Narrow Linewidth, Tunable, CW, Thulium Fiber Lasers with VBG and GMRF stabilization

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ABSTRACT

Eye-safe, high power tunable narrow linewidth lasers are important for various applications such as atmospheric propagation measurements. We have investigated two techniques of generating narrow linewidth thulium 2-µm fiber lasers, utilizing a reflective volume Bragg grating (VBG), and a guided mode resonance filter (GMRF) as a cavity end mirror. A stable narrow linewidth (50 pm), tunable (from 2004 nm to 2054 nm) thulium doped fiber laser using a reflective VBGg was demonstrated. A CW power of 17 W was achieved. Using a GMRF as an end mirror we showed a narrow linewidth (~30 pm) laser with an output power of 5.8W, and at a slope efficiency of 44%.

Keywords: Fiber lasers, VBG, GMRF, Laser stabilization, Tunability

1. Introduction

Efficient laser action at high power, eye safe wavelengths lasers is possible in Thulium (Tm) fiber lasers operating in the 2 µm wavelength regime. Due to the spectrally inhomogeneous nature of the thulium doped fiber, elements which stabilize and spectrally narrow the output are desired for methods of scaling to higher powers, such as spectral beam combing, atmospheric propagation and medical applications [1]. Most commonly, fiber Bragg gratings (FBGs) are used as feedback elements due to their monolithic all-fiber nature and relatively narrow achievable linewidths (<1nm) [2]. However, as the state of high power fiber laser technology progresses, new large mode area (LMA) fiber designs, such as novel photonic crystal fibers [3] and gain guiding index antiguiding fibers [4, 5] are, being created which are not yet compatible with fiber Bragg gratings, as it is difficult to fabricate efficient FBGs in fibers with such large mode areas. In order to provide linewidth control in laser systems based on these LMA fibers, other technologies must be investigated.

Recently, volume Bragg gratings (VBGs) have been explored as viable options for linewidth stabilization and selection in Tm fiber lasers and for high power scaling [6, 7, 8]. VBGs have been used in fiber lasers, and achieved upwards of 100 W output powers while keeping linewidth relatively narrow [8]. These lasers have been demonstrated in several rare earth ions doped into fibers today, including the Tm ion, which is of interest for this work [6]. However, as discussed in [8], problems with VBGs begin to arise as power levels are increased beyond the 100 W level, the ability of a VBG to keep locked to a wavelength begins to be compromised as heating resulting from absorption of light can cause a wavelength shift, which may be undesirable in wavelength critical systems such as those designed for spectral beam combining.

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Another novel and interesting means of spectral control that could be compatible with very large mode area fiber lasers is the use of a Guided Mode Resonance Filter (GMRF). Previously, GMRFs have been used as cavity end-mirrors to stabilize and narrow the linewidth of erbium-ytterbium fiber lasers, which produced lasing at 1540.8 nm with a linewidth of 0.18 nm with an output power of ~ 1W [9]. Owing to their nature as simple thin film dielectric coatings, these devices may demonstrate enhanced thermal stability.

In this paper we demonstrate, for the first time, a stable spectrally narrow Tm doped Large Mode Area (LMA) fiber laser using an external GMRF and also present our latest laser performance results on the laser resonator made from a VBG as an end mirror.

2. Guided Mode Resonance Filters and Volume Bragg Gratings: a brief description

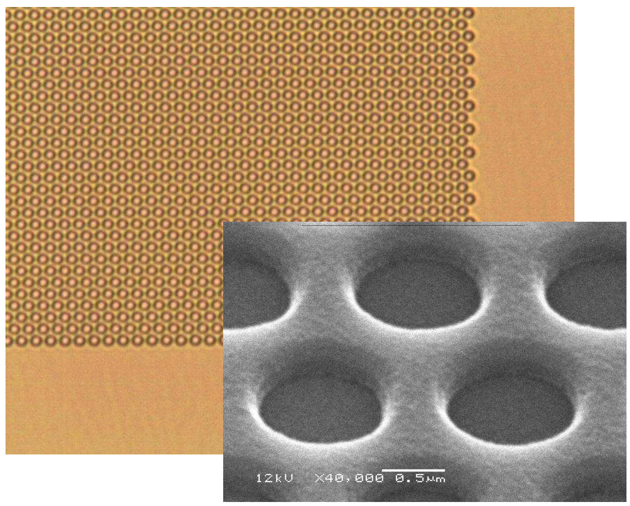

Fig. 1: (Background) Optical microscope top-down photograph of a GMRF device, shows the in-plane hexagonal array of holes. (Foreground) Angled view of an SEM micrograph of a GMRF device, shows the etched SiO_2 layer, exposing the silicon nitride underneath. The unit cell period is 1.514μm and the hole diameters are 1.0μm.

2.1 Guided Mode Resonance Filter

The theory of Guided Mode Resonance Filters (GMRFs) stems from discoveries R. W. Wood made in 1902 concerning variations in the intensity of the diffracted spectral orders over a narrow frequency range [10]. Wood discovered two separate anomalies, the first described by Rayleigh in 1907 concerns the variation of intensity of diffracted orders when orders appear or disappear [11]. The second theory, describing the resonance anomaly seen by Wood was explained by Hessel in 1965 [12]. GMR occurs when a diffraction grating couples the diffracted orders into guided modes in a waveguide structure. A resonance feature can be created when the guided mode leaks back onto the incident wave because of index modulation of the waveguide. GMR filters have shown promise as stable narrow linewidth feedback elements for fiber lasers due to the ability to tailor diffraction gratings to narrow the linewidth and select wavelength over a broad range [13].

GMRFs, used as an external feedback element for the current Tm doped silica fiber, were fabricated at UNC-Charlotte. These GMRFs consisted of a fused silica substrate with a PECVD deposited Si_xN_y waveguide layer, and a diffractive array of holes in a hexagonal lattice configuration [Fig. 1], etched into a PECVD grown top layer of SiO_2 [9]. A two dimensional diffraction grating was produced by way of a hexagonal hole-array patterns. Wavelength and resonance properties are varied by changes in hole size, spacing and waveguide layer thickness. A set of filters were designed to operate at around 2 μm with a spectral reflectivity of ~ 0.4 nm (FWHM).

2.2 Volume Bragg Grating

VBGs are generally fabricated via a holographic process exposing UV light onto photo-thermal-refractive (PTR) glass doped with silver, cerium and fluorine[14]. PTR-glass has a large transparency window (350-2700 nm), low thermal variations in refractive index ($dn/dT = 5\times10^{-8}$ K^{-1}), high damage threshold and they can be designed with high reflectivity (>99.9 %) and bandwidths from tens of pm up to ~0.5 nm [15]. These properties make VBGs highly interesting for narrow linewidth laser development applications.

The VBG [OptiGrate, Orlando, FL] used in the experiment was 5 mm X 5 mm aperture and 6.3 mm long. The surfaces were not AR coated and the grating was tilted ~0.6 degrees in the vertical and horizontal planes relative to the bulk end-face to prevent Fresnel reflections from interfering with the VBG reflectivity. The grating had reflectivity of > 95% when Bragg condition is met and was designed with a line center of 2051.5 nm and a spectral FWHM of 0.55 nm.

3. Experiment

3.1 Spectral measurements of the GMRFs

Several GMRFs, with varying hole-diameters to achieve optimum reflectivity and center wavelength, were characterized by measuring the spectral transmission and subsequently, inferring the reflectivity, assuming there was no loss in the filter itself.

A broadband 2-µm ASE (amplified spontaneous emission) source was developed by using a thulium doped LMA fiber angle cleaved (~8 degrees) at both ends. The fiber was pumped by 790 nm light from a fiber coupled laser diode. The spectral measurements were taken with a McPherson 218 scanning monochromator with a 300 line/mm grating blazed at 2 µm, which with minimum slit width had a resolution of ~0.3 nm (FWHM). The detector used to measure the output from the monochromator was a 0.5 mm diameter thermoelectric cooled InGaAsSb photodiode providing a spectral response in the range 0.8-2.4 µm. The GMRF was placed in the output path of the ASE while spectral data was recorded with the monochromator.

3.2 Performance evaluation of laser oscillators made of GMRF, VBG and an HR mirror at one end of the cavity

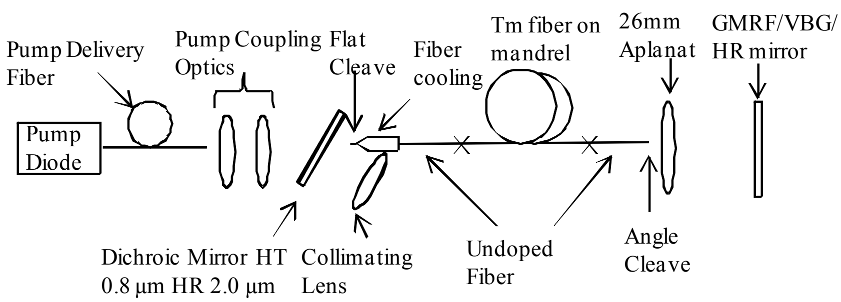

Fig. 2: Schematic of the laser set up

Figure 2 shows a schematic of the experimental setup. Experiments utilized a Tm fiber gain medium which consisted of ~4 m of LMA fiber (Nufern, Inc) with 25 µm diameter, 0.08 NA circular core and 400 µm diameter, 0.46 NA octagonal shaped cladding. Thermal stress associated with the end pumping technique used for pumping the Tm fiber was mitigated by fusion splicing ~1.5 m of undoped fiber with matching core and cladding dimensions to both ends of the active fiber. Thermal management was also incorporated to improve the laser efficiency by means of coiling the active fiber around an aluminum, water-cooled (~14°C) mandrel while the fiber ends were held in water-cooled copper V-grooves. Pumping was accomplished with a ~40 W ~795 nm fiber coupled laser diode from Spectra Physics launched with a 400 µm 0.22NA fiber through two infinite conjugate achromatic doublet pairs with an NA of 0.26. Light was launched through an angled dichroic mirror (HT 0.8 µm, HR 2.0 µm), which was also used as the laser output mirror. Coupling efficiency of the pump light is estimated to be ~70% by launching through a short section of undoped fiber. One fiber end was flat cleaved to provide ~4% Fresnel feedback to the laser resonator and the other end was cleaved to

~8 degrees to avoid parasitic lasing. The resonator was completed with an AR coated Infrasil 26 mm aplanatic triplet lens to collimate the beam to a diameter of ~3 mm on the 5 mm square GMRF, VBG or HR mirror.
A high power VBG laser pumped by a Spectra Physics fiber coupled laser diode with ~200 W, 795 nm pump power and 0.22 NA, 400 micron fiber delivery was also demonstrated. The laser setup is identical to that shown in Fig. 2, with the exception of the higher power pump laser and a 17 mm focal length uncoated aspheric lens in place of the aplanat.

4. Results and discussions

4.1 Characterization of GMRFs

Shown in Fig. 3 is the wavelength versus spectral reflectivity of a typical GMRF. Lorentzian peaks with widths between 0.4-1 nm were measured on the set of filters; this linewidth range approximately matched the desired 0.4 nm designed spectral width.

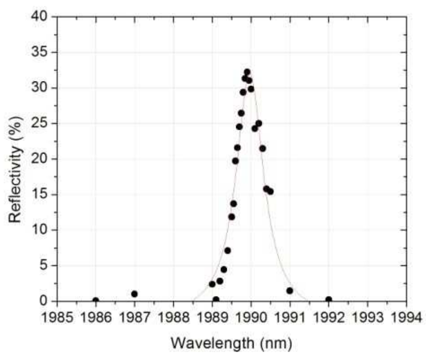

Figure 3: Spectral Reflectivity of GMRF with a FWHM of 0.85 nm.

4.2 Laser measurements

Laser linewidths of the GMRF, and the VBG lasers were measured with a scanning Fabry-Perot interferometer with 98% reflectivity mirrors designed for 2 µm. Alignment of the Fabry-Perot was achieved using a Spiricon Pyrocam III while the InGaAsSb photodiode was used to measure the interference fringes as a function of scan time of the Fabry Perot mirrors. Initial measurement on several lasers, utilizing sixty GMRFs with varying characteristics, at less than twice laser threshold (limited by available pump power) yielded linewidths in the range of 10-30 pm ± 5 pm and slope efficiencies of 10 % to 44%. The GMRF laser with a slope efficiency of 44 % will be discussed in a bit more details in the following paragraphs.

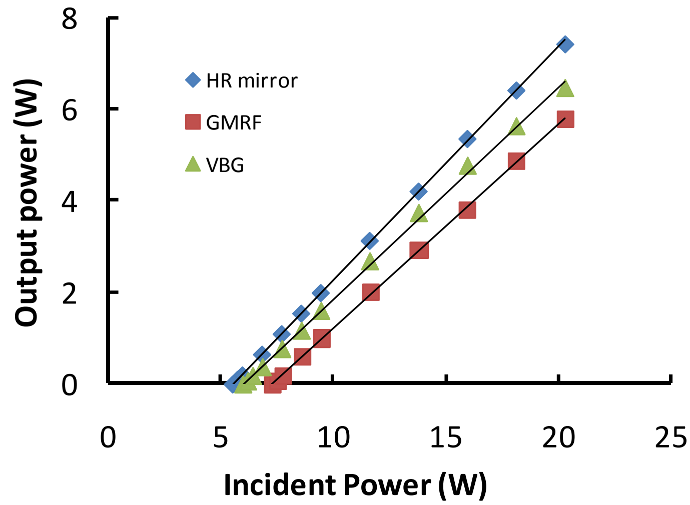

Fig. 4: Performance of laser oscillators with GMRF, VBG and HR mirror as one end-mirror and

Shown in Fig. 4 is laser performance achieved by using either a GMRF, or a VBG as one-end *high reflector* mirror (Fig. 2). To understand the performance of the VBG and GMRF lasers, using the same set up except a HR mirror is used in the place of a VBG and a GMRF, a HR laser performance is also included in Fig. 2. Output coupling for the laser-cavity was created by Fresnel reflection from the flat cleaved LMA fiber. All other aspects of the cavity were kept the same among the three lasers. The measured slope efficiency of the HR mirror laser was the highest (~51%) compared to ~44% for the GMRF laser and ~46% for the VBG laser. The GMRF allowed stable lasing at 1981 nm with narrow linewidth of ~ 0.4 nm which is close to the resoloution limit of the monochromator used to make the measurement. The VBG laser linewidth was 0.3 nm (again limited by the resolution of the monochromator). When the VBG/GMRF was replaced by a dielectic HR mirror, the laser output spectrally broadened to >2 nm and lased at ~2020 nm. The pump power thresholds for the HR, VBG and GMRF lasers were measured to be 5.6 W, 6.0 W, and 7.3 W, respectively. It should be noted that slope is quoted with respect to launched pump power, as the launch efficiency is ~70%. The smaller slope efficiency and higher threshold of the GMRF cavity was due to the lower peak reflectivity of the available GMRFs. This is clearly seen during the experiment, as output power was observed to be exiting both ends of the laser cavity, a clear sign that the reflectivity of the GMRF was not high enough. Using the well known equation for estimating the ratio of output power from each end of a laser resonator [16]

$$\frac{P_1}{P_2} = \frac{1 - R_1}{1 - R_2}\sqrt{\frac{R_2}{R_1}}$$

where $P_{1,2}$ is the power output from end 1 or 2 of the fiber laser and $R_{1,2}$ is the reflectivity of end 1 or 2 of the fiber laser resonator, the reflectivity of the GMRF was estimated to be 50%.

Using the fabricated GMRFs we have demonstrated, as a proof of concept, both stable and spectrally narrow outputs at the available pump powers. Most of the tested GMRFs had peak reflectivities between 20-35% with the best GMRFs having reflectivities around 50%, resulting in producing lower laser efficiencies and much higher thresholds which will be remedied with optimization of future GMRFs. Modeling optimization of the GMRF suggests spectral reflectivity can be improved to beyond > 90% peak reflection and thus enable efficient, stable feedback at significantly higher laser powers and efficiencies. Fabrication of such high-efficiency GMRFs is currently being explored which will enable future experiments investigating thermal stability of GMRFs at higher powers.

4.3 High power and tunable VBG laser

The output power characteristics of two lasers incorporating either a VBG or a HR mirror as a cavity feedback element are shown in Fig. 5. These lasers are formed on the same cavity demonstrated in Fig. 2, but higher pump power (up to 50W absorbed) was available to pump these lasers and the lens used to collimate the light in the free space cavity was an uncoated 17 mm asphere. Tuning was achieved by rotating the VBG and feeding back the diffracted beam, using a high reflector mirror, into the cavity. The laser with the HR mirror produced a maximum output power of 19 W with a slope efficiency of 51% with respect to absorbed pump power and an absorbed pump power threshold of ~8.0W. The VBG laser performed very similarly with a maximum output power of 17 W, a slope efficiency of 46% with respect to absorbed pump power and an absorbed pump power threshold of 8.0 W. The slightly higher thresholds in these versions of the laser are due to the 17 mm asphere being much higher loss (~15%) than the AR coated 26 mm aplanat used in the earlier section 4.2 of laser measurement.

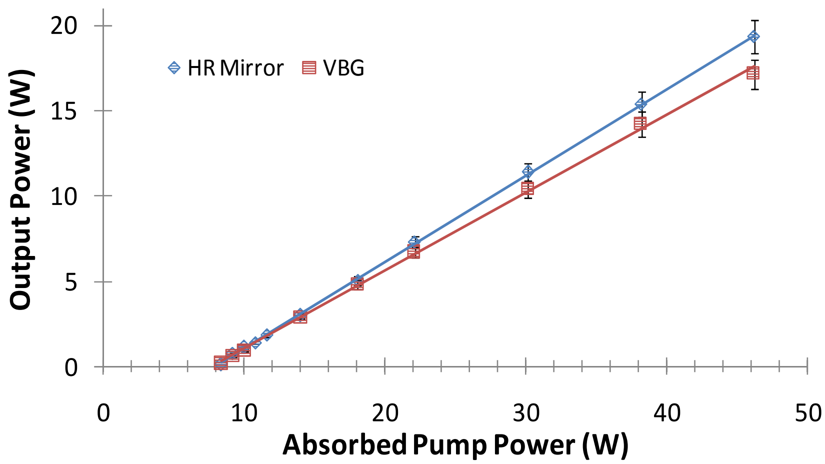

Fig. 5: Output power versus absorbed pump power for HR and VBG lasers. Note that error bars denote 5% error associated with fluctuations in the power meter readout.

The spectral characteristics were measured with the same monochromator used in earlier GMRF measurements, and also with an Optical Spectrum Analyzer (AQ6375, Yokogawa Inc). The spectrum of the HR mirror laser showed a number of significant lines lasing simultaneously over a total bandwidth of 12 nm, centered ~ 2027 nm. This wavelength was observed to be highly dependent on the gain in the fiber laser, when no HR mirror is used and the laser was operated with only ~ 4% Fresnel reflection feedback on both ends the center wavelength shifts down towards 2007 nm and the number of lasing lines decreases. The harder the laser is pumped, the broader the laser spectrum becomes. When the VBG is used as an end-mirror, the laser line center jumps to 2053.9 nm and the linewidth drops to approximately

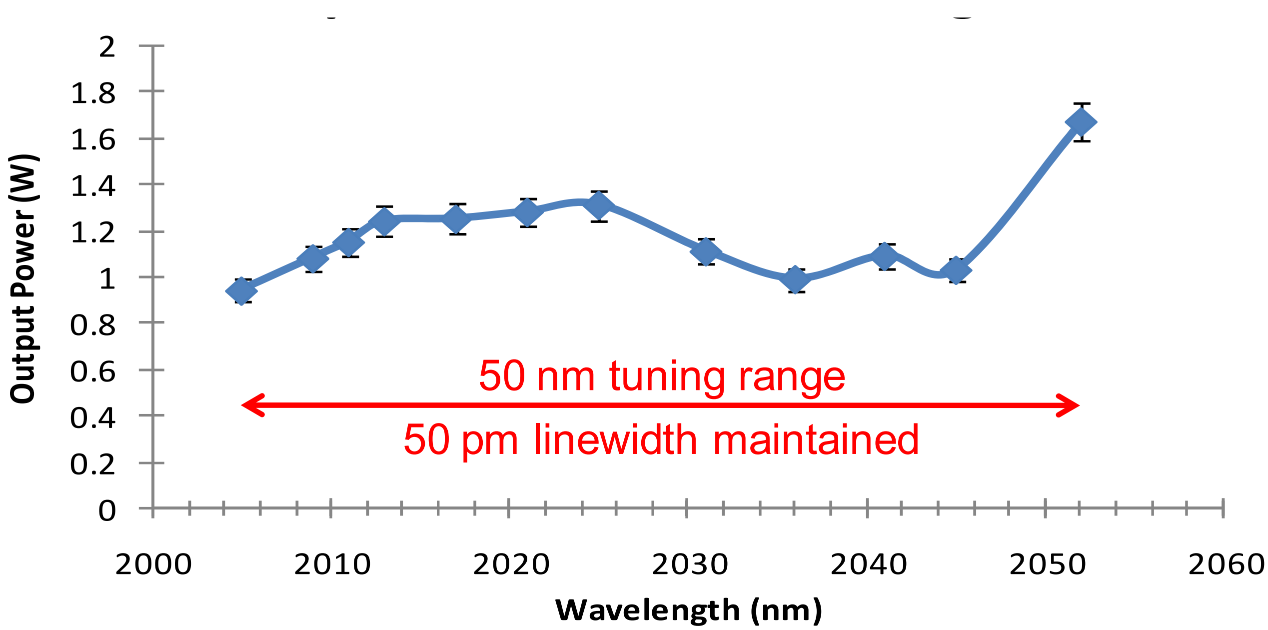

Fig. 6: Tunining curve of the VBG laser

50 pm (limited only by the resolution of the OSA). It should be noted that the line center measured by the monochromator and OSA is different from the line center specified by OptiGrate by ~3 nm. This discrepancy is most likely due to differences in calibration of the scanning monochromator, OSA and the measurement technique used to characterize the VBG at OptiGrate. The VBG stabilized spectrum showed no sign of jitter and the laser stayed locked to the line even as pump power levels were increased. There were no signs of other parasitic lasing from the cavity formed by the two flat cleaved fiber ends. This is because the feedback from the VBG is much stronger than the Fresnel reflections for the fiber facets, and hence the VBG feedback forces the laser to oscillate in that spectral regime only. It should be noted that the VBG was able to force the laser to operate quite far from the peak of the gain defined by where the laser operated with the HR mirror or when free lasing from two Fresnel reflections.

A Spiricon Pyrocam III was used to image the output beam, and to measure its divergence using the well known technique of scanning along the beam as it is focused through greater than the Rayleigh range of a 1 meter focal length lens. Such a long focal length lens was used to ensure that the beam waist was large enough to be accurately detected on the relatively low resolution Spiricon (85 x 85 μm pixel size). The value of M^2 was <1.4. This relatively high beam quality is expected because although the V parameter of this fiber was approximately 3.06, the 11 cm coiling diameter was sufficient to strip off any higher order modes from the low NA core.

5 Conclusions and future work

In this paper we have described preliminary measurements of two novel approaches utilizing a VBG and a GMRF as end mirrors to generate stable, narrow linewidth Tm fiber lasers at moderate power level. Several GMRFs with varying characteristics were designed, fabricated and characterized. While spectral measurements on almost all of the GMRFs gave a very narrow linewidth (between 10 to 30 ± 5 pm), the reflectivities of the GMRFs varied from 20% to ~50%. A theoretical model predicted that reflectivity as high as 90% is possible in these GMRFs and new set of GMRFs are being fabricated for further investigation. Our initial measurement demonstrated a GMRF laser with a laser threshold of ~7 W and a slope efficiency of > 44% with respect to the incident pump power.

Also, we showed stable, narrow linewidth (~50 pm) 17 W of output power at 2-µm. The slope efficiency of this VBG laser was 46%. The VBG laser tuned from 2004 nm to 2054 nm. Further investigation is on to improve the laser performance and output power using GMRFs and VBGs as end mirrors.

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References

1. Sevian A., et al., "Efficient power scaling of laser radiation by spectral beam combining,". Opt. Lett, **33** 384-386 (2008).
2. Liu C. -H. et al., "High-power single-polarization and single-transverse-mode fiber laser with an all-fiber cavity and fiber-grating stabilized spectrum," Opt. Lett., **31,** 17-19 (2006).
3. Limpert J., Schmidt O., Rothhardt J., Roser F., Schreiber T., Tunnermann A., Opt. Express **14**, 2715 (2006)
4. Siegman A. E, "Gain guided, index-antiguided fiber lasers," J. Opt. Soc. Am. B **24**, 1677–1682 (2007).
5. Sudesh V., McCombT., Chen Y., Bass M., Richardson M., Ballato J., and Siegman A. E., "Diode-pumped 200 µm diameter core, gain-guided, index-antiguided single mode fiber laser" Appl. Phys. B, v90, p 369 (2008).
6. McComb T., Sudesh V., and Richardson M., "Volume Bragg grating stabilized spectrally narrow thulium fiber laser" Opt. Lett. **33**, 881 (2008).
7. Jelger P., and Laurell F., "Efficient narrow-linewidth volume Bragg grating locked nd:fiber laser," Opt Express **15**, 11336 (2007).
8. Jelger P., et al., "High-power linearly-polarized operation of a cladding-pumped Yb fibre laser using a volume Bragg grating for wavelength selection," Opt. Express, **16,**. 9507-9512 (2008).
9. Mehta A. A., Rumpf R. C., Roth Z. A., and Johnson E. G., "Guided Mode Resonance Filter as a Spectrally Selective Feedback Element in a Double-Cladding Optical Fiber Laser," IEEE Photon Technology Letters, **19**, 2030-2032 (2007).
10. Wood R. W., "On a remarkable case of uneven distribution of light in a diffraction grating spectrum," Proceedings of Phys. Society of London **XVIII** 269 (1902)
11. Rayleigh L., "On the Dynamical Theory of Gratings," Proc Roy Soc London, **79**, 399-416 (1907).
12. Hessel A., and Oliner A. A., "A New Theory of Wood's Anomalies on Optical Gratings," Appl. Opt. **4,** 1275-1297 (1965).
13. Rumpf R. C., and Johnson E. G., "Modeling fabrication to accurately place GMR resonances," Optics Express **15**, 3452-3464 (2007).
14. Efimov O. M., Glebov L., Smirnov V.. "High efficiency volume diffractive elements in photo-thermo-refractive glass," United States Patent 6,673,497. January 6, 2004.
15. Efimov O. M, Glebov L. B, Glebova L. N., Richardson K. C., and Smirnov V. I., "High-efficiency Bragg gratings in photothermorefractive glass," Appl. Opt. **38**, 619-627 (1999).
16. Rigrod W. W., "Saturation effects in high-gain lasers," J. of Appl. Phys., **36,** 2487-2490 (1965).