Optics and Laser Technology 109 (2019) 157–167

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Optimum splicing of high-index core microstructured optical fibers and traditional single-mode fibers using improved field model

Dinesh Kumar Sharma[a,*], Anurag Sharma[b], Saurabh Mani Tripathi[c]

[a] *Department of Applied Sciences, Ajay Kumar Garg Engineering College, Adhyatmik Nagar, Ghaziabad 201009, India*
[b] *Department of Physics, Indian Institute of Technology Delhi, New Delhi 110016, India*
[c] *Department of Physics and Center for Lasers & Photonics, Indian Institute of Technology Kanpur, Kanpur 208016, India*

HIGHLIGHTS

- Improved field model developed recently is used for high-index core triangular MOFs.
- Fundamental propagation characteristics of MOF as a mode-field expander are investigated.
- Mode-field diameters for Large-mode area MOFs at the degree of collapse ratio of 0% are determined.
- Splice losses between solid-core large-mode area MOFs and standard single-mode fiber (SMF) is evaluated.
- Controlled all air-holes collapse method is used for low-loss splicing between MOFs and traditional SMF.

ARTICLE INFO

Keywords:
Microstructured optical fibers
Splice losses
Controlled air-hole collapse method
Mode-field diameter
Single-mode fibers
Variational principle

ABSTRACT

Traditional fusion splicing technologies are not usable for the high-index core triangular lattice microstructured optical fibres (MOFs), as the characteristic air-holes pattern often collapse during splicing, significantly increasing splice losses due to distortion of the waveguiding structure. The low-loss splicing of MOF and the traditional single-mode fibre (SMF) can be achieved by enlarging the mode-field diameter (MFD) of MOF, facilitating to an optimum mode-field match at the splicing interface. Using our recently developed improved field model Sharma and Sharma (2016), we aim to investigate the modal characteristics of high-index core MOF as a mode-field expander, and low-loss splicing between an MOF and the standard step-index single-mode fiber by using controlled all air-hole collapse method. For comparison, experimental and the numerical simulation results have been included, as available in the literature. Relative errors are also given.

1. Introduction

Microstructured optical fibers (MOFs), referred to as holey fibers or photonic crystal fibers [2–7], with all-in-fiber configurations such as optical switches, high-power fiber lasers, supercontinuum light sources, and the gas sensors are attractive for their compact size, light weight, low cost, compatibility and the easy integration with optical fiber communication systems for network applications [2,8–11]. MOF with very different cross-sectional structure from traditional single-mode fiber (SMF), consisting of large number of regular microscopic air-holes in the transverse plane have gained much attention as they can be designed to yield desired optical properties such as tailorable dispersion control, endless single-mode guidance, high birefringence, extremely high or low nonlinearity [2–10]. MOFs typically have two kinds of cross-section: one is an air-silica microstructured cladding surrounding a solid-silica core, and the other is an air-silica microstructured cladding surrounding a hollow-core (or air-core). The light guiding mechanism of the former is provided by means of the total internal reflection, while the latter is based on the photonic bandgap effect [3–7]. High-index core (or the solid-core) MOFs have evolved as an attractive alternative to traditional optical fibers due to their unique and adjustable transmission properties; moreover, they have vastly extended the possibilities for fluid/liquid sensing, compared to standard fibers [2,11]. Unlike standard optical fibers, they may be designed to be single moded from the visible to near-infrared region [2–7]. Since the high-index core (or index-guiding) MOF is a single material optical fiber/waveguide with no boundary between two types of glasses with different thermal expansion coefficients leads to ultimate attenuation level of MOF might be even lower than that of conventional fibers. From attenuation point of view, one can speculate that high-index core MOFs

---

* Corresponding author.
E-mail addresses: dk81.dineshkumar@gmail.com (D.K. Sharma), asharma@physics.iitd.ac.in (A. Sharma), smt@iitk.ac.in (S.M. Tripathi).

https://doi.org/10.1016/j.optlastec.2018.08.004
Received 28 July 2017; Received in revised form 21 July 2018; Accepted 2 August 2018

may compete with conventional circularly symmetric fibers for data transmission applications [12–14]. It is well known that MOF optical characteristics strongly depend on the cladding configuration such as the number of air-holes, their size, shape, orientation, transversal distribution and the nature of dielectric material, providing useful modal and the dispersive properties. Therefore, large-mode area, high numerical aperture, low transmission, and low-loss splicing are easily attainable via MOF technology [2–10,15]

Optical fibers with unconventional structures have significantly different mode field compared to that of conventional SMFs and, thus, the splice losses with conventional step-index SMFs is a crucial issue for their practical implementation [14,16]. For an example, in telecommunication systems, coupling by a direct splice to traditional optical fiber would be preferable but the small core size of MOF make coupling of light a challenging task resulting large coupling losses due to high mode-field mismatch. The mismatch between the core-sizes, and hence, between the mode sizes, make splicing of MOF to SMF inefficient and lossy, and it remains as a key problem hindering the widespread development of MOF based devices and the sensors [16–20]. For enhancing MOF applicability in optical communication or sensing, robust low-loss splicing of MOF to traditional step-index single-mode fiber without compromising the integrity of air-holes structure, is extremely vital [14,17–21].

Fusion splicing between two classical step-index SMFs are well established; however, for the case of fusion splicing between two MOFs (or different MOF) the air-holes are easily collapsed. Therefore, it is imperative that the splicing process does not cause any severe deformation on air-holes, and their structure in MOFs [18–22]. As known, SMF required more fusion energy than MOF to achieve the melting point during the same heating time, so the center of laser beam (or heat source) is required to make an appropriate offset toward SMF, which can balance different energies required by SMF and MOF during splicing, effectively avoiding the collapse of air-holes in MOF caused by high power [21–23]. For minimizing the air-hole collapse in splicing MOF-SMF, one have to choose weaker fusion current and shorter fusion time compared to parameters of splicing SMF-SMF when fusion splicing MOF-SMF [22–24]; however, suitable arc energy should be required to soften the tips of MOF and SMF, for achieving good mechanical strength of joint interface [25–28]. The air-hole collapse can also be caused by improper fusion duration time and optical power. Therefore, analysis for temperature characteristics of fusion splicing between two MOFs (or different MOF) and SMFs is also required [23,28].

Other factors which contribute to splice losses between MOF and the traditional step-index fiber include mode-field mismatch, transverse offset, core axis misalignment, angular misalignment, deformation of the fiber cross-section, and end-face stuffing; moreover, the impurity that infiltrates into the air-holes also changes the characteristics of MOFs. For fusion splicing between an MOF and the SMF, the mode-field mismatch and the air-hole collapse during splicing are the two main factors [17–24]. Complete (or partial) collapse of air-holes and the bubble generation in the vicinity of joint interface is definitely harmful for achieving the robust splicing as it may destroy the light guiding characteristics of MOF, and hence, significantly increases the losses. However, under certain conditions, collapse of air-holes can help for reducing the mode-field mismatch and thus reducing the splice losses [14,20–22]. Also, it enables to form a coreless region in the MOF without bisecting the fiber which might be used to implement an efficient and the cost effective free space connector [22].

The splicing of solid-core MOF to standard SMF using a conventional fusion splicer has been reported by Bennett et al. [21]. In the literature, various splicing methods have been proposed, for achieving low-loss splicing of fibers with similar mode-field diameters (MFDs) such as arc fusion splicer [19,20], filament splicer [21], CO_2 laser [23], and the gradient-index fiber lenses [29]. Splice loss of 0.7–1.1 dB for the solid-core MOF by using an arc of short duration and weak power has been reported by Bourliaguet et al. [17]. In 2007, Xiao et al. [20] applied the repeated arc discharges on the joint interface to gradually collapse the air-holes of MOF, and achieved splice losses of 0.9–1.41 dB and 1.45–2.01 dB for solid-core and the hollow-core MOFs, respectively. Splice losses of 1.5–2.0 dB has been reported by Thapa et al. [30] using the offset electrode arc discharge method. Splicing of the polarization-maintaining MOF to an SMF with an arc fusion splicer was reported by Kristensen et al. [24], where low-loss splicing was achieved by matching the mode-field diameters of two fibers. An effective splicing method on MOFs using CO_2 laser [31] to control the air-hole collapse was also demonstrated by Fu et al. [32], facilitating the exceptionally low-loss for splicing MOFs with single-mode fibers. Park et al. [22] empirically investigated the optimum fusion splicing condition for low-loss splicing of MOF having large-mode area by controlling the arc-power and arc-time of conventional electric arc fusion splicer, and they measured the tensile strengths of the fusion splicing for MOF-MOF case and for the MOF-SMF one. However, these methods introduce polarization-dependent losses and they are not suitable for splicing small-core MOF and traditional single-mode fiber due to structural dissimilarities. In spite of that, at the joint interface a clear interface usually occurs, causing significant reflection of light leading to instability in fiber-based sensing applications [16,20].

To overcome the problems, several indirect methods have been suggested in the literature such as tapered intermediate MOF [33,34], integrating an SMF with MOF during the manufacturing stage of MOF [35] and the use of photopolymer microtips directly grown on the SMF [36]. In this direction, Bachelot et al. [37] demonstrated a new application of the micrometer-sized polymer tips integrated by the free-radical photo polymerization at the end of optical fiber, acting as the microlens to increase the intrinsic fiber numerical aperture, and allowing the effective collection of light. They have achieved coupling efficiency of 70% (1.5 dB loss), and claimed this self-growing tip a powerful tool for light coupling in the integrated optics. However, in these methods special manufacturing platform is required which make the fiber based devices bulky, and strongly limits their common use [20,38]. Xiao et al. [39] has been presented a method to splice MOF and the fiber/waveguide pigtails by using a capillary as a sleeve, while another method involves putting a cuvette over the gap of splicing point between MOF and a standard telecom fiber. Another possible approach to overcome this problem is to design the small-core MOF with doped cores [14,19], which will guide light even when air-holes are completely collapsed during splicing; however, this will also put limitations on the flexibility in design. Liu et al. [40] proposed and experimentally demonstrated the light beam coupling between a single-mode fiber (which is pre-tapered to match its propagation constant to that of nonlinear MOF) and the MOF, based on the fused biconical tapering (FBT) technique, and they achieved the coupling ratio exceeding 90% between SMF and the MOF.

In 2012, an effective method (applicable for both the solid-core and the hollow-core MOFs) for low-loss splicing between an MOF and the SMF with a conventional electric-arc fusion splicer has been demonstrated by Zhu et al. [41], where nitrogen gas is pumped into the air-holes of MOF, for controlling the air-hole collapse ratio so as to optimize the mode-field match at the joint interface. Such approach protects the optimum mode-field match between small-core MOF and the large-core SMF at the splice interface [42]. Nevertheless, this method becomes ineffective for MOF with a single layer of large air-holes surrounding an extremely small-core, since the MFD does not increase with the collapse of air-holes. Another attempt of low-loss splicing such MOFs (with sub-wavelength core size and high numerical aperture) was suggested by Tse et al. [43]. An alternative approach for achieving low-loss splicing between an MOF and the standard fiber involve changing the relative size of cladding air-holes of MOF [44–48] instead of controlling the overall fiber dimensions, has been introduced by Laegsgaard and Bjarklev [14]. By gradually collapsing the air-holes of an MOF, effective index contrast between the core and cladding can be reduced, leading to expansion of the guided mode to a desired size, to