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Strain Related Characteristics of Composite Cavity Fibre Lasers

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ABSTRACT
A novel composite cavity fibre laser (CCFL) design is being investigated for its use in sensing applications. A CCFL can be fabricated simply by writing three spectrally matched Bragg gratings directly into a continuous length of doped fibre. When strained evenly, so that the strain experienced by both cavities are the same, the strain response of the CCFL is expected to be similar to that of a FBG or single cavity fibre laser sensor. However, if the internal cavities are strained unevenly, simulations derived from theoretical analysis suggest that the wavelength-encoded and intensity-encoded sensitivities can become significantly different from that of a typical single cavity fibre laser. A 3cm/9cm CCFL was tested using three different straining formats, and results agree well with theoretical expectations.

KEYWORDS: Fibre laser, Fibre sensing, Fibre laser sensor head.

1. INTRODUCTION

Typical fibre Bragg grating (FBG) or single cavity fibre laser sensors have a linear wavelength response to strain (approximately 1.17pm/με for bare fibre sensors operating in the 1550nm region) [1-4]. Such sensors have negligible sensitivity in terms of reflectivity (for the FBG), or in output intensity (for the fibre laser). With a composite cavity fibre laser (CCFL) based sensor, shown in Figure 1, similar responses can be achieved. But unlike typical fibre sensors, the CCFL can also be adjusted to have a non-linear wavelength response and a substantial intensity response.

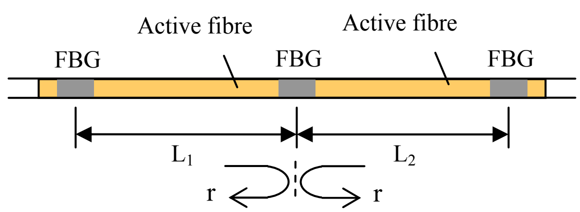

Figure 1. Novel composite cavity fibre laser with active internal feedback.

The CCFL is essentially three wavelength matched FBGs written in a long length of active fibre [4]. When strained evenly (i.e. both sub-cavities L_1 and L_2 experience the same strain), the lasing output of a CCFL sensor will behave similarly to typical FBG sensors, distributed Bragg reflector (DBR) or distributed feedback (DFB) fibre laser sensors. But if the CCFL sensor is strained unevenly, distinctive responses are expected. A non-linear response with alternating sections of higher and lower wavelength sensitivity can be achieved. Such characteristics can be used to improve the sensitivity of dynamic sensing systems that detect small signals, such as a fibre laser hydrophone. Simulations also show that the feedback phase also affects the threshold gain, and thus influence the output intensity. Uneven straining can be achieved by various means, such as coating the sub-cavities inhomogeneously with materials of different Young's Modulus.

An in-house fabricated 3cm/9cm CCFL was used to examine three different straining formats: both cavities strained, only the 3cm cavity strained, and only the 9cm cavity strained. Results agree well with the simulations.

2. THEORETICAL ANALYSIS AND SIMULATIONS

2.1 Theoretical Analysis of CCFL

A brief explanation of the theoretical analysis applied to solve the boundary value problem for the fields in the CCFL is given below, which is similar to that used in [6-7]. Taking into consideration that both cavities of the CCFL allow for

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optical gain (i.e. internal feedback) and that FBGs have symmetrical reflectivity from either direction, the general condition for the phase and gain threshold conditions for the CCFL can be written as

$$1 = r_A r_B e^{i\phi_1} g_1 + r_B r_C e^{i\phi_2} g_2 + \left(1 - 2r_B^{\ 2}\right) r_A r_C e^{i(\phi_1 + \phi_2)} g_1 g_2 \tag{1}$$

Where r_A, r_B and r_C are the amplitude reflection coefficients for the FBGs from left to right respectively, ϕ_1 and ϕ_2 are the round trip phase for the first and second cavity respectively, and g_1 and g_2 are the round trip gain for the first and second cavity respectively. Equation (1) for the CCFL is significantly different to its counter part for the traditional semiconductor external cavity laser, and gives rise to distinct properties. By defining a complex feedback parameter z,

$$z = \frac{1 - r_B r_C e^{i\phi_2} g_2}{1 + \left(1 - 2r_B^{\ 2}\right)\dfrac{r_C}{r_B} e^{i\phi_2} g_2} \tag{2}$$

Equation (1) can be written as

$$g_1 = \frac{e^{-i\phi_1}}{r_A r_B} z = \frac{e^{-i\phi_1}}{r_A r_B} e^{G_z + i\phi_z} = e^{2(\gamma_2 - \alpha_2)L_2} \tag{3}$$

where G_z and ϕ_z are related to the magnitude and phase of z respectively, γ_1 and α_1 are the gain and loss coefficients per unit length respectively of the first cavity, and L_1 is the length of the first cavity. From Equation (3), the threshold gain and phase conditions (hence also lasing wavelength) of the CCFL can be derived by collecting the real and imaginary terms,

$$2\gamma_{1threshold} L_1 = 2\alpha_1 L_1 - \ln(r_A r_B) + G_z \tag{4}$$

$$\phi_z - \phi_1 = p2\pi \text{ , } p \text{ integer} \tag{5}$$

In Equation (4), it can be seen that the term G_Z can be considered as a additive term which alters the threshold gain.

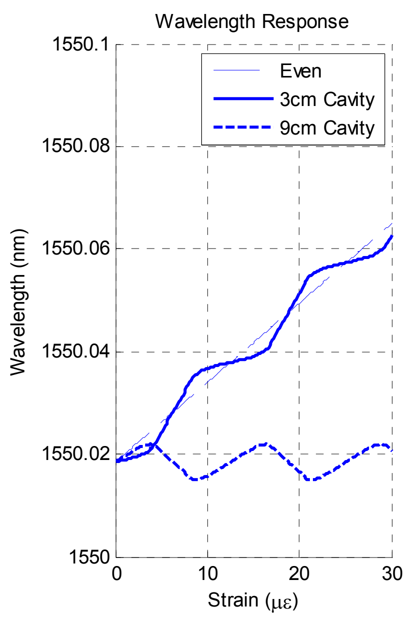
2.2 Simulated Responses

For the simulations, $r_B = 0.8$, $r_C g_3 = 0.7$, the cavity lengths L_1 and L_2 are 3cm and 9cm respectively, the effective refractive index of both cavities are assumed to be 1.456, and the strain-optic coefficient is set to zero. Three different straining formats are considered, and the simulated results are shown in Figure 2, where significantly different results were observed between the even format and the uneven formats.

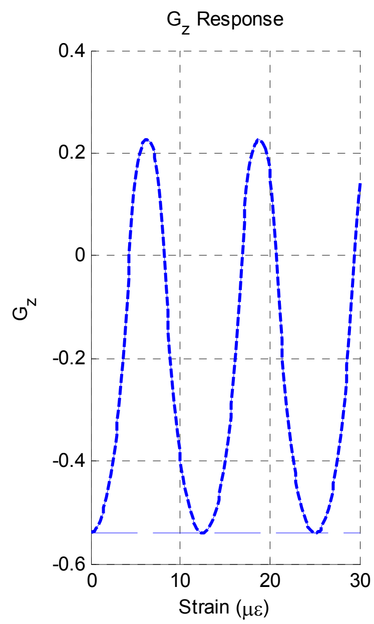
A linear wavelength response is expected for the even straining format. For the case of a bare fibre CCFL, the sensitivity can be adjusted by applying -0.22 as the strain-optic coefficient, to become approximately 1.17pm/με. No change is expected in the threshold gain due to strain. These show that under the even straining format, a CCFL sensor is comparable to other typical FBG based sensors.

For the case of only the 3cm cavity strained, alternating sections of faster and slower wavelength response (still positive) can be observed, which on the whole still follow the wavelength response of the even straining format. By applying pre-strain to bias the CCFL to operate at a wavelength with high wavelength sensitivity (i.e. 6 με in Figure 2a), a CCFL sensor packaged in this uneven format can have a companding (or compansion) behaviour (rate of wavelength shift is inversely proportional to absolute strain change). This should be beneficial for small dynamic signal sensing, such as the hydrophone. It should be noted, that the amplitude of the oscillating wavelength sensitivity is related to $r_C g_3$, which in turn is determined by the reflectivity of the FBG and pump power applied to the CCFL. Fluctuations in G_z are also expected, which should affect the output power of the CCFL and cause it to be applicable in intensity-based sensing systems.

For the case of only the 9cm cavity strained, the lasing wavelength oscillates (alternating sections of positive and negative response) between a confined range. With adequate fringe counting methods, this sensing format can be applied for sensing static signal with large dynamic range, while requiring a smaller wavelength window than other typical FBG based sensors, and therefore allows for higher capacity multiplexing. The fluctuations in G_Z against strain were found to be the same as those of the other uneven case (identical result in Figure 2b).



(a)



(b)

Figure 2. a) Simulated wavelength response for three different straining formats.

b) Simulated G_Z response for three different straining formats.

3. EXPERIMENT SETUP

The experiment setup used to operate the CCFL, and to detect the wavelength shift is shown in Figure 3.

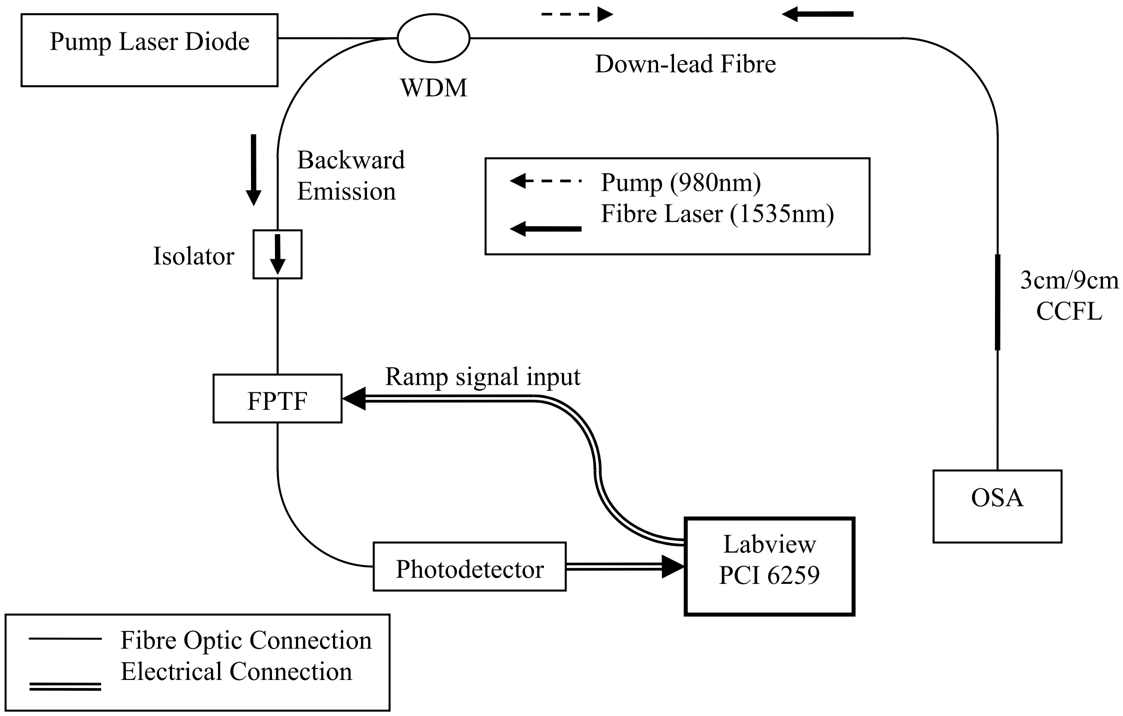


Figure 3. Experiment setup used to operate and examine the CCFL.

The 980nm pump wavelength is channelled to the CCFL via a wavelength division multiplexer (WDM) and a length of downlead fibre. The downlead fibre used is STACKER YALE fibre with single mode cutoff at 890 to 950nm, whose mode field diameter is approximately 10μm at 1550nm. The WDM also serves to channel the CCFL emission to a *MICRON OPTICS Fiber Fabry Perot Tunable Filter* (FPTF), which has approximately 1.75GHz (~14pm) spectral width for high resolution measurements. A FPTF is required to detect the wavelength shift of the CCFL, as an optical spectrum analyser (OSA) does not have the resolution required to detect the minute changes in wavelength.

When optically pumped, the fibre laser produces emission in the 1535nm region from both ends. The backward emission is used for detecting the wavelength shifts, as it does not contain any residue pump wavelength. An isolator is placed after the WDM to prevent undesirable back reflections into the CCFL. An OSA is connected to the forward emission, to monitor the general status of the CCFL.

The gluing arrangements applied to the 3cm/9cm CCFL to examine the three sensing formats are shown in Figure 4. For each format, an upper gluing point is used to secure the CCFL against a floating shelf, so that it is hung vertically. A lower gluing point is then used to secure a light weight basket. Weights are placed in the basket to control the strain applied to the section of the CCFL between the two gluing points.

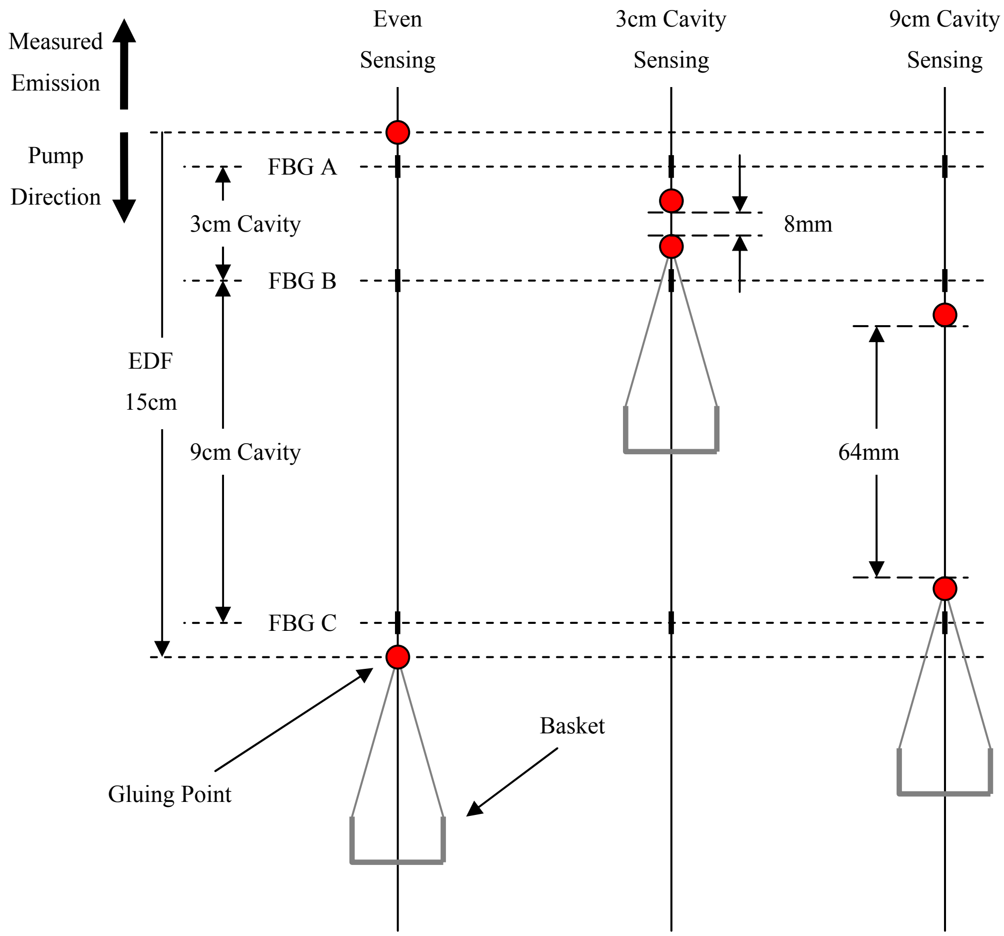


Figure 4. Gluing arrangements applied to the 3cm/9cm CCFL to examine three sensing formats.

Since it is important for the three FBGs to remain spectrally matched, glue cannot be applied to the sections which contain the gratings. And after the glue is cured, it was measured that only 8mm of the 3cm cavity and 64mm of the 9cm cavity remain to experience the straining. To ensure consistency in the results, the same CCFL was used (acetone was used to dissolve the glue after each set of measurements), and 28mW of pump power was delivered to the CCFL in all three cases.

4. RESULTS

The wavelength response of the CCFL under the three sensing formats are shown in Figure 5 to 7. Due to the wavelength ambiguity introduced by the FPTF, the results are expressed in terms of relative frequency shift, rather than wavelength. At 1535nm, a 1nm shift is approximately equivalent to a relative frequency shift of 127GHz.

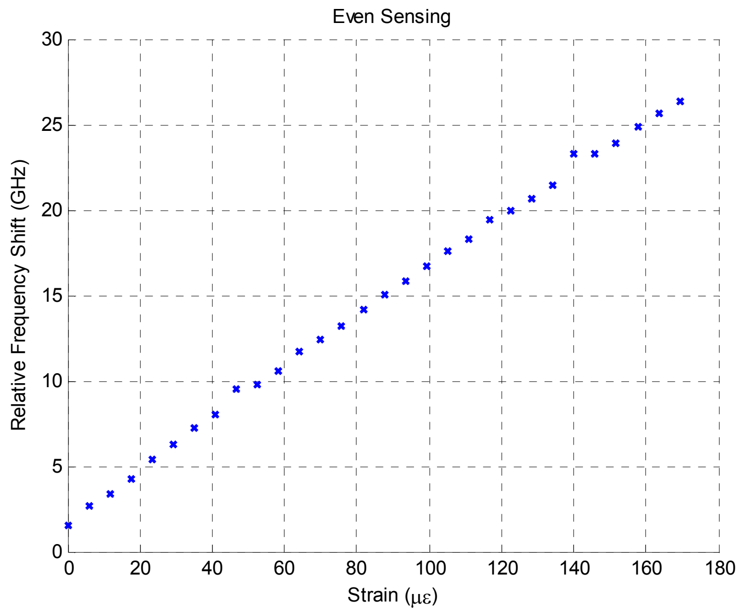


Figure 5. Linear response of the even sensing format.

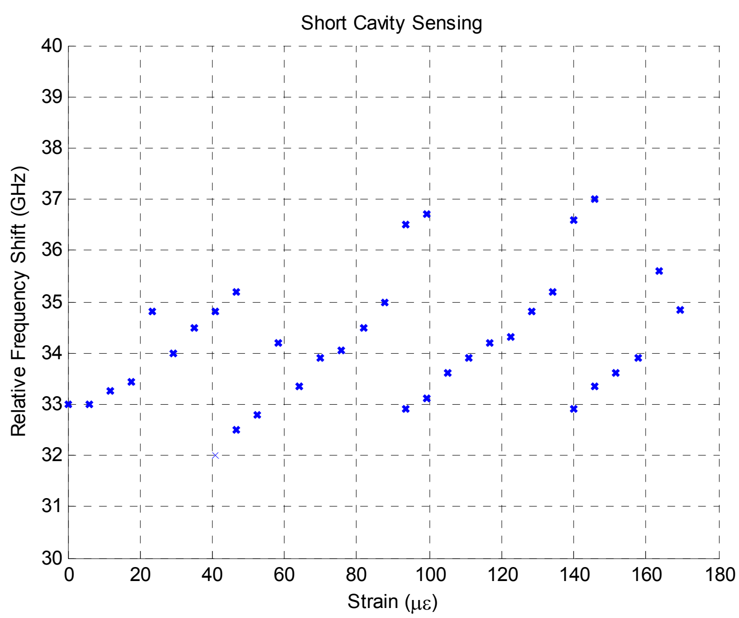


Figure 6. Response of the short cavity sensing format.

For the even straining format, a linear response of 1.17pm/με was observed, which was intuitively and theoretically expected. For the short cavity sensing format, four sections with a response of approximately 0.26pm/με was observed. The response was broken into four sections as a result of the mode moving out of the spectral width of the FBGs, i.e. four lasing modes had scanned through the FBG's spectral width over 170με. Also, the response is lower than suggested by Figure 2 because only 8mm of the 3cm cavity is exposed to the straining.

For the long cavity sensing format, the lasing wavelength appears to be limited to two bands that about approximately 1GHz apart, and rather insensitive to strain. The reason of the insensitivity is attributed to the application of a large value of $r_C g_3$, caused by the high reflectivity of the FBGs and also high pump power, which vastly reduces the amplitude of the wavelength sensitivity shown in Figure 2. By reducing the FBG reflectivity during fabrication, the range of values of $r_C g_3$ that can give rise to the distinctive responses can be increased, so that the distinct features of the CCFL sensor can be better examined.

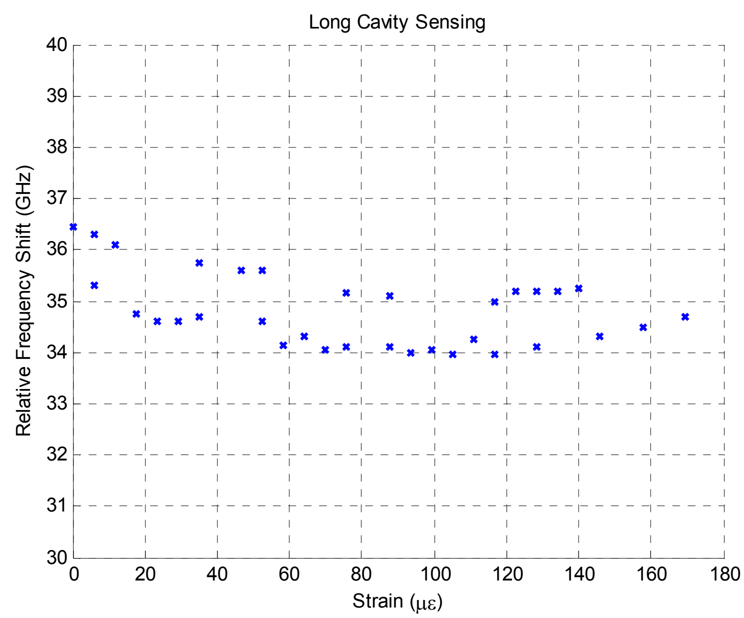


Figure 7. Response of the long cavity sensing format.

Figures 8 to 10 illustrate the spectral footprint occupied by the three sensing formats. It can be seen that although the even sensing format is simplest to operate, it also take up a large spectral window, thus the number of sensors that can be multiplexed are less than sensors in the uneven sensing formats.

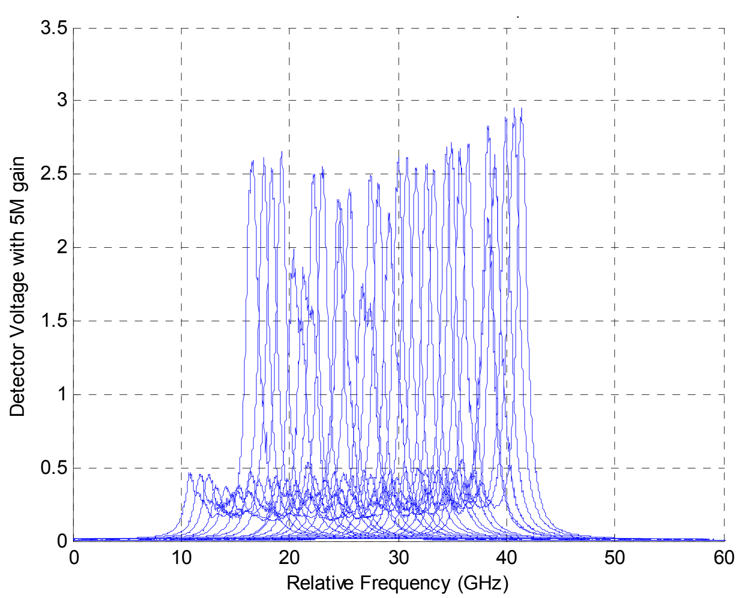


Figure 8. Spectral footprint of the even sensing format over 170με.

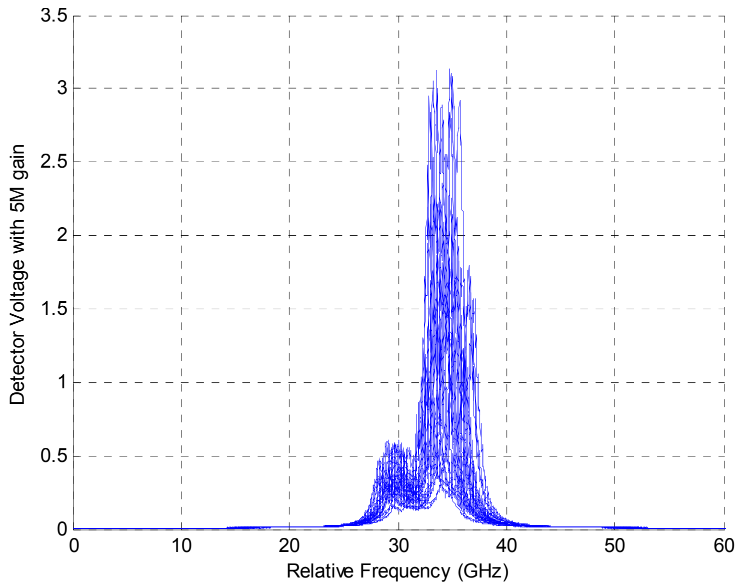


Figure 9. Spectral footprint of the short cavity sensing format over 170με.

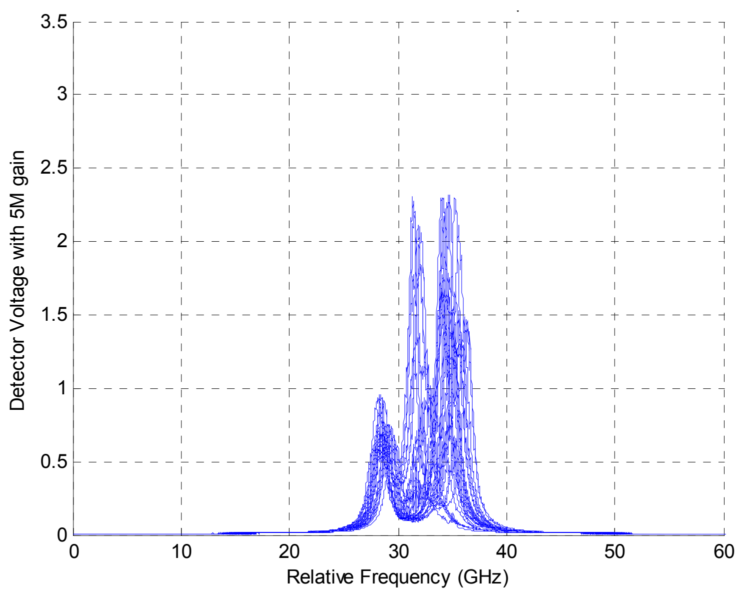


Figure 10. Spectral footprint of the long cavity sensing format over 170με.

For the even sensing format, its spectral footprint is proportional to the dynamic range of the sensor (strain applied). For the two uneven formats, the spectral footprint are mostly determined by the spectral width of the FBGs. From the tail of the FPTF scans, it can be seen that the emission profiles essentially remained in the same position over 170με.

Alternatively, rather than causing one of the cavities to experience strain, if the coating or packaging methods are used to prevent only one cavity from straining instead (still unevenly strained), then the CCFL can be applied in dual parameter strain-temperature sensing. Strain will cause localised fluctuations, and temperature changes will shift the overall spectral position of the emission profile.

When sensing signals with a large dynamic range, the buffering or reserved wavelength slot required for a CCFL operating in the uneven format will be significantly less than that of a typical FBG based sensor. Hence improved multiplexing is possible, if fringe counting or similar methods is applied.

5. CONCLUSION

A novel composite cavity fibre laser (CCFL) design is being investigated for its use in sensing applications. A CCFL is essentially three spectrally matched Bragg gratings written in a continuous length of doped fibre. Theoretical analysis was derived for the CCFL, and was found to be distinct to that of the tradition semiconductor external cavity laser. Simulations show that when the cavities of the CCFL are strained evenly, the strain response of the CCFL is the same as that of a FBG or single cavity fibre laser sensor. However, if the internal cavities are strained unevenly, the responses can be altered significantly. Alternating sections of higher and lower wavelength sensitivity were identified, as well as threshold gain fluctuations. Such characteristics can be beneficial to applications such as hydrophone, whose signal of interest is dynamic and small in amplitude.

A 3cm/9cm CCFL was used to test three different sensing formats, to investigate the differences in even and uneven straining. The preliminary results were consistent with theoretical expectations. Further work in fabricating CCFL with FBGs of lower reflectivity is required to emphasise the distinctive feature of the uneven sensing formats.

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