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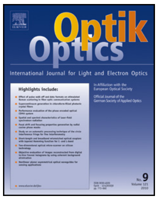

Multimode VIS–NIR transmission through silver coated hollow optical waveguides

J. Griffiths*, C. Dowding, A. Kirk

School of Engineering, University of Lincoln, Brayford Pool, Lincoln LN6 7TS, United Kingdom

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ABSTRACT

Multimode transmission of continuous wave 633 nm radiation and 1064 nm Q-switched Nd:YAG pulses using silver coated hollow core optical waveguides (HCWs) with bore diameters of 700 μm and 1000 μm is reported. The effect of launch conditions, input beam polarization and waveguide bore diameter on the pulse energy transmission and potential for focussing the beam effectively at the HCW exit is detailed. An optimal launch *f*-number range of 155–165 is identified for minimizing the exit angle.

1. Introduction

Transmission of laser pulses with high peak powers in the visible to near-infrared (VIS–NIR) spectral range using hollow core waveguides (HCWs) has the potential for application in processes such as laser ignition, laser surgery, remote sensing and laser induced breakdown spectroscopy [1–3]. A key challenge in such applications is obtaining a beam of sufficient quality at the exit of a waveguide, as beam quality is intrinsically linked to the potential for focusing a beam to a small spot.

HCWs comprise glass capillary tubes with reflective coatings, typically metallic, deposited on the inner surface, resulting in a flexible and durable waveguide which exhibits low attenuation losses. The effect of launch conditions on single and low order mode transmission *via* HCW was characterized by Nubling and Harrington [4]. Single and low order mode transmission *via* HCW is possible when the bore diameter is in the order of 30–50 times the wavelength of the laser radiation [5]. Nubling and Harrington reported *f*-numbers of 15, 22 and 30 as optimal for minimizing attenuation losses during single mode transmission of 10.6 μm laser radiation *via* 1 m long HCWs with 320 μm, 530 μm and 700 μm bore diameters, respectively.

The attenuation loss and modal properties for low order mode transmission of 10.6 μm wavelength laser radiation *via* silver coated HCW was also investigated by Bledt et al. [5]. The number of modes propagating was shown to be dependent on bore diameter, with bore diameters equal to approximately 30 times the wavelength required to ensure single mode behaviour.

Compared with low order mode infrared (IR) transmission, relatively little information regarding effect of launch conditions on HCW exit beam quality exists for multi-mode delivery when compared with single and low order mode delivery. Joshi et al. reported delivery of high peak power radiation from a Q-switched Nd:YAG operating at 1064 nm *via* a 2 m long cyclic olefin polymer coated HCW [6]. An *f*-number of 55 was identified as suitable, producing an exit beam with a beam quality factor (M^2) of 15. It was noted that, as the *f*-number was increased or decreased relative to this value, the beam quality and transmission was degraded. However, Dumitrescu reported improved exit beam quality at a higher *f*-number for delivery of 1064 nm laser radiation *via* HCW, with an M^2 of 12 obtained at an *f*-number of 83 [1].

In this work, a thorough experimental investigation into the multimode transmission of VIS–NIR laser radiation using silver coated HCWs with bore diameters of 700 μm and 1000 μm is reported. The effects of launch conditions, input beam characteristics and HCW bore diameter on output beam quality are investigated. Optimal launch conditions for minimizing exit angle are presented.

2. Experimental set-up

The experimental set-up is shown in Fig. 1. Two laser sources were used in this investigation. The first was a Q-switched Nd:YAG TEM_{00} laser (Brilliant; Quantel, Ltd) with an M^2 of 1.84, pulse

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* Corresponding author. Tel.: +44 01522 837 936.
E-mail address: JGriffiths@lincoln.ac.uk (J. Griffiths).

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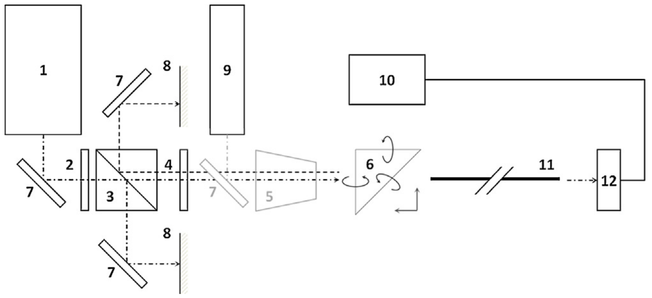

Fig. 1. Experimental set-up with (1) Nd:YAG laser source, (2) 1/2 wave plate, (3) polarizing beam splitting cube, (4) 1/4 wave plate, (5) 2× beam expander, (6) 5-axis launch assembly, (7) beam-steering mirror(s), (8) beam dump(s), (9) HeNe laser source, (10) data acquisition and control computer, (11) HCW and (12) LBA camera. The dashed-dot line represents the optical path whereas the dashed line represents the optical path for back reflections. Greyed elements could be removed from the beam path when required. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

duration of 4 ns, operating at 10 Hz repetition rate and 1064 nm wavelength. The second was a HeNe TEM_{00} laser (R-30599; Research Electro-Optics, Inc) with an M^2 of 1.1 operating in continuous wave mode at 633 nm wavelength. The HCWs were mounted in a 5-axis stage with 3 mm of coarse travel in x, y and z directions as well as ±3.5° and ±5.0° pitch and yaw, respectively. At both their input and output ends the HCW's sat in a V-groove. At the input end the HCWs were lightly secured in place using a quick release clamp (HFF001, Thorlabs, Inc.). A free-standing distance of 2 cm from the input face of the HCW to the quick release clamp was allowed to minimize stresses at the input face. A laser beam analysis (LBA) camera (Spiricon SP620U, Ophir Optronics Solutions Ltd) was used to determine the output angle at the HCW exit.

A polarization based optical attenuator was used to manipulate the laser power. This method of attenuation was preferred to changing the flashlamp/Q-switch delay time to manipulate the output power as the latter can lead to changes in the propagation characteristics of the beam [7,8]. A power meter (Maestro; Gentec Electro-Optics, Inc.) connected to a data acquisition and control computer was used to determine the transmission properties of the HCWs. An optical isolator, consisting of a 1/4 wave plate placed after a polarizing beam splitting cube along the optical path, was used to protect the laser source from back reflections.

3. Methodology

The effect of input angles θ_{input} of up to 10 mrad on exit angle θ_{exit} (rad) for 1 m long HCWs (held roughly straight) was determined using the experimental set-up shown in Fig. 1. The HCWs consisted solely of quartz capillary tubing with a thin silver film deposited on the inner surface. The HCWs were developed by Matsuura et al. who published details of the manufacturing process [9]. Two HCW bore diameters α of 700 μm and 1000 μm were utilized in this investigation, with outer diameters of 850 μm and 1600 μm, respectively. Five spherical plano-convex lenses with focal lengths f of 150, 200, 250, 300 and 500 mm were used in conjunction with a 2× beam expander to vary the launch angle at the input face of the HCWs. The optimal launch conditions for a given combination of launch angle and HCW were determined by manipulating each of the five axes individually to minimize the spot size incident on the LBA camera. Using the LBA camera's on-board photodiode power meter, optimal coupling of the laser radiation into the HCW could also be ensured. A schematic diagram of the HCW launch assembly is shown in Fig. 2.

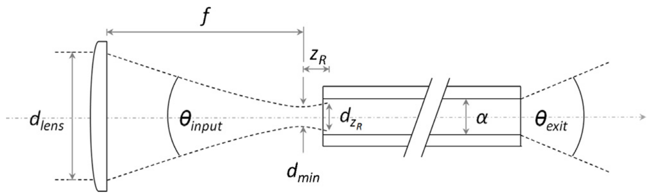

Fig. 2. Schematic of HCW launch/exit configuration. The dashed lines represent the marginal rays whereas the dashed-dot line represents the optical axis.

The input angle was calculated as the full divergent angle of the beam at a distance from the focal position equal to the Rayleigh range:

$$z_R = \frac{\pi d_{\text{min}}^2}{4M_{\text{in}}^2 \lambda} \tag{1}$$

where $M^2{}_{\text{in}}$ is the beam quality factor of the input beam, λ is the laser wavelength (nm) and d_{min} is the focal spot size prior to the input face of the HCW (m), which can be calculated using:

$$d_{\text{min}} = \frac{4M_{\text{in}}^2 f\lambda}{\pi d_{\text{lens}}} \tag{2}$$

where f is the focal length of the launch optic (m) and d_{lens} is the beam diameter incident on the lens (m). The diameter of the beam at a distance from the focal position equal to z_R can be calculated using Eq. (3), with the input angle calculated using Eq. (4).

$$d_{z_R} = d_{\text{min}} \left[1 + \left(\frac{4M_{\text{in}}^2 \lambda z_R}{\pi d_{\text{min}}^2} \right)^2 \right]^{0.5} \tag{3}$$

$$\theta_{\text{input}} = 2\tan^{-1}\left(\frac{d_{z_R} - d_{\text{min}}}{2z_R} \right) \tag{4}$$

Care was taken to ensure that the diameter of the beam at a distance from the focal position equal to z_R was smaller than the bore diameter for all launch configurations used.

4. Results and discussion

4.1. Effect of launch conditions

Exit angle and $M^2{}_{\text{exit}}$ as a function of θ_{input} is plotted in Fig. 3(a)–(d) for both bore diameters and wavelengths. Despite the multimode nature of the beam upon exiting the HCWs, the M^2 factor was utilized as a useful means of quantifying the beam quality at the exit of the HCWs.

It was found that θ_{exit} was consistently smaller for the 1000 μm bore diameter over the range of input angles tested, revealing a dependence of output beam divergence for propagating modes on bore diameter which is consistent with theory [4]. A general trend revealed in Fig. 3(a)–(d) is exit angle decreasing as launch angle is reduced, which can be attributed to the propagation of fewer modes. A noticeable exception to this trend is observed over a launch angle range of 2 mrad to 4 mrad, with launch angles of approximately 2.6 mrad shown to result in optimal exit beam quality for both bore diameters and wavelengths, revealing an optimal launch angle for coupling to lower order modes.

The exit beam mode profiles for the optimal launch angles with respect to beam quality are shown in Fig. 4(a)–(d) for both bore diameters and wavelengths, confirming the multimode nature of the beam. This is to be expected when considering the bore diameters used in this work, which far exceed the 30λ threshold required for single mode behaviour [5].

At 1064 nm wavelength the pulse energy transmission for the optimal launch angle of 2.62 mrad was found to be 89% and 93% for