Phase-sensitive mid infrared frequency comb interferometry for plasma electron density measurements

Andrew Gardner *[a], Mateusz Mrozowski [a], Vasili Savitski [a]
[a] Fraunhofer UK Centre for applied photonics. Glasgow, United Kingdom
*andrew.gardner@fraunhofer.co.uk

ABSTRACT

Accurate values of plasma electron density can be challenging for long running fusion reactions as complete temporal information from startup is necessary. Furthermore traditional techniques can introduce errors due to fringe jumping. Here we present a prototype interferometer that can measure relative phase. It is based on dual frequency comb spectroscopy with quantum cascade lasers at the wavelength of ~8 um. This method relies on phase differences between neighbouring comb lines eliminating the need for pervious plasma electron density knowledge and minimizing fringe jumping errors. The instrument performance was verified: 1) by measuring the phase induced by a material with known absorption characteristics (polypropylene). The frequency comb phase shift after propagating through a sample with both negative and positive phase gradients was measured and showed good correlation with the expected one calculated using the known refractive index and absorption characteristics of this material. 2) by measuring the relative phase change induced by two counter rotating plane-parallel plates. The measurements were taken by adjusting the tilting angle of plane-parallel plates. Good correlation between the measured slope of the phase shift w.r.t. the wavenumber and that simulated with the known dispersion parameters of the plates was demonstrated. The noise of this system was evaluated. The phase error occurs due to comb instability, amplitude instability and the phase drift between the two frequency comb sources. This phase error combined with the frequency of each comb line was used to determine the plasma electron density error. With this suggested instrument the error associated with the line integrated plasma electron density is in the order of 10^{17} m^{-3}, with an upper limit measured as 1.3×10^{27} m^{-2}. The cut-off plasma density is 4.4×10^{23} m^{-3}. The results of measurement and simulation demonstrate the validity of the built instrument for reliable phase shift measurements applicability for use in long running fusion reactions necessary for powerplant operations.

1. INTRODUCTION

Plasma electron density measurements are fundamental to running a plasma fusion reaction. As more focus moves toward developing long term fusion reactions the development of devices that can offer real-time feedback that are still robust and accurate are necessary.

Interferometers are a powerful tool when determining the plasma electron density as the electron density is directly related to the refractive index of the plasma and the optical path length change [1]. By having a reference background and probe measurement the line integrated plasma electron density can be determined along the path of the beam. Currently there are several methods for determining the plasma electron density: two colour interferometry, dispersion interferometry and far infrared interferometry [2][3]. These methods rely on one or two beam to probe the plasma to determine the plasma electron density. For accurate determination of the phase these systems must take measurements from the startup of the plasma to have a correct fringe count. These methods relying on absolute phase can result in errors when fringe jumps occur between measurements.

A method for determining the plasma electron density using dual comb spectroscopy (DCS) was proposed by [4]. The advantage of using a frequency comb approach is that errors due to fringe jumping are eliminated, as this device relies on relative phase shifts between the comb teeth rather than temporal phase evolution.

DCS has many benefits such as fast acquisition speeds, and excellent sensitivity. It allows the full spectral region of the comb to be acquired simultaneously without any moving parts. DCS relies on two combs with slightly different comb tooth spacing, one to interrogate the sample and one to act as a local oscillator [5]. To measure the phase information of the sample one comb interrogates the sample while the local oscillator bypasses the sample. Often both combs are used to interrogate the sample which results in the samples phase information being lost while maintaining only the amplitude data. After interrogation on the detector, frequency combs with a slight difference in offset frequency produce a heterodyne signal in RF domain, which can be measured directly. Each RF line corresponds to a certain optical frequency, which through calibration of the spectrometer can be extract both the magnitude and phase information of the two combs before interfering.

Phase change due to change in the plasma electron density is a combination of pathlength change and line integrated plasma electron density derived in [4].

This phase error occurs from several factors including comb instability, amplitude instability and most importantly the phase drift between the two frequency comb sources. To estimate the lower noise limit of the plasma electron density due to phase noise at least three wavelengths must be sampled. This is generally not an issue for QCL frequency combs where hundreds of comb lines are expected.

In this paper a proof-of-concept dual frequency comb interferometer device is shown to measure phase, with an outline of the subsequent processing tools to calculate the corresponding plasma electron density, associated limits and noise.

2. METHODOLOGY

To verify this instrument a process to allow repeatable phase shifts was implemented. These controllable and repeatable phase changed allow comparison between experimental results and simulation work. this ensurse that this instrument can measure not only the correct phase spectrum over the spectral range of the device but also the correct absolute phase when compared a background measurement.

The phase sensitive dual comb spectrometer consists of three parts: 1) a QCL frequency comb source (Iris-core, IRsweep AG, Switzerland). 2) The detection stage, this includes two MCT detectors for both the reference and signal channels. 3) the sample stage which consisted of parallel plane plates. The QCL frequency source consists of two QCL frequency combs which are designated as the reference comb and the sample comb. The frequency combs are centred on 1265cm^{-1} with a spectral range of 1230-1310 cm^{-1} with a frequency space between individual teeth of 4 MHz. This produces ~ 220 resolved comb lines with a combined power of ~500 mW.

To process experimental data a python script was written to convert the detector outputs to phase. A dual comb interferometer returns the complex ratio of the signal and reference detector for each wavenumber point. To turn this measurement into phase the argument of the complex ratio is taken with quadrant correction, this resulting phase is in terms of ±π rad. Phase jumps are incompatible with finding the plasma electron density using a gradient fitting method meaning this phase must not be limited to ±π rad. The result of this is a smooth phase spectrum with no fringe jumps.

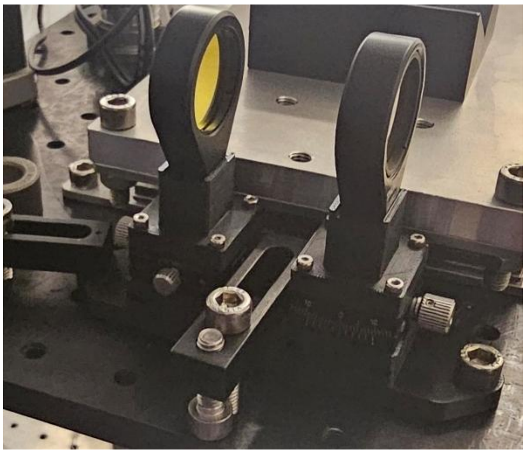

Figure 1: Image of plane parallel plates at 0° of rotation. plates consist of 5mm thick ZnSe mounted on goniometer

For measuring the phase change with the DCS method we use the approach suggested in [6]. A setup consisting of two plane parallel plates of either ZnSe or CaF2 on goniometer stages was built. PPP consists of two mutually parallel polished plates of the same material and thickness properties mounted on goniometers shown in fig 1. When placed in the optical path, the path of the light rays is conserved due to refraction on both surfaces. In the case of these plates being rotated on the optical axis a change to the optical path length occurs. This optical path length change induces a phase change, allowing controllable and predictable phase change [6]. Since the experimental set up uses a retroflector, this phase change is multiplied by two.

For experiments two sets of plates were used: i) a set consisted of two ZnSe windows with thickness of 5mm ii) a combination of these two ZnSe windows with two CaF_2 ones with thickness of 5mm.

For every angle of rotation of the plates, the spectrometer measures the phase difference at each wavenumber between the reference and the signal channels, i.e. the phase of the sample comb was measured in reference to the phase measurement when the goniometer pair was at a tilting angle 0° This phase difference is plotted as a function of wavenumber and the gradient of this plot for each angle is calculated. This gradient is then plotted as a function of the angle of rotation. The phase gradient represents what would be the plasma density value in future deployment of the system. The measured phase gradient is then compared with that calculated for the plates using equation from [6], to validate the performance of the system.

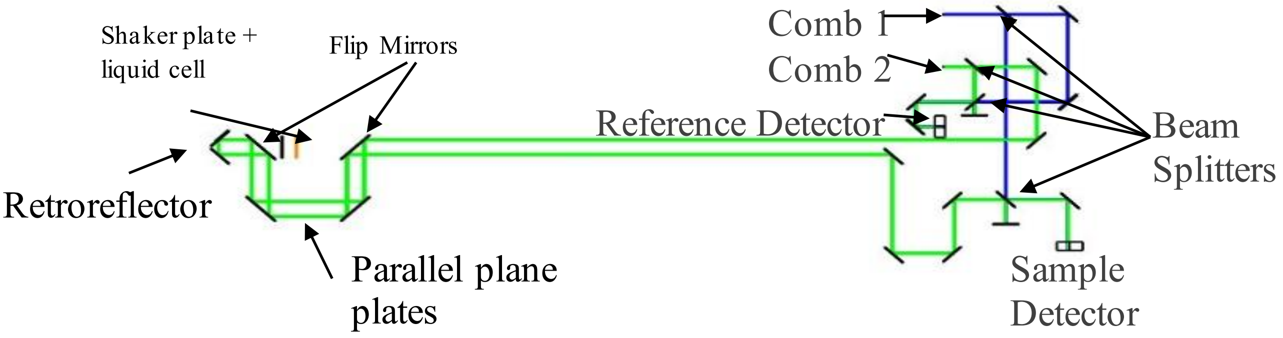

Figure 2: Experimental set up of dual comb interferometer for experiments with PPP..

3. RESULTS

The measurements were taken for tilting angles 0 – 12° and the phase gradient as a function of the tilting angle was plotted in fig 3.

Figure 3 shows the gradient of the measured phase as a function of wavenumber (symbols) in comparison with the theoretical values found with equation 3 (solid lines). There is a clear difference between the ZnSe and the ZnSe + CaF_2 simulations, this is expected as a larger optical path length is seen with the addition of the CF_2 plate. This is reflected in the results found experimentally where the addition of the CaF_2 plate results in a similar change in the gradient of phase. The simulation and the experimental work agree well with each other, small discrepancies can be seen due to tilting angle errors and asymmetry between the two plates. The large errors seen in the early angles can be explained by instabilities of the comb. To reduce these errors each measurement was taken 3 times. The agreement in the results between the simulation work and experimental show the validity of the built instrument for reliable phase shift measurements.

The lower limit of plasma density is determined by both the frequency of individual comb lines and the phase error. The frequency of the comb lines is set for all measurements so the determining factor for plasma density is the phase error measurements.

This phase error occurs from several factors including comb stability, amplitude instability and the phase drift between the two frequency comb sources. The manufacturer estimates 20 mrad/1.5 min of phase drift [7].

The phase error was calculated with 2000 measurements taken over 9 s. All measurements were taken with 1 ms acquisition time. These measurements were taken with no sample present, resulting in a zero line. Since the background is taken immediately before the measurements are recorded, the first phase measurement is zeroed while small deviations in phase are present in subsequent acquisitions due to the frequency sources being unlocked. Figure 4 shows phase plots for 0ms, 25ms and 51 ms showing these random fluctuations in phase.

To determine the stability of the combs an Allan deviation was plotted for 30 minutes shown in fig 5. Every 100 ms an acquisition of 1 ms would be taken, this ensures enough time has passed to process the data stopping the memory buffer from filling. The interferometer measured a background with no sample and each acquisition was taken with this same path resulting in a zero phase line. The derivative of these phase spectra were processed with an Allan deviation and plotted. This plot shows that after 30 minutes the lack of phase locking does not cause an increase in phase error. After 30 minutes the Allan deviation was ~10^{-3} . This means that measurements taken 30 minutes apart will have an instability in phase gradient of ~0.1%. This Allan deviation plot has yet to show the turning point where an increase in time results in an increase in uncertainty showing the system is still dominated by random noise rather than any systematic noise (i.e. errors from phase unlocked comb sources).

With the phase error evaluated the electron plasma density error can be evaluated with method described in reference [4]. For this instrument it was calculated to be 10^{17} m^{-3}.

The upper limit of measurable electron plasma density is determined by two cut offs [4]: 1) fringe jump cut off density, 2) plasma cut off density.

The fringe jump cut off density is the maximum electron plasma density before a fringe jump occurs between any neighbouring comb tooth.

In this case of a comb centred on 8 µm with 4 MHz frequency difference between comb teeth the upper limit was found to be 1.3×10^{27} m^{-3}. This value increases as frequency increases so a comb centred on shorted wavelengths can achieve a higher fringe cut off density.

The Plasma cut off density is the density at which the plasma becomes totally reflective to a laser wavelength.

For this instrument the limits for measurable electron plasma density is $10^{17} – 10^{23}$ m^{-3}. These values are within the typical fusion plasma densities of ~ 10^{21} m^{-3}.

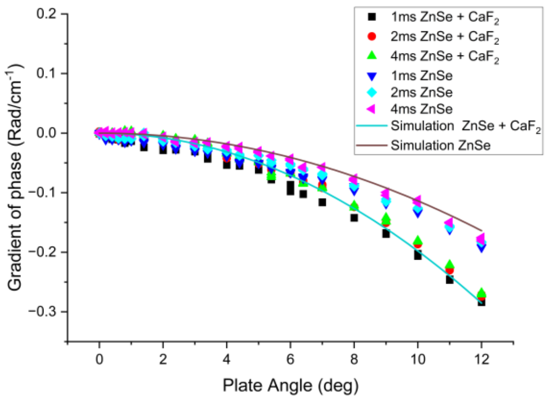

Figure 3: Phase gradient vs plate angle. Solid lines: gradient of phase vs wavelength for 5mm thick ZnSe and 5mm thick ZnSe + 5mm thick CF_2 . Dots: phase measured with dual comb interferometer over a range of acquisition times (1 – 4 ms) for ZnSe and ZnSe + CF_2. Measurements taken 3 times for each angle/acquisition time combination with the gradient of the phase vs wavenumber plot corresponding to each dot

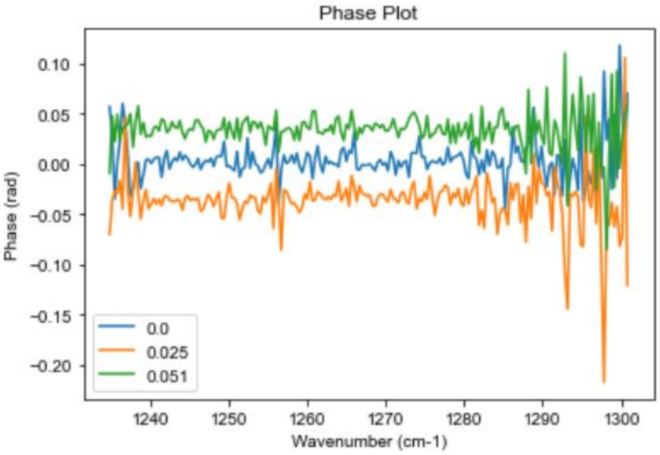

Figure 4: Phase vs wavenumber plot of zero line at 0, 25 and 51 ms. Gradient and shape is similar but y offset is shifted due to the lack of phase locking between the comb sources.

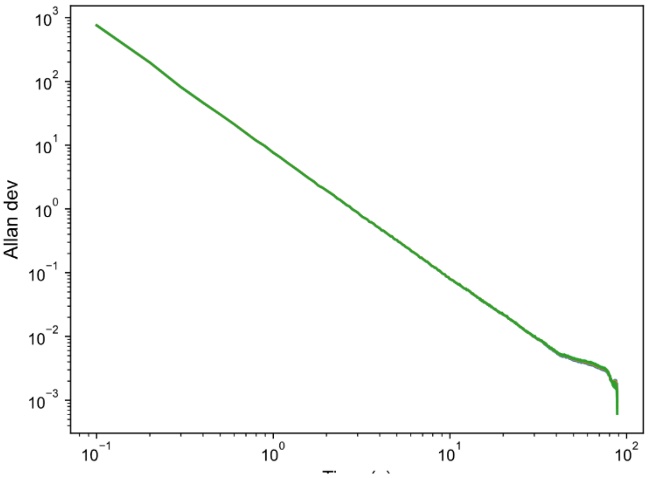

Figure 5: Allan deviation of phase measurements taken over 30 minutes.

4. CONCLUSION

The potential of a dual comb spectrometer for electron plasma density measurements for hot fusion reactions was shown. The capabilities of measuring phase were proven with precise phase measurements with parallel plane plates. Furthermore, the limits of this instrument were calculated and compared to real world scenarios.

Python scripts were designed to unwrap phase information from 0 - 2π to values greater than 2π to allow derivation of electron plasma density. This code was validated with measurements taken on a material with known transmission and phase spectrum.

The comparison between simulation and experimental data demonstrate the validity of the instrument in reliable phase measurements. The validating experiment consisted of two counter rotated parallel plates. This consisted of two ZnSe plates and later included an additional pair of CaF_2 plates. This experiment showed good correlation between the simulated and experimental results confirming this instrument's ability to measure the correct phase.

The limits of measurable electron plasma density were explored; the upper limit was bounded by both the fringe jump cut off density and the plasma cut off density at 1.3x10^{27} m^{-2} and 4.4x10^{23} m^{-2} respectively. The lower limit of plasma density value is determined by the phase measurements error and was estimated as 10^{17} m^{-2}. The error analysis showed that the lack of phase locking in the instrument does not impact the results of measurement for a duration of up to 30 minutes. These limits show that this instrument can work in hot fusion reactions which typically run at the plasma density of 10^{21} m^{-2}.

With the experiments outlined in this report a dual comb spectrometer has potential to work in a hot fusion reactors. The next step for this work is validation of the approach of in real world scenarios with hot plasma.

ACKNOWLEDGEMENTS

This project has been supported by UK Atomic Energy Authority through the Fusion Industry Programme. The Fusion Industry Programme is stimulating the growth of the UK fusion ecosystem and preparing it for future global fusion powerplant market. More information about the Fusion Industry Programme can be found online: https://ccfe.ukaea.uk/programmes/fusion-industry-programme/

REFERENCES

[1] - Hutchinson, I. H. (2002). Principles of Plasma Diagnostics: Second Edition. *Plasma Physics and Controlled Fusion*, *44*(12), 2603–2603. https://doi.org/10.1088/0741-3335/44/12/701

[2] - Lee, K. C., Juhn, J.-W., Nam, Y. U., Kim, Y. S., Wi, H. M., Kim, S. W., & Ghim, Y. -c. (2016). The design of two color interferometer system for the 3-dimensional analysis of plasma density evolution on KSTAR. *Fusion Engineering and Design*, *113*, 87–91. https://doi.org/10.1016/j.fusengdes.2016.10.008

[3] - Ivanenko, S. V., Solomakhin, A. l, Zubarev, P. V., Kvashnin, A. N., Kovalenko, Yu. V., Puryga, E. A., Solokha, V. V., Kurskiev, G. S., Zhiltsov, N. S., Shulyatiev, K. D., Khilchenko, A. D., Minaev, V. B., & Bagryansky, P. A. (2024). Dispersion interferometry diagnostic at Globus-M2. *Fusion Engineering and Design*, *202*, 114409. https://doi.org/10.1016/j.fusengdes.2024.114409

[4] - Arakawa, H., Tojo, H., Sasao, H., Kawano, Y., & Itami, K. (2014). A new method for determining the plasma electron density using optical frequency comb interferometer. *Review of Scientific Instruments*, *85*(4), 043508. https://doi.org/10.1063/1.4870925

[5] - Coddington, I., Newbury, N., & Swann, W. (2016). Dual-comb spectroscopy. *Optica*, *3*(4), 414–426. https://doi.org/10.1364/OPTICA.3.000414

[6] - Shevkunov, I., & Petrov, N. V. (2022). Phase Retardation Analysis in a Rotated Plane-Parallel Plate for Phase-Shifting Digital Holography. *Journal of Imaging*, *8*(4), 87. https://doi.org/10.3390/jimaging8040087

[7] - Gianella, M., Nataraj, A., Tuzson, B., Faist, J., & Emmenegger, L. (2020). High-Resolution and Gapless Dual Comb Spectroscopy with Current-Tuned Quantum Cascade Lasers. *2020 Conference on Lasers and Electro-Optics (CLEO)*, *28*(5), 1–2. https://doi.org/10.1364/OE.379790