

Chapter 5

The exposure cell

5.1 Introduction

This chapter describes the development of an exposure cell that allows the delivery of a well-controlled and well-characterized dose of mm-wave radiation to a biological sample. The cell is a two-port device, essentially a fundamental mode waveguide straight with a sample tube transecting the waveguide cavity. It is central to the operation of the apparatus. This simple design was selected on the basis that it minimized uncontrolled power losses. The general approach is also found in microwave calorimeters and the exposure system described by Furia and Gandhi (Furia, Hill, et al. 1986). The load is selected to ensure a good match between the source and load. Unlike the apparatus described by Furia and Gandhi, the culture medium is not contained in a re-circulating system.

In the literature review (Chapter 2), several types of experimental mm-wave apparatus for irradiating samples are described. Most commonly employed are horn antennas. Other approaches have included Teflon stirred irradiators, which directly couple with cell culture. In all cases, the apparatus is designed to achieve uniform mm-wave power distribution in a test sample. Another approach to minimize heterogeneity is to use thin films or cell monolayers (Alekseev & Ziskin 2001) (Alekseev & Ziskin 2000). The penetration depth of mm-wave radiation in lossy materials such as distilled water is in the 0.78 - 0.23 mm range (Gandhi 1983). Sample thickness is a particularly important parameter in relation to the distribution of power within a sample.

A number of biological effects have been described as “non-thermal”, although this conclusion should be reached with caution. Firstly, high specific absorption rates (SARs) can evolve under relatively low-intensity exposure conditions, sufficient to cause rapid, albeit small, changes in

temperature. One consequence of this is a non-uniform heating of the sample where local “hot spots” exceed the average temperature within the sample and induce convection (Khizhnyak & Ziskin 1994). Another effect relates to near-field and far field exposure patterns (Gapeyev et al. 1996). Consequently, the potential for experimental artefact in apparatus is high, and this may account for some of the frequency-specific effects rather than a (Furia, Hill, & Gandhi 1986a; Gos P et al. 1997) non-linear induced effect in the biological system.

The exposure cell described here utilizes a fundamental-mode waveguide-cavity structure that has been designed to minimize local heating effects and hot spots. Dosimetry can be divided into two areas: Firstly, the power absorbed in the sample or **average SAR**. This can be derived very accurately by measuring reflected and transmitted power from the test sample. Secondly, the power distributed within the sample or **local SAR**. The approach taken here is to use simulation. Initial design concepts concentrated on optimising dosimetry rather than the convenience of readily available culture flasks and dishes found in the microbiology laboratory.

5.1.1 Design and construction of the cell

A number of designs were evaluated and a two-port device, essentially a fundamental-mode waveguide straight with the sample and holder (cuvette) inserted through the waveguide cavity, was found to be the most satisfactory. The cuvette insertion slots were positioned in the centre of the waveguide broadside wall in order to minimise propagation into free space. The exposure cell was fabricated from copper block and then electroplated with gold.

In this two-port scheme, millimetre wave radiation can be either:- i) absorbed into the cuvette and sample, ii) reflected (S_{11}), iii) transmitted (S_{21}), or iv) radiated into free space through evanescent mode propagation (i.e., leakage) from the waveguide slot (Fig. 5). Simulated electric field strengths in the sample can be used to derive local SAR

distribution and port S parameters. The exposure cell was constructed from two halves that allowed the sterile cuvette to be located and secured by a bolting system whereby two symmetrical sections form the cell, with the partition in the centre of the waveguide broadside wall. The waveguide was fundamental mode over the 26 – 40 GHz operational range (Ka band).

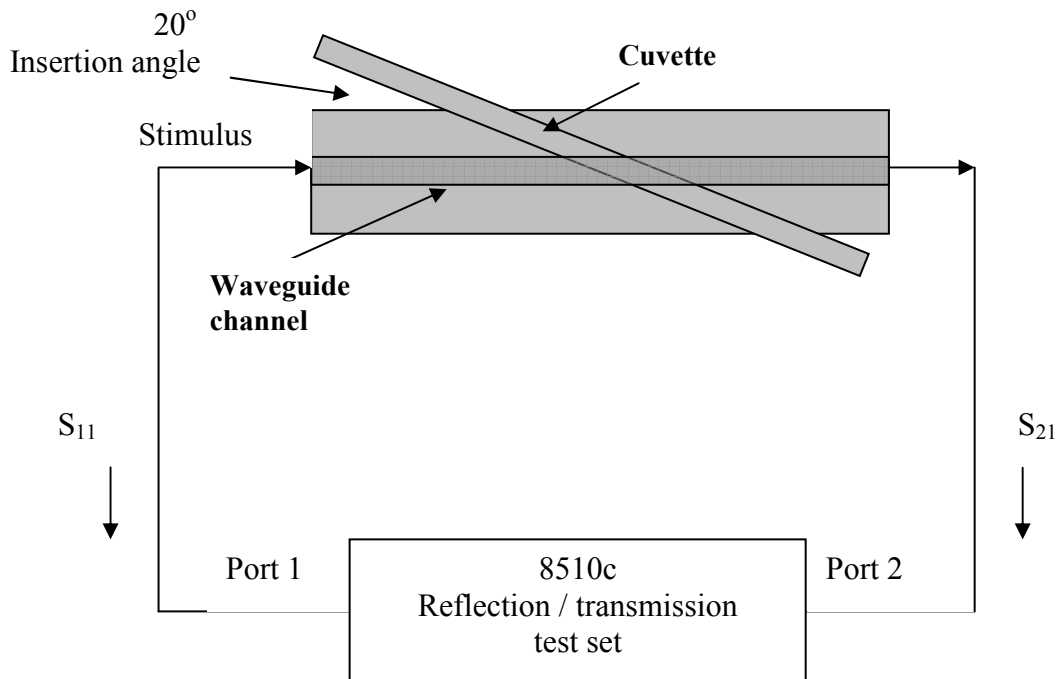
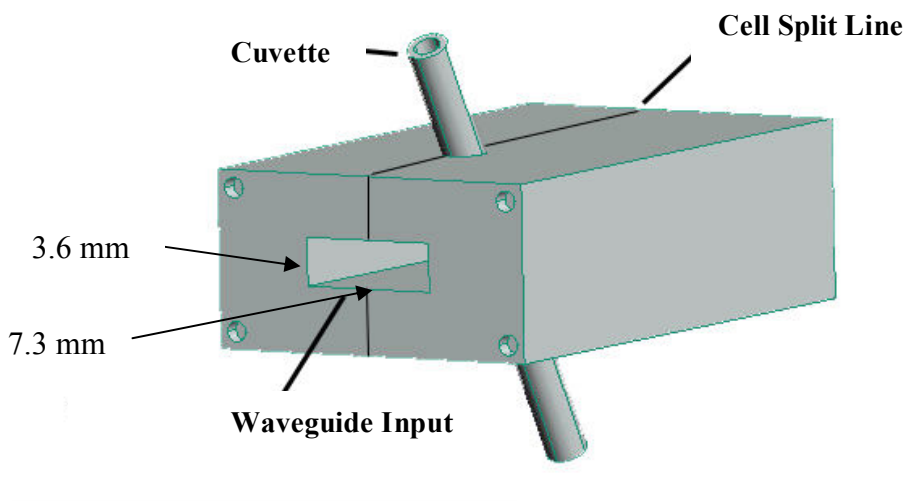


Fig. 12 The exposure cell

A coax-waveguide adapter (Flann Microwave, Bodmin, U.K.) interfaced the network analyser to the waveguides in the test set. A flexible waveguide length and a waveguide bend were used to make interconnections between the exposure cell and the coax-waveguide adapter. Critical to the optimisation of the irradiation cell is the sample tube positioning and dielectric properties.

Also important is the electrical impedance mismatch between the sample (load) and power source output. This was minimized by selection of an insertion angle less than 20 degrees (see simulation, Chapters 5 and 6) to the horizontal of the sample tube, although at a penalty of having a lower SAR. The waveguide (Flann Microwave, Bodmin, U.K.) The thickness of the waveguide wall, the cuvette diameter and its material (dielectric constant) were selected to minimize the possibility of fundamental-mode waveguide propagation along the cuvette. Unless suppressed, this propagation would represent an uncontrolled loss of signal power from the sample. Simulation of our design showed the effect to be negligible, typically 60 dB lower than the power level at the centre of the cell.

Adjoining waveguide sections exit the exposure chamber through opposing panels. The tube insertion points, waveguide wall thickness, tubing diameter and its material (dielectric constant) were selected to minimize the possibility of fundamental-mode waveguide propagation along the tube.

5.1.2 Selection of sample tube material

As the cell culture came into direct contact with the inner surfaces of the tube, biocompatibility was an important parameter in the selection of tubing material. Other parameters included the materials' ability to withstand sterilization by an autoclave (409 K, 20 min). Other methods of sterilization such as ethylene oxide could also be used although they would be much less convenient. Another important aspect was the transmission and reflection characteristics of the tubing material. Oxygen

depletion in the test cuvette could potentially induce stress in the cell culture and so oxygen permeability was a further factor in selection of the tube material. The tube also had to have good optical transmission characteristics as light measurements needed to be made of the bioluminescent cell culture.

The losses with the tubing material itself had to be low. Suitable materials included PTFE, Quartz and silicone tubing. The mechanical properties of the tubing were important, as the tube had to be free-supporting within the guide. Also, the achievable internal and external diameters using manufacturing processes such as extrusion can be considered. Ultra-thin films provided best local SAR homogeneity but this had to be weighed against the practicalities of operating a sample 'flow' system. The sample tube internal bore had to be less than 1 mm and preferably less than 0.5 mm. Simulation was used to explore the occurrence of "hot-spots" with different sample geometries i.e. plane face, tube etc in the waveguide. Using a tube it was possible to remove "edge" effects that resulted in localized heating. A 0.5 mm internal bore was sufficient for the absorption of a substantial fraction of the incident power in the sample, but still allowed transmission of sufficient power to do full s-parameter analysis. Silicone tube was selected on the basis that it satisfied the above requirements (see results section, Chapter 6 for additional information).

Fig. 13 shows the two halves of the waveguide-cavity exposure-cell. Mounting brackets were used to secure the collimator guide blocks both pre and post exposure. The silicone tube is retained in a groove milled into the collimator blocks. Also shown are two collimator guide holes in the exposure-cell block itself.

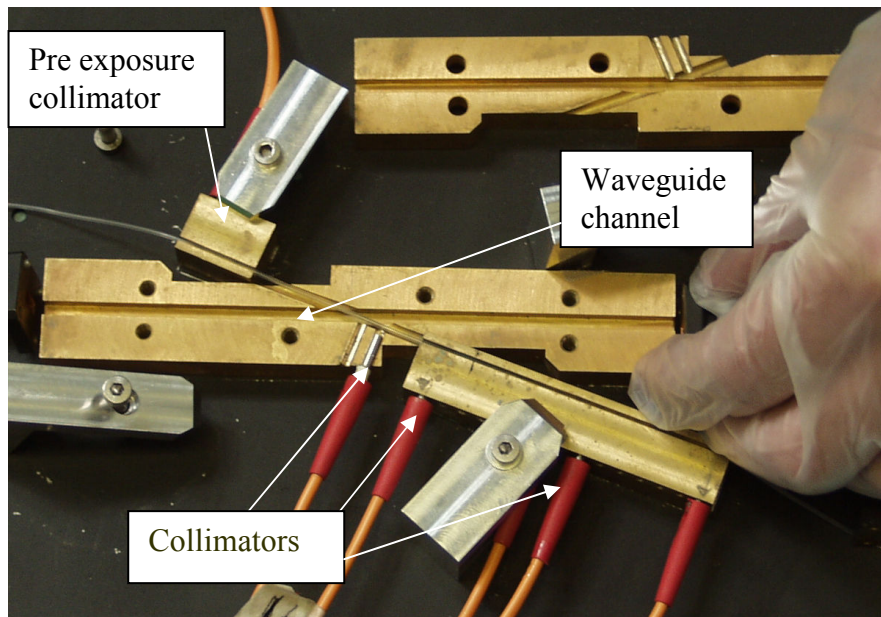


Fig. 13 Exposure cell shown with the two halves prior to assembly

5.1.3 Network analysis and simulation

Ansoft HFSS, a 3D solver employing the finite element method, was used for all the simulation work. Preliminary modelling and validation were undertaken with a waveguide exposure cell model that could be resolved as a simple multi-port device and evaluated in terms of its millimetre wave scattering ‘S’ parameters in the simulation. A quantitative evaluation for “hot spots”, and regions likely to produce convection effects, was performed (see Chapter 6). Sample electric field distributions were exported from the HFSS post-processor on a Cartesian grid with user definable spacing, and the local SAR. Local SAR is related to electric field strength using the equation below.

$$local\ SAR = \frac{\sigma |E|^2}{\rho_m}$$

ρ_m = mass density

σ = effective conductivity

E = electric field strength $V\ M^{-1}$

Circuit modelling indicated that use of a low ($< 20^\circ$) tube insertion angle would minimize power reflection from the tube across the frequency band thereby ensuring that maximum power is transferred from source to sample. The network analyser (8510c, Hewlett Packard, USA) was controlled over a GPIB bus. In this two-port set-up, mm-wave radiation is either i) absorbed in the sample and tube wall, ii) reflected (S_{11}), iii) transmitted (S_{21}), or iv) propagates into free space through evanescent-mode propagation (i.e., leakage) at the point where the sample tube enters the guide (unless suppressed, this propagation would represent an uncontrolled loss of signal power from the sample).

S_{21} is scatter toward port two from port one and S_{11} is scatter toward port one from port two. From the principle of conservation of energy and confidence in minimal leakage from the cavity itself, average SAR can be calculated with a high degree of accuracy.

$$P_{absorbed} = P_{in} - (|s_{21}|^2 + |s_{11}|^2)$$

The predictive qualities of the simulation were dependent on accurate representation of dielectric properties for reference liquids and cuvette materials since these strongly affect the sample electrical impedance. A look-up table covering the 27.5 – 35 GHz region, at 25 °C, was computed for both pure water and saline (3% NaCl) using the Debye equation, and a modified version with additional terms for salinity (Stogryn A 1971). For example the dielectric constant was 38 and dielectric loss constant was 34. The additional constituents of typical microbiological culture medias had little impact on dielectric properties. Values for quartz and PTFE were readily available in the literature and two values quoted for silicon were interpolated.

Simulation using HFSS showed the effect to be small, typically 60 dB lower than the power level at the centre of the cell (see Chapter 6, results). This important parameter ensured that the pre exposure detector

was adequately isolated. The exposure cell design optimizes test sample response to power available from a mm-wave source that is 'swept' in the frequency domain. Obtaining a clear understanding of the spatial distribution of power in biological samples remains a significant challenge. For methodology on segmented-flow generation see 3.4. Because of the differences of the dielectric properties of media / air the segmented flow causes large changes in the value of transmission loss (S_{21}) but small changes in (S_{11}).

5.1.4 Location of collimators

Fig. 14 Cross section of the exposure cell

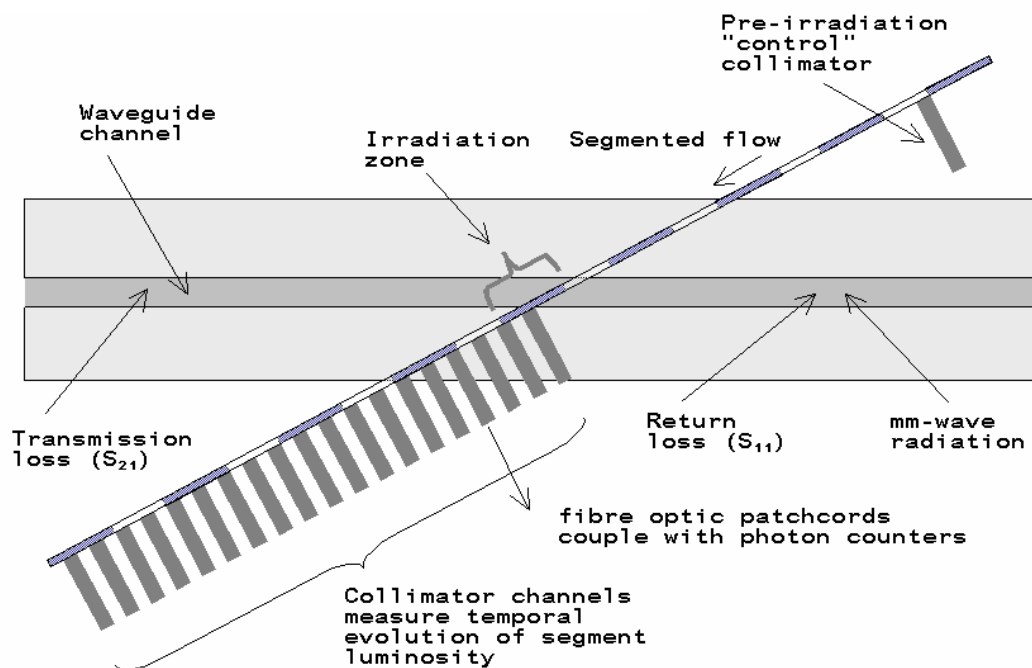


Fig. 14 shows a cross-section through the waveguide exposure cell. Multiple collimator guide channels are shown.

Summary

High-frequency electromagnetic simulation software and circuit analysis were used to optimize the exposure-cell design concept. In particular, the simulation models allow the identification and evaluation of conditions that predispose to localized heating, 'hot spots' which may induce physical-effect based artifacts.