Infrared Fibers and Their Applications

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About the cover: Images are of polycrystalline KRS-5 fibers extruded at Hughes Research Laboratories in 1977. The polycrystalline grain structure and red color are characteristic of KRS-5 (TlBrI) fibers. The transparency of these fibers at wavelengths from 2 to more than 20 μm sparked worldwide interest in IR fiber optics, which led to the development of many other crystalline, glass, and hollow IR fiber optics.

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Preface

This book is an outgrowth of more than 25 years working in the field of infrared fiber optics. I was first introduced to the new and rather arcane area of IR fibers when I was working at Hughes Research Laboratories (HRL) in Malibu, CA. Back in 1977 Hughes had large research programs aimed at the development of highly transparent IR laser window materials, initially for CO_2 lasers operating at 10.6 μm, but later for other IR gas lasers operating between 3 and 12 μm. During this period of active laser window research at HRL and many other laboratories in the U.S., some excellent optical materials were fabricated with very low loss. Specifically, some of the best materials developed included the alkali halides (polycrystalline NaCl and KBr), the alkaline earth fluorides (CaF_2), two-six compounds (ZnSe and ZnS), and sapphire. At about the same time, the U.S. Army was interested in building a surveillance satellite that employed short, <25- cm-long IR transmissive fibers to relay information from the exterior of the satellite to an interior HgCdTe detector. At the time of this army program the requirements placed on the IR fibers were daunting: develop fibers capable of transmitting wavelengths from 2 to as long as 20 μm! There was no fiber in existence in the late 1970s that could come even close to this transmission range. To accomplish this goal, the research group at HRL decided to exploit the technology developed in the pursuit of low-loss IR window materials and somehow fabricate these materials into fiber optics. The first group of materials studied was the chalcogenide glasses, in particular the arsenic sulfide and selenide glasses. While these glasses had, in fact, been made into fiber some years earlier, they turned out to be unsuitable for the army application. Not only did they not transmit sufficiently far into the infrared, but they were also too brittle. Therefore, HRL researchers developed a new technique of hot extrusion to extrude polycrystalline KRS-5 (TlBrI) into fiber. The KRS-5 fibers did, in fact, transmit well beyond 20 μm, but they were ultimately abandoned as they exhibited a nasty aging problem, i.e., loss of transmission in time; they were also toxic.

At essentially the same time as the polycrystalline fibers were being developed at HRL, fluoride glass was invented and drawn into fiber at the University of Rennes by Lucas and Poulain, while Garmire and her group at University of Southern California were constructing simple and efficient hollow rectangular waveguides made from aluminum strips. The impetus for this spurt of IR fiber activity in the late 1970s and early 1980s was the universal desire to have a flexible and reliable fiber optic analogous to silica glass fibers for non-telecommunication applications such as the delivery of CO_2 laser power for laser surgery and IR fiber sensors. But the holy grail was the possibility of reducing the loss in solid-core IR fibers to the theoretical limit, which for many IR materials was as much as 10^3 times lower than the intrinsic loss of 0.2 dB/km for silica fibers. The idea of having a fiber with losses in the range of 10^{-3} dB/km was very enticing. For example, one could envision thousand-kilometer long, repeaterless fiber links for use in undersea communication systems for connecting submarines to land-based stations. Unfortunately, while the theoretical foundations for the predicted intrinsic losses for many IR crystalline and glassy materials are still sound, no IR fiber has ever been produced to date that has a loss less than silica fiber at 1.55 μm. In fact, the real advantage today for IR fiber optics is their application in short-haul applications, which generally require fibers less than 10 m in length.

Over the many years of my involvement with IR fiber optics, I have found that most people are interested in these special fibers because of their obvious need for the transmission of IR light greater than about 2 μm. Their primary concern is determining which IR fiber is best for a particular application. What I have tried to do in this book is to keep this concern paramount in the discussions of the various types of IR fibers. Simply put, this is not a book that will, for example, exhaustively detail the bulk properties of every fluoride glass made to date or any other IR optical material; rather, the emphasis is on the salient properties of the IR fiber materials that are today the best in their class. To this end the reader will find that the discussions surrounding the properties of the materials are always aimed at a better understanding of the IR fibers made from these materials rather than just a listing of all the bulk material properties. I would expect that the reader will first turn to the chapters on the individual IR fibers, Chapters 4 through 7, to find the most important characteristics of a particular IR fiber, and then refer to Chapters 8 through 11 for details on the many applications of these fibers. In this way this book should serve as a ready reference guide for those wishing to learn about the candidate fibers for their particular application.

This book is intended to be a complete reference for the field of IR fiber optics. I have included a historical recounting of the development of IR fiber optics as well as a summary of the best fibers in each of the three categories of IR fibers: crystalline, glass, and hollow waveguides. The theoretical aspects of solid-core fibers and hollow waveguides are covered in Chapters 2 and 3, respectively. Because the optical principles of solid and hollow-core waveguides are somewhat different, I chose to separate the theory into these separate chapters. The next four chapters detail the four main types of IR fibers available today: fluoride glass, chalcogenide glass, crystalline, and hollow waveguides. Each of these chapters is designed to familiarize the reader not only with the properties of each fiber but also the limitations and shortcomings of each fiber type. In fact, the optical and mechanical properties of all IR fibers often fall far short of those for conventional silica fiber. However, this does not mean that there is not a place for an IR fiber; rather, it suggests that the design considerations of any system employing IR fibers should take into account the lower transparency and reduced strength of these special fibers.

The final four chapters cover a wide range of IR fiber applications, including fiber optic chemical and temperature sensors, laser power delivery, fiber amplifiers, and new and emerging applications. The last chapter includes the most recent IR fiber structures based on hollow 1D, photonic bandgap fibers. Photonic bandgap fibers are emerging as a new type of fiber that has the promise of one day exhibiting ultralow loss across a broad IR wavelength range.

Throughout the book I have tried to keep the units consistent for all of the IR fiber types. In particular, I have attempted to keep the units for loss, usually dB/m, and wavelength, usually microns, the same for all of the optical data. I have referenced theoretical sections and equations in the chapters on the individual fibers and their applications. This is an advantage over an edited text where cross referencing between chapters is difficult. Finally, the references at the end of each chapter include the latest developments and, in particular, the recent applications for these fibers. In fact, what is often of most interest is the myriad of new applications for these fibers. It is my hope that readers of this book will find suitable information and encouragement to implement these special fibers in new and novel applications. Many of the IR fibers discussed in the book are now commercially available so that many of the earlier drawbacks to their use have been overcome by better packaging and better technical assistance from the manufacturer. My best recommendation to all those who have asked me about the best IR fiber for a particular application is to first select the best IR fiber candidates based on their optical and mechanical properties and then carefully test and evaluate the candidate fibers, keeping in mind that IR fibers are not equal to silica fibers.

There are many people with whom I have had contact over my years working in this field. The IR fiber community is rather small in contrast to the enormous efforts in manpower and dollars poured into the development of silica fiber optics. Many of my colleagues have been in the field for as long as I have and they are now also enjoying renewed interest and growth in this field. I want to thank all of my IR fiber colleagues who helped me better understand IR optical materials, fiber fabrication, and applications. I would especially like to thank the following: Slava Artjushenko, Larry DeShazer, Martin Drexhage, Jerry Fitzgibbon, A. Ray Hilton, Sr., Abraham Katzir, Jacques Lucas, Mitsunobu Miyagi, Yuji Matsuura, Jas Sanghera, George Sigel, and Danh Tran. I am forever indebted to the many graduate and undergraduate students who have worked tirelessly with me to develop an ever better IR fiber. Thanks to the staff at SPIE Press, including my editor Sharon Streams and Rick Hermann. The writing of this book has been a labor of love supported throughout by my loving wife Jeanne and daughter Julie. Finally, I found time away from my favorite subject of IR fibers to engage in ballroom dancing—a nonoptical form of relaxation and fun.

James A. Harrington