R9 and R8	0.08359												
R2	190.708	R0	190.493	R2 and R0	0.21478												
R3	190.811	R0	190.493	R3 and R0	0.31744												
R4	190.91	R0	190.493	R4 and R0	0.41692												
R5	191.007	R0	190.493	R5 and R0	0.51324												
R6	191.1	R0	190.493	R6 and R0	0.60638												
R7	191.19	R0	190.493	R7 and R0	0.69634												

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