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Numerical study on the beam quality evolution of the thermally-guided very-large-mode-area fiber

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ABSTRACT

The beam quality variations of transverse modes with thermal load in the thermally-guiding (TG) very-large-mode-area (VLMA) fiber are numerically investigated in this paper. It is found that the beam qualities of transverse modes can be optimized with the production of thermal load. The beam quality variations are not monotonous due to the thermally-induced index increment, which can be concluded into three stages (the “initial”, “transition”, and “steady” stage). The effects of fiber parameters such as index difference and core size are also studied. Furthermore, two practical cases of mode mixture are considered and the effects of higher-order mode content and the phase shift on the beam quality are revealed. It shows that the higher beam quality doesn’t suggest lower higher-order mode content, and the phase shift will increase the uncertainty of beam quality. It is also suggested that by controlling the thermal effect, the overlap between two modes can be reduced to suppress the beam quality degradation caused by phase shift. The pertinent results can provide significant guidance on designing the high power TG VLMA fiber lasers with high beam quality preservation.

1. Introduction

Fiber lasers have attracted much attention because of the high efficiency, good flexibility and robustness, and have been widely used in communication, industrial processing and medical treatment [1,2]. Nowadays, the output power has reached 10 kW with the near-diffraction beam quality [3]. However, limited by several physical limitations, such as nonlinear effects, thermal effects, and pump brightness, et.al, the output power of fiber lasers cannot be improved unlimitedly. Among these limitations, the nonlinear effect is one of the most important aspects [4,5]. In order to overcome this limitation, the very large mode area (VLMA) fiber is proposed, which promotes the nonlinear threshold by enlarging the mode field area (MFA) of the signal light simultaneously with single-mode realization [6–13]. Various schemes of VLMA fiber were demonstrated to date such as gain-guided, index-antiguided fiber [6,7], leakage channel fibers [8,9], chirally-coupled core (CCC) fibers [10,11] and large-pitch fiber [12,13] et al. In these schemes, the micro-structures are utilized to increase the loss of higher-order mode or the gain of fundamental mode, and up to 50–100 μm mode field diameters have been achieved with single-mode operation. In spite of this, when utilized as active fiber in a fiber laser system, these fibers have to face with thermal effects caused by quantum defect, which will lead to the mode field shrinking and thus aggravate the nonlinearity [14–16].

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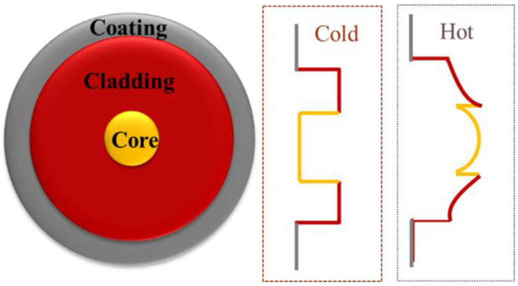

Fig. 1. The scheme of TG-VLMA structure.

At present, a novel scheme of VLMA fiber, the thermally-guided (TG) VLMA active fiber was present [17], in which the thermal effects are utilized to form the waveguide rather than being suppressed. The structure of TG-VLMA fiber is similar to the double cladding fiber (DCF), as shown in Fig. 1. However, different from the traditional DCF, the core index of TG-VLMA is not larger, but equal or lower to some degree than the inner cladding. It means that the waveguide should not be formed by the original numerical aperture (NA) of the fiber core in "cold" state (without the thermal load). What forms the waveguide is the thermal effect when utilized as gain fiber. It will introduce an increment of temperature in the fiber, which is parabolic-shape in the core and logarithmic decay in the cladding. For silica, the most commonly used medium in fiber fabrication, its index will increase monotonously with the temperature because of the thermal-optic effect [18,19]. Consequently, the temperature increment can be translated into a thermally-induced index increment with a bulge over the core region and a logarithmic distribution over the cladding, which compensates the original index depression. Then, the thermally–induced core-index guiding waveguide can be realized and enables the optical field propagating in the core. With this thermal-induced waveguide, TG VLMA fiber should be more resistant to the thermal effects which limit the scaling of mode area. Moreover, it provides a feasible approach to realize ultra-low numerical aperture (NA) by controlling the thermal guiding effect, which is also beneficial to the enlargement of core size. Besides, compared with other VLMA fibers, there is no micro-structure needed in the TG VLMA fiber, which makes the fabrication and the splice with other components easier.

Nowadays, the study on TG VLMA fiber is still in primary. In 2014, a proof-of-concept experiment was proposed by Jena University [17]. By a TG-VLMA fiber with 42 μm core and index difference of 2×10^{-5}, the output with 68 μm mode field diameter was obtained, which verified the feasibility of very large mode area output realization and shows a power scaling potential of approximately 20 kW according to Ref. [4]. In 2016, the transverse mode evolution in TG-VLMA fiber with thermal load was studied [20], and the numerical model of the TG VLMA fiber amplifier was also presented [21]. However, there is still plenty of study need to be profound, i.e., how the beam quality evolves in TG-VLMA fiber, and how to preserve the beam quality by controlling the thermal guiding effect? These questions are important for its application in fiber lasers or amplifiers, and should be studied based on the beam quality evolution of supported eigenmodes in the fiber. Although there have been several investigations on the beam quality of eigenmodes in traditional DCF fibers [22–24], the mode evolution is unique in TG-VLMA fiber according to Ref. [20] because of its "cold" anti-guide index structure and thermally-dependent waveguide. Thus, the pertinent beam quality should also be different from the cases of other ones and need to be investigated in detail.

In this paper, the beam quality variations of the transverse modes in TG VLMA fiber are investigated for the first time, to our knowledge. The paper is arranged as follows. In Section 2, the calculation method of the transverse mode beam quality in TG VLMA fiber is demonstrated. In Section 3, the beam qualities of pure eigenmodes versus thermal load and the effects of fiber parameters are studied. Based on these, two practical cases of mode mixtures are also studied in order to reveal the effects of higher-order mode content and phase shift on the beam quality. The conclusions will be drawn in Section 4.

2. Calculation of the transverse mode beam quality in TG VLMA fiber

2.1. Analytical formulation of beam quality M^2 factor

Beam quality factor M^2 is a key parameter to evaluate the performance of the output beam, which describes the distinguish of an arbitrary beam from an ideal Gaussian beam. More close to Gaussian-shape, the better beam quality the beam has. The beam quality M^2 is minimum for an ideal Gaussian beam with the value of 1, and should be larger than 1 for an arbitrary real beam. Because of the different definition of beam width, several methods for beam quality characterizing have been presented. Among these methods, the most widely used one is the second-order intensity moment definition proposed by Siegman [25,26]. With this method, the beam quality M^2 factor can be calculated according to the optical field distribution. Specifically, the near-field second-order intensity moments ω_{0x} and ω_{0y} in X-direction and Y-direction, which describe