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Mapping the thermal distribution within a silica preform tube using regenerated fibre Bragg gratings

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ABSTRACT

The temperature profile of the reaction zone inside the silica substrate tube during thermal heating with a H_2/O_2 flame under conditions identical to those used in the fabrication of optical fibre preforms using a modified chemical vapour deposition lathe has been characterised with ultra-high temperature stable regenerated optical fibre Bragg gratings. Experimental and theoretical results indicate a significant drop in temperature – up to several hundred degrees – across the tube wall from outside to inside. These results are in contradiction with the broadly accepted assumption that there is no significant thermal gradient across the tube itself. An array of regenerated gratings demonstrates that optical fibre grating based sensing can achieve distributed ultra-high temperature mapping and monitoring in harsh environments.

1. Introduction

Modified chemical vapour deposition (MCVD) [1] is the most commonly used method for the fabrication of specialty optical fibre preforms. The MCVD process essentially involves high temperature oxidation of halide chemicals, such as $SiCl_4$ and $GeCl_4$, in the reaction zone inside a high purity silica waveguide substrate tube and subsequent formation and deposition of solid oxide particles (commonly referred to as 'soot') on the internal walls. The oxide particles are commonly generated by homogeneous reactions in the gas phase [2] with input halides reacting at high velocities in the presence of oxygen so that chemical equilibrium is attained [3]. The heat is usually provided by a travelling oxy-hydrogen flame, with several passes required to gradually build up the preform layer-by-layer through particle sintering. Viscous sintering has been experimentally determined to be the mechanism responsible for the consolidation of the particulate layers, with gas thermal conductivity and composition of dopants greatly influencing the deposition rate [4]. The composition of each layer, estimated through analysis with chemical thermodynamics [5,6], can be adjusted by changing the gas composition to create the desired refractive index profile. Defect concentrations in the glass can be modified through control of the deposition temperature, by depositing in oxygen deficient conditions, and by using additional co-dopants [7]. After the deposition process, the tube is collapsed at higher temperatures forming a solid preform rod.

The 'soot' particles formed in the reaction zone are carried within a laminar gas flow, where the influence of thermophoresis, arising from thermal gradients across the substrate, is regarded as the most dominant mechanism for subsequent particle deposition [8–11]. The deposition occurs after the soot particles move past the reaction zone as they reach the cooler zone just ahead of the travelling flame, where they are either deposited on the tube wall or pass through as waste. Aberrations in the uniformity of the refractive index profile in between the sintered layers have been observed, particularly when more than one component has been deposited. These differences have been attributed to variation in particle size, morphology and chemical composition (variation in reaction temperature, density, boiling point and so on) which affect the deposition efficiencies of the different components. Although not widely recognised, it is clear that the control of thermal gradients adds an additional element of control over dopant distribution and final concentrations for a given external flame temperature. A better understanding of the dynamic temperature gradients experienced by the chemicals inside the tube is desirable,

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given this significant temperature dependence of the different processes involved during deposition.

Previous experimental studies have been restricted to improving thermophoretic efficiencies in the MCVD process through techniques such as air cooling of the substrate tube during manufacture and axial carbon-dioxide laser heating of the tube [12,13]. The inside wall temperature has been assumed to be similar to that measured from the outside with pyrometers and thermocouples [9,14]. The justification has been that the maximum temperature of the gas does not play a major role in the gas kinetics except in the case of very high flow rates and that thermal equilibrium is achieved quickly [9]. Accurate internal temperature mapping has to date, however, been limited to theoretical studies. Theoretical predictions of temperature, axial and radial velocities, and $SiCl_4$ and SiO_2 concentrations as a function of preform radius have been reported along with variations to the deposition efficiencies as a function of carrier gas properties [14], all largely on the assumption that there is little difference between outer and inner temperatures. These include investigations of temperature dependence of particle deposition efficiency of submicron particles [9], improvements in process yields by maintaining a temperature gradient between the gas stream and tube wall [15], and the mapping of the trajectories of the particles generated in the reaction zone as a function of particle size, tube rotation and particle density [16,17]. The studies of particle trajectories have also included theoretical predictions of tube wall temperature gradients [16,17]. A numerical analysis of the unsteady heat and mass transfer during the deposition of SiO_2 and GeO_2 has been reported with respect to torch traversing speed, wall temperature and concentration of GeO_2 particles [18]. In contrast to MCVD work, some experimental measurements of preform rod surface temperatures have been reported for the outside vapour deposition (OVD) process during variations in burner carriage speed and the carrier gas flow rates [19]. The preform rod surface temperatures were measured radially and axially with a thermocouple with such variations.

To the best of our knowledge, there have been no actual experimental measurements characterising the temperatures inside the reaction zones of the MCVD process. This is despite such knowledge being considered crucial in helping reduce the dependency of specialist optical fibre fabrication on trial-and-error, or "black-art", fabrication of contemporary research and development. An accurate temperature map of the inside of the tube is essential, not only for the MCVD process to be optimised and made reproducible, but as well for the fabrication of a new generation novel multi-stage coated particles to create preforms with nano-composite material functionality. These chemical processes hinge on accurate thermal control; for example, variation of a 100 °C can often alter the reaction rate by an order of magnitude [9].

In this contribution, we expand on our recent report on using specialised optical fibre Bragg gratings to investigate the internal MCVD substrate tube reactor temperatures in detail [20]. These novel gratings are ultra-high temperature stable regenerated fibre Bragg gratings (FBGs) [21] and are ideal probes, both as single units and also in multiplexed arrays. A general introduction into the type of fibre gratings available and their temperature performances can be found in the review article [22]. With this method the actual temperatures can be measured, and mapped, *in situ* at extreme temperatures with high resolution allowing for a direct comparison with past theoretical modelling often based on a range of as yet untested assumptions. These FBG based optical temperature sensors are destined to replace electrical thermocouples in a range of sensing applications, especially where electronic solutions are not an option, or are preferably avoided altogether. These include, for instance, distributed sensor applications where there is a risk of explosion, where the distance to the point of measurement is long, in areas of high radiation, or where the signal is corrupted by high electrical field interference. We demonstrate another important advantage of these optical sensors – the ability to perform distributed, simultaneous temperature measurements in harsh environments using an array of regenerated gratings. We do these experiments for a range of realistic fibre fabrication conditions, including transverse/longitudinal position, gas-flow, flame traversing speed and multiple passes with thermal lag effects. Whilst some past assumptions are shown to be valid – such as the zero net effect of a nitrogen cooling curtain on heat transfer within the substrate tube, a key outcome is showing that the assumption of a more or less uniform temperature profile across a substrate tube is not consistent with the observation of a large temperature drop between the outside and inside regions. Simulation without the starting assumption that there is no temperature gradient across the tube wall indicates that this gradient is in fact expected.

2. Experiments and results

The substrate tube used for the experiments was a silica MCVD tube (OD/ID 25/19 mm, Heraeus synthetic fused silica), fixed at both ends onto an MCVD lathe fitted with a rotary-seal gas supply. We note that this is a standard specialty fibre grade tube and much smaller and thinner than those used in conventional telecommunications fibre. The Heathway model MCVD system includes a state-of-the-art lathe and control system from Control Interface. The pyrometer (IMPAC IS 140 from LumaSense Technologies) has a specified uncertainty and repeatability better than 0.3% and 0.1% of reading in °C +1 °C, respectively. The experiments were carried out using thermally stabilised regenerated FBGs. The seed FBG ($R_{max} > 50$ dB) was directly written using an ArF laser ($\lambda = 193$ nm, $f_{pulse} = 7$ mJ/cm^2, $f_{cum} = 4.8$ J/cm^2) and a phase mask ($\Lambda = 1052$ nm, $L = 1$ cm) into a H_2-loaded ($P = 200$ bar, 24 h, $T = 80$ °C) high-NA germanosilicate optical fibre. Regeneration was undertaken using the method reported previously [21–23]. After regeneration, the grating was stabilised at 1100 °C for 45 min to allow for ultra high temperature performance [21–25].

Given the finite length of the grating, to reduce spatial chirping of the grating period, and therefore spectral broadening and amplitude decrease, when subjected to major temperature gradients near the reaction zone of the MCVD lathe, the FBG was sleeved with a short length of stainless steel tubing (OD/ID 3/1 mm, $L = 12$ mm). This helped to spread the heat uniformly over the grating length. To facilitate suspension of the grating inside the substrate tube, the fibre pigtail was inserted into ~1 m long stainless steel tubing and linked to the short length containing the FBG using a short silica tube. The grating was then carefully inserted into the substrate tube and fixed on the tailstock end of the lathe. The thermocouple was also packaged and mounted in the same way – Fig. 5(b) illustrates the burner and tube and a schematic of the setup. To maintain minimum noise from Fresnel reflected light originating from the end of the fibre, a short length of dummy-fibre was spliced onto the FBG-containing fibres with the cores offset to each other. This exercise was necessary because angled cleaves, the standard method to minimise Fresnel back reflections at fibre ends, were found to fuse to a rounded shape at high temperatures. The packaged FBG sensor was interrogated in reflection mode with a C band swept wavelength system based on an Erbium amplified spontaneous emission (ASE) source and a wavelength tunable filter [26]. The tunable filter was scanned at a frequency of 20 Hz while the reflection spectrum was monitored continuously with a detector. This system provided a continuous measurement of the temperature experienced by the FBGs as a function of time.

The whole system was calibrated using a standard *K*-type thermocouple positioned next to the FBG in the centre of the substrate tube to provide two separate references between the outside