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Investigation of multipass Yb-doped fiber amplifiers: supplement

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This document provides details on fiber amplifier model used in numerical calculations. Equations describing the model are presented below:

$$\pm\frac{dP_{s,p}{}^{\pm}(z)}{dz} = \Gamma_s(N_2(z)\sigma_e(\lambda_s) - N_1(z)\sigma_a(\lambda_s))P_{s,p}{}^{\pm}(z) - \alpha P_{s,p}{}^{\pm}(z) \quad \textbf{(S1)}$$

$$\pm\frac{dP_p{}^{\pm}(z)}{dz} = \Gamma_p\big(N_2(z)\sigma_e(\lambda_p) - N_1(z)\sigma_a(\lambda_p)\big)P_p{}^{\pm}(z) - \alpha P_p{}^{\pm}(z) \quad \textbf{(S2)}$$

$$\pm\frac{dP_{ASE,n}{}^{\pm}(z)}{dz} = \Gamma_{ASE}\big(N_2(z)\sigma_e(\lambda_n) - N_1(z)\sigma_a(\lambda_n)\big)P_{ASE,n}{}^{\pm}(z) + \frac{2\Gamma_{ASE}\sigma_e(\lambda_n)hc^2}{\lambda_n{}^3\Delta\lambda}N_2(z) - \alpha P_{ASE,n}{}^{\pm}(z) \quad \textbf{(S3)}$$

$$N_2(z) = N_t\frac{B(z)}{C(z)} \quad \textbf{(S4)}$$

$$B(z) = \frac{\Gamma_p\lambda_p\sigma_a(\lambda_p)\,P_p(z)}{hcA} + \frac{\Gamma_s\lambda_s\sigma_a(\lambda_s)\,P_s(z)}{hcA} + \sum_{n=1}^{k}\frac{\Gamma_{ASE}\lambda_n\sigma_a(\lambda_n)\,(P_{ASE,n}{}^{+}(z) + P_{ASE,n}{}^{-}(z))}{hcA} \quad \textbf{(S4.1)}$$

$$C(z) = \frac{\Gamma_p\lambda_p\left(\sigma_a(\lambda_p) + \sigma_e(\lambda_p)\right)\,P_p(z)}{hcA} + \frac{\Gamma_s\lambda_s\big(\sigma_a(\lambda_s) + \sigma_e(\lambda_s)\big)\,P_s(z)}{hcA} + \sum_{n=1}^{k}\frac{\Gamma_{ASE}\lambda_n\big(\sigma_a(\lambda_n) + \sigma_e(\lambda_n)\big)(P_{ASE,n}{}^{+}(z) + P_{ASE,n}{}^{-}(z))}{hcA} + \frac{1}{\tau_r} \quad \textbf{(S4.2)}$$

$$N_1(z) = N_t - N_2(z) \quad \textbf{(S5)}$$

$$P_p(z) = P_p{}^{+}(z) + P_p{}^{-}(z) \quad \textbf{(S6)}$$

$$P_s(z) = \sum_{p=1}^{l} P_{s,p}{}^{+}(z) + P_{s,p}{}^{-}(z) \quad \textbf{(S7)}$$

$$P_{ASE}(z) = \sum_{n=1}^{k} P_{ASE,n}{}^{+}(z) + P_{ASE,n}{}^{-}(z) \quad \textbf{(S8)}$$

Here:

$P_p(z), P_s(z), P_{ASE}(z)$ denote pump, signal and ASE power, respectively, versus coordinate z along the fiber. Symbol $\pm$ indicates forward (+) and backward (-) propagation directions. Index n in ASE power notation means ASE channel number, and index p in signal power notation indicates number of polarization state. k denotes total number of ASE channels, and l denotes total number of signal polarization states.

$\Gamma_p, \Gamma_s, \Gamma_{ASE}$ denote overlap factor between doped area (fiber core) and intensity distribution of pump, signal, and ASE, respectively.

α is the fiber attenuation coefficient. We neglected this parameter in our calculations.

N_t is ytterbium dopant concentration. $N_1(z), N_2(z)$ are ground-level and upper-level populations, respectively, versus coordinate z along the fiber.

λ_p, λ_s are pump and signal wavelength, respectively. λ_n denotes center wavelength of n-th ASE channel. $\Delta\lambda$ is ASE channel spectral bandwidth.

$\sigma_a(\lambda)$, $\sigma_e(\lambda)$ denote absorption and emission cross-sections of ytterbium (Yb) ions at λ wavelength, respectively. We used analytical description of absorption and emission cross-sections of Yb in germanosilicate glass provided in reference [1]. This description is based on experimental measurements provided in reference [2].

τ_r is excited-state lifetime, A is area of fiber core, h is Planck constant, c is speed of light.

In our model we assumed core-pumped fiber amplifier configuration. Required parameters of gain medium were evaluated based on specifications of commercially available fiber PM-YSF-HI. Specific values of some parameters we used in the calculations are provided in the Table S1.

Table S1. Values of active fiber parameters used in numerical modelling.

Parameter	Value
$\boldsymbol{N_t}$	3×10^{25} m^{-3}
$\boldsymbol{\Gamma_p}$	0.772
$\boldsymbol{\Gamma_s, \Gamma_{ASE}}$	0.744
$\boldsymbol{A}$	28.3 μm^2
$\boldsymbol{\tau_r}$	0.84 ms
$\boldsymbol{\alpha}$	0
$\boldsymbol{k}$	40
$\boldsymbol{\Delta\lambda}$	4.35 nm
$\boldsymbol{\lambda_p}$	976 nm
$\boldsymbol{\lambda_s}$	1030 nm

References

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2. R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," IEEE J. Quantum Electron. **33**, 1049–1056 (1997).