Advances in optical fibers fabricated with granulated silica

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Abstract: The sol-gel based granulated silica preform fabrication method is presented as a versatile "rapid prototyping" platform for specialty optical fiber production, enabling arbitrary geometries, large flexibility of doping composition and concentration, and homogeneous dopant distributions.

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1. Introduction

Modern optical fiber fabrication technology enables the production of specialty optical fibers, e.g. with non-standard shapes, exotic materials, or high dopant concentrations, which are the driving force for advancements in many application areas, such as high power fiber lasers, nonlinear optics, and telecommunications. Several preform production techniques are available for the realization of these special properties, e.g. modified chemical vapor deposition (MCVD), stack-and-draw, or powder technology, amongst many others. The fiber designs obtainable with a particular technique are often limited by the achievable homogeneity of the dopant distribution in the preform, which impacts the maximum core size and doping concentrations, and additionally by a certain required geometrical symmetry arising from the preform production process [1, 2].

In this contribution we review the recent advances of specialty optical fiber production based on our granulated silica technology, where we merge the benefits of the granulate-based sol-gel method with the advantages of the powder-in-tube technique. As a result, our method overcomes the fabrication constraints of the conventional techniques and offers complete freedom in the production of fibers with any geometry, a high degree of flexibility in dopant composition and concentrations, and a high level of control over the refractive index contrast, while it does not pose any inhomogeneity limits to the core diameter. Hence, it is ideally suited to complement the more conventional techniques like MCVD for the versatile and cost-effective "rapid prototyping" of specialty optical fiber preforms from in-stock sol-gel-based granulated silica [3-6].

2. Preform Fabrication

Our approach, which is in ongoing development and summarized in Fig. 1, combines the sol-gel based production of homogeneously doped silica granulate with the powder-in-tube technique [7]. The sol-gel process allows us to reach high dopant concentrations (up to several at.%) and homogeneity down to the molecular level with considerable less effort than traditional glass production methods, and even in cases when several dopants at the precursor level are involved. The simplicity and flexibility of the process, which starts from liquid alkoxide precursers mixed in solution near room temperature, enables the precise control of the concentration of the co-dopants, which in turn

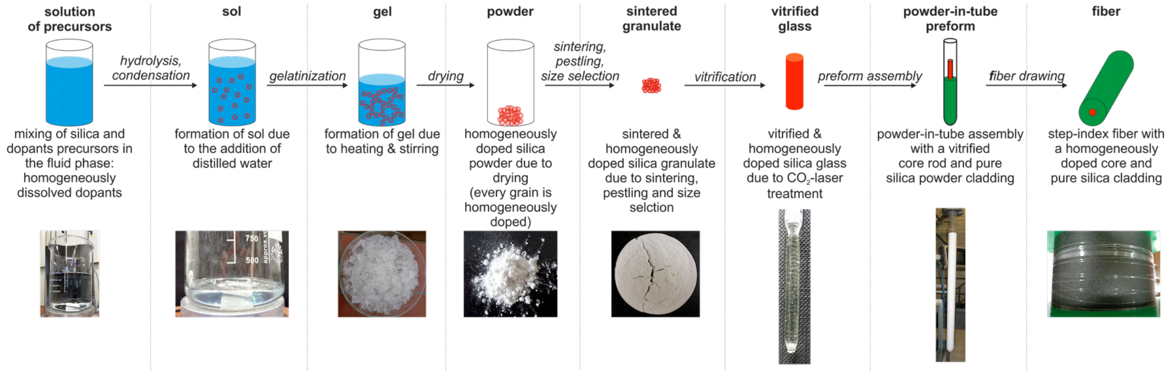

Fig. 1: Schematic overview of our preform fabrication method based on the sol-gel-based production of homogenously doped silica granulate combined with the powder-in-tube technique.

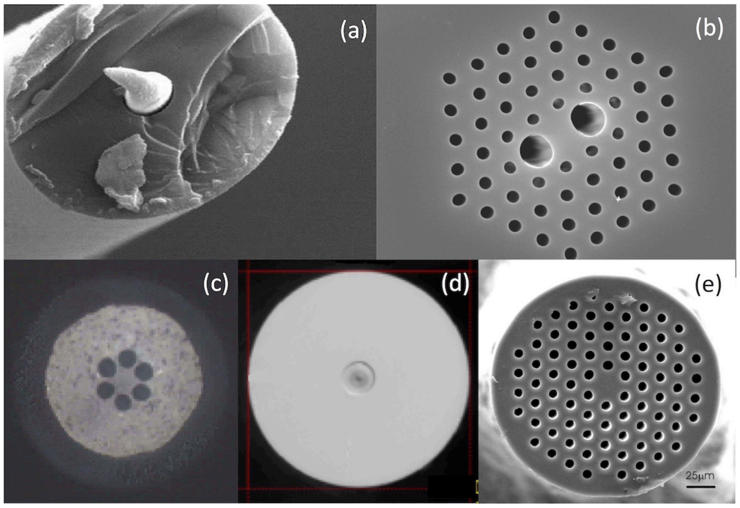

Fig. 2: Selected fiber geometries fabricated with the granulated silica method. (a) Fiber with metallic core. (b) Polarization-maintaining photonic crystal fiber. (c) Leakage-channel fiber. (d) Large-mode area (LMA) Yb^{3+}-doped step-index fiber. (e) LMA Yb^{3+}-doped photonic crystal fiber.

gives full control over the refractive index. The combination with the powder-in-tube technique then facilitates full flexibility in the desired geometry of the fiber and allows rapid production of fiber preforms from in-stock granulate.

The dried powder resulting from the sol-gel process is sintered, ground and sieved, yielding coarse granulated silica with a grain size of several 100 µm and the desired homogeneous doping distribution. While in principle this granulate could be used directly for the powder-in-tube preform assembly, we found that this leads to large scattering losses in the order of 1 dB/m due to microbubble formation and the adsorption of water and impurities. Significant advances in the reduction of background losses could be made by adding an intermediate vitrification step before fiber drawing, e.g. using CO_2 laser based small zone vitrification. In conjunction with other refinements of the process, we now achieve background loss levels in the order of 0.02 dB/m at 1550 nm [7].

3. Example Fibers

The granulated silica method allows the fabrication of specialty optical fibers with a large variety of geometrical designs and dopants, and a selection of examples are shown in Figs. 2 and 3. These include rare-earth doped fibers with large core diameters and high doping concentrations realized in step-index design or with photonic lattice cladding, which are required for the development of high power ultrashort pulse amplifiers where short fiber lengths and large mode areas are desirable to decrease the threshold for the onset of detrimental nonlinear effects. So far, homogeneously doped cores with diameters above 60 µm and doping concentration up to 0.3 at.% were successfully fabricated [7]. Current work aims to increase the doping concentration to several at.%, which is significantly higher than concentrations obtainable with alternative methods. We also investigate the possibility of exploiting the benefits of the sol-gel based granulated silica method for the production of active leakage-channel fibers (LCF), which are attractive candidates to further increase the mode field diameter of the amplifying fiber while simultaneously guarantee effectively single-mode guidance. Since our method allows the homogeneous doping not only of the core, but also of the surrounding cladding region, a monolithic LCF design becomes conceivable, in which the mechanical and thermal properties of core and cladding glasses are perfectly matched. This can simply be achieved by using the same chemical composition for core and cladding glasses and replacing the active rare-earth dopant used in the core by a different non-active rare-earth element in the cladding. In this way we aim to avoid modal instabilities at high power levels, which have been linked to thermal property mismatch between core and cladding materials.

Figure 3 shows multi-core and multi-dopant fiber designs highlighting the ease with which the freedom of dopant choice and composition can be combined with a non-standard geometry. Figure 3 (a) shows a multi-core structure with seven differently doped cores. Five different rare-earth ions have been chosen as dopants, i.e. Nd3+, Ho3+, Tm3+, Er3+, and Yb3+, which can all be pumped at a single wavelength around 800 nm. The cores can be pumped either individually or simultaneously, and each core emits its fluorescence spectrum independently and largely undisturbed in its respective active wavelength region between about 900 and 2100 nm.

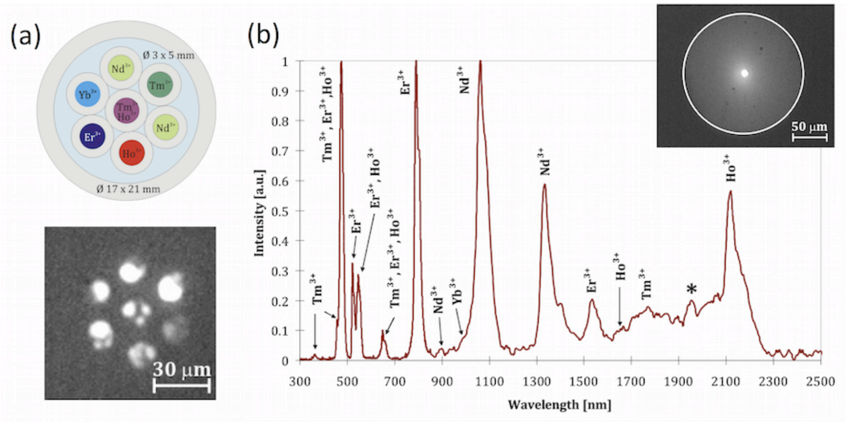

Fig. 3: Broadband emission from multi-dopant fibers containing Neodymium, Erbium, Ytterbium, Holium and Thulium doping. Both multi-core (a) and single-core (b) versions have been realized. A typical fluorescence spectrum of the single-core fiber is also shown in (b).

When all five dopants are combined in a single core (Fig. 3 (b)), cross-excitation between the dopants leads to an ultra-broadband emission spectrum in the range 365 – 2300 nm. The spectrum consists of narrow lines in the visible spectral region, and a continuous band spanning over more than one octave from 925 nm to about 2300 nm. The displayed results were obtained with fibers fabricated directly from dry granulated oxides [6], and consequently the recorded background losses were in the order of several dB/m, resulting in very low output powers in the µW regime. However, using the recent progress in our sol-gel based granulated silica approach we are currently working towards significantly improved broadband emitting fibers, which could be promising candidates for broadband ultrashort pulse amplification, spectroscopy, sensing applications, and for increasing the available amplifier bandwidth for wavelength-division multiplexed communication channels in next-generation telecom networks.

4. Conclusion & Outlook

The sol-gel based production of homogeneously doped silica granulate as base material for the powder-in-tube technique is a powerful fabrication technology for the cost-effective and versatile “rapid prototyping” of specialty optical fiber preforms. It results in highly homogeneous doping distributions, offers a large choice of possible dopant compositions and concentrations, and allows free-form optical fiber geometries. Advancements in the processing of granulates have resulted in drastic reduction of background losses, which are competitive for the fabrication of high quality active fibers with large core diameters and high doping concentrations. Further, the method allows the fabrication of novel multi-dopant, broadband amplifying fibers that have interesting potential applications in telecommunications, sensing, and ultrashort pulse amplification. Current research focuses on the further reduction of background losses, the fabrication of extended lengths of fibers without scattering centers, and the inclusion of novel functional co-dopants, such as graphene.

5. References

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