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Celebrating Optical Glass – the International Year of Glass (2022): feature issue introduction

JOHN BALLATO,[1] ULRICH FOTHERINGHAM,[2] MATHIEU HUBERT,[3] STEFAN NOLTE,[4,5] LAETICIA PETIT,[6] AND KATHLEEN A. RICHARDSON[7,*]

[1] *Department of Materials Science and Engineering, Clemson University, Clemson, SC 29634, USA*
[2] *Schott AG, Research & Development, Hattenbergstraße 10, 55122 Mainz, Germany*
[3] *Corning Incorporated, Science & Technology, Corning, New York, USA*
[4] *Friedrich Schiller University Jena, Institute of Applied Physics, Abbe Center of Photonics, Albert-Einstein-Straße 15, 07745 Jena, Germany*
[5] *Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Center of Excellence in Photonics, Albert-Einstein-Straße 7, 07745 Jena, Germany*
[6] *Photonics Laboratory, Tampere University, Tampere, Finland*
[7] *College of Optics and Photonics, CREOL, Department of Materials Science and Engineering University of Central Florida, Orlando FL, USA*
[*] *kcr@creol.ucf.edu*

Abstract: We introduce the *Optical Materials Express* feature issue that celebrates historic and recent advances in optical glass. In honor of the United Nations declaring 2022 to be the International Year of Glass (IYOG), this issue comprises a collection of twenty-seven manuscripts that highlight processing, characterization/metrology and applications where glass has changed our world.

1. Introduction

Glass is a ubiquitous material, and since its initial discovery for largely artistic purposes, it has come to be a core part of our lives. For the optics community, we cannot imagine a world without glass, as the ability to 'see' all within our universe, would not be possible. Because the momentum and innovation that results in such progress is the combined efforts of the Materials Science and the Optics communities, *Optical Materials Express* represents an ideal venue for this topic. Hence, this issue is dedicated to the many contributors cited in the papers here, that have forged the path that has enabled this material to shine in our world and beyond.

2. Feature issue summary

The fields touched by optical glass are numerous and varied and the science and engineering that has gone into the design, processing, characterization and manufacturing of specific optical glass and glass ceramic materials is multi-disciplinary in nature. The components and optical systems realized by the creation of new glasses in their diverse forms and geometries are far reaching and have impacted everyday life for much of our global community. This issue reviews the past and present in our field, outlining the future challenges in both optical science and engineering that inspire optical glass scientists and their collaborators across many fields. The contributions in this issue are in the form of selected reviews along with both invited and contributed papers. Critical to our celebration is the introduction in an opinion piece by Parker and Durán, as to how the International Year of Glass (IYOG) 2022 came to be [1], as well as a piece highlighting education and training of the global workforce needed to sustain our field going forward. In addition, we highlight multiple topic areas of interest to OMEX readers.

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2.1. Optical glasses

When it comes to optical glasses, fused silica stands apart thanks to the simplicity of its composition (SiO_2), its outstanding thermal properties and optical transparency (often considered as “the clearest glass in the world”), as well its manufacturing process based on flame hydrolysis instead of the more traditional glass melting techniques. In this IYOG issue, Moore and Smith review the history of fused silica as an optical material and describe its key role in applications such as space shuttle windows, optical fiber, deep UV lens elements or high-density integrated circuits [2].

The history of optical glasses and optical imaging cannot be dissociated from the name of Otto Schott, one of the most ingenious pioneers in the field. In their paper, Fotheringham, et. al., describe the intricate relationship between material development and optical design and the role O. Schott played in this endeavor [3]. Similarly, the history of SCHOTT’s contribution to laser glass is reviewed by Usher-Ditzian [4]. While many optical glasses are designed to be transparent and colorless, compositions and processes can be designed to exploit – on purpose - interactions between light and glass to create colored or patterned glasses with unique functionality. Borelli and Schroeder pay a tribute to this special category of glasses, called photosensitive glasses, and present an array of optical effects (photochromism, polarization, optical bleaching, etc. . .) and applications for these materials in diverse applications [5]. Photoluminescence is another key property of certain optical/photonics glasses, and the development of these materials is critical in various fields (including optoelectronics, biomedical sciences, or environmental engineering). S. Annurakshita et. al., demonstrate the hierarchical arrangement of persistent luminescent microparticles in photonic glasses using second-harmonic generation microscopy, unraveling the formation and distribution of distinct and highly localized persistent luminescent in these glasses [6].

2.2. Optical fibers

The modern conveniences we all enjoy and expect in an information age would not be possible if not for the marriage of glass and light in the form of hair-thin optical fibers. Despite their ubiquity and utility, there remain numerous challenges and needs where optical fibers can provide solutions to future problems. To this end, this special feature includes five articles that span a broad range of what is possible when novel glasses, fiber structures, and modern manufacturing methods are used to enhance access and performance. Three papers focus on enhancing the spectroscopic behavior of optical fibers, each in different ways. Kochanowicz, et al., studies the use of multiple rare-earth dopants in soft glass fibers [7] whereas Schröder, et al., consider sol-gel coatings to non-resonantly enhance luminescence in side-emitting fibers [8]. Blanc, et al., review nanoparticle-containing fibers as novel means to enhance light scattering as is useful for various sensor systems [9]. Of course, the future of manufacturing is an equally important consideration. Accordingly, Maniewski, et al., discuss advances in the rapid prototyping of silica fibers [10]. Finally, in a magnum opus, Ohishi [11] reviews the state of the art in supercontinuum generation and infrared imaging using soft glass fibers.

2.3. Crystals embedded in glass

Since the discovery of glass-ceramics by Stookey in 1954 [12], effort has been focused on the development of novel glass-ceramics possessing unique or enhanced properties. Challenges related to the control of the nucleation and growth of the crystals in the oxyfluoride glass matrix are discussed in the paper by Cruz et. al. [13]. Readers interested in perspectives for preparing other advanced materials within this field are encouraged to read this paper.

When the nucleation and growth process is well controlled, glass-ceramics can be obtained with promising properties, one of the examples presented in this special issue is Zerodur, an optical

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lithium aluminosilicate (LAS) glass-ceramic. Some insight on the diverse uses for this glass-ceramic is given by Mitra in [14]. Cao et. al., discuss the preparation of transparent potassium germanate glass-ceramics and their potential applications [15]. Due to the high-volume fraction of small (10 nm) Cr^{3+}-doped $ZnGa_2O_4$ (ZGO) crystals, this highly transparent glass-ceramic is reported to emit light in the 650-800 nm range in response to mechanical stimulation-termed mechanoluminescence (ML) [16] potentially enabling this glass-ceramic as promising for stress field imaging and for light delivery within biological tissue.

Crystalline phase(s) can also be deliberately precipitated both globally and with superb spatially specific control in glass after exposure to optical radiation followed by thermal treatment. Such glasses include photo-thermo-refractive (PTR) glass [17] as well as infrared glasses developed for gradient refractive index (GRIN) applications. Mechanisms of the photo-thermo-crystallization in silicate and spatially controlled precipitation in chalcogenide glasses are reviewed by Shirshnev et. al., in [18]. The use of these glasses as diffractive or refractive optical elements operating from near UV to long wavelength IR spectral region is also discussed in this paper.

2.4. Optical glass characterization methods

The suitability of optical materials for their purpose is determined by the precise attainment of both the desired dispersion relation and the desired transmission, including the absence of absorbing impurities. Both the history and the latest state-of-the-art of the corresponding refractory and spectroscopic measurement methods are reported by Engel in his paper [19]. Despite the remarkable progress made, there are still challenges in this area, which result from special optical tasks. Gradient refractive index profiling is one, for example, when the tiny dimensions of optical fibers are affected. In their paper, Ferraro et. al., describe their approach with X-ray-based μ-tomography [20]. Another example for a refractive index gradient with tiny dimensions is the interaction layer at the surface of an optical element, which can result from conventional polishing. In their paper, Gerhard and Köhler investigate this indirectly by analyzing the altered composition in the utmost tens of nanometers of the surface via X-ray photoelectron spectroscopy. They find this alteration to have an impact on the performance of polished optical elements [21].

2.5. Laser materials and processing methods

Apart from the unique properties of the different glasses, an important aspect for many applications is the ability to be further functionalized by other processing techniques. Such functionalization might be achieved by laser or other processing methods. In their article Piacentini et. al., review recent research on processing with femtosecond laser pulses, where the nonlinear interaction between the glass and the light pulses enables to inscribe 3D photonic integrated circuits as well as buried microchannels and more complex optical elements for applications e.g. in lab-on-a-chip devices, high harmonic generation and astrophotonics [22]. With the help of wavefront shaping, McArthur et. al., demonstrate how to overcome aberrations and to inscribe such localized modifications deep inside the material to realize e.g. extended volume Bragg gratings [23]. A different processing regime is addressed by Radhakrishnan et. al. They report on tailored localized densification of the glass matrix by focusing two spatially separated femtosecond laser pulses to induce shockwaves [24]. Further localized laser-induced modifications include so-called self-organized nanogratings and similar structures. In this respect, Lei et. al., provide a review of the recent progress in femtosecond laser anisotropic nanostructuring, highlighting applications as geometric phase optical elements, space variant polarization converters as well as multiplexed optical data storage [25]. Information storage is also one application addressed by Jiao et. al., who report on the precipitation of $CsPbBr_3$ quantum dots (QD) in silicate glass by picosecond laser pulses [26]. Further applications of these QD include light emitting devices as well as anti-counterfeiting. However, such localized heating and crystallization is not limited to laser

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processing. Musterman et. al., show the production of nanoscale single crystal architectures of Sb_2S_3 in Sb-S-I glasses by electron beam heating [27]. Localized glass functionalization is also demonstrated by Goillot et. al., by a thermo-electrical imprinting process, enabling the defined alignment of liquid crystals [28].

2.6. Education outlook

Critical to our celebration is a discussion of needs inferred in multiple locations throughout the issue, related to the skills necessary to realize the next generation of optical glasses and multi-functional glass-based materials which are on the horizon. A summary of the education and training challenges our community faces going forward is presented looking through a 'future-facing' lens. Ballato et. al., [29] review the historic manner in which optical glass science has been taught to date and the advanced learning strategies educators are developing to implement now. With innovation in methods of education on creating new optical materials, we can ensure the training of the global workforce needed to sustain future advances in our field, remains innovative as well.

Acknowledgments. In honor of the International Year of Glass 2022, we recognize the researchers that have contributed to this field. Clearly beyond the topics covered in this issue, we acknowledge the many who have contributed to our field of optical glass materials, the historic developments which pave the way to the exciting opportunities ahead where their future potential to our community, is yet to be realized. We extend our gratitude to all the authors and reviewers for their contributions. We also thank Dr. Stavroula Foteinopoulou for her support of this feature issue, and the Optica staff for their exceptional work throughout the review and production processes.

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