Thulium doped fiber amplifier in the S/S^+ band
Employing Different Concentration profiles

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Thulium Doped Fiber Amplifier in the S/S\(^+\) Band Employing Different Concentration Profiles

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Abstract
This work contains a comparative study for the signal gain of thulium-doped fiber amplifier (TDFA) in the S-Band. Different doping techniques are used to obtain different concentration profiles in silica fibers. The optimal one is found to be the step like profile. TDFA is investigated in new prepared glass hosts. These hosts include: silicate, bismuth, fluoride, tellurite, chalcohalide, and heavy metal oxide. The effect of the different parameters on signal gain of the optical amplifiers is studied, followed by a comparison to select the best glass host. Results showed that the highest gain can provide by bismuth (Bi) glass host and broad band gain from 1450 nm to 1520 nm with a peak wavelength around 1480 nm. A maximum gain above 28.5 dB is obtained with 11 m long Bi-T DFA. These characteristics indicate that Bi-T DFA is a very promising candidate for S-band amplifiers.

Index Terms: Thulium, Concentration Profile, Optical Fiber Amplifiers, Wavelength Division Multiplexing (WDM).

1. Introduction
Increasing demands on the capacity of wavelength division multiplexing (WDM) transmission systems now require newly developed transmission windows beyond the amplification bandwidth (1530-1560 nm; C-band) supported by erbium-doped fiber amplifiers (EDFAs)[1, 2]. Transmission in the L-band (1570-1610 nm) using a gain-shifted EDFA has already been widely recognized as practical [3, 4]. However, one of the most promising bands is S-band. Thulium doped optical fiber amplifiers (TDFAs) for S(1480-1530 nm)/S\(^+\)(1450-1480 nm) bands have been studied extensively in recent years, as the candidates for the next generation amplifiers competing L band EDFAs and other rare-earth doped fiber amplifiers [5]. The advantages of this band are fiber loss which is slightly higher than in the C band, dispersion-shifted fiber (DSF) has a small normal dispersion in this band, and the band is less susceptible to bending loss than the L or C bands. Even though, there have been much increased experimental reports for S and S\(^+\)-band T DFA [6, 7]. The complexity of the amplification dynamics from the number of involving energy levels and difficulty for measuring experimental parameters from the lack of materials and characterization tools such as tunable pumping sources make it very hard to predict the performance of T DFA in detail.
In this paper, the gain of TDFAs has been investigated focusing on the trivalent thulium ion Tm$^{3+}$ as a dopant and two possible types of hosts, namely, silicate and bismuthate Bi$_2$O$_3$). Bi$_2$O$_3$-based host glasses are being investigated in the Bi$_2$O$_3$–GeO$_2$ and Bi$_2$O$_3$–SiO$_2$ systems, which show broadband emission as compared with fluoride and tellurite glasses [8]. On the other hand, fusion spliceability of TDF to conventional SiO$_2$ fibers is a practical requirement to obtain mechanical reliability, low loss and low cost. Bi$_2$O$_3$-based glass is fusion-spliceable to silica fibers using conventional fusion splicing machines.

II. Spectroscopic Considerations

A Tm$^{3+}$ ion has several laser transitions. The main transitions are 0.48, 0.8, 1.47, 1.9 and 2.3 µm [1, 6]. We will focus on the 1.47 µm transition where the stimulated emission occurs between the two excited levels $^3$H$_4$ $\rightarrow$ $^3$F$_4$. However, little attention has been paid to this transition because there are two problems with regard to realizing highly efficient optical amplification with this:

1. The host glass material should have low-phonon energy like fluoride glass; therefore lasing and amplification are essentially impossible in silica glass which is a common material for fiber fabrication [6].

2. This transition is a four-level system and the lifetime of the upper level is shorter than that of the lower level [6].

Concerning the former problem, the fluoride fiber fabrication technique has been improved recently and single-mode low-loss fibers are commercially available. But to date, three approaches have been proposed to solve the latter problem.

1. Co-lasing with the $^3$F$_4$ $\rightarrow$ $^3$H$_6$ transition which corresponds to an emission of 1.8–1.9 µm [6].

2. Minimizing the actual lifetime of the lower level by energy transfer to co-doped ions, such as Tb$^{3+}$ or Ho$^{3+}$ ions [7, 9]. These approaches are based on direct pumping at 0.64 $\sim$ 0.67 µm or 0.79 $\sim$ 0.8 µm [6].

3. Using different pumping techniques as up-conversion and dual wavelength pumping technique shown in Fig. 1. These techniques were firstly developed for thulium doped fluoride fiber amplifiers [8] and finally applied to silicate fibers doped with Tm$^{3+}$ ions to optimize gain and power conversion efficiency and to reduce total pump power [10].

TDFAs with up-conversion pumping behave like amplifiers based on three-level transition even though $^3$H$_4$ $\rightarrow$ $^3$F$_4$ is a four level transition. At the first ground state, $^3$H$_6$ ions are excited to the $^3$H$_5$ level and decay to the metastable $^3$F$_4$ level by multiphonon relaxation. These ions are re-excited to the $^3$F$_{2,3}$ levels by excited state absorption (ESA). The transition ($^3$F$_4$ $\rightarrow$ $^3$F$_{2,3}$) has approximately $10^3$ times higher absorption cross section than transition ($^3$H$_6$ $\rightarrow$ $^3$H$_5$). So, up-conversion pumping at 1.05 µm efficiently reduces the population at $^3$F$_4$, and simultaneously increases that of the $^3$H$_4$ level, leading to a fractional population inversion of unity. This forces TDFAs to normally operate in the S' band (1450-1480 nm) [6]. Pumping wavelengths at 1050, 1047 and 1064 nm [6, 11, and 12] are useful to provide amplification but at the expense of high pump power due to the very low ground state absorption GSA to level $^3$F$_4$ through $^3$H$_5$, it is not a very efficient process. The reason for the chosen pump wavelengths is that the peak of the exited state absorption ESA from $^3$F$_4$ to $^3$F$_2$ is around 1050 nm.

Dual wavelength pumping schemes consist of a main pump source generally at (1050, 1047 and 1064 nm) and an auxiliary one normally at 1560 µm. Dual pumping schemes are generated to face the high pumping power, the problem that faces the conventional up-conversion pumping schemes. Dual pumping can control magnitude or population.
inversion as well as fractional inversion through power optimization between these two pump sources and hence gain shift to longer wavelengths (1480-1510 nm) can be achieved through GS-TDFA [13,14]. Also, the gain profiles as well as the gain tilt can also be controlled by auxiliary pump radiation. But, it suffers from the multistage complexity when dealing with it theoretically or experimentally [10]. In the dual-pump scheme, a reduction of 95 mW from the total pump used for up conversion pumping was reached [10].

Fig.1 Energy-level diagrams of thulium ions and pumping schemes, (a) conventional up-conversion pumping scheme. (b) 1.05-1.56 μm pumping scheme. (c) 1.4-1.56 μm pumping scheme.

III. Description of the Mathematical Model

The principle of energy conservation in terms of input output powers can be expressed as [1]:

\[ P_{s}^{\text{out}} \leq P_{s}^{\text{in}} + \frac{\lambda_{p}}{\lambda_{s}} P_{p}^{\text{in}}, \]  

where \( \lambda_{p}, \lambda_{s} \) are the pump and signal wavelengths, and \( P_{p}^{\text{in}} \) is input pump power, \( P_{s}^{\text{out,in}} \) is the output and input signal powers, respectively. The fundamental physical principle here is that the amount of signal energy that can be extracted from a TDFA can not exceed the pump energy that is stored in the device. Equation (1) can be rewritten, in terms of the amplifier gain \( G \), assuming there is no spontaneous emission, as:

\[ G = \frac{P_{s}^{\text{out}}}{P_{s}^{\text{in}}} \leq 1 + \frac{\lambda_{p}}{\lambda_{s}} \frac{P_{p}^{\text{in}}}{P_{s}^{\text{in}}}, \]  

The maximum possible amplifier gain corresponds to the case where each pump photon is converted into one signal photon and all pump photons are actually absorbed by the amplifying medium. In actual amplifiers, the finite number of rare earth ions existing in the medium limits the absorption of pump photons. In addition, the gain also depends on the fiber length. Hence, the amplifier gain can be represented by:

\[ G_{\text{max}} = \exp(\rho \sigma_{s} L), \]  

where \( \rho \) is the rare-earth element concentration (atom/m\(^{3}\)), which can be expressed in different doping methods and \( \sigma_{s} \) is the signal-emission cross section (m\(^{2}\)). Furthermore,
Eq. (2) shows an important relationship between signal input power and gain. When the input power is very large so that, \( P_{\text{s, in}} >> \left( \frac{\lambda_p}{\lambda_a} \right) P_{\text{p, in}} \), the maximum amplifier gain reaches the limit of unity, which corresponds to a condition of medium transparency. This last relation also shows that for achieving a maximum gain, \( G_{\text{max}} \), the signal input or input flux cannot exceed a value given by:

\[
P_{\text{s, in}} \leq \left( \frac{\lambda_p}{\lambda_a} \right) \frac{P_{\text{p, in}}}{(G - 1)}. \tag{4}
\]

When determining the maximum gain, Eqs. (3) and (4) must be considered together. Consequently, the maximum possible TDFA gain is given by the lowest value of the two gain expressions, i.e.

\[
G_{\text{max}} \leq \min \left\{ \exp \left( \rho \sigma \sqrt{L} \right), 1 + \frac{\lambda_p}{\lambda_s} \frac{P_{\text{p, in}}}{P_{\text{s, in}}} \right\}. \tag{5}
\]

Also, as the fiber length increases for low pumping powers, the gain starts to decrease after a certain length because the pump does not have enough energy to create a complete population inversion in the downward portion of the amplifier. In this case, the un-pumped region of the fiber absorbs the signal resulting in signal loss rather than gain in that section. From Eq. (2), one can note that the maximum output signal power depends on the ratio \( \lambda_p/\lambda_a \). For the pumping scheme to work, one needs to have \( \lambda_p < \lambda_a \) and to have an appropriate gain, it is necessary that \( P_{\text{s, in}} < P_{\text{p, in}} \). Thus, the power conversion efficiency (PCE) will have the form:

\[
PCE = \frac{(P_{\text{s, out}} - P_{\text{s, in}})}{P_{\text{p, in}}} \approx P_{\text{s, out}}/P_{\text{p, in}} \leq \frac{\lambda_p}{\lambda_a} \leq 1. \tag{6}
\]

The maximum theoretical value of the PCE is \( \lambda_p/\lambda_a \). For absolute reference proposes, it is helpful to use the quantum conversion efficiency (QCE), which is wavelength independent and is defined by:

\[
QCE = \left( \frac{\lambda_p}{\lambda_a} \right) \text{PCE}. \tag{7}
\]

The maximum value of QCE is unity, in which case all the pump photons are converted to signal photons. From Eq. (5), it is clear that the concentration of the rare-earth element affects the signal gain. Thus, one can start to study the thulium concentration profiles obtained by various doping methods. A detailed study of erbium concentration profile in silica from a thin metal film has been performed as a function of initial width, \( w \) and diffusion depth, \( d \), by F. Caccavale et al. [15].

### III.1 Thermal Diffusion Method

In this part, the signal gain is studied as a function of the initial thulium thin film width, \( w \), and diffusion depth, \( d \). The thulium concentration profile is given [15]:

\[
\rho(x, y) = \frac{P_o}{2} \exp \left[ -\left( \frac{y}{d} \right)^2 \right] \times \left[ \text{erf} \left( \frac{x + w}{d} \right) - \text{erf} \left( \frac{x - w}{d} \right) \right] + \frac{\lambda_p}{\lambda_a} P_{\text{p, in}}, \tag{8}
\]
where \( d = \sqrt{2D_z t} \) is the diffusion depth, \( d_x = \sqrt{2D_x t} \) is the lateral diffusion width.

The ratio \( \frac{d_x}{d} = \frac{\sqrt{D_x}}{\sqrt{D_z}} \) is kept constant to an approximate value of 0.75 and \( \rho_o \) is the surface concentration where \( \rho_o = 4.0 \times 10^{24} \text{ atom/m}^3 \) is considered. The signal gain profile as a function of \( w \) and \( d \) can be obtained from the average thulium concentration as:

\[
\rho(d, w) = \frac{\int \int P_e \times \exp\left[-\left(\frac{y}{d}\right)^2\right] \times \left[\text{erf}\left(\frac{x+w}{d_x}\right) - \text{erf}\left(\frac{x-w}{d_x}\right)\right] \, dx \, dy}{\int \int \, dx \, dy}.
\]

(9)

**III.2 Ion Implantation Method**

An alternative approach is the ion implantation, where Tm concentration profile as function of implantation process parameters is given by [15]:

\[
\rho(x, y) = \begin{cases} 
\frac{P_e}{2} \times \exp\left[-\left(\frac{y-d}{a_w}\right)^2\right] \times \left[\text{erf}\left(\frac{x+w}{a_s}\right) - \text{erf}\left(\frac{x-w}{a_s}\right)\right] & \text{for } 0 < y < d \\
\frac{P_e}{2} \times \exp\left[-\left(\frac{y-d}{a_w}\right)^2\right] \times \left[\text{erf}\left(\frac{x+w}{a_s}\right) - \text{erf}\left(\frac{x-w}{a_s}\right)\right] & \text{for } d < y
\end{cases}
\]

(10)

The implanted fiber should be thermally annealed to restore the crystalline structure in order to reduce the scattering losses. The annealing process leads to a smoothing of the initially implanted thulium profile. Denote the value of the tail width of semi-Gaussian ion depth distribution as \( a_y \) and the value of the spreading length of the lateral distribution as \( a_x \) to be equal to 0.3 µm and 0.5 µm, respectively. These values are exactly like that reported in [15], \( w \) Where \( \rho_o = 4.0 \times 10^{24} \text{ atom/m}^3 \). \( a_{ym} \) and \( a_{sm} \) represent the tail-width of semi-Gaussian ion depth distribution toward the surface and in-depth, respectively, \( a \) is the spreading length of the lateral distribution. Implantation depth \( d \) and initial implantation strip width \( w \) are kept as independent parameters and the parameter \( d \) is a function of the implantation energy.

**III.3 Step-Like Concentration Profile**

This is a non-conventional doping method; a doping profile with such distribution has been obtained and given by [15]:

\[
\rho(x, y) = \begin{cases} 
\frac{P_e}{2} \times \left[\text{erf}\left(\frac{x+w}{a_s}\right) - \text{erf}\left(\frac{x+w}{a_s}\right)\right] & \text{for } 0 < y < d \\
\frac{P_e}{2} \times \left[\text{erf}\left(\frac{x+w}{a_s}\right) - \text{erf}\left(\frac{x+w}{a_s}\right)\right] & \text{for } d < y
\end{cases}
\]

(11)

where the surface concentration \( \rho_o = 4 \times 10^{24} \text{ atom/m}^3 \). \( a_x = a_y = 0.5 \text{ µm} \) and the thulium profile depth \( d \) and width \( w \) are kept as independent parameters.

Concentration is then used in Eq. (3) to plot the signal gain using the optimum amplifier length, \( L_{opt} \), which is equal to 11 m.
VI. Results and Discussion

Signal Gain Using Different Doping Methods
1. Thermal diffusion method

The concentration \( p_0 \) is taken as \( 1.9 \times 10^{24} \) atom/m\(^3\) and the gain \( G \), as a function of \( d \), presents its maximum in the range \( d = 3-5 \) \( \mu \)m, Fig.2 (a, b and c). For smaller values of \( d \), gain, rapidly decreases, as the total amount of thulium vanishes when \( d \) tends to 0. For \( d > 5 \) \( \mu \)m, the gain decreases of about 0.5 dB and saturates to this value. A further increase of the diffusion depth does not really affect the gain. For \( d = 3-5 \) \( \mu \)m, the gain increases with \( w \) and as a consequence, a maximum gain of 10.85 dB for \( d = 4 \) \( \mu \)m and \( w = 4 \) \( \mu \)m is obtained. This maximum corresponds to \( L_{\text{opt}} = 11 \) m and \( P_{\text{max}} = 1000 \) mW. If we consider \( p_0 = 4 \times 10^{24} \) atom/m\(^3\), the gain dependence on \( d \) and \( w \) is similar to the previous case, and shown in Fig.2, the results are: \( G_{\text{max}} = 22.84 \) dB when \( d = 4 \) \( \mu \)m, \( w = 4 \) \( \mu \)m; \( L_{\text{opt}} = 11 \) m and \( P_{\text{max}} = 1000 \) mW. The main difference with the previous case, apart from the increase in signal gain, is the significant reduction in the required length of the active device.

![Gain graph](image)

**Fig. 2a** Signal gain at \( p_0 = 4 \times 10^{24} \) atom/m\(^3\) with \( \sigma_v = 1.6377 \times 10^{-25} \) m\(^3\) and amplifier length \( L = 11 \) m

![Gain with diffusion depth graph](image)

**Fig. 2b** Signal gain at \( p_0 = 4 \times 10^{24} \) atom/m\(^3\) with \( \sigma_v = 1.6377 \times 10^{-25} \) m\(^3\) and amplifier length \( L = 11 \) m

![Gain with diffusion width graph](image)

**Fig. 2c** Signal gain at \( p_0 = 4 \times 10^{24} \) atom/m\(^3\) with \( \sigma_v = 1.6377 \times 10^{-25} \) m\(^3\) and amplifier length \( L = 11 \) m

2. Ion implantation method

Figure 3 shows the signal gain for ion implanted silica fiber, where it increases with implantation depth. The increasing rate is rapid for low values of \( d \), then it reaches a
maximum around 2-3 μm then decreases rapidly at higher depths. Also, gain increases with width for small values of d but at higher values of d, the gain decreases with w until it reaches zero. The optimal Tm profile has the following parameters: d = 2 μm, w = 4 μm, with $G_{\text{max}} = 6.47$ dB, $L_{\text{opt}} = 11$ m and $P_{\text{max}} = 1000$ mW. Also, if we consider $\rho_o = 4 \times 10^{24}$ atom/m$^3$ the gain dependence on d and w is similar to the previous case.

![Graph showing signal gain vs. d and w](image)

**Fig. 3a** Signal gain at $\rho_o = 4 \times 10^{24}$ atom/m$^3$ with $\alpha_o = 1.6377 \times 10^{-23}$ m$^2$ and amplifier length $L = 11$ m

**Fig. 3b** Signal gain at $\rho_o = 4 \times 10^{24}$ atom/m$^3$ with $\alpha_o = 1.6377 \times 10^{-23}$ m$^2$ and amplifier length $L = 11$ m

**Fig. 3c** Signal gain at $\rho_o = 4 \times 10^{24}$ atom/m$^3$ with $\alpha_o = 1.6377 \times 10^{-23}$ m$^2$ and amplifier length $L = 11$ m

### 3. Step like method

Figure 4 shows the gain dependence on both width, w, and depth, d. It is seen that the gain has a proportion relation with both w and d. As for small values of w and d the value of gain is small and then it increases.

For silica fibers and for $\rho_o = 4 \times 10^{24}$ atom/m$^3$, the maximum gain obtained with different doping method with $L = 11$ m, d = 4 μm and w = 4 μm (for thermal diffusion), and d= 2 μm and w = 4 μm (for ion implantation, and step like) can be summarized in Table 1.

<table>
<thead>
<tr>
<th>Concentration in (atom/m$^3$)</th>
<th>$\rho = 1.9 \times 10^{24}$ atom/m$^3$</th>
<th>$\rho = 4 \times 10^{24}$ atom/m$^3$</th>
<th>$\rho = 9 \times 10^{24}$ atom/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{max}}$ in dB (Thermal Diffusion)</td>
<td>10.85</td>
<td>22.84</td>
<td>51.39</td>
</tr>
<tr>
<td>$G_{\text{max}}$ in dB (Ion implantation)</td>
<td>6.47</td>
<td>13.62</td>
<td>30.65</td>
</tr>
<tr>
<td>$G_{\text{max}}$ in dB (Step like)</td>
<td>8.78</td>
<td>23.73</td>
<td>53.39</td>
</tr>
</tbody>
</table>

Table 1 Maximum TDFA signal gain using silica host glass.
Fig. 4a Signal gain at $p_e=4\times10^{24}$ atom/m$^3$ with $\sigma_e=1.6377\times10^{-25}$ m$^2$ and amplifier length $L=11$ m

Comparing different doping method, Figs. 2-4, it can be seen that for diffusion and ion implantation methods, the diffusion depth is more effective in signal gain than the thulium film width $w$.

The procedure is repeated for the bismuthate glass host fiber amplifier and the maximum gain is calculated for the different profiles and the same lengths and the results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Concentration in (atom/m$^3$)</th>
<th>$p=1.9\times10^{24}$ atom/m$^3$</th>
<th>$p=4\times10^{24}$ atom/m$^3$</th>
<th>$p=9\times10^{24}$ atom/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{max}}$ in dB (Thermal diffusion)</td>
<td>13.04</td>
<td>27.45</td>
<td>61.76</td>
</tr>
<tr>
<td>$G_{\text{max}}$ in dB (Ion implantation)</td>
<td>7.78</td>
<td>16.37</td>
<td>36.84</td>
</tr>
<tr>
<td>$G_{\text{max}}$ in dB (Step like)</td>
<td>10.54</td>
<td>28.52</td>
<td>64.16</td>
</tr>
</tbody>
</table>

Table 2 Maximum TDFA signal gain using bismuthate based fiber with $L=11$ m, $d=2$ $\mu$m and $w=4$ $\mu$m.

**Effect of Amplifier Length**

Figure 5 represents the signal gain against the amplifier length for the three different doping methods. It is observed that the best performance corresponds to the step-like doping.
Wavelength Dependence of the Amplifier Gain

For silica host glass, Figs. 6 and 7 show the wavelength dependence of the signal gain at different values of amplifier length and thulium concentration, respectively. The zero value of the signal gain starts at 1360 nm and increases exponentially until it reaches its maximum value at 1467 nm and then decreases. The same behavior, with different values, is obtained for bismuthate host in Figs. 8 and 9.
From Figs. 6-9, it is clear that the maximum signal gain has a direct proportionality with the concentration, \( p \), and the amplifier length, \( L \). This is not a practical case, because the gain expressed in Eq. (3) cannot be enhanced by increasing the amplifier length or the rare concentration, due to the principle of energy conservation Eq. (1), which limits the output signal power, \( P_{\text{out}} \), expressed in Eq. (2). In addition, higher thulium concentration increases optical losses in glass fiber with consequently decreases the gain [1, 8]. Also, the amplifier length corresponding to maximum gain is related to the pump power [10, 8]. For a given pump power, we find amplifier gain becomes maximum at an optimum value of \( L \) and then decreases. The reason is that the end portion of the amplifier remains un-pumped and absorbs the amplified signal.

The whole procedure is repeated for four other different glass hosts and a comparison for the results obtained is given in Table 3, for the different doping methods. This includes \( \lambda_{\text{op}} \), the wavelength corresponding to the maximum gain, \( G_{\text{max}} \), and \( \Delta\lambda \), the amplifier bandwidth corresponding to the half value of the maximum gain.

<table>
<thead>
<tr>
<th>Glass type</th>
<th>( \lambda ) (nm)</th>
<th>( \Delta\lambda ) (nm)</th>
<th>( G_{\text{max}} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal Diffusion</td>
<td>Ion Implantation</td>
<td>Step Like</td>
</tr>
<tr>
<td></td>
<td>( \text{d}=4\mu \text{m} ) ( \text{w}=4\mu \text{m} )</td>
<td>( \text{d}=2\mu \text{m} ) ( \text{w}=4\mu \text{m} )</td>
<td>( \text{d}=2\mu \text{m} ) ( \text{w}=4\mu \text{m} )</td>
</tr>
<tr>
<td>Silicate</td>
<td>1466</td>
<td>52</td>
<td>22.84</td>
</tr>
<tr>
<td>Bismuthate</td>
<td>1480</td>
<td>98</td>
<td>27.45</td>
</tr>
<tr>
<td>Fluoride</td>
<td>1461</td>
<td>59</td>
<td>27.23</td>
</tr>
<tr>
<td>Tellurite</td>
<td>1463</td>
<td>78</td>
<td>27.34</td>
</tr>
<tr>
<td>Chalcohalide</td>
<td>1483</td>
<td>67</td>
<td>21.19</td>
</tr>
<tr>
<td>Heavy metal oxide</td>
<td>1498</td>
<td>110</td>
<td>29.20</td>
</tr>
</tbody>
</table>

Table 3: Maximum values of signal gain using different doping methods with optimal fiber length \( L_{\text{opt}}=11 \) m.

V. Conclusion

Effects of different doping methods on the signal gain are studied for different glass hosts. From the obtained results, one can observe that the highest gain can be provided by bismuthate glass host followed by the silicate glass host. Results showed a broadband gain from 1450 nm to 1520 nm with a peak wavelength around 1480 nm. A maximum gain above 28.52 dB was obtained with 11 m long Bi-thulium doped fiber (TDF). Moreover, the Bi-TDF is fusion-spliceable to conventional SiO\(_2\) fibers. These characteristics indicate that Bi-TDF is a very promising candidate for S-band amplifiers.

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