Microwaves in a Multidisciplinary Future

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1 Background

The science and engineering of microwave power is continuing to grow in scope. As new innovations emerge, researchers in industry and academia are witnessing an explosion in multidisciplinary applications of microwaves. The advantages of microwave energy are finding new appreciation in many diverse areas, but despite these emerging applications, there are still many open questions surrounding the fundamental mechanisms of microwave irradiation, leading to a rich scientific landscape for those involved in microwave power.

The Centre for High Frequency Engineering (CHFE) is a large microwave engineering research group based at Cardiff University in the UK [1], with 13 academic staff, led by Professor Adrian Porch. Research activities in the group span the breadth of microwave energy applications, including in chemistry, physics, biology and medicine, power amplifier device design, modelling and characterisation, microwave and mm-wave hybrid circuits and microwave microfluidics. Recent expansion into compound semiconductor materials for microwave power applications has seen the Institute for Compound Semiconductors being established, with state-of-the-art equipment and facilities for microwave device fabrication and characterisation. The group has strong international industrial links with a diverse range of companies, including IQE, MACOM, Arelis Thompson Broadcast, DSTL, Diamond Microwave, European Space Agency, Kelvin Nanotechnology, NXP Semiconductors, Oxford Instruments Plasma Technology, Plessey Semiconductors, Merck KGaA (Darmstadt), Microsemi and Renishaw.

2 Microwave Multidisciplinarity

For over 20 years, the group has worked developing innovations in microwave power and measurements. CHFE carries out a range of interdisciplinary research with industrial and academic partners. Key projects include:

- Microwave methods in hydrogen storage and production
- Additive manufacturing
- Microwave detection and treatment of bacteria and bacterial spores
- Non-invasive blood glucose measurements
- In situ measurements during microwave heating, using magnetic resonance, infra-red, neutron and x-ray scattering measurements.

Here we look at some recent work emerging from the group applying microwave innovations across a range of disciplines.

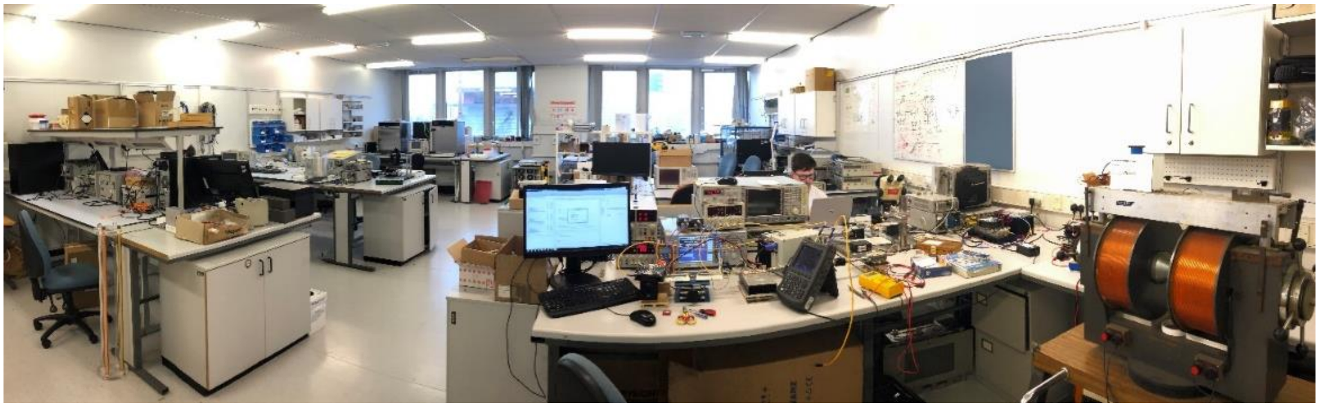

Figure 1: The interdisciplinary microwave characterization laboratory, Centre for High Frequency Engineering, Cardiff.

3 Microwaves in the production and storage of hydrogen.

Hydrogen as an energy carrier promises a sustainable energy revolution. However, one of the greatest challenges for any future hydrogen economy is the necessity for large scale hydrogen production not involving concurrent CO_2 production. The high intrinsic hydrogen content of diesel and other liquid-range alkane hydrocarbons offers a route to CO_2-free hydrogen production through their catalytic deep dehydrogenation. Using microwaves, results show that high-purity hydrogen can be liberated from fossil fuels by microwave-promoted catalytic dehydrogenation. Using Fe and Ni particles supported on silicon carbide, a H_2 production selectivity from all evolved gases of some 98% is achieved, with less than a fraction of a percent of adventitious CO and CO_2. The major co-product is solid, elemental carbon. [2-4]

4 New in-situ measurements for microwave heating

Microwave heating experiments often present impressive results under very different heating conditions. The complexity of heating heterogeneous materials in microwaves leads to many fundamental questions. Experiments to simultaneously heat and measure materials under microwave irradiation can help to shed light upon these complex mechanisms:

(i) Electron paramagnetic resonance (EPR) measurements are a useful tool to explore radical chemistry. A unique dual mode X-band continuous wave EPR resonator for simultaneous EPR measurement and rapid MW induced sample heating has been developed in Cardiff. This is currently generating unprecedented results in microwave driven catalysis and in fundamental chemistry via temperature-jump experiments to measure the properties of chemical systems far from thermodynamic equilibrium [5].

(ii) In situ neutron scattering experiments can reveal details of structure and phase changes taking place during microwave irradiation. Using a microwave resonator with a thinned-down aluminum cavity wall, scattering experiments can be carried out for either material processing using high power microwaves or dielectric measurements. Figure 2 shows one of the devices used for in situ spectroscopy under microwave irradiation. In this example, neutrons are used to reveal the absorption and desorption of ammonia with simultaneous microwave dielectric measurements. Also shown are the superimposed data of the absorption/desorption cycles showing a surface plot of Bragg diffraction during ammonia absorption and desorption within a metal-organic framework under ammonia (ND3) and argon (Ar) flows. The intensity of the Bragg lines is represented by the colour scale on the right. The results of these studies allow the identification of materials with useful ammonia storage properties and provide a new metric for the measurement of gas absorption within mesoporous solids using microwaves. [6]

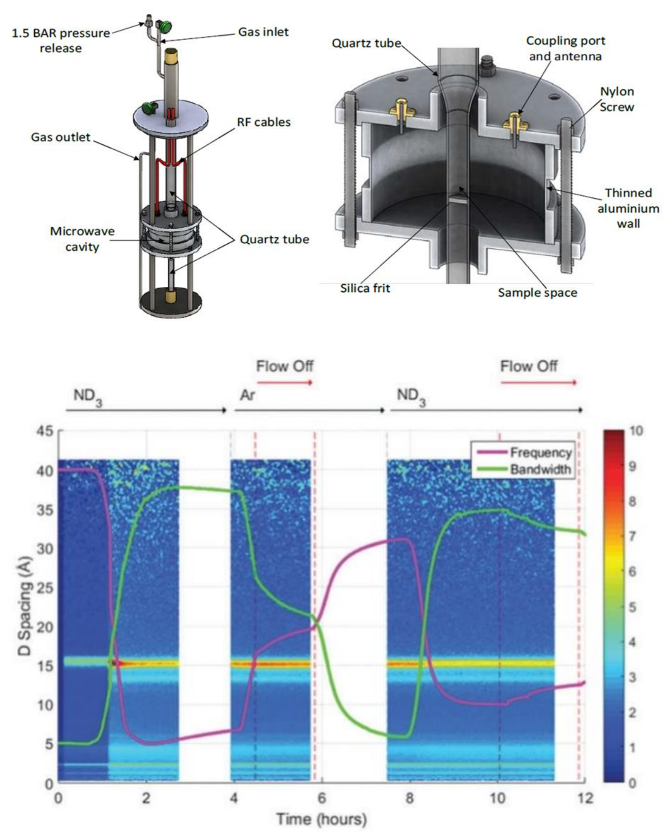

Figure 2: Schematic diagram of the experimental housing for the Microwave Cavity Resonator in the neutron diffractometer and a superimposition of the surface plot of Bragg diffraction and dielectric data (frequency and bandwidth) during ammonia absorption and desorption under ammonia (ND3) and argon (Ar) flows.

5 A new theoretical framework for heating of catalysts and powders

Recent work has established new approaches to microwave heating of powders. Analytical models of dipole absorption in conducting spheres reveal that by simple selection of the size and conductivity of a powder, the heating rate and dominant heating mechanism can be controlled [7]. As shown in Figure 3, for poorly conducting materials, the optimum heating is dominated by the interaction of the electric field *E*, is size independent, and occurs at a conductivity of $\sigma = 3\omega\varepsilon_0$, where ω is the angular frequency and ε_0 is the permittivity of free space. For highly conducting materials, the heating is dominated by the magnetic field H, is size dependent, and is optimum at a particle-radius to skin-depth (a/δ) ratio of 2.41. This knowledge provides a framework for selecting powder materials for heating applications and enables a deeper exploration of the very different mechanisms in electric- or magnetic-field driven heating.

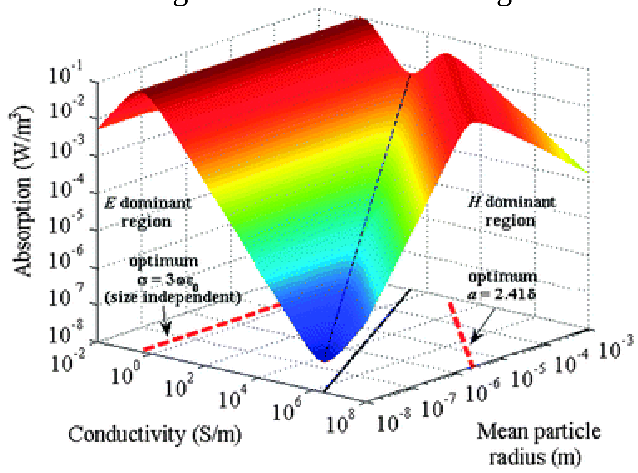

Figure 3: Heating rates in powders of different particle radius and conductivity.

6 Non-invasive measurements of blood glucose

One in eleven adults has diabetes (463million people) and 10% of global health expenditure is spent on the diabetes. Three in four of people with diabetes live in low- and middle-income countries. Affordable self-monitoring techniques usually involve the use of finger-prick devices, test strips and the glucose meters, which can be painful and only give discrete readings. Using microwaves, the Centre for High Frequency Engineering at Cardiff University has been pursuing non-invasive and continuous monitoring of blood glucose [8] and is now working towards commercialization of the sensor device.

Figure 4: The microwave non-invasive blood glucose sensor

7 Future plans

Rapid expansions are taking place in Cardiff related to microwave device fabrication and characterization. In addition, the Centre for High Frequency Engineering is recruiting academic staff to expand the multidisciplinary research portfolio. We continue to explore new partnerships in diverse areas of microwave chemistry, medicine and energy materials. In particular, in microwave catalysis and new in situ measurements to develop a deeper understanding of scientific and engineering challenges in microwave chemistry. Given the buoyant research climate in the field of microwave power applications, and the important unanswered questions that characterize microwave research, we expect this trend to continue.

For further readings

1. Cardiff - Capital City of Wales: https://www.youtube.com/watch?v=UqicqIMGGpI
2. Gonzalez-Cortes S. et al., Wax; A benign hydrogen-storage material that rapidly releases H2-rich gases through microwave-assisted catalytic decomposition. *Scientific Reports* 6, article number: 35315, 2016.
3. Jie X. et al.; Rapid production of high-purity hydrogen fuel through microwave-promoted deep catalytic dehydrogenation of liquid alkanes with abundant metals. *Angewandte Chemie - International Edition* , 2017, **56**(34), 10170-10173.
4. Jie X. et al; The decarbonisation of petroleum and other fossil hydrocarbon fuels for the facile production and safe storage of hydrogen. *Energy and Environmental Science*, 2019, **12**(1), 238-249.

5. Folli, A.et al.; A novel dual mode X-band EPR resonator for rapid in situ microwave heating. *Journal of Magnetic Resonance*, 2020, **310**, article number: 106644.
6. Barter, M.et al.; Simultaneous neutron powder diffraction and microwave dielectric studies of ammonia absorption in metal-organic framework systems, *Physical Chemistry Chemical Physics*, 2018, **20**, 10460-10469.
7. Porch, A., Slocombe, D. R. and Edwards, P. P.; Microwave absorption in powders of small conducting particles for heating applications, *Physical Chemistry Chemical Physics*, 2013, **15**(8), pp. 2757-2763.
8. Choi, H.et al.; Microwave noninvasive blood glucose monitoring sensor: penetration depth and sensitivity analysis, IEEE International Microwave Biomedical Conference (IMBioC 2018) Philadelphia, PA, US. IEEE, 2018, 52-54.

About the author

Daniel R. Slocombe received the Ph.D. degree in Electronic Engineering from Cardiff University, UK. From 2002 until 2006 he was an engineer in the Royal Air Force and from 2012 until 2015 he was a Research Fellow in the Inorganic Chemistry Laboratory at the University of Oxford, UK. He is currently Head of Teaching for the Department of Electrical and Electronic Engineering at Cardiff University and is a member of the Centre for High Frequency Engineering. He has carried out research in many areas of microwave science and high frequency materials including microwave activation of catalytic processes, synthesis of functional oxides, dielectric spectroscopy and new methods using Electron Paramagnetic Resonance.