Stable 2.1 µm near 100% polarized Ho-doped all-fiber laser based on a polarizer-free cavity scheme

Sida Xing, Svyatoslav Kharitonov*, Jianqi Hu, Davide Grassani and Camille-Sophie Brès

Ecole Polytechnique Fédérale de Lausanne (EPFL), Photonic Systems Laboratory, PHOSL-STI-IEL, Station 11, CH-1015 Lausanne, Switzerland

* svyatoslav.kharitonov@epfl.ch

Abstract *A highly polarized Ho-doped truly all-fibre laser was demonstrated without in-cavity polarizer. Utilizing PM-FBG and loop mirror, maximum 0.5W output power with 30% slope efficiency, 70dB ASE suppression and 99.997% degree of polarization was recorded at 2.1µm*

Introduction

The atmosphere has a low-loss window at the 2.09 ~ 2.1µm range[1], such that compact and robust fiber lasers within this wavelength range are attractive for coherent light detection and ranging (LIDAR)[2] and can be potential sources for new optical communication windows[3]. In both areas of applications, modulation of the laser is essential either to transmit information in hollow core fibers or to improve the LIDAR performance[4,5]. Modulators require stable, linearly polarized and narrow-linewidth input. Therefore, developing linearly polarized and long term stable laser source is important for optical system at this wavelength range. A highly-polarized laser offers another degree of freedom for data retrieval, which has been used for a long time in polarization backscattering LIDAR[6]. Besides, the optical system should possess a high and stable degree of polarization (DOP)[7].

During the past years, intensive studies have been made on the development of 2.1µm fibre lasers. Utilizing the broad emission band of Tm^{3+}, on the one hand, Tm-doped all-fibre lasers covering 1925nm to 2200nm have been demonstrated with a slope efficiency of more than 42% and amplified spontaneous emission (ASE) suppression of about 40dB for wavelength near 2100nm[8]. On the other hand, Ho-doped fibre lasers have an emission cross-section favouring the longer wavelengths and have been demonstrated to lase efficiently until 2171nm. The most efficient 2116 nm wavelength of Ho-doped fibre laser, exhibits a slope efficiency of 43% and ASE suppression of more than 50dB[9]. However, up to now, there is a lack of high efficiency lasers emitting polarized light directly from the cavity in this wavelength range. Due to their insertion loss, limited bandwidth (typically ~50nm around 2µm), and low availability as fiberized components, it is preferable to avoid the use of polarizers. Instead high quality polarized light should directly be generated from the laser cavity. In addition, a completely all-fibre and simple cavity design is ideal for long-term stability, power handling and compactness.

In this work, we demonstrate the first all-fiber laser at 2.1µm emitting highly polarized light with more than 99.997% DOP and at least 65dB ASE suppression. This high DOP was achieved thanks to the combination of polarization sensitive fiber elements – polarizaion maintaining fiber Bragg grating (PM-FBG) and fiber loop mirror (FLM) – as cavity high reflective (HR) and low reflective (LR) mirror, respectively. The laser can emit at a single or dual wavelength at any ratio with a slope efficiency of 30%

Experimental Setup

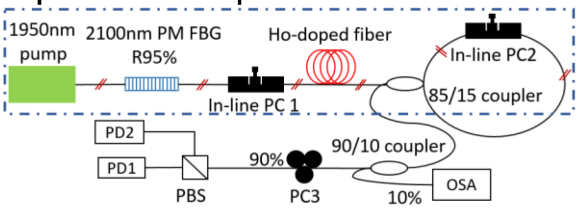

Fig. 1 Experimental setup of the laser cavity and characterization setup. PM-FBG: polarization maintaining fiber Bragg grating; PC: polarization controller; PD: photodetector; PBS: polarization beam splitter

The pump laser is a homemade Tm-doped fiber laser at 1950nm. An L-band amplifier seeded at 1620nm was used to pump the Tm-fiber. The maximum output power is approximately 2.3W and has a bandwidth less than 0.08nm. The experimental setup of the Ho-doped fiber laser is shown in the dashed box of Figure 1. The PM-FBG was fabricated on Nufern PM1950 fiber and has Bragg wavelengths centered at 2100.2nm and 2100.7nm on fast and slow-axis, respectively. The bandwidth and reflection for both axes are the same, 0.175nm and 95.85%. An SM2000 fiber was inserted inside the inline polarization controllers (PC1 and 2) and each of them has less than 0.4dB insertion loss (measured at 2.004µm). A 1.7m of Ho-doped double cladding fiber (Nufern SM-HDF-10/130) was used as active medium. SMF-28 pigtails were spliced for core pumping. The coupler was measured to have a coupling ratio of approximately 85/15 at 2100nm and used as an FLM at the output. Another inline polarization controller was inserted for tuning the reflectivity of FLM, hence maximizing the ASE suppression and slope efficiency. The coupler was also made of SM2000 to reduce loss in the 2.1µm range. The mating sleeves inside the fiber cavity are labeled with red double diagonal marks in Figure 1.

The monitoring/characterization setup of the laser is indicated in Figure 1 as well. The laser output was connected to a 90/10 coupler. An optical spectrum analyzer (OSA) was connected to the 10% port for spectrum recording. The 90% coupler port was connected to a 3-paddle PC (PC3) and then through a polarization beam splitter (PBS) for power monitoring on both polarization axes. The integrating sphere sensor has a sensitivity of -30dBm, which was used to monitor the low power port of PBS. A thermal detector was used for monitoring the high-power port.

Result and Analysis

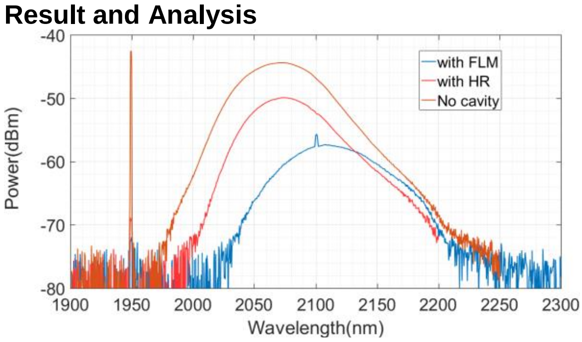

Fig. 2 ASE spectrum recorded with FBG-FLM cavity (blue); HR-FBG cavity (red); and forward ASE of fiber (orange). By implementing an FLM with lower reflection, the Ho^{3+} ASE center was red-shifted towards 2100nm.

By tuning PC2 inside FML, maximum and minimum reflection of 44% and 0.15% was recorded at 2.1µm, leading to an insertion loss of approximately 0.7dB. The forward ASE of our 1.7m Ho-doped fibre is centered at approximately 2070nm. We built another linear cavity using a free-space mirror as broad band reflective element to evaluate the effect of the FLM on the laser performances (Figure 2). This cavity utilized the free space mirror as HR (R>98%) and the PM-FBG as LR. The ASE central wavelength stays roughly the same as cavity-less forward ASE. Implementing an FLM lowers the in-cavity energy. The gain cross section was redshifted due to less population inversion, which induces a loss favoring long wavelength side[10], thus increasing 2100nm lasing efficiency and ASE suppression.

A broad range spectrum was recorded to study the ASE suppression and pump absorption (Figure 3(a)) from 1900nm to 2300nm with a resolution of 2nm at four pump power levels – from the 400mW to maximum pump power of 2.3W. When FLM was optimized to have the maximum reflection, an ASE suppression of more than 70dB was measured at the maximum pump power of 2.3W. Laser slope efficiency was then checked by inserting the laser output directly into an integrating sphere sensor. Lasing threshold was found to be 590mW and slope efficiency is approximately 30% for the slow axis (Figure 3(b)); Single-wavelength lasing on either axis was found to have the same slope efficiency and threshold while dual-wavelength lasing has ~0.2dB lower efficiency. Maximum output power of 480mW was reached, limited by the power of our pump laser. No indication of saturation is observed. We were limited by the resolution of our OSA for estimation of the laser linewidth. An upper boundary of 0.06nm can be found in Figure 3(d).

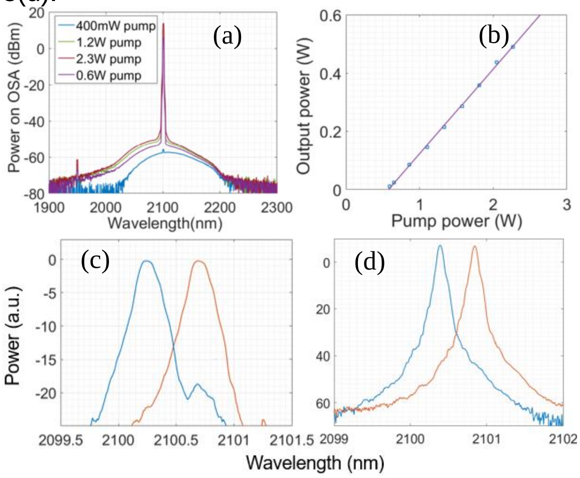

Fig. 3 (a). Broad range spectrum of laser; recorded with 2nm resolution; (b). 2100.9nm output power with respect to 1950nm pump laser; (c). Reflection of PM-FBG, tested with low power; (d). Laser spectrum when lasing on fast (blue) and slow axis (orange), respectively

The peaks were measured at approximately 2100.4nm and 2100.9nm, for fast and slow axis, respectively. Compared to the measurement at low power, shown in Figure 3(c), the small drift from the initial central wavelength is a result of thermal expansion when FBG heated up by laser. This expansion redshifts the FBG center wavelength on both axes, with the same amount, as was measured here.

PC1 was tuned to select to lase on fast or slow axis and PC2 was tuned to maximize the output power. As FLM is a polarization sensitive element, PC2 also helps to enhance the degree of polarization (POD). The long-term spectrum/linewidth stability was then monitor on OSA and power meters. In Figure 4(a) and (b), a superposition of the laser linewidth over about 2.5 hours was plotted using more than 2000 recorded trace at a resolution of 0.05nm. The linewidth jitter does not exceed 12 pm both for single- and dual-wavelength operation regimes. The technique for the linewidth jitter evaluation is stated elsewhere[10]. To check the laser polarization property of dual-wavelength operation, inline PC1 and 2 were then tuned to achieve roughly equal power on both axes. The two lasing wavelengths are expected to be perpendicular to each other. The longer lasing wavelength was maximized on PD1 after the polarization beam splitter (PBS) by tuning the PC3 and then recorded by OSA. Then, keeping the PC3 unchanged, the spectrum of the other PBS output was immediately recorded. A DOP of more than 99.999% can be clearly observed in Figure 4(c) for both lasing axes, showing that a good orthogonality between the two lasing wavelengths is preserved. Stability of the dual wavelength lasing condition was then monitored for ~40min with 1000 traces shown in Figure 4(d).

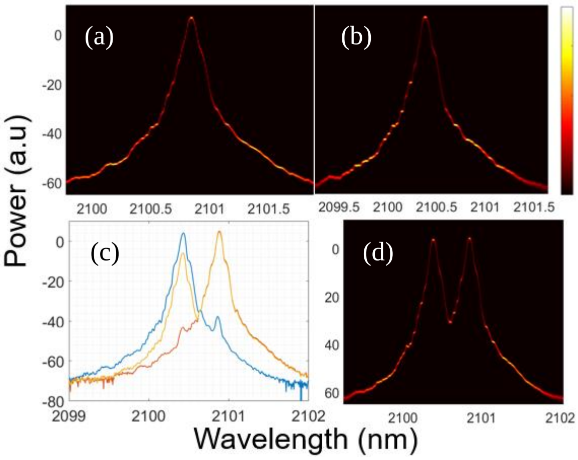

Fig. 4 (a). Laser line distribution when lasing at fast axis; (b) Laser line distribution when lasing at slow axis; (c) Spectrum recorded on two port of PBS (blue and orange) with paddle PC1 fixed. The yellow trace is an intermediate state while optimising PC3. (d) laser distribution of dual-wavelength lasing. All data were recorded after 30 min of heating-up. The color bar (range from 0 to 1) corresponds to the probability of recording the laser line on a certain pump power and wavelength coordinate.

The power stability of single wavelength lasing and dual wavelength lasing were also recorded with power meter as demonstrated in Figure 5(a) and (b). The monitoring time for dual wavelength lasing and single wavelength lasing was 40 min and 120 min, respectively. Limited by the sensitivity of our integrating sphere sensor, the DOP can only be estimated to a lower boundary of 45dB. During single wavelength operation, the laser exhibits a good stability in terms of both power and polarization. For dual wavelengths operation, optical power at the cavity output on both polarization axes is equally distributed.

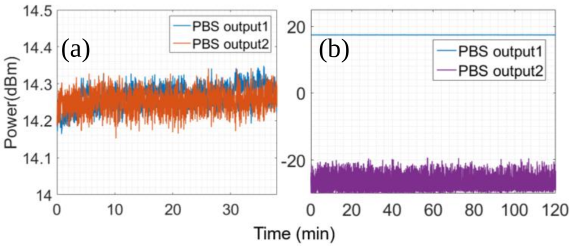

Fig. 5 (a) Power meter readings for dual-wavelength lasing corresponding to Fig 4(d); (b). Power and polarization stability when lasing on single axis. Data recorded after 30min of heating up.

Conclusion

We have demonstrated an all-fiber polarization stable laser without external stabilizers at 2.1μm. The laser efficiency was degraded by the loss between connectors. The highest connection loss comes from the mode field mismatch and Fresnel reflection between SMF-28 and PM 1950, which is around 1dB. Splicing all cavity components is an effortless way to increase the slope efficiency, but also enhance the high-power stability of the laser. Also, PM-FBG with higher reflection can be implemented. This laser is a promising light source for LIDAR and new telecommunication window.

Acknowledgement

This work is supported by the European Research Council under grant agreement ERC-2012-StG 306630-MATISSE.

References

[1]. Henderson, S. W. et al. "Coherent laser radar at 2 μm using solid-state lasers". IEEE Transactions on Geoscience and Remote Sensing 31, 4-15,1992
[2] Cariou, J.-P., *et al*, M. "Laser source requirements for coherent lidars based on fiber technology". Comptes Rendus Physique 7, 213-223, 2000
[3] Simakov, N. et al. in Optical Fiber Communication Conference. Tu2C.6, 2015
[4] Mullen, et al . "Hybrid LIDAR-radar: Seeing through the scatter". IEEE Microwave Magazine 1, 42-48, 2000
[5] Prasad, et al. "An all-fiber, modular, compact wind lidar for wind sensing and wake vortex applications." SPIE Defense+ Security.2015.
[6] Schotland, et al. "Observations by lidar of linear depolarization ratios for hydrometeors." Journal of Applied Meteorology 10.5,1011-1017. 1971:
[7] Biele, et al. Polarization lidar: Corrections of instrumental effects. Optics Express 7, 427-435, 2000
[8] Li, J. et al. "Wide wavelength selectable all-fiber thulium doped fiber laser between 1925 nm and 2200 nm". Optics Express 22, 5387-5399, 2014
[9] Simakov, et al, A. "A cladding-pumped, tunable holmium doped fiber laser". Optics Express 21, 28415-28422,2 013
[10] Kharitonov, S, et al. "Isolator-free unidirectional thulium-doped fiber laser." Light: Science & Applications 4.10， 2015
[11] Agger, et al. Emission and absorption cross section of thulium doped silica fibers. Optics Express, 14(1), 50-57, 2006