# Coupling of Organic Semiconductor Amplified Spontaneous Emission Into Polymeric Single-Mode Waveguides Patterned by Deep-UV Irradiation

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***Abstract*—Single-mode waveguides were fabricated by deep ultraviolet radiation in poly(methyl methacrylate) (PMMA). Using a masking process, the radiation modifies the refractive index of the PMMA forming core and cladding regions for waveguiding. Following the fabrication of the waveguides, the small molecule material aluminum tris(8-hydroxyquinoline) doped with the laser dye DCM is deposited directly onto the waveguide structures. By optical pumping ($\lambda = 355$ nm) amplified spontaneous emission was observed at the end facets of the waveguides.**

***Index Terms*—Alq3 : DCM, amplified spontaneous emission (ASE), deep ultraviolet (DUV), mirrorless lasing, organic semiconductor, PMMA, waveguide.**

## I. INTRODUCTION

The combination of lasers and microoptics such as waveguides has been under investigation for a wide range of applications. Especially the area of optical interconnects in telecommunication on board-to-board level based on vertical-cavity surface emitting lasers and multimode waveguides has gained much interest [1], [2]. Another class of applications are waveguide-based sensors for chemical analysis systems [3].

For miniaturization and production-cost reasons, a monolithical integration of lasers and waveguides is desired. The fabrication process and the unique properties of organic semiconductor lasers [4], [5] makes them ideally suited for such challenges. They can cover a wide range of light emission wavelengths spanning from the ultraviolet (UV) throughout the whole visible range. Even using only one active laser material, the tunability can be higher than 50 nm [6], [7].

We report on the coupling of organic semiconductor amplified spontaneous emission (ASE) into single-mode waveguides. ASE, also called mirrorless lasing [8], [9], of the small molecule material aluminum tris(8-hydroxyquinoline) ($\mathrm{Alq}_3$) doped with the laser dye 4-Dicyanomethylene-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran (DCM) was induced by optical pumping, coupled into the waveguides and subsequently detected at the end facets of the poly(methyl methacrylate) (PMMA) substrate. In order to realize an integrated device, we deposited the active laser material directly on waveguides written in PMMA [10]. In this manner, a low threshold laser device is combined with waveguides to create a versatile low cost plastic integrated optics system.

## II. WAVEGUIDE FABRICATION

PMMA is commonly used in microoptics and microfluidics. It is transparent in the visible and infrared region, it is biocompatible, and it can also be shaped by processes like hot embossing [11]. Another unique feature is the possibility of directly inscribing waveguides through deep ultraviolet (DUV) radiation [12].

The PMMA material we used was Hesa-Glas, a homopolymer from Notz Plastic (thickness 500 $\mu$m). Waveguide patterns are inscribed into the polymer substrate by lithographic techniques using standard photomasks (Cr on quartz). The DUV irradiation results in a local and controlled increase of the refractive index in the illuminated areas of the polymer surface. This generates the integrated optical waveguide structures in the polymer plate. A scheme of the process is shown in Fig. 1.

Because only a thin surface layer of a few microns is modified by the DUV radiation, a single polymer layer can serve both as the substrate and waveguide. The use of a single polymer substrate minimizes the mismatch in the thermal expansion coefficient of the substrate and waveguide material. No additional strain relief layer is needed. The induced refractive index change is up to 0.008 and has a graded index profile with an exponential decay which reaches a depth of about 5 $\mu$m. In our case, the refractive index changes from 1.4797 to 1.4847 (measured at 633 nm) for the plain and the exposed material, respectively.

For DUV modification, a commercial UV-exposure equipment (Maskaligner EVG 620) is used. A DUV lamp combined with a cold mirror with reflectance in the wavelength range of 200–240 nm is used in the exposure system. The waveguides are

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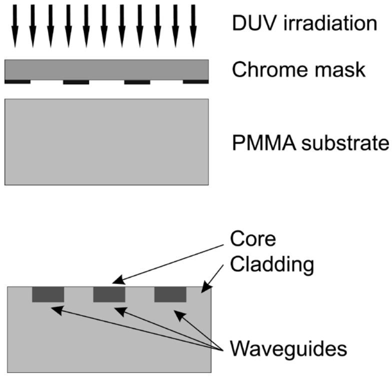

Fig. 1. Fabrication of single-mode waveguides by DUV modification of PMMA. Under DUV illumination through a chrome mask the refractive index of the PMMA material is altered, forming core and cladding regions for optical waveguiding.

fabricated using vacuum contact at a dosage of 5 J at 240 nm. Several waveguides with a width of 3 and 5 $\mu$m, respectively, and a pitch of 1 mm are written onto the substrate.

After fabrication, the polymer substrates are separated by a wafer saw. No further polishing of the end facets is required. The samples show a typical coupling loss to a single-mode fiber of 0.5 dB/facet. The waveguide losses were determined using the cut-back method. The attenuation of the waveguides is 0.1 dB/cm for wavelengths between 600 and 800 nm. This value makes them ideally suited for waveguiding the ASE of $\mathrm{Alq_3:DCM}$ centered at ~630 nm.

## III. SAMPLE FABRICATION

The PMMA plate including the waveguides was used as the substrate in the following laser material deposition process. It was cleaned using isopropanol and left in a vacuum chamber overnight in order to minimize the influence of oxygen on the organic material.

We deposited a patch of the organic laser material $\mathrm{Alq_3:DCM}$ (layer thickness ~350 nm; $\mathrm{Alq_3}$ purchased from Sensient; DCM from RadiantDyes) onto the substrate in a thermal evaporation process under high vacuum conditions ($< 3 \times 10^{-7}$ mbar). The materials were co-evaporated with a concentration of the laser dye DCM of 4 mol% in the host material $\mathrm{Alq_3}$. The fabricated sample is shown in Fig. 2.

## IV. EXPERIMENTAL RESULTS

The organic material has a refractive index of approximately 1.76 thus forming a slab waveguide on the PMMA substrate ($n \sim 1.48$). The material is optically pumped with a short pulse UV-laser (Crystal Laser FTSS 355-Q; frequency-tripled neodymium-yttrium-aluminium-garnet, wavelength 355 nm; repetition rate 6 kHz, pulsewidth 1.5 ns, 150 nJ per pulse) under inert gas atmosphere (see Fig. 3 for a scheme of the experimental setup). At high enough pump power densities (>50 kW/cm$^2$), the gain in the active material exceeds the losses and spontaneously emitted photons are amplified in the waveguide. A collapse of the emission spectrum is observed, since only those photons are amplified whose energy coincides with the spectral position of the maximum material gain. Fig. 4 shows the resulting gain narrowing from ~85-nm full-width at half-maximum (FWHM) for the photoluminescence (PL) spectrum to ~11 nm in the ASE case. Even without a resonator structure, the emission spectrum of the $\mathrm{Alq_3:DCM}$ material is spectrally narrowed. The wavelength maximum is shifting from 618 to 628 nm for the PL and ASE spectrum, respectively. To demonstrate waveguiding of the ASE in the fabricated single-mode waveguides, we pumped the active material perpendicular to the substrate (see Fig. 3). The pump beam was focused by a $4\times$ microscope objective to an elliptical pump spot size of ~0.1 mm$^2$. It was found that an elliptical pump spot positioned along the underlying waveguide resulted in a maximum output power. The induced ASE in the $\mathrm{Alq_3:DCM}$ material is coupled into the subjacent waveguide via evanescent field coupling. We estimate a coupling efficiency of 6% from simulations using the beam propagation method. Further optimization of the coupling geometry and the coupling length should result in much higher values.

The light output at the end facet of the PMMA substrate was measured by a fiber coupled power meter and spectrometer as well as imaged using a near-field camera system. Detection of pump light eventually coupled into the waveguide was

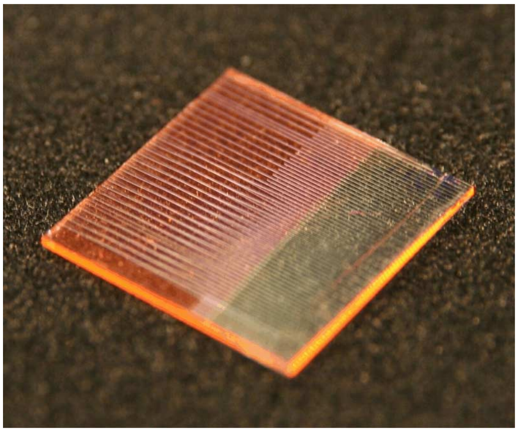

Fig. 2. Picture of the sample. The waveguides can be seen as thin lines across the sample. The patch on top of the waveguides is the laser material $\mathrm{Alq_3:DCM}$.

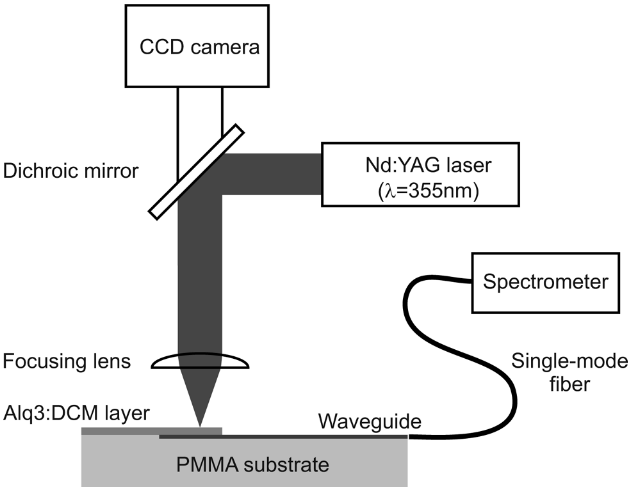

Fig. 3. Scheme of the experimental setup. Waveguides fabricated by DUV irradiation on a PMMA substrate are covered on one side by the active laser material $\mathrm{Alq_3:DCM}$. By pumping this material with a UV laser, mirrorless lasing is observed at the waveguide end facet. The guided light is coupled into an optical fiber and analyzed.

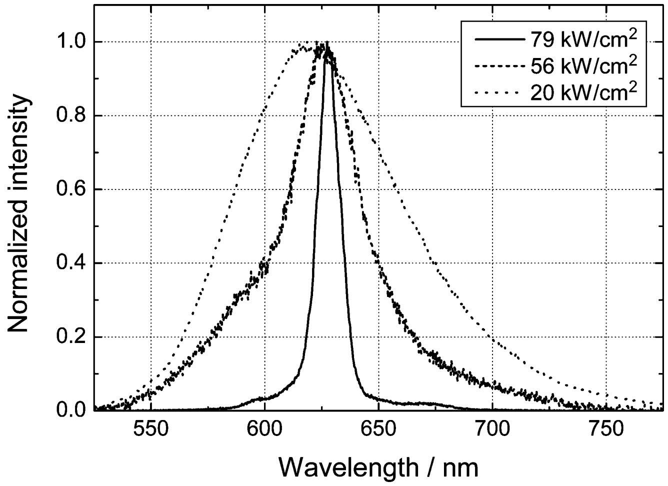

Fig. 4. Spectra of the emission of $Alq_3$ : DCM deposited on a PMMA substrate at different pump power densities. The PL spectrum is collapsing at higher pump power densities indicating the ASE in the material.

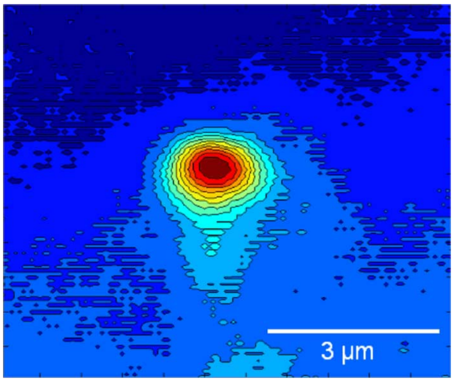

Fig. 5. Mode profile of the light output from the end facet of a 3-$\mu$m PMMA waveguide.

prevented by the use of an absorbing long pass filter (ITOS GG435). The maximum observed peak power of the pulsed ASE output [9] was in the order of 1.1 $\mu$W for the 5-$\mu$m waveguides. The output spectra at different pump power densities can be seen in Fig. 4.

One example for a near-field mode profile of the emission at a waveguide end facet is displayed in Fig. 5. The waveguide clearly shows a single-mode behavior as expected.

## V. CONCLUSION

We have demonstrated the coupling of the ASE of $Alq_3$ : DCM into single-mode waveguides. In combination with an optical analysis system, the structure can provide an easily integrable single-mode light source. By using different active organic compounds, one can profit from the wide range of light emission wavelengths of these materials. Using shadow masking technology, even the integration of several different laser sources on one substrate is possible.

Increasing the pump laser intensity and repetition rate [13] will enhance the output intensity significantly. Also an improved waveguide coupling scheme could provide a better efficiency of the device.

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