Please cite this article as: J. Griffiths, C. Dowding, A. Kirk, Multimode VIS–NIR transmission through silver coated hollow optical waveguides, Optik - International Journal for Light and Electron Optics, Volume 127, Issue 2, January 2016, Pages 728-731, ISSN 0030-4026, http://dx.doi.org/10.1016/j.ijleo.2015.10.148.

doi:10.1016/j.ijleo.2015.10.148

http://www.sciencedirect.com/science/article/pii/S0030402615015168

MULTIMODE VIS-NIR TRANSMISSION THROUGH SILVER COATED HOLLOW OPTICAL WAVEGUIDES

J. GRIFFITHS[1*], C. DOWDING[1], A. KIRK[1]

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

Tel: +44 01522 837 936

E-mail: JGriffiths@lincoln.ac.uk

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.

KEYWORDS:

Fiber optics, hollow core waveguides, near-infrared, launch conditions, Nd:YAG laser.

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* 1m 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 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 Figure 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 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^o and ±5.0^o 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 minimise 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.

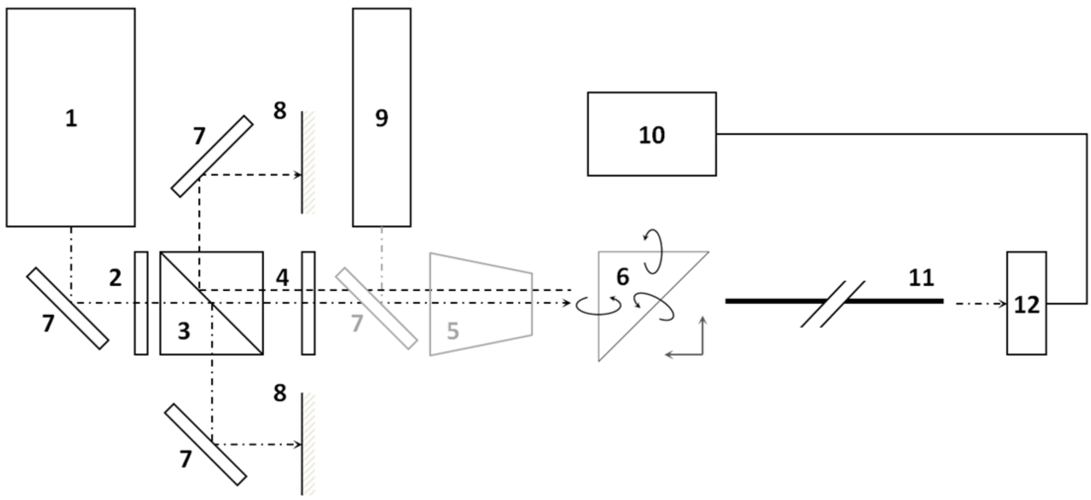

Figure 1: Experimental set-up with (1) Nd:YAG laser source, (2) ½ wave plate, (3) polarizing beam splitting cube, (4) ¼ wave plate, (5) 2X beam expander, (6) 5-axis launch assembly, (7) beam-steering mirror(s), (8) beam dump(s), (9) HeNe laser source, (10) data acquisition and control computer, (11) 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.

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 ¼ 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 Figure 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 2X 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 minimise 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 Figure 2.

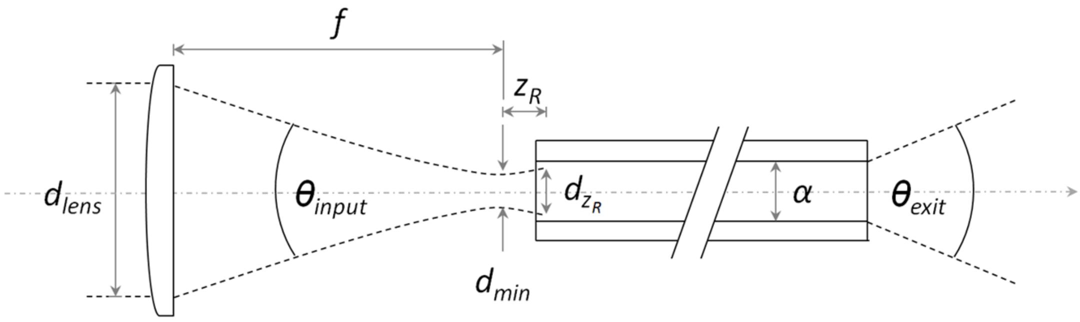

Figure 2: Schematic of HCW launch/exit configuration. The dashed lines represent the marginal rays whereas the dashed-dot line represents the optical axis.

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:

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

where M^2_{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:

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

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 Equation 3, with the input angle calculated using Equation 4.

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

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

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_{exit} as a function of θ_{input} is plotted in Figures 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.

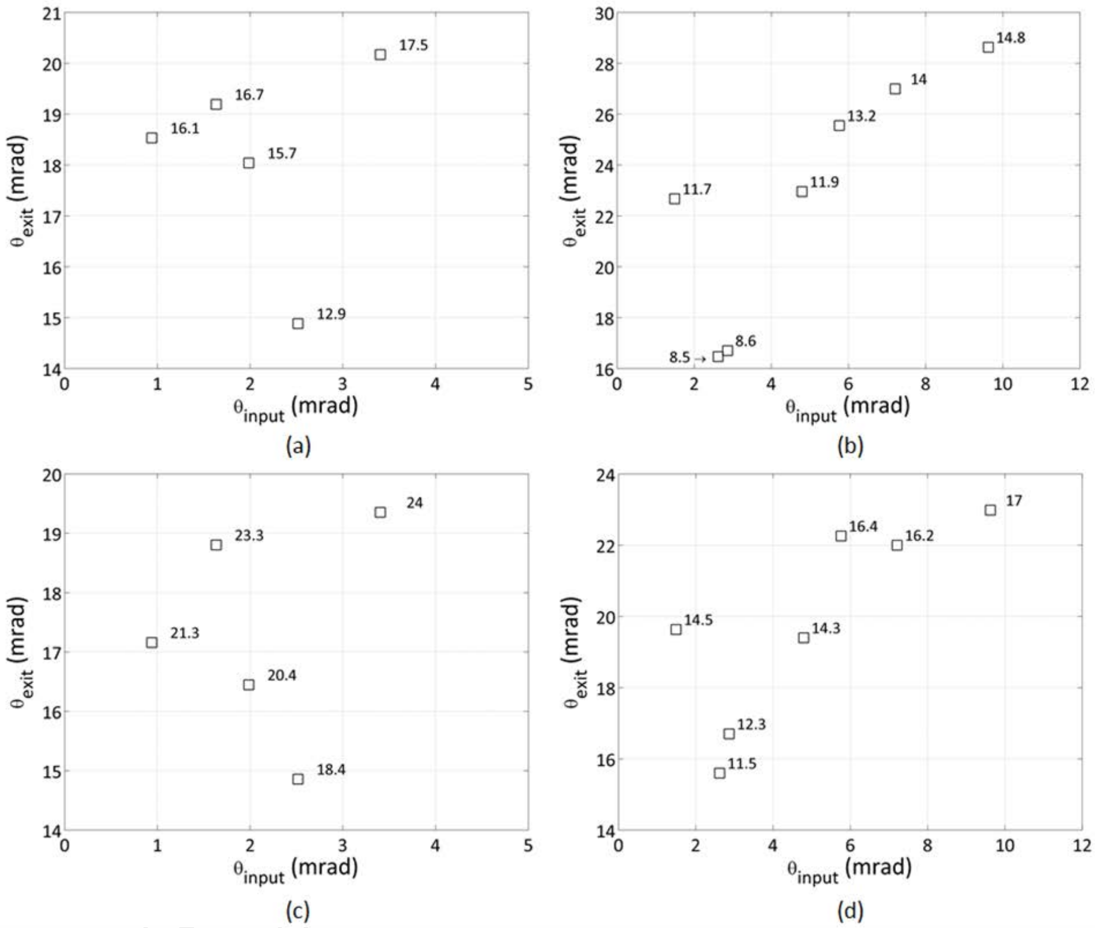

Figure 3: Exit angle as a function of input angle for (a) 633 nm wavelength and 700 µm bore diameter, (b) 1064 nm wavelength and 700 µm bore diameter, (c) 633 nm wavelength and 1000 µm bore diameter and (d) 1064 nm wavelength and 1000 µm bore diameter. Data point labels are the corresponding M^2_{exit} values.

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 Figures 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 Figures 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].

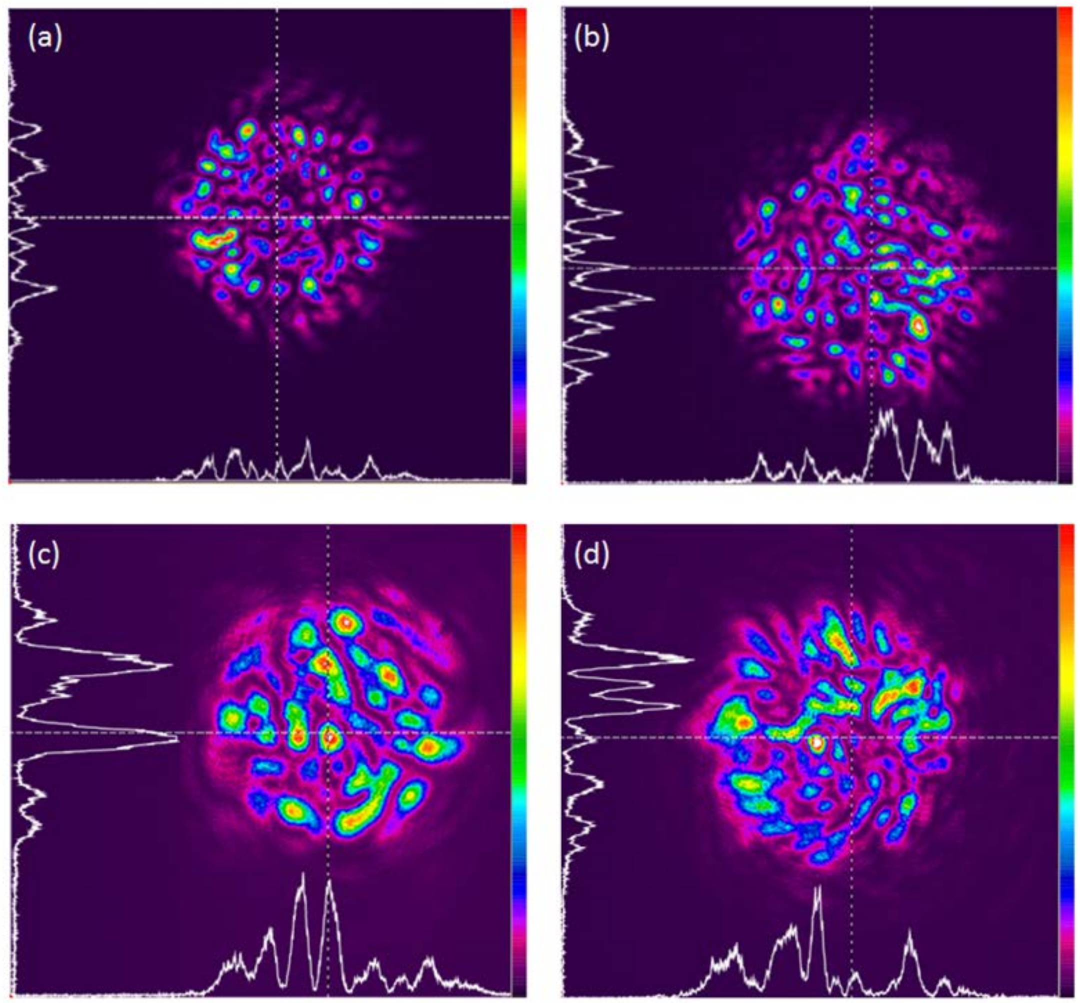

Figure 4: Mode profiles for (a) 633 nm wavelength, 700 μm bore diameter and 2.52 mrad input angle, (b) 633 nm wavelength, 1000 μm bore diameter and 2.52 mrad input

angle, (c) 1064 nm wavelength, 700 μm bore diameter and 2.62 mrad input angle, and (d) 1064 nm wavelength, 1000 μm bore diameter and 2.62 mrad input angle.

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 the 700 μm and 1000 μm bore diameter HCWs, respectively. This was based on input pulse energies in the order of 5 mJ. The relative reduction in pulse energy transmission for the 700 μm bore diameter is consistent with the experimental observations in literature, with waveguide losses exhibiting an inverse cubic relationship with α [10-12].

The maximum transmitted pulse energy was approximately 45 mJ for both bore diameter HCWs at 1064 nm wavelength. This is comparable to maximum transmitted pulse energies reported for solid core silica step index fibers [13]. For transmitted pulse energies up to and including this damage threshold, no spark formation was observed at the input face of the HCW. Transmitted pulse energies above this value resulted in localized damage to the reflective inner coating, initially occurring approximately 3 cm downstream of the quick release clamp for both bore diameters. This can be attributed to strong absorption of the laser radiation in the reflective coating due to micro-bending as a result of manipulation of the 5-axis launch assembly [14]. This initial damage acted as a nucleation point for further damage, which proceeded intermittently by the process of ablation. It should be noted that isolated instances of damage occurred at distances of up to 7 cm downstream of the quick release clamp.

The effect of input polarization at 1064 nm wavelength was determined for the optimal launch angle of 2.62 mrad. The beam exiting the optical isolator was circularly polarized. By rotating the ¼ wave plate on the optical isolator through 45^{o}, varying degrees of elliptical polarization could be obtained. Furthermore, by removing the ¼ wave plate altogether, linear polarization could be obtained. No appreciable change in mode structure of the output beam or transmitted pulse energy was observed for any of the aforementioned polarization configurations. However, it should be noted that Parry *et al.* observed that linear polarization plays a key role in determining the transmission properties and laser induced damage threshold (LIDT) of HCWs when in a bent configuration [14]. It was shown that linear polarization parallel to the direction of bend reduced both the transmission and LIDT. Using this arrangement, a maximum transmitted pulse energy of 61 mJ at 1064 nm was reported for a HCW with a bore diameter of 1000 μm.

4.2 Potential for focussing at the HCW exit

In this case, focussing of the beam to diameter d_{focus} using a single a-spherical focussing optic with an effective focal length of 15 mm, placed 300 mm downstream of the HCW exit along the optical axis, is considered. The intensity (Equation 5) at the focal point for the two optimal configurations identified in Section 4.1 for the 700 μm and 1000 μm bore diameters, both of which correspond to an input angle of 2.62 mrad, is shown in Table 1 for an input pulse energy of 5 mJ.

$$I_0 = \frac{4P}{\pi d_{focus}^{\ 2}}$$

(5)

α (μm)	M^2_{exit}	Transmission (%)	d_{focus} (μm)	I_0 (MW/m^2)
700	8.50	89	34.65	47.18
1000	11.50	93	48.89	24.76

Table 1: M^2_{exit}, pulse energy transmission, d_{focus} and I_0 with varying bore diameter (1064 nm wavelength, 5 mJ pulse energy, 10 Hz repetition rate, 4 ns pulse duration 2.62 mrad input angle).

Table 1 reveals that higher focal intensities can be achieved by focussing light exiting the 700 μm bore diameter relative to the 1000 μm bore diameter. This is due to the higher beam quality, which is more than sufficient to compensate for the reduction in transmission. For the same focal configuration and considering the experimentally determined maximum pulse energy transmission of 45 mJ, corresponding focal intensities of 425 MW/m^2 and 223 MW/m^2 are calculated for the 700 μm and 1000 μm bore diameters, respectively.

4.3 Optimal *f*-number for multimode VIS-NIR transmission

A convenient parameter to use when describing launch conditions for HCWs is *f*-number; that is, the ratio of the focal length of the focussing optic to the beam diameter incident on the lens, Equation 6. The *f*-number is particularly useful as it incorporates key laser parameters relevant to the focussing of the beam. Exit angle as a function of *f*-number is shown in Figure 5 for both bore diameters and wavelengths used in this investigation.

$$f\# = \frac{\pi d_{min}}{4M_{in}^2\lambda} = \frac{f}{d_{lens}} \qquad (6)$$

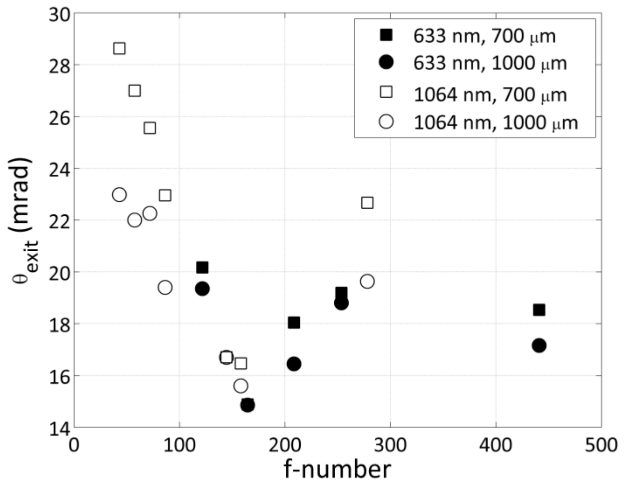

Figure 5: Exit angle as a function of *f*-number.

The smallest exit angles were achieved with *f*-numbers in the order of 155 for both bore diameters and wavelengths used in this investigation. Values for θ_{exit} over *f*-number range of approximately 80-90 are in good agreement with experimental observations of Dumitrescu, who reported an output half angle of 8 mrad for an input *f*-number of 83 [1]. The closest corresponding *f*-number for this study of 86 produced an output half angle of 9.7 mrad.

Optimal *f*-numbers of 158 and 165 were found for 1064 nm and 633 nm wavelengths, respectively. This suggests that there is negligible dependence on α or λ for optimal multimode transmission *via* HCW. The data for 633 nm suggests that there is potential for further reduction of θ_{exit} at higher *f*-numbers (> 450). However, such *f*-numbers would invariably yield focal spot diameters larger than the bore diameter of the HCWs and as such would be unsuitable for high power applications due to laser induced damage as a result of heat generation or ablation at the HCW input face [4].

5. CONCLUSIONS

Optimal launch conditions for multimode transmission of VIS-NIR laser radiation using silver coated hollow core waveguides (HCWs) with bore diameters of 700 μm and 1000 μm have been identified.

The effect of input angles of up to 10 mrad on the HCW exit angle and subsequent beam quality factor M^2 were determined. It was found that the 1000 μm bore diameter consistently resulted in a smaller exit angle, consistent with theory. Conversely, the M^2 was consistently lower for the 700 μm bore diameter. Operating at 1064 nm, of the various optical configurations tested in this work, a launch angle of 2.62 mrad was found to give the highest pulse energy transmission (~90 %) and best beam quality for both HCW bore diameters. The mode profile and pulse energy transmission characteristics were shown to be ostensibly independent of changes in input beam polarization. A maximum transmitted pulse energy if approximately 45 mJ was determined for both HCW bore diameters, above which laser induced damage occurred.

An optimal launch *f*-number range of 155-165 was identified for minimizing the exit angle and thereby achieving optimal beam quality at the exit of the HCW. Results suggest a negligible dependence on bore diameter or wavelength for optimal launch *f*-number for multimode transmission of VIS-NIR laser radiation *via* HCWs. Further work is required to determine the effect of HCW length and bend configuration on optimal launch *f*-number.

ACKNOWLEDGEMENTS:

The authors would like to thank Siemens Industrial Turbomachinery Ltd (SITL) for funding this investigation as part of a wider investigation into laser ignition for gas turbines.

REFERENCES:

[1] Dumitrescu C, Puzinauskas P, Olcmen S, Buckley S, Joshi S, Yalin A. Fiber-optic spark delivery for gas-phase laser-induced breakdown spectroscopy. Applied Spectrocopy 2007;61(12):1338-1343.

[2] Patimisco P, Spagnolo V, Vitiello MS, Scamarcio G, Bledt CM, Harrington JA. Low-Loss Hollow Waveguide Fibers for Mid-Infrared Quantum Cascade Laser Sensing Applications. Sensors 2013;13(1):1329-1340.

[3] Yalin A. High power fiber delivery for laser ignition applications. Opt Express 2013;21:A1102-A1112.

[4] Nubling RK, Harrington JA. Launch conditions and mode coupling in hollow-glass waveguides. Opt Eng 1998;37(9):2454.

[5] Bledt CM, Harrington JA, Kriesel JM. Loss and modal properties of Ag/AgI hollow. Appl Opt 2012;51(16):3114-3119.

[6] Joshi S, Yalin A, Galvanauskas A. Use of Hollow Core Fibers, Fiber Lasers, and Photonic Crystal Fibers for Spark Delivery and Laser Ignition in Gasses. Applied Optics 2007;46(19):4057-4064.

[7] Mullett J, Dodd R, Williams C, Triantos G, Dearden G, Shenton A, et al. The influence of beam energy, mode and focal length on the control of laser ignition in an internal combustion engine. J Phys D 2007;40(15):4730.

[8] Chen Y-, Lewis JWL, Parigger C. Spatial and temporal profiles of pulsed laser-induced air plasma emissions. Journal of Quantitative Spectroscopy and Radiative Transfer 2000 10/16;67(2):91-103.

[9] Matsuura Y, Tsuchiuchi A, Noguchi H, Miyagi M. Hollow fiber optics with improved durability for high-peak-power pulses of Q-switched Nd:YAG lasers. Appl Opt 2007;46(8):1279-1282.

[10] Doradla P, Joseph C, Kumar J, Giles R. Propagation loss optimization in metal/dielectric coated hollow flexible terahertz waveguides. SPIE Photonics West OPTO 2012;8261:82610P-82610P-10.

[11] Kriesel JM, Hagglund GM, Gat N, Spagnolo V, Patimisco P. Spatial mode filtering of mid-infrared (mid-IR) laser beams with hollow core fiber optics. SPIE Photonics West 2015(8993).

[12] Sampaolo A, Patimisco P, Kriesel JM, Tittel FK, Scamarcio G, Spagnolo V. Single mode operation with mid-IR hollow fibers in the range 5.1-10.5 µm. Opt Express 2015;23(1):195-204.

[13] El-Rabii H, Gaborel G. Laser Ignition of Flammable Mixtures via a Solid Core Optical Fiber. Appl Phys B 2007;87:139-144.

[14] Parry JP, Stephens T, Shephard J, Jones J, Hand DP. Analysis of optical damage mechanisms in hollow-core waveguides delivering nanosecond pulses from a Q-switched Nd:YAG laser. Applied Optics 2006;45(36):9160-9167.