Revolutionizing astronomy and beyond

TOPTICA's high-power sodium guide star lasers push the frontiers of adaptive optics

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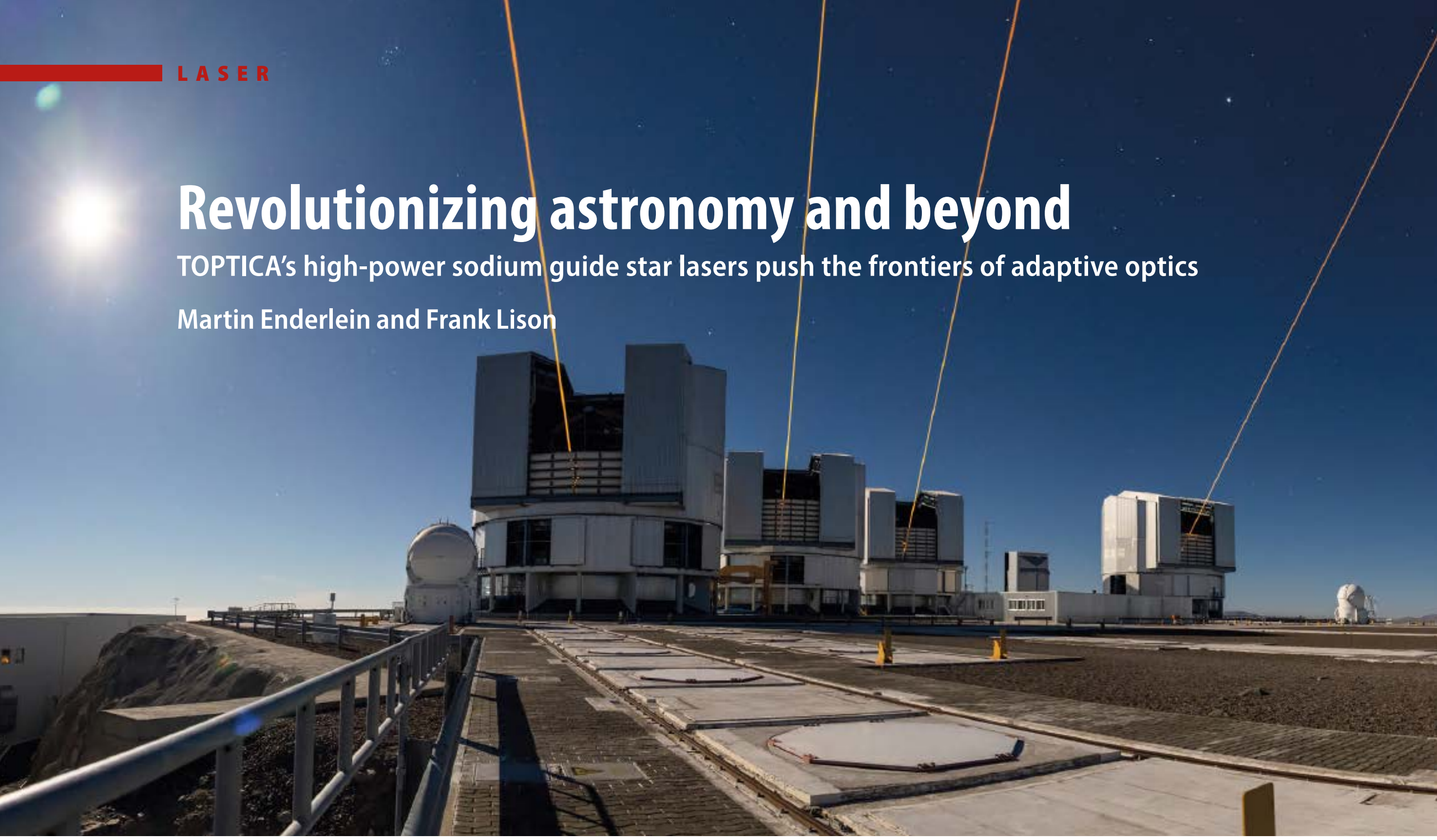


Sodium guide star lasers enable the correction of atmospheric turbulence in ground-based telescopes through adaptive optics (AO), surpassing the limitations of natural stars with artificial beacons at 589 nm. Evolving from 1990s dye lasers to single-frequency Raman fiber amplifiers (RFA), output powers have increased to over 100 W through the suppression of stimulated Brillouin scattering and coherent beam combination techniques. Spectral enhancements further improve the efficiency of sodium excitation and reduce saturation effects. Beyond astronomy, AO can support optical satellite links, space situational awareness, and space debris deorbiting via laser momentum transfer. Due to its wavelength versatility, RFA technology is widely applicable, in particular for scaling quantum computers with high-power, low-noise sources.

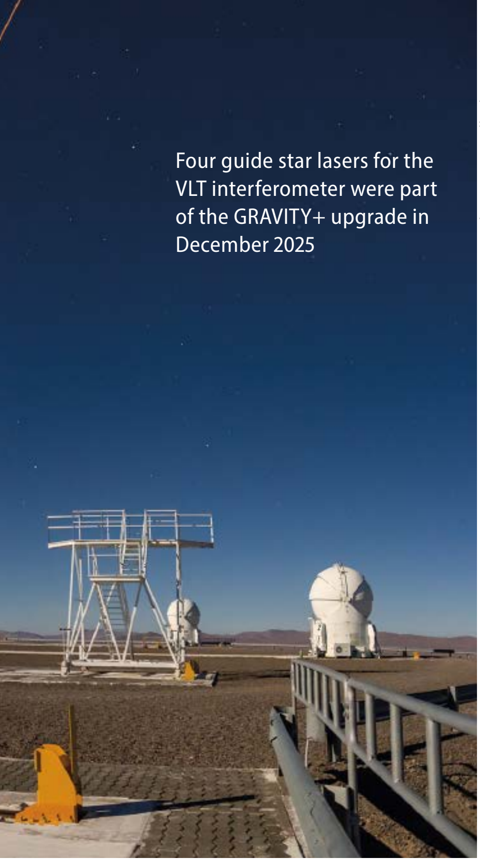
Ground-based telescopes face a major challenge: Earth's atmosphere. While it protects life on the planet, it also distorts incoming light from celestial objects. Atmospheric turbulence, caused by changes in temperature, pressure, and wind shear, causes rapid fluctuations in the air's refractive index. This leads to wavefront distortions on timescales down to and even below milliseconds, which bend and scatter light from distant stars or galaxies, resulting in blurry, shifting images.

Known as 'seeing', this effect limits the angular resolution of even small telescopes. For typical observation sites, the optical resolution does not improve significantly for telescope diameters above 20 – 30 cm. Larger optical telescopes are seeing-limited, and without seeing correction, their only advantage would be the ability to collect more light. For the largest telescopes with a diameter up to ten meters, such as the ones at Keck, Gemini, and Subaru Observatories on Mauna Kea (Hawaii) and the ESO Very Large Telescope (VLT) at Paranal (Chile), that could theoretically resolve details down to about 0.01 arcseconds at visible wavelengths, turbulence usually decreases the resolution to 0.5 – 1 arcseconds.

These distortions not only turn point sources into fuzzy blobs but also decrease contrast in extended objects, making it harder to study exoplanets, black holes, and distant galaxies.

Adaptive optics: restoring clarity through dynamic correction

To combat these distortions, adaptive optics (AO) systems offer a real-time solution. AO mimics the eye's focusing ability on a larger scale, using a closed-loop feedback system to detect and correct wavefront distortions. A wavefront sensor, such as a Shack-Hartmann device, splits incoming light into subapertures and measures local wavefront slopes, reconstructing the distorted phase map. This data controls actuators on a deformable mirror, often a thin glass sheet with piezoelectric or magnetic elements, that applies opposite deformations to flatten the wavefront. Unlike post-detection image corrections, which manipulate the recorded intensity pattern to mitigate blurring and artifacts after the light has reached



Four guide star lasers for the VLT interferometer were part of the GRAVITY+ upgrade in December 2025

Image: A. Berdeu / ESO, [1]; all others: TOPTICA

High-power sodium guide star laser testing at Allgäu public observatory in Ottobeuren, Germany, in 2025

the detector, adaptive optics directly compensates for phase distortions in the wavefront prior to detection, enabling sharper, higher-fidelity imaging by preserving the phase information of the light. Operating at frequencies up to a few kilohertz, AO can restore diffraction-limited performance. First conceived in the 1950s by Horace Babcock, AO advanced within the military in the 1980s and was adopted by scientific astronomy in the 1990s. Systems such as those at ESO's VLT have led to major breakthroughs, including the discovery of the Galactic Center's supermassive black hole, which earned the 2020 Nobel Prize in physics. However, AO requires a bright reference 'guide star' to probe the turbulence column along the line of sight.

Natural guide stars: limitations in sky coverage

Natural guide stars (NGS) are bright stars used as references for AO corrections. The adaptive optics system analyzes the star's distorted light to compute aberrations, assuming the target object lies within the isoplanatic patch – the angular region where turbulence is largely homogeneous, typically 10 – 30 arcseconds in the near-IR. Bright guide stars (magnitude < 12) provide sufficient photons for accurate wavefront sensing. However, even though there are hundreds of billions of stars in our galaxy, suitable NGS are sparse. Only about 1 % of the sky has one nearby, severely limiting astronomical observations. This 'sky coverage' issue limits AO to crowded fields, such as the galactic plane, thereby excluding vast swaths of extragalactic space. Fainter stars demand longer integration times, reducing loop speeds and correction quality.

Artificial guide stars: beacons in the sky

Artificial guide stars overcome the limitations of natural guide stars by providing on-demand references. Laser guide star (LGS) systems project a laser beam upward, exciting atoms or molecules in the upper atmosphere to fluoresce and form a bright spot.

There are two types of laser guide stars: Rayleigh LGS and sodium LGS. The first ones use backscattering from air molecules at up to 20 km, but their low altitude causes the cone effect (focus anisoplanatism), where the sampled turbulence does not represent the full column to infinity. Additionally, they are used in pulsed mode, which requires specific AO systems synchronized with the laser pulses.

Sodium LGS targeting the mesospheric sodium layer at approximately 90 km avoid these downsides by better mimicking a stellar altitude. The sodium layer is constantly replenished by micrometeoroids and asteroids and consists of a 10 km high, highly concentrated layer of sodium atoms. Above and below the neutral sodium layer, either ions or molecules are present. The sodium density in this layer varies by up to one order of magnitude depending on the time of year, latitude, and wind speed. A typical value is a column density of $4 \cdot 10^{13}\ \mathrm{m}^{-2}$.

Tuned to the sodium D2 line at 589 nm, the laser excites atoms, which re-emit the light isotropically,

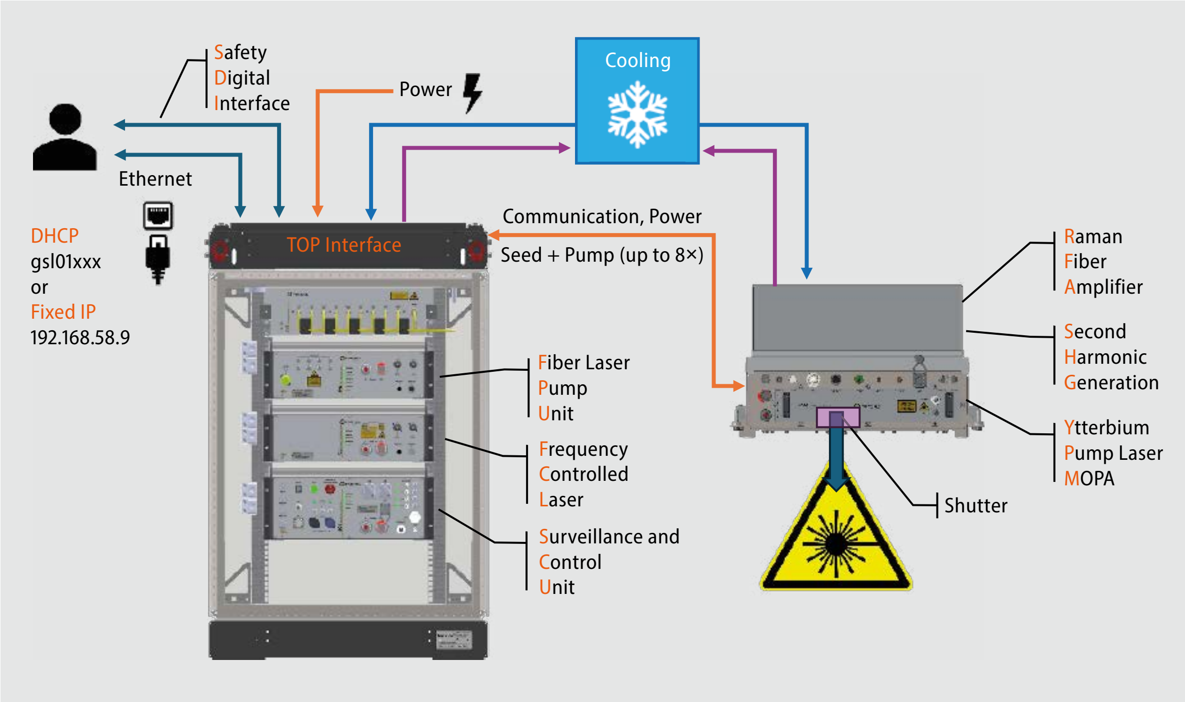


Fig. 1 TOPTICA's second-generation guide star laser platform introduced in 2025. It consists of a laser cabinet with the seed laser and pump diodes, and a laser head containing an ytterbium-doped fiber pump laser, the RFA and the second-harmonic generation.

appearing as a star of typical magnitude 8 – 10. Multi-LGS setups can differentiate multiple turbulence layers for wide-field corrections.

Laser technology for artificial guide stars: history and Raman fiber amplifiers

Sodium LGS lasers must deliver high power (> 10 W) at exactly 589 nm with narrow linewidth (~ 5 MHz), ensuring efficient excitation through optical pumping. Early systems used dye lasers, pumped by argon-ion lasers, but they were bulky, inefficient, and maintenance-heavy, requiring clean rooms attached to the telescopes. In the 1990s, solid-state lasers emerged, such as sum-frequency generation (SFG) of the Nd:YAG lines 1064 and 1319 nm. But laser systems were still extremely complex and fragile. By the 2000s, fiber-based tech advanced, with Toptica Photonics introducing the first compact guide star laser systems based on a design which was developed by engineers at ESO headquarters in Garching, Germany, near Munich.

A key innovation was the single-frequency Raman fiber amplifier (RFA), which amplifies seed light via stimulated Raman scattering in optical fibers. In these RFAs, a low-power single-frequency seed at 1178 nm is amplified by a 1120 nm pump in a polarization-maintaining fiber, shifting energy via molecular vibrations, and afterwards frequency-doubled to 589 nm. RFAs offer wavelength agility, low noise, and scalability, outperforming dye or SFG in efficiency and reliability.

Toptica's SodiumStar, in use since 2014 at the VLT, Keck, Gemini, and Subaru telescopes, uses frequency-doubled RFAs for > 20 W output at 589 nm, designed for high-elevation sites, gravity-invariance, and fully remote operation. In 2025, a completely redesigned second generation of the laser platform was introduced, with higher output powers and many new features (**Fig. 1**).

Challenges in astronomy and beyond: AO in space applications

As a general technology for mitigating atmospheric effects, adaptive optics is expanding into additional space applications. Today, it is the only proven technology that provides full diffraction-limited optical access from ground to space. Optical systems excel at detecting small debris (down to 1 cm) that radar has difficulty with, especially in low-Earth orbit (LEO). In satellite communications, laser links offer Tbit/s data rates, far exceeding radio frequencies. Looking further ahead, AO can be used to precisely focus high-power laser beams onto space debris, slowing them down through light pressure or laser ablation, aiding their entry into the atmosphere and thereby their destruction. For these emerging applications, AO faces unique challenges due to fast-moving objects and/or the need for daytime operation. Therefore, control loops must become faster, requiring higher LGS brightness. Even in astronomy, where sodium LGS already enable high-resolution imaging, challenges remain. AO correction for observations in the visible spectrum also demands higher bandwidths and brightness levels for the LGS signal. Another major limitation is tip-tilt indeterminacy: the LGS laser beam experiences atmospheric tilt on both the uplink and downlink, canceling out absolute tip-tilt information in the return signal. Telescopes then still need a faint NGS for low-order corrections, which again limits sky coverage. In uplink scenarios with fast-moving objects in LEO, AO must sample the atmosphere at an angular offset ahead of the satellite's current position due to the finite speed of light. This point-ahead angle is comparable to the isokinetic angle, which describes the angular coherence length of low-order atmospheric disturbances. As a result, the satellite itself is not a reliable reference for tip-tilt correction, and uplink beam wander cannot be corrected effectively. In both cases, an on-axis laser-generated tip-tilt source would be highly advantageous.

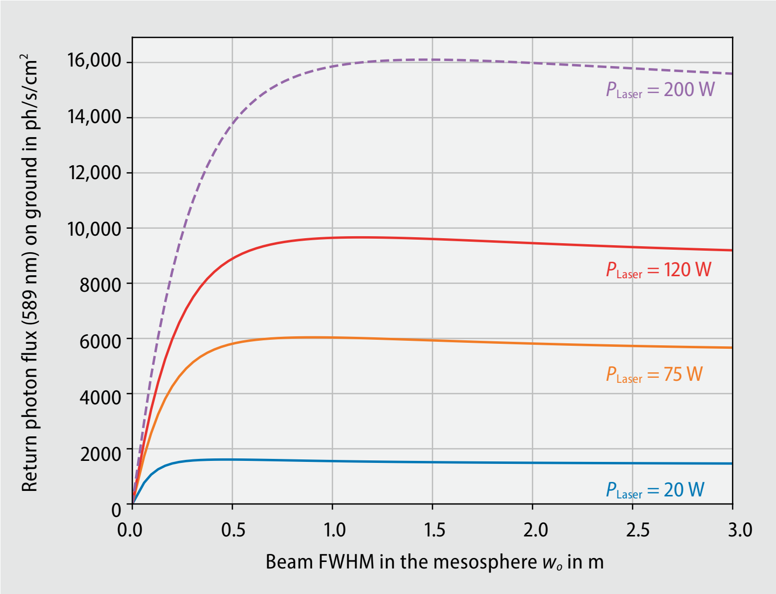


Fig. 2 Simulation of sodium guide star return flux on the ground for different 589 nm laser powers and spot sizes in the mesosphere.

Scaling output power: from single to hundreds of watts

Power scaling in sodium LGS lasers has advanced to meet demands for faster AO loops and brighter stars. Early 1990s demonstrations at around 5 W were sufficient for basic AO. By the 2000s, systems reached 10 – 20 W with improved dyes and SFG. RFAs sped up progress: Toptica's mid-2010s models achieved 20 W at 589 nm in an extremely robust setup. Challenges include nonlinear effects in fibers such as stimulated Brillouin scattering (SBS), where acoustic waves backscatter light, limiting power scaling. SBS suppression through optimized fiber strain patterns broadening the Brillouin gain spectrum enabled 50 W by 2020. Recent breakthroughs at Toptica Projects achieved 130 W at 1178 nm from a single RFA and 140 W continuous-wave operation at 589 nm (10 MHz linewidth locked to the sodium D2 transition) via coherent beam combination (CBC) of two RFAs, followed by resonant doubling with LBO crystals. Prototypes with 75 W at 589 nm were delivered in 2025, with linear flux scaling observed on-sky, and simulations suggest saturation only around 200 W for a spot size of 1 m at the mesosphere (**Fig. 2**).

Spectral optimizations for enhanced efficiency

To maximize sodium excitation, spectral tweaks optimize photon-sodium interactions. Considering the hyperfine structure of sodium's D2 line, it is necessary to constantly depopulate the F = 1 dark state using a second laser line, called a repumper, that can be generated by applying a phase modulation (PM) at 1.7 GHz to the 589 nm laser (see sodium level scheme in **Fig. 3a**). By combining amplitude modulation (AM) and PM, single-sideband spectra can be produced at the laser output, thereby enhancing the efficiency of sodium excitation (**Fig. 3b**).

Laser frequency chirping sweeps the laser frequency (e.g. 0.1 – 1 MHz/μs) to avoid spectral hole burning, where prolonged excitation depletes velocity classes, reducing return flux. Chirping refreshes the interaction volume. As a simpler alternative, linewidth broadening to 10 – 50 MHz via phase modulation distributes power spectrally, mitigating saturation without complex chirps. Especially when combined with AO-precorrected uplinks for spot sizes of less than 1 m, leading to very high sodium irradiation, these technologies can recover flux lost due to saturation effects as has been demonstrated in experiments with ESO and partners at their test site on La Palma [2].

Polychromatic laser guide stars

On-axis tip-tilt correction will be the next frontier in AO. One approach to tackle the tip-tilt indeterminacy is a polychromatic LGS, which exploits atmospheric

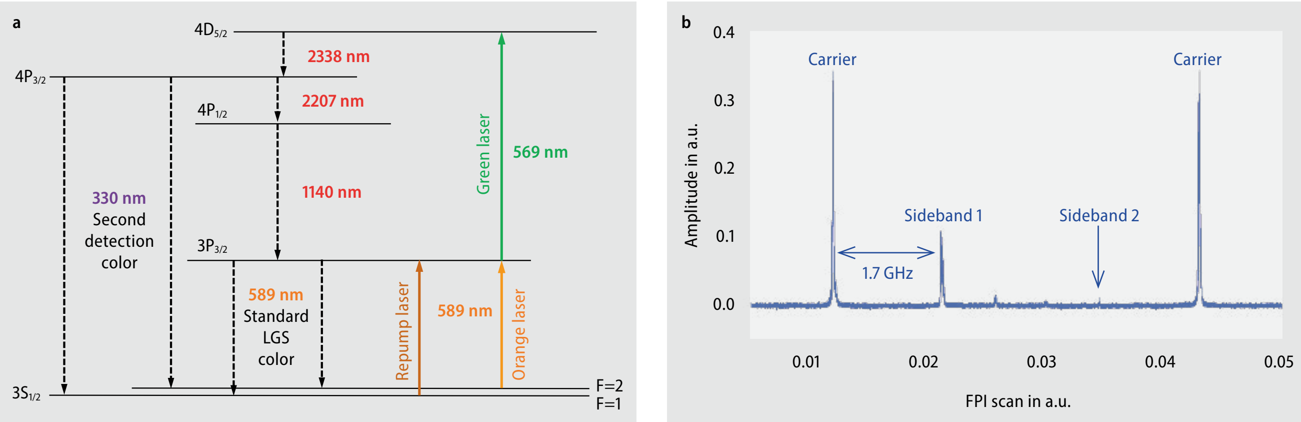


Fig. 3 (a) Sodium level scheme showing the relevant transitions for monochromatic and polychromatic guide stars, (b) single-sideband spectrum with 1.7-GHz modulation measured with a 4-GHz Fabry-Perot interferometer at 589 nm.

dispersion across multiple wavelengths (e.g., UV and visible) to retrieve tip-tilt data (**Fig. 4**). For instance, by exciting sodium to emit at disparate lines, the differential shift due to refraction reveals the absolute tilt, potentially eliminating NGS dependence. In 2026, first on-sky experiments with dual-wavelength excitation of the sodium $4D_{5/2}$ state with a combination of lasers at 589 and 569 nm are planned. The emission cascade involves wavelengths between 330 nm and 2.3 μm (**Fig. 3a**), with the combination of 330 nm and 589 nm probably being the most advantageous for tip-tilt determination. The second excitation wavelength of 569 nm requires an additional high-power laser system that can be built on the current SodiumStar platform using the same RFA technology.

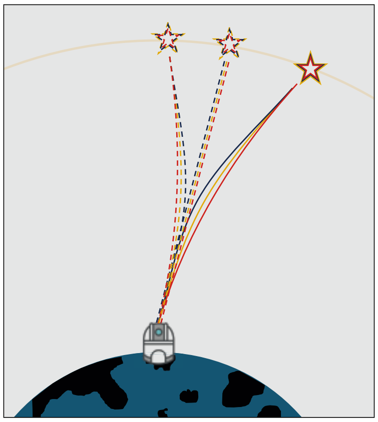


Fig. 4 Illustration of the determination of the absolute tip-tilt (uncertainty about the absolute position of the LGS in the sky) by measuring the differential tip-tilt between different emission wavelengths of a polychromatic LGS.

Raman fiber amplifiers in quantum technologies

Single-frequency RFAs, with SBS suppression via strain and/or modulation, are also beneficial for various other applications due to their wavelength versatility and ability to access spectral regions where no rare-earth-doped fiber amplifiers are available. Particularly for scaling quantum technologies, SBS-suppression techniques can be used to produce high-power sources with low-intensity noise. Another notable possibility is generating substantial power at 148.4 nm, the laser wavelength for thorium nuclear clocks, via frequency quadrupling from 593.5 nm [3]. These clocks promise unprecedented precision, surpassing atomic standards for fundamental physics experiments and GPS enhancements.

Summary

Amid the surging relevance of access to space and quantum technologies, Toptica's suite of single-frequency lasers unlocks unprecedented performance across both fields, from visible and daytime-AO to entanglement at scale.

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