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High-Order Harmonic Generation

BY M.D. PERRY, K.C. KULANDER, J.K. CRANE, K. SCHAFER, K. BUDIL, AND T. DITMIRE, LAWRENCE LIVERMORE NATIONAL LABORATORY, LIVERMORE, CALIF.; A. L'HUILLIER, P. BALCOU, AND P. SALIERE, SPAM, CENTRE D'ETUDES NUCLEAIRES DE SACLAY, GIF SUR YVETTE, FRANCE

Extremely high-order harmonic radiation generated from the interaction of intense (>10^{14} W/cm^2) subpicosecond laser pulses with dense gases offers research scientists a new source of coherent soft x-ray radiation. Harmonic radiation extending to the 33rd harmonic of 1064 nm radiation was first reported in 1989.[1] However, during the past year the most dramatic developments in this new area of nonlinear optics have occurred. Harmonic radiation extending below 7 nm was reported by several groups,[2] many of the observations were well described by both quantum and classical theories,[3] the coherence of this XUV source was demonstrated,[4] and coherent control of the output XUV polarization using a second field of different frequency was shown.[5]

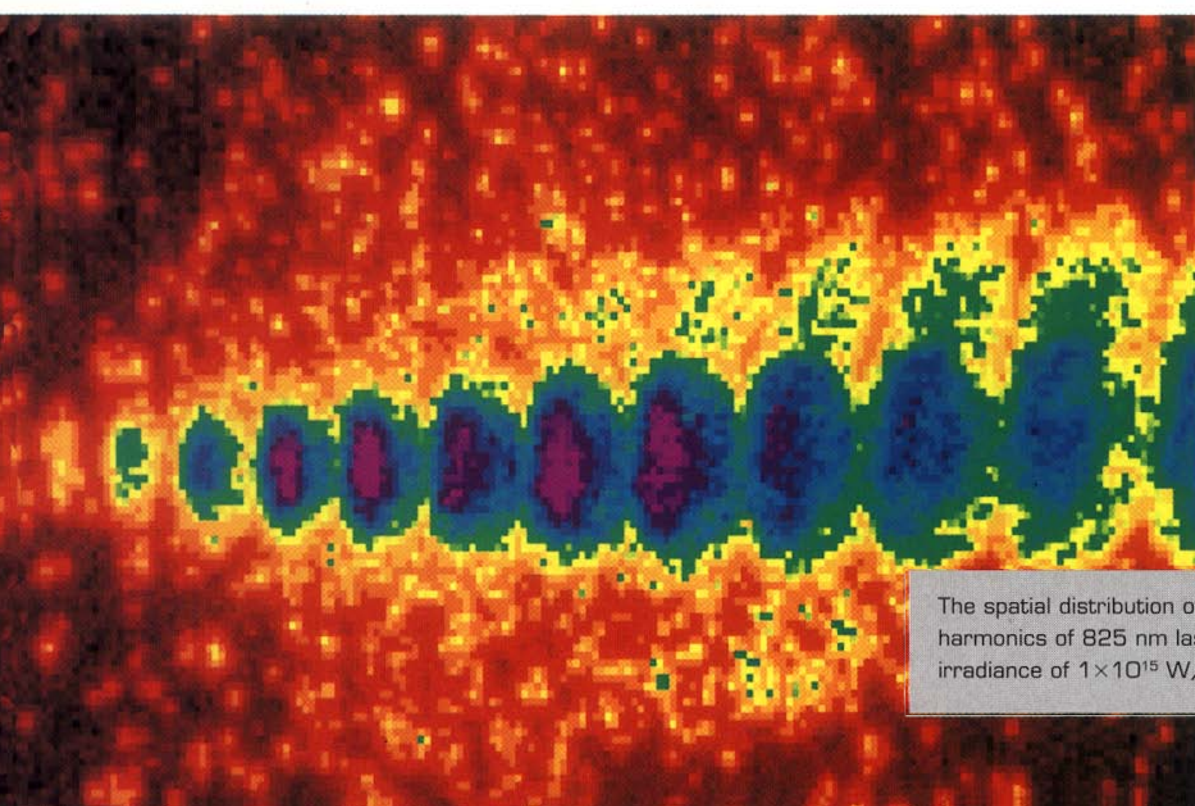
High-order harmonic emission occurs when a bound electron is excited to the continuum and driven by the intense laser field across the anharmonic atomic potential. The quasi-free electron can return to the ground state by emitting a photon of energy equal to the sum of the ionization potential, IP, and its kinetic energy. It can be shown both classically and quantum mechanically[3] that the maximum energy of the harmonic emission is approximately

$$IP + 3Up,$$

where Up(eV)=9.33×10^{-14} I(W/cm^2) λ^2 (μm) is the electron's quiver energy, I is the laser intensity, and λ is the laser wavelength.

The macroscopic nature of harmonic emission complicates the single atom description. Phase matching between the harmonic field and the driving field of the laser influences the overall efficiency (< 10^{-6}) and coherence of the high-order harmonics[4]. The figure below shows the spatial distribution of the 41st to 65th harmonics of 825 nm laser light in neon at an irradiance of 1×10^{15} W/cm^2.[6] The smooth, essentially Gaussian distributions indicate the high degree of spatial coherence of the radiation that makes it possible to re-image this light to nearly the diffraction limit for use in applications.

An important distinction between harmonic generation and x-ray, laser-produced XUV radiation is the tunability of the harmonic spectrum. By tuning the incident laser wavelength or by selecting different harmonics, complete coverage from 7-100 nm may be achieved. We are currently using this tunable harmonic source for XUV spectroscopy of the rare gases. Although current harmonic generation systems are limited to the 10 Hz repetition rate of the laser, dramatic advances in kilohertz repetition rate-short pulse lasers will extend the average power of this new source of coherent XUV radiation.



The spatial distribution of the 41st to 65th harmonics of 825 nm laser light in neon at an irradiance of 1×10^{15} W/cm^2.

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Uncooled Lasers for Deployment of Fiber in the Loop

BY C.E. ZAH, R. BHAT, AND T.P. LEE, BELLCORE, RED BANK, N.J.; Z. WANG, D. DARBY, D. FLANDERS, AND J.J. HSIEH, LASERTRON, BURLINGTON, MASS.

Among other factors, the wide-spread deployment of fiber in the loop (FITL) is hindered by the lack of availability of low-cost laser transmitters that emit at 1.3 µm and operate reliably over a temperature range of −40° to 85°C. To date, commercial laser transmitters have relied on thermoelectric (TE) coolers to maintain the laser temperature constant against the variations in the ambient temperature. However, the TE cooler and associated controller add substantial costs to the laser transmitter. A significant new advancement[1] over existing approaches[2-4] has been made by prototyping a laser that incorporates a strained quantum well structure based on the AlGaInAs/InP material system.

The commercial $Ga_xIn_{1-x}As_yP_{1-y}$/InP lasers emitting at wavelengths in the optical fiber window (1.3-1.5 µm) have shown a strong temperature dependence on threshold current and external quantum efficiency. We believe that it is partly due to Auger recombination in the low bandgap material and partly due to poor electron confinement resulting from the small conduction band offset of the conventional $Ga_xIn_{1-x}As_yP_{1-y}$/InP material system.

In this work, we examined design considerations for making highly efficient, uncooled semiconductor lasers and fabricated 1.3-µm ridge waveguide strained quantum well lasers for high temperature operation. To prevent carrier overflow across the quantum well barriers under high temperature operation, we used the $Al_xGa_yIn_{1-x-y}As$/InP material system which increased electron confinement energy. The carrier induced loss such as intervalence band absorption loss is reduced by using strained quantum wells as the active layer.[5]

These lasers exhibit excellent extrinsic temperature characteristics. When the heat sink temperature changes from 25°-100° C, the differential quantum efficiency decreases by a small amount 0.3 dB (see Fig. 1(a)). Also, a maximum operating temperature of 140° C and a large modulation bandwidth of 14 GHz at 85° C have been obtained. For these lasers operating at 85 °C with more than 5 mW output power, a mean-time-to-failure (MTTF) of 110 years is projected from a preliminary life test. With these newly-designed uncooled lasers, low cost and reliable transmitters are being built for FITL applications (see Fig. 1(b)).

ACKNOWLEDGMENT

We are grateful to F. Favire for device fabrication, B. Pathak and M.C. Wang for device characterization, W. Lin for numerical modeling, N.C. Andreadakis for facet coating, D.M. Hwang for TEM measurement, and M.A. Koza for material growth.

(a)

(b)

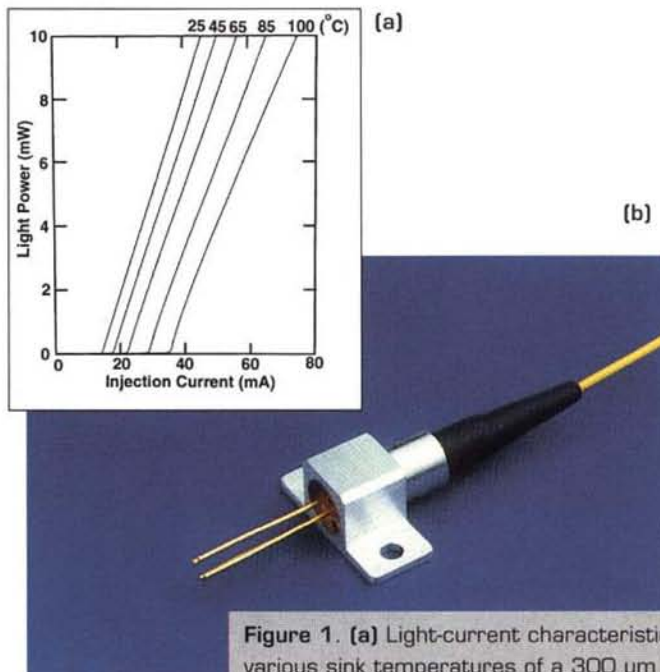

Figure 1. (a) Light-current characteristics at various sink temperatures of a 300 µm long AlInGaAs compressive-strained five-quantum-well laser with a 70% high reflection coating on the rear facet. **(b)** The uncooled laser in a cylindrical package for FITL applications.

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