SHORT IN-FIBRE BRAGG GRATINGS FOR MEASURING MHZ ULTRASONIC FIELDS

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1. INTRODUCTION

There is a need for the assessment of the safety of ultrasound for medical applications [1,2] due to the trend towards increasing output powers from diagnostic ultrasound equipment and the widening use of high intensity ultrasonic fields in a range of therapeutic applications. Often the assessment of such fields is based upon theoretical models of some complexity and so a direct determination of them *in vivo* is of importance. Conventional detection is most commonly achieved using piezoelectric devices but suffers from a susceptibility to electromagnetic interference and signal distortion. To overcome these "electrical" problems several approaches utilising optical fibres based on interferometric or polarimetric techniques have been described [e.g. 3,4]. In this paper we demonstrate that in-fibre Bragg gratings too may be used to detect high frequency (MHz) ultrasonic fields. These devices offer distinct advantages such as ease of multiplexing, simultaneous measurement of temperature, and a potentially low cost. We found however, that the acoustic coupling from the ultrasonic field to the grating leads to the formation of standing waves in the fibre. Because of these standing waves, the system response is complex and, as we show, the grating does not act as an effective probe. However, significant improvement in its performance may be gained with short gratings coupled with appropriate desensitisation of the fibre.

2. EXPERIMENT

The arrangement used to interrogate the grating is shown in figure 1. This utilised a ramped lithium niobate phase modulator (closely set to produce a 2π peak-to-peak phase excursion) to frequency shift the light in one arm of an unbalanced Mach-Zehnder interferometer (MZ) and thus allowed the use of heterodyne signal processing. Light from a pig-tailed superluminescent diode (*Superlum*, Moscow) giving an output power of 1mW centred at 824nm with a bandwidth of $\approx$42nm was launched into the unbalanced MZ; hence a channelled spectrum was created at the interferometer's outputs which was incident on the grating. Incorporated in one arm of the MZ was the phase modulator. The other arm contained a variable air gap which allowed the optical path difference (OPD) between the two arms to be adjusted.

Provided that the OPD between the MZ's arms is longer than the source coherence length and shorter than the effective coherence length of the back-reflected light from the grating, interference signals are observed at the detector which can be expressed as

$$I(\lambda_B) = A(1 + V\cos[\omega' t + \Phi + \delta\Phi \sin\omega t + \phi(t)]) \qquad (1)$$

Here, λ_B is the wavelength of the reflected light from the modulated grating, ω' is the angular frequency of the ramp modulation, A is proportional to the grating reflectivity, V is the visibility of the signals (dependent on the grating bandwidth and the polarisation properties of the system), $\Phi = 2\pi.OPD/\lambda_B$ and $\phi(t)$ is a random phase drift term. A sinusoidally strain-induced change in λ_B from the grating - ($\delta\lambda_B$) - induces a change in phase shift in equation 1, given by $\delta\Phi \sin\omega t = [2\pi.OPD/\lambda_B{}^2].[\delta\lambda_B] \sin\omega t$ where ω is the angular frequency of the ultrasound incident on the grating. Hence, from equation 1, strain induced changes in λ_B induce a corresponding phase modulation of the electrical carrier produced by the phase modulator, which we measured by determining the amplitudes of the upper and lower side-band frequency components observed on a radio frequency spectrum analyser. The phase modulator was ramped at and hence generated a carrier signal at 10MHz. The grating we used had a nominal Bragg wavelength of 820nm, a bandwidth of 0.2nm, a reflectivity of 80% and a length of 5mm. The transducer was driven at its resonant frequency of 1.911MHz in water, and generated a maximum acoustic pressure of ≈ 2Atm (measured using a calibrated PVDF hydrophone) in a focal spot of radius ≈ 1 - 2mm.

3. RESULTS AND DISCUSSION

3.1. *5mm GRATING*

In our preliminary experiments we observed two striking anomalies in the response of the system to the ultrasound. Consider figure 2 which shows a spectrum analyser trace recorded in a typical experiment. Firstly, note that the upper and lower side-band frequency components (the first order Bessel functions) are asymmetric, and secondly note the existance of a large homodyne signal at 1.911MHz, which was up to several dB's greater than the side-band magnitudes.

Now consider figure 3 in which we scanned the focal spot of the acoustical field longitudinally along the fibre/grating and recorded one of the side-band powers (normalised by its corresponding carrier signal power) with displacement. Note the multiple "peaks" and "troughs" in the system response which are observed over a distance that is much greater than the grating length. This too is another unexpected result since the radius of the focal spot is only about 1mm. However, consider the average distance between the peak responses which is 1.475mm. If we hypothesise that the acoustic coupling from the ultrasonic field to the optical fibre leads to the formation of stationary waves in the fibre, this value leads to an experimental acoustic wavelength of 2.95mm which is close to the predicted value of 3.087mm for compressional waves at 1.911MHz in fused quartz. We repeated these experiments but now driving the transducer at 1.6MHz and found an experimental value of 3.76mm which is again close to the predicted value of 3.68mm. Using the same system, we then modulated the grating with low frequency (10^2 Hz) sound waves in air and higher frequency (76kHz) sound waves in water. In both these cases, the system response was as originally expected, with symmetric side-bands and no homodyne signal observed.

Hence we conclude the following. Compressional standing waves are set up by the ultrasound in the fibre (although the acrylic jackets which are on either side of the grating and which are, in the case of figure 3, spaced about 1cm apart, do tend to attenuate the acoustic modes). Since these waves must only partially modulate the grating (as their length is < the grating length), this means that the grating is subject to a *non-uniform* strain and so leads to regions of the grating acting as spectral filters for the back-reflected light from other regions of the grating. This gives rise to an amplitude modulation (the homodyne signal) and, as we show in [5], the amplitude modulation in turn gives rise to the asymmetric side-bands. We finally note that the wavelength of the lower frequency sound is greater than the length of the grating, hence in these cases the grating was subject to a more uniform strain and so none of the anomalies in the system response were observed.

3.2. *1mm GRATING*

Based on our hypothesis, it is apparent that for the grating to operate correctly in response to the MHz acoustic field, the grating length should be made smaller than the acoustic wavelength in fused quartz. In order to demonstrate this, we took a standard 5mm grating and gradually removed small pieces of it from one end until approximately only 1mm of grating was remaining. As each piece was removed, we recorded the system response to the ultrasonic field using the shortened grating, and noted a dramatic decrease in the homodyne signal along with more symmetric side-band magnitudes.

However because of the results of figure 3, it is apparent that this shortened grating on its own cannot be used as a high frequency probe since it will exhibit insufficient longitudinal resolution. In order to obtain an improved performance we must first desensitise nearly all the fibre to the acoustical field. This we did by jacketing the fibre with PVC sleeving (diameter < 1mm) such that only the 1mm grating at the end of the fibre was exposed to the field. The results of a longitudinal a scan of the acoustic focal spot is shown in figure 4 and, as may be seen, this data compares favourably with the diameter of the main diffraction maximum of the transducer.

We finally show in figure 5 the detected magnitude of one of the side-bands (normalised by its corresponding carrier signal) as a function of acoustical pressure incident on the grating. It is clear that the system response is linear and (for this probe) we determined a noise limited pressure resolution of $\approx 4.5 \times 10^{-3}$ Atm / $\sqrt{\text{Hz}}$.

4. CONCLUSIONS

Thus far we have shown that a Bragg grating may function effectively as an ultrasonic probe with mm resolution if: (a) the grating length is much less than the acoustic wavelength in fused quartz and (b) the grating/fibre is appropriately desensitised. One final point should however be noted. By shortening the grating we have dramatically reduced its reflectivity (as well as increased its bandwidth). In our case we found a reduction in the back-reflected light intensity of well over 100. Gratings of lengths less than 1mm but with 90% reflectivity can be manufactured and so we anticipate a greatly improved pressure resolution using such gratings.

5. REFERENCES

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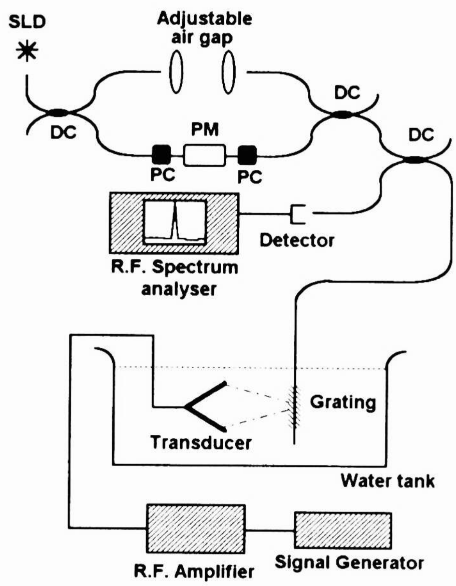

Figure 1. Experimental arrangement
PM = phase modulator
PC = polarisation controller
DC = directional coupler

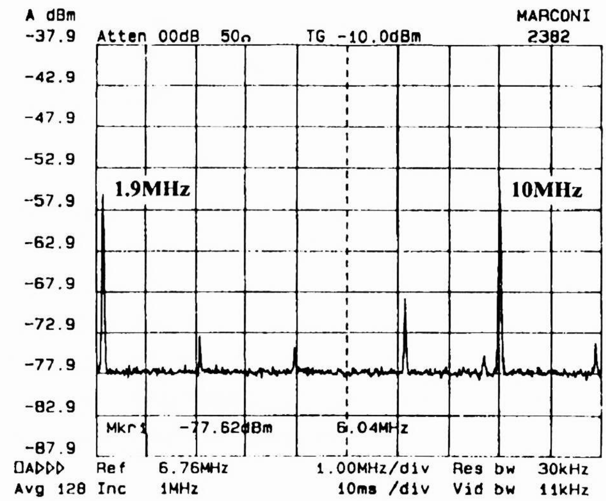

Figure 2. Spectrum analyser trace

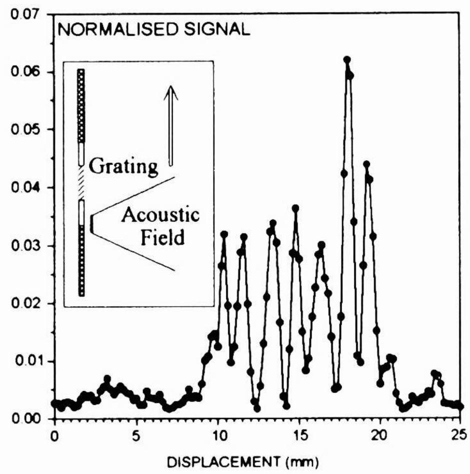

Figure 3.
Longitudinal scan for 5mm grating

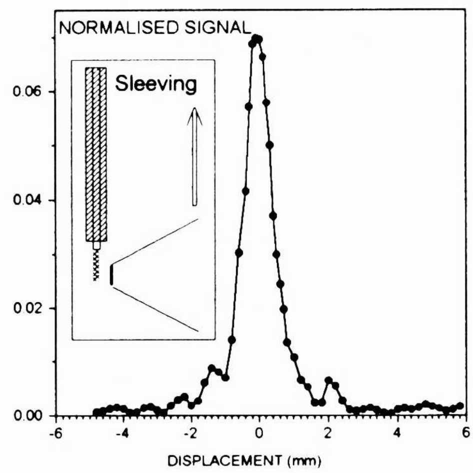

Figure 4.
Longitudinal scan for 1mm grating

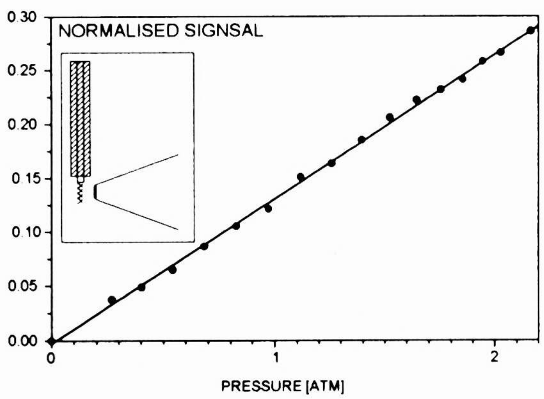

Figure 5.
Side-band amplitude (normalised by carrier amplitude) as a function of acoustical pressure incident on 1mm grating.