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The features of the optical pumping active fibers with three-piece inner clad

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ABSTRACT

This paper presents simple model of distribution of the pump radiation in active three-piece inner clad fibers (GTWave3) and analytical solutions of the relevant differential equations. Based on these solutions has been produced the analysis of the dependence distribution of the pump radiation and value of the effective length GTWave3 from key parameters of this type of a fiber (the active-region absorption coefficient and the coupling coefficients). Also in work presents comparison of the pump distribution into the GTWave3 and GTWave2 (two-piece inner clad) fibers.

1. Introduction

High power fiber lasers and amplifiers have been increasingly used in various fields of modern science and technology [1,2]. Significant progress in this field is due to the development of double-clad optical fibers [3] (DCF) that served as the basis for fiber lasers with the cladding-pump. The basic problem of DCF is the occurrence of local overheating near the injection points of the pump radiation. This issue is becoming increasingly important with increasing power of fiber lasers [1]. A possible solution of this problem is to use the active fibers with a multi-piece inner clad [4–7]. These fibers are called GTWave or DSCCP (distributed side-coupled cladding-pumped) active fibers. In this type of fiber, pumping radiation is injected into the active fiber owing to optical coupling [8–10] between the active fiber and one or more passive fibers; this helps to distribute the heat load along the fiber length. Special features of distribution and absorption of the pump radiation in the active fibers with two-piece inner clad (GTWave2 fibers) were studied in [11,12]. In work [11] presents a simple model that takes into account the phenomenon of optical radiation absorption in the active core of GTWave2 fiber, as well as the phenomenon of optical coupling of between fibers located in the inner clad. In previous works on the theoretical study of the distribution of the pump radiation in GTWave2 fibers [13–15] consideration was made only from the point of view of the transmission of radiation, the absorption of radiation in the active core was not considered. Active fibers with three-piece inner clad (GTWave3 fibers), i.e. the inner clad contains two passive and one active fibers, are also of interest to create high power fiber lasers and amplifiers [1,2]. This type of fiber can naturally increase the number of injection points of the pump radiation, i.e. the possibility exists to decrease magnitude of pumping power initially injected at each end. Thus, the availability of simple analytical solutions, which can be used to estimate the distribution of the pump power along the length of the fibers within the GTWave3, is important in the design of high-power fiber lasers and amplifiers.

In this work, we extended the model offered in [11,12] for GTWave2 fibers to the case with GTWave3 fibers. In this model becomes possible to study the influence of parameters GTWave3 fiber on the distribution and absorption of the pump radiation in the active and passive fibers.

2. Theoretical model

Fig. 1 gives schematic structure of GTWave3 fiber. The inner clad of the fiber contains an active fiber (fiber 1) with the absorbing core and also two passive coreless fibers (fibers 2 and 3). In practice, pumping radiation is injected into passive fibers 2 and 3 and then coupled into active fiber 1 when propagating along the fiber. In general, pumping radiation could be injected in all three fibers. In this work, passive fibers 2 and 3 are assumed to be completely similar and positioned at the same distance from the active fiber. So, coupling coefficients can be expressed as the following relationships: $k_{21} = k_{31} = k_{pa}, k_{12} = k_{13} = k_{ap}, k_{23} = k_{32} = k_p$, where k_{21} and k_{31} – are coupling coefficients for passive fibers and active fiber, k_{12} and k_{13} – are coupling coefficients for the active fiber

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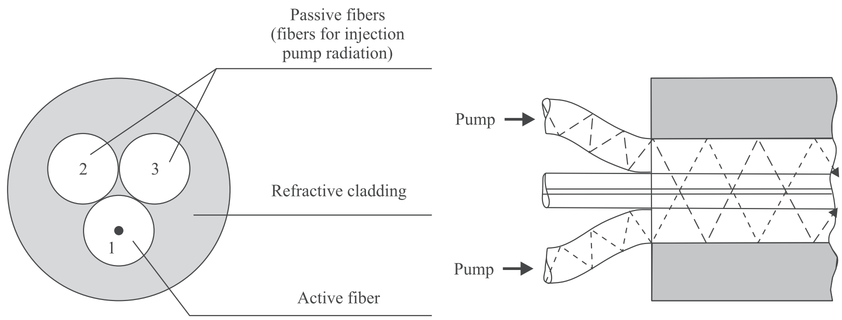

Fig. 1. Schematic of active fiber with three-element inner cladding.

and passive fibers, k_{23} and k_{32} – are coupling coefficients for passive fibers. The term "coupling coefficient" means the effective coupling coefficient that characterizes transfer of radiation from all light-guide modes (like in [11,12]) because the passive light-guide and the inner clad of the active light-guide are multimode ones for pumping radiation [8–10]. In this case, the change in the pumping radiation power in each fiber can be described by a set of differential equations:

$$\begin{aligned}
&\pm\frac{dP_p^{\pm}(z)}{dz} = -(\gamma(z)+\alpha_p+2k_{ap})P_p^{\pm}(z)+k_{pa}P_{pp}^{\pm}(z)+k_{pa}P_{ppp}^{\pm}(z),\\
&\pm\frac{dP_{pp}^{\pm}(z)}{dz} = -(k_{pa}+k_p+\alpha_p)P_{pp}^{\pm}(z)+k_{ap}P_p^{\pm}(z)+k_pP_{ppp}^{\pm}(z),\\
&\pm\frac{dP_{ppp}^{\pm}(z)}{dz} = -(k_{pa}+k_p+\alpha_p)P_{ppp}^{\pm}(z)+k_{ap}P_p^{\pm}(z)+k_pP_{pp}^{\pm}(z),
\end{aligned}\tag{1}$$

where $P_p^{\pm}(z)$ – is pumping power in the active fiber, $P_{pp}^{\pm}(z)$ – is pumping power in passive fiber 2, $P_{ppp}^{\pm}(z)$ – is pumping power in passive fiber 3 (sign "±" shows the radiation propagation direction), $\gamma(z)$ – is the coefficient that describes absorption in the active core (the active-region absorption coefficient), α_p – coefficient determining the loss of pump radiation are not related to the absorption of the active region (assuming it equal for all fibers).

The active-region absorption coefficient $\gamma(z)$ is a function of coordinate z, which describes the location along the fiber length. This parameter connects the differential equations for the pump radiation with kinetic equations for the concentrations.

In general, the system of differential Eq. (1) should be supplemented by the following boundary conditions:

$$\begin{aligned}
&P_p^+(0)=P_p^0, \quad P_p^-(L)=P_p^L\\
&P_{pp}^+(0)=P_{pp}^0, \quad P_{pp}^-(L)=P_{pp}^L,\\
&P_{ppp}^+(0)=P_{ppp}^0, \quad P_{ppp}^-(L)=P_{ppp}^L
\end{aligned}\tag{2}$$

where L – is the fiber length, P_p^0 and P_p^L – is the pumping radiation power at the ends of active fiber 1, P_{pp}^0 and P_{pp}^L – is the pumping radiation power at the ends of passive fiber 2, P_{ppp}^0 and P_{ppp}^L – is pumping radiation power at the ends of passive fiber 3.

The system of differential Eqs. (1) with the boundary conditions (2) can be solved analytically if $\gamma(z) = const$. This situation takes place in two cases: the case of a small-signal gain [16] and the case of a strong pump [17]. The corresponding analytical solutions of the differential Eqs. (1) have the following form:

$$\begin{cases}
P_p^+(z) = C_1e^{\frac{z}{2}\kappa^{(+)}}+C_2e^{-\frac{z}{2}\kappa^{(-)}}\\
P_p^-(z) = C_3e^{\frac{z}{2}\kappa^{(-)}}+C_4e^{-\frac{z}{2}\kappa^{(+)}}
\end{cases};\tag{3}$$

$$\begin{cases}
P_{pp}^+(z) = C_5e^{-\chi z}+\beta^{(+)}C_1e^{\frac{z}{2}\kappa^{(+)}}+\beta^{(-)}C_2e^{-\frac{z}{2}\kappa^{(-)}}\\
P_{pp}^-(z) = C_6e^{\chi z}+\beta^{(-)}C_3e^{\frac{z}{2}\kappa^{(-)}}+\beta^{(+)}C_4e^{-\frac{z}{2}\kappa^{(+)}}
\end{cases};\tag{4}$$

$$\begin{cases}
P_{ppp}^+(z) = -C_5e^{-\chi z}+\nu^{(+)}C_1e^{\frac{z}{2}\kappa^{(+)}}+\nu^{(-)}C_2e^{-\frac{z}{2}\kappa^{(-)}}\\
P_{ppp}^-(z) = -C_6e^{\chi z}+\nu^{(-)}C_3e^{\frac{z}{2}\kappa^{(-)}}+\nu^{(+)}C_4e^{-\frac{z}{2}\kappa^{(+)}}
\end{cases}.\tag{5}$$

Here, we introduced the following designations:

$$\varepsilon^{(+)} = \gamma+2\alpha_p+2k_{ap}+k_{pa}+k_p$$

$$\varepsilon^{(-)} = \gamma+2k_{ap}-k_{pa}-k_p,$$

$$\chi = 2k_p+k_{pa}+\alpha_p,$$

$$\rho = \sqrt{\left(k_p+\varepsilon^{(-)}\right)^2+8k_{ap}k_{pa}},$$

$$\kappa^{(+)} = \rho+\left(k_p-\varepsilon^{(+)}\right), \quad \kappa^{(-)} = \rho-\left(k_p-\varepsilon^{(+)}\right),$$

$$\beta^{(+)} = \frac{2k_{ap}k_{pa}+k_p^2+k_p\left(\varepsilon^{(-)}+\rho\right)}{k_{pa}\left(3k_p-\varepsilon^{(-)}+\rho\right)},$$

$$\beta^{(-)} = \frac{2k_{ap}k_{pa}+k_p^2+k_p\left(\varepsilon^{(-)}-\rho\right)}{k_{pa}\left(3k_p-\varepsilon^{(-)}-\rho\right)},$$

$$\nu^{(+)} = \frac{\left(2(k_{pa}+k_p+\alpha_p)+\kappa^{(+)}\right)\left(k_p+\varepsilon^{(-)}+\rho\right)-4k_{ap}k_{pa}}{k_{pa}\left(3k_p-\varepsilon^{(-)}+\rho\right)}$$

$$\nu^{(-)} = \frac{\left(2(k_{pa}+k_p+\alpha_p)-\kappa^{(-)}\right)\left(k_p+\varepsilon^{(-)}-\rho\right)-4k_{ap}k_{pa}}{k_{pa}\left(3k_p-\varepsilon^{(-)}-\rho\right)}.$$

Integration constants C_1, C_2, C_3, C_4, C_5 and C_6 are determined from the boundary conditions (2):

$$C_1 = \frac{2\left(P_{pp}^0+P_{ppp}^0\right)-P_p^0\left(2\beta^{(-)}+\nu^{(-)}\right)}{2\left(\beta^{(+)}-\beta^{(-)}\right)+\nu^{(+)}-\nu^{(-)}},$$

$$C_2 = -\frac{2\left(P_{pp}^0+P_{ppp}^0\right)-P_p^0\left(2\beta^{(+)}+\nu^{(+)}\right)}{2\left(\beta^{(+)}-\beta^{(-)}\right)+\nu^{(+)}-\nu^{(-)}},$$

$$C_3 = -\frac{2\left(P_{pp}^L+P_{ppp}^L\right)-P_p^L\left(2\beta^{(+)}+\nu^{(+)}\right)}{2\left(\beta^{(+)}-\beta^{(-)}\right)+\nu^{(+)}-\nu^{(-)}}e^{-\frac{L}{2}\kappa^{(-)}},$$

$$C_4 = \frac{2\left(P_{pp}^L+P_{ppp}^L\right)-P_p^L\left(2\beta^{(-)}+\nu^{(-)}\right)}{2\left(\beta^{(+)}-\beta^{(-)}\right)+\nu^{(+)}-\nu^{(-)}}e^{\frac{L}{2}\kappa^{(+)}},$$