

# Continuous-wave Lasers in Polymer waveguides

J. Yang, C. Grivas(\*), M.B.J. Diemeer, A. Driessen, and M. Pollnau  
Integrated Optical Micro Systems, MESA+ Institute for Nanotechnology,  
University of Twente, Enschede, the Netherlands

\* On leave from Optoelectronics Research Centre, University of Southampton,  
Southampton, United Kingdom  
E-mail: [j.yang@ewi.utwente.nl](mailto:j.yang@ewi.utwente.nl)

**Abstract**—Channel waveguides based on a polymer, 6-fluorinated-dianhydride/epoxy, which is actively doped with a rare-earth-ion-doped complex, Nd(thenoyltrifluoroacetone)<sub>3</sub> 1,10-phenanthroline, have been fabricated. Photoluminescence peaks at 880 nm, 1060 nm, and 1330 nm have been experimentally observed. By optimization of the fabrication procedure of both, host material and optical structure, continuous-wave laser operation on both, the four-level and quasi-three-level transitions near 1060 nm and 880 nm, respectively, has been demonstrated in channel waveguides.

**Keywords**—photodefined polymer, organic complex, neodymium, polymer waveguide laser, continuous-wave polymer laser

## I. INTRODUCTION

Polymer waveguides have emerged as a viable technology for integrated optical devices due to their low cost, capability of integration with other material systems, and ease of fabrication and modification of their chemical structure. This latter property offers enormous flexibility in the design of waveguide laser media. Research in the area of solid-state polymer lasers over the last years resulted in numerous reports on semiconducting [1] and dye-doped [2] polymer sources, which due to absorption by excitons in their excited triplet state operate in the pulsed regime. Although rare-earth-ion-doped polymers offer a suitable medium for the generation of continuous-wave (CW) laser emission, they are notably absent from the list of polymer sources realised, which is largely due to the fluorescence quenching of the dopant ions. The latter occurs by coupling of their excited state to high-energy vibrational modes of C-H and O-H bonds both in the polymer host and in the complex, where they are encapsulated in order to be dissolved in the polymer [3], thereby imposing a requirement for high pump powers, which are usually destructive for the active medium.

Here, waveguide laser operation of Nd<sup>3+</sup>-complex-doped polymer channel waveguides near 1060 and 880 nm is reported, which is, to the best of our knowledge, the first demonstration of a rare-earth-ion-doped polymer waveguide laser as well as CW polymer laser.

## II. WAVEGUIDE FABRICATION

The fabrication process of channel waveguides has been detailed in Ref. [4]. In brief, a neodymium complex, Nd(TTA)<sub>3</sub>phen, was synthesized and incorporated into the

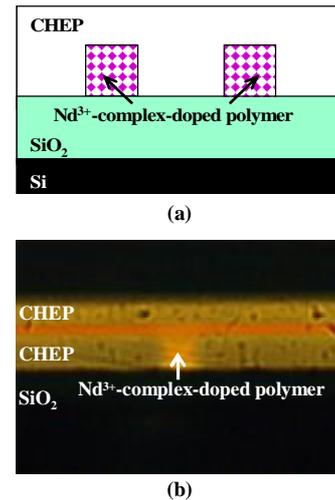


Figure 1. (a) Geometry of the buried Nd<sup>3+</sup>-complex doped polymer waveguides and (b) optical microscope picture of a channel waveguide cross section

fluorinated host 6-FDA/epoxy. The fluorine ligands and the fluorination of the host material significantly decrease the luminescence quenching originating from high-energy vibrations of C-H and O-H bonds in the polymer host.

By spin-coating onto a thermally oxidized silicon wafer and subsequently photodefining a cycloaliphatic epoxy prepolymer (code name CHEP) [5], inverted channels in the low-refractive-index CHEP polymer were obtained. The core material, a Nd(TTA)<sub>3</sub>phen doped 6-FDA/epoxy solution, was then backfilled via spin-coating and 5×5 μm<sup>2</sup> Nd-complex-doped channel waveguides were realized after thermal curing. An additional 3-μm-thick CHEP layer was spin-coated on top of the channels as the upper cladding layer. Figures 1a and b show the geometry of the Nd<sup>3+</sup> doped 6-FDA/epoxy channel waveguide and an optical microscope picture of a channel waveguide cross section, respectively. The Nd<sup>3+</sup> concentration for the laser experiment is 1.03×10<sup>20</sup> cm<sup>-3</sup>.

The photoluminescence of the Nd<sup>3+</sup>-doped polymer channel waveguides was investigated by pumping the channel waveguides at 800 nm using a Ti:sapphire laser, and the resulting fluorescence collected from the output face of the waveguide was measured by a spectrometer and an InGaAs

detector (Fig. 2). Three luminescence bands near 880 nm, 1060 nm, and 1330 nm were identified, corresponding to the

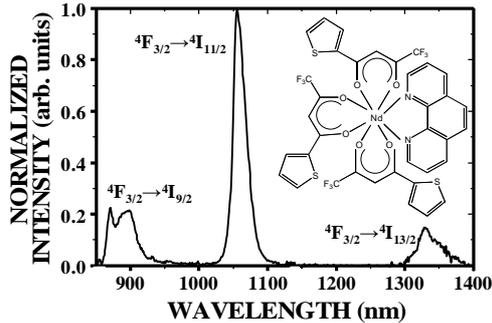


Figure 2. Luminescence spectrum of a buried  $\text{Nd}^{3+}$ -complex-doped polymer waveguide (corrected with respect to the response of the detector).

transitions between the metastable  $^4\text{F}_{3/2}$  state and the lower lying  $^4\text{I}_{9/2}$ ,  $^4\text{I}_{11/2}$ , and  $^4\text{I}_{13/2}$  states of the  $\text{Nd}^{3+}$  ions, respectively. The luminescence lifetime of  $\text{Nd}^{3+}$  in the 6-FDA/epoxy host was measured to be 141  $\mu\text{s}$ , thus demonstrating that the fluorination effectively diminishes non-radiative quenching of the luminescence.

### III. LASER EXPERIMENTS

Laser operation was achieved with a CW Ti:sapphire pump laser emitting at 800 nm. To form the laser cavity two high-reflective (HR) mirrors at the signal wavelength were attached at the end-faces of the 7.5-mm-long waveguides.

CW laser emission was observed near 1060.2 nm above a threshold of 50 mW of absorbed pump power, and is given in Fig. 3a. The laser power characteristics were studied using a set of four outcoupling mirrors with a transmission of 1.8%, 3%, 4%, and 5% at the laser wavelength. The laser output as a function of absorbed pump power is given in Fig. 3b (closed dots). The maximum output power of 0.98 mW and the highest slope efficiency of 2.15% were obtained with 5% outcoupling.

Laser operation was also achieved on the quasi-three-level transition near 878 nm (Fig. 3a) above an absorbed pump power threshold of 67 mW when the cavity was formed with two HR mirrors. Re-absorption losses combined with the relatively low stimulated-emission cross section at this wavelength compared to the dominant four-level transition require high pump powers, which however is in conflict with the need to maintain the pump power at a low level to avoid adverse effects on laser performance induced by thermal degradation of the material. Using 2.2% outcoupling, we obtained a slope efficiency of 0.35% and a laser threshold of 74.5 mW (open dots in Fig. 3b).

### IV. CONCLUSION

Successful design of a polymer host material and an organic complex to encapsulate the Nd ions enabled the development of Nd-complex-doped channel waveguide lasers operating on either the four-level or the quasi-three-level

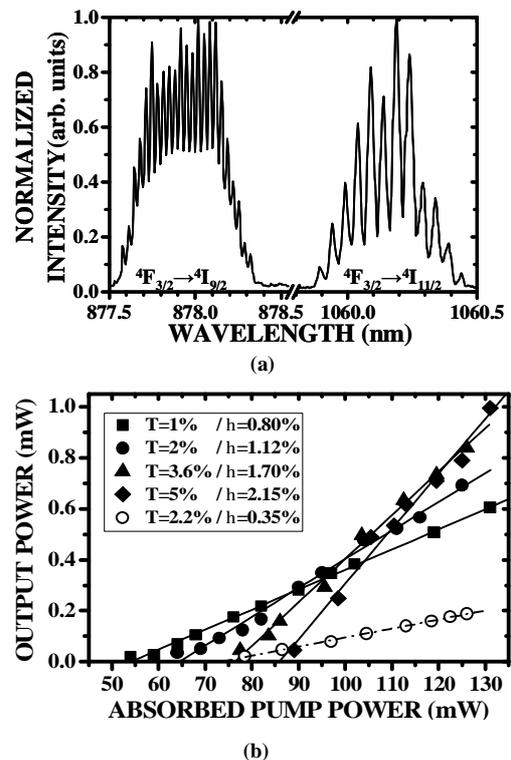


Figure 3. Laser emission of a buried  $\text{Nd}^{3+}$ -complex-doped polymer waveguide at 1060.2 nm and 878 nm: (a) typical laser spectra and (b) input-output curves.

transition near 1060.2 nm and 878 nm, respectively. The lasers exhibit remarkable lifetime stability as they can withstand at least two hours of uninterrupted operation whilst producing output powers of up to 0.98 mW. This is the first demonstration of a rare-earth-doped polymer waveguide laser as well as a CW polymer laser.

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