Increased Sensitivity of Long Period Grating Hydrogen Sensors Through Coupling to Higher Order Cladding Modes

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1. Motivation

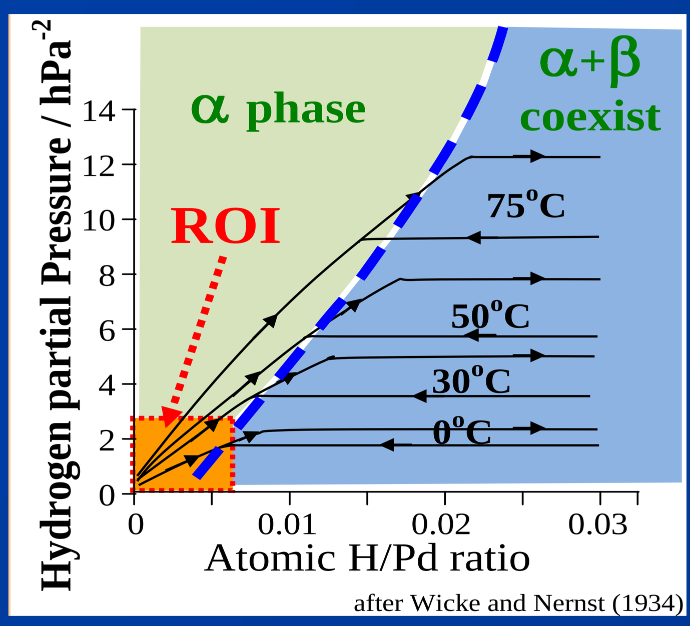
Reliable hydrogen detection technologies required for safety applications

- Hydrogen often suggested as future fuel source
- Hydrogen explosive at 4 - 97% in air
- Most systems based on the absorption of hydrogen in palladium
- Optical system preferable for safety reasons
  - No heating
  - No electrical currents
- LPG based hydrogen sensors demonstrated
  - Low responsivity
  - High order modes are more sensitive
- Increase in responsivity leads to decreased equipment cost/requirements
- AWE have a specific requirement:
  - Long term monitoring (>10yrs)
  - Hostile environment
  - Low hydrogen concentrations (<1.5%)
  - Long term fluctuations
  - Remote monitoring system
  - Selective to hydrogen
- Optical solution is preferred

2. Palladium (Pd) - Hydrogen

Palladium absorbs hydrogen readily

- Molecular hydrogen is dissociated on Pd surface
- Atomic hydrogen then absorbed into the lattice
- Hydrogen sits in interstitial lattice sites
- Essentially a non bonding process
- Provides a strain on the lattice
- Strain alters the electron bonds
- Gives a small change in refractive index

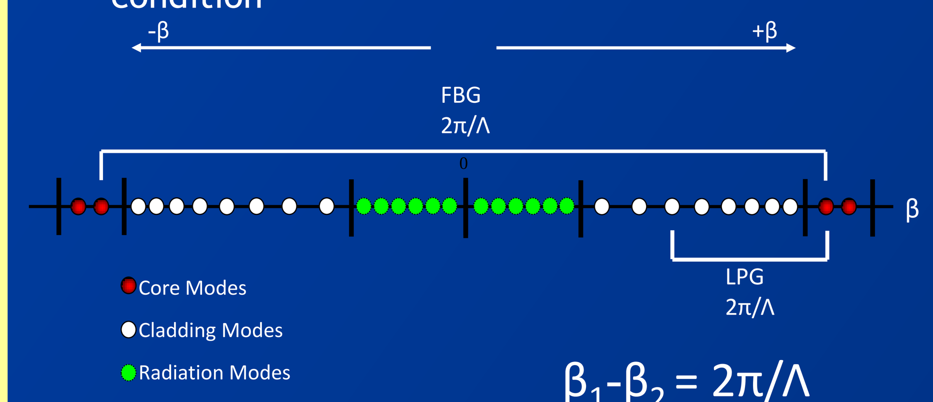


- At low concentrations (<4%) process is reversible
- At higher concentrations lattice phase shift proves destructive
- Most sensor systems based on the absorption of hydrogen in palladium

3. Long Period Gratings

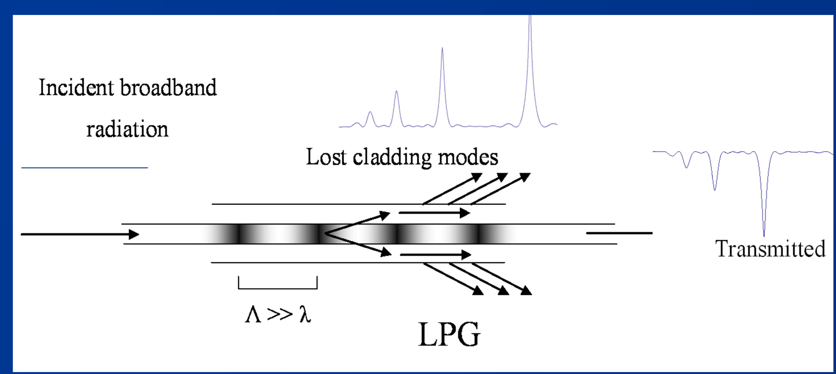
Similar structure to FBGs: a periodic change to the core refractive index

- Excites significantly different effects
- Modes are resonantly coupled via phase matching condition

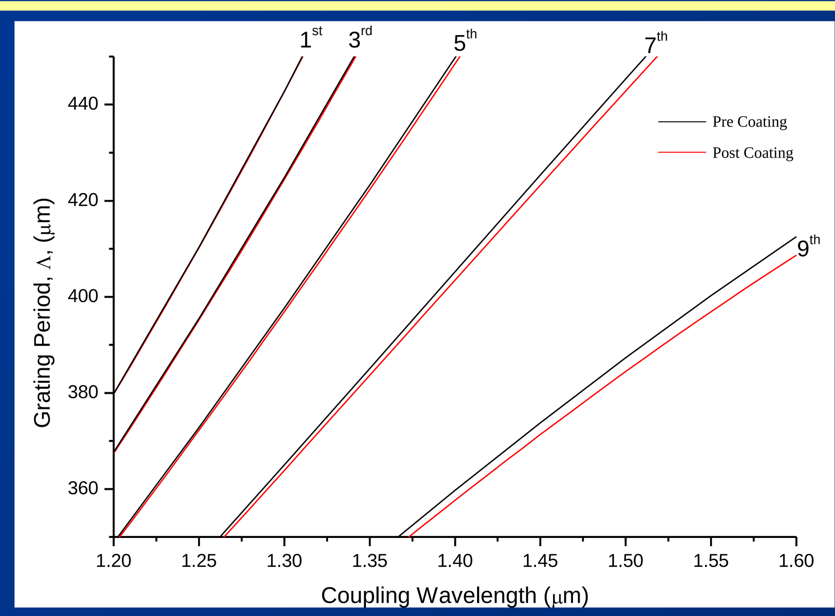


$$\beta_1 - \beta_2 = 2\pi/\Lambda$$

- Core mode is coupled into cladding modes
- Cladding modes non lossless, giving attenuation bands in transmission spectrum



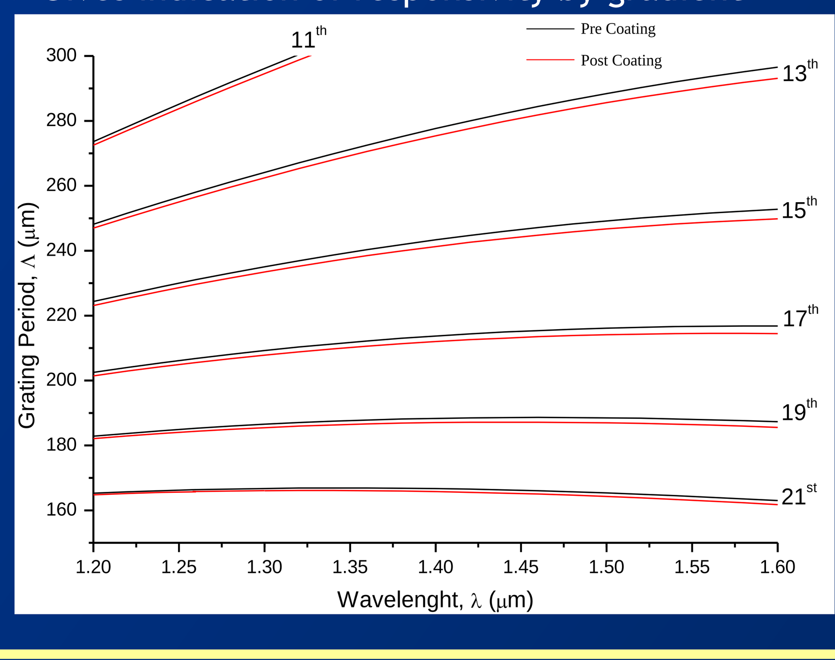
- Demonstrated sensitivity to strain, temperature, bend and <u>external refractive index</u>



- Standard Phase matching condition

$$\lambda_v = \Delta\,(n_{ec}(\lambda) - n_{ev}(\lambda))$$

- Gives indication of responsivity by gradient

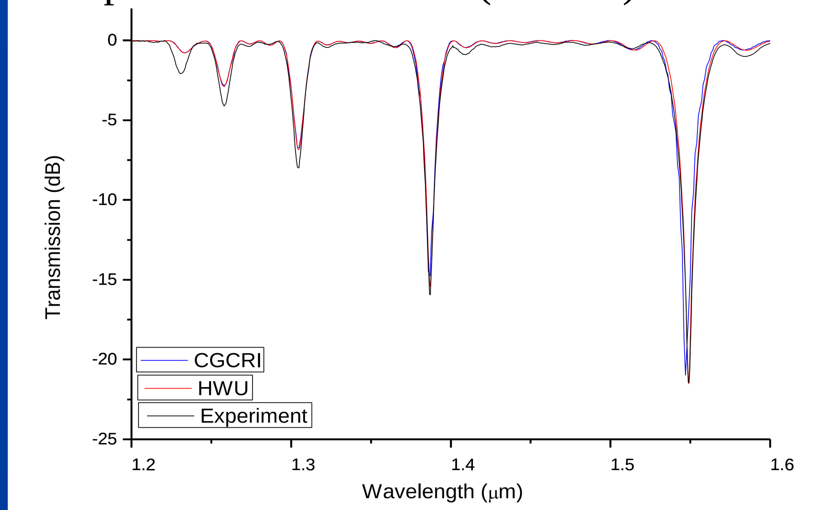


4. Modelling

Model developed at Heriot-Watt based on Erdogan*

- Model solves dispersion equations for available core and cladding modes
- Coupled mode theory then applied to determine the transmission spectrum
- Circularly symmetric 3 layer solution
- Model validated by comparing to independent CGCRI model based on matrix method

Modelled and experimental transmission spectrum of uncoated (air clad) LPG



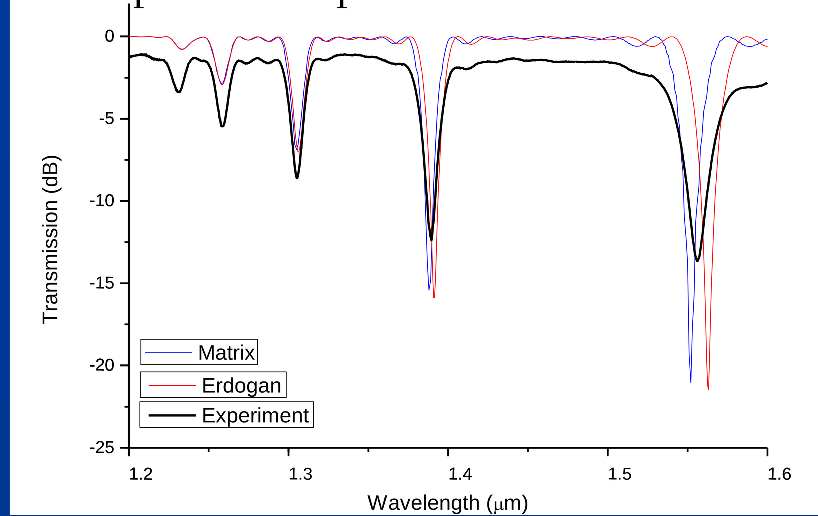
- Model accurately predicts resonant wavelengths
  - (to within 10^{-6} RIU)

T. Erdogan, "Cladding-mode resonances in short- and long-period fiber grating filters," Journal of the Optical Society of America A, 14(8), 1760-1773 (1997).
T. Erdogan, "Fiber grating spectra," Journal of Lightwave Technology, 15(8), 1277-1294 (1997).
T. Erdogan, "Cladding mode resonances in short- and long-period fibre grating filters: errata," Journal of the Optical Society of America A, 17(11), 2113 (2000).

Erdogan Model not applicable to metal jacketed case

- Total internal reflection index guiding replaced by reflective layer
- External refractive index larger than cladding
- Necessary to re-evaluate Erdogan's assumptions

Modelled and experimental transmission spectrum of palladium coated LPG

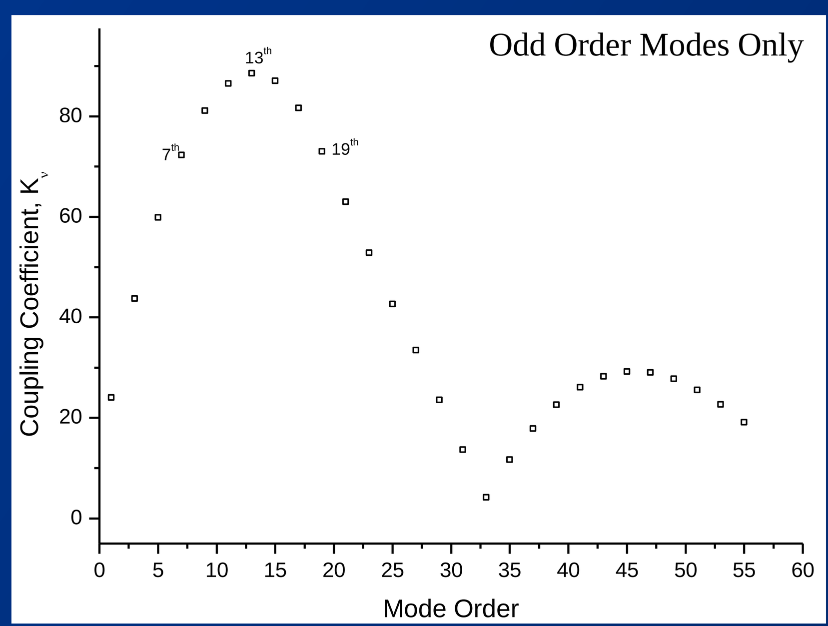


- Returned to the general case outlined by Tsao*
- No alteration of LPG structure
- Retain circular symmetry
- Pd refractive index determined through ellipsometry*
- Effective refractive index of cladding modes experimentally verified to remain lower than the cladding index despite metal layer

C. Tsao, [Optical fibre waveguide analysis] Oxford University Press, (1992).
R. M. Carter, P. Morrall, R. R. J. Maier *et al.*, [Optical characterisation of RF sputter coated palladium thin films for hydrogen sensing] Spie-Int Soc Optical Engineering, Bellingham(2011).

Phase matching curves combined with couplings coefficients suggest sensitive modes

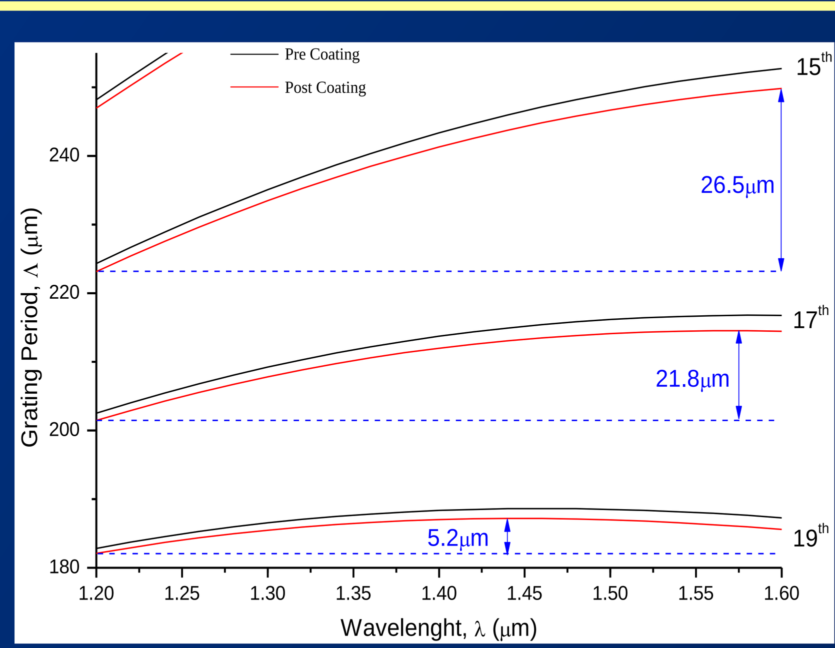
- Phase match plots indicate higher sensitivity (flatter curves) to the phase match turning point
- Higher order modes are not necessarily useful
- Necessary to determine the coupling coefficients in the presence of palladium



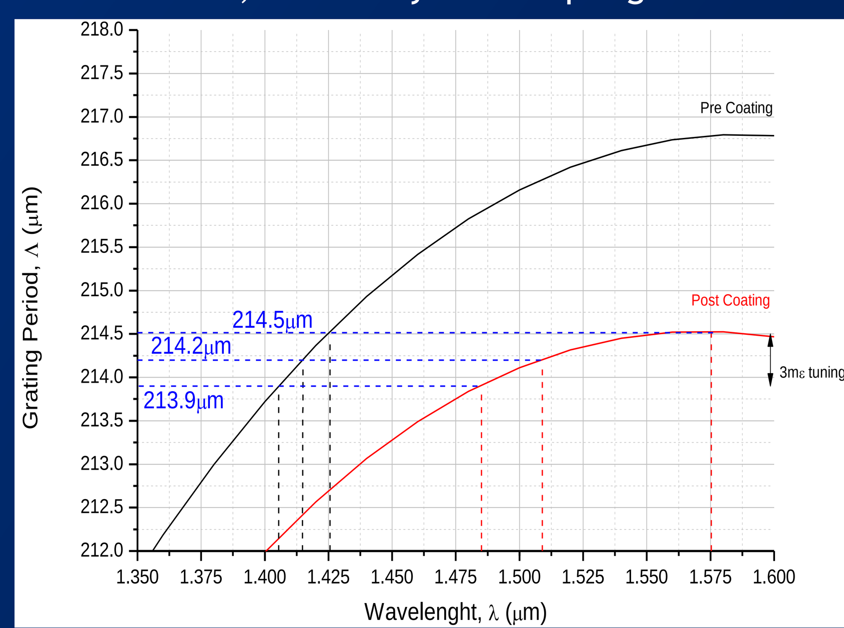
- Coupling coefficients remain high to the ~19th order
- Phase matching curves suggest highest sensitivity at 19th-21st order modes

Practical consideration of inscription must be taken into account

- Higher order modes give flat resonances
  - Easy to miss intended resonance conditions



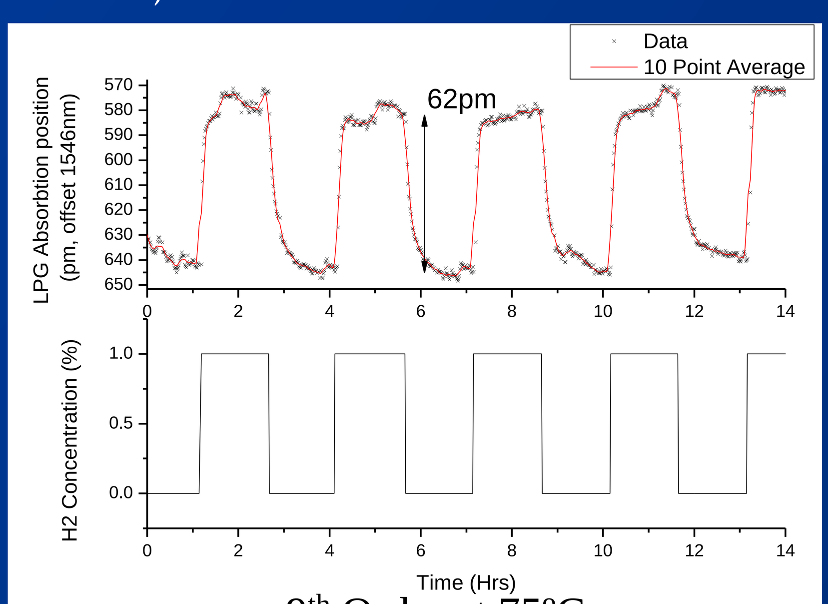
- Difference between pre and post coated spectrum makes inscription to exact specifications challenging
- Slightly lower order modes are preferable for manufacture, sensitivity and coupling coefficient



5. Results

Early results show small response for low order modes

- Early experiments focused on lower order modes
- Efforts made to characterise Pd thin films and LPGs separately
- 9th order shows 62pm shift to 1% H_2 (20nm feature)

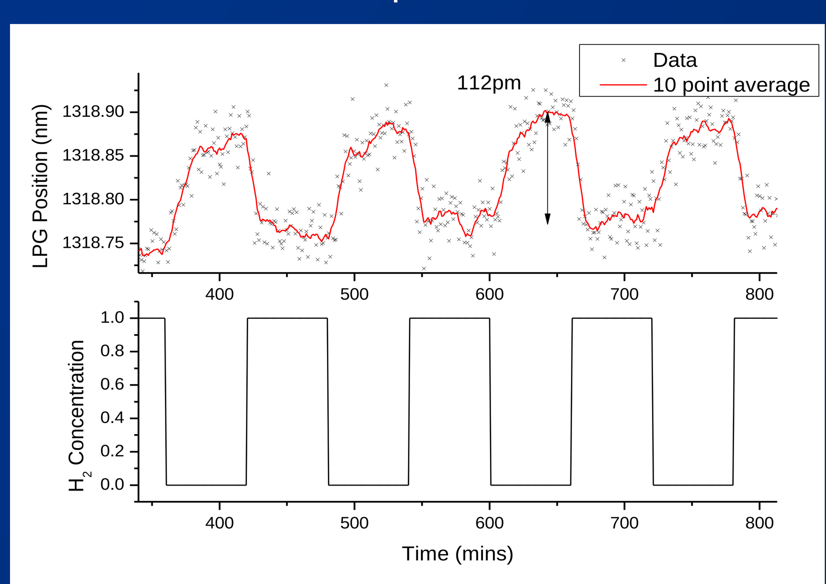


9th Order at 75°C

- Small shift is very challenging to measure
  - Requires expensive equipment
  - Long scan times
- System highly temperature dependant
- Relatively slow response (~1hr-2hrs)
- Experiments moved on to modelling complete LPG-Pd system
  - Higher order modes identified as more attractive sensor elements

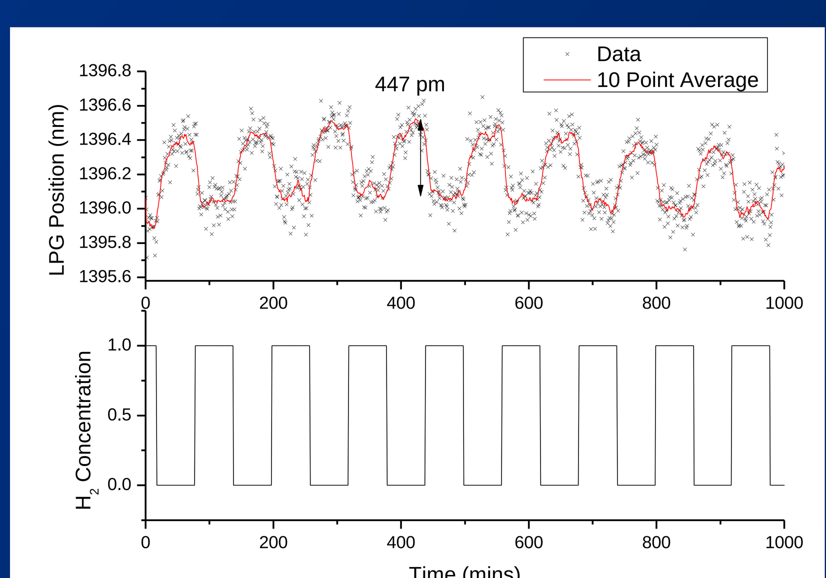
As expected higher order mode demonstrates improved response

- 15th order shows ~112pm to 1%



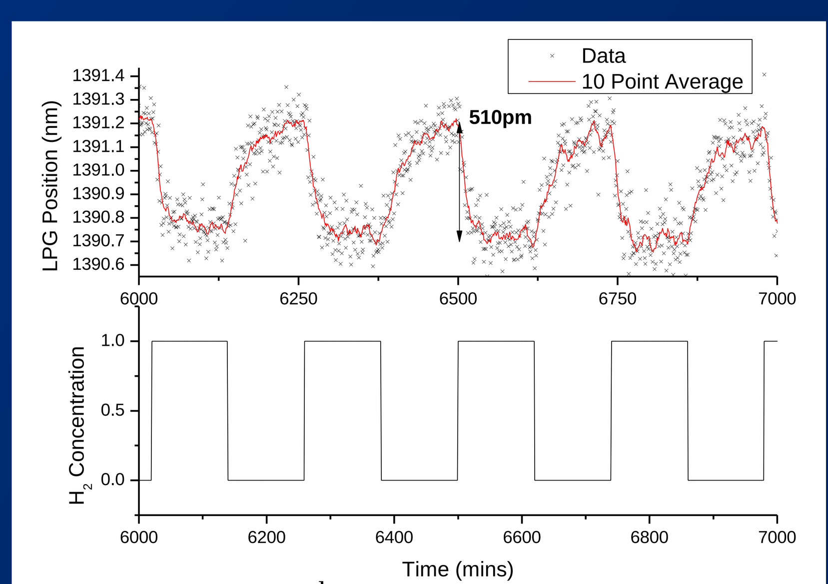
15th Order at 70ºC

- 17th order shows ~447pm to 1%



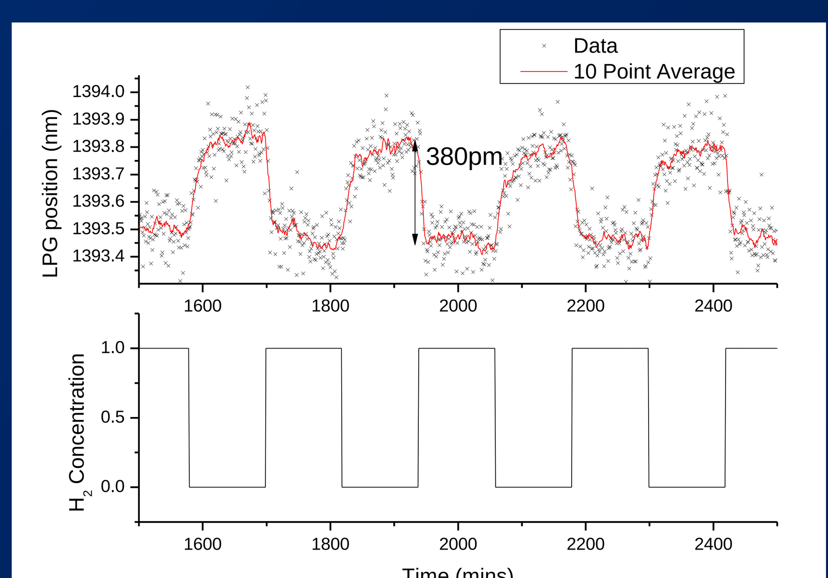
17th Order at 70ºC

Temperature affects response



17th Order at 25ºC

- Lower temperature gives larger but slower response
- Cycling time too short for equilibrium in this case
- Thermal noise scales with response



17th Order at 50ºC

6. Conclusions

High mode order LPG-Pd sensors were investigated

- Analysis of the full dispersive solutions to the modelling of metal jacketed LPGs has been carried out
- High sensitivity and coupling coefficient designs have been calculated
- A range of high mode order LPG elements were manufactured by the CGCRI

High sensitivity sensors have been demonstrated

- 17th order LPG sensor has been demonstrated with 7 times responsivity of 9th order
- Scale and speed of response dependant on temperature
- Thermal sensitivity (noise) scales with sensitivity to external environment
  - No improvement in signal to noise ratio
  - Improvement in absolute response
- Thermal insensitivity/compensation requires further research

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