

# Continuous-wave Lasing in a Solid Polymer

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Incorporation of rare-earth ions into polymers is challenging due to the immiscibility of their salt precursors with organic solvents. This problem can be overcome by encapsulating the ions with organic ligands to form stable complexes that can be easily dispersed in polymer solutions. Furthermore, the ligands can shield the dopant ion from impurities in the surrounding matrix that otherwise would quench the luminescence [1]. By optimizing the fabrication procedure of both, host material and optical waveguide structure, we have succeeded in demonstrating optical net gain and the first continuous-wave (cw) laser emission in a solid polymer. The lasers operate near 1060 nm and 873 nm, providing up to 0.98 mW of output power.

## 1. A Polymer for Rare-earth-ion Doping

A polymer host material, based on a cycloaliphatic diepoxy cured with a fluorinated dianhydride, has been developed. When activated with the rare-earth-ion-doped complex, neodymium(thenoyltrifluoroacetone)<sub>3</sub> 1,10-phenanthroline (Fig. 1, left), the typical absorption and emission lines of the Nd<sup>3+</sup> ion were detected. Luminescence quenching, which usually occurs in polymers due to high-energy vibrations from O–H and C–H chemical bonds, was eliminated by the neutral 1,10-phenanthroline ligand and by applying fluorinated chelates to the complex, respectively, and absorption due to the polymer host occurs only in the wavelength range longer than 1100 nm.

The functionalities of active doping and photo-definition were divided over two different polymers. While the properties of the core material were optimized to incorporate the Nd-complex, the cladding material was chosen for its simple processing properties, especially the straight-forward photodefinition of channel waveguide structures (Fig. 1, right). Thermally oxidized silicon wafers were used as substrates, with the oxide layer acting as the lower cladding layer. A 5-μm-thick layer of the negative photoresist was spin-coated onto the oxidized silicon wafer. After UV exposure through a mask and subsequent curing and development, inverted channels were obtained. The Nd<sup>3+</sup>-complex-doped core material was then backfilled via spin-coating. As a result, 5×5-μm<sup>2</sup> Nd<sup>3+</sup>-complex-doped polymer channels were obtained. An additional 3-μm-thick CHEP layer was deposited on top of the channels as the upper cladding layer by spin-coating and thermal curing.

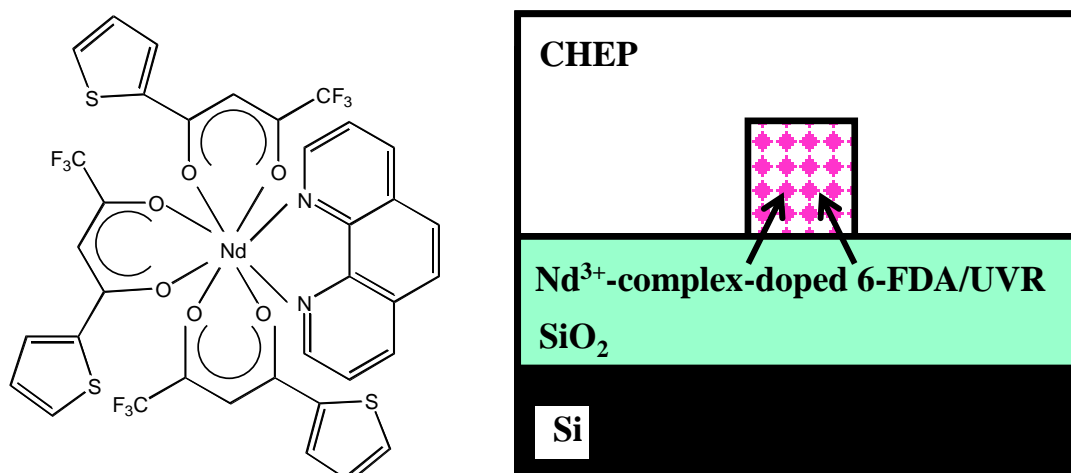


Fig. 1. (left) The chemical formula of Nd(TTA)<sub>3</sub>phen [2]; (right) geometry of the Nd<sup>3+</sup>-doped polymer channel waveguides [3].

## 2. Nd<sup>3+</sup>-doped Waveguide Amplifiers and Integration with Polymer Optical Backplanes

These Nd<sup>3+</sup>-complex-doped polymer channel waveguides were applied to demonstrate amplifiers with various lengths and Nd<sup>3+</sup> concentrations [4]. Internal net gain at 865-930 nm and 1064 nm was experimentally demonstrated and theoretically investigated under continuous-wave excitation at 800 nm. The small-signal gain measured in a 1-cm-long sample with a Nd<sup>3+</sup> concentration of  $1.03 \times 10^{20} \text{ cm}^{-3}$  was 2.0 dB/cm at 873 nm (Fig. 2, left) and 5.7 dB/cm at 1064 nm. A peak gain of 2.8 dB at 873 nm in a 1.9-cm-long waveguide with a Nd<sup>3+</sup> concentration of  $0.6 \times 10^{20} \text{ cm}^{-3}$  and of 8.0 dB at 1064 nm in a 4.4-cm-long waveguide with a Nd<sup>3+</sup> concentration of  $1.03 \times 10^{20} \text{ cm}^{-3}$  (Fig. 3, right) was obtained at a launched pump power of 25 mW. By use of a rate-equation model, the internal net gain at these two wavelengths was calculated and the macroscopic parameter of energy-transfer upconversion as a function of Nd<sup>3+</sup> concentration was derived [4]. Ease of fabrication, compatibility with other materials, and low cost make such rare-earth-ion-doped polymer waveguide amplifiers suitable for providing gain in many integrated optical devices.

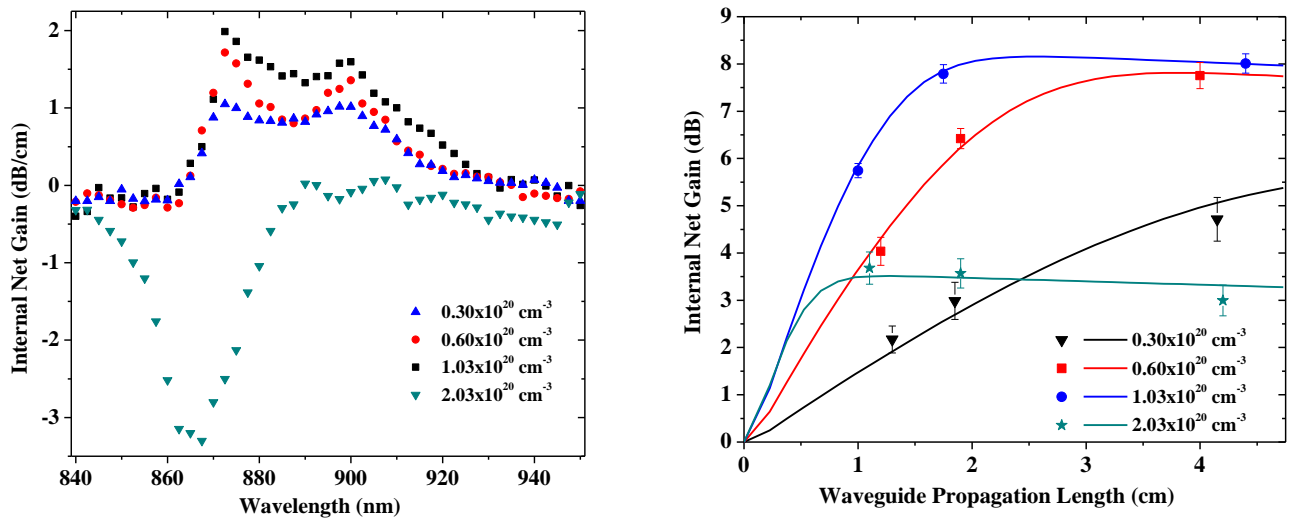


Fig. 2. (left) Internal net gain spectrum at 840-950 nm for different Nd<sup>3+</sup> concentrations and a launched pump power of 25 mW [4]; (right) measured (dots) and calculated (lines) internal net gain at 1064 nm versus propagation length for a launched pump power of 25 mW [4].

Furthermore, a solution for compensating losses in optical interconnects was provided. Large-core Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> channel waveguide amplifiers [5] (as an alternative to the polymer waveguide amplifiers described above) were characterized and tested in combination with passive polymer waveguides. Coupling losses between the two waveguides were investigated in order to optimize the channel geometries of the two waveguide types. The width of the Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide was tapered down from 8  $\mu\text{m}$  to 2.5  $\mu\text{m}$  and back to 8  $\mu\text{m}$  to improve the pump intensity in the active region (Fig. 3, left). Light at 880 nm was propagated through a  $6 \times 6\text{-}\mu\text{m}^2$  polymer channel waveguide (IBM Research - Zurich) and coupled into 3- $\mu\text{m}$ -thick Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguides with different Nd<sup>3+</sup> concentrations of 0.39, 0.50, and  $0.91 \times 10^{20} \text{ cm}^{-3}$ . A maximum internal net gain of 0.87 dB was observed in a 4-cm-long Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide with a Nd<sup>3+</sup> concentration of  $0.50 \times 10^{20} \text{ cm}^{-3}$  (Fig. 3, right). Finally, a maximum 0.21-dB net gain at a signal wavelength of 880 nm was demonstrated in a structure in which an Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide was coupled between two polymer waveguides (Fig. 3, left). The gain can be improved by increasing the pump power and adjusting the waveguide properties of the amplifier.

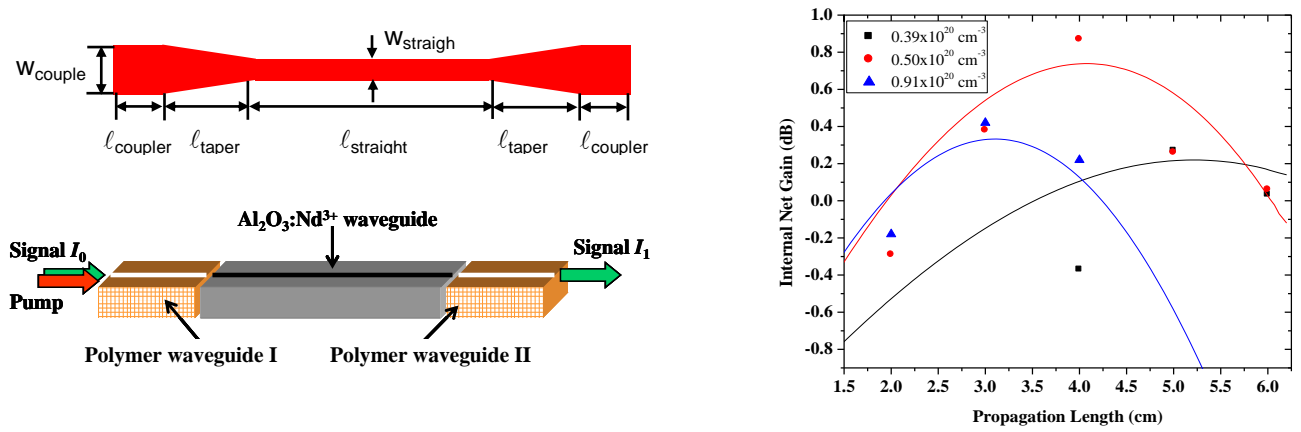


Fig. 3. (left) Top view of an Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> tapered waveguide and schematic of the demonstration of amplification in optical backplanes by coupling an Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide to two polymer waveguides [6]; (right) measured (dots) and calculated (lines) internal net gain at 880 nm of a polymer waveguide coupled with an Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide versus propagation length in the Al<sub>2</sub>O<sub>3</sub>:Nd<sup>3+</sup> waveguide for different Nd<sup>3+</sup> concentrations [6].

### 3. The First Continuous-wave Laser in a Solid Polymer

For the first time ever, continuous-wave laser operation was obtained in a solid polymer host [2]. Laser operation at 1060.2 nm was demonstrated in the Nd<sup>3+</sup>-complex-doped polymer channel waveguides above an absorbed pump threshold of 50 mW. The highest slope efficiency of 2.15% was obtained with 5% outcoupling, resulting in a maximum output power of 0.98 mW (Fig. 4, left). Lasing was also achieved on the quasi-three-level 878-nm transition above a threshold of 74.5 mW. A slope efficiency of 0.35% and an output power of 190  $\mu$ W were obtained with 2.2% outcoupling. Long-term, stable cw laser operation over at least 2 h was demonstrated, indicating the durability of the polymer gain medium (Fig. 4, right) [7].

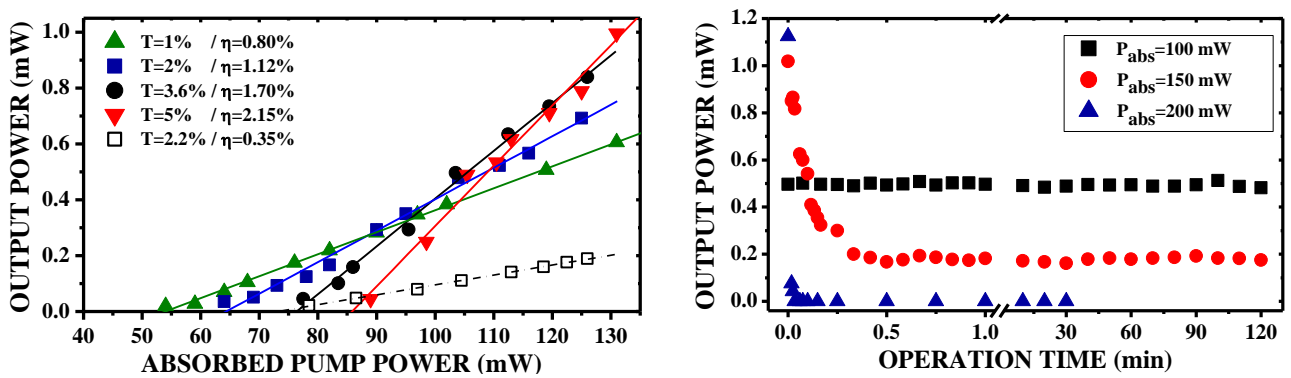


Fig. 4. (left) Output power as a function of absorbed pump power for the four-level and quasi-three-level laser transitions at 1060.2 nm (filled symbols) and 878.0 nm (open symbols), respectively [7]; (right) Laser output power as a function of operation time for different absorbed pump power regimes [7].

## Collaborations

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## References

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