

Novel technique for mode selection in a multimode fiber laser

J. M. O. Daniel,^{1,*} J. S. P. Chan,¹ J. W. Kim,^{1,2} J. K. Sahu,¹ M. Ibsen,¹ and W. A. Clarkson¹

¹Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK

²Currently with the Department of Applied Physics, Hanyang University, Sa-1-dong, Ansan-si, Gyeonggi-do, 426-791, South Korea

*jmod1g09@orc.soton.ac.uk

Abstract: A simple technique for transverse mode selection in a large-mode-area (multimode) fiber laser is described. The technique exploits the different spectral responses of feedback elements based on a fiber Bragg grating and a volume Bragg grating to achieve wavelength-dependent mode filtering. This approach has been applied to a cladding-pumped thulium-doped fiber laser with a multimode core to achieve a single-spatial-mode output beam with a beam propagation factor (M^2) of 1.05 at 1923 nm. Without mode selection the free-running fiber laser has a multimode output beam with an M^2 parameter of 3.3. Selective excitation of higher order modes is also possible via the technique and preliminary results for laser oscillation on the LP_{11} mode are also discussed along with the prospects for scaling to higher power levels.

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1. Introduction

Over the last decade, laser sources based on cladding-pumped rare-earth-doped optical fibers have seen rapid development driven by the needs of a range of applications. The main attractions of fiber-based sources are derived from their geometry which offers relative immunity from thermal loading and its detrimental effects, as well as flexibility in mode of

operation. Furthermore, the tight confinement of active ions within the core region allows the construction of lasers with low thresholds and high efficiency. Scaling the output power in continuous-wave (cw) or pulsed mode of operation generally requires increasing the fiber core area to increase the damage threshold and to suppress unwanted nonlinear loss processes which can be detrimental to performance. However, as the core area is increased it becomes increasingly difficult to maintain good output beam quality, since the core supports higher-order modes, which eventually lase leading to degradation in beam quality. The situation may be further exacerbated by modal interference, which can cause temporal variation in beam quality and poor pointing stability [1]. Many approaches for alleviating this problem have been developed. These include the use of special large-mode-area core designs [2], micro-structured fibers [3], selective active-ion doping [4] and the use of distributed mode filtering (e.g. by either bending the fiber [5]) to suppress higher order modes or by means of secondary high loss structures resonant with higher order modes [6,7] or by careful launching into the fundamental mode of a multimode waveguide [8]. However, most of these approaches add complexity and cost to the fiber design and become increasingly difficult to implement effectively as the core size is increased.

In this paper we describe an alternative approach for mode-selection that is applicable to a fiber laser oscillator. Our approach exploits the different spectral responses of in-fiber Bragg gratings (FBGs) in a multimode core and free-space Bragg gratings (i.e. volume Bragg gratings (VBGs)) to simultaneously achieve wavelength selection and spatial mode selection in a simple fiber laser with an external feedback cavity architecture. This approach has been applied to a cladding-pumped Tm-doped silica fiber laser with a multimode core to selectively excite the fundamental mode (LP₀₁) or the next higher order mode (LP₁₁).

2. Principle of operation

The number of allowed modes in a multimode step-index fiber depends on the refractive index of the core (n_{core}), the refractive index of the surrounding cladding material (n_{clad}) and the diameter of the core. Each mode is characterized by an effective propagation constant and related effective refractive index (n_{eff}), where $n_{\text{core}} > n_{\text{eff}} > n_{\text{clad}}$. The value of n_{eff} for a particular mode depends on the core design, but as a rough guide low order modes have a smaller mode size than higher order modes and hence have a higher value for n_{eff} . If a fiber Bragg grating (FBG) with period, Λ_1 , is written into the core then the wavelength, λ_{FBG} at which the Bragg condition is satisfied is simply given by [9]:

$$\lambda_{\text{FBG}} = 2n_{\text{eff}}\Lambda_1 \quad (1)$$

Thus, higher order modes will experience reflection at shorter wavelengths than lower order modes. In contrast, a Bragg grating written into a bulk material (i.e. a volume Bragg grating) with period, Λ_2 , provides maximum reflectivity at wavelength, λ_{VBG} , given by [10]:

$$\lambda_{\text{VBG}} = 2n_{\text{VBG}}\Lambda_2 \cos(\theta) \quad (2)$$

where θ is the angle of incidence and n_{VBG} is approximately equal to the refractive index of the bulk material. In this case, the wavelength at which the Bragg condition is satisfied is approximately the same for all modes. Thus, by forming a laser resonator with a multimode fiber as active medium and with feedback for laser oscillation provided by a FBG and an external cavity containing a VBG it is possible to restrict lasing to a single-spatial-mode (or reduce the number of lasing modes compared to a free running laser) by selecting the period and angle of incidence on the VBG such that

$$\Lambda_2 \cos(\theta) = \frac{n_{\text{eff}}\Lambda_{\text{FBG}}}{n_{\text{VBG}}} \quad (3)$$

where n_{eff} is the effective index of the desired lasing mode. This assumes that the fibre is of sufficient uniformity that intermodal coupling is negligible [8].

3. Experimental set-up and results

As an initial proof-of-concept, the fiber laser configuration shown in Fig. 1 was constructed and tested. The laser cavity comprised a 4 m length of Tm, Ge co-doped double-clad fiber (TDF) with feedback for lasing provided by a FBG and an external feedback cavity containing a VBG. The fiber gain element was fabricated in-house via the standard modified chemical vapour deposition and solution doping technique. The resulting fiber has a 18 μm diameter alumino-silicate core (0.22NA) with approximately 1 wt.% Tm and a D-shaped pure silica inner-cladding of outer dimension, 300 μm . The later was coated with a low refractive index UV-cured polymer coating yielding a high numerical aperture of ~ 0.49 (calculated) for the inner-cladding pump guide. Germanium was also added to the core to make the fiber photosensitive, allowing direct writing of the FBG in the active fiber and hence avoiding the need for splicing a matched passive (photosensitive) fiber that could influence the modal content and increase cavity loss. The photosensitivity of the fiber was further enhanced by hydrogen loading. The V parameter of the core at $\sim 2 \mu\text{m}$ was calculated to be ~ 6.3 and hence the core could support propagation on a number of higher order modes. The FBG was UV-written in the fiber close to one end, so that only a short section of fiber ($\sim 5 \text{ cm}$) remained before the FBG.

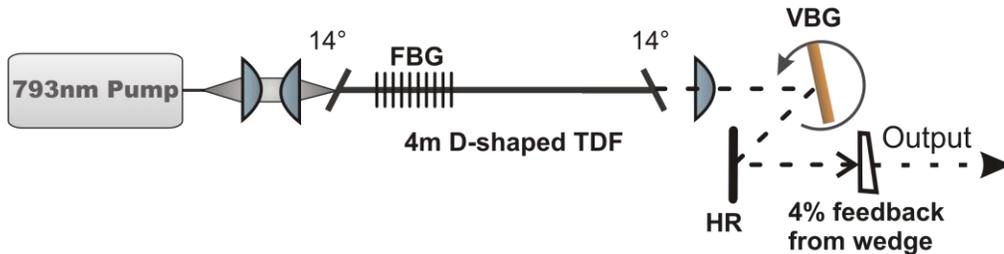


Fig. 1. Experimental layout of cladding-pumped Tm-doped fiber laser.

The FBG yielded an estimated reflectivity of 25% at a Bragg wavelength of 1923 nm for the fundamental mode and had a linewidth of $\sim 0.1 \text{ nm}$ (FWHM). Figure 2 shows the calculated Bragg reflection maxima for higher order modes versus wavelength for our TDF assuming a step-index profile. The wavelength separation of the reflection maxima for adjacent modes depends on the core diameter and numerical aperture and on the transverse intensity profile of the modes. The wavelength separation of the Bragg reflection maxima for the two lowest order modes (i.e. LP_{01} and LP_{11}) is predicted to be $\sim 3.5 \text{ nm}$. It should be noted that the linewidth of the FBG should be smaller than the wavelength separation of the desired spatial mode and adjacent modes as this is a prerequisite for achieving adequate modal discrimination.

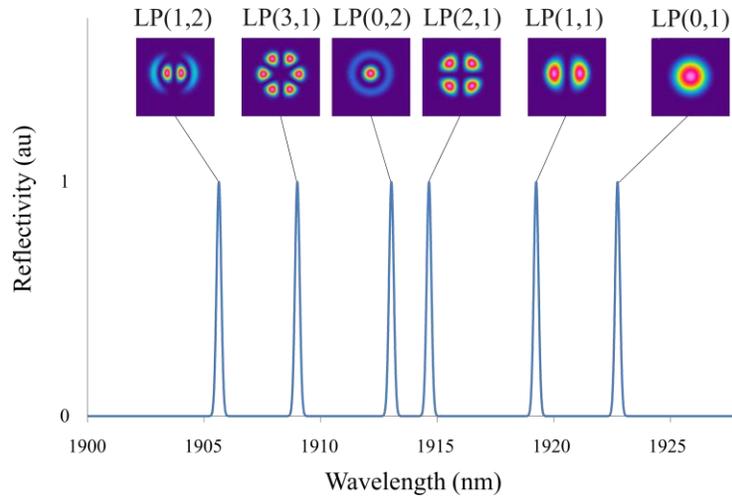


Fig. 2. Calculated reflectivity spectrum for fiber Bragg grating written in multimode Tm-doped fiber.

Both end facets of the fiber were angle-cleaved at 14° to suppress broadband feedback and help suppress parasitic lasing. The fiber was cladding pumped with light from a fiber-coupled diode source at 793 nm, this was launched into the TDF facet adjacent to the FBG with a launching efficiency of 90% yielding a maximum available launched pump power of 33 W. The cladding absorption coefficient for pump light at 793 nm was measured, via the cut-back technique, to be ~ 3 dB/m; hence a TDF length of ~ 4 m was selected for efficient pump absorption. Feedback for lasing at the opposite end of the TDF was provided by a simple tunable external feedback cavity comprising an 8 mm focal length collimating lens, a VBG, a plane mirror with high reflectivity ($>99.5\%$) from $\sim 1.9 - 2.0 \mu\text{m}$ and an uncoated fused silica wedge. The latter served as the output coupler and due to its low Fresnel reflection coefficient ensured that most of the laser output exited the cavity through the fused silica wedge. The VBG was designed to have high reflectivity ($>95\%$) at 1932 nm at normal incidence to the grating with a reflection bandwidth of ~ 0.5 nm (FWHM). The front and back surfaces were antireflection coated at $\sim 1.9 - 2.0 \mu\text{m}$ and angled slightly with respect to the grating. The VBG was aligned at non-normal incidence, so that the feedback wavelength could be adjusted (i.e. by tilting the VBG and plane mirror) to match the FBG reflection wavelength for the desired spatial mode whilst maintaining a fixed output beam direction. This arrangement has the additional attraction that laser radiation is reflected twice from the VBG for each round-trip of the cavity leading to a reduction in the feedback bandwidth and hence improved modal discrimination. Further reduction in the feedback bandwidth could be achieved (if required) by employing additional wavelength selective components (e.g. etalons, birefringent filters) in the external feedback cavity.

The TDF laser was initially tested in a free-running laser configuration with the VBG replaced by a high reflectivity plane mirror. The laser yielded a multimode output beam with a beam propagation factor (M^2) of ~ 3.3 (see Fig. 3(a)). With the VBG present in the external cavity and aligned to provide feedback at 1923 nm (i.e. to match Bragg wavelength for the LP_{01} for the FBG) lasing on only the fundamental (LP_{01}) mode was achieved. The beam propagation factor (M^2) was measured to be 1.05 confirming the diffraction-limited nature of the output beam and that there is negligible coupling to higher order modes. The far-field transverse beam profile (recorded with the aid of a pyroelectric array camera) is shown in Fig. 3(b). Adjusting the angle of the VBG and plane high reflectivity mirror to decrease the feedback wavelength to match the FBG reflection peak corresponding to the next (higher order) mode allowed selective excitation of the LP_{11} mode as shown in Fig. 3(c). In this case

the lasing wavelength was measured to be 1919 nm in close agreement to the predicted value (see Fig. 2).

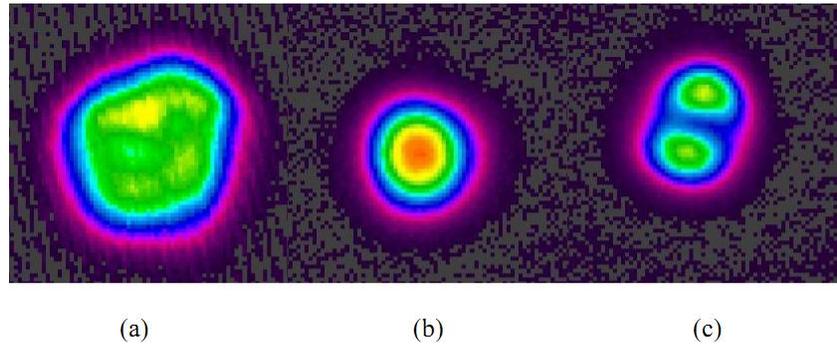


Fig. 3. Output beam profile for: (a) Free running operation. (b) VBG tuned to 1923 nm to excite the LP₀₁ mode. (c) VBG tuned to 1919 nm to excite the LP₁₁ mode.

Figure 4 shows the output power for LP₀₁ and LP₁₁ mode operation as a function of launched pump power. At the maximum launched pump power of ~34 W the laser yielded output powers of 2.6 W for LP₀₁ mode operation and 3.6 W for LP₁₁ mode operation with corresponding slope efficiencies with the respect to launched pump power of 11% and 16% respectively. The higher output power and slope efficiency for LP₁₁ mode operation is attributed to the better spatial overlap for the LP₁₁ mode with the inversion distribution [11]. The difference in slope efficiency for LP₀₁ and LP₁₁ operation should be less pronounced at higher power levels (i.e. far above threshold) when the intensity in the wings of the LP₀₁ mode is well above the saturation intensity. The relatively low slope efficiencies for both LP₀₁ and LP₁₁ operation can be attributed to hydrogen loading, which leads to a large increase in core propagation loss. The Tm fiber (with and without hydrogen loading) was tested in simple free-running laser configurations. The slope efficiency for the TDF laser without hydrogen loading was approximately 40% and roughly a factor-of-two higher than for the TDF laser with hydrogen loading. The core propagation loss in the hydrogen-loaded TDF was estimated to be ~1 dB/m. Hence, by hydrogen loading only the section of TDF where the FBG is to be written it should be possible to achieve a substantial increase in output power and efficiency. A modified hydrogen loading rig to allow selective loading of short sections of fiber is currently under development. It should also be noted that the TDF used in our experiments had a rather low Tm concentration and thus was not designed to enhance the efficiency via promoting the ‘two-for-one’ cross-relaxation process (${}^3\text{H}_4 + {}^3\text{H}_6 \rightarrow {}^3\text{F}_4 + {}^3\text{F}_4$). Hence, further optimization of the core design with high Tm concentration should yield a further improvement in efficiency commensurate with conventional Tm fiber laser architectures. The extent by which the core diameter can be increased using this approach, whilst retaining robust single-mode operation and avoiding mode distortion, is the subject of ongoing studies. Preliminary calculations suggest that core diameters around 70 μm should be feasible for two-micron operation.

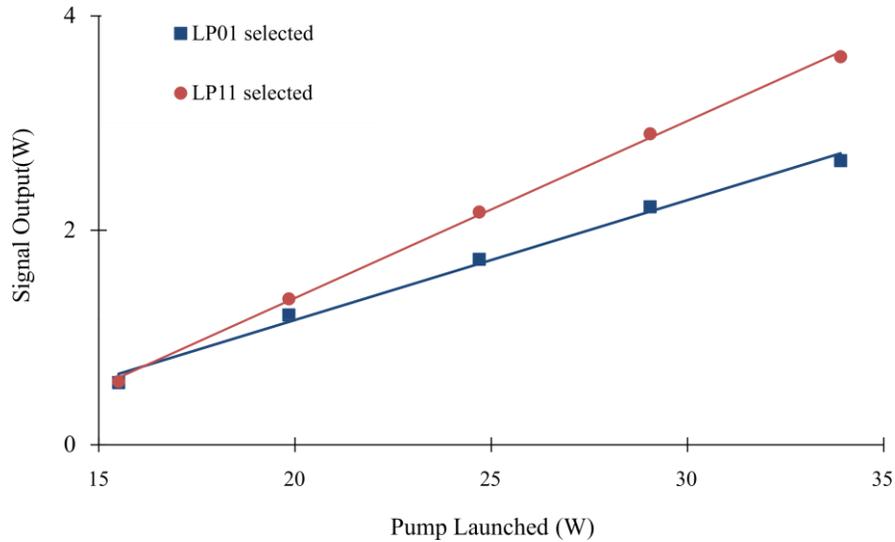


Fig. 4. Laser output power versus launched pump power for LP₀₁ and LP₁₁ mode operation.

5. Conclusion

We have demonstrated a simple and effective method for mode selection in a fiber laser oscillator with a multimode fiber. The technique exploits the different spectral responses of fiber Bragg grating and free-space wavelength-selective elements (e.g. VBGs) to provide selective feedback for a particular mode (e.g. the fundamental mode) and thereby suppress lasing on other modes. This approach can be applied to simple multimode (or large-mode-area) core designs and avoids the need for complicated and costly fibers with special core geometries designed to provide built-in suppression of higher-order modes. In this preliminary proof-of-concept study applied to a Tm fiber laser, the output power and efficiency were limited by high background core propagation loss due to hydrogen loading. Further optimization of the fiber design in combination with the use of selective hydrogen loading should yield a dramatic improvement in performance. Preliminary calculations suggest that it should be possible to scale the core diameter to $\sim 70 \mu\text{m}$ whilst maintaining robust single-mode operation at $\sim 2 \mu\text{m}$. This would pave the way for a simple Q-switched Tm fiber laser oscillator with pulse energies in the multi-millijoule regime and beyond. Moreover, the ability to selectively excite higher order modes with larger transverse dimensions than the fundamental mode should help to improve extraction efficiency and raise energy damage thresholds opening up the prospect of even higher pulse energies.