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Optimisation of Power Detection Interrogation Methods for Fibre Bragg Grating Sensors

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Abstract Summary

We present a method to optimise the performance of power detection interrogation systems for fibre Bragg grating sensors. The performance of the different systems can be optimised in terms of their sensitivity and/or dynamic range.

Keywords- fibre Bragg grating; modelling; optimisation; sensing

I. INTRODUCTION

Intensiometric detection with Fibre Bragg Gratings (FBGs) was first reported by Webb et al [1]. This was an essential interrogation method, as they were interested in the use of FBG for the detection of high frequency ultrasound, particularly, *in vivo*. This initial work utilised a narrow bandwidth source, power detection method, making use of the FBG as a spectrally reflective element. Following this, work by Takahashi et al used the FBG as a transmissive filter [2]. Both the reflected and transmitted signals can also be utilised in an interrogation system for high frequency signals [3]. Following this work on power detection methods to utilise FBG to detect high frequency ultrasound came the use of edge filter detection methods. The first edge filter detection method made use of a matched linear FBG filter [4]. In place of the matched FBG, other edge filter detection systems have also made use of interference filters [5], Wavelength Division Multiplexing (WDM) couplers [6], and Arrayed Wave Guides (AWGs) [7].

The previously mentioned intensiometric detection systems are essential for the detection of high frequency dynamic signals, such as ultrasound. However, FBGs are typically utilised as spectral transduction elements, where the change in the measurand is detected via a shift in the peak wavelength of the FBG. As such, the signal measured is effectively independent of any input optical power fluctuations. Also, this allows a large number of FBGs to be multiplexed together along a single optical fibre, with Wavelength Division Multiplexing (WDM) [8]. However, the measurement of the wavelength shift is relatively slow, and also expensive. For example, the SFI710 interrogator is capable of 40kHz sampling on eight channels (Fiberpro, San Jose, CA), while the si920 interrogator is capable of 100kHz sampling on four channels (Micron Optics, Atlanta, GA). These two top of the line interrogators can therefore not be used for the detection of high frequency ultrasound (above 100kHz).

The need to use FBGs as intensiometric sensors for the detection of high frequency ultrasound leaves a lot of questions to be asked. The most important of which is how will a given intensiometric detection system perform, particularly in terms of the sensitivity and dynamic range? To answer this question we have built on previous work, based on analytical [9], and numerical modelling [10], of intensity based FBG interrogation methods, to optimise these detection systems. Here we present a means of optimising power detection based systems, in terms of either their sensitivity or the dynamic range.

II. THEORY

A. Power Detection Methods

In the power detection methods, the shift in the FBG peak wavelength (the Bragg wavelength) is detected due to the spectral properties of the Light Source (LS). The FBG acts as a filter that splits the incident optical power into a component reflect and a component transmitted. As the applied measurand changes the Bragg wavelength, the total power transmitted and reflected will change. There are three types of power detection methods, linear edge source [11], narrow bandwidth source [1, 2, 3], and matched source [9]. The difference between these is the Full Width Half Maximum (FWHM) of the sensing FBG relative to the FWHM of the LS. For linear edge source power detection, the LS FWHM is greater than the FBG FWHM. That is, the LS is broader than the FBG, and as a result, the edge of the LS appears almost linear to the FBG. In contrast, for narrow bandwidth source power detection, the LS FWHM is less than the FBG FWHM. That is the LS is narrower than the FBG, and as a result, the edge of the FBG appears almost linear to the LS. Finally, for the matched source power detection, the LS FWHM is equal to the FBG FWHM.

B. Analytical Model

We assume that the spectral output of the LS is a Gaussian, given by,

$$L(\lambda) = \frac{P}{\Delta\lambda_L}\sqrt{\frac{\ln 16}{\pi}}\exp\left[-\ln 16\left(\frac{\lambda-\lambda_L}{\Delta\lambda_L}\right)^2\right]. \quad (1)$$

Here, λ_L is the centre wavelength of the LS, $\Delta\lambda_L$ is FWHM of the LS, and P is the total optical power emitted by the LS.

The spectral response of the FBG can is also assumed to be Gaussian. That is,

$$S(\lambda) = S_0 \exp\left[-\ln 16\left(\frac{\lambda-\lambda_S}{\Delta\lambda_S}\right)^2\right], \quad (2)$$

where λ_S is the Bragg wavelength, $\Delta\lambda_S$ is the FWHM of the Gaussian, and S_0 is the peak reflectivity of the FBG, which will typically have a value of one for a single FBG sensors (as in this model).

The portion of the LS power that is reflected, R, by the FBG as a function of wavelength is given by

$$R = \int_{-\infty}^{\infty} L.Sd\lambda = S_0 L_0\sqrt{\frac{\pi}{\alpha_S+\alpha_L}}\exp\left[-\frac{\alpha_S\alpha_L}{\alpha_S+\alpha_L}(\lambda_S-\lambda_L)^2\right]. \quad (3)$$

C. Performance Characteristics

The maximum sensitivity, s_{max}, is defined as the derivative of the reflected power with respect to the Bragg wavelength λ_S, maximized over λ_S

$$s_{\max} = \max_{\lambda_S}\left(\frac{dR}{d\lambda_S}\right). \quad (4)$$

While the maximum sensitivity is a measure of the rate of change of the output with respect to the input, the dynamic range is a measure of the range of inputs over which a change in output is observed (based on a linear approximation of the output at the maximum sensitivity point). The dynamic range can therefore be defined as the ratio of the maximum reflected power to the maximum sensitivity,

$$DR = \frac{R_{\max}}{s_{\max}}. \quad (5)$$

III. Modelling Results

Previous work investigating the above power detection model has shown that there are well defined analytical relationships for the maximum sensitivity and dynamic range [9], given respectively by,

$$s_{\max} = S_0 P\sqrt{\frac{2\ln 16}{e}}\frac{\Delta\lambda_S}{\Delta\lambda_S^2+\Delta\lambda_L^2}, \quad (6)$$

and,

$$DR = \sqrt{\frac{e}{2\ln 16}(\Delta\lambda_S^2+\Delta\lambda_L^2)} \quad (7)$$

We can then investigate the three general cases of interest in power detection, matched source ($\Delta\lambda_S = \Delta\lambda_L = \Delta\lambda$), narrow bandwidth source ($\Delta\lambda_S >> \Delta\lambda_L$), and linear edge source ($\Delta\lambda_S << \Delta\lambda_L$).

A. Matched Source

For matched source power detection we can set the FWHM of the FBG equal to the FWHM of the LS. This then gives,

$$s_{\max} = \frac{S_0 P}{\Delta\lambda}\sqrt{\frac{\ln 16}{2e}}. \quad (9)$$

Here we see that the sensitivity is related to the reflectivity, the incident optical power, and the FWHM of the FBG and LS.

Similarly, we can simplify the dynamic range to be,

$$DR = \sqrt{\frac{e}{\ln 16}}\Delta\lambda. \quad (10)$$

Here we see that the dynamic range for matched source power detection only depends on the width of the devices.

B. Narrow Bandwidth Source

For the narrow bandwidth source power detection, we need the FWHM of the FBG to be much greater than the FWHM of the LS. The maximum sensitivity equation behaves asymptotically as

$$s_{\max} \sim \sqrt{\frac{2\ln 16}{e}}\frac{S_0 P}{\Delta\lambda_S}. \quad (11)$$

The dynamic range for the narrow bandwidth source power detection behaves asymptotically as,

$$DR \sim \sqrt{\frac{e}{2\ln 16}}\Delta\lambda_S. \quad (12)$$

Here we see that for the performance of the narrow bandwidth source only the FWHM of the FBG is important, along with the reflectivity of the FBG and the LS power.

C. Linear Edge Source

Finally, for the linear edge source, where the FWHM of the FBG is much less than the FWHM of the LS, the maximum sensitivity behaves asymptotically as

$$s_{\max} \sim \sqrt{\frac{2 \ln 16}{e}} \frac{S_0 P \Delta\lambda_S}{\Delta\lambda_L^2}, \tag{13}$$

while the dynamic range behaves as

$$DR \sim \sqrt{\frac{e}{2 \ln 16}} \Delta\lambda_L . \tag{14}$$

That is, while the sensitivity for the linear edge source is dependent of the FWHM of the FBG and LS, the dynamic range is depends only on the FWHM of the LS.

IV. Optimisation Results

For the optimisations we considered the three power detection methods, utilising various sources available in the Photonics Laboratory at ECU; this includes a tunable laser which has a FWHM of 0.082nm and an optical power of 6.5mW, and a SLD with a FWHM of 40nm and an optical power of 25mW.

A. Matched Source

Using Equations (9) and (10), the maximum sensitivity and dynamic range of the tunable laser can be calculated to be 56.6mW/nm and 0.081 nm, respectively. An ideal peak reflectivity of 1 has been assumed for the FBG.

B. Narrow Bandwidth Source

Rearranging (7) enables the dynamic range of the narrow bandwidth source system to be optimised via the selection of the FBG FWHM. This gives,

$$\Delta\lambda_S = \sqrt{\frac{2 \ln 16 \, DR^2}{e} - \Delta\lambda_L^2} . \tag{15}$$

Again, the available tunable laser was used for the LS FWHM and *P*. Fig. 1 shows the required FBG FWHM to achieve the desired dynamic range. Here we see that the greater the desired dynamic range, the greater the FBG FWHM required. Note that the possible dynamic range is restricted by the condition

$$DR > \sqrt{\frac{e}{2 \ln 16}} \Delta\lambda_L . \tag{16}$$

Similarly, rearranging (6) gives the equation to optimise the sensitivity of the narrow bandwidth source case via the selection of the FBG FWHM. This gives,

$$\Delta\lambda_S = \frac{P}{s_{\max}} \sqrt{\frac{\ln 16}{2e}} \pm \sqrt{\frac{P^2 \ln 16}{2 e s_{\max}^2} - \Delta\lambda_L^2} \tag{17}$$

Fig. 2 shows that full plot of this relationship, although the shaded area to the bottom violates the requirement for a narrow bandwidth source system (that the FBG FWHM is greater than the LS FWHM). As expected, to achieve a greater sensitivity in a narrow bandwidth source system, a narrower FBG is required. Note also that the behaviour of the log-log plot is approximately linear in the limiting case, with a gradient of -1.

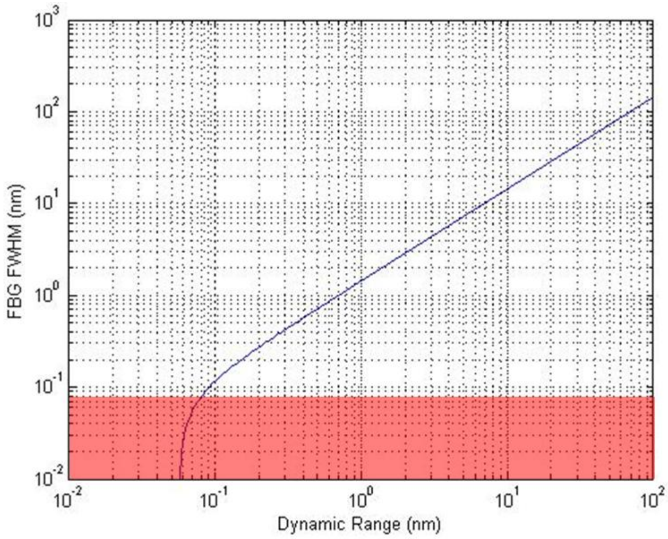

Figure 1. Optimising the dynamic range for the narrow bandwidth source, using a laser with a FWHM of 0.082nm and a P of 6.5mW. Note, the lower shaded region violates the requirement for a narrow bandwidth source.

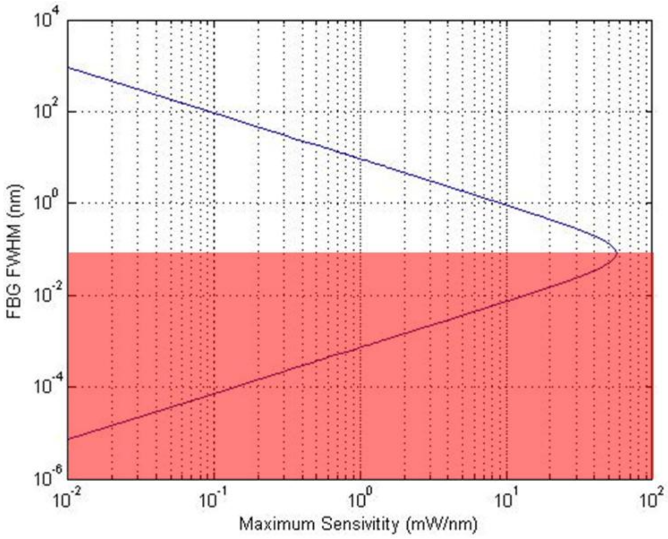

Figure 2. Optimising the sensitivity for the narrow bandwidth source, using a laser with a FWHM of 0.082nm and a P of 6.5mW. Note, the lower shaded region violates the requirement for a narrow bandwidth source.

C. *Linear Edge Source*

Equations (15) and (17) still apply for the linear edge source system.

Fig. 3 shows the required FBG FWHM to achieve the desired dynamic range. As expected from Equation (14), the dynamic range is virtually independent of the FBG FWHM, as indicated by the vertical section of the graph.

Fig. 4 shows the effect of changing from the relatively narrow laser to the SLD (compared to Fig. 2). Again, the shaded region, now the upper half, is not a linear edge source as the FBG FWHM is greater than the LS FWHM. Here we can see that the maximum achievable sensitivity is significantly less than the case in Fig. 2. However, the dynamic range is significantly greater. Also note that the sensitivity increase with FBG FWHM, as the amount of power from the broad band light source reflected by the FBG increase with its FWHM.

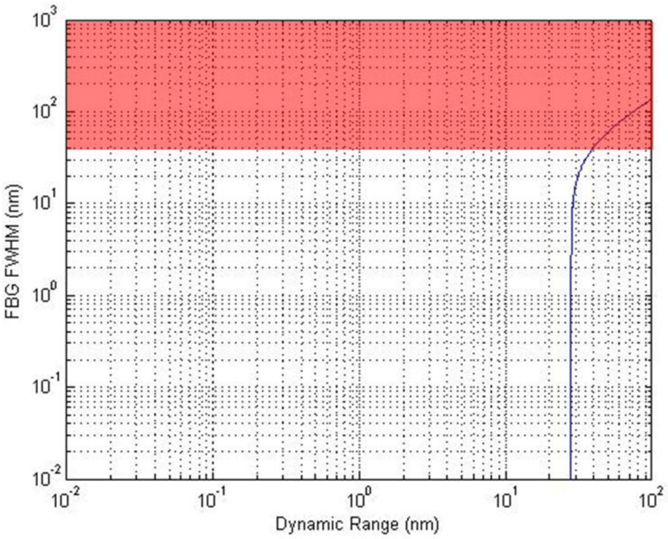

Figure 3. Optimising the dynamic range for the linear edge source, using a SLD with a FWHM of 40nm and a P of 25mW. Note, the upper shaded region violates the requirement for a linear edge source.

V. Conclusion

In conclusion, we have used a previously developed analytical model for power detection systems to optimise these interrogation systems. All three power detection methods were investigated, including narrow bandwidth source, linear edge source, and matched source power detection. Optimisation was then performed on these three power detection systems in terms of their dynamic range and maximum sensitivity. For power detection systems, the sensitivity is always maximised by matching the FBG FWHM to the LS FWHM. For a narrow bandwidth source, increasing the FBG FWHM decreases the maximum sensitivity, while for a linear edge source, increasing the FBG FWHM increases the maximum sensitivity. In terms of the dynamic range, the wider the FBG (and the LS for the matched source) the greater the dynamic range.

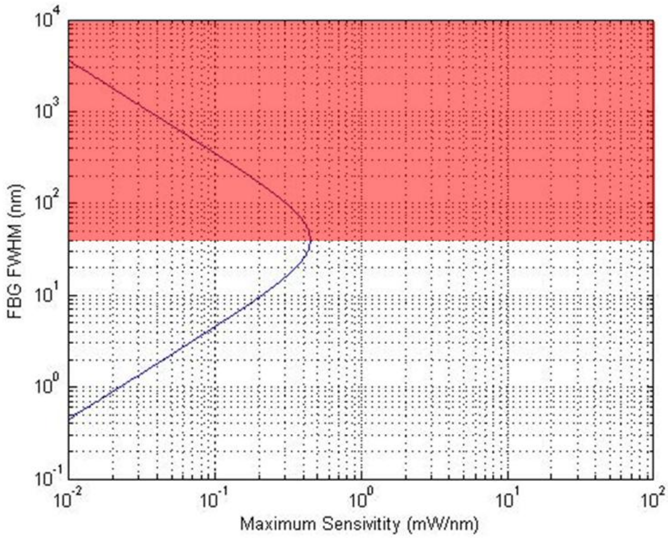

Figure 4. Optimising the sensitivity for the linear edge source, using a SLD with a FWHM of 40nm and a P of 25mW. Note, the upper shaded region violates the requirement for a linear edge source.

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