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Efficiency and beam quality deterioration in double-cladding fiber amplifiers induced by core misalignment of fusion splices

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ABSTRACT

In this study, the efficiency and beam quality deteriorations in double-cladding fiber (DCF) amplifiers induced by core misalignment of series fusion splices are investigated. The losses of guide modes and power conversions between fundamental mode and high order modes (HOM) are well described according to mode coupling theory. Furthermore, a typical fiber amplifier with three fusion splices and bending mode-selection is established to discuss the mechanism of deteriorations in total systems. Mode competition theory is also introduced to describe different modes powers and beam quality changes with fiber length. Based on these calculations, the accumulations of deterioration caused by series fusion splices are intuitively illustrated. These simulations of laser performance show good accordance with the experimental results. An effective method to significantly enhance the performance of the fiber amplifier is also shown and discussed.

1. Introduction

In typical fiber amplifier system [1,2], fusion splices are usually used to connect different system components, e.g.: fiber oscillators, pump and their combiners, FBGs, active and passive fibers. However, core misalignments at fiber fusion splices caused by the differences in fiber kinds and parameters always lead to core modes conversions and losses [3–5]. Therefore, laser performance deterioration, which is caused by energy conversions from fundamental mode to HOMs and cladding modes respectively, occurs in both beam quality and efficiency.

At this stage, this kind of deterioration in single splice can be well described according to mature mode coupling theory [4] or beam propagation algorithm [5]. However, when it comes to the actual laser systems with series fusion splices, the deterioration in laser propagation and gain process becomes more complex because of the accumulation and mode competition. Considering the costs and accuracy of fusion platform, the influence on efficiency and beam quality of core misalignment at each splice should be explicitly and intuitively stated to guide the designs of laser systems.

Thus, in our study, according to mode coupling [4] theory and mode competition theory [6], we quantitatively describe the influence on efficiency and beam quality of series fusion splices in an actual fiber amplifier with splices and bending mode-selection. Core modes losses and mode conversions in single DCF splice with core misalignment are fully discussed in Section 2. And in Section 3, the accumulation of these effects along fiber length is calculated and the deteriorations of laser performance are presented clearly. Intuitive charts and trends of simulation results are illustrated to guide the design and analysis of fiber amplifiers. Meanwhile, experiments at the hundreds of watts level are carried out in Section 4 to validate our analysis, and show good accordance with the simulation one. Moreover, pre-mode-selection as an effective method for significant enhancing the fiber amplifier performance is also discussed in terms of reasons and effects.

2. Core loss and beam quality deterioration in single fusion splice induced by core misalignments

Before discussing fiber amplifiers system with series fusion splices and mode-selection in this study, core mode losses and conversions at each fusion splice should be calculated first. The energy conversion between different modes can be well described by the mode coupling theory [4]. Under the conditions of core misalignments, the core mode distributions are shifted between two joint fiber cores. Core modes power conversions can be elaborated by the mode coupling coefficient, following the definition of coupling coefficient $\kappa_{i,j}$ [7]:

$$\kappa_{i,j} = \frac{\left| \int_A E_i \cdot E_j * ds \right|^2}{\left(\int_A E_i \cdot E_i * ds \right) \cdot \left(\int_A E_j \cdot E_j * ds \right)} \tag{1}$$

where E_i and Ej are the normalized electric field distributions of mode i and j, respectively. In this paper, discussions are focused on

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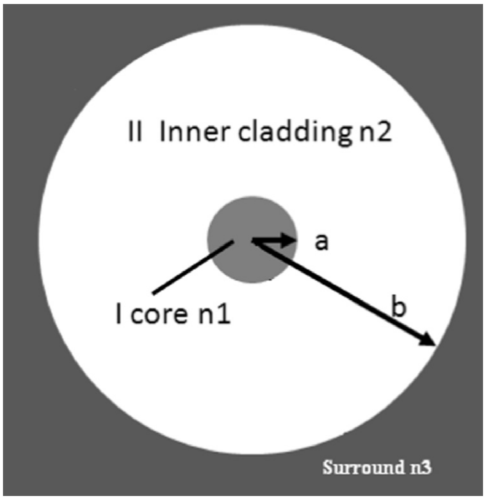

Fig. 1. Structure and parameters of typical DCF. Quantities a and b are the radii of core and inner cladding, respectively. The reflective index of fiber core, inner cladding and extramural coating are $n1$, $n2$ and $n3$ ($n1 > n2 > n3$).

the mode coupling from fundamental mode to high order modes in DCFs (as shown in Fig. 1 with $n1 > n2 > n3$). The parameters of DCF in our applications are 20/400 μm of core/inner cladding diameter and 0.06/0.46 of core/inner cladding N.A. [8]. Fiber core modes field distribution can be expressed according to the weak guiding approximation as follows [9]:

$$
\begin{aligned}
E_r^{co} &= i\frac{E_{lm}^{co}}{J_l(U)}J_l\left(\frac{U}{a}r\right)\sin\ l\phi\ \exp(i\phi)\exp[i(\beta z-\omega t)] \quad r\le a\\
E_\varphi^{co} &= -\frac{E_{lm}^{co}}{J_l(U)}J_l\left(\frac{U}{a}r\right)\sin\ l\phi\ \exp(i\phi)\exp[i(\beta z-\omega t)] \quad r\le a\\
E_r^{co} &= i\frac{E_{lm}^{co}}{K_l(W)}Kl\left(\frac{W}{a}r\right)\sin\ l\phi\ \exp(i\phi)\exp[i(\beta z-\omega t)] \quad r> a\\
E_\varphi^{co} &= -\frac{E_{lm}^{co}}{K_l(W)}Kl\left(\frac{W}{a}r\right)\sin\ l\phi\ \exp(i\phi)\exp[i(\beta z-\omega t)] \quad r> a
\end{aligned}
\tag{2}
$$

where $U = a\sqrt{k_0{}^2 n_1{}^2 - \beta^2}$, $W = a\sqrt{\beta^2 - k_0{}^2 n_2{}^2}$, $\beta = (2\pi/\lambda)n_{efflm}$ is the propagation constant. E_{lm}^{co} is the normalization factor. $J_l(U)$ and $K_l(W)$ is the Bessel function of the first kind and modified Bessel function of the second kind, respectively. The core mode LP_{01} and LP_{11} (two polarization directions) are in the fiber core mode cavity. M^2 factor of beam quality can also be calculated according to the following equations based on the superposition of core modes electric field $E(x, y)$ [5].

$$
\begin{aligned}
M_x^2 &= 2\sqrt{\iint (x - x_0(z_0))^2 |E(x, y)|^2 dxdy}\\
&\quad \times \sqrt{\iint \left|\frac{\partial E(x, y)}{\partial x}\right|^2 dxdy}\\
M_y^2 &= 2\sqrt{\iint \left(y - y_0(z_0)\right)^2 |E(x, y)|^2 dxdy}\\
&\quad \times \sqrt{\iint \left|\frac{\partial E(x, y)}{\partial y}\right|^2 dxdy}
\end{aligned}
\tag{3}
$$

where $x_0(z_0)$ and $y_0(z_0)$ are the first intensity moments of the same plane giving the center coordinates of the beam; $E(x, y)$ is the power-normalized electrical field distribution of linear combination of the core modes. It should be mentioned that the beam quality changes caused by the interference of fiber core modes [10] are not discussed in this study.

According to Eqs. (1)–(3), power conversions with the increasing core misalignment of different modes can be calculated and shown in Fig. 2, and the corresponding M^2 factor changes are also illustrated in Fig. 3. As shown in Figs. 2 and 3 the fiber core modes show different sensitivities to one-direction core misalignments. With pure LP_{01} mode injection shown in Fig. 2a, energy mainly transmit from LP_{01} to LP_{11} (red curve and blue curve in Fig. 2a) instead of forming core losses (gray curve in Fig. 2a). The M^2 factor of this direction slightly increases and reaches to 1.2 with 5 μm core misalignment. However, with pure LP_{11} mode injection shown in Fig. 2b, the energy of LP_{11} mode is more easily to form core losses although the M^2 factor of this direction drops with the increasing of core misalignment due to the appearance of fundamental mode LP_{01}.

As we can see in Figs. 2 and 3, mode conversions between fiber core modes and core loss formations are both increasing with the core misalignment in fusion splice. Based on the results of mode coupling process analysis, the deteriorations of laser performance caused by this phenomenon have significant accumulation characteristics: the amount of HOMs and core losses will grow faster at next splice as laser propagate through series fusion splice. Thus, the fusion splices which are close to the output end should be paid more attention in order to avoid fiber core loss because of the large amount of HOM caused by the previous splices.

3. Efficiency and beam quality deterioration in fiber amplifiers

In order to discuss the efficiency and beam quality deterioration in a fiber laser amplifier, a typical structure of double-cladding

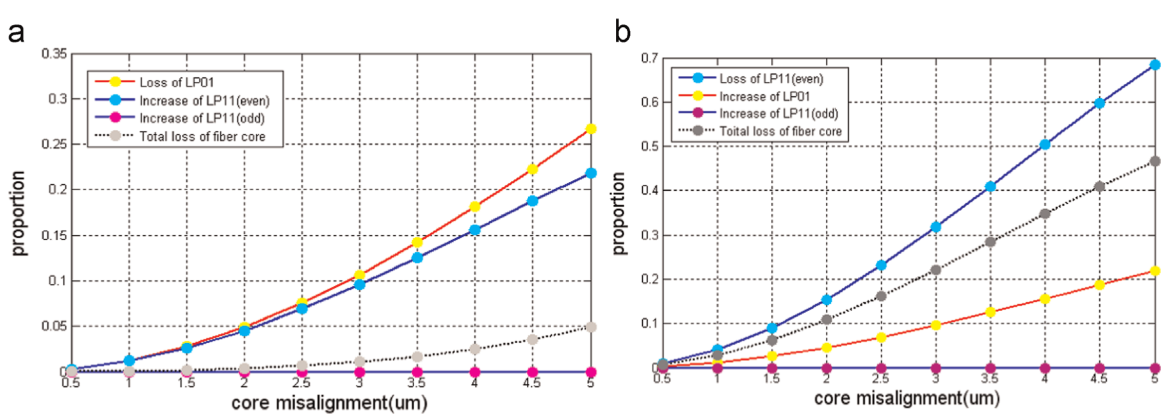

Fig. 2. Fiber core modes coupling process under core misalignment (a) Fiber mode conversions between core modes and loss formations with pure LP_{01} injection. (b) Fiber mode conversions between core modes and loss formations with pure LP_{11} injection (For interpretation of the references to color in this figure the reader is referred to the web version of this article.).