Laser in der Materialbearbeitung
Forschungsberichte des IFSW

M. Vogel
Specialty Fibers for High Brightness
Laser Beam Delivery

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Herausgegeben von
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Das Strahlwerkzeug Laser gewinnt zunehmende Bedeutung für die industrielle Fertigung. Einhergehend mit seiner Akzeptanz und Verbreitung wachsen die Anforderungen bezüglich Effizienz und Qualität an die Geräte selbst wie auch an die Bearbeitungsprozesse. Gleichzeitig werden immer neue Anwendungsfelder erschlossen. In diesem Zusammenhang auftretende wissenschaftliche und technische Problemstellungen können nur in partnerschaftlicher Zusammenarbeit zwischen Industrie und Forschungsinstituten bewältigt werden.

Das 1986 gegründete Institut für Strahlwerkzeuge der Universität Stuttgart (IFSW) beschäftigt sich unter verschiedenen Aspekten und in vielfältiger Form mit dem Laser als einem Werkzeug. Wesentliche Schwerpunkte bilden die Weiterentwicklung von Strahlquellen, optischen Elementen zur Strahlführung und Strahlformung, Komponenten zur Prozessdurchführung und die Optimierung der Bearbeitungsverfahren. Die Arbeiten umfassen den Bereich von physikalischen Grundlagen über anwendungsorientierte Aufgabenstellungen bis hin zu praxisnaher Auftragsforschung.

Die Buchreihe „Laser in der Materialbearbeitung – Forschungsberichte des IFSW“ soll einen in der Industrie wie in Forschungsinstituten tätigen Interessentenkreis über abgeschlossene Forschungsarbeiten, Themenschwerpunkte und Dissertationen informieren. Studenten soll die Möglichkeit der Wissensvertiefung gegeben werden.

Speciality Fibers for High Brightness Laser Beam Delivery

von Dr.-Ing. Moritz Vogel
Universität Stuttgart

Herbert Utz Verlag · Wissenschaft
München

Als Dissertation genehmigt
von der Fakultät für Konstruktions-, Produktions- und Fahrzeugtechnik
der Universität Stuttgart

Hauptberichter: Prof. Dr. phil. nat. habil. Thomas Graf
Mitberichter: Prof. Dr. rer. nat. Alois Herkommer

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation
in der Deutschen Nationalbibliografie; detaillierte bibliografische
Daten sind im Internet über http://dnb.ddb.de abrufbar.

Zugleich: Dissertation, Stuttgart, Univ., 2014

D 93

ISBN 978-3-8316-4382-0

Printed in Germany

Herbert Utz Verlag GmbH, München
Tel.: 089-277791-00 · www.utzverlag.de

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Extended Abstract

The tremendous impact of solid-state lasers on material processing and the rapid increase of the beam quality as well as the output power are driving forces in the development of new optical fibers and high-power suitable beam delivery systems. The power scalability of such systems over significant distances is limited by the onset of several nonlinear effects inside the waveguide material, mainly stimulated Brillouin scattering and stimulated Raman scattering.

Within this work, finite element calculations are used to simulate and optimize different fiber structures. Moreover, the production of some of the optimized fibers is considered and experiments to measure their attenuation, mode-structure and bending losses are introduced.

One approach to increase the mode field area and therefore the power handling capabilities is to assemble several coherently coupled cores in a common cladding to distribute the power and to increase the power handling capabilities. This approach is known as multicore fiber (MCF). A single-mode MCF consisting of 19 coupled cores with a large mode field area of $A_{\text{eff}} = 465\,\mu\text{m}^2$ was investigated. The fiber has a close to Gaussian field distribution and can be used as, and be spliced to, a (single mode) step index fiber. The bending sensitivity of the 19-core fiber is close to a manageable limit so that the fiber has to be handled carefully to avoid sharp bends. However, by avoiding bending radii smaller than 0.2 m and splicing the fiber to a fiber laser, a high-power test with 356 W (limited by the available laser source) was demonstrated.

Bragg-type photonic bandgap fibers offer the possibilities to reduce the bending sensitivity of large mode area fibers. Therefore, Bragg fibers (BF) were investigated as well and a method of optimizing their multilayer cladding was developed. Based on an optimized structure several fibers were produced and characterized in the laboratory. The optimized BFs were virtually free of bending losses and they showed

a much lower bend-induced mode field deformation when compared to step index fibers.

Another type of fiber which uses loss management to achieve and maintain a high beam quality, the leakage channel fiber (LCF), was also examined. At first, a simple LCF with 5 holes was investigated. The measurements revealed an effective mode area of $A_{\text{eff}} = 383\,\mu\text{m}^2$ and a beam propagation factor of $M_x^2 = M_y^2 = 1.1$. Then the influence of additional microstructured layers was examined. It was found that if the design is limited by high bending losses, increasing the number of layers is not sufficient to substantially reduce these losses but the differential losses between the fundamental mode and higher-order modes can be increased. Furthermore, the bending sensitivity could be reduced by changing the hole sizes from smaller holes in the inner microstructured layer to larger holes in a second layer to further optimize the fiber.

Additionally, the use of cladding resonances in LCFs is considered. By carefully designing the fiber diameter, core-guided higher-order modes can be resonantly coupled to cladding modes substantially improving the differential losses. The final design with a fundamental mode area of $708\,\mu\text{m}^2$ can be used as a standard single-mode fiber, efficiently guiding diffraction-limited high-power beams.

Larger mode field areas can be achieved if more modes are allowed to propagate with low losses. A LCF for the use with present high-power fiber lasers and amplifiers which usually show a minor LP_{11} mode content was designed. The fiber guides LP_{01} and LP_{11} modes and exhibits a fundamental mode area of $A_{\text{eff}} = 1187\,\mu\text{m}^2$.

Besides the comprehensive studies of (asymptotically) SM fibers, the possibility to transport a fundamental mode beam in multimode fibers was also investigated. Based on the assumption that a large difference of the effective refractive index Δn_{eff} (e.g., $\geq 10^{-4}$) prevents mode coupling, several step index fibers and a 7-core multicore fiber were tested. In particular, a fiber with a core diameter of $30\,\mu\text{m}$ and an NA of 0.06 was intensively studied. When a Gaussian beam is carefully injected into this fiber using suitable coupling optics, a high beam quality can be maintained within the fiber. A beam propagation factor of $M^2 \approx 1.12$ was measured after $10\,\text{m}$ of fiber even when the fiber was strongly bent or moved. Cutback measurements showed that the beam propagation factor does not change noticeably with the fiber length. The NA of the fiber is high enough to prevent bending losses for bends with $R > 0.1\,\text{m}$. The bend-induced mode field reduction and deformation was measured using a special experimental setup and compared to simulation results. A high power test resulted in a M^2 of 1.35 after a 100 m long fiber measured at a output power of 800 W.

Finally, in accordance with the fundamental mode transport in multimode fibers requirements for the transport of radially and azimuthally polarized modes are proposed. Based on this conditions three different fiber concepts for maintaining radially and azimuthally polarized modes are suggested. The results of simulations demonstrate the potential of these fibers for the delivery of such special modes. Parametric studies are used to maximize the mode field areas of the different fiber concepts. As a result, specialty fibers with higher mode field areas as published so far are proposed. For instance, a fiber with a ring-shaped core around a central air hole maintaining the TE_{01} mode with a mode field area of 280 µm^2 at 1 µm wavelength.

Chapter 1

Introduction

1.1 Motivation

In 1960 when T. H. Maiman demonstrated the first laser [1] no one could have foreseen the versatile fields of applications lasers cover today. Maiman himself claimed: "A laser is a solution seeking a problem.", (e.g., interview with New York Times 1964 [2]). However, soon after he realized the first laser in the visible wavelength range scientists intensified the work on a new concept of communication system termed "optical communication" which could transport a tremendous amount of information. But atmospheric influences would render free space optical communication useless and a suitable beam guiding system was missing. Evacuated straight or highly reflecting tubes would be bulky and expensive and losses of optical waveguides at that time such as multimode fiber bundles were much too high.

In 1966 K. C. Kao and G. A. Hockham suggested the use of glass fibers with a small core and only a very small refractive index difference between core and cladding (of about 1%). Such a fiber works as a single-mode waveguide without the problem of multimode dispersion [3]. Furthermore, they compared the absorption, scattering and other losses of different materials including crystals, inorganic glasses, and organic polymers. They identified glasses as the most promising materials, estimated a Rayleigh scattering loss on the order of a few decibels per kilometer at 1 µm wavelength, and stated that with the reduction of impurities the absorption can be further decreased. The first measurements were performed with fiber bundles and showed losses of several thousand dB/km. In the late 60s commercially available rods and tubes were used to draw multimode fibers with a transmission

loss of 140 dB/m and even 40 dB/m from preforms produced from a double layered melt at the University of Southampton (GB) [4].
In 1970 Kapron *et al.* reported on a single-mode fiber with a transmission loss of 20 dB/km produced at Corning Glass Works (USA) [5]. Kapron and his co-workers added a suitable oxide dopant to adjust the refractive index of the glass. Instead of using different glasses with similar melting temperatures to form core and cladding of the fiber, both were based on silica. This work triggered further research in laboratories worldwide. At that time the water content of the preform glass was the main cause for transmission losses in optical fibers especially in the infrared. Later the researchers at the Bell Telephone Laboratories developed the "modified chemical vapor deposition" (MCVD) process which reduced the water content in the glass and therefore significantly reduced the losses [6]. With further variations of this technique and the development of suitable polymer coatings to prevent fiber fractures and to protect the fiber from water and dust, a robust, flexible, and low loss beam guiding system was achieved. The development of such fibers together with the invention of the erbium amplifier in 1987 [7] led to the breakthrough of optical communications which has revolutionized the way of communication.
At the same time various laser systems at different wavelength were developed, out of which only a few made their way to industrial applications. The first high-power laser system was the CO_2 gas laser [8] which has been the dominating tool in the field of high-power material processing for many decades and is still widely-used for cutting and welding applications.
With the appearance of diode lasers as highly efficient pump sources for solid-state lasers, the latter became more powerful and their running costs were reduced. Together with new laser designs for improved heat management such as thin-disc [9] and fiber [10] lasers, the output power as well as the beam quality of solid-state lasers has increased tremendously over the past years [11, 12].
However, the successful commercialization of high-power solid-state lasers is partly attributed to the fact that they usually operate at a wavelength of about 1 µm which enables efficient and flexible beam transport with silica optical fibers. The beam transport of CO_2-lasers at about 10 µm instead is realized by the free space beam and "flying optics" which is much more expensive and has the drawback of focal shifts at the workpiece.
On the other hand, the tremendous impact of solid-state lasers on material pro-

cessing and the rapid increase of beam quality and output power are driving forces in the development of high-power capable beam delivery systems. But the power scalability of such systems over significant distances is limited by the onset of several nonlinear effects inside the waveguide material [13], mainly stimulated Brillouin scattering and stimulated Raman scattering. Since the threshold of most nonlinear effects is proportional to the intensity, increasing the effective mode area is the key to increase the power handling capabilities. Starting from a standard single-mode fiber used for optical communication systems with an effective mode area of about $30\,\mu m^2$, the core size must be increased significantly to meet this goal.
To keep the waveguide single-mode, the numerical aperture (NA) of the fiber has to be decreased at the same time. Besides the difficulties of producing low NA fibers, a very low NA results in an excessive bending sensitivity which does not allow the use of such fibers for flexible beam delivery applications with reasonable bending radii. Similar problems are faced by the task of a further power scaling of fiber lasers and amplifiers. In order to overcome these problems, several specialty fiber concepts are investigated with the help of simulations and experiments within this work.
Besides the power and the beam quality of laser sources, other properties of laser beams have recently attracted a lot of attention due to applications in material processing. For example, special field distributions and polarization states such as radially and azimuthally polarized ring-shaped modes may improve the quality and the speed of sheet metal cutting or drilling [14, 15]. Therefore, the conditions for fiber-based beam delivery of such modes are also studied within this work.
The topics and structure of this work are explained in the following paragraph.

1.2 Structure of this Work

The fundamentals of fiber optics are briefly reviewed in chapter 2. First, step index fibers are introduced and analyzed by means of geometrical optics. Then, wave optics is used to obtain the wave equation and the mode structure of optical fibers. The discussion includes the most important nonlinear effects such as stimulated Raman and Brillouin scattering. General fiber properties such as attenuation and bending losses are described as well as the conditions for mode mixing. The quality of the transmitted laser beam which is related to the mode mixing is also discussed. Chapter 2 concludes with an overview of different types of specialty fiber concepts, for instance, multicore fibers, photonic bandgap fibers, and leakage channel fibers. Chapter 3 focuses on the methods used for the simulation of these fibers. Finite element calculations with COMSOL Multiphysics are discussed and it is shown how the eigenmodes of straight and bent fibers are calculated and how losses are computed by means of perfectly matched layers.

Chapter 4 begins with a description of the fiber handling and then explains all experiments used for the characterizations of the fibers. Especially, the procedures for obtaining the overall fiber attenuation and for examining the influence of fiber bends on light traveling inside the fiber are described as well as measuring the beam propagation factor to estimate the beam quality.

The results of the theoretical and experimental investigations are compared and discussed simultaneously because the simulations and experiments have been carried out in parallel and inspired each other. Chapter 5 is subdivided according to the different kinds of specialty fibers described in chapter 2. Furthermore, the use of large core multimode fibers for the transport of fundamental mode beams is investigated in chapter 6 and the results of a high-power test with more than 800 W are shown. An outlook concerning the beam delivery of radially and azimuthally polarized beams is given in chapter 7 and some preliminary considerations, experiments, and simulations are presented. Finally, the most important results are summarized in chapter 8.

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