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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
- Optical system preferable for safety reasons
- No heating
- ➤ No electrical currents

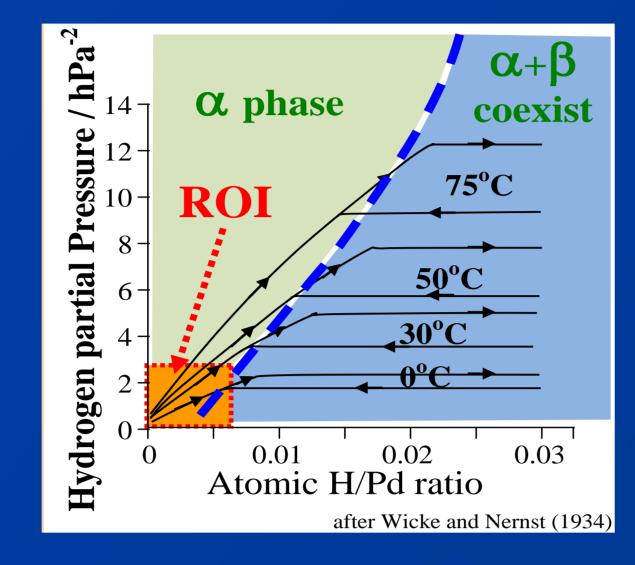
hydrogen in palladium

- LPG based hydrogen sensors demonstratedLow 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 fluctuationsRemote 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 latticeHydrogen sits in interstitial lattice sites
- Fesentially a non-honding process
- Essentially a non bonding process
- Provides a strain on the lattice
- Strain alters the electron bonds
- > Gives a small change in refractive index

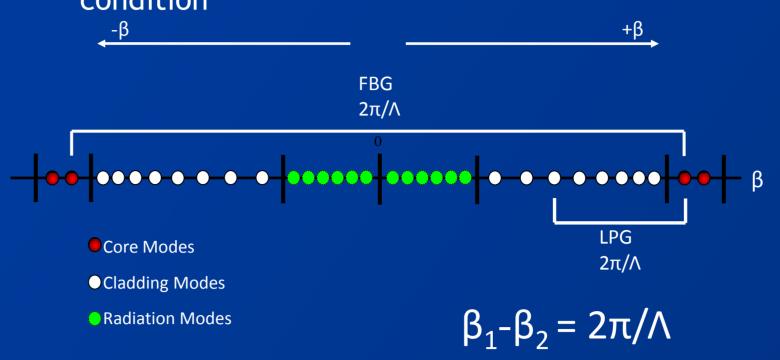


- At low concentrations (<4%) process is reversible
 At higher concentrations lattice phase shift proves destructive
- Most sensor systems based on the absorption of hydrogen in palladium

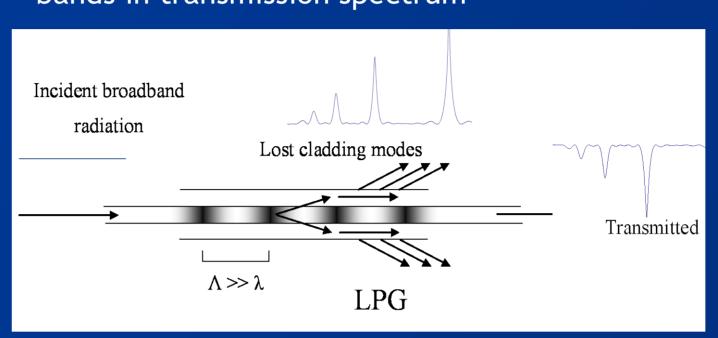
3. Long Period Gratings

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

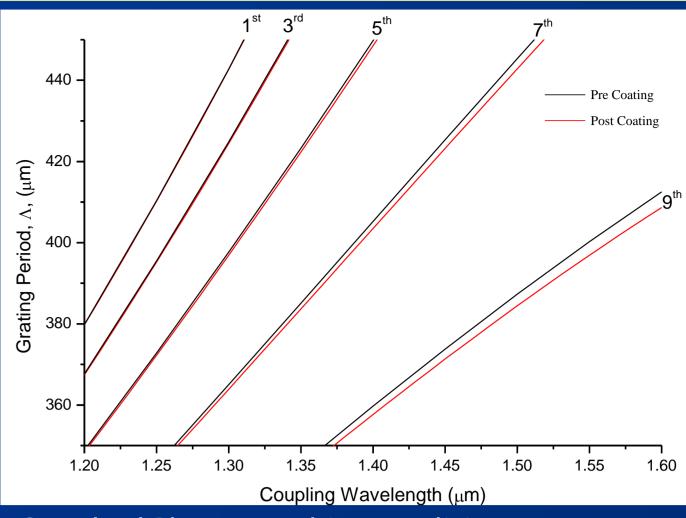
- >Excites significantly different effects
- Modes are resonantly coupled via phase matching condition



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



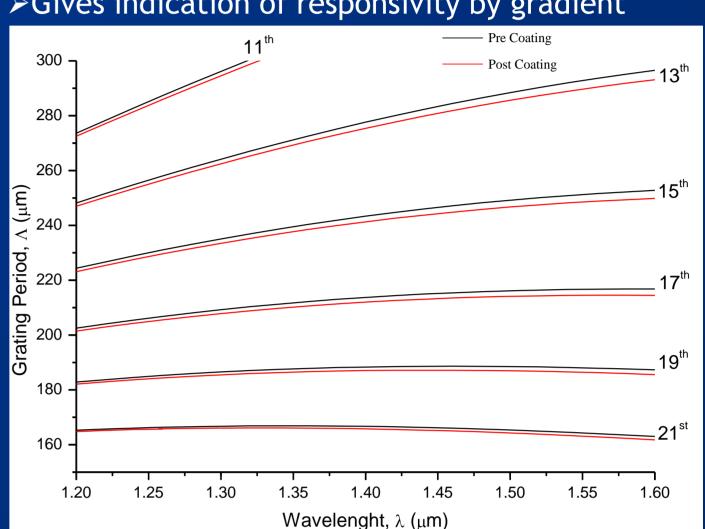
➤ Demonstrated sensitivity to strain, temperature, bend and <u>external refractive index</u>



➤ Standard Phase matching condition

$$\lambda_{v} = \Delta \left(n_{ec}(\lambda) - n_{ev}(\lambda) \right)$$

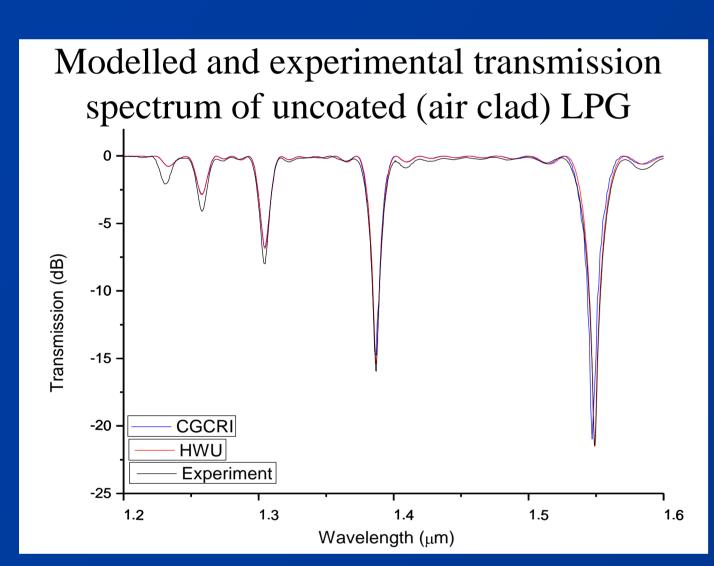
>Gives indication of responsivity by gradient



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



➤ 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).

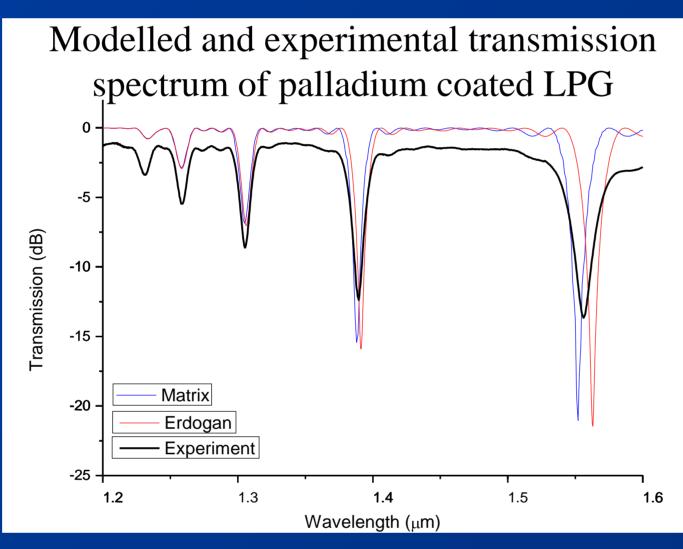
T. Erdogan, "Fiber grating spectra," Journal of Lightwave Technology, 15(8), 1277-1294 (1997).

(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

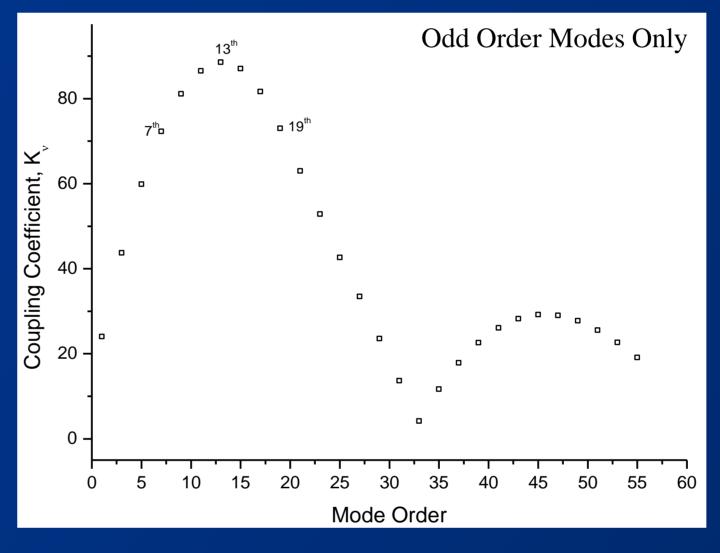


- Returned to the general case outlined by Tsao*
- ➤ No alteration of LPG structure
- > Retain circular symmetry
- ➤Pd refractive index determined through ellipsometry*
- Effective refractive index of cladding modes experimentally verified to remain lower than the cladding index despite metal layer

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

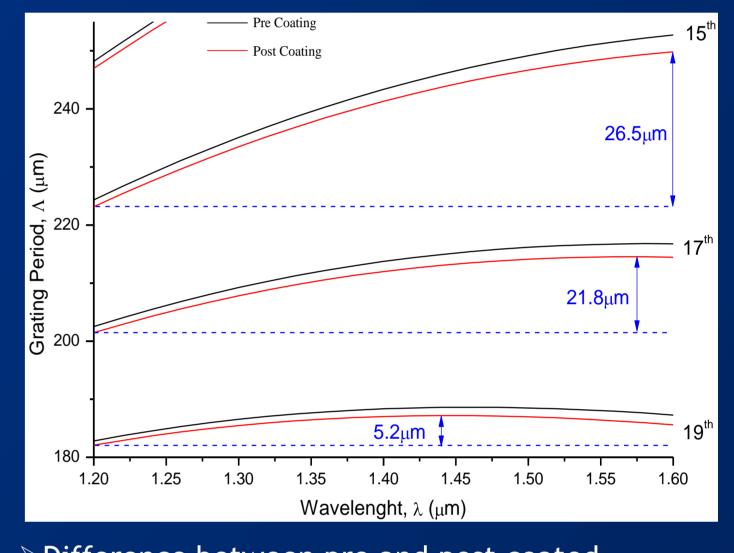
- ➤ Phase match plots indicate higher sensitivity (flatter curves) to the phase match turning point
- Higher order modes are not necessarily useful
 Necessary to determine the coupling coefficients
- in the presence of palladium



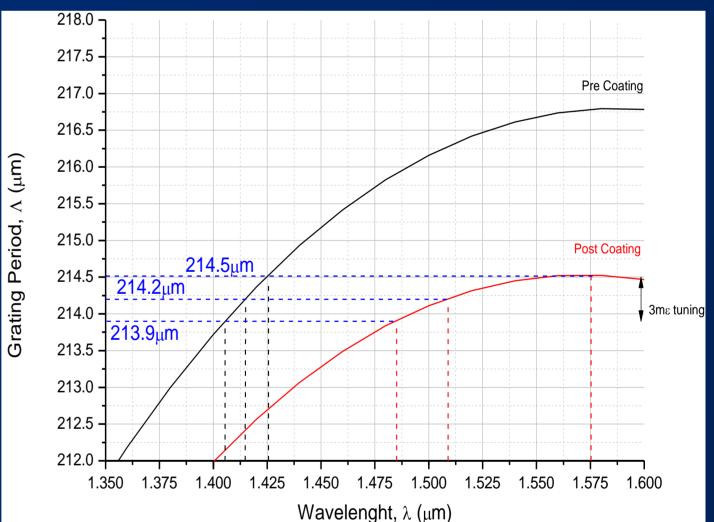
- Coupling coefficients remain high to the ~19th order
- ➤ Phase matching curves suggest highest sensitivity at 19th-21st order modes

Practical consideration of inscription must be taken into account

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



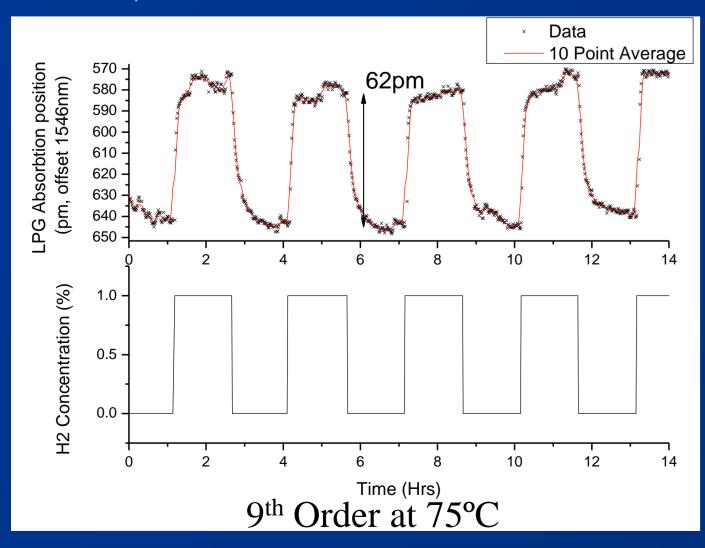
- Difference between pre and post coated spectrum makes inscription to exact specifications challenging
- Slightly lower order modes are preferable for manufacture, sensitivity and coupling coefficient



5. Results

Early results show small response for low order modes

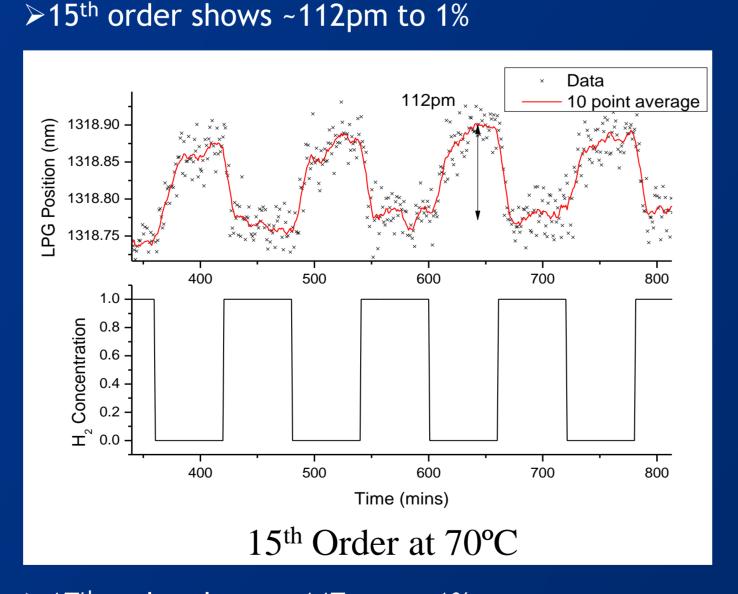
- ►Early experiments focused on lower order modes►Efforts made to characterise Pd thin films and
- LPGs separately ▶9th order shows 62pm shift to 1% H₂ (20nm feature)



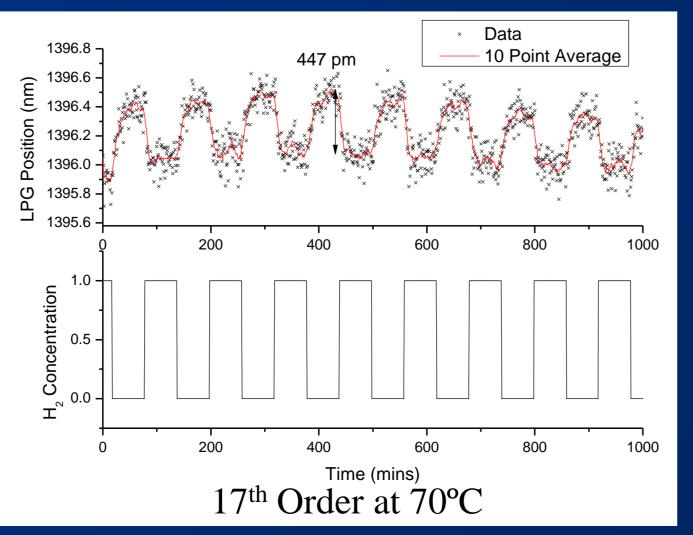
➤ Small shift is very challenging to measure
 ➤ Requires expensive equipment
 ➤ Long scan times
 ➤ System highly temperature dependant

- ➤ Relatively slow response (~1hr-2hrs)
- Experiments moved on to modelling complete LPG-Pd system
 - ➤ Higher order modes identified as more attractive sensor elements

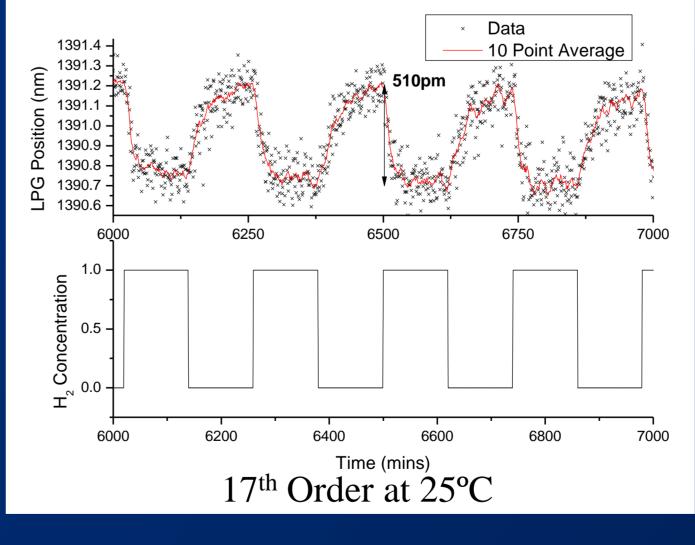
As expected higher order mode demonstrates improved response



➤17th order shows ~447pm to 1%



Temperature affects response



- Lower temperature gives larger but slower response
 Cycling time too short for equilibrium in this case
 Thermal noise scales with response
 - 1394.0 1393.9 1393.7 1393.4 1600 1800 2000 2200 2400 17th Order at 50°C

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
- 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



