An Innovative New Planar Evanescent Microwave Sensor for Refractive Index Measurement

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ABSTRACT

'Seed corn funding' for innovative technologies from the Plymouth University Innovation team has led to development of a new patented planar evanescent microwave sensor with an internally fabricated recessed cavity for use with liquid samples in a range of potential aqueous applications, such as refractive index sensing. Here we present microwave transmission results for a series of polar and non-polar fluids inserted into the internal cavity of a microwave channel waveguide, and investigate the recess sensing response.

KEYWORDS: *Evanescent microwave sensor, metal/dielectric applications.*

I. INTRODUCTION

We discuss the fabrication of a range of microwave evanescent sensors based on planar optical waveguide principles, and the testing of a preliminary technology demonstrator in late 2015, for scoping of a wide range of potential sensing applications. Further possible microwave based evanescent sensors beyond the scope of this paper are discussed in our recent Plymouth University Research and Innovation Report [1]. Such evanescent microwave sensors are able to prove the near surface region from millimetre to metric scales, without any direct radiation of energy into the external environment, with potential for detection of various dielectric or metal materials of sensing interest. These devices follow similar optics planar sensor device designs already proven by the author [2]. This paper will look at the operation of an evanescent microwave sensor for refractive index sensing, an application of a device under patent [3], and presented in contemporary literature [4 - 5]. This paper will start by discussing the theoretical background of integrated waveguide sensors before looking at the experimental methodology used. Results and a discussion of results are then presented, followed by some ideas for future work and the conclusions.

II. THEORETICAL BACKGROUND

a. Integrated Channel Microwave Wave Guide Sensor Devices

Traditional microwave sensing methods mostly concern direct radiation of microwave energy emitted from a transmitter into the external environment, relying on either direct reflection of microwaves for detection or back-scattered from a point, surface, or volume source. Current radar sensing methods radiate microwave energy in a dispersive manner with cumulative additional losses from absorption and scattering, resulting in high attenuation and likely detection of transmitter action, which although not a problem for civilian activities could be disastrous for military operations. A possible innovative, and hitherto untried, microwave solution is provided through Attenuated Total Reflection (ATR) which has been used for several decades to couple optical radiation into thin film waveguide modes for evanescent sensing with prisms [6-8] and in more recent decades in planar waveguide geometries [9], with wave guide modes travelling within the wave guides, but sensing the near surface interface evanescently. Optical systems have a degree of limitation on the scale of environmental applications, as they only sense in close proximity to the surface region to a typical range of tens of wavelengths, ideal for bio-sensing applications, but not for large-scale phenomena. However, the flat geometry of planar or channel waveguides offers significant sensitivity for *in-situ* probing of the optical properties of attached surface layer properties and adjacent media because of the extended surface path length [9 - 10].

Similarly scaled fabrication of Microwave Wave Guide Sensors (MWGS) operated at microwave wavelengths (typically 1 - 10 cm) provide a mechanism for increased interaction length and strong confinement of electromagnetic fields. The method provides potentially novel and innovative probes for exploration, rather than the more common radiative methods, e.g. radar employing either pulse delay ranging, or the Doppler effect. Evanescent fields also bring reduced detection probability, and *may* prove to be important in near-field sensing underwater of littoral and ocean environments. Due to high losses in water, especially from suspended sediments within soil, most radiative systems are prevented from achieving good ranges across most of the electromagnetic spectrum except for high power LIDAR systems. The potential of a new innovative waveguide method to sense terrestrial near sub-surface objects of interest on the scale of mm to metres may be of interest to certain specific applications, e.g. mine detection. Fundamental microwave waveguide theory and the principles of the design of such waveguides is considered elsewhere and will not be examined here [11 - 12]. An evanescent channel microwave sensor capable of detection through variable sand depth was demonstrated recently [5].

Microwave guiding, until now, has been considered largely from a viewpoint that waveguides are simply a passive low loss means of transferring microwave radiation along sealed metal waveguides, delivering radiation from source to antenna, without considering that a waveguide *may* act as a sensor in its own right at some point in the microwave propagation path. Furthermore we sought to increase sensitivity superstrate microwave environment changes in the immediate vicinity of the waveguide by selecting a region to insert a recess to better access the confined fields.

As already noted planar and channel optical waveguides have been used extensively previously as research probes to utilise the interaction of evanescent fields, notably for optical detection in the superstrate media adjacent to the waveguide surface [9-10]. Similar designed robust dielectric microwave waveguides can include lateral constraints or *channels* to probe changes in microwave absorption spectra of adjacent '*optically*' thick surface layers, changes in the immediate environment's microwave refractive index properties, due to the presence of varied metal and dielectric materials, gratings, and other required functional features.

III. METHODOLOGY

a. Waveguide Fabrication

Wax waveguide fabrication was divided between Dr J Fisk, who helped fabricate several straight channel waveguides, and Mr Ben Lavers who fabricated the channel waveguide with a rectangular shaped recess (indentation) used here for liquid refractive index measurements, and also fabricated several one dimensional wax surface gratings using various 'designer' moulds of different surface undulation periodicity. Fabrication of this refractive index sensor with the indented or embedded 'pot', is one of a family of devices for sub-surface wave guiding with sensing interaction. Wax waveguides should be regarded as 'leaky' Fabry Perot waveguides, with loss increasing as waveguide length increases. Inhomogeneities in the paraffin wax used, i.e. small air inclusions, resulted in a moderate scattering loss that was improved in fabrication with more homogeneous materials such as Poly Tetra Fluoro Ethylene (PTFE) [5].

Paraffin wax was used in all our early waveguide designs as it was easy to pour into pre-fabricated waveguide moulds and then to 'sculpt' into more intricate designs as required, or add further functionality. The waveguide used in this paper was fabricated from paraffin wax blocks heated with a gentle applied heat in small sections until fully melted and was then poured into a suitable mould, and permitted to cool to room temperature. Some additional wax 'layers' were usually added later to take up any contraction volume losses as the waveguide cooled. The recess was formed by initial insertion of a small plastic block larger than the optical cuvettes that were to be used, and gently pried out of the wax waveguide after cooling. Further device fabrication could incorporate additive layer deposition rather than precise laser cutting methods to ensure accurate recess construction. The 'target' dimensions for the finished waveguide were set at 20 mm (> ½ λ) thickness, 70 mm width (max.), and 252 mm (9 λ) length which allowed up to ½ λ at each end for coupling to give a maximum practical cavity length between both horn masks of approximately 10 λ. Rough shaping of the wax was achieved on all sides with a flexible craft blade (Stanley knife). Surface flatness was refined with a drawknife with a flat metal edge drawn across the faces running in the same direction.

All the while dimensions and orthogonality were closely checked with a Vernier caliper and a set square. When approaching the chosen target dimensions three grades of abrasive wet and dry paper were used to smooth the finished surface. The waveguide external final dimensions were 20.1 mm thick x 66.1 mm wide x 252.0 mm long.

b. Experimental Arrangement

The experimental arrangement used to set up the microwave cavity, throughout this work, consisted of paired 2.8 cm microwave transmitter and microwave receiver units, with guide horns (*Philip Harris*). These units were securely mounted onto a 500 mm rail optical bench with mounting stages allowing various degrees of freedom/movement (Eliot). The optical rails permitted accurate alignment of the microwave units prior to sensor operation and permitted variation of the microwave cavity (and thus waveguide) length. They provided a stable base for the scissor jack stage (Leybold) on which glass support blocks (113 mm x 63 mm x 18 mm), Radar Absorbing Material (RAM) and the waveguide were installed. The typical experimental arrangement is shown in fig. 1.

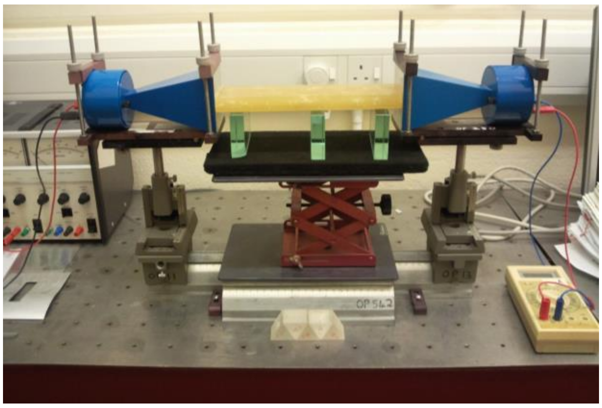

Fig. 1: Microwave cavity experimental arrangement with the transmitter (blue) to the left, and the receiver (blue) to the right (shown with waveguide installed) - TM mode.

Transmitter and receiver units were mounted on variable tilting stages held firmly with clamps which centralised the cylindrical part of each microwave horn housing at the rear. Horns were then centralised on the stages at the front opening face. Longitudinal centrelines were drawn on the microwave units and the clamps to allow horizontal alignment of all the components making up the entire cavity using the horizontal millimetre adjustment screws provided on the rail mounts. Both stages were aligned vertically by firstly ensuring that each was horizontal using a spirit level on the stage base. Then both the transmitter and receiver units were brought face to face and adjustment of the vertical millimetre screws on each rail mount carried out until precise alignment was achieved. Once aligned stages could easily be slid further apart on the rails. Laminated aluminium foil masks (fig. 2) could then be placed in front of the microwave horns. These aluminium foil masks measured approx. 82 mm × 82 mm externally (the dimensions of the outer perimeter of the horn face) with a centralised aperture 36 mm wide × 17 mm tall cut out. The aperture of the mask was ½ the actual internal horn width aperture of 74 mm and greater than ½ λ (> 14 mm) tall.

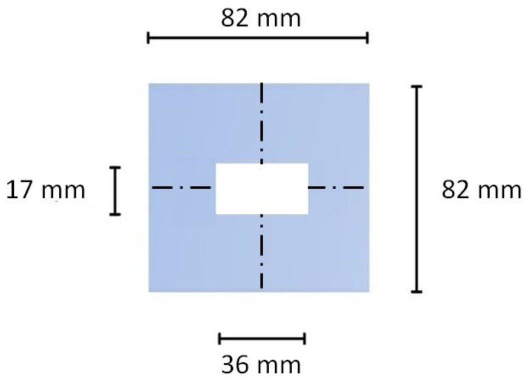

Fig. 2: Microwave horn mask dimensions (not to scale).

Orthogonal centrelines were added to each mask to allow accurate alignment with the horns and stage clamps. These centrelines were subsequently helpful in aligning the installed waveguide when placed on the waveguide supports. Masks could easily be removed from the horns, rotated through 90° and re-attached when the cavity polarisation was changed to TE mode from the initial orthogonal TM mode. The cavity microwave source used was powered by a Farnell LT30-2 dual power supply with one output set to 10 V (nominal). Power output was checked with a Farnell DM141 multi-meter to allow monitoring of output waveguide microwave stability. A microwave receiver output voltage (in mV) was monitored using one of two available digital multi-meters – an RS T100B and a Fluke 89 IV (which allowed data logging), are both shown in fig. 3.

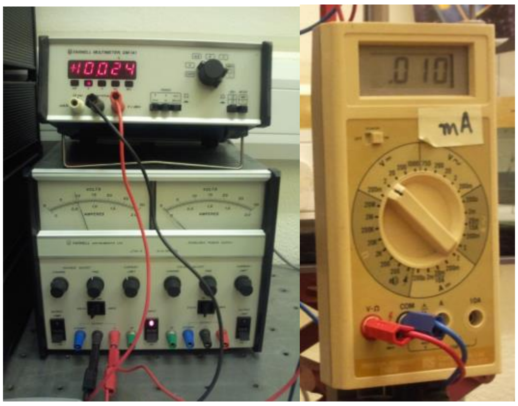

Fig. 3: Transmitter power supply and receiver monitoring meters.

Temperature measurements were made during the study using 3 instruments, and for waveguide experiments of temperature sensing [1]. First, ambient laboratory temperature measured at the optical bench surface was monitored with a dual readout digital thermometer (RS 427-461). The unit also had a remote wired sensor which could be positioned precisely for local temperature measurement. A RS Components' thermocouple unit (RS 610-067) was also available for temperature measurement of specific test samples, surfaces and the waveguides themselves. Finally, the temperature setting on the Fluke 89 IV multi-meter mentioned previously was available for logging temperature readings during routine testing. A cavity shield (300 mm × 150 mm × 150 mm) was constructed and clad in adhesive aluminium foil tape for covering the 'working' section of the waveguide cavity when required, to prevent stray microwave radiation propagation into the laboratory environment (fig. 4).

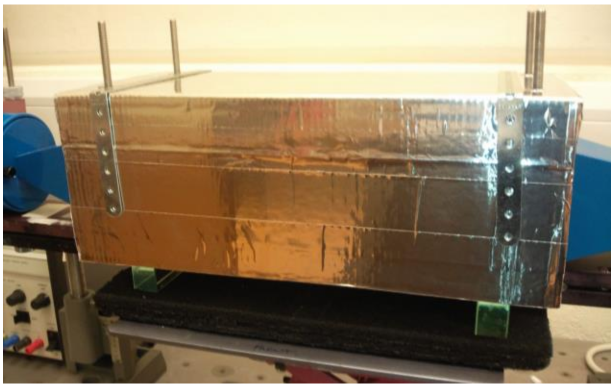

Fig. 4: Microwave cavity shield.

c. Refractive Index Measurements

This section focuses on process of examining any observed dependence between microwave waveguide output signal levels with changing refractive index of known standard refractive index fluids. The methodology looked at the waveguide microwave output for standard refractive index fluids available from Cargille [13] for a range of optical refractive index. Refractive index was also checked against an Abbe refractometer [14]. We also looked at the waveguide microwave output for a range of liquids. The specific Abbe used was a Bellingham-Stanley Abbe. A wax channel waveguide was used with a recessed chamber (fig. 5) into which standard Ocean Optics TM spectrometer cuvette cells (for measurement of liquids) could be placed lengthways in the same position repeatedly to avoid accessed guided waves variation.

Fig. 5: Wax channel waveguide with a recessed chamber holding an Ocean Optics TM spectrometer cuvette cell.

This waveguide design was chosen to be designed with a recess so the material to be probed in the fluid filled optical spectrometer cuvettes would have maximum access to electromagnetic fields guided in the waveguide, in the most sensitive part of the wax waveguide path length, although waveguides have been designed and manufactured from various materials including PTFE [1]. Standard Ocean Optics Spectrometer cuvettes were chosen to fit in the recess.
We examined the conjecture that the recess design would result in an increase in waveguide coupling. Each cuvette used had the following dimensions: length 4.38 mm, square cross-section 12.1 mm × 12.1 mm, with a fluid volume = 3.25 cm^3. For this work two Cargille refractive index fluid series were purchased: Series A and Series AA of aliphatic/alicyclic hydrocarbons (trade secret) very slightly soluble in water (< 0.1 %), colourless and odourless.

IV. RESULTS AND DISCUSSION

a. Refractive Index Oils

This section focuses on the examination of any observed dependence between microwave waveguide output signal level with changing refractive index of cuvette containing liquid. Measurement for Series AA are shown in fig. 6 for optical refractive index values in the optical refractive index range of N = 1.40 to 1.45 with air as the reference superstrate media, as a function of time. Data samples are already averaged over 2 second intervals by the data logger.

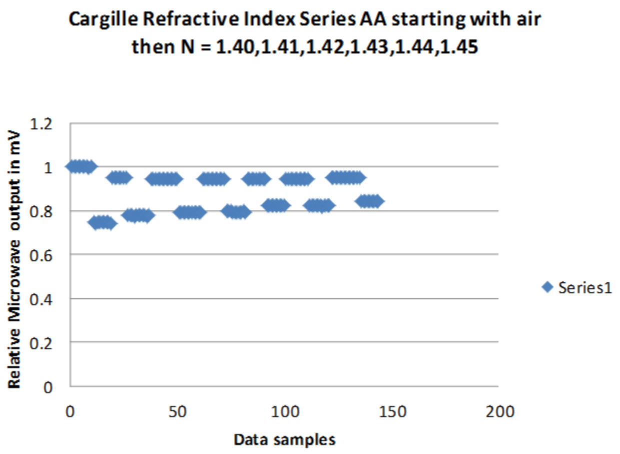

Fig. 6: Relative microwave waveguide output in mV for a range of Cargille Series AA refractive index fluid.

Once averaged and plotted as a function of relative microwave output for the different refractive indices the following graph fig. 7 is obtained.

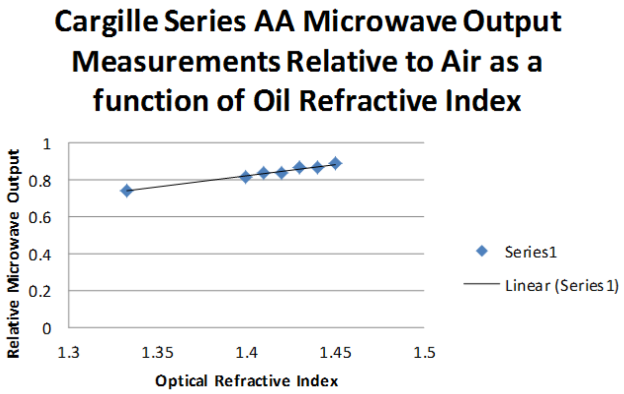

Fig. 7: Microwave waveguide output for wax recessed waveguide as a function of Cargille Series AA for different refractive index.

In fig. 7 there is a strong linear relationship between recessed wax microwave waveguide output (in mV) and the optical refractive index fluid placed into the recessed waveguide structure. Using a simple regression analysis the microwave output y is given by: y = 1.2462 x - 0.9207 where x is the optical refractive index of the matching fluid in question, with R^2 = 0.9833 showing very good correlation between microwave output power level and oil refractive index. A second series of measurements with Cargille Series A, a hydrogenated terphenyl composition of aliphatic/alicyclic hydrocarbons (trade secret), insoluble in water, and a series of oily light yellow liquids is given in fig. 8.

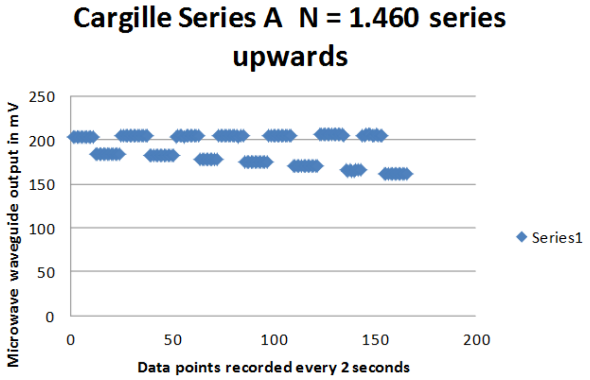

Fig. 8: Microwave waveguide output in mV for the Cargille Series A is shown as a function of optical refractive index.

Averaging all the time dependent results allows us again to find the average time dependent microwave output for each optical refractive index value as seen in fig. 9.

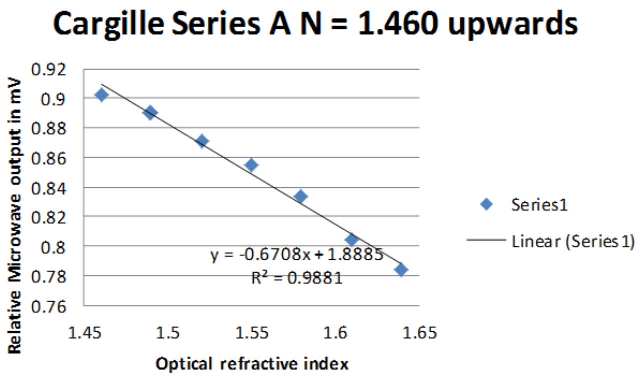

Fig. 9: Microwave waveguide output for various Cargille Series A liquids.

As can be seen by examining fig. 9 there is a strong linear relationship between the recessed wax microwave waveguide output (in mV) and the refractive index fluids placed in the recessed waveguide structure. Using a simple regression analysis the microwave output y is given by: y = -0.6708 x + 1.8885 where x is the optical refractive index of the particular matching fluid in question, with R^2 = 0.9881 showing very good correlation between microwave output power level and the different oils' refractive indices. Air was again used as the reference superstrate media. A sample of Castro GT oil (refractive index N = 1.489 using the Abbe Refractometer) was found to give an almost identical microwave output to the oil having refractive index = 1.49, demonstrating the repeatability of the method.

b. Refractive Index Oils

Considering the lower index range of several other liquid optical materials available, and again using the Abbe spectrometer we obtain the following table 1 of results.

Material	Refractive Index	Relative Transmission Ratio
Distilled Water	1.333	0.743112
NaCl sal-st	1.34	0.704583
NaCl con-mst	1.335	0.718008
Iso Propyl Alcohol	1.379	0.775618
Methanol	1.329	0.794849
Methyl Ethyl Ketone	1.381	0.737555

Table 1 Refractive index for different liquids.

Which when plotted together in a graph with all the various other fluids appear as shown in fig. 10 below.

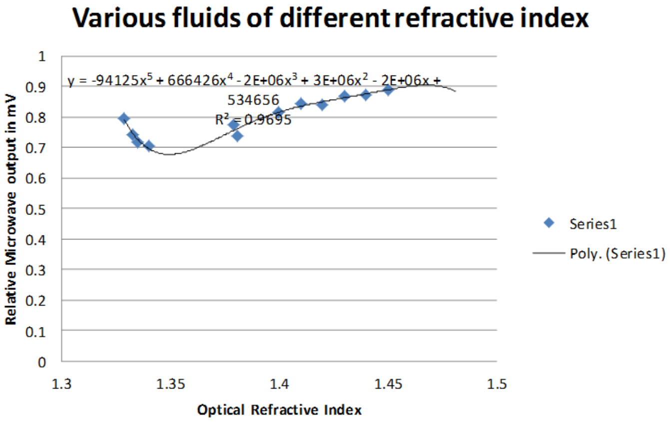

Fig. 10: Relative microwave output in mV for various fluids of different refractive index.

As can be seen by examining fig. 10 for a range of fluids there appears to be a slight dip in microwave transmission, corresponding to a maximum absorption in the range 1.35 - 1.4. This can be fitted with a 5th order polynomial and has a very good regression fit with $R^2 = 0.9695$. It is suggested the lower index end is dominated by OH^- and H^+ ions and ionic polarity whilst the higher index end is largely covalently bonded with Van der Waals forces dominating and is largely non-polar.

c. Refractive Measurements on Enhancement of Guided Wave Access

In each experiment a wax channel waveguide was used having a recessed chamber (fig. 11) into which a standard Ocean Optics ™ spectrometer cuvette cell (for measurement of liquids) could easily be placed lengthways in exactly the same position each time to avoid any variation of accessed guided waves. Various liquids, within cuvettes were placed within the recess, and other solid materials not discussed in this paper. Next an identical wax insert placed into the recess, spacing the cuvette away from the evanescent fields. We investigated the increased interaction with the guided wave mode arising from its having a recessed section of the guide into which to a cuvette was placed (fig. 11). Results are given in fig. 12. The first data is the microwave output for the recessed waveguide filled with a blank wax insert (left). The next data sequence shows the microwave transmission for a cuvette filled with sand (middle). The final data sequence shows the microwave transmission for a sand filled cuvette placed into the recess itself (right).

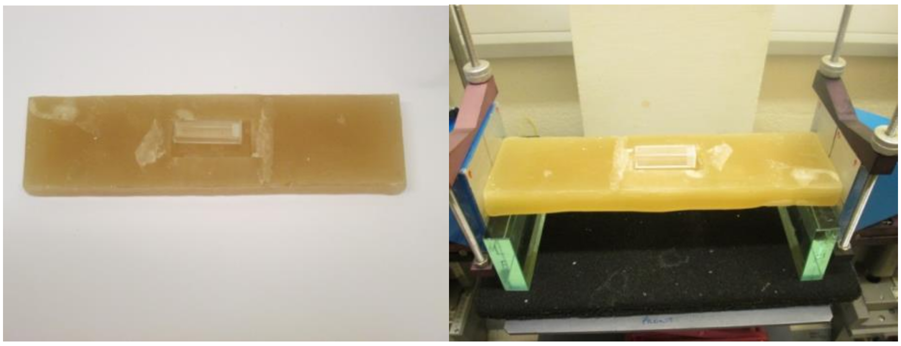

Fig. 11: a) Blank cell in recessed waveguide, and b) Recessed waveguide filled with wax insert and blank cell on top.

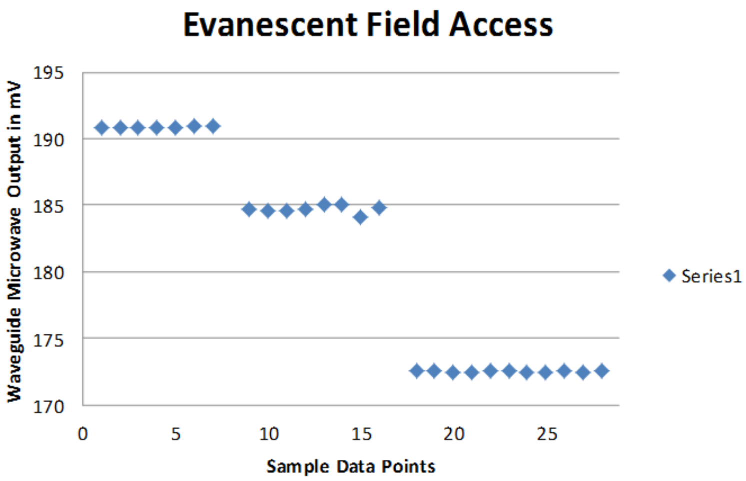

Fig. 12: Typical evanescent field access experimental results.

The percentage increase in waveguide transmission loss due to the use of a recessed region of the waveguide is observed to be 6.6 % greater. The decrease due to sand with the blank insert is a 3.6 % fall compared with the waveguide alone. We can also compare this decrease with the decrease for sand placed into the recess previously occupied by the insert, which is a 9.6 % decrease. This gives rises to a 6.6 % overall decrease due to the recess, and thus an increased sensitivity for change related measurements.

Having already examined some common food products with the microwave recess we undertook an initial food examination of the differences between cooked and uncooked food. For this experiment two eggs of as near identical size as possible were chosen. One egg was cooked for 3 minutes by boiling in a pan of hot water, the other left uncooked. The two eggs were then placed into the recess in the same position in sequence with a portion of the long length of the egg penetrating into the recess: (empty/unboiled back of recess/unboiled front of recess/empty/ boiled back of recess/boiled front of recess). Waveguide transmission figures were first observed as a timed series, and then plotted here as a time *averaged* result in fig. 13.

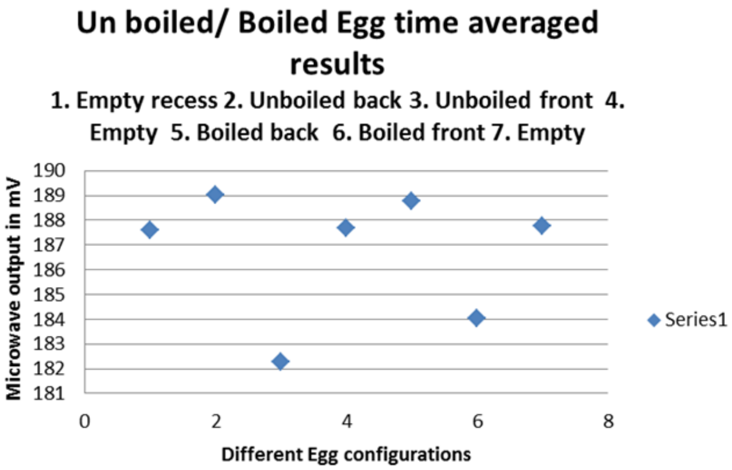

Fig. 13: Boiled/Unboiled egg sequence.

The relative microwave output changes between a boiled egg relative to an unboiled egg shown for the back: a relative microwave ratio of 99.9% and for the front: a relative microwave ratio of 97.5%.These results show that in each case there is a relative drop in transmission which is detectable at a signal level of typically 5 - 7 mV. It is demonstrated that changes in food structure after cooking are detectable. Consequently the cooked egg is seen to have up to a 2.5% reduction in microwave output, principally due to lack of available free resonant bonds in the material inside the egg to absorb as much microwave energy. It is observed that for both liquids and solids use of a recess allowed greater interaction with the electromagnetic fields within the waveguide. It is possible to use the recess to investigate the enhancement of electromagnetic field interaction. A greater waveguide response will likely be found by filling the recess with fluid, effectively flooding the whole cell, ideal for more sensitive response to salinity and other changes of fluid-filled systems.

V. FUTURE WORK

The experimental arrangement which was presented in this paper will be used shortly to characterise further liquid, and liquid-solid mixtures. A range of differently sized and shaped recesses will also be studied. Channel waveguides with such recesses will be fabricated from a range of materials in order to optimise waveguide transmission, and to minimise attenuation losses. The egg experiment provides the basis for further substantive food-based measurements: cooked vs. uncooked, in-date vs. out-of-date, moisture content-related experiments, etc. eggs, could be achieved easily in wax as long as no temperature variation is required, to optimally increase any interaction for better differentiation between ‘good’ and ‘bad’ states of food.

VI. CONCLUSION

Use of a recessed waveguide allowed the dependence of microwave output for a range of various standard Cargille optical refraction fluids and other fluids to be investigated. A recess allowed greater interaction with the electromagnetic fields within the waveguide and an increase in sensitivity when compared with samples placed on, rather than in the recess. Further materials were also characterised with the recess in this way [1]. Without the financial support of ‘Seed corn funding’ for new innovative technologies from the Plymouth University Research and Innovation team this work would not have been possible, nor the patent that arose from this work, emphasising the importance of recognising innovation within STEM subjects.

ACKNOWLEDGEMENTS

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Benjamin Lavers is a FE student specialising in STEM subjects, with particular interest in chemical engineering, and has helped pioneer fabrication of channel and planar microwave sensing devices.