Miniature fibre optic ultrasonic probe

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ABSTRACT

We investigate the feasibility of using optical fibre Bragg gratings for the sensing of ultrasonic fields for medical applications. In preliminary experimental investigations, ultrasonic waves with a frequency of 950kHz have been detected with a noise limited pressure resolution of approximately 10^{-2} atmospheres in a 3kHz measurement bandwidth.

Keywords: Optical fibre sensor, Bragg grating, ultrasound, medical.

1. INTRODUCTION

Optical fibre Bragg gratings are attracting a considerable amount of interest within the optical sensing community. They take the form of a periodic modulation of the refractive index of the fibre core and reflect light of a wavelength satisfying the Bragg condition[1]. The grating period, and hence the reflected wavelength, is dependent on the temperature or strain of the fibre; so by monitoring the reflected wavelength these measurands may be recovered. Currently, most interest is centred around using gratings to monitor strain in composite materials for aerospace applications and in concrete structures, such as bridges. Optical fibre based devices - and Bragg gratings in particular - are also of potentially great benefit to medicine. Their small diameter means they are well suited to minimally invasive procedures, and with their dielectric nature they naturally lend themselves to medical applications involving the presence of electromagnetic fields.

There is continuing need for the assessment of the safety of medical applications of ultrasound due to the trend towards increasing output powers from diagnostic ultrasound equipment and the widening use of high intensity ultrasound in a range of therapeutic applications. Often the assessment of such fields is based upon theoretical models of some complexity and measurements made in phantoms. The fields present in the body are likely to be influenced by many factors and there is a dearth of information regarding the measurement of ultrasonic fields and parameters *in vivo* and *in situ.*

In this paper we report preliminary investigations of the possibility of monitoring high frequency (~MHz) ultrasonic waves using in-fibre Bragg gratings.

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2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig. 1. An Ar^+ laser pumped Ti:sapphire laser was used as the source. This was convenient for our laboratory investigations, though it would have to be replaced by a diode laser in a practical, cost effective system. The source produced several hundred mW of power at 815nm, which was then attenuated to give a launched power of 100μW into the fibre. The source bandwidth was approximately 0.09nm. The Bragg grating had a peak reflecting wavelength of 815nm, a peak reflectivity of 90% and a bandwidth of 0.2nm.

The emission wavelength of the Ti:sapphire laser was tuned so that the reflected power from the grating was approximately half of the maximum attainable. In this way we knew that the system was biased so that any change in the reflected wavelength would result in a near maximum change in the power reflected from the grating. The optical power returned from the grating was monitored using a silicon photodiode in a transimpedance circuit connected to an r.f. spectrum analyser.

The acoustic waves at 950kHz were generated using a 4.7cm diameter concave piezoelectric transducer with a radius of curvature of 5.0cm. The acoustic waves were focused to a near diffraction limited spot of radius 2mm in the region of which the fibre grating was situated. The transducer was driven from a signal generator *via* an r.f. amplifier delivering up to 30W of electrical power. From previous work we estimated that this resulted in approximately 10W of acoustic power being emitted from the acoustic transducer.

3. RESULTS

3.1 Dynamic range

The grating was oriented normal to the acoustic propagation direction and was positioned so as to maximise the signal on the spectrum analyser. As a test of the dynamic range of the system, the voltage from the detector circuit was recovered as a function of the electrical power driving the ultrasonic transducer. The results, covering nearly five orders of magnitude, are shown in Fig. 2.

3.2 Acoustic intensity profile

To demonstrate the spatial resolution of the grating the detector voltage was monitored as the grating was translated normal to both the direction of propagation of the acoustic wave and the axis of the fibre (i.e. out of the plane of the paper in Fig. 1). The results are illustrated in Fig. 3.

3.3 Noise limited resolution

The grating was again positioned so as to give a maximum signal from the detector. In order to determine the noise limited resolution of the system, 30W of electrical power were directed at the piezoelectric transducer, resulting in a peak pressure amplitude in the neighbourhood of the grating of approximately 14 atmospheres (Atm). This latter figure was calculated by assuming a diffraction limited spot size, averaging the intensity over the grating length and taking account of the ~1/3 electrical to acoustic power conversion efficiency of our transducer. The signal to noise ratio measured by the r.f.

spectrum analyser was 58dB with a 3kHz bandwidth. Therefore if we define the noise limited resolution as being the r.m.s. pressure amplitude that leads to unity signal to noise ratio, the resolution may be calculated to be $1.2.10^{-2}$Atm, corresponding to $2.2.10^{-4}$Atm/$\sqrt{}$Hz.

4. DISCUSSION

Considering first of all the data presented in Fig. 2. We would expect the system to be linear over many orders of magnitude. The upper limit would occur when the acoustically induced modulation of the wavelength reflected by the grating becomes comparable to the width of the grating reflectivity profile. However, this condition is far from being reached with the powers used in this work. The figure does show an essentially linear response though there is considerable scatter in the data. We attribute this to the rudimentary nature of the signal processing used. Any drifts in the laser emission wavelength, the laser power, the launching efficiency or the grating wavelength would result in a change in the sensitivity of the transduction process. This problem is now being addressed by the use of more sophisticated signal processing schemes[2].

The diffraction limited focal spot radius for the acoustic transducer used here may be calculated to be 2mm, and this compares favourably with the data presented in Fig. 3. Normal to the fibre axis, the spatial resolution will be comparable to the fibre dimension - here 125microns. Along the fibre axis, the spatial resolution will be limited by the grating length. In our case that was approximately 5mm, though high reflectivity gratings can be produced that are much shorter than this.

The length of the grating also determines the bandwidth of the system if an omnidirectional response is required. If the grating length is comparable to, or greater than, the acoustic wavelength then a certain amount of averaging will occur along the grating length considerably reducing the sensitivity to acoustic waves travelling along the fibre axis. In this study we simply aimed to demonstrate that gratings could be used to sense high frequency ultrasound and therefore the grating length was not minimised. If a grating of 1mm length were to have been used, the omnidirectional bandwidth would have been approximately 1MHz. The bandwidth for normally incident acoustic waves could be at least an order of magnitude above this.

The detector used in Section 3.3 where the noise limited resolution was measured was not optimised for this application and considerable improvements are expected from using a recently acquired avalanche photodiode unit. Finally it should be pointed out, that for many (if not most) of the applications for grating sensors currently under investigation, the sensitivity of the grating to both temperature and strain is a major problem. Several approaches have been described for decoupling the two effects[3], though they all add considerably to the complexity of the signal processing and limit the resolution attainable. Luckily, the problem does not occur in this application, since temperature induced wavelength shifts will occupy a very low frequency range, whilst the signals of interest occur at high frequency.

5. CONCLUSION

We have shown that in-fibre Bragg gratings may be used to sense high frequency (MHz) ultrasonic waves, such as are increasingly being used in medicine. Initial results have demonstrated a resolution of $2.2.10^{-4}$Atm/$\sqrt{}$Hz, though we believe there is considerable potential for improvement.

6. REFERENCES

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2. see for example Kersey A D, *Proc. SPIE*, **2071,** 30-48, 1993.
3. see for example Xu M G, Archambault J-L, Reekie L and Dakin J P, *Electron. Lett.*, **30,** 1085-1087, 1994.

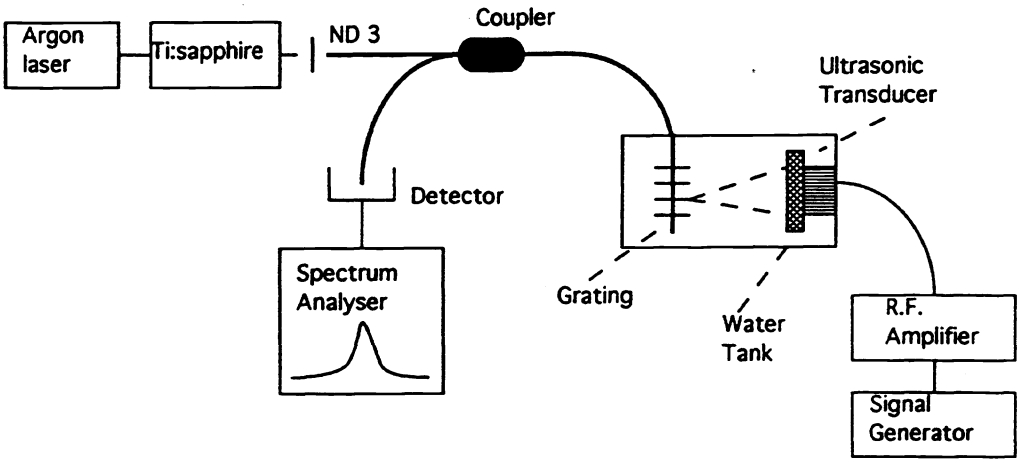

Fig. 1. Experimental arrangement.

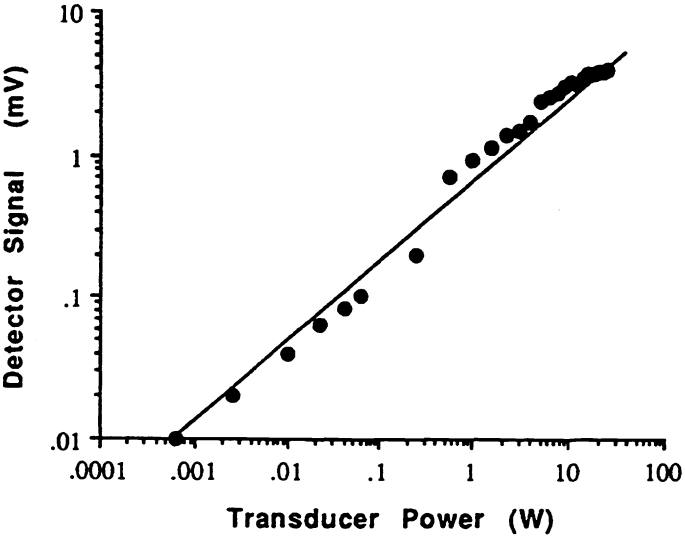

Fig. 2. Detected signal as a function of electrical power to transducer.

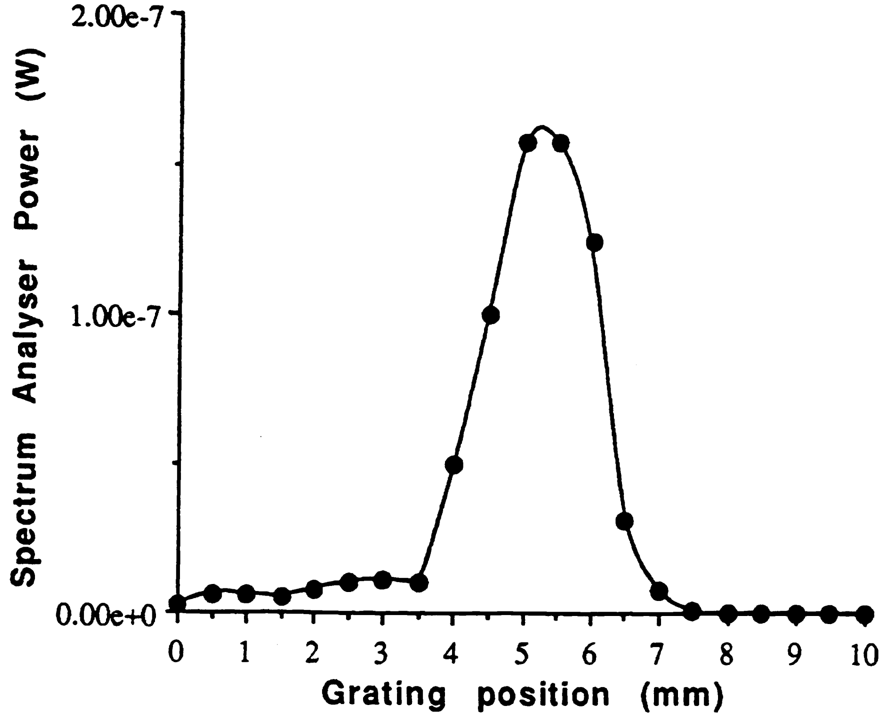

Fig. 3. Detected signal power as a function of lateral fibre grating position.