Long cavity length composite cavity fibre laser with single longitudinal mode and narrow linewidth

Long Cavity Length Composite Cavity Fibre Laser with Single Longitudinal Mode and Narrow Linewidth

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ABSTRACT

The composite cavity fibre laser (CCFL) is demonstrated for its capability in maintaining single longitudinal mode operation, whilst having longer cavity length than typical distributed Bragg reflector or distributed feedback fibre lasers, and hence also higher output power. These two attributes should enable the CCFL to be useful in sensing applications. A long cavity length CCFL can be fabricated simply by writing three spectrally matched Bragg gratings directly into a continuous length of doped fibre. This is analogous to the use of feedback cavities in semiconductor laser designs to maintain single longitudinal mode. Results from in-house fabrications show that long cavity length CCFLs can be fabricated to have single longitudinal mode and narrow linewidth characteristics similar to that of a distributed feedback fibre laser, and also significantly higher output power.

KEYWORDS: Fibre laser, Long cavity fibre laser, Single longitudinal mode, Fibre sensing.

1. INTRODUCTION

Interferometric-based high performance sensing systems which make use of fibre laser sensor heads had been reported for some time [1]. The sensitivity of these systems requires the fibre laser(s) to have single longitudinal mode and narrow linewidth, so that unbalanced interferometers with long delay lengths can be applied to amplify the phase difference. In order to facilitate for the needs of single longitudinal mode and narrow linewidth, typical fibre laser designs have restricted cavity length. As such, little development was reported of long cavity length fibre lasers.

Conventional distributed Bragg reflector (DBR) fibre lasers have cavity length in the order of a few centimeters, so that the combination of its Fabry Perot resonance and the spectral width of the fibre Bragg gratings (FBGs) may impose single longitudinal mode operation. As for distributed feedback (DFB) fibre lasers, although they are inherently single moded, their 'effective' lasing cavity is localized around the phase shift, and is inversely proportional to the coupling efficiency of the grating [2]. A typical coupling coefficient of $150m^{-1}$ results in an effective cavity that is less than 1cm. The effective cavity length may be increased by applying a step-apodized profile [3] to increase output power, but doing so also increases the complexity of the fabrication procedure.

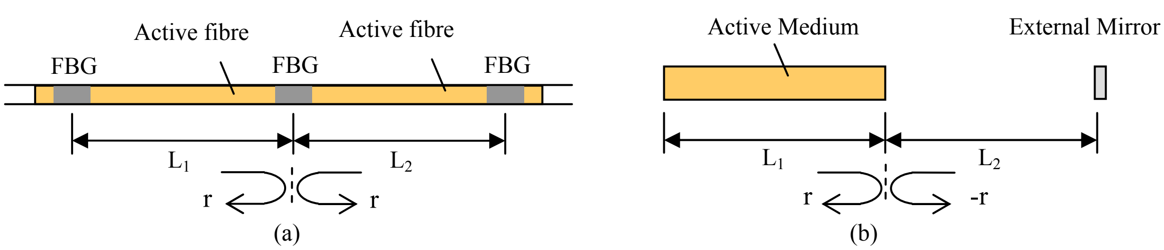

Figure 1. a) Novel composite cavity fibre laser with active internal feedback;
b) Traditional semiconductor external cavity laser.

The composite cavity fibre laser (CCFL) design can be applied to realize long cavity length fibre laser which has single longitudinal mode. The CCFL is essentially three wavelength matched FBGs written in a long length of active fibre [4], as shown in Figure 1a. The CCFL takes after a similar approach as the semiconductor external cavity laser, which was effective in significantly reducing the number of output modes. However, the CCFL is distinct in two key aspects: firstly, both cavities of the CCFL allow for optical gain (i.e. internal feedback); secondly, the middle reflector of the CCFL is

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symmetric. Based on these two key differences, the CCFL is distinguishable from other multi-cavity semiconductor or fibre laser designs (such as external cavity, coupled cavity, self injection etc).

A reported case that was most similar to the CCFL is that of a totally integrated coupled-cavity fibre laser [5], where a 1cm section of heavily doped Erbium doped fibre (EDF) was spliced between two of the three FBGs (optical gain in one cavity only). This design demonstrated robust single-frequency operation with reduced linewidth. Other researchers utilized external feedback via FBG to produce self injection fibre lasers, which demonstrated highly stable single mode and single polarization operations [6-8].

By applying unequal sub-cavity lengths, the CCFL is expected to exhibit asymmetric power characteristics. Since the gain of the cavity is related to the length of the cavity, higher intensity should be observed in the direction that houses the longer cavity, when the laser is operating past threshold. As such, the CCFL can also be fabricated as bi-directional lasers (sub-cavities with same length) or uni-directional lasers (significantly disproportioned sub-cavity lengths).

We present results of a 2cm/8cm CCFL with total cavity length of 10cm, which was fabricated in-house by the scanning UV side exposure technique [9]. This CCFL demonstrated single longitudinal mode property similar to that of a DFB fibre laser, with approximately 15kHz linewidth. This CCFL was also found to have asymmetric output intensity, the higher of which is significantly stronger than that of the DFB fibre laser. Having single mode operation with increased cavity length over typical fibre lasers, such CCFLs could have desirable coherence characteristics and higher output power as well as longer gauge length, making them attractive for fibre sensor applications.

2. CCFL FABRICATION

Figure 2 illustrates the 2cm/8cm CCFL design, whose results are shown throughout this article. All three FBGs are 6mm in length, and the structure is centered in a 12cm length EDF. The EDF used had 33.4 dB/m peak absorption at 1530nm, and 13.2 dB/km background loss at 1200nm. No apodisation was applied when writing the gratings. Using a tunable scanning laser, the transmission loss spectrums of the CCFL during various stages of fabrication were monitored, and are shown in Figure 3.

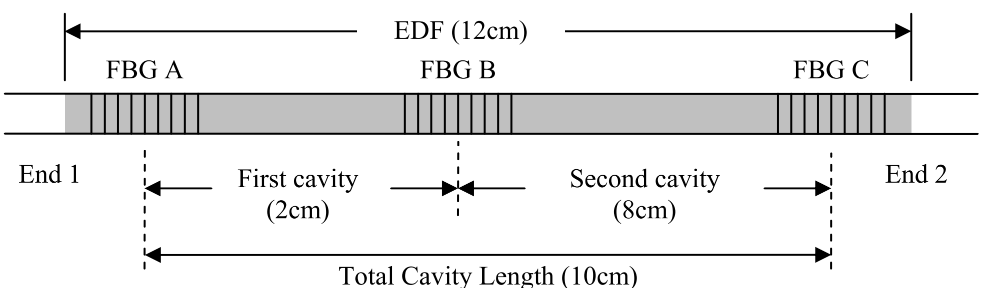

Figure 2. Schematic of the 2cm/8cm CCFL.

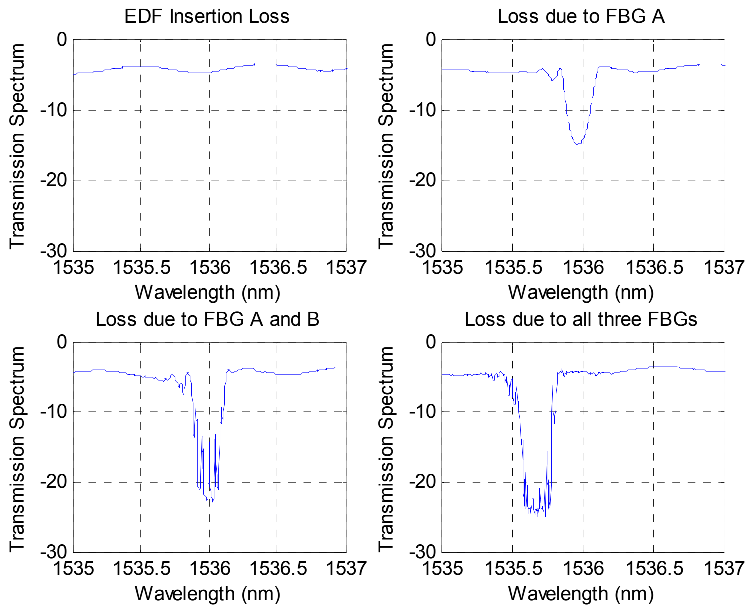

Figure 3. Transmission spectrums of a 2cm/8cm CCFL obtained with a tunable laser, at various stages of fabrication.

Prior to grating writing, approximately -5dB insertion loss was measurable, which can be attributed mostly to the absorption of the EDF. After FBG A was written, a typically smooth and symmetric loss profile can be observed with 3dB width of 0.15nm, and provided -10dB loss at the Bragg wavelength. It is not possible to monitor FBG B and C individually, but due to the high repeatability of the writing system, similar attributes (such as reflectivity, spectral width and location) are expected.

After FBG B was written, fine and mostly symmetric modal details in the order of the free spectral range of a 2cm Fabry Perot cavity can be observed. When all three FBG's were written, the modal structure had became even more complicated due to the establishment of the 8cm cavity. The approximately 0.3nm shift in the structure's wavelength is caused by the relaxation of the pre-strain applied during the writing process (in order to span the EDF horizontally). As the spectral width of the CCFL structure remains similar, it can be assumed with confidence that the Bragg wavelengths of all three FBGs are matching.

3. EXPERIMENT SETUP

The connections and equipment used to test the CCFL are shown in Figure 4. A 980nm laser diode is used to pump the CCFL via a wavelength division multiplexer (WDM). The 2cm/8cm CCFL is spliced to the downlead fibre with the 8cm cavity towards the WDM, and the other end is index matched with paraffin oil to eliminate undesired reflections. The WDM directs the returning 1535nm CCFL emission through an isolator for three different type of measurements.

An optical spectrum analyzer (OSA) is used to measure the output intensity for the four pump-output arrangements listed in Table 1. P_{11} and P_{22} are measured in reflection with respect to pump power, whilst P_{21} and P_{12} are measured in transmission. The difference in loss between the reflecting and transmitting paths (due to wavelength division multiplexer and isolator) are accounted for in the results.

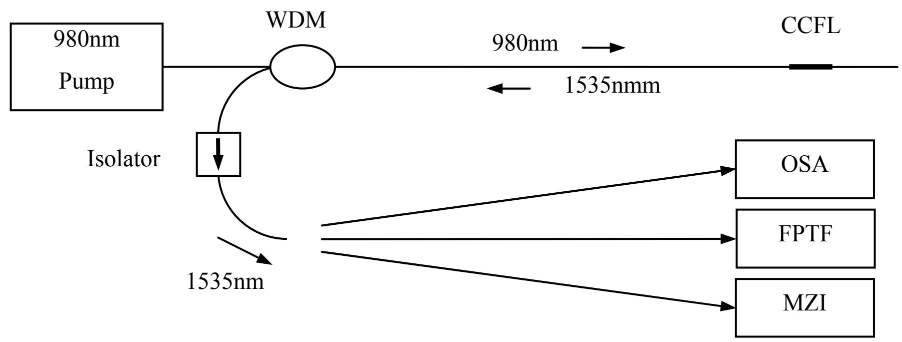

Figure 4. Schematic of testing system.

Table 1. Four output power ratios.

P_{11}	Output power measured from End 1 when pumped via End 1
P_{21}	Output power measured from End 2 when pumped via End 1
P_{12}	Output power measured from End 1 when pumped via End 2.
P_{22}	Output power measured from End 2 when pumped via End 2.

Since the OSA is regarded to have insufficient resolution for discerning single or multiple longitudinal mode(s), a Fabry Perot tunable filter (FPTF) with adequate resolution is used for the mode shape measurements. The benefit of high resolution by using a FPTF comes at the expense of wavelength ambiguity, as its voltage-to-wavelength response is prone to temperature drift and warm-up creep. A *MICRON OPTICS Fiber Fabry Perot Tunable Filter*, which has approximately 1.75GHz (~14pm) spectral width, is used for high resolution mode shape measurements.

An unbalanced Mach Zehnder interferometer (MZI) is used for linewidth measurements by the delayed-self homodyne technique [10]. A 50km delay fibre was used to ensure incoherent mixing. The interference signal is detected with a PIN diode detector, whose output is digitized at 500kHz. Fourier transform is performed on the digitized time signal, and the CCFL's FWHM linewidth can then be determined by analysing the -3dB frequency point.

4. RESULTS

4.1 Single Longitudinal Mode

Figure 5 shows the lasing spectrum of the 2cm/8cm CCFL that was recorded using an optical spectrum analyser (OSA). Figure 6 shows the mode shapes of the 2cm/8cm CCFL and a π-phase shifted DFB fibre laser (fabricated using 6cm of the same type of EDF). The comparison shows that the 2cm/8cm CCFL, with much longer cavity length, has single longitudinal mode output similar to the DFB fibre laser.

Also noticeable is that the peak intensity of the 2cm/8cm CCFL was 6dB higher than the DFB fibre laser. This difference in output intensity is attributed to the difference in effective cavity length, which enables the CCFL to utilize more of the pump power. In this context, long cavity length CCFLs may be considered to be more efficient in general than DBR or DFB fibre lasers with shorter cavity lengths.

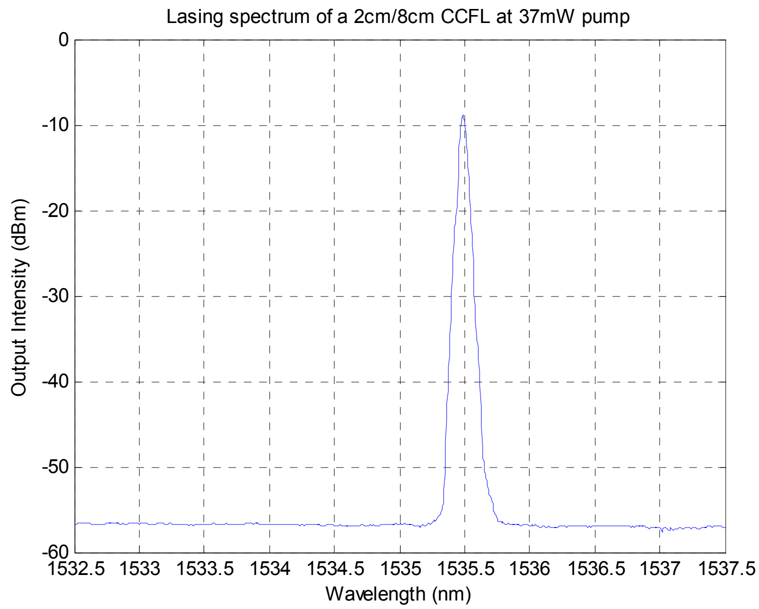

Figure 5. Lasing spectrum at 37mW pump power recorded with OSA, under the P_{21} arrangement. Sensitivity was set to -70dBm.

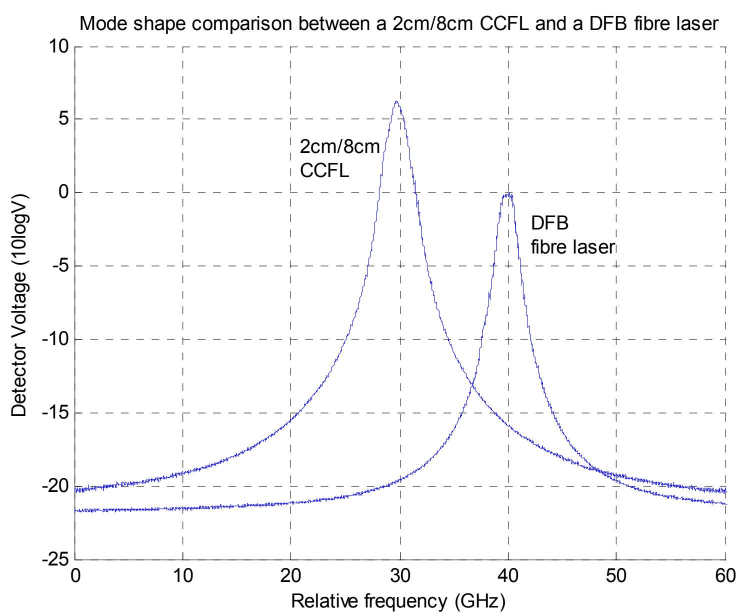

Figure 6. Lasing mode shapes of the 8cm/2cm CCFL (under P_{22}) and a DFB fibre laser.

Both scans obtained when the fibre lasers were pumped at 85mW.

4.2 Linewidth

Linewidth results for the 2cm/8cm CCFL is shown in Figure 7, where the linewidth can be determined to be approximately 15kHz. The pump power applied was 25mW, chosen so that that the laser intensity is maximized without the measurements being dominated by self pulsation effects.

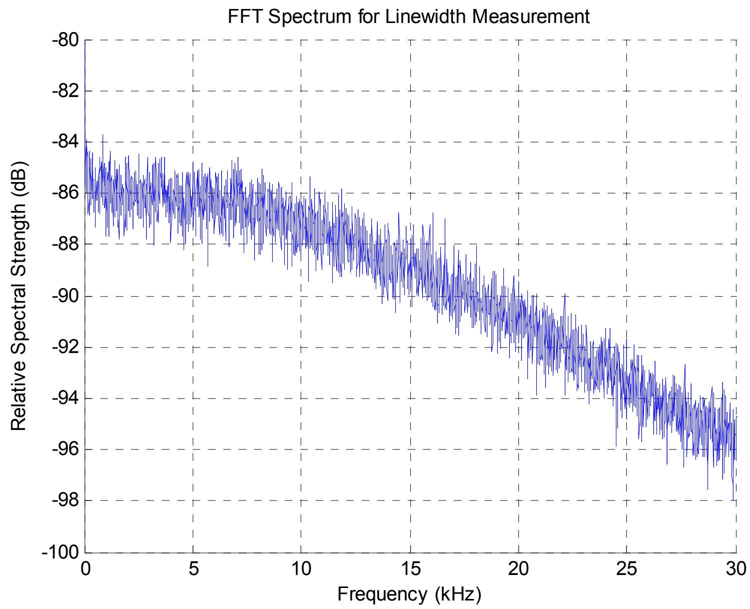

Figure 7. Linewidth measurement of a 2cm/8cm CCFL using delayed self-homodyne technique.

4.3 Threshold Characteristics

Shown in Figure 8 are the threshold characteristics of the 2cm/8cm CCFL for the four pump-output arrangements listed in Table 1. Also shown in is the threshold characteristics of the 6cm long DFB fibre laser, whose mode shape was shown in Figure 6.

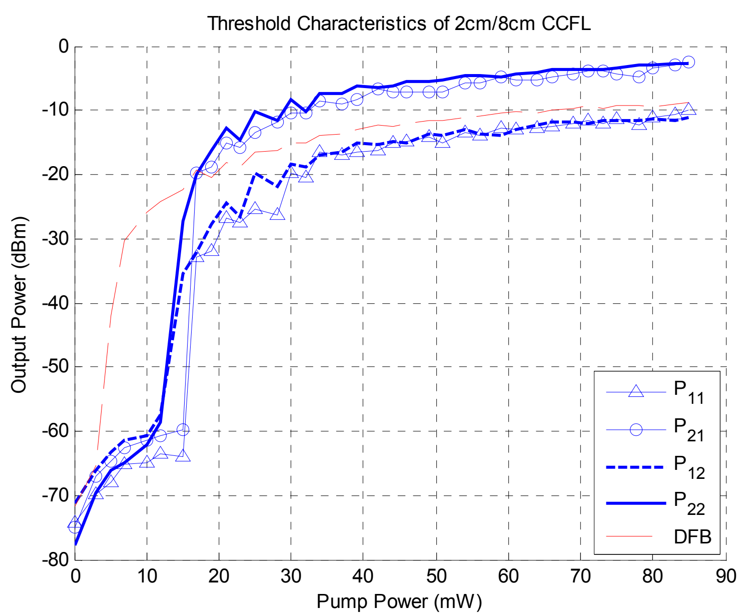

Figure 8. Threshold characteristics of all four pump-output arrangements of a 2cm/8cm CCFL, and threshold characteristic of a DFB fibre laser for comparison.

In Figure 8, it can be seen that from 30mW pump upwards, the 2cm/8cm CCFL under P_{22} and P_{21} (i.e. output from End 2) have matching output power, and similarly for P_{11} and P_{12} (output from End 1). Hence the output power difference between the two ends of the CCFL should be attributed to the internal cavity lengths (end with the longer cavity produces higher output intensity) rather than the pumping direction. It is thought that if EDF with higher doping concentration is used, then pump depletion effects will become prominent, and the pumping direction may have an effect on the power asymmetry.

Comparison with the DFB fibre laser shows that between 30mW to 85mW pump power, the output power of the 2cm/8cm CCFL from End 2 were at least 6dB stronger than the DFB fibre laser. This increase in efficiency is attributed to the longer total cavity length of the CCFL, so that more of the 980nm pump power is transferred into 1550nm lasing output. The noticeable fluctuations in output power between 20mW to 30mW pump power were cause by the the mode hopping of the pump laser diode.

All four of the CCFL's threshold characteristics displayed higher threshold pump power than the DFB fibre laser, which is also attributed to the longer cavity length of the CCFL. Among the CCFL's four threshold characteristics, it was observed that pump-output arrangements P_{11} and P_{21} (i.e. pump via End 1) were 5mW lower than those of P_{11} and P_{21} (pump via End2). This was expected because the 8cm sub-cavity is towards End 2, which requires higher threshold gain to overcome its cavity loss when compared against the 2cm cavity.

Figure 9 shows the threshold of various CCFLs with various internal cavity lengths under the P_{22} pump-output arrangement. The CCFLs with L_2 less than 5cm are written in 8cm sections of EDF, whilst the other two are written in 12cm sections of EDF. As expected, CCFLs with longer combined cavity lengths had higher output power. The length of EDF used also seems to have a bearing on the output power.

4.4 Power Asymmetry

To further examine the relationships between pumping and output directions, four power ratios for the 2cm/8cm CCFL are shown in Figure 10. The definitions of the four power ratios are defined in Table 2.

From Figure 10, it can be noticed that R_{P1} and R_{P2} are approximately 8dB from 30mW to 85mW of pump power. Asymmetric output power is beneficial for improving efficiency for systems where only one output of the fibre laser is used for detection. On the other hand, R_{O1} and R_{O2} remain close to 0dB over the same range of pump power.

R_{P2} for other CCFL designs at 85mW pump power are shown in Figure 11. From cutback measurements, the loss due to splices was determined to have a standard deviation of 1.5dB, which can account for some of the spread of the measurements. Among the CCFLs tested, it was found that as the internal cavity length ratio $R_L=L_2/2\text{cm}$ increased, the power asymmetry also increased. Hence bidirectional and unidirectional CCFL can be fabricated by designing the internal cavity length ratio.

Table 2. Four output power ratios.

R_{P1}	Power asymmetry for pumping via End 1 $10\log P_{21} - 10\log P_{11}$
R_{P2}	Power asymmetry for pumping via End 2. $10\log P_{22} - 10\log P_{12}$
R_{O1}	Change in output power of End 1 due to pumping direction $10\log P_{12} - 10\log P_{11}$
R_{O2}	Change in output power of End 2 due to pumping direction $10\log P_{22} - 10\log P_{21}$

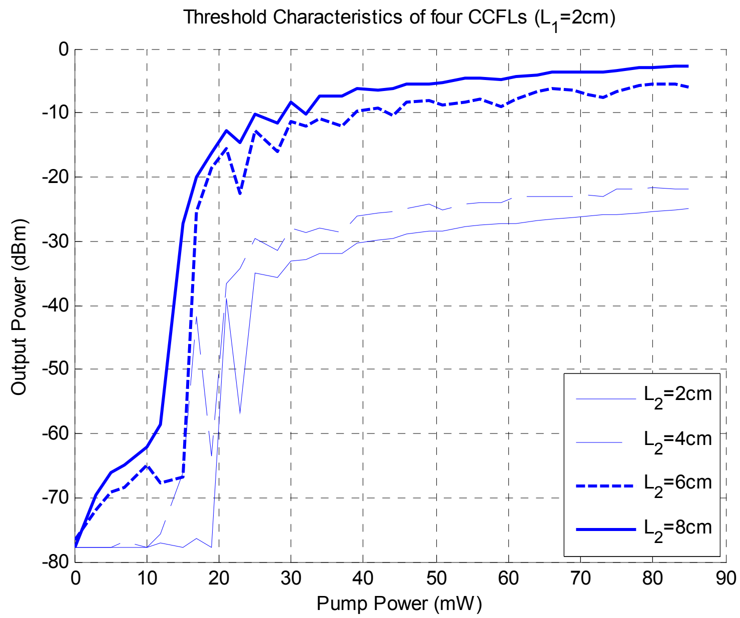

Figure 9. Output power for P_{22} pump-output arrangement of various CCFLs (L_1 = 2cm) when pumped at 85mW. The dotted lines are deduced by averaging the measurements.

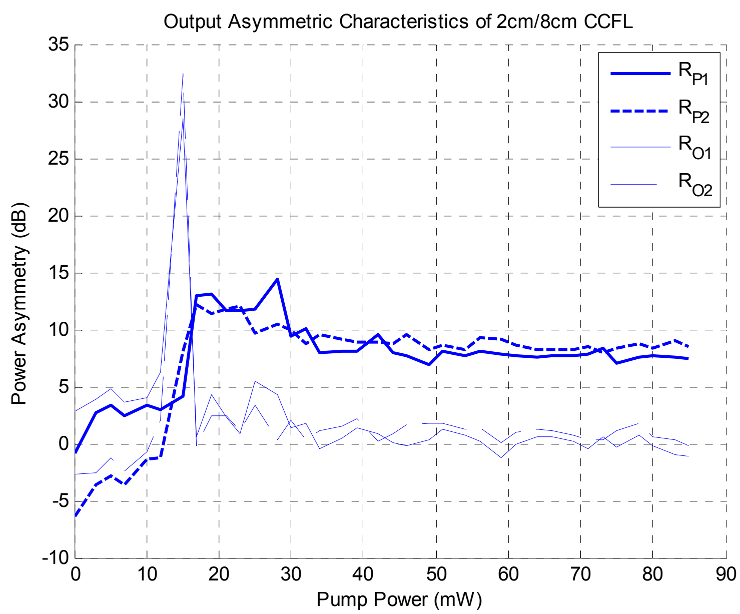

Figure 10. Output power ratios of the 2cm/8cm CCFL.

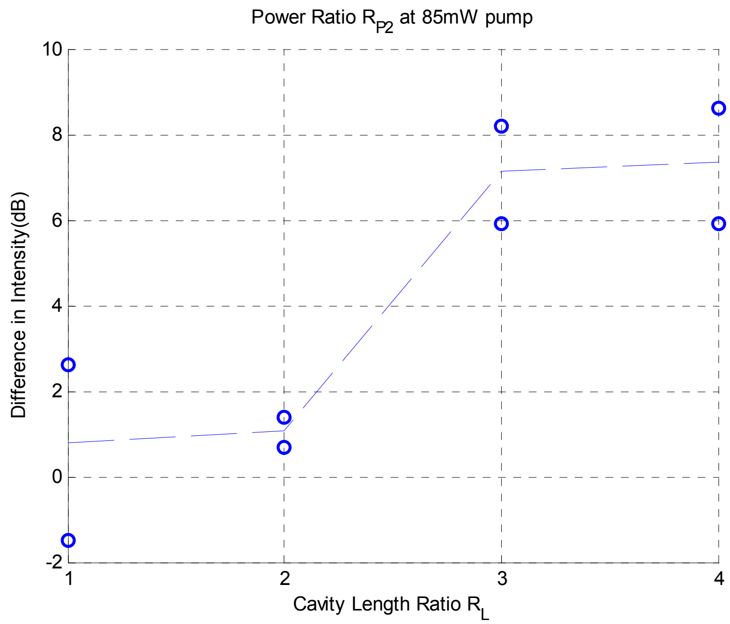

Figure 11. Power asymmetry R_{P2} of various CCFLs when pumped at 85mW. Dashed line obtained by averaging measurements.

5. CONCLUSION

A fully integrated composite cavity fibre laser (CCFL) can be fabricated easily using existing fabrication methods, by writing three FBGs directly into a length of EDF. Results show that by using internal feedback, the CCFL can maintain single longitudinal mode output whilst having longer cavity length than typical single mode fibre lasers designs. The CCFL have linewidth in the order of tens of kHz, higher output intensity and efficiency due to the longer cavity length. By using unequal internal cavity lengths, asymmetric CCFLs can also be fabricated. This combination of attributes makes the CCFL beneficial to sensing applications, in both interferometric-based and intensity-based fibre laser sensing systems.

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