Twenty questions on the frontier of laser science and technology

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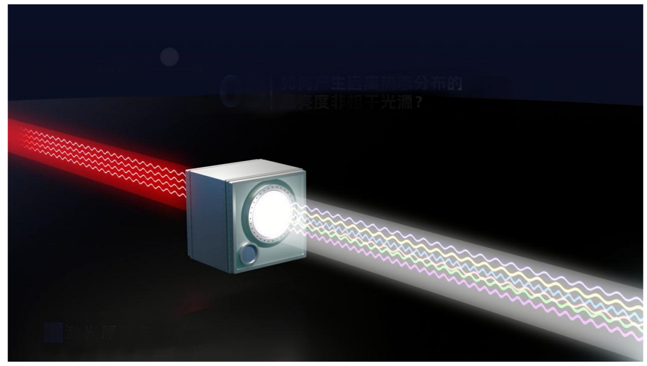
On May 16, 1960, the first laser was invented, opening a new chapter in the exploration of light. Since then, laser technology has grown into a major area of science and technology.

In celebration of the 60th anniversary of the founding of the Shanghai Institute of Optics and Fine Mechanics (SIOM), the institute has launched a public call for questions and challenges that could serve as guidance in the future development of laser science and technology.

SIOM, established in 1964, is the earliest and largest laser research institute in China, focusing on modern optics, lasers, and optoelectronics.

In this event, more than 100 questions were gathered, and experts from related fields were invited to evaluate them. About 100 experts participated in the voting, selecting 20 questions, as listed in the following.



1: Are there ultimate limits to the wavelength, linewidth, intensity, and pulse width of lasers? What are those limits?

Generally, shorter laser wavelengths are more difficult to achieve. We have now reached the X-ray regime. Can it be extended further? The narrowest linewidth of lasers is currently in the millihertz range. Is there a fundamental limit on the linewidth of lasers? Can laser intensity reach the Schwinger limit in a vacuum? The shortest pulse duration has been achieved at 47 as—is there an ultimate limit for this?

2: What is the size limit of integrated photonic lasers?

Compared with electronic chips, integrated photonic chips offer lower power consumption, faster computation, and higher parallelism. Lasers are central to these chips as the light source, determining the capacity and integration density. With nanometer-scale lasers already obtained using plasmonics, is this the physical limit, or can a radiation amplification mechanism working at an even smaller scale be found?

3: What are the energy and power limits of fiber lasers?

Fiber lasers have vast application potential, but they face limitations in achieving high-power or high-energy outputs, which restrict their use in scientific research and industry. What factors determine the energy and power limits of single-fiber outputs? Does a limit exist for the power output from fiber bundles?

4: Is it possible to achieve the conversion of matter–photon–matter in a vacuum, thereby enabling the transmission of matter?

Stimulated radiation involves the transition of bound electrons among energy levels, which only represents a small portion of an atom's total energy. Pair annihilation converts matter entirely into photon energy, whereas high-energy photons can generate particle–antiparticle pairs through scattering. Could these processes be harnessed to achieve matter-to-photon-to-matter conversion, enabling matter transmission?

5: What are the key challenges in realizing high-gain laser fusion, and how can they be solved?

The National Ignition Facility has achieved fusion energy output exceeding input laser energy. However, further improvements in ignition gain are required to approach practical fusion energy. Can this be accomplished with current methods? What key scientific and technological challenges remain to be addressed?

6: Can ultrastrong lasers produce new particles beyond the standard model?

Under extreme physical conditions, physical laws may transcend the standard model, potentially giving rise to new, unknown particles. Could ultrastrong lasers create such extreme conditions and stimulate particles beyond the current theoretical framework?

7: How can we achieve portable ultra-intense, ultrafast laser devices?

Ultra-intense, ultrafast lasers can generate high-energy particle beams and radiation sources. However, their widespread application is hindered by the stability, portability, efficiency, and source quality they generate. Solving these challenges is essential to developing portable devices and expanding their applications in fields such as biology, medicine, energy, and information.

8: How can we produce high-quality extreme ultraviolet (EUV) lasers?

EUV light sources are vital for nanometer-scale lithography and for studying atomic and molecular dynamics. Producing EUV lasers presents numerous challenges in laser–matter interactions, nonlinear optical material, optical transmission medium, and system stability. How can these challenges be overcome to improve the efficiency and quality of EUV sources?

9: What is the approach to generate high-brightness incoherent light sources far from thermal radiation?

Incoherent, high-intensity light similar to sunlight has important applications in fields such as laser fusion and spectroscopy. Is there a method to decouple coherence from intensity and create incoherent light sources without compromising their intensity?

10: How does one overcome the bottlenecks in realizing practical, on-chip ultrastable lasers?

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Ultrastable lasers have widespread applications, but current sources are relatively large, complex, expensive, and difficult to maintain. With advancements in tunable microfrequency lasers, on-chip optical combs, and optical cavity technology, can we develop low-cost, highly integrated, on-chip ultrastable laser sources?

11: Can attosecond laser pulses be efficiently amplified?

Attosecond pulses are currently generated through high-order harmonic processes, but their single-pulse energy remains low, limiting their applications. Amplifying these pulses in the EUV band could be an effective way to boost their energy, but a gain medium for the EUV band is lacking, and constructing a resonant cavity in this wavelength range is highly challenging.

12: How do we find a way to realize stimulated emission via nuclear energy level transitions, potentially leading to gamma-ray lasers?

Laser wavelengths currently range from microwaves to X-rays, all of which are closely related to electron behavior. As we gain deeper insights into nuclei, controlling nuclear energy level transitions is a possible way to produce shorter-wavelength gamma-ray lasers. However, achieving energy-level inversion is extremely difficult in nuclear systems.

13: What are the precision, scale, and efficiency limits of laser-based nanomanufacturing?

The advent of light-field manipulation empowers the development of laser nanomanufacturing. Is it possible to use lasers to achieve rapid, stable, single-atom-level manufacturing on a macroscopic scale? The combined capabilities of precision, scale, and efficiency will determine the prospects for its future application.

14: How can we achieve low-cost, long-life, high-capacity optical storage technology?

Optical storage is seen as a key solution for future cold data storage, thanks to its low power consumption and long lifespan. However, achieving a technology that meets all these necessary criteria remains a challenge.

15: Can artificial intelligence accurately predict and design new laser materials and gain media?

The relationship between laser material structure and laser performance is not fully understood, and discrepancies exist between experimental studies and theoretical predictions. Can artificial intelligence empower the design of new materials of lasers for specific needs?

16: What are the possible approaches to enable precise multi-parameter measurements and control for ultrafast light fields?

Light fields carry information such as frequency, phase, polarization, and spatiotemporal distribution. As pulse durations decrease, jointly identifying and controlling these parameters becomes increasingly difficult. This requires new techniques in ultrafast optics, polarization analysis, phase reconstruction, etc.

17: In environments with strong interference, how can we push the limits of detecting and extracting weak optical signals?

In scenarios such as optical imaging through clouds and fog, optical signals are often overwhelmed by strong background noise. No effective methods have been found to filter out background light, limiting the ability to detect and extract weak signals.

18: How can we use lasers to achieve reliable detection of rapidly moving, distant, and small targets?

Dynamic laser detection encounters difficulties in identifying and resolving small targets due to their rapidly shifting states and substantial environmental interference. Advancements in laser detection technology are important to resolve these challenges and achieve reliable target recognition.

19: Is it possible to miniaturize X-ray free-electron lasers (XFELs)?

Free-electron lasers are important sources of short-wavelength coherent radiation. However, their large size limits their application scenarios. Laser-driven electron acceleration can greatly reduce the acceleration distance, and experiments have preliminarily validated radiation amplification after injection into an undulator. Can this approach be extended to the X-ray regime to achieve a truly miniaturized XFEL?

20: Is there a stimulated emission principle for fermions?

Photons are bosons and can be used to generate large numbers of identical states via stimulated emission, producing lasers. However, fermions such as electrons are subject to the Pauli exclusion principle and cannot occupy the same quantum state. Is it possible to generate identical fermion pairs through pairing mechanisms, thereby achieving stimulated emission for fermions?

Liangliang Ji is a principle investigator at the Shanghai Institute of Optics and Fine Mechanics. He works on laser–plasma interaction and extreme-field physics. He joined the institute in 2016, after a stay at Duesseldorf University in Germany (2012–2014, Humboldt fellowship) and Ohio State University in the US (2014–2016). He is now leading a group to build an experimental platform based on the world's first 100 PW-class laser to explore strong-field QED physics and laser-driven particle acceleration.