Optics Communications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Multicore chalcogenide photonic crystal fibers for large mode area and mode shaping☆

Changshen Yi [a,*], Peiqing Zhang [a,b], Shixun Dai [a], Xunsi Wang [a], Yehao Wu [a], Tiefeng Xu [a], Qiuhua Nie [a]

[a] *Infrared Materials and Devices Laboratory, Ningbo University, Ningbo, Zhejiang 315211, China*
[b] *State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yatsen Unversity, Guangzhou, Guangdong 510275, China*

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form
24 August 2013
Accepted 26 August 2013

Keywords:
Multicore photonic crystal fiber
Phase locking
Mode shaping
Chalcogenide glasses

ABSTRACT

Phase locking and mode shaping in multicore $Ge_{20}Sb_{15}S_{65}$ chalcogenide photonic crystal fibers are proposed and demonstrated. By manipulating the geometrical structure of the fibers, a large mode area of 1962 μm^2 resulting from in-phase supermodes and equal amplitudes was obtained, which can significantly reduce the nonlinear damage in chalcogenide fibers in the infrared spectrum. With the coherent beam combining technology of multicore photonic crystal fibers, the far-field combining beam exhibits high brightness and high beam quality. Calculations show that with good phase locking and mode shaping, a seven-core photonic crystal fiber can achieve 49 times enhanced intensity compared with single-core fibers.

1. Introduction

Photonic crystal fibers (PCFs) have attracted considerable attention because of their interesting and unique optical properties [1]. Particularly interesting are multicore photonic crystal fibers (MCPCFs) that can be used in a broad range of applications, such as optical switches, vector bend sensors, power splitters [2], and phase-locked high-power lasers and amplifiers. MCPCF lasers and amplifiers offer an attractive strategy for upscaling the power of fiber-based sources [3–5]. Such fibers provide larger mode areas, which can reduce thermo-optical damage and stress-induced beam distortion in high-power fiber lasers and amplifiers [6–12]. However, high beam quality in a multicore-fiber can be achieved only when individual core outputs are phase locked [8,13,14]. A great amount of research has been aimed at making multicore fibers operate in a particular in-phase supermode. For example, the use of an external Talbot cavity[8,13], self-organization by optimizing pump intensity[13], or an all-fiber approach by adding passive single-mode fiber were investigated [8,15,16]. MCPCFs have a more flexible structural design that facilitates phase locking and mode shaping compared with conventional fibers. Mafi et al. studied a nearly closely packed multicore structure with a very strong evanescent coupling constant [13]. They demonstrated that the selection of in-phase supermode could be "self-organized" by manipulating the MCPCF geometrical structures, which were much more compact than in previous methods. Another interesting feature of MCPCFs is the option to control and modify the shape of their modes by varying the structure of air holes around the guiding cores [17,18].

In this study, a closed-packed seven-core PCF based on the environmental non-arsenic chalcogenide glass of $Ge_{20}Sb_{15}S_{65}$ was designed. The $Ge_{20}Sb_{15}S_{65}$ glass was fabricated by a melt quenching method. Spectral measurements show that this glass exhibits several interesting optical properties, including a wide wavelength transparency window (from approximately 1 μm to above 12 μm), a high refractive index (>2), and a large nonlinear coefficient n_2 (100–1000 times larger than that of silica glass). These chalcogenide glass-based optical fibers are attractive as a transporting medium for high-power infrared (IR) lasers such as CO_2 lasers [19–27]. Furthermore, chalcogenide-based glass offers the possibility of introducing relatively high concentrations of rare-earth doping for amplification and lasing applications. However, high nonlinearity, which is strongly desired in optical demultiplexing, Raman amplification, and broadband spectrum generation, limits its application for high-power laser transmission and high-power fiber amplification. Large mode area PCFs can effectively resolve this problem. In this work, a large mode area multicore chalcogenide PCF was designed, the mode and phase properties of which can both be tailored. An advanced finite-difference beam propagation technique is employed to investigate the mode properties of

---

☆This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-No Derivative Works License, which permits non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

[*] Corresponding author. Tel.: +86 18857496637.

E-mail addresses: yichangshen@126.com (C. Yi), zhangpeiqing@nbu.edu.cn (P. Zhang), daishixun@nbu.edu.cn (S. Dai).

0030-4018/$ - see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.08.080

Please cite this article as: C. Yi, et al., Optics Communications (2013), http://dx.doi.org/10.1016/j.optcom.2013.08.080

the designed PCF and to provide feedback to optimize the structural parameters. Accordingly, with well-designed parameters, phase locking and custom-shaped modes in the MCPCFs were achieved. The mode area and the coherent combining beam intensity of the designed MCPCF are significantly better compared with single-core fibers.

2. Theoretical analysis of modes in the seven-core PCF

According to the coupled mode theory, the supermode in multicore fibers can be symmetric, mixed-symmetric, or sometimes totally antisymmetric. Assuming that a core couples onlyto its nearest neighbors, the complex field of a core E_m, which is the sum of the electric field in the core and the electric field coupled from the nearest neighbors, can be expressed by the following equation [28]:

$$\frac{dE_m}{dz} = -i\beta_m A_m(z)e^{-i\beta_m z} + \sum_n k_{m,n} A_n(z) e^{-i\beta_n z} \tag{1}$$

where $A_m(z)$ is the amplitude of the field in the mth core, n represents the number of the nearest neighbor cores, and k and β are the coupling coefficient and propagation constants, respectively. k can be calculated as follows [29]:

$$k_{m,n} = \frac{k_0^2}{2}\int \left[n^2(x,y) - n_m^2(x,y)\right]\varepsilon_n(x,y)\varepsilon_m(x,y)dx\,dy \tag{2}$$

where $\varepsilon_m(x,y)$ [$\varepsilon_n(x,y)$]is the normalized electric field distribution when only the mth (nth) core is present, $k_0 = 2\pi/\lambda$ is the wave vector in the free space and λ is the free space wavelength, and $n(x,y)$ is the refractive index distribution of the whole PCF, whereas $n_m(x,y)$ is the refractive index distribution when only mth core is present. The complex amplitude distribution across the whole multicore fiber is then given by

$$\vec{E}^{\,v}(x,y,z) = \sum_m A_m(z)E_m(x,y)\exp(i\beta_m z) \tag{3}$$

Q4 where v is the mode number representing the v-th supermode. Thus, the complex amplitude distribution for N different supermodes can be calculated by solving the eigenvalue equations.

Fig. 1 shows a typical seven-core PCF. Solving the eigenvalue equations yields seven supermodes corresponding to seven eigenvectors: [0 −1 1 −1 1 −1 1], [0 −1 0 1 −1 0 1], [0 −1 1 0 −1 1 0], [0 1 0 −1 −1 0 1], [0 −1 −1 0 1 1 0], [$\sqrt{7}$ −1 1 1 1 1 1 1], and [−$\sqrt{7}$ −1 1 1 1 1 1 1]. The eigenvectors [$\sqrt{7}$ −1 1 1 1 1 1 1] and [−$\sqrt{7}$ −1 1 1 1 1 1 1] correspond to symmetric and antisymmetric supermodes, that is, in-phase supermodes and out-of-phase supermodes, respectively. The others are all mixed-symmetry modes. As required by coherent beam combining technology, every combining beam should have the same phase so that the output beam can achieve high power and optimum beam quality. The in-phase supermode, where all cores have the same phase, is the most desired operation mode in this MCPCF. The purpose of this work is to obtain an MCPCF with in-phase supermode, which also features a large mode area and custom-shaped modes.

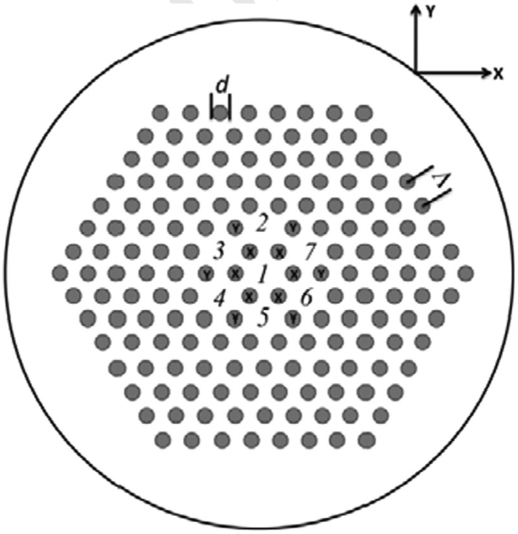

Fig. 1. The designed seven-core PCF. The cores are marked for illustration purposes only. The rectangular coordinate in the top right corner of picture is also for illustration purposes.

3. Phase locking and mode shaping in chalcogenide MCPCFs

One feasible approach to remarkably scale the total output power of coherent beam combination is mode shaping, which is realized by a special multicore fiber design for obtaining a flat in-phase supermode that consists of roughly equal field amplitudes in all cores by fiber engineering. Fig. 1 shows a designed PCF with seven cores. The refractive index of the matrix material of $Ge_{20}Sb_{15}S_{65}$ is $n = 2.2716$ at the wavelength $\lambda = 3$ μm (measured by the method of least deflection angle). The air holes are located at a triangular lattice with a pitch $\Lambda = 10$ μm and $d = 4.5$ μm. The mode properties of the MCPCF are obtained by employing the perturbation theory of coupled modes. The advanced finite-difference beam propagation method was used to find the eigenvectors of the modes in the designed fiber. This method has been proven ideal for the design and modeling of photonic devices, and it brings important capability to the photonics area [30]. For the designed fiber above, eigenvectors [$\sqrt{7}$ −1 1 1 1 1 1 1] and [−$\sqrt{7}$ −1 1 1 1 1 1 1] were obtained, corresponding to symmetric mode (in-phase mode) and antisymmetric mode (or antiphase mode), respectively. Although the in-phase mode and antiphase mode are existent and are bound together in the fiber, their propagation behavior will become significantly different as they exit the fibers. Therefore, the antiphase supermode can be easily removed by using an external Talbot cavity or a passive single-mode fiber [31]. As required by coherent combining, only in-phase modes are discussed in this work. Fig. 2(a) and (b) shows the obtained in-phase mode. The field in the central core has the same phase as that of the six neighbors, which is crucial for the coherent beam combining. The mode area of the in-phase supermode in this fiber is calculated as 1133 μm^2, which is much larger than that in traditional single-core fibers. However, the mode intensity in Fig. 2 exhibits a bell-shaped profile, which is still not ideal for coherent beam combining and high beam quality.

Studies have shown that the mode coupling strength between the cores will greatly affect the mode shape. Thus, to achieve ideal mode shaping, the structural parameters of the fiber still need to be optimized [17]. For this purpose, the mode properties of the designed fiber were analyzed while adjusting the diameter of air holes marked with the characters “X” or “Y”. As shown in Fig. 3, the intensity difference between the central core and the ring cores varies greatly as the diameters of air holes marked with “X” or “Y” are changed independently. The intensity difference roughly approaches zero when the diameters of the air holes marked with “X” or “Y” are approximately 4.789 and 3.535 μm, respectively. However, the required high precision of the air hole size increases the difficulty in fabricating the multicore fiber. As shown in Fig. 3, the intensity difference can be reduced by increasing the diameter of the “X” air holes or by reducing the diameter of the “Y” air holes. Reducing the diameter of the “X” air holes while simultaneously increasing the diameter of the “Y” air holes would make a good balance of coupling between the guiding cores and lead to a flat-shaped in-phase

Please cite this article as: C. Yi, et al., Optics Communications (2013), http://dx.doi.org/10.1016/j.optcom.2013.08.080