Investigation on Photodarkening in Silica Optical Fibers for High Performance Fiber Devices

Abstract

Photodarkening (PD) is the phenomenon that induces optical power loss, related to material defects activated in a silica glass, when the glass is irradiated at wavelengths resonant to the defects. The PD can lead to serious performance degradations and lifetime limitations of optical devices such as fiber laser and fiber amplifier, and its suppression requires optimization of materials and device operation conditions. In particular, the PD can notably take place in an ytterbium (Yb)-doped fiber when the fiber is pumped at the wavelength corresponding to Yb absorption band or visible wavelength. PD in Yb-doped fiber induces a broad excess optical loss peaking at visible wavelengths, and extending to the Yb emission band in the near infrared (NIR) range. The induced loss is a detectable problem for high power operation. More seriously, the PD influences pump efficiency and impairs the Yb-doped fiber laser performances together with the excess loss. Therefore, PD should not be simply treated as an excess background loss, but ought to be explicated together with pumping efficiency for the power decay in both Yb-doped fiber laser and amplifier.

This thesis investigates on improving of performance of Yb-doped fiber laser through PD reduction spanning laser cavity design to material engineering. Firstly, I investigate device level PD suppression. It is found that the significance of PD is dependent of pump wavelength selection. It has been known that the Yb inversion is the only decisive factor considered for the PD. I show in this thesis that a pumping wavelength of Yb ions is another non-negligible factor to determine the PD effects. My experimental results indicate that under the same inversion level, a 976 nm pumping leads to more significant PD than 916 nm pumping. Therefore, provided that other conditions are invariant, selecting 916 nm as the pump wavelength is beneficial to supress the PD effect in laser or amplifier operations.

Besides the pump wavelength selections, the output coupling ratio of Yb-doped fiber laser has to be elaborately selected when the PD factor is considered. Output power as function of cavity reflectivity has been investigated without considering PD effects. However, the extra cavity loss induced by PD is dependent on the selection of cavity reflectivity due to the variation of population inversion in cavity. Therefore, in this thesis I firstly point out that once the PD induced loss is considered, the optimal coupling out ratio has to be adjusted. This finding delivers non-trivial impact in fiber laser cavity improvement and guide more appropriate cavity parameter selection.

In a material level PD suppression, I report a method of suppressing PD while increasing Yb concentration. An equi-molar aluminium: phosphorus (Al:P) composition has been known to suppress the PD, but the realization of the equi-molar Al:P with very high Yb concentration has been hindered by complexity in fabrication process. A highly Yb doped Al:P fiber was fabricated at NTU, and I report its characteristics and PD suppression behavior.

Finally, this study led to investigation of new material for saturable absorber to build a 1 μm pulsed fiber laser. I adopted a novel carbon based material called carbon nanoparticles (CNPs), as a modulator in passive Q-switched Yb-doped fiber laser. Different from any other reported optical materials working as saturable absorber, CNPs can be efficiently obtained via a simple and low-cost flame synthesis process in-house without heavy equipment. I report this new finding in the context of demonstration of Q-switched fiber laser.

The works presented in this thesis provide a comprehensive analysis on impacts of the laser cavity structure and introduce a novel PD-free highly Yb-doped fiber with high lasing efficiency. Thus, this thesis contributes to technology progress on fiber lasers and devices adopting fiber lasers.

Journal publications:

1. **Huizi Li**, Liling Zhang, Raghuraman Sidharthan, Daryl Ho, Xuan Wu, Nalla Venkatram, Handong Sun, Tianye Huang, and Seongwoo Yoo*, "Pump Wavelength Dependence of Photodarkening in Yb-Doped Fibers," J. Lightwave Technol. 35, 2535-2540 (2017).
2. **Huizi Li**, Jie Ma, Jun Wang, Dingyuan Tang and Seongwoo Yoo*, "Carbon Nanoparticles as a Novel Optical Modulator for Pulsed Fiber Laser," (Submitted to Optics Express)
3. **Huizi Li**, Jie Ma, Jun Wang, Dingyuan Tang and Seongwoo Yoo*, "Photodarkening Impact on Laser Cavity Design with Output Coupler adjustment," (In preparation)

Conferencen publications:

1. **Huizi Li**, Liling Zhang, Raghuraman Sidharthan, Daryl Ho, Xuan Wu, Seongwoo Yoo* "Dependence of photodarkening under different wavelength pumping." SPIE paper 9728-110, 2016
2. **Huizi Li**†, Jie Ma†, Mengying Zhang, Jun Wang, Dingyuan Tang, and Seongwoo Yoo* "Carbon Nanoparticles as an Optical Modulator for Passively Q-switched Fiber Laser." in Conference on Lasers and Electro-Optics, OSA Technical Digest (online) (Optical Society

of America, 2018), paper JTu2A.174.

3. R. Sidharthan, S. H. Lim, K. J. Lim, D. Ho, C. H. Tse, J. Ji, **H. Li**, Y. M. Seng, S. L. Chua, and S. Yoo, "Fabrication of Low Loss Low-NA Highly Yb-doped Aluminophosphosilicate Fiber for High Power Fiber Lasers," in Conference on Lasers and Electro-Optics, OSA Terchnical Digest (online) (Optical Society of America, 2018), paper JTh2A.129.