Optical Fiber Technology 45 (2018) 363–367

Contents lists available at ScienceDirect

Optical Fiber Technology

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

Method for determination of effective coupling coefficients in (1 + 1)GTWave fibers

Mariya G. Slobozhanina*, Anton N. Slobozhanin, Alexander V. Bochkov, Dmitry V. Khmelnitsky

Federal State Unitary Enterprise "Russian Federal Nuclear Center – Academician E.I. Zababakhin All-Russian Research Institute of Technical Physics", Vasil'eva 13, 456770 Snezhinsk, Russia

ARTICLE INFO

Keywords:
Fiber with multi-piece inner clad
GTWave fibers
Effective coupling coefficients
Optical pumping

ABSTRACT

This paper proposes a theoretical and experimental method to determine the effective coupling coefficients for the pump radiation in (1 + 1)GTWave fibers and also gives mathematical expressions derived from analytical solutions for the pump radiation power distribution to estimate values thereof. The conditions for carrying out experiments to measure effective coupling coefficients, as well as results of these measurements are presented.

1. Introduction

In the past few decades, high-power fiber lasers and amplifiers became ingrained in various fields of modern science and technology [1]. A possible design variant thereof is to use fibers with the multi-piece inner cladding as an active element [2]. These active fibers are designated either as GTWave [3,4] or DSCCP (distributed side-coupled cladding-pumped) [5–8]. In such a case, we have a side pumping configuration when pumping radiation is injected into the active fiber owing to the optical contact between the active fiber and one or more passive fibers; this helps to distribute the heat load along the fiber length. Papers [5,6] proposes a simple model of (1 + 1)GTWave active fiber (the refractive cladding contains one active fiber and one passive fiber) wherein effective coupling coefficients describe optical coupling between fibers. These coefficients are mean values along the fiber length, which govern transition of the total pumping radiation (all optical modes). A strict analysis of the optical coupling or crosstalk in a system of several parallel fibers located in a common reflecting clad is present in [9,10]. However, in the GTWave system the fibers can be considered parallel only on a small part of its length (fibers are twisted during the drawing). Therefore, the application of the averaging of the coefficients describing the optical coupling as done in model [5,6] and extended to the case of (2 + 1)GTWave in [11] is largely relevant. Note that the active and passive fibers are considered to be similar in composition, which makes it possible to take the loss coefficient for them to be equal. This situation is often realized in practice. In addition, paper [5] presents analytical solutions that assume strong pumping approximation [12] and thus allow analysis of pumping distribution in (1 + 1)GTWave fibers [6]. The maximum output power of the single-mode fiber laser based on this type of fiber is 1 kW [7]. Until recently, no method how to measure effective coupling coefficients is reported though results of the numerical analysis that uses specific values of these coefficients are regularly compared with the experimental data obtained with a newly-developed all-fiberized super-fluorescence ytterbium laser source [8].

Therefore, the present study is focused on the description of the theoretical and experimental method for determining effective coupling coefficients in (1 + 1)GTWave fibers. Mathematical expressions allowing estimation of these coefficients are derived from analytical solutions of differential equations for pumping power distribution included in the model [5]. Experimental conditions and experimentally measured effective coupling coefficients for fibers in (1 + 1)GTWave system are also provided. It should be noted that in this paper we do not consider the dependence of the effective coupling coefficient on the numerical aperture of the pump source.

2. Theory

Fig. 1 gives schematic structure of (1 + 1)GTWave fiber. The refractive clad of this fiber contains an active fiber (fiber 1) with the absorbing core and also a passive coreless fiber (fiber 2). In practice, pumping radiation is injected into the passive fiber 2 and then coupled into the active fiber 1 when propagating along the fiber. In general, pumping radiation could be injected into all fibers under consideration.

Papers [5,6] propose a simple model of pumping radiation distribution in (1 + 1)GTWave fiber. According to this model, effective coupling coefficients (hereafter coupling coefficients) describe optical coupling between fibers located in the inner clad. So, let us assume that

* Corresponding author.
E-mail address: dep5@vniitf.ru (M.G. Slobozhanina).

https://doi.org/10.1016/j.yofte.2018.07.019
Received 23 January 2018; Received in revised form 3 June 2018; Accepted 10 July 2018
1068-5200/

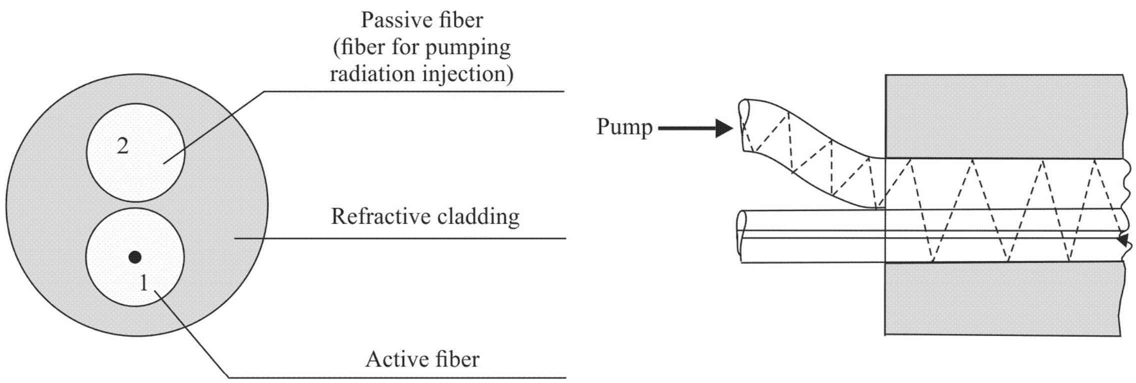

Fig. 1. Schematic of active (1 + 1)GTWave fiber.

optical radiation is injected into the endface of one or simultaneously all fibers in (1 + 1)GTWave system uniformly over their cross-section but optical radiation is injected into the clad provided that this is the active fiber. Assume that in the considered spectral range, values of these coupling coefficients are independent of optical radiation wavelength.

The system of differential equations of the theoretical model describing the pumping radiation distribution in (1 + 1)GTWave [5,6] can be solved analytically if the active-region absorption coefficient is constant along the fiber length. This situation obviously takes place in two cases: the case of a small signal [13] and the case of strong pumping [12]. Equations for unilateral radiation propagation have the following form:

$$\begin{cases} \frac{dP_p(z)}{dz} = -(\gamma + \alpha)P_p(z) - k_{ap}P_p(z) + k_{pa}P_{pp} \\ \frac{dP_{pp}(z)}{dz} = -(k_{pa} + \alpha)P_{pp}(z) + k_{ap}P_p(z) \end{cases}, \tag{1}$$

where $P_p(z)$ – is pumping power in the active fiber; $P_{pp}(z)$ – is pumping power in the passive fiber; k_{ap} – is the coupling coefficient between the active and passive fibers; k_{pa} – is the coupling coefficient between the passive and active fibers; α – is the loss coefficient; γ– is the active-region absorption coefficient. The system of differential Eq. (1) should be supplemented by the following boundary conditions that are extended relative to [5,6]:

$P_p(0) = P_p^0$, $P_{pp}(0) = P_{pp}^0$.

In order to separate effects of optical coupling and loss from effects of radiation absorption by the active region, let us consider a spectral band wherein the active-region absorption turns out to be small enough ($\gamma \ll k_{ap}$, $\gamma \ll k_{pa}$ and $\gamma \ll \alpha$) and thus can be neglected. So, solution of the system of differential Eq. (1) with the selected boundary conditions has the following form:

$$\begin{cases} P_p(z) = \frac{k_{pa}}{k_{ap}+k_{pa}}e^{-\alpha z}\left[P_p^0\left(1 + \frac{k_{ap}}{k_{pa}}e^{-(k_{ap}+k_{pa})z}\right) + P_{pp}^0(1 - e^{-(k_{ap}+k_{pa})z})\right] \\ P_{pp}(z) = \frac{k_{ap}}{k_{ap}+k_{pa}}e^{-\alpha z}\left[P_p^0(1 - e^{-(k_{ap}+k_{pa})z}) + P_{pp}^0\left(1 + \frac{k_{pa}}{k_{ap}}e^{-(k_{ap}+k_{pa})z}\right)\right]. \end{cases} \tag{2}$$

If we take the sum of expressions (2) given that $P_p^0 + P_{pp}^0 = P_{in}$, we obtain:

$$P(z) = P_p(z) + P_{pp}(z) = P_{in}e^{-\alpha z}. \tag{3}$$

Expression (3) helps to estimate the loss coefficient when taking measurements of the pumping radiation power leaving the system; note that at the inlet, radiation can be injected either into both fibers or only into one of them. It is easy to see that the loss coefficient in (1 + 1)GTWave fibers is determined by a simple modification of the standard "break off" method.

Than we obtain expressions to determine coupling coefficients. First, consider the case when optical radiation is injected only in the passive fiber, i.e. when $P_p^0 = 0$ and $P_{pp}^0 = P_{in}$. Then solutions (2) normalized to the initial pumping power can be written in the following form:

$$\begin{cases} pp(z) = \frac{P_{pp}(z)}{P_{pp}^0} = \frac{P_{pp}(z)}{P_{in}} = \frac{k_{pa}}{k_{ap}+k_{pa}}e^{-\alpha z}\left(\frac{k_{ap}}{k_{pa}} + e^{-(k_{ap}+k_{pa})z}\right) \\ CT_{act}(z) = \frac{P_p(z)}{P_{pp}^0} = \frac{P_p(z)}{P_{in}} = \frac{k_{pa}}{k_{ap}+k_{pa}}e^{-\alpha z}(1 - e^{-(k_{ap}+k_{pa})z}) \end{cases}. \tag{4}$$

where $CT_{act}(z)$ – is the ratio of pumping power in the active fiber at point z to the power injected into the passive fiber in (1 + 1)GTWave system. Similarly, we write over the expression (2) for the case when optical radiation is injected only in the active fiber, i.e. when $P_p^0 = P_{in}$ and $P_{pp}^0 = 0$:

$$\begin{cases} p = \frac{P_p(z)}{P_p^0} = \frac{P_p(z)}{P_{in}} = \frac{k_{ap}}{k_{ap}+k_{pa}}e^{-\alpha z}\left(\frac{k_{pa}}{k_{ap}} + e^{-(k_{ap}+k_{pa})z}\right) \\ CT_{pas} = \frac{P_{pp}(z)}{P_p^0} = \frac{P_{pp}(z)}{P_{in}} = \frac{k_{ap}}{k_{ap}+k_{pa}}e^{-\alpha z}(1 - e^{-(k_{ap}+k_{pa})z}) \end{cases}. \tag{5}$$

If $\alpha \ll k_{ap}$, $\alpha \ll k_{pa}$, effects of optical coupling and loss can be distinguished. This approximation should be performed in any real GTWave system for its effective operation. As a result, we obtain the following coupling coefficients from (4) and (5):

$$\begin{aligned} k_{ap}z = f_{ap}^C &= -\frac{CT_{pas}}{CT_{act}+CT_{pas}}\ln(1-(CT_{act}+CT_{pas})) \\ k_{pa}z = f_{pa}^C &= -\frac{CT_{act}}{CT_{act}+CT_{pas}}\ln(1-(CT_{act}+CT_{pas})) \end{aligned} \tag{6}$$

and

$$\begin{aligned} k_{ap}z = f_{ap}^p &= -\frac{1-p}{2-(p+pp)}\ln((p+pp)-1) \\ k_{pa}z = f_{pa}^p &= -\frac{1-pp}{2-(p+pp)}\ln((p+pp)-1) \end{aligned}. \tag{7}$$

Hereinafter you will find main stages of the proposed theoretical and experimental method for determining coupling coefficients in (1 + 1)GTWave fibers:

I. During the experiment, power at the outlet of the active and passive fibers is measured for a set of fiber lengths when radiation is injected only into the passive or only into the active fiber; then normalized values p, pp, CT_{act}, and CT_{pas} are calculated.
II. Experimental data are used to determine f_{ap}^C, f_{ap}^p, f_{pa}^C, and f_{pa}^p for each fiber length.
III. Values of coupling coefficients k_{ap} and k_{pa} are determined from the set of data (given for example by the least square method).

3. Experiment

Consideration is given to the experimental implementation of the above theoretical and experimental method. A test object is a single-