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# Delivery of the diode pumped Er:YLF laser radiation by special hollow glass waveguides

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## 1. Introduction

Lasers utilization in many applications in industry or medicine often requires a laser radiation transfer from the laser system to the place of the radiation action. The main delivery systems up to now are based on three systems - optical fiber, articulated arm, and hollow waveguide [1]. Most of the optical fibers have a trouble with the solid core, i.e. its homogeneity, flexibility, or damage threshold. This is not the case of hollow waveguides. In our case, hollow waveguides based on fused silica glass capillary tube were used. A reflective metallic layer is deposited on the inside wall of this tube and it is followed by a polymer film (Fig. 1). The inner metallic layer was composed of silver onto which a cyclic olefin-polymer (COP) dielectric film was applied. The polymer-coated waveguides offer little aging effect and non-toxicity when a proper polymer is chosen. The aim of presented study is the investigation of 3 µm wavelength radiation transfer by special hollow glass waveguide.

For a generation of laser radiation at spectral range ~ 3 µm the active medium doped with erbium ions can be used. The erbium-doped active media allow to generate laser radiation in spectral range 2.7 - 2.94 µm if the laser transition $^4I_{11/2} \rightarrow {}^4I_{13/2}$ is used [2]. Since the laser radiation in this spectral range is strongly absorbed in the water these lasers can be used in medicine (surgery, ophthalmology, urology) [2].

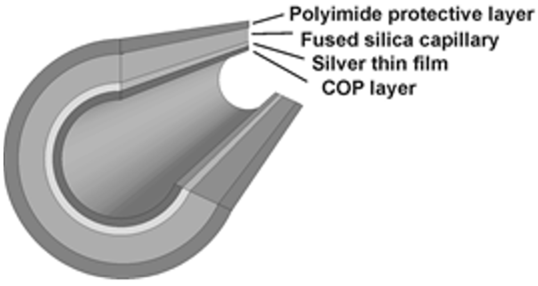


Fig. 1. Scheme of the COP/Ag hollow glass waveguide.

## 2. Results

As 3 µm laser radiation source, diode pumped Er:YLF laser was designed and constructed. The tested crystal Er:YLF (6 % of $Er^{3+}$, a – cut, Unioriental Co., Ltd.) had a form of rectangular block. It was plane-parallel (9 mm long) and face-polished without anti-reflection coatings (3 × 3 mm). The Er:YLF was placed inside the resonator (length 91 mm) consisted of a flat pumping mirror (PM, HT @ 960 - 980 nm and HR @ 2.8 µm) and spherical output coupler (OC, radius 100 mm, R = 90 % @ 2.8 µm). For longitudinal pumping, the fiber-coupled (core diameter 100 µm, NA = 0.22) laser diode (LIMO35-F100-DL976-EX1202, LIMO) was used. The laser diode operated in the pulsed regime (pulse duration 5 ms, frequency 10 Hz, maximal mean pump power 1020 mW, emitted wavelength 976.5 nm, focusing optic 3:10).

The Er:YLF laser emitted radiation at 2675 nm with linewidth 2.5 nm at FWHM and 2825 nm with linewidth 5 nm at FWHM. The maximal output power 176.2 mW with slope efficiency 27.5 % and laser threshold 59.1 mW with respect to absorbed power were reached. Beam profile of Er:YLF laser radiation was close to fundamental mode (Fig. 2).

Inner/outer diameter of investigated COP coated silver hollow glass waveguides were 700/850, 540/700, 320/540, and 250/360 µm; waveguide length was up to 112 cm. The basic coupling system can be made by only one focusing lens. For our case of mid-infrared radiation delivery, the fused silica ($CaF_2$) material was utilized due to its high transmission in this spectral region. The focal length of lens used was 55 mm.

The beam waist in focal plane was investigated experimentally. The resolution and sensitivity of the commercially available beam analyzer for spectral region about 3 µm are not suitable for measuring value of beam waist lower than units of hundreds of micrometers. Therefore, the knife-edge method was applied to analyze the beam diameter in the focal plane. For mean power 175.8 mW (repetition rate 10 Hz, pulse length 5.45 ms) the beam focus diameter measured was equal to 200 µm. To optimize a beam diameter for 250 µm inner diameter waveguide, it was changed position of focus lens and then diameter in focal plane was 150 µm. A special protector of the waveguide input part was employed for safekeeping the waveguide face and inner waveguide layers while setting up the transmission optimization. [3].

The transfer of the diode pumped Er:YLF laser radiation by a special cyclic olefin polymer-coated silver hollow glass waveguides was investigated. Transmission as a function of the input laser power and spatial distributions of the output beams were analyzed. The results of laser radiation delivery by straight and bend (at angle 90° with bending radius of 18 cm) waveguides are summarized in Tab. 1. The maximal transmission of 91 % was reached for 700 µm inner diameter waveguide. The laser beam spatial structure behind COP/Ag hollow glass waveguide was formed by individual peaks compared to the fundamental mode in front of the waveguide (Fig.2).

Table 1. Summary of delivery of the diode pumped Er:YLF laser radiation by special hollow glass waveguides; bending of waveguide: angle of 90 degrees and bend radius of 18 cm.

| Inner waveguide diameter | Waveguide length | Transmission, straight waveguide | Transmission, bend waveguide |
|---|---|---|---|
| 700 µm | 112 cm | 91.0 ± 1,8 % | 86.0 ± 1,5 % |
| 540 µm | 105 cm | 82.8 ± 1,9 % | 78.4 ± 1,4 % |
| 320 µm | 80 cm | 88.3 ± 1,4 % | 85.1 ± 1,6 % |
| 250 µm | 105 cm | 84.1 ± 1,1 % | 83.5 ± 1,9 % |

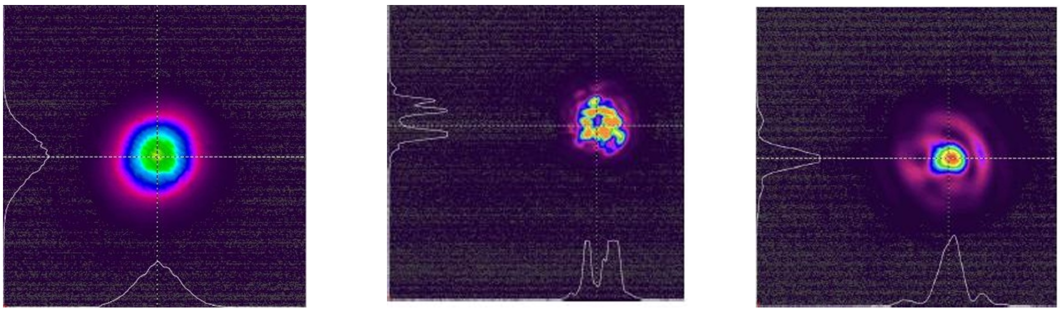

Fig. 2. Output beam structure of Er:YLF laser (left), 700 µm (middle), and 250 (right) inner diameter hollow waveguide.

## 3. Conclusion

The delivery of the diode pumped Er:YLF laser radiation with repetition rate 10 Hz and pulse length 5 ms by a special cyclic olefin polymer-coated silver hollow glass waveguide was investigated firstly. The hollow waveguides had a length up to 112 cm and various inner diameters. i.e. 250, 320, 540, and 700 µm. The beam spatial structures in front of and behind waveguide were recorded. The hollow glass waveguide transmission was proved up to 91 %. It was also analyzed transmission by bent waveguides at the angle of 90 degrees and bend radius of 18 cm. The output peak power maximum amplitude was obtained 2.51 W with radiation parameter: pulse duration 5.45 ms, output energy 14.6 mJ, and output mean power 146 mW. The maximum energy density behind waveguide with 250 µm inner diameter measured was 57 kJ/cm$^2$ with corresponding energy density 198.7 kJ/cm$^2$ in front of waveguide. The results reached show the great potential of the simple compact delivery system described with a sufficient transfer efficiency for use in various applications, especially in medicine.

## 4. References

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