Compact, all fibre, linearly polarised, single-mode Ytterbium doped fibre laser utilizing point-by-point inscribed intra-core fibre Bragg gratings

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ABSTRACT

We report on the development of a compact, all fibre laser source operating at 1 μm with a linearly polarized (extinction ratio > 20 dB) and very narrow linewidth (12 pm) output. The unique cavity design included a fibre Bragg grating high reflector and output coupler, inscribed via the point-by-point method directly into the active core. A single splice within the cavity between the fibre incorporating the high reflector and the output coupler permitted re-orientation of the stressors at an angle of 90 degrees to each other, which produced a single lasing polarisation. This simple technique removed the need for a more complicated and expensive polarization controller.

KEYWORD LIST: Lasers, Fibre laser, Bragg gratings, point-by-point method, polarization maintaining, all-fibre.

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1. INTRODUCTION

Fibre lasers have significantly advanced over the last 15 years and have become an important and mature technology. High slope efficiencies, power scalability, broad wavelength tunability, diffraction limited beam qualities at high power and cheap laser diode pump sources make fiber lasers well suited for a range of applications. However for airborne applications such as LIDAR or countermeasure systems, there are elevated demands on stability and robustness, consequently the use of conventional external bulk optics[1] to control the fibre lasers wavelength and linewidth is unviable.

Fiber Bragg gratings (FBGs) written using 1 or 2 photon UV processes can be utilized to generate a narrowband laser output (~ 0.25 -1 nm), but because they require the fibre to be photosensitive, they can not be easily written into non-photosensitive rare-earth doped laser fibre[2]. Typically gratings are written into standard photosensitive fibers without rare-earth dopants and spliced onto the fiber containing the active core[3]. This procedure produces an additional step in the fabrication process, introduces an additional loss to both the pump and laser light, and diminishes the overall robustness of the laser.

Recently, point-by-point (PbP) inscribed fibre Bragg gratings (FBG) were written directly into the active core of a ytterbium doped double clad silica laser fibre in order to overcome these issues[4]. The point-by-point technique refers to the use of a single femtosecond pulse tightly focused into the core of an optical fibre in order to modify the refractive index of the core locally and hence create one period of the grating. By translating the optical fibre synchronized with the repetition rate of the femtosecond laser it is possible to build up a structure consisting of many periods designed to have a stop band at the required wavelength[5]. Initial experiments demonstrated up to 5 W of CW output power at the predetermined 1080 nm wavelength, in a very narrow linewidth of only 15 pm (3.87 GHz) which is 17 times narrower then systems exploiting interference FBGs. The very narrow linewidth feature offered by these PbP FBGs makes efficient frequency doubling into the visible spectrum possible since the bandwidth is smaller then the phase matching bandwidth of even long periodically poled ferroelectric crystals. The fibre laser showed great stability in terms of output power, wavelength drift and linewidth fluctuations over a 4 hour period of test which was further improved by the implementation of passive temperature stabilization of the FBG. There was no observable degradation to the laser performance and hence the FBG after consecutive experiments, spanning a duration of 4 hours each, which shows that the generated refractive-index contrast is not washed out by the high intracore irradiances.

Building on these recent results we present a low power, all-fibre oscillator exploiting the advantages of the point-by-point technique to generate a simplified cavity and a very narrow 12 pm laser linewidth. By placing a single splice within the cavity between the fibre containing the high reflector and the output coupler, with the fibres oriented so that the stressors were perpendicular to each other, the laser was forced to lase of a single state of linear polarization. This novel technique removed the need for a more complex device such as a polarization controller and hence aided the development of a robust laser source.

2. EXPERIMENT

The initial experimental arrangement is shown in Fig. 1 below.

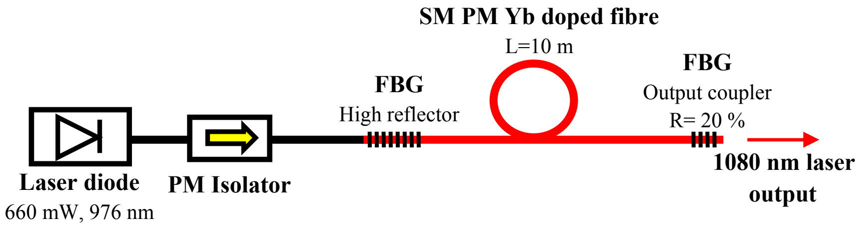

Figure 1: Initial laser setup.

The pump source for the laser was a single mode fiber coupled, 976 nm, 660 mW, laser diode with an external FBG for stabilization (JDS Uniphase, 30-7602-660). A 980 nm isolator was used to prevent any back reflections to the laser diode (Agiltron inc., OIST-32911E331). The active fiber used was polarisation maintaining, single mode, Yb^{3+}-doped silica fiber (Nufern, PM-YSF-HI) with a 6 µm core diameter (N.A. 0.11), a birefringence of 2.5×10^{-4}, and a peak absorption coefficient of 250 dB/m at 976 nm, in the small signal regime. After conducting some absorption measurements on a low doped ytterbium fibre (same specifications as above except 80 dB/m of absorption), and taking the difference in ion concentration into account the cavity length was set to 10 m for the high doped fibre, in order to maximise the absorption of the pump light. Two PbP FBGs, a high reflector and a low reflecting output coupler, were inscribed into the core of the active fibre in order to create the frequency selective feedback for the cavity. In order to fabricate the FBGs, the fiber was mounted on a high-precision air bearing translation stage, with the polymer cladding stripped off. The fibre was rotated about its optical axis such that the plane of the stressors was perpendicular to the writing laser beam. Femtosecond laser pulses were focused through the cladding into the active core using a 0.8 NA, 20 X oil immersion objective lens. The pulses generated by a regeneratively amplified Ti:Sapphire laser operating at 800 nm had < 120 fs pulse duration, at a 1 kHz repetition rate and a pulse energy of 160 nJ. The FBG, which acted as the highly reflecting cavity end mirror, was 30 mm long and had a period of 1.13 µm, which corresponds to a third-order grating for 1080 nm light, while the output coupling FBG was only 4 mm long and had a peak reflectivity of 20 %. The transmission spectrum for both the output coupler and high reflector are shown in Fig. 2.

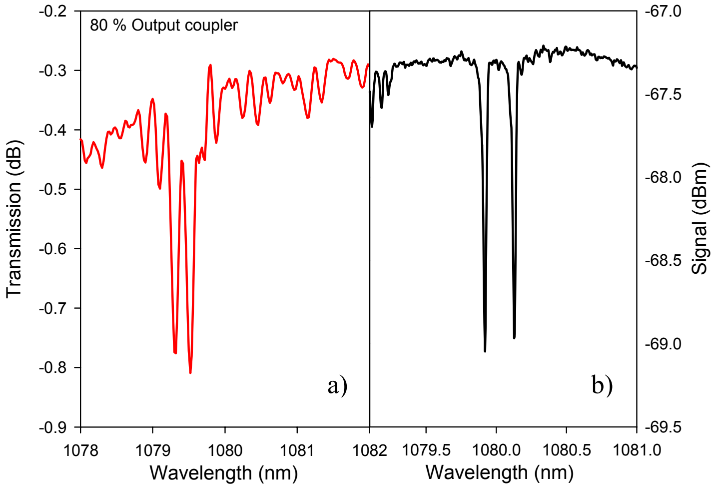

Figure 2: Transmission spectra for both the output coupler (a) and the high reflector (b). In the case of the output coupler the spectra is normalized to a pristine fibre with no grating.

The laser system was tested and it was determined that the high reflecting FBG induced a large insertion loss (greater then 3 dB) at the 976 nm pump light which severally degraded the output of the laser system. The larger out of band insertion loss at 976 nm as compared to 1080 nm was mainly attributed to the smaller difference between the pump wavelength and the physical size of the refractive index modification which caused an increase in scattering losses. Since it was not efficient to propagate the pump through the high reflector the cavity had to be redesigned as shown in Fig 3.

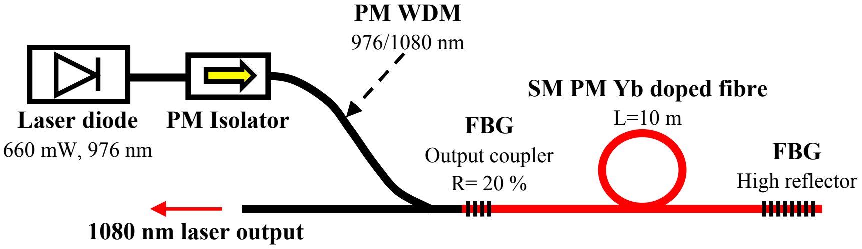

Figure 3: Redesigned laser setup.

The system redesign involved the implementation of a wavelength division multiplexer (WDM) for 976/1080 nm (AFW Technologies, PFWDM-9806-N-B-Q-P). As can be seen from Fig. 2 the output coupler had a insertion loss for the shorter wavelengths (i.e. 976 nm) of > 0.4 dB but an accurate figure at the pump wavelength was hard to obtain due to ground state absorption and the lack of white light sources at this wavelength. As can been seen in Fig. 2 both gratings have twin stop bands (reflection bands) in their respective transmission spectra, therefore strain tuning one of the gratings to overlap with the other will overlap the two stop bands of one grating with the other effectively creating two cavities; one for each polarisation and hence leading to a laser that lases off both states of polarisation independently. In order to make the laser operate off only a single laser peak some sort of polarisation discrimination must be implemented. The technique we used is depicted in Fig. 4 below.

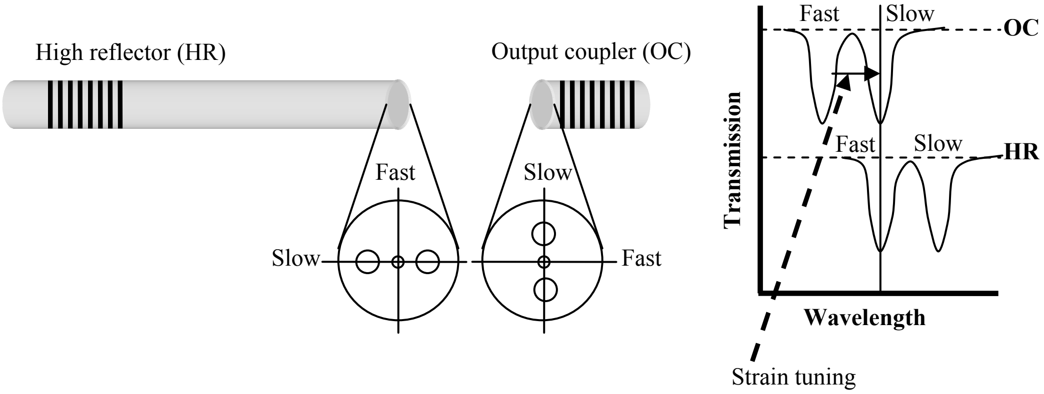

Figure 4: Depicts the alignment of the axes of the fibres with the various cavity elements in them in order to obtain a single state of polarization.

The output coupling FBG was spliced so that the slow axis was parallel to the fast axis of the fibre with the highly reflecting FBG in order to spectrally overlap only a single wavelength of the FBGs. The output coupler was placed in a strain tuning rig in order to refine the spectral overlap between the peak corresponding to the slow axis of the output coupler and the peak corresponding to the fast axis in the fibre with the highly reflecting FBG as depicted in Fig. 4.

3. RESULTS/DISCUSSION:

Upon testing, it was determined that the fibre laser system operated off only a single wavelength and hence a single polarization at a time. The output power as a function of launched pump power is shown in Fig. 5 for the laser operating polarized parallel to the slow axis of the output coupler corresponding to the shorter wavelength.

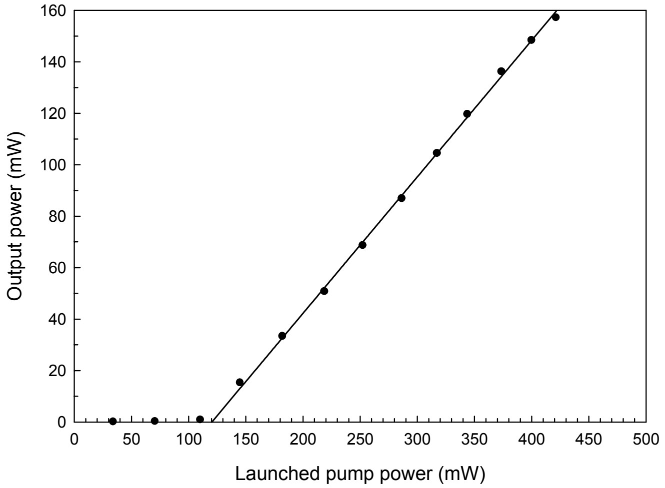

Figure 5: Output power as a function of the launched power for the laser operating polarized parallel to the slow axis of the output coupler element.

The slope efficiency was 53 % with a threshold of 120 mW pump power. The maximum output power generated was 157 mW. The slope efficiency can further be optimized by cutting back the cavity length, which, however, was not the scope of these experiments. The optical spectrum of the laser is shown in Fig. 6 for an output power of 157 mW.

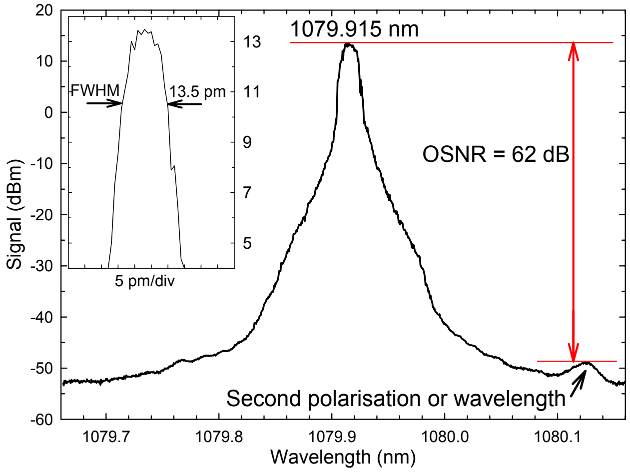

Figure 6: Optical spectrum of the fibre laser operating at high power.
Inset: Higher resolution scan of the laser peak.

The center wavelength was 1079.915 nm with a bandwidth of 13.5 pm. The optical signal to noise ratio was measured to be 62 dB. In Fig. 6 it can be seen that there is a greater amount of ASE at the wavelength corresponding to the other polarization/wavelength. This is due to the ASE being double passed through the cavity after reflecting off the high reflector.

The degree of polarization of the fibre laser was measured using a half wave-plate (HWP) and a polarizing beam cube. It was determined that the output had an extinction ratio of > 20 dB (or 99 % of the light polarized in a single linear direction). It was determined that the majority of the light that was not polarized, and hence that reduced the extinction ratio of the fibre laser, was actually amplified spontaneous emission (ASE) due to a short length of active fibre that was on the outside of the cavity in front of the output coupler. This ASE was present even at high power operation. By carefully cleaving the fibre closer to the output coupler some of the ASE would be reduced and hence this will yield a greater extinction ratio.

The stability of the fibre laser was tested over a period of 1 hour. The output power, center wavelength, and laser linewidth are shown in Fig. 7 a, b, & c respectively.

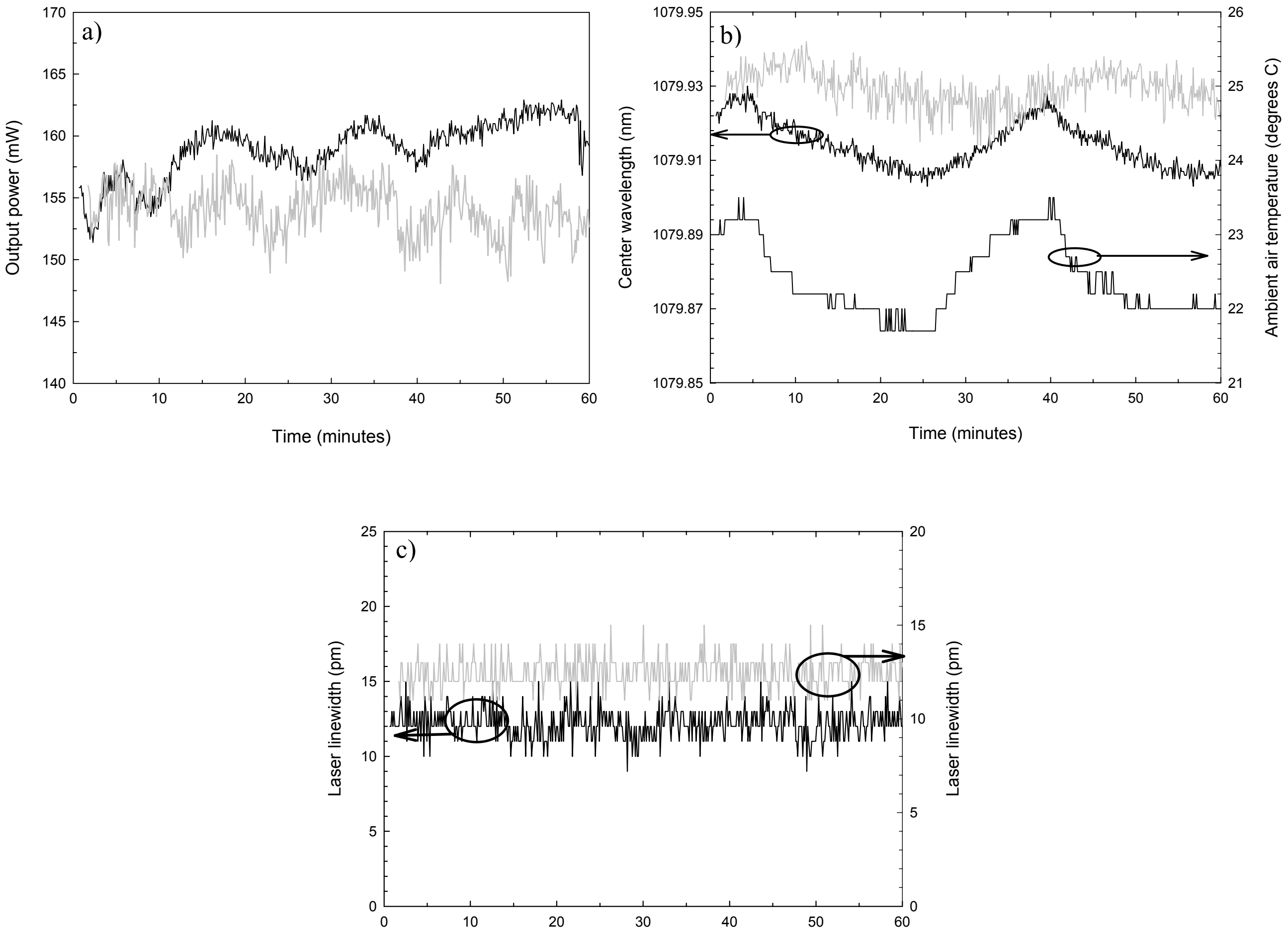

Figure 7: **a)** Output power over a 1 hour period. **b)** Center wavelength and ambient air temperature over a 1 hour period. **c)** Laser linewidth over a 1 hour period. Black curves – FBGs cooled with fans. Grey curves – FBGs uncooled.

The average output power during the 1 hour experiment with cooling of the FBGs implemented was 159 mW with a standard deviation of 2.22 mW or 1.4 %. In order to determine how much of the output power instability was due to the actual pump source, the fibre laser output power and laser diode output power were recorded for 1 hour at approximately 30 mW of output power from the fibre laser. The results are shown in Fig. 8 below.

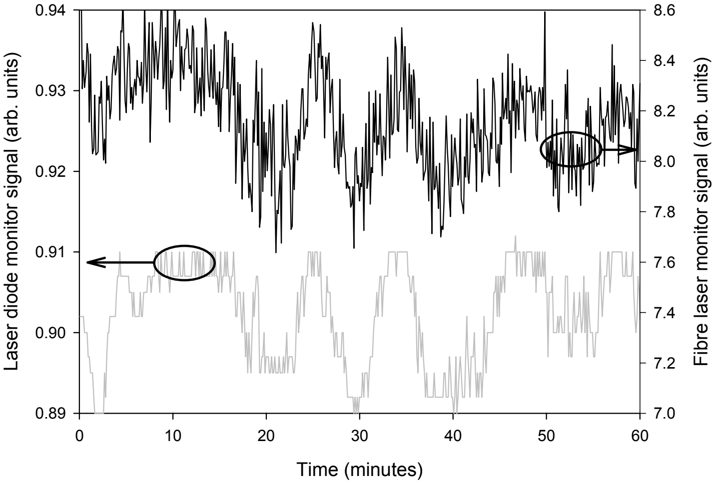

Figure 8: Laser diode and fibre laser output power over a 1 hour period.

It can be seen that all of the major power fluctuations in the fibre laser's output power correspond closely to the output of the laser diode. Therefore the majority of the 1.4 % amplitude fluctuations in the fibre lasers output power are due to fluctuations in the output power from the pump laser diode. Also from Fig. 7 a) it can be seen that there is less higher frequency noise in the output power of the fibre laser when passive temperature stabilization is implemented.

From Fig. 7 b), it can be seen that the amplitude of the high frequency components in the drift of the center wavelength are reduced by passive temperature stabilization. It can also be seen that the graph has a saw tooth profile in it, which was hypothesized was due to fluctuations in the ambient temperature around the grating induced by cycling in the air conditioning system. For comparison the ambient temperature of the room was measured and the results are presented in Fig. 7 b). Clearly, the ambient temperature has the same time cycle as the wavelength fluctuations. Since the maximum temperature variation was 1.8 °C, and taking into account the thermo-optic coefficient for the fibre, the change in wavelength would be 18 pm. From Fig. 7 b) it can be seen that the wavelength shifts ~ 20 pm, in the cooled case, which is consistent. Hence the change in the ambient temperature of the room is the major component in the laser wavelength drift and by enclosing the gratings within a stable environment or immersing in water the wavelength drift should be eliminated. Finally the average laser linewidth was (12 ± 1) pm for both the cooled and uncooled case.

4. CONCLUSION

We have demonstrated a compact all fibre laser source operating with a single linear state of polarization (extinction ratio > 20 dB) and a very narrow linewidth of 12 pm. By immersing the gratings in water and stabilizing the pump source, the fibre laser is expected to yield great stability. The novel approach for obtaining a single state of linear polarization and the inscription of the FBG's directly into the active core act to simplify the system by removing other components that may be needed for other schemes and therefore increase the physical robustness of the system. This compact fibre laser source will no doubt lend itself well to airborne applications demanding the greatest robustness and also visible wavelength generation.

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