Hollow Waveguide (HWG) Optical PCB Technology for EO Instrumentation

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07/09/11

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Background

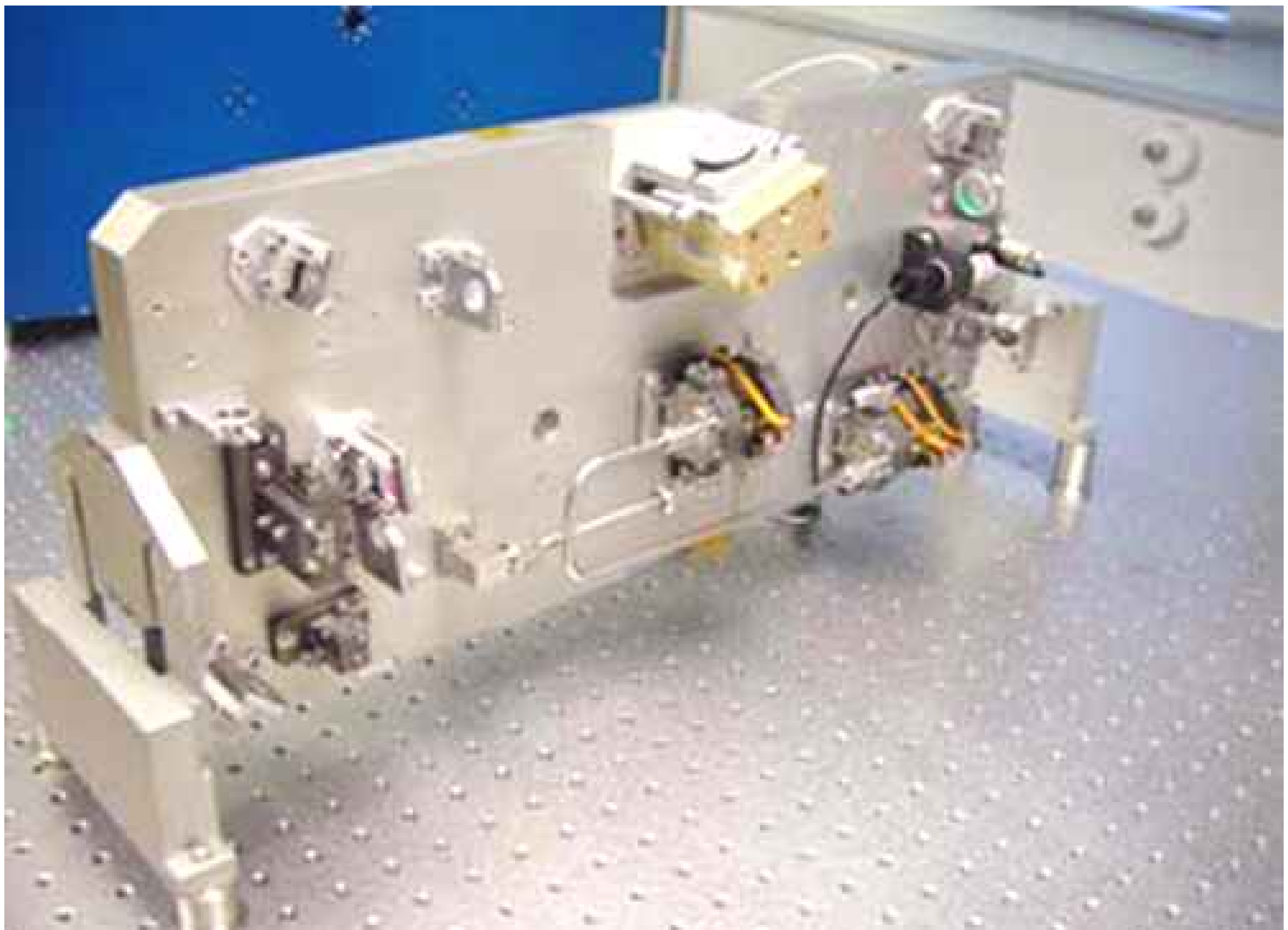
- **Conventional optical and laser systems are**
  - Bulky and heavy
  - Difficult to align, and keep aligned, for optimum performance
  - Expensive to manufacture
- **For EO Instrument key constraints are:**
  - Weight and size
  - Robustness to optical misalignment in space flight environments
  - Optical efficiency
  - Cost
- **Goal**

  More compact, optically robust, lower mass, lower cost systems with improved optical performance – demonstrate feasibility in practice with an hollow waveguide based optical PCB approach

Example of Current Lidar Technology

Centre for eo Instrumentation

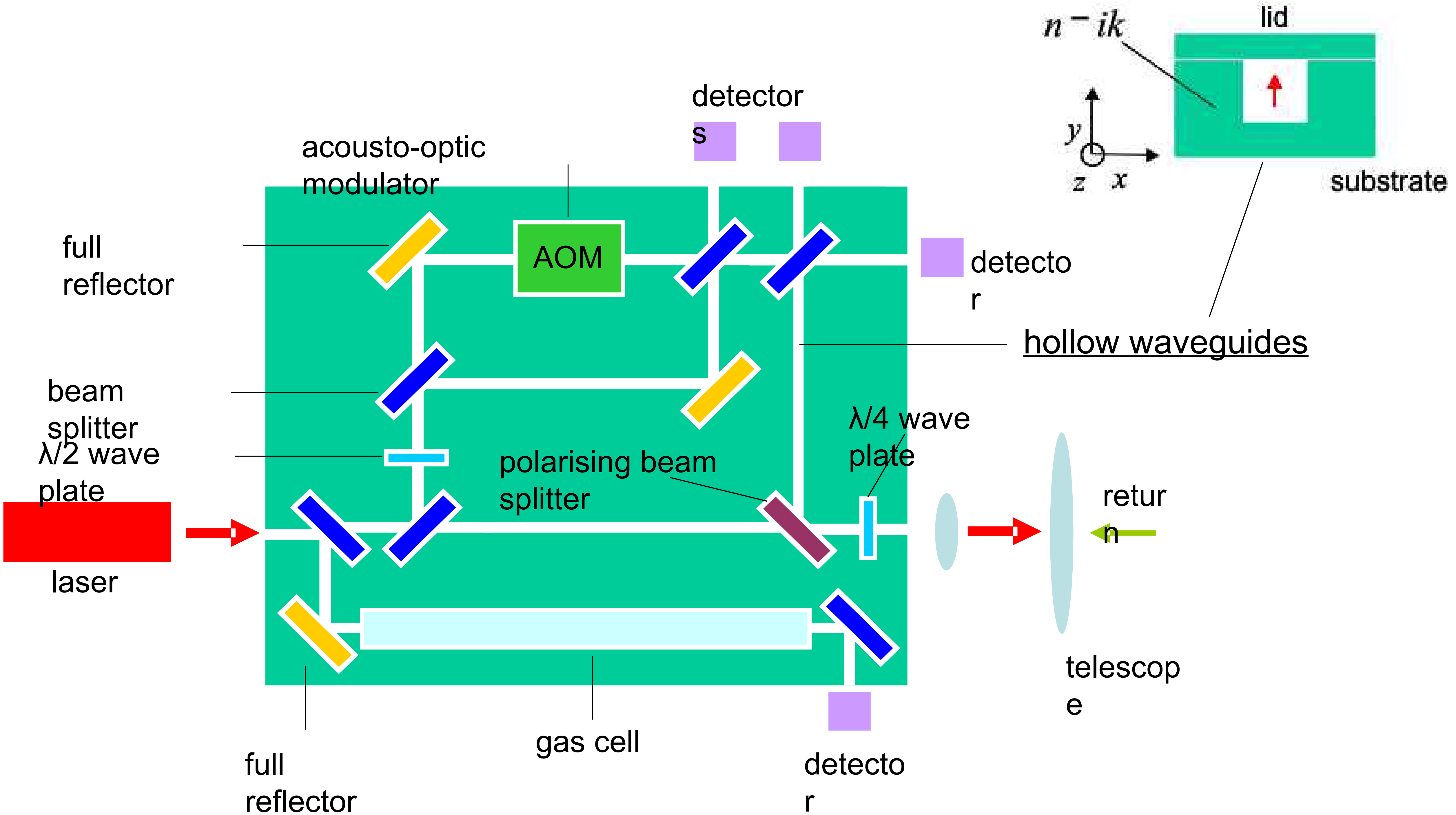
Michael Kavaya, NASA Langley RC - Compact 2.0 ≅ m Laser Transceiver



Abstract

NASA Langley Research Center (LaRC) is engaged in the development and demonstration of a Differential Absorption Lidar (DIAL) / Integrated Path Differential Absorption (IPDA) instrument to make precise, high-resolution CO_2 measurements to investigate sources, sinks, and fluxes of CO_2. This laser transceiver will feature performance characteristics needed for an ASCENDS system that will be capable of delivering the CO_2 measurement precision required by the Earth Science Decadal Survey (DS).

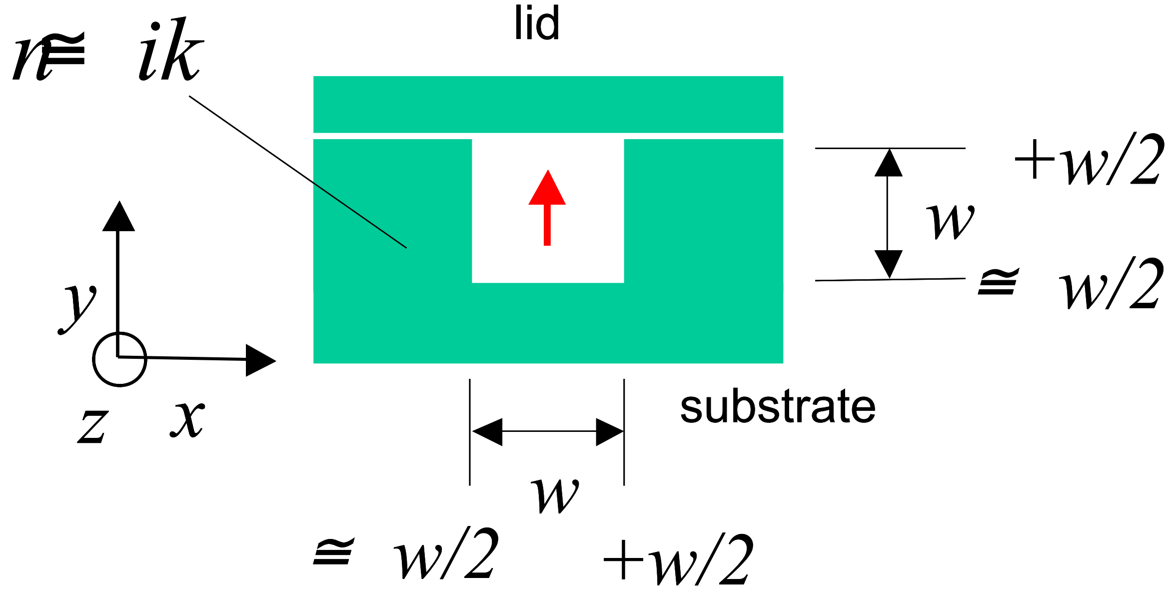
2.05 μm Hollow Waveguide DIAL Demonstrator

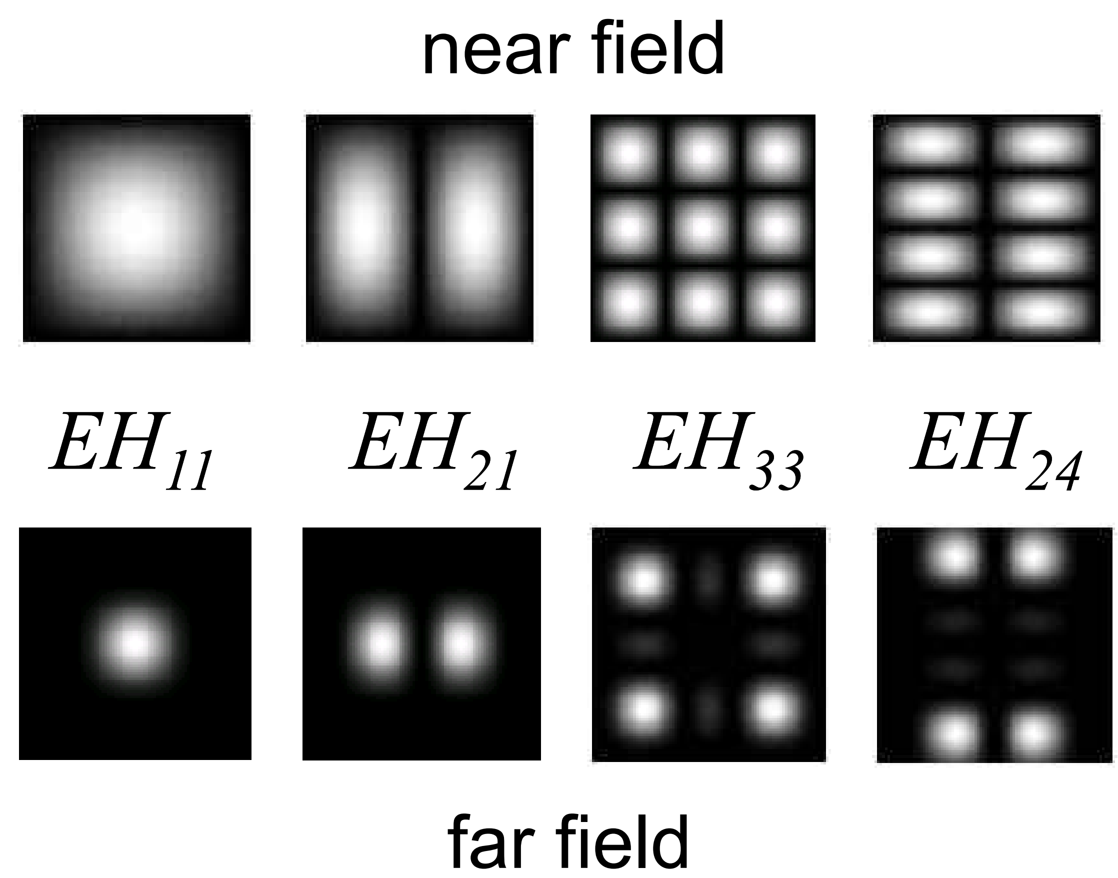


Advantages of hollow waveguides

- Broad waveband high power transmission characteristics, c.f. solid core waveguides and fibres
- Easier angular alignment tolerances, c.f. free-space
- No optical interface – no AR coatings or index matching gel - easy to integrate any required discrete component
- No beam diffraction - small/fixed beam diameter, smaller foot-print circuits
- No need for bulky, optically unstable, high cost mounts
- Compact, rugged, low cost systems, very good optical performance
- The optical equivalent of the electronic PCB

Hollow Waveguide Propagation Theory

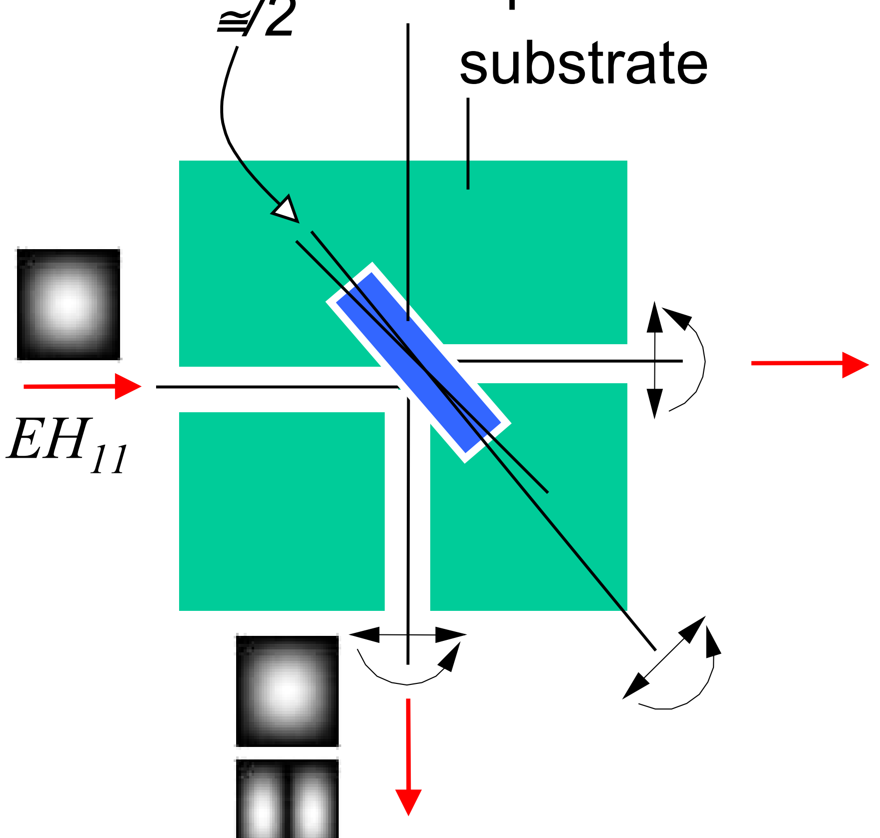




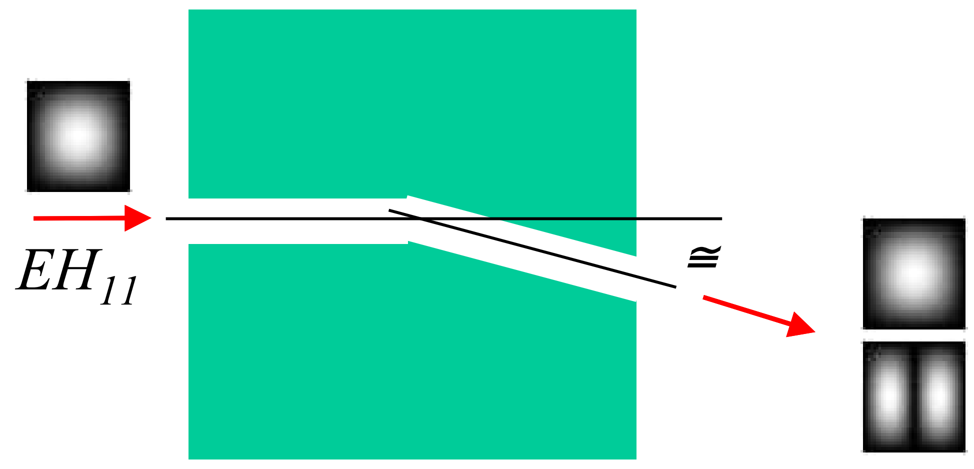
attenuation coefficients depend on wavelength, guide width and wall index

$$\alpha_{pq} = \frac{\lambda^2}{w^3}\left[p^2 \mathrm{Re}\left(\frac{1}{\left[(n-ik)^2-1\right]^{1/2}}\right) + q^2 \mathrm{Re}\left(\frac{(n-ik)^2}{\left[(n-ik)^2-1\right]^{1/2}}\right)\right]$$

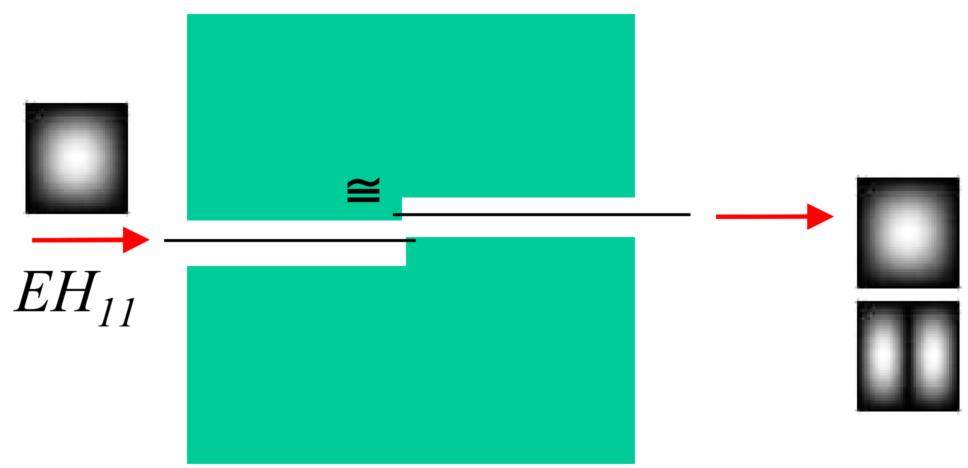
Alignment tolerances



angular misalignment



lateral misalignment

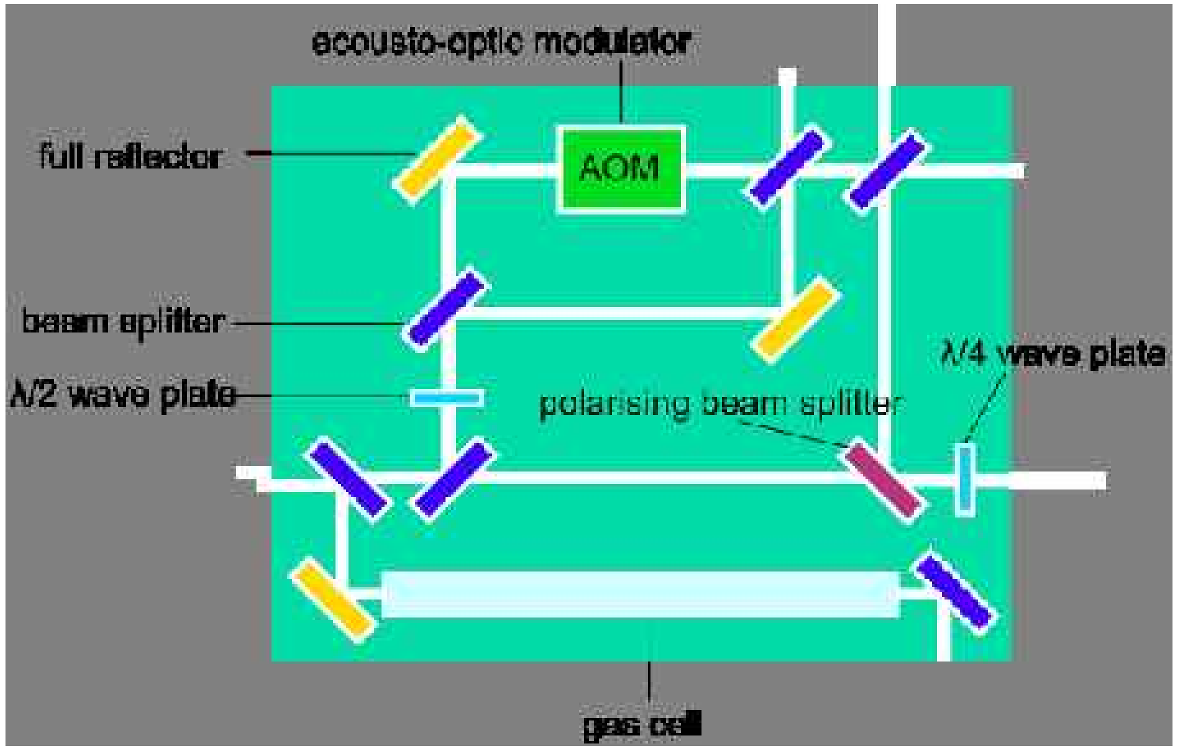


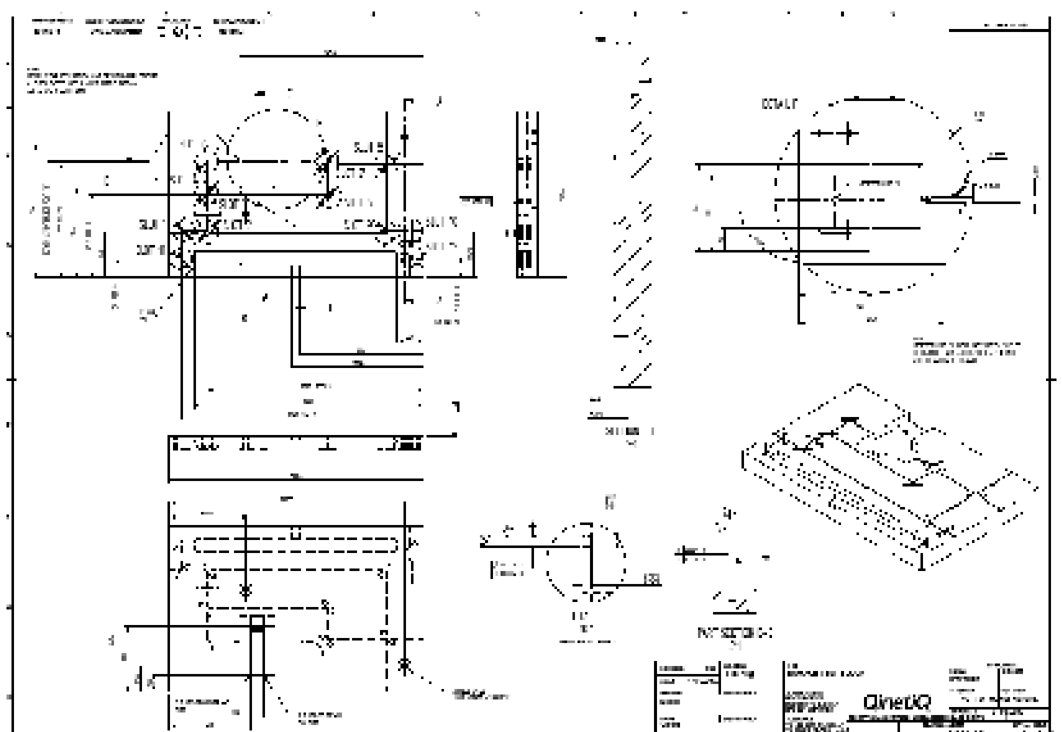
design criteria

$$\cong \cong \frac{\cong}{5w}$$

$$\cong \cong \frac{w}{15}$$

Design and Manufacture





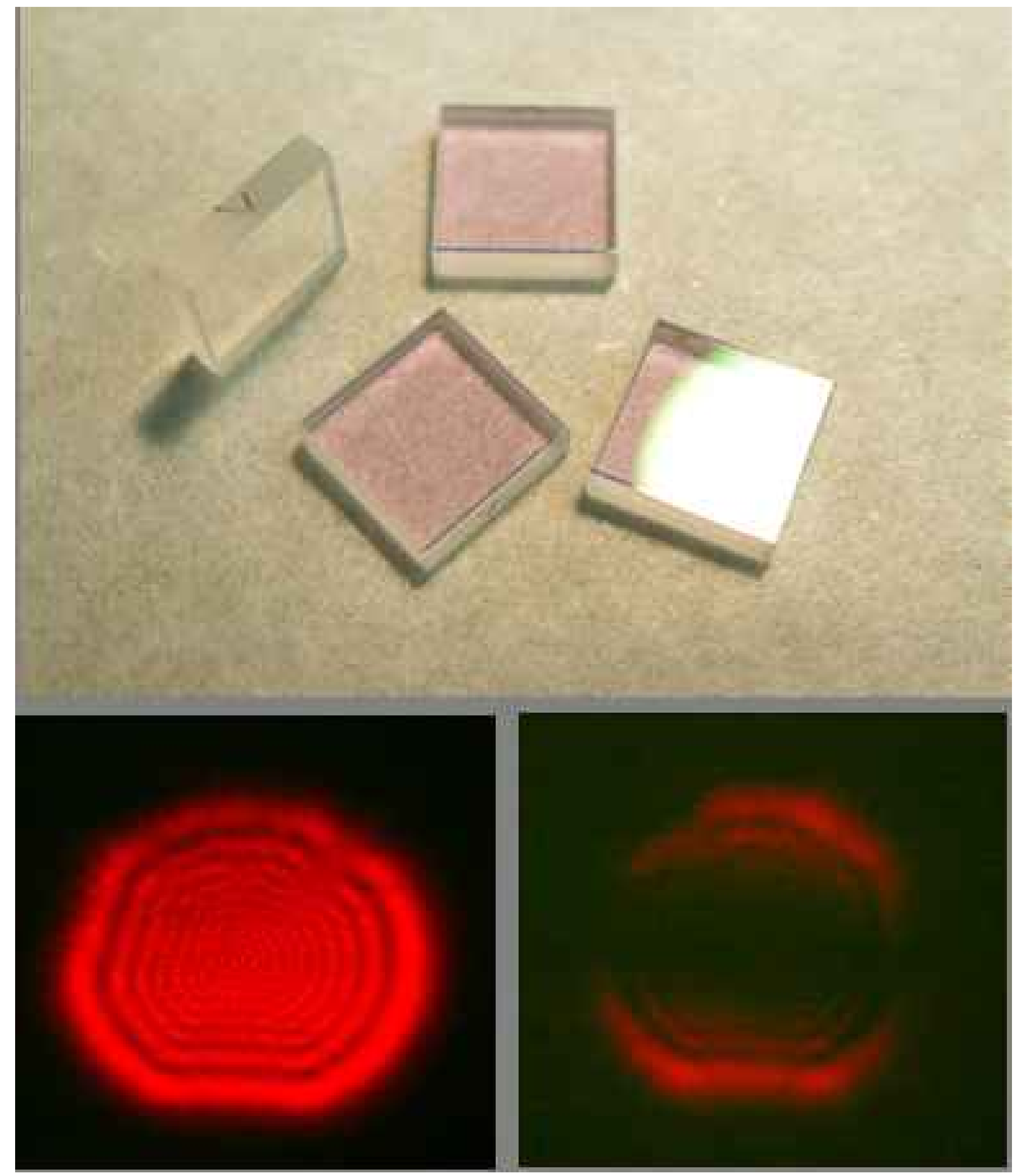
Optical circuit component specifications

- Optical components procured for both the DIAL circuit and damage test work

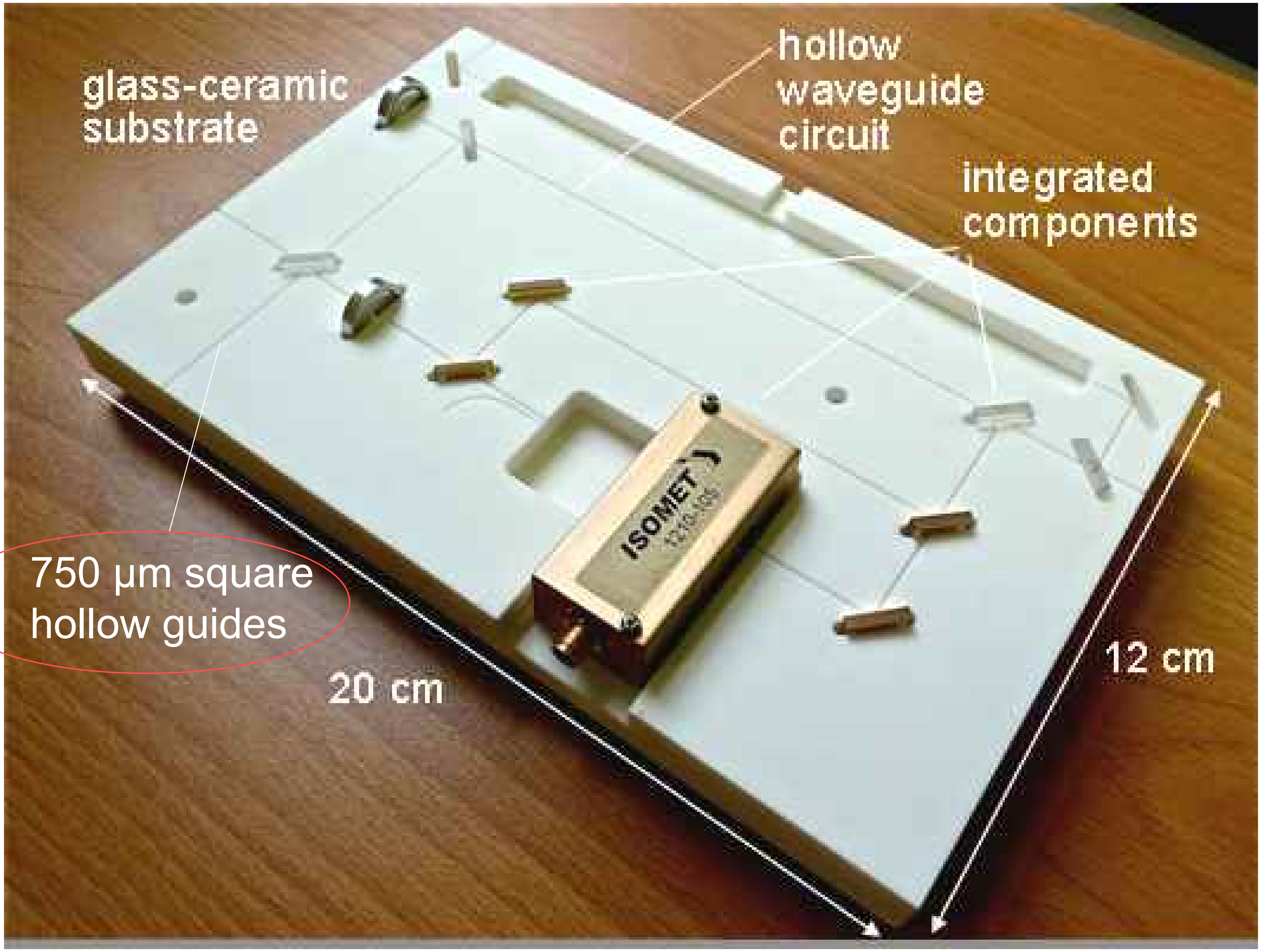
- 12 mm cross-section components have been selected - trade off between
  - Easing angular alignment tolerances
  - Maintaining a compact and lightweight breadboard

- Custom manufactured components
  - High parallelism between front and back surface
    - Better than 25 μradians
  - Chamfered edges to ease circuit assembly

- Theoretical modelling presented previously indicates that excellent transmission fidelity should be achievable

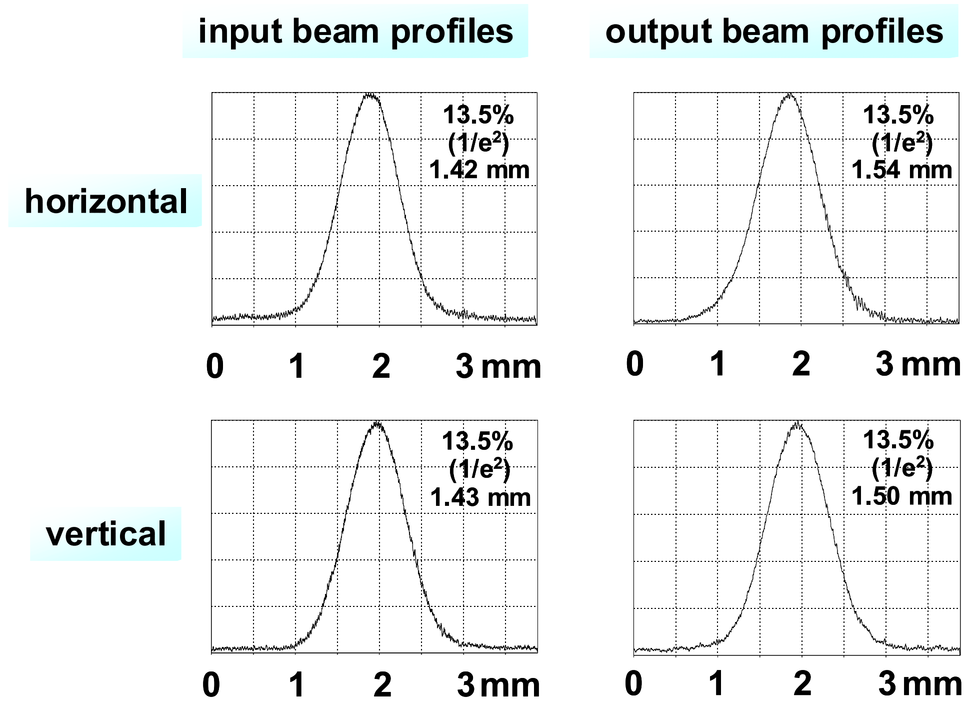


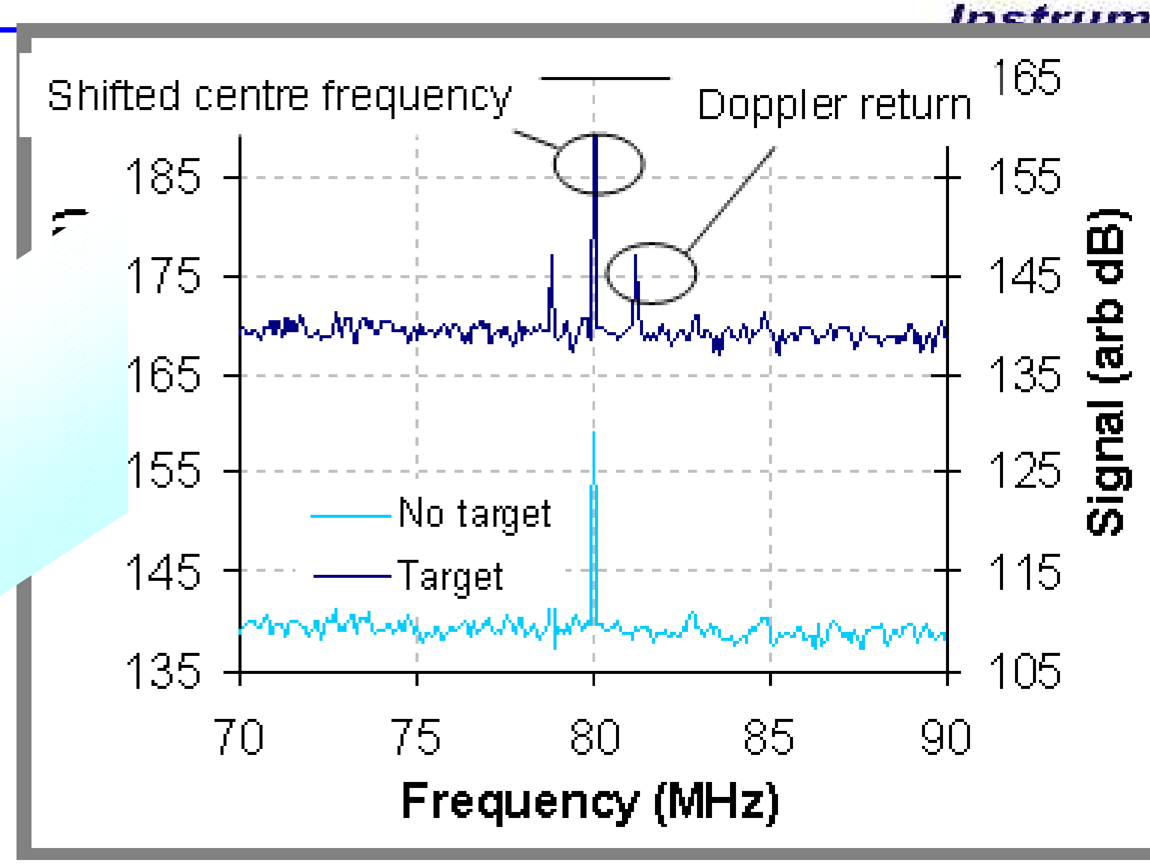
Partially Assembled 2.05 µm System



Hollow waveguide optical circuit board for 2.05 µm DIAL demonstrator formed in machineable-glass ceramic (Macor) substrate using precison CNC milling techniques - note range of components in alignment slots – beam splitters/combiners, wave plates, modulator etc

Assessment of DIAL Demonstrator





Environmental Tests

Vibration
30 g rms

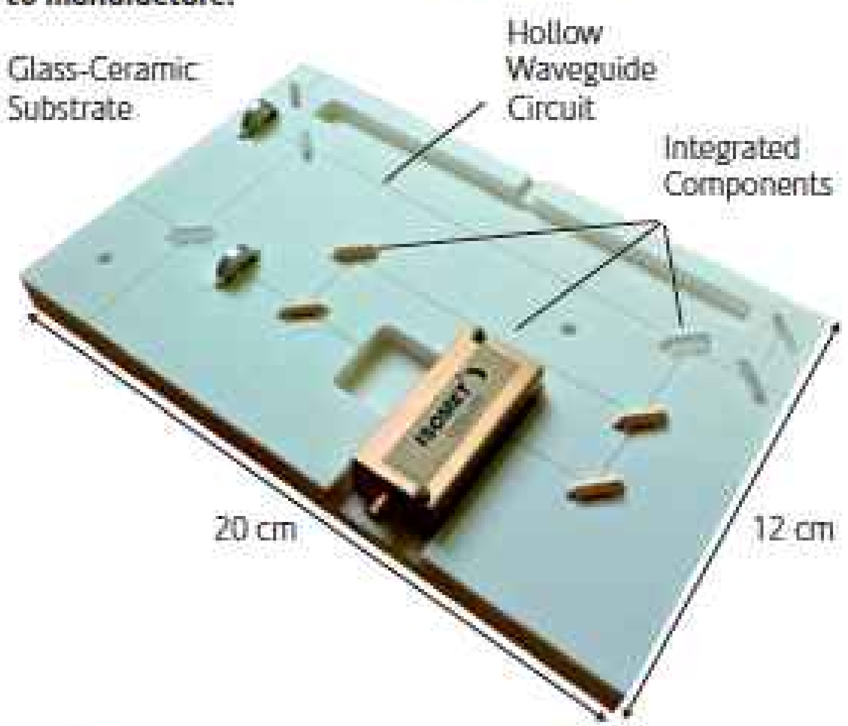
Temperature
cycling -45ºC – 80ºC

Shock
far field shock of 200 g

Measured Heterodyne Mixing efficiency	Precision slot	Sprung slot	Precision slot fixed component
Before vibration	96 %	82 %	96 %
After vibration	94 %	80 %	96 %

Technology Could Revolutionise Optical and Laser Systems

A new optical circuit board technology developed as part of a project funded by the Centre for Earth Observation Instrumentation (CEOI) has the potential to significantly improve the performance of optical circuits. It can also make them more rugged, more compact and much cheaper to manufacture.



A high performance, compact, rugged, differential adsorption lidar (DIAL) system for measurement of atmospheric CO_2 based on a hollow waveguide optical circuit board approach.

The hollow waveguide (HWG) based optical circuit board technology was originally invented by QinetiQ. In collaboration with the University of Leicester, University College London and the Centre for Terrestrial Carbon Dynamics, the technology was further developed to demonstrate a miniaturised laser spectrometer system for the measurement of atmospheric carbon dioxide - a critical greenhouse gas pollutant associated with global warming. In addition to the successful development of the technology, the project also highlighted its potential for a very wide range of laser and optics based space instruments both for Earth Science and Planetary Exploration.

Manufacturing advantage

The approach represents the optical equivalent of the electronic printed circuit board. An innovative manufacturing approach, in conjunction with automatic pick-and-place equipment, could lead to high volume low cost mass production of a very wide range of integrated optic sensors.

The HWG circuit board also has a number of advantages compared with conventional solid core integrated circuits. The hollow core has very broad waveband, high power, transmission characteristics and the fact that there is no refractive index step to bridge means discrete components can be easily integrated. The hollow core can also provide the basis of flow cells for the analysis of gases and liquids using absorption, spectroscopic and interferometric techniques.

Disruptive technology

Current optical circuit manufacturing techniques lead to instruments which are bulky, sensitive to misalignment, and are expensive to manufacture. The advantages of the HWG optical circuit board technology, are that they can lead to optical and laser systems which are more compact, more rugged and much cheaper to manufacture.

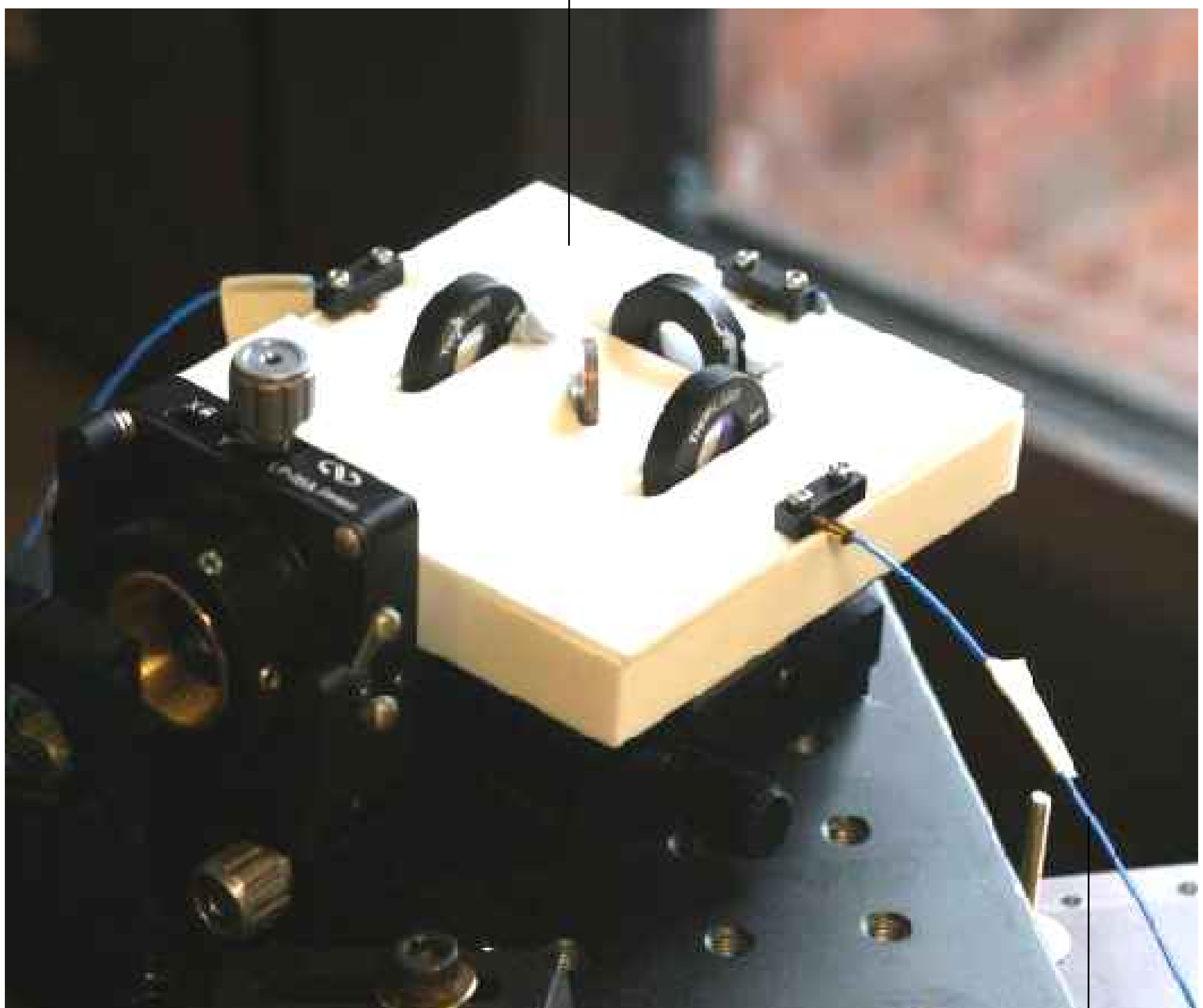
HWG optical PCBs also provide an integration platform for a very wide range of discrete optical and micro-optical components of both an active and passive nature. These include, beam splitters, lenses, waveplates, polarisers, absorption cells, lasers, amplifiers, detectors, modulators etc. These will enable the realisation of integrated systems for a diverse range of applications in the fields of space, environment, health, security and defence, including:

- *Spectrometers, interferometers and radiometers for earth science and planetary exploration*
- *Laser radars, including lidar-on-a-chip based on hollow silicon technology for space and defence applications*
- *Biochemical sensors, including lab-on-a-chip for DNA analysis, for health, defence and pharmaceutical development*
- *Gas sensors and fluid sensors for environmental and industrial monitoring and health care*
- *Telecomms modules based on micro-optical components integrated on fibre pig-tailed hollow waveguide optical circuit boards*
- *Generic optical test and measurement instrumentation*

Further information about this technology and others funded by the CEOI can be found at www.ceoi.ac.uk. You can also contact the Project Lead - Professor R Mike Jenkins tel: +44 (0) 1684-895084, email: rmjenkins@qinetiq.com, Dr Brian J Perrett, tel: +44 (0) 1684-895788, email: bjperrett@qinetiq.com or the CEOI Director, Professor Mick Johnson: Tel: +44(0)1438 774421, email: mick.johnson@astrium.eads.net.

Fibre interfaced HWG Macor subsystem

hollow waveguide (HWG) Macor subsystem

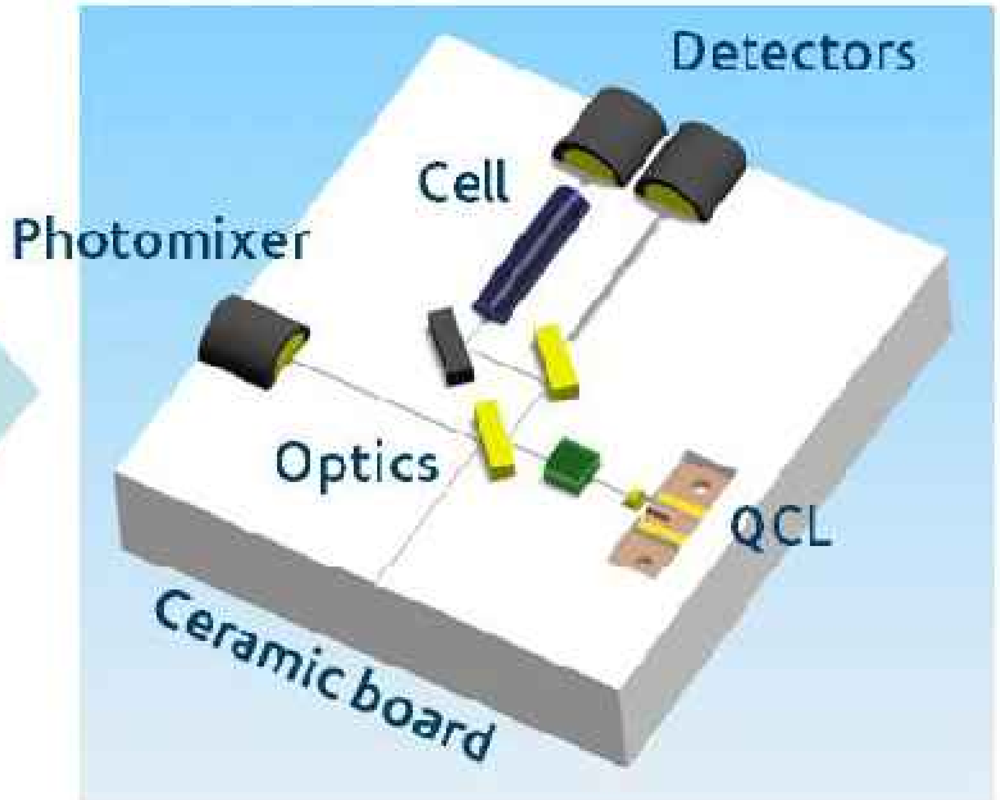


Demonstration of fibre interfacing of a hollow waveguide Macor subsystem to polarisation maintaining single mode fibres, thus providing additional flexibility in terms of integration of fibre-optic components and plug & play functionality

1.55 µm polarisation maintaining single mode fibre

Laser Heterodyne Radiometry at 9.7 µm

75cm x 75cm



7cm x 7cm

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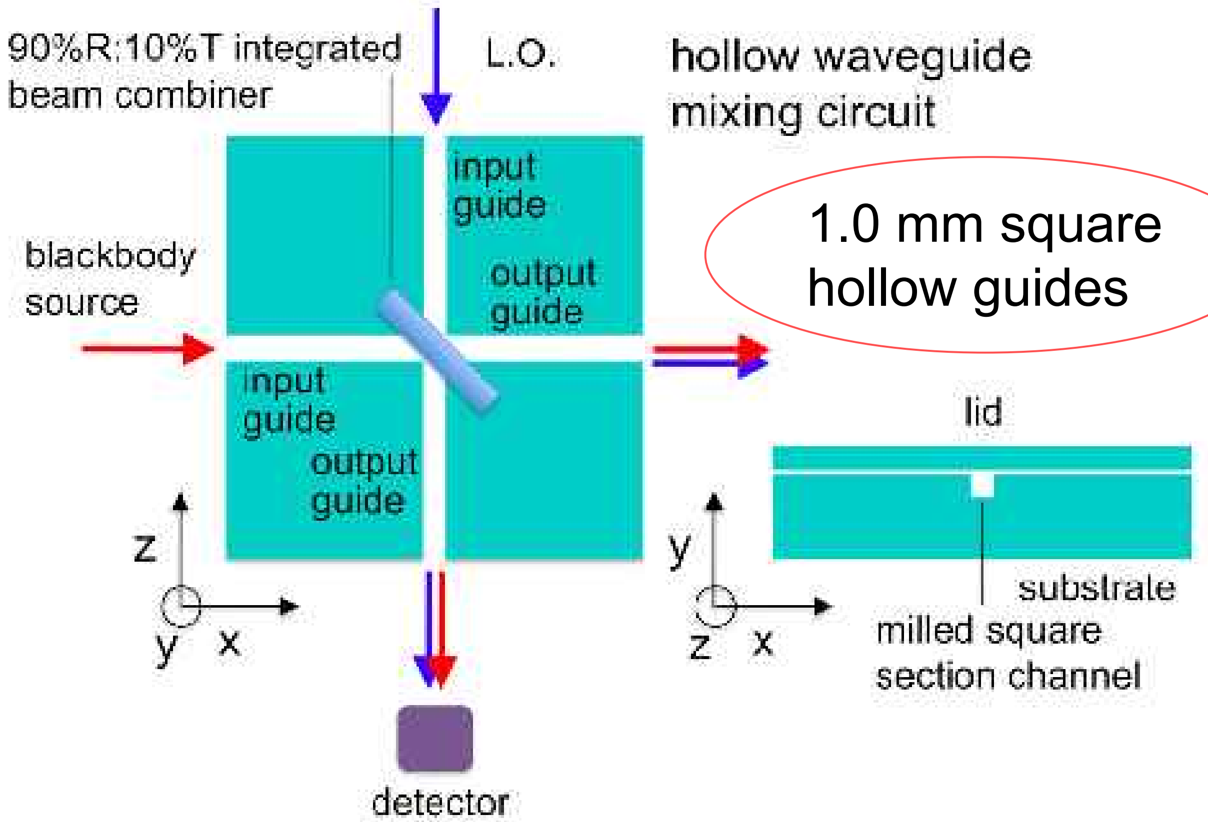
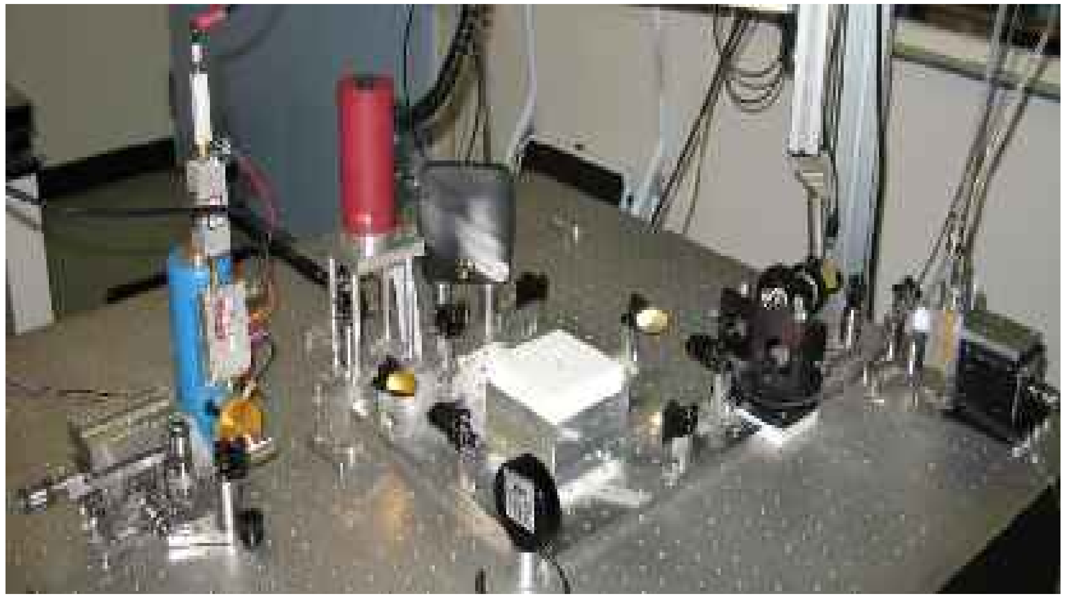
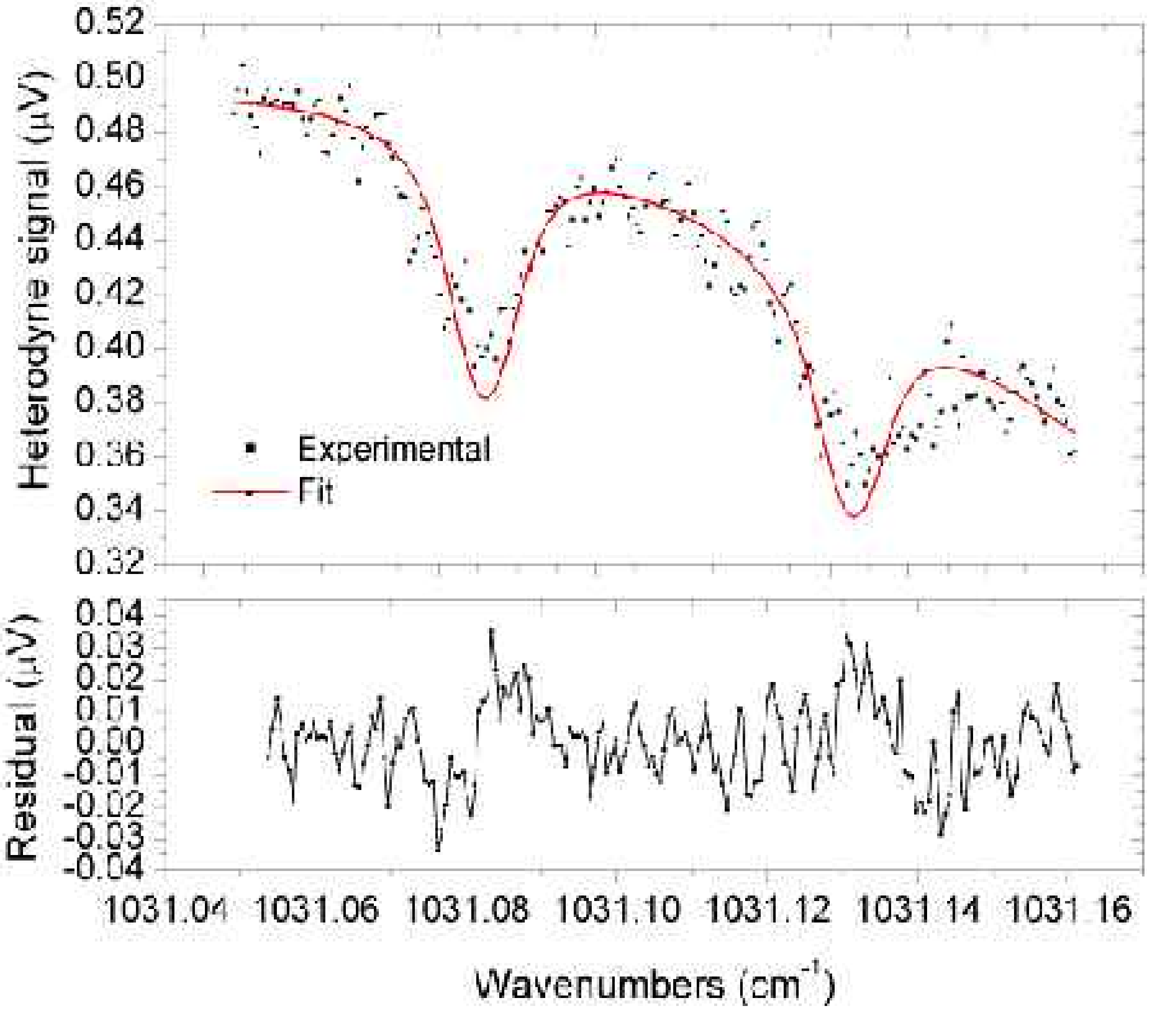
Demonstration of photomixer at 9.7 μm





Comparison of measured and fitted absorption spectra of Carbonyl Sulphide with thermo-electrically cooled detector



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Advantages of HWG photomixer

"Hollow waveguide photomixing for quantum cascade laser heterodyne spectro-radiometry," Weidmann et al, May 2011 / Vol. 19, No. 10 / OPTICS EXPRESS

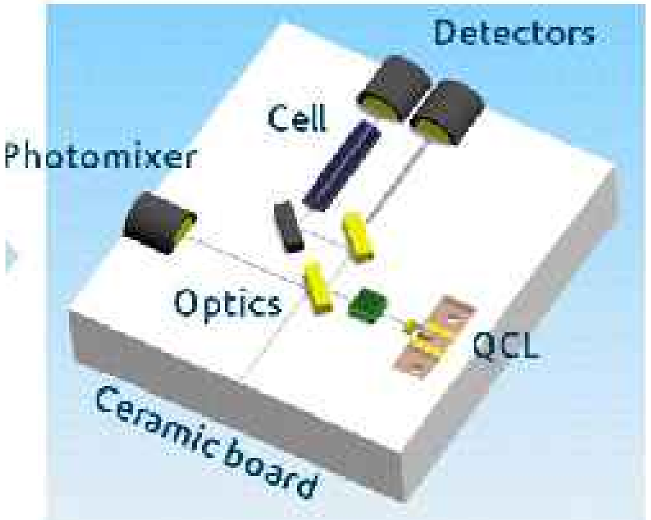
- The first measurements were made using a thermoelectrically cooled detector opening the way for LHR systems without the need for cryogenic cooling.

- Routine heterodyne detection sensitivities within a factor of two of the fundamental shot noise limit

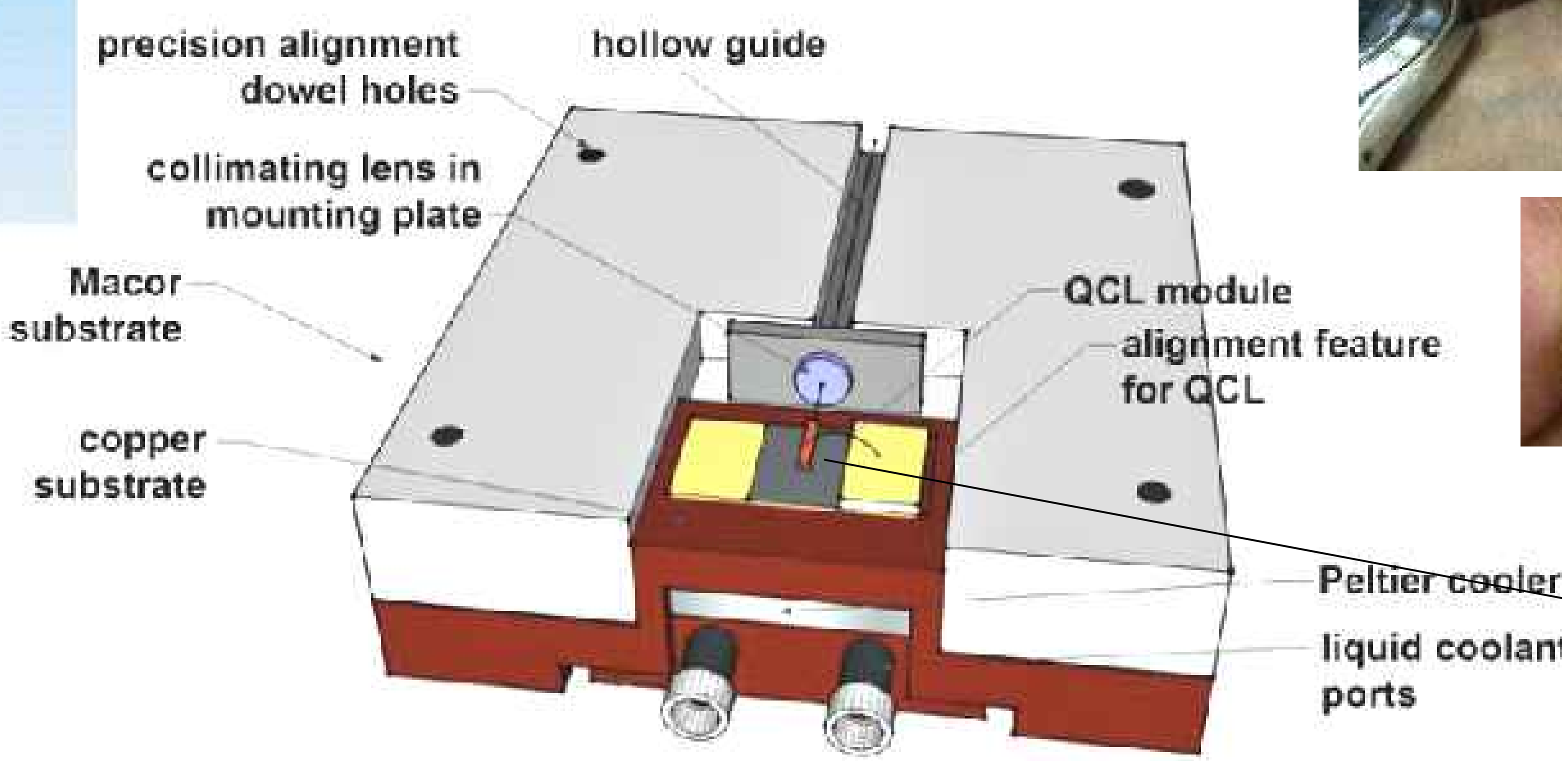
Damien Weidmann received an unsolicited email from Robert Menzies (JPL), a pioneer of laser heterodyne systems for atmospheric sounding, saying……

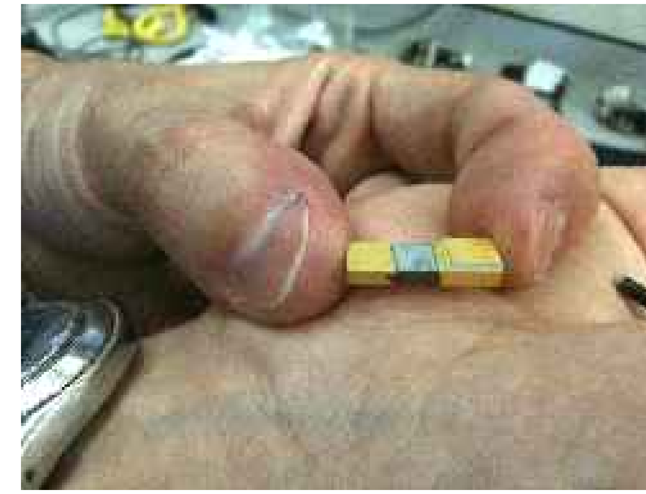
"I'm very impressed with the work that you and your colleagues reported in Optics Express on the topic of hollow waveguide photomixing using a QCL local oscillator. <u>The performance that you report is a real breakthrough in my opinion. Congratulations on advancing the performance capabilities of laser heterodyne radiometry!".</u>

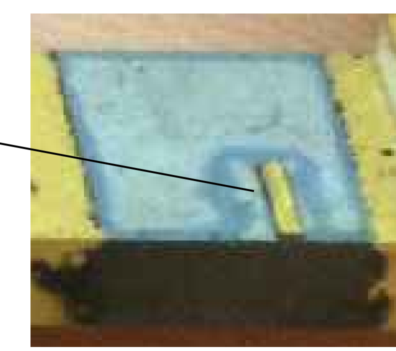
New programme on active component integration



Integrated QCL demonstrator







Schematic of the integrated QCL sub-module to be developed during the project. A different sub-module will be developed for the detector

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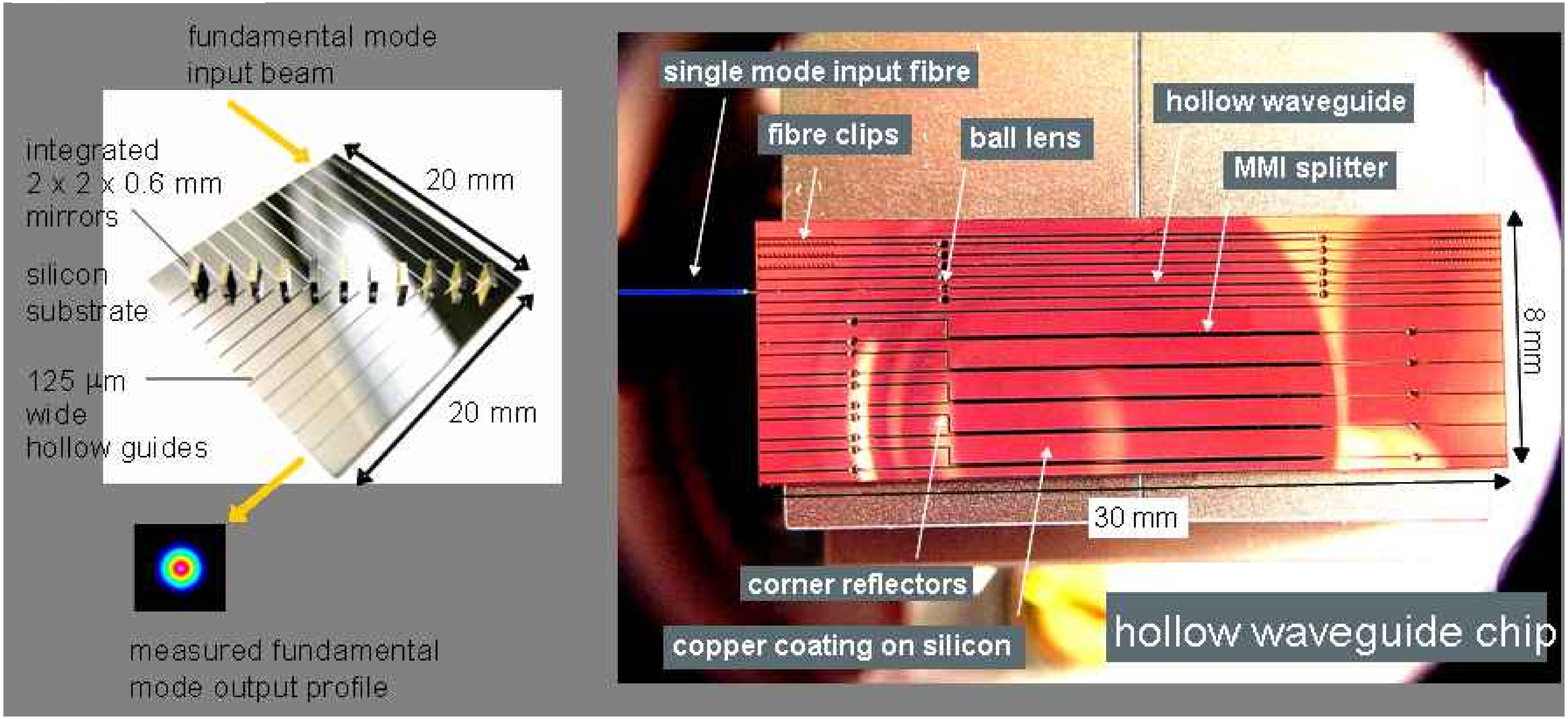
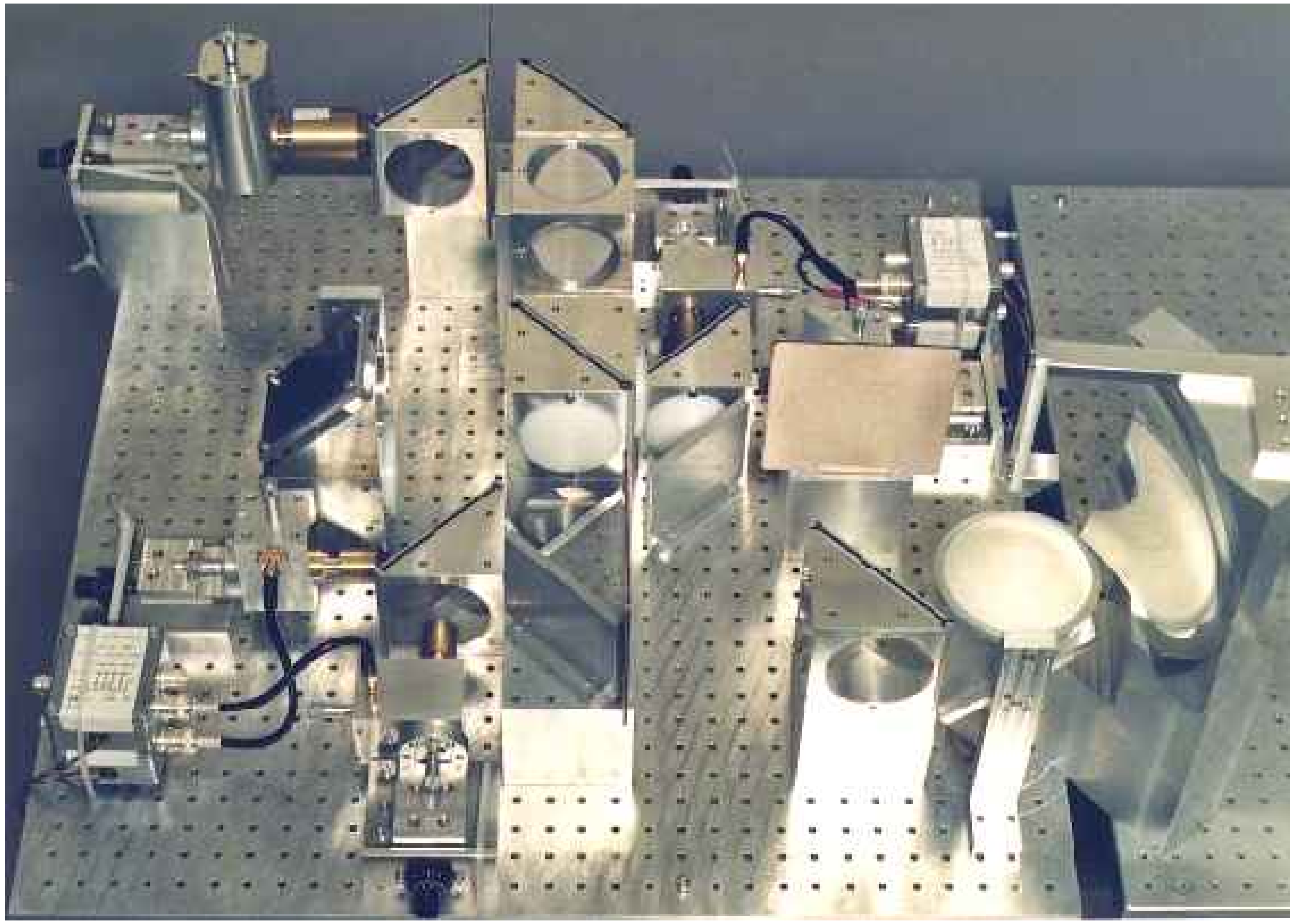
Examples of Hollow Silicon Optical PCB



Examples of hollow silicon waveguide chips including component alignment slots formed using Deep Reactive Ion Etching (DRIE)

Quasi-optical CWFM radar

University of St Andrews



This system uses a continuous output whose frequency is swept up and down. This technique is called Continuous Wave Frequency Modulation (CWFM) radar. The system operates at frequencies from 80GHz up to 140GHz and can provide cm range resolution even at very short ranges (down essentially to zero). systems like this are being considered for tasks as varied as car collision avoidance and missile 'seeker heads'.

CEOI Funded Innovations

- Hollow waveguide optical PCB successfully applied to EO demonstrators – laser heterodyne radiometer performance particularly impressive
- Easy component integration - no need for sophisticated mounts and manual alignment – alignment slots formed in substrate – automatic component placement can lead to very rugged, low cost manufacture
- Hollow waveguide have broad waveband high power transmission characteristics – u.v. to far-IR
- No beam diffraction - small/fixed beam diameter
- Optical guidance eases angular alignment tolerances and improved performance
- Space flight hardened performance demonstrated in practice
- <u>New approach to compact, rugged, low cost systems, providing very good optical performance realised</u>

Technology Transfer Potential

Potential areas for technology transfer include:

- Generic value and applicability to wide range of laser and electro-optic systems
- Compact rugged DIAL system for atmospheric CO_2 monitoring
- Analytical instrumentation – spectrometers, radiometers and interferometers (recent CEOI collaboration with Damien Weidmann and new current CEOI funded work)
- Modules for fibre optic telecomms - JDSU
- Combined Optical + Electronic Printed Circuit Boards (OPCB)
- Sensing – fluidic, gas and biochemical (including lab-on-a chip for DNA analysis)

Hollow Waveguide (HWG) Optical PCB

Centre for eo Instrumentation

Overview/Team

- Brian J Perrett and Rob Scott, QinetiQ, Malvern.
  bjperrett@qinetiq.com, rfscott@qinetiq.com
- Roland Leigh, Paul Monks, Tim Stevenson, J Lawrence, University of Leicester.
- Phillip Lewis, S Hancock, Mathias Disney, UCL.
- Shaun Quegan, CTCD, University of Sheffield.
- Damien Weidmann, STFC (RAL)
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