Research Letter

Optimization of Multiple Active Ion Doped Fiber Amplifiers for Three Communication Windows

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We present for the first time a theoretical model of Er^{3+} - Tm^{3+} - Pr^{3+} codoped fiber pumped with both 800 nm and 980 nm lasers to explore possibility of this co-doped system as all-wave fiber amplifier. The rate and power propagation equations of the model are solved numerically and the dependence of the gains at 1310, 1470, 1530, 1600, 1650 nm windows on fiber length is calculated. The results show that with pump power of 200 mW/200 mW, when the concentrations of Pr^{3+} , Tm^{3+} , Er^{3+} are around 1.7×10^{24} , 3.9×10^{24} , 1.2×10^{24} (ions/ m^3), respectively, the signals at 1310, 1470, 1530, 1600, 1650 nm may be nearly equally amplified with gain of 13–16.0 dB in the active fiber with length of 23.5 m; the co-doping concentrations and fiber length and pump powers may be further optimized to reduce the ripple.

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1. Introduction

All-wave fiber in which OH group was suppressed is attracting increasing interest in optical transmission system and network because it has low loss windows of 400 nm covering the range 1250–1650 nm. Wavelength Division Multiplexing (WDM) has been the most important technology of large capacity optical transmission system, and optical amplifiers are the key devices of WDM system. Although Fiber Raman Amplifier (FRA) is a promising candidate for long haul and large capacity transmission system, it requires high pump power due to its lower pump efficiency; thus, the solution scheme for all-wave fiber transmission system is not available yet. Compared to FRA, rare-earth doped fiber amplifier has high gain and high pump efficiency, and in the past decade, the research on the rare-earth doped fiber amplifier has been focusing on the single-rare earth-doped fiber amplifiers, and all the amplifiers have their own bandwidths. Er^{3+} -doped fiber amplifier (EDFA) with new split-band configuration [1, 2] was reported providing gain bandwidth of more than 100 nm covering the range 1500–1600 nm; Tm^{3+} -doped fiber amplifiers (TDFAs) [3–5] and Pr^{3+} -doped fiber amplifiers (PDFAs) [6] separately provided

amplification in range of 1450–1520 nm and 1280–1340 nm, respectively.

Recent research on emission properties of Er^{3+} - Tm^{3+} co-doped and Pr^{3+} - Er^{3+} co-doped fibers showed that the combination of the emission at 1530 nm window due to $\text{Er}^{3+}:^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition with the emission at 1470 nm window due to $\text{Tm}^{3+}:^3\text{H}_4 \rightarrow ^3\text{F}_4$ transition may generate a larger seamless emission spectrum up to 200 nm in the co-doped system [7–12]. Meanwhile, the research on emission properties of Pr^{3+} - Er^{3+} co-doped fiber showed that the combination of the emission at 1530 nm window due to $\text{Er}^{3+}:^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition with the emission at 1310 nm window due to $\text{Pr}^{3+}:^3\text{F}_4 \rightarrow ^3\text{H}_5$ transition may generate an emission spectrum having two peaks centered at 1310 nm and 1530 nm windows [7–13]. In this article, we present a theoretical model of Er^{3+} - Tm^{3+} - Pr^{3+} co-doped fiber amplifier for the first time to explore the possibility of this multiple rare-earth doped system for all-wave fiber transmission system application. After the rate and power propagation equations of the doped system are solved numerically and analyzed, the parameters of doped fiber are optimized to achieve the equalized gains for 1310, 1470, 1530, 1600, 1650 nm bands.

FIGURE 1: Schematic of energy levels and transition configurations of Er^{3+} - Tm^{3+} - Pr^{3+} co-doped telluride fiber amplifier pumped with both 800 nm and 980 nm laser diodes.

2. Theoretical Model

Figure 1 shows the schematic of the energy levels and electron transitions and energy transfer process of Er^{3+} - Tm^{3+} - Pr^{3+} -co-doped system pumped by both 800 nm and 980 nm lasers. Following the diagram, the rate equations can be written as an equation group:

$$\begin{aligned}
 \frac{\partial N_1}{\partial t} &= -(W_{13} + W_{14})N_1 + A_{21}N_2 + (W_{31} + A_{31})N_3 \\
 &\quad + (W_{41} + A_{41})N_4 - W_{\text{ET63}}N_1N_6 - W_{\text{ET74}}N_1N_7, \\
 \frac{\partial N_2}{\partial t} &= -(W_{24} + A_{21})N_2 + (W_{42} + A_{42})N_4, \\
 \frac{\partial N_3}{\partial t} &= W_{13}N_1 - (W_{31} + A_{31})N_3 + W_{\text{ET63}}N_1N_6, \\
 \frac{\partial N_4}{\partial t} &= W_{24}N_2 - (W_{41} + W_{42} + A_{41})N_4 + W_{\text{ET74}}N_1N_7, \\
 \frac{\partial N_5}{\partial t} &= -(W_{57} + W_{58})N_5 + W_{68}N_6^2 + W_{\text{ET63}}N_1N_6 \\
 &\quad + W_{\text{ET74}}N_1N_7 + (W_{65} + A_{65})N_6 + W_{\text{ET6-10}}N_6N_9 \\
 &\quad + W_{\text{ET7-11}}N_7N_9 - W_{\text{ET12-8}}N_5N_{12}, \\
 \frac{\partial N_6}{\partial t} &= -W_{\text{ET63}}N_1N_6 - (W_{65} + A_{65})N_6 \\
 &\quad - W_{\text{ET6-10}}N_6N_9 + A_{76}N_7 - 2W_{68}N_6^2, \\
 \frac{\partial N_7}{\partial t} &= W_{57}N_5 + A_{87}N_8 - (W_{\text{ET74}}N_1 + A_{76})N_7 \\
 &\quad - W_{\text{ET7-11}}N_7N_9, \\
 \frac{\partial N_8}{\partial t} &= W_{58}N_5 - W_{\text{ET12-8}}N_{12}N_5 - A_{87}N_8 + W_{68}N_6^2, \\
 \frac{\partial N_9}{\partial t} &= -(W_{9-12} + W_{\text{ET6-10}}N_6 + W_{\text{ET7-11}}N_7)N_9 \\
 &\quad + W_{\text{ET12-8}}N_5N_{12} + (W_{10-9} + A_{10-9})N_{10} - W_{9-10}N_9, \\
 \frac{\partial N_{10}}{\partial t} &= -(W_{10-9} + A_{10-9})N_{10} + W_{9-10}N_9 + W_{\text{ET6-10}}N_6N_9 \\
 &\quad + A_{11-10}N_{11} + (W_{12-10} + A_{12-10})N_{12} \\
 &\quad - W_{10-12}N_{10} - W_{10-13}N_{10},
 \end{aligned}$$

$$\begin{aligned}
 \frac{\partial N_{11}}{\partial t} &= W_{\text{ET7-11}}N_7N_9 - A_{11-10}N_{11} + A_{12-11}N_{12}, \\
 \frac{\partial N_{12}}{\partial t} &= W_{9-12}N_9 + A_{13-12}N_{13} \\
 &\quad - (W_{\text{ET12-8}}N_5 + A_{12-11} + W_{12-10})N_{12} + W_{10-12}N_{10}, \\
 \frac{\partial N_{13}}{\partial t} &= W_{10-13}N_{10} - A_{13-12}N_{13},
 \end{aligned} \tag{1}$$

where N_1 - N_4 are the population densities of Pr^{3+} ion at energy levels $^3\text{H}_4$, $^3\text{H}_5$, $^3\text{F}_4$, $^1\text{G}_4$, N_5 - N_8 are the population densities of Er^{3+} ion at energy levels $^4\text{I}_{15/2}$, $^4\text{I}_{13/2}$, $^4\text{I}_{11/2}$, and $^4\text{I}_{9/2}$, N_9 - N_{13} are the population densities of Tm^{3+} ions at energy levels $^3\text{H}_6$, $^3\text{F}_4$, $^3\text{H}_5$, $^4\text{H}_4$, $^1\text{G}_4$. W_{13} , W_{31} , A_{31} are the stimulated absorption and emission rates, spontaneous emission rate between $^3\text{H}_4$ and $^3\text{F}_4$ levels of Pr^{3+} , respectively. W_{24} , W_{42} , A_{42} are the stimulated absorption and emission rates, spontaneous emission rate between the $^3\text{H}_5$ and $^1\text{G}_4$ levels of Pr^{3+} , respectively. A_{21} is the spontaneous emission rate between the $^3\text{H}_4$ and $^3\text{H}_5$ levels of Pr^{3+} . W_{56} , W_{65} , A_{65} are the stimulated absorption and emission rates, spontaneous emission rate between the $^4\text{I}_{15/2}$ and $^4\text{I}_{13/2}$ levels of Er^{3+} , respectively. W_{58} , A_{87} , A_{76} are the 800 nm-pump absorption rate, spontaneous emission rate from $^4\text{I}_{9/2}$ to $^4\text{I}_{11/2}$ levels, spontaneous emission rate from $^4\text{I}_{11/2}$ to $^4\text{I}_{13/2}$ levels of Er^{3+} , respectively. W_{10-12} , W_{12-10} , A_{12-10} are the stimulated absorption and emission rates, spontaneous emission rate between the $^3\text{H}_4$ and $^3\text{F}_4$ levels of Tm^{3+} , respectively. W_{9-12} , W_{9-10} , W_{10-9} , A_{10-9} , A_{12-11} , A_{11-10} are the 800 nm pump absorption rate, stimulated absorption rate, stimulated emission rate, spontaneous emission rate between $^3\text{H}_6$ and $^3\text{F}_4$ levels of Tm^{3+} , nonradiation transition rate from $^3\text{H}_4$ to $^3\text{H}_5$, nonradiation transition rate from $^3\text{H}_5$ to $^3\text{F}_4$, respectively. W_{1-4} , W_{5-8} , W_{10-13} are 980 nm pump absorption rates between the $^3\text{H}_4$ and $^1\text{G}_4$ levels of Pr^{3+} , between the $^4\text{I}_{15/2}$ and $^4\text{I}_{9/2}$ levels of Er^{3+} , and between the $^3\text{H}_6$ and $^3\text{H}_4$ levels of Tm^{3+} , respectively. $W_{\text{ET6-3}}$, $W_{\text{ET7-4}}$, $W_{\text{ET6-10}}$, $W_{\text{ET7-11}}$, $W_{\text{ET12-8}}$ stand for the transfer rates from $\text{Er}^{3+} : ^4\text{I}_{13/2}$, $\text{Pr}^{3+} : ^3\text{H}_4$ to $\text{Er}^{3+} : ^4\text{I}_{15/2}$, $\text{Pr}^{3+} : ^3\text{F}_4$, from $\text{Er}^{3+} : ^4\text{I}_{11/2}$, $\text{Pr}^{3+} : ^3\text{F}_4$ to $\text{Er}^{3+} : ^4\text{I}_{15/2}$, $\text{Pr}^{3+} : ^1\text{G}_4$, from $\text{Er}^{3+} : ^4\text{I}_{11/2}$, $\text{Tm}^{3+} : ^3\text{H}_6$ to $\text{Er}^{3+} : ^4\text{I}_{15/2}$, $\text{Tm}^{3+} : ^3\text{H}_5$, from $\text{Er}^{3+} : ^4\text{I}_{13/2}$, $\text{Tm}^{3+} : ^3\text{H}_6$

to $\text{Er}^{3+}{}^4\text{I}_{15/2}$, $\text{Tm}^{3+}{}^3\text{F}_4$, from $\text{Tm}^{3+}{}^3\text{H}_4$, $\text{Er}^{3+}{}^4\text{I}_{15/2}$ to $\text{Tm}^{3+}{}^3\text{H}_6$, and from $\text{Er}^{3+}{}^4\text{I}_{9/2}$, $\text{Tm}^{3+}{}^3\text{H}_6$ to $\text{Er}^{3+}{}^4\text{I}_{15/2}$, $\text{Tm}^{3+}{}^3\text{F}_4$, respectively. The transition rates:

$$W_{ij} = \frac{\sigma_{ij}P_k}{h\nu_k A_{\text{eff}}} \quad (i, j = 1 \sim 12, k = s, p), \quad (2)$$

where σ_{ij} is cross-section of the transition between i and j level, and A_{eff} is the effective cross-section area. Propagation of the pump and signal and ASE power along the fiber is described by the differential equation group:

$$\begin{aligned} \frac{dP_{S1}}{dz} &= \Gamma_{1310}(N_3\sigma_{\text{prseB}} - N_2\sigma_{\text{prsaB}})P_{S1} - \alpha_{1310}P_{S1}, \\ \frac{dP_{S2}}{dz} &= \Gamma_{1470}(N_{12}\sigma_{\text{tmseA}} - N_{11}\sigma_{\text{tmsaA}})P_{S2} - \alpha_{1470}P_{S2}, \\ \frac{dP_{S3}}{dz} &= \Gamma_{1550}(N_6\sigma_{\text{erse}} - N_5\sigma_{\text{ersaA}} - N_8\sigma_{\text{ersaB}})P_{S3} - \alpha_{1550}P_{S3}, \\ \frac{dP_{S4}}{dz} &= \Gamma_{1600}(N_3\sigma_{\text{prseA}} - N_1\sigma_{\text{prsaA}})P_{S4} - \alpha_{1600}P_{S4}, \\ \frac{dP_{S5}}{dz} &= \Gamma_{1650}(N_{10}\sigma_{\text{tmseB}} - N_9\sigma_{\text{tmsaB}})P_{S5} - \alpha_{1650}P_{S5}, \\ \frac{dP_{P1}}{dz} &= -\Gamma_{800}[(N_5\sigma_{\text{erpa}} - N_8\sigma_{\text{erpe}}) \\ &\quad + (N_9\sigma_{\text{tmpe}} - N_{12}\sigma_{\text{tmpe}})]P_{P1} - \alpha_{800}P_{P1}, \\ \frac{dP_{P2}}{dz} &= -\Gamma_{980}[(N_1\sigma_{\text{prpa}} - N_4\sigma_{\text{prpe}}) + (N_5\sigma_{\text{erpa}} - N_7\sigma_{\text{erpe}}) \\ &\quad + (N_{10}\sigma_{\text{tmpe}} - N_{13}\sigma_{\text{tmpe}})]P_{P2} - \alpha_{980}P_{P2}, \\ \frac{dP_{\text{ASE1}}}{dz} &= \Gamma_{1310}(N_3\sigma_{\text{prseB}} - N_2\sigma_{\text{prsaB}})P_{\text{ASE1}} \\ &\quad + 2h\nu\Delta\nu N_3\sigma_{\text{prseB}} - \alpha_{1310}P_{\text{ASE1}}, \\ \frac{dP_{\text{ASE2}}}{dz} &= \Gamma_{1470}(N_{12}\sigma_{\text{tmseA}} - N_{11}\sigma_{\text{tmsaA}})P_{\text{ASE2}} \\ &\quad + 2h\nu\Delta\nu N_{12}\sigma_{\text{tmseA}} - \alpha_{1470}P_{\text{ASE2}}, \\ \frac{dP_{\text{ASE3}}}{dz} &= \Gamma_{1550}(N_6\sigma_{\text{erse}} - N_5\sigma_{\text{ersaA}} - N_8\sigma_{\text{ersaB}})P_{\text{ASE3}} \\ &\quad + 2h\nu\Delta\nu N_6\sigma_{\text{erse}} - \alpha_{1550}P_{\text{ASE3}}, \\ \frac{dP_{\text{ASE4}}}{dz} &= \Gamma_{1600}(N_3\sigma_{\text{prseA}} - N_1\sigma_{\text{prsaA}})P_{\text{ASE4}} \\ &\quad + 2h\nu\Delta\nu N_3\sigma_{\text{prseA}} - \alpha_{1600}P_{\text{ASE4}}, \\ \frac{dP_{\text{ASE5}}}{dz} &= \Gamma_{1650}(N_{10}\sigma_{\text{tmseB}} - N_9\sigma_{\text{tmsaB}})P_{\text{ASE5}} \\ &\quad + 2h\nu\Delta\nu N_{10}\sigma_{\text{tmseB}} - \alpha_{1650}P_{\text{ASE5}}, \end{aligned} \quad (3)$$

where P_{P1} , P_{P2} are the pump powers at 800 nm, 980 nm, respectively. P_{S1} , P_{S2} , P_{S3} , P_{S4} , P_{S5} are the powers of the signals at 1310, 1470, 1530, 1600, and 1650 nm bands, respectively. P_{ASE1} , P_{ASE2} , P_{ASE3} , P_{ASE4} , P_{ASE5} are the powers of the ASE at 1310, 1470, 1530, 1600, and 1650 nm bands, respectively. Γ_{1310} , Γ_{1470} , Γ_{1530} , Γ_{1600} , Γ_{1650} are overlapping factors at 1310, 1470, 1530, 1600, 1650 nm bands, respectively, and calculated from [14], and ν is signal frequency. $\alpha(\nu)$ is the frequency dependent background loss of the active fiber.

FIGURE 2: Variation of the gain at 1310, 1470, 1530, 1600, 1650 nm with fiber length. Pump power, input signal power are 200 mW/200 mW, -30 dB m, respectively. The optimal concentration $\text{Pr}^{3+} = 1.9 \times 10^{24}$, $\text{Tm}^{3+} = 3.9 \times 10^{24}$, $\text{Er}^{3+} = 1.2 \times 10^{24}$ ions/ m^3 , and energy transfer coefficient $W_{\text{ET}6-3} = 63 \times 10^{-20}$, $W_{\text{ET}6-10} = 200 \times 10^{-22}$.

σ_{tmseA} , σ_{tmseB} , σ_{erse} are the emission cross-sections of ${}^3\text{H}_4-{}^3\text{F}_4$ (1470 nm) and ${}^3\text{F}_4-{}^3\text{H}_6$ (1650 nm) in Tm^{3+} ions and ${}^4\text{I}_{13/2}-{}^4\text{I}_{15/2}$ (1530 nm) in Er^{3+} ions, respectively. σ_{tmsaA} , σ_{tmsaB} , σ_{ersa} are the absorption cross-sections of ${}^3\text{H}_4-{}^3\text{F}_4$ (1470 nm) and ${}^3\text{F}_4-{}^3\text{H}_6$ (1650 nm) in Tm^{3+} ions and ${}^4\text{I}_{13/2}-{}^4\text{I}_{15/2}$ (1530 nm) in Er^{3+} ions, respectively. σ_{prseA} , σ_{prsaA} and σ_{prseB} , σ_{prsaB} are the emission cross-sections of ${}^1\text{G}_4-{}^3\text{H}_5$ (1310 nm) and ${}^3\text{F}_4-{}^3\text{H}_4$ (1600 nm) in Pr^{3+} ions.

The above differential equation group is solved by numerical integration along the active fiber using Newton iterative method and Runge-Kutta method. It was assumed that the energy transfer rates ($W_{\text{ET}63}$, $W_{\text{ET}74}$, $W_{\text{ET}6-10}$, $W_{\text{ET}7-11}$, $W_{\text{ET}12-8}$) were linearly increasing functions of N_{Er}^t , N_{Tm}^t , N_{Pr}^t , respectively, [15, 16] and are expressed with equations:

$$\begin{aligned} W_{\text{ET}63} &= W_{\text{ET}74} = 1.0 \times 10^{-22} + 4.0 \\ &\quad \times 10^{-49}[(N_{\text{Pr}}N_{\text{Er}})^{1/2} - 1.0 \times 10^{25}], \\ W_{\text{ET}6-10} &= W_{\text{ET}7-11} = 1.0 \times 10^{-22} + 4.0 \\ &\quad \times 10^{-49}[(N_{\text{Tm}}N_{\text{Er}})^{1/2} - 1.0 \times 10^{25}], \\ W_{\text{ET}12-8} &= 1.0 \times 10^{-22} + 4.0 \\ &\quad \times 10^{-49}[(N_{\text{Tm}}N_{\text{Er}})^{1/2} - 1.0 \times 10^{25}]. \end{aligned} \quad (4)$$

3. Result and Discussion

Figure 2 shows the variation of the gains at the five bands (1310, 1470, 1530, 1600, 1650 nm) with the fiber length and with optimized dopant concentrations: Pr^{3+} concentration at 1.7×10^{24} , Tm^{3+} concentration at 3.9×10^{24} , Er^{3+}

TABLE 1: Spectral parameters of Er^{3+} -doped and Tm^{3+} and Pr^{3+} doped telluride fiber for numerical calculation.

Parameter	Symbol	Value	Unit	Remarks
Core diameter	2r	5.0	μm	
Background loss	α	0.1	dB/m	
Pr^{3+}	$\sigma_{\text{prseB}}, \sigma_{\text{prsaB}},$	2.0×10^{-25}	m^2	[17]
	$\sigma_{\text{prseA}}, \sigma_{\text{prsaA}},$	6.3×10^{-25}	m^2	
	A_{31}	4000	1/s	
	A_{42}	2778	1/s	
Tm^{3+}	σ_{tmseA}	4.5×10^{-25}	m^2	[18]
	σ_{tmsaA}	4.5×10^{-25}	m^2	
	σ_{tmseB}	8.6×10^{-25}	m^2	
	σ_{tmsaB}	8.6×10^{-25}	m^2	
	A_{10-9}	311	1/s	
	A_{11-10}	131	1/s	
	A_{10-9}	400	1/s	
	σ_{tmpa}	4.5×10^{-25}	m^2	
	σ_{tmpe}	1.0×10^{-27}	m^2	
Er^{3+}	σ_{erse}	8.6×10^{-25}	m^2	[18]
	σ_{ersa}	8.5×10^{-25}	m^2	
	σ_{erpe}	1.0×10^{-26}	m^2	
	σ_{erpa}	4.48×10^{-25}	m^2	
	σ_{erpe}	1.0×10^{-27}	m^2	
	A_{65}	172.4	1/s	
	A_{85}	1804.3	1/s	
	A_{76}	1000	1/s	
	A_{87}	51000	1/s	
Overlap factor	$\Gamma(\lambda)$	0.876		800 nm
		0.500		1310 nm
		0.641		1470 nm
		0.451		1530 nm
		0.300		1650 nm

concentration at 1.2×10^{24} ions/ m^3 and fixed pump powers at 200 mW/200 mW for 800 nm/980 nm.

When fiber length increases from 0.0 to 30.0 m, the gain at 1310 nm increases monotonically from 0.0 to 17.6 dB, and the gains at 1470, 1530, and 1600 nm increase from 0.0 to 17.7 dB, 27.0 dB, 16.0 dB at the fiber lengths 18.0, 14.0, 23.0 m, respectively; after these lengths, they drop. The gain at 1650 nm decreases from 0.0 to -4.8 dB; after the length 14.0 m, it rises. We think that the variation of the gains at 1310–1600 nm with fiber length is reasonable. With fixed pump power and fiber length increasing from 0 to certain level, pump powers are so high that the number of population inversions between the $^1\text{G}_4$ and $^3\text{H}_5$ level of Pr^{3+} ions, the $^3\text{H}_4$ and $^3\text{F}_4$ level of Tm^{3+} ions, the $^4\text{I}_{13/2}$ and $^4\text{I}_{15/2}$ levels of Er^{3+} ions increases; thus, the gains increase. When fiber length is over the level, pump powers are consumed so much that the inversion number drops; thereby the gain decreases. For the channel at 1650 nm originating from the transition from the $^3\text{F}_4$ to $^3\text{H}_6$ levels of Tm^{3+} , it shares same level ($^3\text{F}_4$) with the channel at 1470 nm arising from the transition from $^3\text{H}_4$ and $^3\text{F}_4$ level of the ions, but the shared

level acts as the upper level for 1650 nm channel and the terminated level for 1470 nm; therefore, the gains at 1470 nm and 1650 nm have opposite variation trend with increased fiber length.

4. Conclusions

In conclusion, we have presented a theoretical model of Er^{3+} - Tm^{3+} - Pr^{3+} co-doped fiber amplifier pumped with 800 nm and 980 nm lasers. The rate and power propagation equations of the model have been solved numerically and the dependence of the gains at 1310, 1470, 1530, 1600, 1650 nm windows on the fiber length has been calculated. The results showed that with pump power of 200 mW/200 mW, when concentrations of Pr^{3+} , Tm^{3+} , Er^{3+} are around 1.7×10^{24} , 3.9×10^{24} , 1.2×10^{24} (ions/ m^3), respectively, the signals at 1310, 1470, 1530, 1600, 1650 nm may be nearly equally amplified with gain of 13–16.0 dB in the active fiber with fiber length of 23.5 m. The co-doping concentrations and fiber length and pump powers of the co-doped system may be further optimized to reduce the ripple.

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