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Pulsed infrared radiation transmission through hollow silica waveguides

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ABSTRACT

Transmission measurements of Q-switched and free-running Er:YAG laser radiation, at 2.94 μm and free-running Ho:YAG laser radiation, at 2.06 μm, through hollow silica waveguides of 750 and 1000 μm core diameter were performed. Attenuation measurements were obtained as a function of the laser energy input and as a function of the bending curvature. The output beam quality was also studied as a function of the focal length of the coupling lens and the overall launching conditions for straight waveguides using the appropriate beam profiler.

1. Introduction

Optical waveguides enable delivery of laser radiation in medical, industrial, telecommunication applications, etc. These delivery systems have the ability to transmit wavelengths well beyond 20 μm, have a high-power laser delivery ability due to their air core and they have a potential low cost [1,2]. Initially they were developed for medical [3,4] and industrial applications but more recently they have been used to transmit light for broadband spectroscopic and radiometric applications [5]. In general, hollow waveguides enjoy the advantages of high laser power thresholds, low insertion loss, no end reflection, ruggedness and small beam divergence [7].

In this work, three hollow silica waveguides of core diameter 1000 μm length 0.52 m, 750 μm length 0.58 m and 750 μm length 0.88 m, were evaluated as far as attenuation, spatial and temporal energy distribution of the transmitted laser radiation is concerned. Waveguides were tested in delivering free-running and Q-switched Er:YAG and free-running Ho:YAG laser radiation. Attenuation and bent loss measurements were performed and the beam quality at the output of the waveguide was studied for different focal lengths of the coupling lens using a Spiricon pyroelectric camera connected to a PC laser beam analyzer.

2. Materials and methods

The experimental set-up for the evaluation of the waveguides is the one presented in earlier works of ours [14]. Two different laser sources were used: (i) A pulsed Er:YAG laser source developed in our laboratory, emitting at 2.94 μm, with the ability of operation in the free lasing or Q-switched mode [16]. In the free-running mode the laser emits pulses of 80 μs duration with up to 500 mJ pulse energy, while in the Q-switched mode it emits laser pulses of 190 ns duration with 80 mJ of maximum energy. (ii) A pulsed Ho:YAG laser also developed in our laboratory, operating in the free-running mode, at 2.06 μm. The laser emits pulses of 1 ms duration and up to 150 mJ pulse energy.

The waveguides evaluated in this work were produced by developing a metallic layer of Ag on the inside of the silica glass tubing and then a dielectric layer of AgI over the metal film. Hollow silica waveguides show straight loss less than 1 dB/m and bend loss less than 1.5 dB/m in the wavelength range of 2.5–3.5 μm, according to the manufacturers.

The coupling scheme used consisted of a focusing lens, and a pinhole, with the diameter of the pinhole depending on the beam profile and the waveguides core diameter. In all cases, in order to avoid damaging of the front end of the waveguides, the pinhole was set before the lens focusing level, so that the beam was focused at about 5 mm into the waveguide.

For the bending experiments, where this was possible, the waveguides were placed on a disk, where they could be bent at various bending radii. The laser energy was measured simultaneously in the input and the output ends of the waveguides, with the help of an $\frac{8}{92}$% beam splitter, using two Gen-Tec ED 100 pyroelectric detectors. Alternatively when beam profiles were measured, a Spiricon pyroelectric camera connected to a PC laser beam analyzer was placed at the exit of the waveguide.

The delivery systems evaluated as above were hollow silica waveguides, with core diameters of 750 and 1000 μm, kindly offered by Polymicro Technologies.

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3. Results and discussion

3.1. Attenuation measurements as a function of laser input energy

Measurements of the attenuation for waveguides in straight condition, varying the laser input energy, were obtained. The laser input energy varied from 1.9 up to 15 mJ for the free running Er:YAG case for all waveguides. In the case of the Q-switched Er:YAG laser the input energy varied from 0.5 up to 16 mJ for all waveguides. We did not risk obtaining measurements above 16 mJ in order to avoid damage of the waveguides as these energy values correspond to quite high power densities. In the case of the Ho:YAG laser the input energy varied from 15 up to 17 mJ for all waveguides. Furthermore, it was not possible to achieve higher laser input into the waveguides, without spoiling the Gaussian-like input beam profile. It should be noted that the $\frac{15}{16}$ mJ Q-switched Er:YAG laser energy correspond to $\frac{79}{85}$ kW powers. Assuming a 200 μm beam diameter spot, the power density entering the waveguides is as high as $\frac{252}{270}$ MW/cm^2. The evaluated waveguides seemed to hold up well those power densities. Every data point is an average of 50 measurements, in order to reduce the error down to 0.01 dB/m. The main source of error was the 10% pulse to pulse fluctuation in the measured energy. As it can be seen in Fig. 1a and b, attenuation did not seem to vary significantly with the laser energy input. Table 1 shows the average attenuation as calculated for all waveguides of the same type, transmitting both free-running and Q-switched Er:YAG laser and Ho:YAG laser radiation. The 1000 μm core diameter waveguide exhibited a slightly better mean attenuation value of 0.43 dB/m for free-running Er:YAG laser radiation and 0.27 dB/m for Q-switched Er:YAG laser radiation than that of the 750 μm core diameter waveguide, i.e. 0.63 and 0.47 dB/m, respectively. This is in agreement with the theory predicting that the large bore waveguides transmit the higher order modes over longer lengths and the total loss is less than that of the small bore waveguides [9]. Moreover, from the data presented in Table 1 it can be seen that there is variation between the free-running and the Q-switched Er:YAG laser radiation transmission, with the shorter pulses facing somehow lower attenuations values. As far as the Ho:YAG laser radiation transmission results is concerned, all the waveguides presented higher attenuation values. According to the manufacturers attenuation spectra the waveguides are not offered for 2.06 μm and, therefore, we do not include the relevant energy variation graphs in this text.

3.2. Attenuation measurements as a function of bending curvature for the 750 μm core diameter waveguide

Attenuation was measured as a function of the bending curvature ($1/R$). The laser energy did not exceed 10 mJ, in order to avoid damage of the waveguide. The waveguide has a core diameter of 750 μm and a length of 0.88 m. The delivery system was bent at 90° and 180°, with the curvature varying from 0 to 6.7/m. Because of the short length of the 1000 μm bore diameter waveguide, no bending experiments were performed with this. Results are shown in Fig. 2a and b for the free-running and Q-switched Er:YAG laser. Each data point in the graph is an average of 50 measurements. Table 2 shows the average attenuation as calculated for bending angles of 90° and 180° for the free-running and Q-switched Er:YAG laser. It is observed that bending at 90° angle results in lower attenuation than bending at 180°, as expected. According to Fig. 2, a strong linear dependence with curvature is observed as expected theoretically, with linear regression R^2 values greater than 0.98. This is also in agreement with the $1/R$ proportionality, where R is the bending radius, that Miyagi et al. demonstrated for a dielectric-coated hollow metallic waveguide [6–8]. The deviation of the results from the linear dependence, predicted from the theory, is attributed to the fact that although higher order modes are transmitted in straight

Table 1
Attenuation values of the hollow silica waveguide under straight condition, for free-running and Q-switched Er:YAG and free-running Ho:YAG laser radiation

Waveguide	Free-running Er:YAG (dB/m)	Q-switched Er:YAG (dB/m)	Free-running Ho:YAG (dB/m)
750 μm short	0.62	0.47	3.4
1000 μm	0.43	0.27	9.0
750 μm long	0.64	0.50	3.6

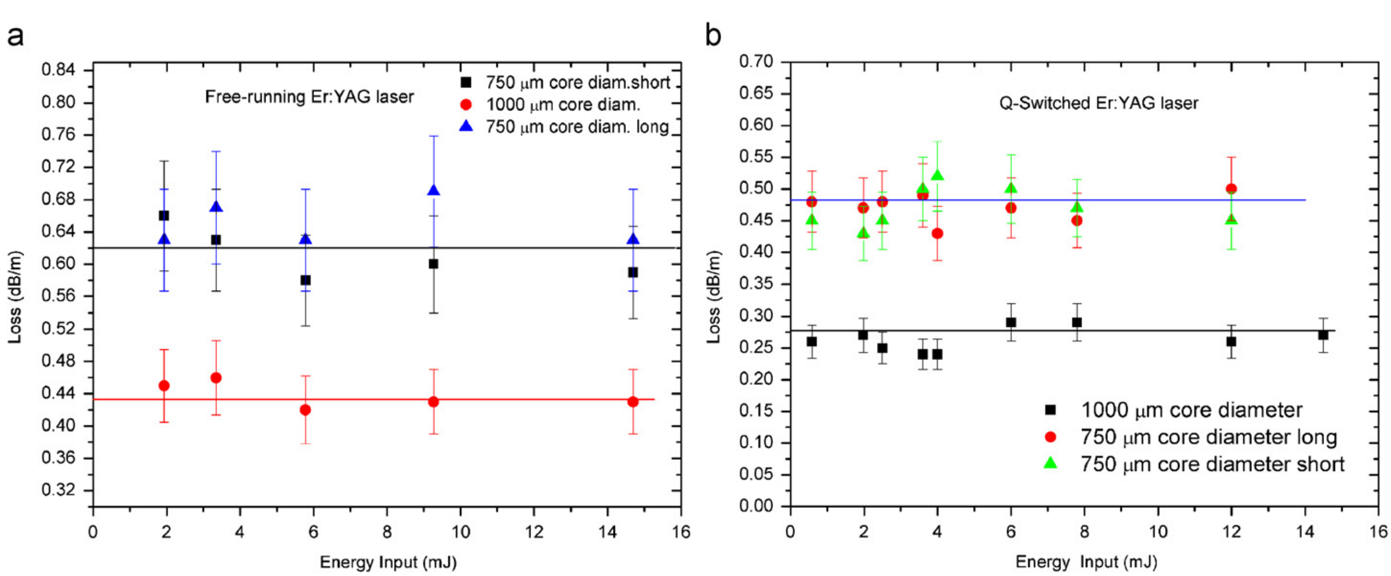

Fig. 1. (a) Attenuation of free-running Er:YAG laser energy as a function of the laser energy input, for the hollow silica waveguides. (b) Attenuation of Q-switched Er:YAG laser energy as a function of the laser energy input, for the hollow silica waveguides.