Article

Numerical Modeling of Mid-IR Lasers Based on Tb-Doped Chalcogenide Multicore Fibers

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Abstract: Mid-IR fiber lasers operating at wavelengths near 5 µm are of great interest for many fundamental and industrial applications, but only a few experimental samples based on active chalcogenide fibers have been demonstrated so far. One of the limitations of the power of such lasers may be a fairly low fiber damage threshold. To solve this problem, we developed and numerically investigated in detail a mid-IR fiber laser at 5.3 µm with multi-W output power pumped into the cladding at a wavelength of 2 µm. We proposed using a Tb-doped chalcogenide multicore fiber with 25 single-mode cores arranged in a 5 × 5 square lattice as an active medium. The proposed laser design surpasses the power limit of single-core chalcogenide fibers. When simulating lasers, we specified realistic parameters of Tb-doped chalcogenide glass based on published experimental data. We performed a comprehensive theoretical analysis, studied the influence of various factors on the characteristics of generation, and found optimal system parameters and expected generation parameters.

Keywords: Tb-doped chalcogenide fiber; multicore fiber; mid-IR fiber laser

1. Introduction

Mid-IR lasers in the 3–6 µm range are in demand for a lot of applications, including scientific, industrial, and medical ones [1,2]. However, the development of lasers in this spectral range is associated with a number of difficulties, so, today, such sources are not widespread, especially with powers at the level of several watts and above. However, significant experimental success has been achieved in this direction [2], for example, quantum cascade lasers [3–5].

Another promising way to develop coherent mid-IR sources is based on fiber lasers. These could be, for example, gas-filled hollow fiber lasers [6–9]. Hollow light waveguides of various designs are made of silica glass [10]. Even very high losses of silica glass in the mid-IR range are not a limitation because the mode is localized away from the walls of the silica waveguide. However, if we speak about lasers based on solid fibers, silica fibers are fundamentally not suitable; fibers based on soft glasses are used in these cases [1,11]. Currently, continuous-wave lasers based on fluoride fibers doped with rare-earth ions make it possible to obtain powers of tens of watts in the wavelength range of about 3 µm [12,13]. However, an advance to notably longer wavelengths in fluoride fiber lasers proves to be very difficult. The longest wavelength achieved in lasers based on fluoride fibers is 3.92 µm [14]; further increase in laser wavelength is limited by multiphonon luminescence quenching in active rare-earth ion transitions. A possible way to overcome this problem is to use chalcogenide fibers doped with rare-earth ions, in which the phonon energy is significantly lower than in fluoride fibers. Chalcogenide fibers based on glasses with various compositions doped with Tb 3+, Pr 3+, Dy 3+, and other ions were produced, and their optical and physicochemical characteristics were comprehensively investigated; optical losses, cross-sections, lifetimes, and other parameters were measured and calculated from...
experimental data [15–20]. Considerable efforts were devoted to numerical simulation of mid-IR chalcogenide fiber lasers; different schemes, including cascade lasing schemes at two successive radiative transitions, were proposed and studied (see book chapter [20] and references therein, as well as original works [16,18,19,21–24]). However, despite the long history of experimental and theoretical works, a fiber laser at a wavelength of about 5 µm based on chalcogenide glasses was first demonstrated only in 2021 [25]. The laser generation with a spike structure at 5.38 µm was achieved in a Tb³⁺-doped selenide fiber pumped at 1.98 µm [25]. Since then, other chalcogenide fiber lasers have been demonstrated in this spectral range using various rare-earth ions [26,27]. Ce³⁺-doped laser with mW power, operating near 4.6 µm or near 5 µm (depending on resonator Q-factor), with in-band pump at 4.16 µm was reported in [27]. Currently, to the best of our knowledge, the highest reported power in chalcogenide fiber lasers at wavelengths around 5 µm is 150 mW [26,28].

With the use of single-core chalcogenide glass fibers, the maximum power achieved may be limited by the fiber damage threshold [28]. This limit may be overcome in multichannel systems. However, in multichannel systems with independent channels, it is necessary to provide their coherent combination, which is not an easy task, even in the near-IR range, to say nothing of the mid-IR. In this work, we propose to use a multicore fiber with 25 coupled doped cores arranged in a 5 × 5 square lattice. At the same time, in such a fiber, the intensity of radiation propagating in each core is reduced, which allows the total power to be increased many times over. When coherently combining channels of multicore fibers, in-phase field distribution is frequently used, which is the most intuitive solution [29,30]. We remind the readers that the in-phase distribution is a wave structure in which the spatial phases of the fields are the same in all cores. However, for the proposed fiber design with coupled cores, we operate with an out-of-phase supermode (in which the spatial phases in the neighboring active cores differ by π) that has a number of advantages compared to the in-phase supermode. As was shown theoretically and experimentally, the in-phase supermode is susceptible to instability at relatively high powers, while the out-of-phase mode is stable [31,32]. Further, the coherent beam combining (CBC) technique for out-of-phase supermode radiation can be easily implemented using only two beam-splitters [33,34]. In this case, a feedback system is not required for channel phasing, and the combining efficiency is significantly higher than that for the in-phase supermode [33]. Moreover, for the out-of-phase supermode, the overlap integral with doped cores is maximal and, hence, the gain is maximal, which makes it possible to implement self-selection of modes in the laser and to obtain lasing in this particular mode. It should be noted that the use of active chalcogenide multicore fibers as a laser medium has not been considered before. The goal of our work is a detailed study of this case, which may be important for the development of mid-IR fiber lasers around 5 µm with a power of several watts.

The rest of the article is organized as follows. In Section 2.1, we describe the laser properties of the considered Tb-doped chalcogenide glass. In Section 2.2, we propose a specific design of a multicore fiber, find the parameters of its out-of-phase supermode in comparison with the in-phase one, and find the efficiency of coherent beam combining of the out-of-phase supermode in the far field. Section 2.3 describes in detail the numerical model used to simulate lasers. Section 3 presents the results of laser modeling and their analysis. Discussion and conclusions are given in Section 4.

2. Materials and Methods

2.1. Model of Active Tb-Doped Chalcogenide Glass

We considered chalcogenide glass doped with Tb ions with a concentration of 2 × 10¹⁹ cm⁻³ as an active medium for lasing, with a focus on the best achievements in the field of synthesis of selenide glasses and the manufacture of optical fibers from them [26]. As far as we know, experimental chalcogenide fiber lasers reported to date were based on selenide glass fibers since they have appropriate optical and physicochemical properties [26]. This is what determined our choice.
Figure 1a shows a simplified diagram of laser levels. We assumed that pumping occurs at a wavelength of about 2 μm at the $^7F_6 \rightarrow ^7F_2$ transition, which can be easily achieved using thulium fiber lasers. Moreover, pumping can also be carried out at a slightly shorter wavelength of about 1.9 μm at the $^7F_6 \rightarrow ^7F_1$ transition using thulium fiber lasers too [28]. Laser generation can occur at the $^7F_5 \rightarrow ^7F_4$ transition at wavelengths of about 5 μm. The emission and absorption cross-sections of this transition are shown in Figure 1b.

![Figure 1. (a) Simplified scheme of the energy levels of Tb$^{3+}$ ions. (b) Emission and absorption cross-sections of $^7F_5 \rightarrow ^7F_4$ laser transition.](image)

The parameters of the active Tb-doped Ga–Ge–Sb–Se glass [26,28] used in our simulation are given in Table 1. It is important to note that the lifetime of the upper $^7F_5$ laser level is long enough to create the necessary inversion between this level and the ground state.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump wavelength at 1 → 4 ($^7F_6 \rightarrow ^7F_2$) transition</td>
<td>$\lambda_p$</td>
<td>2 μm</td>
</tr>
<tr>
<td>Laser wavelength at 2 → 1 ($^7F_5 \rightarrow ^7F_6$) transition</td>
<td>$\lambda_s$</td>
<td>5.3 μm</td>
</tr>
<tr>
<td>Total lifetime of level 2 ($^7F_5$)</td>
<td>$\tau_2$</td>
<td>7.5 ms</td>
</tr>
<tr>
<td>Total (non-radiative) lifetime of level 3 ($^7F_4$)</td>
<td>$\tau_3$</td>
<td>10 μs</td>
</tr>
<tr>
<td>Total lifetime of level 4 ($^7F_2$)</td>
<td>$\tau_4$</td>
<td>0.1 ms</td>
</tr>
<tr>
<td>Absorption cross-section at 1 → 4 ($^7F_6 \rightarrow ^7F_2$) transition</td>
<td>$\sigma_{14}$</td>
<td>$0.7 \times 10^{-20}$ cm$^2$</td>
</tr>
<tr>
<td>Emission cross-section at 4 → 1 ($^7F_2 \rightarrow ^7F_6$) transition</td>
<td>$\sigma_{41}$</td>
<td>$0.7 \times 10^{-20}$ cm$^2$</td>
</tr>
<tr>
<td>Absorption cross-section at 1 → 2 ($^7F_6 \rightarrow ^7F_5$) transition</td>
<td>$\sigma_{12}$</td>
<td>$0.35 \times 10^{-20}$ cm$^2$</td>
</tr>
<tr>
<td>Emission cross-section at 2 → 1 ($^7F_5 \rightarrow ^7F_6$) transition</td>
<td>$\sigma_{21}$</td>
<td>$1.09 \times 10^{-20}$ cm$^2$</td>
</tr>
</tbody>
</table>

2.2. Model of Multicore Fiber: Features and Advantages of Out-of-Phase Supermode

The cross-section of the considered active selenide fiber is shown in Figure 2a. We proposed a fiber design with 25 cores arranged in a $5 \times 5$ square lattice. The diameter of each Tb-doped core was set to 20 μm, and the distance between the centers of neighboring cores was set to 25 μm. The refractive index of the cores was $n \sim 2.545$, which corresponds to a Fresnel reflection coefficient of 19% at a wavelength of 5.3 μm. The refractive index of the undoped cladding was 2.538 (the cladding was assumed to be made of Ga–Ge–Sb–Se selenide glass with slightly different exact composition compared to the glass matrix of the cores). For such a fiber, the $V$-parameter is 2.236 at a wavelength of 5.3 μm, i.e., each core is single-mode at the laser signal wavelength. The cladding diameter was 300 μm. The diameter and the glass composition of the second cladding (“cladding 2” in Figure 2a) are not important in our model, but its refractive index must be lower than the refractive index of the 300 μm undoped cladding for waveguide propagation of the pump. We calculated the supermodes of such a fiber using the finite element method. The fields of the fundamental in-phase supermode and the higher out-of-phase supermode are shown in Figure 2b–c, respectively. It can be seen that the out-of-phase mode is much better localized near the cores; between the cores, there are lines on which the fields take zero values. For
an in-phase supermode, the fields are notably wider. The effective mode areas $A_{eff}$ are calculated as follows:

$$A_{eff} = \left( \frac{\iint P_z dx dy}{\iint |P_z|^2 dx dy} \right)^2,$$

where $P_z$ is the longitudinal $z$-component of the Poynting vector. We found that $A_{eff}$ is 7017 μm² and 4892 μm² for in-phase and out-of-phase supermodes, respectively. In this case, the overlap integrals of supermodes with doped cores calculated as

$$\Gamma_s = \frac{\iint_{\text{cores}} P_z dx dy}{\iint_{\text{cores}} \iint |P_z|^2 dx dy},$$

which are 0.74 and 0.91 for in-phase and out-of-phase supermodes, respectively.

![Cross-section of chalcogenide multicore fiber with Tb-doped cores arranged in a 5 × 5 square lattice. Modeled electric fields of in-phase (b) and out-of-phase (c) supermodes. Intensity distributions of the laser beam before (d), after one (e), and after two (f) steps of CBC, calculated in the far field after propagating a path of 5 cm.](image)

Figure 2. (a) Cross-section of chalcogenide multicore fiber with Tb-doped cores arranged in a 5 × 5 square lattice. Modeled electric fields of in-phase (b) and out-of-phase (c) supermodes. Intensity distributions of the laser beam before (d), after one (e), and after two (f) steps of CBC, calculated in the far field after propagating a path of 5 cm.

Next, we considered CBC of the out-of-phase supermode in the far field using two beam splitters, described in detail in [33,34]. The far field intensity found after the 2D Fourier transform is shown in Figure 2d. The intensity after combining at the first beamsplitter is shown in Figure 2e and after combining at two beamsplitters in Figure 2f. In this case, the combining efficiency was 98%.

2.3. Modeling Laser Action in Tb-Doped Chalcogenide Multicore Fibers

A simplified laser scheme based on the proposed Tb-doped chalcogenide multicore $5 \times 5$ fiber is shown in Figure 3a. We assumed that the reflection coefficient for the signal at the pump end was close to 1. We also assumed that the unabsorbed pump power was not reflected from the output end. The reflection coefficient at the output end $R_2$ varied for the laser wave. We calculated the output power. Further, by calculating the far field distributions and applying two consecutive steps of coherent combining with
two beamsplitters, we modeled a highly efficient system for coherent beam combining of an out-of-phase supermode, as described in Section 2.2.

To simulate a laser based on a double-clad Tb-doped chalcogenide glass multicore fiber, we implemented a numerical model taking into account rate equations for levels $^7F_6$, $^7F_5$, $^7F_4$, and $^7F_2$, equations for the evolution of pump and signal (laser) waves along the z-coordinate, and boundary conditions at the fiber ends. The rate equations for the population densities $n_1$, $n_2$, $n_3$, and $n_4$ (normalization to the concentration of Tb$^{3+}$ ions in the core $N_{TB} = 2 \times 10^{-19}$ cm$^{-3}$) read [20]

$$\frac{\partial n_1}{\partial t} = -(W_{12} + W_{14})n_1 + \left(W_{21} + \frac{1}{\tau_2}\right)n_2 + W_{41}n_4 = 0$$

(3)

$$\frac{\partial n_2}{\partial t} = W_{12}n_1 - \left(W_{21} + \frac{1}{\tau_2}\right)n_2 + \frac{n_3}{\tau_3} = 0$$

(4)

$$\frac{\partial n_3}{\partial t} = -\frac{n_3}{\tau_3} + \frac{n_4}{\tau_4} = 0$$

(5)

$$n_1 + n_2 + n_3 + n_4 = 1,$$

(6)

where $t$ is time; $\tau_2$, $\tau_3$ and $\tau_4$ are the lifetimes of levels 2 ($^7F_5$), 3 ($^7F_4$), and 4 ($^7F_2$), respectively; and $W_{kl}$ are the stimulated emission (if $k > l$) and absorption (if $k < l$) rates from level $k$ to level $l$. The stimulated emission and absorption rates for the pump are [20]

$$W_{41,14} = \frac{\Gamma_p\lambda_p\sigma_{41,14}(P_p^+ + P_p^-)}{\hbar c A_c},$$

(7)

where $\hbar$ is Planck’s constant, $c$ is the speed of light in vacuum, $\sigma_{kl}$ are cross sections, $\lambda_p$ is the pump wavelength, $P_p^+$ ($P_p^-$) is the intracavity power at $\lambda_p$ propagating in the forward (backward) direction (see Figure 3a), $A_c = N \times N \times \pi d^2/4$ is the area of all $N \times N$ Tb-doped cores, and $\Gamma_p$ is the overlap integral of the pumping wave with all doped cores evaluated as $\Gamma_p = A_c/\left(\pi d^2/4\right)$. The stimulated rates for the signal (laser) waves at $\lambda_s$ are [20]

$$W_{21,12} = \frac{\Gamma_s\lambda_s\sigma_{21,12}(P_s^+ + P_s^-)}{\hbar c A_c},$$

(8)

where $\Gamma_s$ is the overlap integral defined by Equation (1) and $P_s^+$ and $P_s^-$ are the intracavity powers of the forward-propagating and backward-propagating laser waves at $\lambda_s$. 

![Figure 3. (a) Scheme of Tb-doped chalcogenide glass fiber laser. CBC is the system for coherent beam combining by summing out-of-phase supermode with two beamsplitters. Evolution of intracavity powers at pump wavelength (b) and at signal wavelength (c) modeled for $P_{pump} = 30$ W, $L = 150$ cm, and $R_2 = 0.19$.](image_url)
The equations for the intracavity power evolution are written as [20]

\[
\frac{dP_p^\pm}{dz} = \Gamma_p N_{TB}(\sigma_{41} n_4 - \sigma_{14} n_1)P_p^\pm - \alpha_p P_p^\pm
\]  

(9)

\[
\frac{dP_s^\pm}{dz} = \Gamma_s N_{TB}(\sigma_{21} n_2 - \sigma_{12} n_1)P_s^\pm - \alpha_s P_s^\pm,
\]  

(10)

where \(\alpha_p\) and \(\alpha_s\) are the background fiber losses at \(\lambda_p\) and \(\lambda_s\). The boundary conditions for Equations (9) and (10) are \([20]\)

\[P_s^-(0) = R_1 P_s^+(0)\]  

(11)

\[P_s^-(L) = R_2 P_s^+(L)\]  

(12)

\[P_p^+(0) = R_1 P_p^-(0)\]  

(13)

\[P_p^-(L) = R_2 P_p^+(L)\].  

(14)

The output power \(P_{out}\) at 5.3 \(\mu\)m is calculated as

\[P_{out} = P_s^+(L) \times (1 - R_2).\]  

(15)

All parameters used in modeling are summarized in Tables 1 and 2.

Table 2. Problem parameters used in modeling.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity multicore fiber length</td>
<td>(L)</td>
<td>30–300 cm</td>
</tr>
<tr>
<td>Diameter of Tb-doped core</td>
<td>(d)</td>
<td>20 (\mu)m</td>
</tr>
<tr>
<td>Distance between core centers</td>
<td>(\Delta)</td>
<td>25 (\mu)m</td>
</tr>
<tr>
<td>Tb concentration in the core</td>
<td>(N_{TB})</td>
<td>(2 \times 10^{-19}) cm(^{-3})</td>
</tr>
<tr>
<td>Numerical aperture (cores/cladding)</td>
<td>(NA)</td>
<td>0.189</td>
</tr>
<tr>
<td>Cladding diameter</td>
<td>(D)</td>
<td>300 (\mu)m</td>
</tr>
<tr>
<td>Effective mode field area at (\lambda_s) 5.3 (\mu)m</td>
<td>(A_{eff})</td>
<td>4892 (\mu)m(^2)</td>
</tr>
<tr>
<td>Overlap integral (pump with Tb-doped cores)</td>
<td>(\Gamma_p)</td>
<td>0.11</td>
</tr>
<tr>
<td>Overlap integral (laser wave with Tb-doped cores)</td>
<td>(\Gamma_s)</td>
<td>0.91</td>
</tr>
<tr>
<td>Background fiber loss</td>
<td>(\alpha)</td>
<td>1.7 dB/m (for Figures 4–8)</td>
</tr>
<tr>
<td>Reflection coefficient at (z = 0)</td>
<td>(R_1)</td>
<td>0.5–5 dB/m (for Figures 9 and 10)</td>
</tr>
<tr>
<td>Reflection coefficient at (z = L) for laser wave</td>
<td>(R_2)</td>
<td>0.19–0.99</td>
</tr>
</tbody>
</table>

We numerically modeled the system of Equations (9) and (10), taking into account the boundary conditions (11)–(14). An iterative method based on the Runge–Kutta algorithm was implemented.

3. Results

Using the mathematical model described in detail in Section 2, we performed a theoretical study of high-power mid-IR multicore fiber lasers. From the general theory of lasers, it is known that the lasing thresholds, slope efficiencies, and maximum output powers are influenced by various system parameters, such as cavity length, output reflectance, optical losses, etc. [35]. Therefore, we carried out a detailed theoretical study of the behavior of a laser based on the proposed multicore fiber as dependent on various parameters.

First, we set a high pump power \(P_{pump} = 30\) W and modeled the output laser power as a function of two variables: cavity fiber length \(L\) and output reflection coefficient \(R_2\) (Figure 4). The output power was calculated for each point in the 500 \(\times\) 500 grid of parameters \((L, R_2)\) to ensure precision in plotting the dependence. With increasing reflection coefficient, the optimal length decreased, as shown by the dotted line in Figure 4. Hereinafter, we set the minimum value of output reflectivity \(R_2 = 0.19\), which corresponds to the coefficient.
of Fresnel reflection from the chalcogenide fiber end [28]. In the simplest case, an increase in the reflection coefficient can be achieved using external mirrors [28]. In principle, there are technologies for applying special coatings to the fiber end, which can either increase or decrease \( R_2 \). But such technologies for chalcogenide glasses are not widespread and well-developed, so, in the analysis, we are limited to \( R_2 = 0.19 \). It is seen from Figure 4 that the maximum laser powers are achieved precisely at minimum \( R_2 \). Note that the highest laser power in a mid-IR fiber laser based on a single-core chalcogenide fiber was obtained when the fiber end was used as an output reflector [28]. For the multicore fiber considered in Figure 2, it can be seen that the optimal cavity length is 100–150 cm, allowing output powers >3.5 W to be obtained in 25 phased channels at a pump power of 30 W.

![Figure 4](image_url)

**Figure 4.** Output laser power vs. fiber cavity length \( L \) and reflection coefficient \( R_2 \) for \( P_{\text{pump}} = 30 \) W. The dashed curve shows the optimal fiber length that maximizes output laser power for certain \( R_2 \).

Next, we fixed the length of the resonator \( L = 150 \) cm and plotted the dependence of the output laser power on two variables, which are the pump power \( P_{\text{pump}} \) and the output reflection coefficient \( R_2 \) on the \( 500 \times 500 \) grid (Figure 5). In this case, the output power at high reflection coefficients is significantly inferior to the output power at low values of \( R_2 \). This is also explained by the fact that, for large \( R_2 \), the optimal resonator length is significantly less than 150 cm (Figure 4).

![Figure 5](image_url)

**Figure 5.** Output laser power vs. pump power \( P_{\text{pump}} \) and reflection coefficient \( R_2 \) for \( L = 150 \) cm.

Then, we plotted standard dependences of the output power on the pump power at two values of cavity length: \( L = 100 \) cm (Figure 6a) and \( L = 150 \) cm (Figure 6b) for different reflectance values. It can be seen that the efficiency is significantly higher for small \( R_2 \). Laser thresholds are visible in enlarged subplots. The larger the value of \( R_2 \), the lower the
threshold, which is fully consistent with the general theory of lasers [35]. The considered resonator lengths differ by a factor of 1.5, but the output powers with the same parameters change slightly for high $P_{\text{pump}}$.

Next, we studied in more detail the influence of the cavity length on the output laser power. Figure 7 shows the dependence of the output power on the resonator length and pump power at a fixed optimal value $R_2 = 0.19$ on the 500 × 500 grid. The dotted line shows the optimal length for a fixed pump power. It can be seen that, the greater the power, the longer this length. At the same time, the optimum is quite smooth, i.e., even with a noticeable deviation from the optimal length, the output power does not change much.

For a better visual perception, we plotted the dependence of the output laser power on the resonator lengths for varying reflection coefficients at three different values of pump power, the dependences clearly show that the maxima are quite smooth. At pump powers < 10 W, lengths < 100 cm should be chosen. But the expected output powers are not very high, so simpler fiber designs are suitable to achieve them.
power: $P_{\text{pump}} = 10$ W (Figure 8a); $P_{\text{pump}} = 20$ W (Figure 8b); and $P_{\text{pump}} = 30$ W (Figure 8c). These dependences clearly show that the maxima are quite smooth. At pump powers <10 W, lengths <100 cm should be chosen. But the expected output powers are not very high, so simpler fiber designs are suitable to achieve them.

In a series of numerical experiments (see Figures 4–8), we set the value of loss $\alpha = 1.7$ dB/m, as in experimental work [28]. Note that, for different samples of chalcogenide fibers, background losses can be either larger or, in principle, smaller. Therefore, we also investigated the impact of background fiber losses on laser performance. We plotted the expected output power versus pump power for varying losses (Figure 9). The enlarged dependences, where the lasing thresholds are clearly visible, are shown on the right panel. Indeed, losses greatly affect the generation efficiency. It can be seen that, at a loss level of $\leq1$ dB/m, laser powers $>5$ W are expected to be obtained. At the same time, due to the reduction in heat dissipation during pump thermalization, the influence of parasitic thermo-optical effects is reduced, which is also a favorable factor for the development of a laser system.

Figure 8. Output laser power vs. fiber intracavity length modeled for $P_{\text{pump}} = 10$ W (a); $P_{\text{pump}} = 20$ W (b); and $P_{\text{pump}} = 30$ W (c) for varied $R_2$.

Figure 9. Output laser power vs. pump power, modeled for $L = 150$ cm, $R_2 = 0.19$, and varied fiber background losses.
We plotted the output power as a function of the fiber cavity length for varying losses for a pump level of 30 W (Figure 10a) as well as for a pump level of 100 W (Figure 10b). At the same time, we assumed that the fiber would not be damaged under the action of such high power. Note that, in contrast to the experimental work in [28], where pumping was carried out into a core with a diameter of 19 μm, in our case, we considered pumping into a cladding of a significantly larger diameter of 300 μm (pumping into a cladding is a standard technique for high-power fiber lasers). Therefore, in our case, at $P_{pump} = 100$ W, the pump intensity is even lower than that achieved in [28]. In this case, the predicted laser powers reach a level of 10 W, which is undoubtedly interesting for many applications (atmosphere monitoring, astronomy, lidars, and so on).

![Figure 10](image_url)

**Figure 10.** Output laser power vs. fiber intracavity length, modeled for $P_{pump} = 30$ W (a); $P_{pump} = 100$ W (b), $R_2 = 0.19$, and varied fiber background losses.

### 4. Discussion and Conclusions

We have studied in detail a mid-IR chalcogenide multicore fiber laser at a wavelength of 5.3 μm with an output power level of several watts when pumped into the cladding at a wavelength of 2 μm. We proposed to use a Tb-doped chalcogenide multicore fiber with 25 single-mode cores arranged in a 5 × 5 square lattice as the active medium. This exceeds the power limit of single-core fibers. For the proposed multicore fiber design, the out-of-phase supermode has a significantly larger overlap integral with doped cores than the in-phase supermode. Therefore, the gain for the out-of-phase supermode is maximal, which makes it possible to achieve self-selection of spatial modes and obtain lasing in the out-of-phase mode. If necessary, additional measures for suppression of other modes can be implemented, for example, by inserting a spatial filter between the mirror and the fiber end and placing a mask with four holes that correspond to the locations of the beams (as in Figure 2d) in the Fourier plane of the filter. Moreover, at the output, all channels can be coherently combined, with an efficiency of 98%, using two beamsplitters. Note that this idea of simple, highly efficient coherent beam combining for one-dimensional and two-dimensional beam arrays with out-of-phase spatial distribution of the fields in adjacent channels was experimentally and theoretically demonstrated in [33,34].

When modeling fiber lasers, we specified realistic parameters of Tb-doped chalcogenide glass, focusing on the experimental data in work [28]. We have made a comprehensive theoretical analysis and studied the influence of various factors on the generation parameters. We have shown that a higher lasing efficiency is achieved with the use of Fresnel reflection at the fiber end rather than using an additional mirror that increases the reflection coefficient, which is in excellent agreement with experimental data [28]. We have shown that a laser power of several watts at a wavelength of 5.3 μm can be generated with a pump power of ~30 W for an active fiber length of ~100–150 cm. We have also investigated the effect of background fiber losses and have shown that, when they are reasonably reduced to <1 dB/m, the output power is expected to increase to >5 W (with a pump power of 30 W). Moreover, the lower the losses, the lower the parasitic contribution.
from thermo-optical effects that arise during pump power thermalization [36–38]. We have also shown that a power level of 10 W in the mid-IR range is theoretically achievable at pump intensities that are experimentally supported by a single-core fiber [28].

Thus, the design of a fiber laser at a wavelength of 5.3 µm based on a Tb-doped chalcogenide multicore fiber proposed in our work may be useful for the development of laser systems with a power level of several watts, which can be interesting for practical applications (atmosphere monitoring, astronomy, lidars, and so on).

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