Novel technique for mode selection in a large-mode-area fiber laser

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Abstract: A novel method for selectively exciting a single-spatial-mode (fundamental or higher-order) in a high-power multi-mode fiber laser resonator is presented. Preliminary results for a cladding-pumped Tm-doped silica fiber laser are discussed.

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1. Introduction

Over the last two decades, 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 achieve good output beam quality since the core supports propagation of higher-order modes with worse beam quality factors (M^2) than the fundamental mode. Many approaches for alleviating this problem have been developed. These include the use of special large mode area core designs, micro-structured fibers, selective active-ion doping and the use of distributed mode filtering (e.g. by bending the fiber) to suppress higher order modes. However, most of these approaches add complexity and cost to the fiber design and become increasingly difficult to implement effectively as the core area is increased.

In this paper we describe a new approach for mode-selection in 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 configuration with an external feedback cavity architecture. In a multimode core, each mode is characterised by an effective refractive index (n_{eff}), where $n_{core} > n_{eff} > n_{cladding}$. The exact value for n_{eff} for a particular mode depends on the details of the fiber design and the mode, 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 FBG is written into the core with period, Λ_1, then the wavelength, λ_1, at which the Bragg grating provides maximum reflectivity is given by $\lambda = 2 n_{eff} \Lambda_1$. Hence, the wavelength at which the Bragg grating provides maximum reflectivity will decrease as the mode's effective refractive index decreases. Thus, higher order modes will experience a stronger reflection at shorter wavelengths than lower order modes. By contrast, a VBG with period, $\Lambda_{2,}$ provides maximum reflectivity at wavelength, λ_2, given by $\lambda_2 = 2 n_v\Lambda_2$, where the effective refractive index, n_v, is approximately equal to the refractive index of the bulk material and varies very little from mode to mode due to the absence of a waveguiding geometry. Thus, by forming a laser resonator with a multimode fiber core as the active medium with feedback for laser oscillation provided by a FBG in the core and by an external cavity with a VBG it is possible to restrict lasing to a single-spatial-mode or a few spatial modes with effective refractive index n_{eff} chosen such that the period of the volume Bragg grating is $\Lambda_2 = n_{eff} \Lambda_1 / n_v$. In this way, it is possible to selectively excite the fundamental mode or a higher-order mode in slightly multimode fibers.

2. Experiment and results

As an initial proof-of-concept the fiber laser configuration shown in Fig. 1 was constructed and tested. The laser comprised a 4 m length of Tm, Ge co-doped double-clad fiber (TDF) with a 22 µm core size (0.22NA) and a D-shaped pure silica inner-cladding of diameter, 300 µm. The fiber core's V parameter at ~2 µm was calculated to be ~7.6 and hence the core could support propagation on a number of higher order modes leading to multimode lasing under normal operating conditions.

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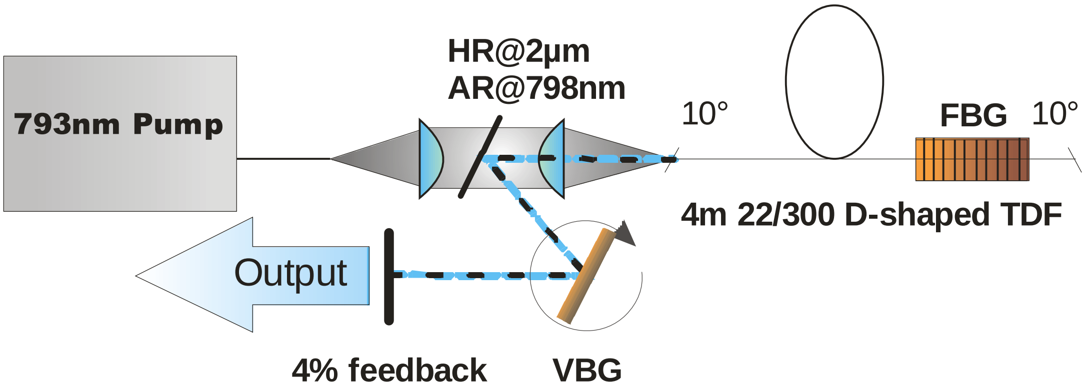
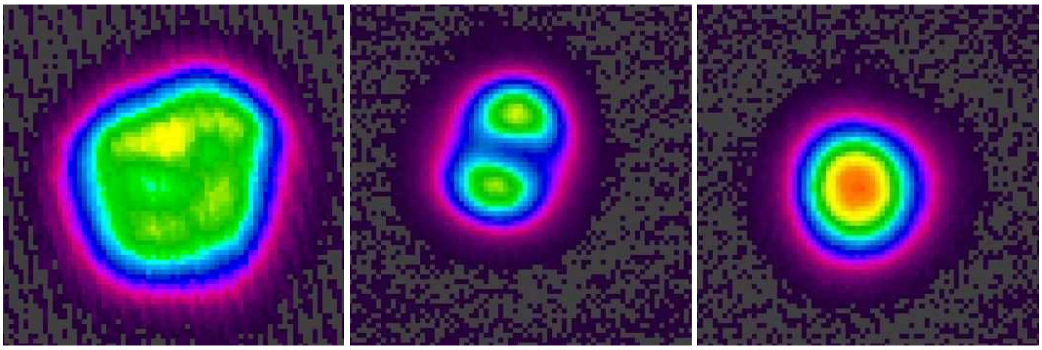


Figure 1. *Tm-doped silica fiber laser configuration (FBG = Fiber Bragg Grating, VBG = Volume Bragg Grating).*

Feedback for lasing was provided by a FBG written directly into the fiber core and by a simple external cavity containing a VBG and a wedged output coupler with a reflectivity of ~4%. This arrangement allowed the feedback wavelength to be varied by simply adjusting the angle of the VBG and the wedged mirror. The reflectivity bandwidth for the VBG was ~0.5 nm, the FBG had a feedback reflectivity of 25%.



(a) **(b)** **(c)**

Figure 2. *output beam profile for* **(a)** *free funning operation* **(b)** *VBG tuned to 1919nm (LP_{11})* **(c)** *VBG tuned to 1923nm (LP_{01})*

Under free running conditions (i.e. with the VBG replaced by a broadband high reflector) the Tm fiber laser produced a multimode output (as shown in Fig. 2(a)). Figures 2(b) and 2(c) show the laser operating on only the fundamental mode (LP_{01}) at ~1923 nm or the next higher order mode (LP_{11}) at 1919 nm achieved by simply adjusting the angle of the VBG (and wedged mirror) so that the feedback wavelength coincides with FBG feedback wavelength for the relevant modes. In the former case the M^2 parameter for the output was measured to be 1.05 confirming the diffraction-limited nature of the output beam. At present output powers are limited to <5 W due to the non-optimal nature of the resonator design and high propagation loss in the fiber core attributed to hydrogen loading during the process of writing the grating. Further optimisation of the Tm fiber design and resonator design should yield a significant improvement in performance

3. Conclusion:

We have demonstrated a new method of mode selection in a multi-mode fiber laser oscillator. This approach should be particularly useful for scaling pulse energy from Q-switched fiber lasers whilst retaining good beam quality, potentially benefiting a range of applications.