Composite Cavity Fiber Laser with Asymmetric Output Intensity and Wavelength

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***Abstract*— The composite cavity fiber laser (CCFL) is relatively simple in its fabrication, as it is essentially three wavelength matched Bragg gratings in a section of doped fiber. By using internal feedback with unequal sub-cavity lengths, unidirectional CCFLs with significantly asymmetric output power from its two outputs can be achieved. Preliminary results also show that it is possible for the lasing frequency of the two outputs to be different by a few GHz.**

KEYWORDS: Fiber Amplifier, Fiber Laser, Erbium Doped Fiber Amplifiers and Lasers

I. INTROCUCTION

In recent years, fiber laser-based sensors attracted considerable research interest. In particular, two types of fiber lasers, distributed Bragg reflector (DBR) and distributed feedback (DFB) fiber lasers had received much attention. Having single longitudinal mode, narrow linewidth and high coherence characteristics, these lasers are suitable for high performance fiber sensing applications. Similar to these two types of fiber lasers, a composite cavity fiber laser (CCFL) can also have single longitudinal mode, with linewidth in the order of tens of kHz [1]. A coupled-cavity fiber laser was reported in [2], which demonstrated robust single-frequency operation with reduced linewidth. Reports of other self injection fiber lasers showed that passive feedback using FBG are capable of achieving highly stable single mode and single polarization operation [3]-[5].

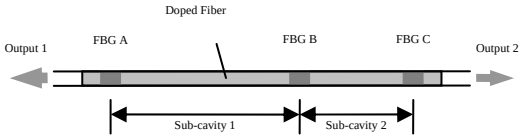

Fig. 1 Composite cavity fiber laser.

The CCFL design investigated is a multiple cavity fiber laser fabricated by writing three wavelength matching fiber Bragg gratings (FBGs) directly into a length of doped fiber, as shown in Fig. 1, and should not be confused with composite cavity fiber ring lasers.

When the sub-cavity lengths are unequal, asymmetrical power characteristics from the two outputs of the CCFL can be intuitively expected. Such a case would be similar to DBR fiber lasers with dissimilar grating strengths, or DFB fiber lasers whose phase shift is not in the centre of the grating [6][7]. In the following paper is reported the asymmetrical output intensity and asymmetrical lasing frequency characteristics of in-house fabricated CCFLs.

II. DESIGN AND FABRICATION

The formation of a CCFL with sub-cavity lengths of 2cm and 8cm (2cm/8cm CCFL) is shown in Fig. 2. The gratings were written using the scanning UV side exposure technique with a phase mask [8]. The transmission loss spectra of the CCFL were obtained by using a tunable scanning laser during various stages of fabrication. All three FBGs are 6mm in length, and the structure is centered in a 12cm length of Erbium doped fiber (EDF). The EDF used has 33.4 dB/m peak absorption at 1530nm, and

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13.2 dB/km background loss at 1200nm. The EDF was stripped of its coating for the grating writing process, and the coating was not reapplied after the CCFL had been fabricated. The majority of the results shown throughout the remainder of this paper are of this 2cm/8cm CCFL.

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 FBGs 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.

III. EXPERIMENT SETUP

The experiment system for examining the asymmetrical properties of the CCFL is shown in Fig. 3. A 980nm laser diode was used as the pump source which is connected to the CCFL by a wavelength division multiplexer (WDM) fiber coupler. When pumped, the CCFL gives off emission at 1535nm in both directions.

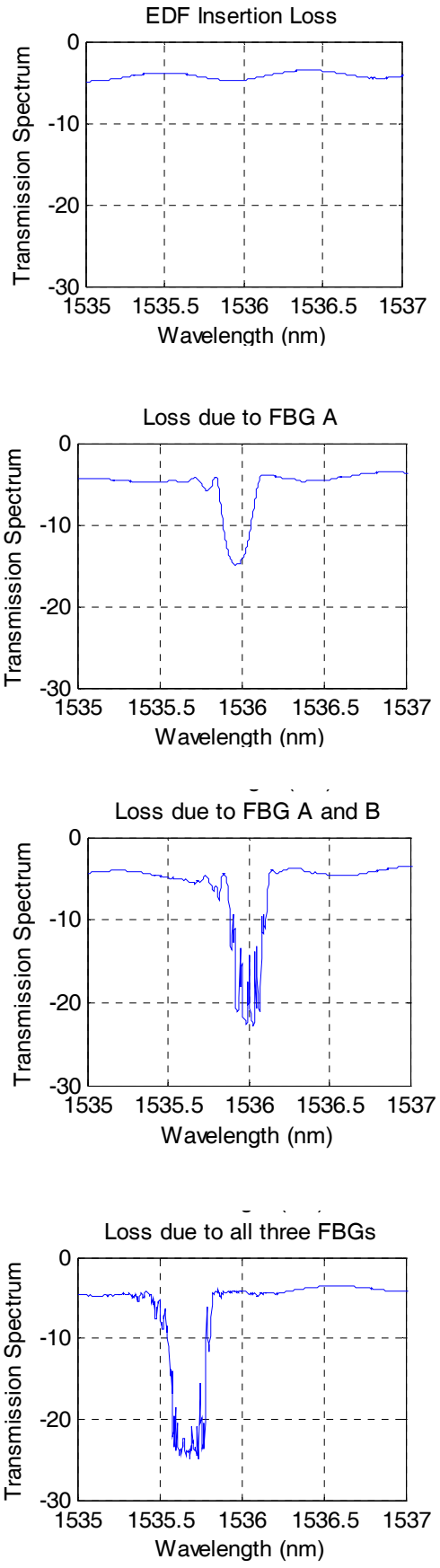

Fig. 2 Transmission spectra of a 2cm/8cm CCFL obtained with a tunable laser, at various stages of fabrication.

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The optical signal from Output I and Output II are connected directly to an optical spectrum analyzer (OSA) 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 of Output I and Output II (due to wavelength division multiplexer and isolator) are accounted for in the results.

To measure the difference in lasing frequency of Output I and Output II, a Fabry-Perot tunable filter (FPTF) with approximately 1.75GHz (~14pm) spectral width was used. An additional WDM was applied to Output II to suppress the pump wavelength's influence on the measurements, and a 3dB coupler was used so that the combined spectrum of the outputs could also be measured. A saw tooth voltage was applied to the FPTF, and the CCFL is spliced with the 8cm sub-cavity towards the pump source.

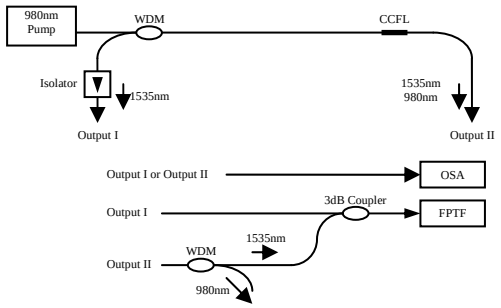

Fig. 3 Schematic of experiment system.

TABLE 1 FOUR OUTPUT POWER RATIOS.

P_{11}	Output power measured from 2cm when pumped via 2cm
P_{21}	Output power measured from 8cm when pumped via 2cm
P_{12}	Output power measured from 2cm when pumped via 8cm.
P_{22}	Output power measured from 8cm when pumped via 8cm.

IV. ASYMMETRICAL CHARACTERISTICS

The threshold characteristics of the 2cm/8cm CCFL for the four pump-output arrangements listed in Table 1, are shown in Fig. 4. Also, the threshold characteristics of the 6cm long DFB fiber laser are shown.

In Fig. 4, 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 (the 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 fiber laser shows (for the range 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 fiber 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 caused by the mode hopping of the pump laser diode.

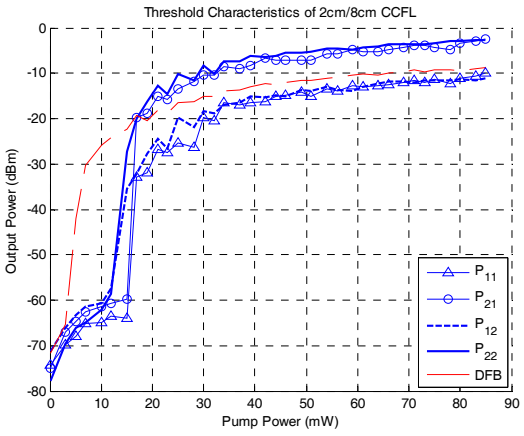

Fig. 4 Threshold characteristics of all four pump-output arrangements of a 2cm/8cm CCFL, and threshold characteristic of a DFB fiber laser for comparison.

All four CCFL's threshold characteristics displayed higher threshold pump power than the DFB fiber laser, which is also attributed to the longer cavity length of the CCFL. Among the CCFL's four threshold characteristics, it

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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 End 2). This was expected because the 8cm sub-cavity is towards End 2, which requires higher threshold gain to overcome its cavity loss when compared to the 2cm cavity.

Figure 5 shows the threshold of various CCFLs with various internal cavity lengths under the P22 pump-output arrangement. The CCFLs with L2 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.

To further examine the relationships between pumping and output directions, four power ratios for the 2cm/8cm CCFL are shown in Fig. 6. The definitions of the four power ratios are defined in Table 2. From Fig. 6, it can be seen 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 fiber laser is used for detection. On the other hand, RO1 and RO2 remain close to 0dB over the same range of pump power, as it was pointed out previously the pumping direction had negligible effect on the output power, except about threshold, where the asymmetry reached over 30dB.

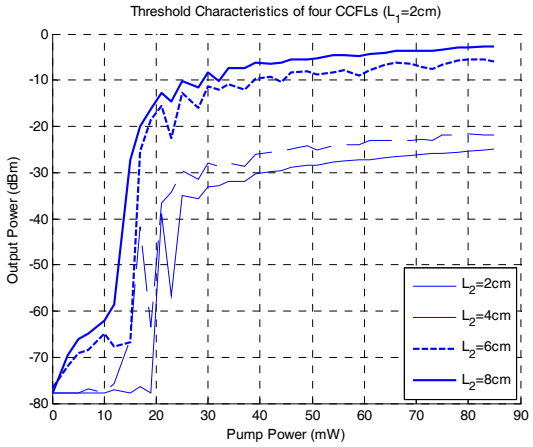

Fig. 5 Output power for P_{22} pump-output arrangement of various CCFLs (L_1 = 2cm) when pumped at 85mW. The dotted lines are deduced by averaging the measurements.

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 $10\log P_{22} - 10\log P_{21}$

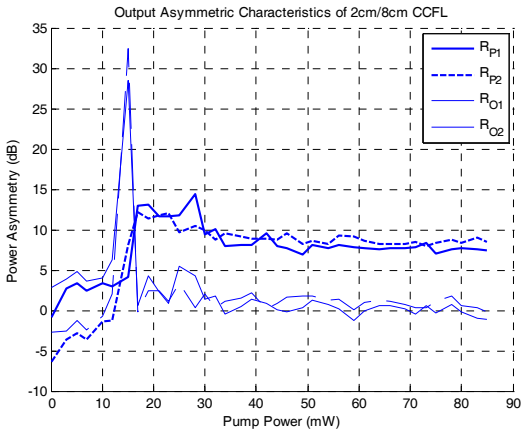

Fig. 6 Output power ratios of the 2cm/8cm CCFL.

R_{P2} for other CCFL designs at 85mW pump power are shown in Fig. 7. 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 RL=L2/2cm increased, the power asymmetry also increased. Hence bidirectional and unidirectional CCFL can be fabricated by designing the internal cavity length ratio.

Figure 8 shows the FPTF scans of the 2cm/8cm CCFL. When scanned on their own, both P_{21} and P_{22} arrangements showed the emission to have single longitudinal mode. However, when the coupler is used to measure the combined spectral shape, two lasing peaks with roughly 2GHz (~16pm) separation can be observed. Such characteristics might be applicable in the generation of microwave signals, or make possible innovative sensing systems.

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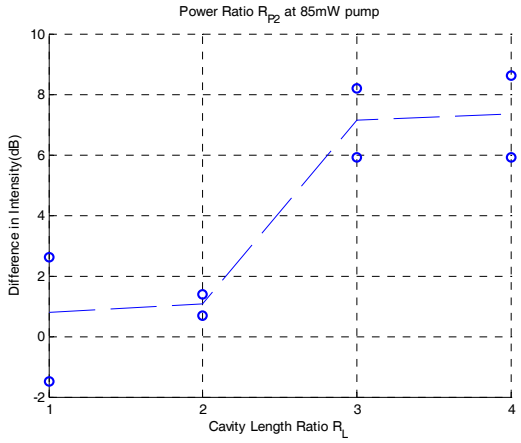

Fig. 7 Power asymmetry R_{P2} of various CCFLs when pumped at 85mW. Dashed line obtained by averaging measurements.

The cause(s) of the CCFL's ability to have different lasing frequency from the outputs are yet to be determined. More detailed investigation using a polarization controller will aid to identify if the two different lasing frequencies are in fact the two polarization modes of the single longitudinal mode.

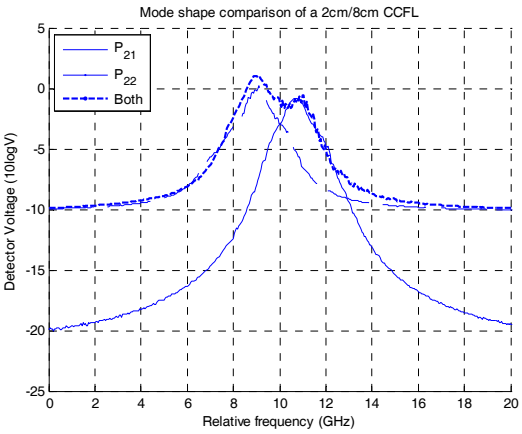

Fig. 8 Fabry-Perot tunable filter scans from the 2cm/8cm CCFL.

Another explanation for the asymmetry in frequency is that the two sub-cavities were operating as two separate lasers that are partially mode locked, so that single mode operation can be maintained from each direction of the CCFL, but at slightly difference frequencies. The transmission spectrum of the 2cm/8cm CCFL measured by a scanning tunable laser in higher resolution is shown in Fig. 9 (zoom in of the final plot of Fig. 2), where transmission peaks in the order of 16pm can be observed within the stop band.

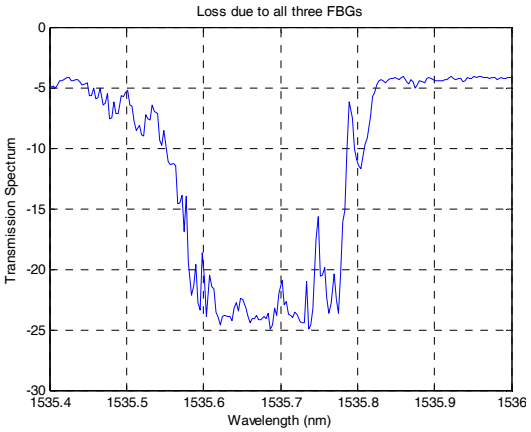

Fig 9 Transmission spectra of the 2cm/8cm CCFL obtained with a tunable laser.

V. CONCLUSION

A composite cavity fiber laser (CCFL) can be fabricated easily by writing three gratings into doped fiber using existing grating writing systems. Experimental characterization of in-house fabricated CCFLs showed that asymmetrical output power can be achieved by applying unequal sub-cavity lengths, to produce uni-directional lasing. It was identified that the pumping direction does not affect the asymmetry in output power, but it can affect the lasing threshold. Further investigation in the CCFL's asymmetrical lasing frequency characteristics are needed to determine its cause, and potential in applications.

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