Optically Cooled Yb-Doped Silica Fiber Lasers

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Abstract: This presentation will discuss recent breakthroughs in optical (laser) cooling of Yb-doped silica fibers using anti-Stokes pumping, and the exciting upcoming generation of silica fiber amplifiers and lasers that run cold.

In normal operation, fiber lasers and amplifiers generate heat arising dominantly from the laser transition's quantum defect, absorption by impurities, and nonradiative relaxation. Waste heat limits several of these devices' performance metrics, causing in particular frequency, mode, power, and gain instabilities, shortened lifetime, and sometimes catastrophic failure. These issues are mediated by removing the heat with external cooling systems, but these systems introduce other problems, including vibrations, asymmetrical cooling, modal instabilities, and increased size and cost.

In recent years, significant progress has been made toward developing an alternative cooling solution based on anti-Stokes pumping (ASP).[1] The difference with conventional Stokes pumping is that the gain medium is pumped at a wavelength above (instead of below) the mean wavelength of its fluorescence spectrum. Electrons are excited preferentially from the top levels of the laser ions' lower manifold to the bottom levels of the upper manifold. To reach thermal equilibrium (Boltzman distribution), they must acquire phonon energy from the nucleus, as opposed to creating phonons as in Stokes pumping. This extra energy is removed from the host when the electrons relax to the ground state and emit photons with a mean energy *greater* than the pump photon energy. As the photons escape from the host, this energy is removed and the gain medium cools.[1]

This principle has been applied for years to cool many crystals doped with Yb^{3+}, Tm^{3+}, or Er^{3+}, some down to cryogenic temperatures.[1] Because air convection introduces heat into the fiber, ASP cooling is typically performed in a vacuum, which is often undesirable. However, it has been successful in silica only in recent years.[3-4] The primary reasons are that for significant cooling, the rare-earth concentration must be very high (more cooling ions per unit volume) and the level of absorbing impurities in the host very low (less spurious heating by absorption of pump photons), which is easier to accomplish in crystals. The maximum achievable rare-earth concentration is typically limited by concentration quenching.[3] Cooling in a fiber was first observed in Yb-doped fluoride, mainly because Yb^{3+} tends to be less prone to quenching than other rare-earth ions, and fluorides less prone to quenching than silicate hosts. Cooling in silica fibers therefore required engineering silica compositions with a high quenching threshold (such as aluminosilicates) and ultra-low levels of impurities such as OH^-, a persistent byproduct of the fabrication of oxide fibers.

Recent progress in this direction has led to the first demonstration of cooling in Yb-doped silica, both at Stanford (single-mode fibers at atmospheric pressure in 2020)[3] and UNM (performs and rod-like fibers in a vacuum, with a record temperature drop of 6K in 2021).[4] Our multi-university team capitalized on this significant advancement to demonstrate the first radiation-balanced (no net temperature increase) silica fiber amplifier[5] and laser.[6] Core-pumped at 1040 nm, the fiber amplifier produced 17 dB of gain at 1064 nm while the fiber experienced no net temperature increase.[5] The fiber laser emitted 114 mW of 1065-nm light with a 41% slope efficiency and an average fiber temperature within 3 mK of room temperature.[6] Since then, a new class of Yb-doped silica fibers doped with Ca, Sr, or Ba nanoparticles was also shown to cool successfully.

This presentation will summarize the status of this budding field, and point to some of the exciting prospects and challenges moving forward.

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2 S. R. Bowman, "Lasers without internal heat generation," *J. Quantum Electron.* 35, 115–122 (1999).
3 J. Knall, *et al.*, "Experimental comparison of silica fibers for laser cooling," *Opt. Lett.* 45, 4020–4023 (2020).
4 M. Peysokhan, *et al.*, "Laser cooling of ytterbium-doped silica glass by more than 6 Kelvin," in *Conf. on Lasers and Electro-Optics*, paper FTu2L.6 (2021).
5 J. M. Knall, *et al.*, "Radiation-balanced silica fiber amplifier," *Phys. Rev. Lett.* 127, 013903 (2021).
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Biography: Michel Digonnet is a professor in the Applied Physics Department at Stanford University. His research focuses mainly on high-precision photonic sensors, especially fiber-optic gyroscopes for aircraft navigation, resonant gyroscopes utilizing ultra-low-loss cm-size ring resonators fabricated using SiN technology, acoustic fiber sensors and accelerometers utilizing optical-MEMS diaphragms, slow-light fiber-Bragg-grating strain and temperature sensors, and exceptional-point sensors. He is also involved in cutting-edge research on laser cooling of rare-earth-doped fibers and devices.