Semiconductor Optics

Short Fiber Lasers Produce Record Power/Length of 1.33W/cm

Nasser Peyghambarian, Tiequn Qiu, Pavel Polynkin, Axel Schulzgen, Li Li, Valery Temyanko, Masud Mansuripur and Jerome V. Moloney

In this paper we present experimental results[1] achieved with short (7 cm) phosphate fiber lasers which generate more than 9.3 W multimode and 4 W single mode output power. To our knowledge, the power generated per unit fiber length of 1.33W/cm represents a record in the fiber laser world. This research may enable the development of on-chip, watt-level single-frequency light sources in the 1,550 nm wavelength band.

High power fiber lasers are a hot topic.[2] Most high power fiber lasers use silica fibers measuring several tens of meters in length. It is impractical for such lasers to be integrated into very compact devices, such as those produced on chips or small boards. What's more, when single frequency output is needed, long fiber lasers are unsuitable because of the difficulties inherent in selecting a single frequency from their closely spaced longitudinal modes. Short fiber lasers, those with a cavity length measured in centimeters, promise single mode and single frequency operation.

The maximum output power of a centimeters long fiber laser is limited for the most part to the milliwatt level[3] because of the difficulty of increasing ion doping concentrations in the fibers and of achieving high pump absorption with a double-cladding pump scheme. By solving these problems, we were able to boost the output power of such fiber lasers by more than one order of magnitude.

The schematic layout of the fiber laser is shown in the inset of Fig. 1. The phosphate glasses used for fiber fabrication have high solubility of rare-earth ions and low clustering effects, which allows us to increase the concentration of Er^{3+} (1.1×10^{26} ions/m^3) and Yb^{3+} (8.6×10^{26} ions/m^3) ions without enhancing the detrimental quenching processes. To achieve the "chaotic propagation" of the pump which improves pump absorption, the fiber has a D-shaped clad and an off-center circular core. The core diameters of the multimode and single mode fiber lasers are 19 μm and 13.5 μm. The numerical apertures of the multimode and single mode fiber lasers are 0.17 and 0.07. The fibers have an inner clad diameter of about 125-130 μm. For both single mode and multimode fiber lasers, we used fibers measuring 7 centimers in length. The fiber laser cavities were formed by dielectric coatings at the fiber ends and an output coupler. The performances of both lasers are plotted in Fig. 1. We obtained up to 9.3 W power from the multimode fiber laser with $M^2 < 3.5$ and 4 W from the single mode fiber laser with $M^2 < 1.2$. To our knowledge, these are the highest powers ever generated from multimode and single mode fiber lasers with fiber lengths shorter than 10 centimeters.

In addition, we demonstrated a new side-pumping scheme compatible with short fiber lasers.[4] We used six pump delivery fibers which provided inputs for 12 independent pump diodes at 976 nm. The side-pumped laser constitutes a 12 cm long circular fiber with 18 μm core doped with the same Er-Yb concentrations as those of the end-pumped fiber lasers. The performance of this laser is shown in Fig. 1 by the triangular symbols. Up to 5 W output power with optical-to-optical slope efficiency of 24 percent was obtained from this laser. This work was supported by the MRI program under AFOSR contract.

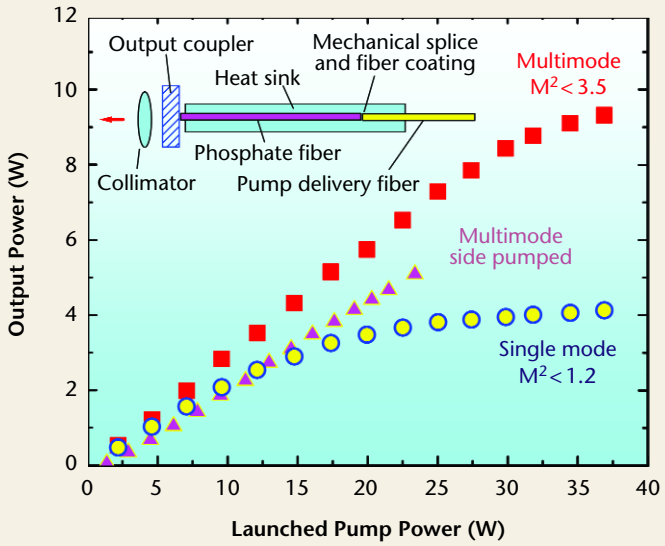

Figure 1. Performance of 7-cm multimode (*squares*) and single mode (*circles*) end-pumped fiber lasers and 12-cm side-pumped multimode fiber laser (*triangles*). Inset shows the schematic layout of the end-pumped fiber laser.

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Excitonic Light Does Not Have To Come From Excitons

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An unexcited semiconductor crystal has a forbidden range of electron energies which separate the filled valence band from the empty conduction band. Electrons in the valence band can be excited into the conduction band by optical absorption, a process which leaves behind holes in the valence band. The resultant neutral plasma of electrons and holes has long been known to emit light peaked at energy less than the bandgap energy E_g.

The interpretation of the cause of this phenomenon has been that the electrons and holes quickly pair up to form excitons, bound electron-hole pair analogues to hydrogen atoms, which then emit light at their 1s-absorption resonance. But recent investigations[1] based on a fully microscopic theory have predicted a very different mechanism.

Here, an electron and hole in the plasma come close together and emit a photon at the exciton resonance by transferring the excess kinetic energy to the remaining plasma via Coulomb interaction between charged particles. This scenario makes it questionable whether excitonic luminescence monitors the buildup and decay of excitonic population (as assumed before) since one may be monitoring the dynamics of plasma instead.

Following above-bandgap picosecond excitation of very high quality InGaAs quantum wells, our study[2] measures the photoluminescence spectrum, along with the excitation-dependent absorption spectrum, at the exciton resonance at and above the bandgap. The spectra were taken over a wide range of carrier densities and lattice temperatures. The carrier temperature was obtained from the above-bandgap spectrum, and the carrier density was determined from the reduction in exciton absorption.

The measured spectra were compared to spectra computed with a fully microscopic theory to determine whether the excitonic emission originated from the plasma or from an exciton population.[3] An adiabatic treatment of the photon-assisted polarization leads to an Elliott-type formula that explicitly shows that the emission is always peaked at the exciton transition energies regardless of whether the source of the luminescence consists of pure plasma or an excitonic population. These two can be distinguished by the fact that, for a given carrier density and temperature, the ratio of the excitonic luminescence to the above bandgap luminescence is higher for an exciton population than for a plasma; see Fig. 1.

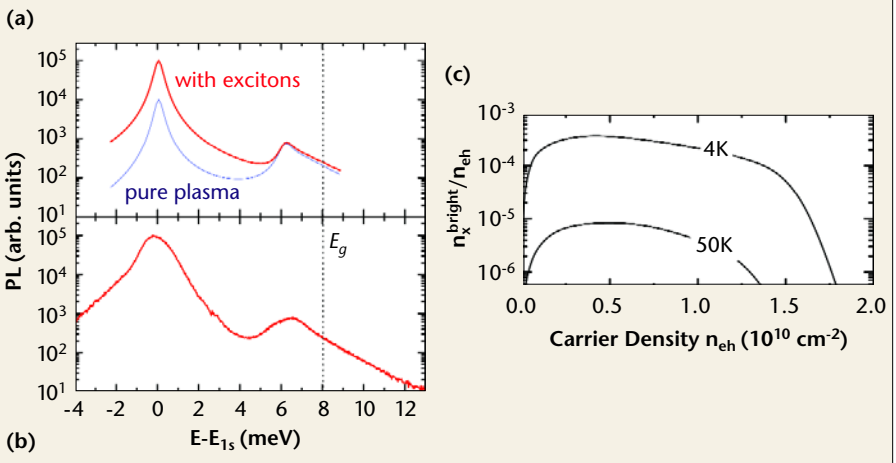

Figure 1. (a) Calculated and (b) measured photoluminescence (PL) spectra for intermediate carrier densities at 4K lattice temperature emitted at the 1s exciton resonance. (c) Optically active q≈0 exciton contributions as a function of the carrier density on a logarithmic scale for lattice temperatures of 4 K and 50 K.

The conclusion for our InGaAs/GaAs system is that for all densities and for lattice temperatures above about 30 K, the excitonic luminescence is explained by plasma emission alone. The same is true for the higher densities at 4 K lattice temperature. Only for intermediate carrier density and low lattice temperature is the excitonic photoluminescence dominated by emission from excitons.

In this intermediate density low temperature range, however, even a tiny amount of an optically active excitonic population—for our material system it is only 0.04 percent of the carrier density for best exciton formation conditions[4,5]—leads to massive changes of the emission spectra.

The invariably old but always new lesson learned from this study is that once again, one shouldn't always believe what one sees: *Light from exciton resonances does not always imply the existence of excitons.*

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3. What we actually compare is β(0), where β(ΔE) is defined as PL/[CαLexp(-ΔE/k_BT_c)], where ΔE = E - E_{1s}, PL and αL are respectively the measured PL and nonlinear absorption measured at E, and C and T_c are fit to make β = 1 in the continuum. This definition takes out the expected temperature dependence, reduces lineshape effects and shows the departure from thermal equilibrium. In order to compare spectra directly here, where the theoretical linewidth is narrower, the peak αL values are made equal.
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