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Abstract

We show that the learned neural networks (NNs)-based solver of Raman amplifier (RA) equations enables ultrafast and accurate power evolution and gain spectra predictions in bidirectional-pumped RAs. This NNs model also provides a universal solution for intricate broadband RA's optimizations.

Motivations

- Current numerical solvers are computationally demanding which need to be run every time a new gain profile is needed.
- The available analytical solutions are derived under small signal regime or pumped by a single wavelength which are not applicable in widely-used practical scenarios.
- Practical fiber-optic system deployment requires accurate and ultra-fast RA's gain response and flattening.
- Physics-informed NNs have been used for RAs modeling and optimization [1, 2].

Physical model

The design and analysis are based on an appropriate model that includes fibre attenuation, Rayleigh backscattering and SRS-induced Raman interactions in all directions, described by a set of Raman coupled differential equations (RCDEs) [3]:

$$\pm \frac{dP_{s/p}^{\pm}(z, \nu)}{dz} = -\alpha(\nu)P_{s/p}^{\pm}(z, \nu) + \gamma(\nu)P_{s/p}^{\mp}(z, \nu) + \int_{\zeta > \nu} \left\{ \frac{g_R(\nu - \zeta)}{A_{eff}} [P_{s/p}^{\pm}(z, \zeta) + P_{s/p}^{\mp}(z, \zeta)] \cdot P_{s/p}^{\pm}(z, \nu) \right\} d\zeta \quad (1)$$

Physical Model Embedding

$$\mathcal{L} = w_1 \sum_{ch=1}^{N_p+N_s} |Eq. (1) \text{ right side} - Eq. (1) \text{ left side}| + w_2 \sum_{ch=1}^{N_s+N_p} [P_{s/p}^+(0) - \hat{P}_{s/p}^+(0)] + [P_{s/p}^+(L) - \hat{P}_{s/p}^+(L)]$$

minimize loss, \mathcal{L}

Training Loop

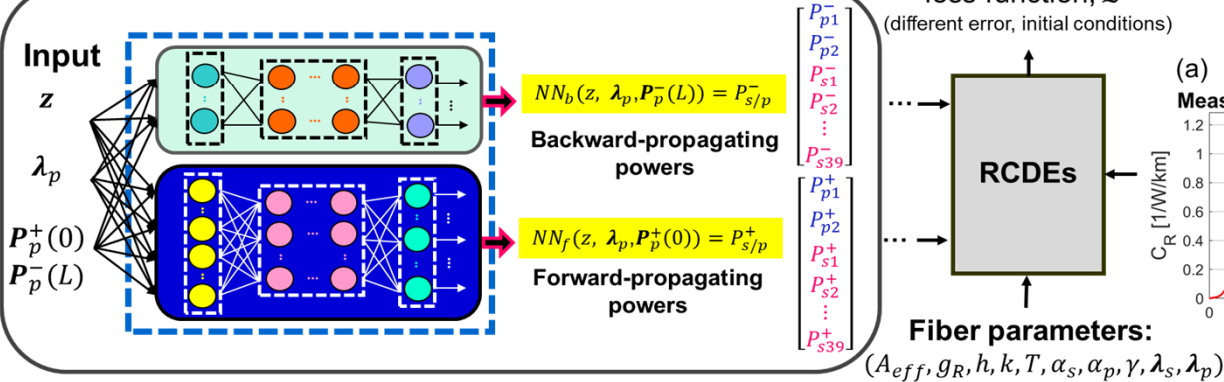
loss function, \mathcal{L}

(different error, initial conditions)

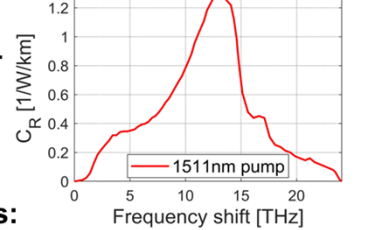
Working principle:

- ① Put RCDEs into the physical model embedding block.
- ② Run training loop.
- ③ Loss converged.
- ④ NNs output the solution of RCDEs.

Neural Networks Solving RCDEs



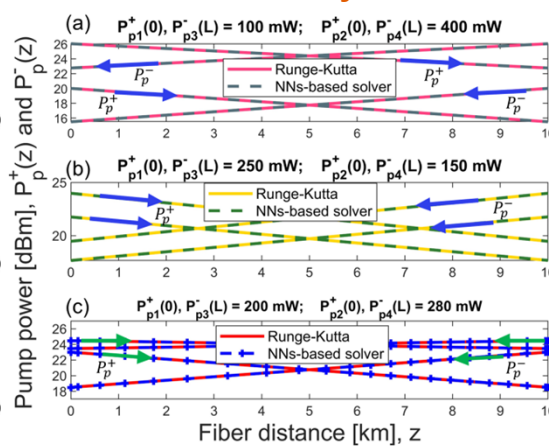
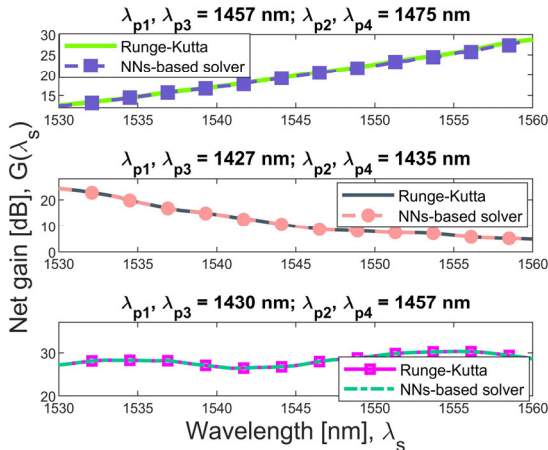
(a) Measured Raman gain efficiency



Fiber parameters:

($A_{eff}, g_R, h, k, T, \alpha_s, \alpha_p, \gamma, \lambda_s, \lambda_p$)

Results and Analysis



➤ A new NNs-based solver is proposed and enables accurate predictions of power evolution and gain spectra compared to Runge-Kutta.

➤ The prediction execution time using our proposed solver is reduced with several orders of magnitude compared to Runge-Kutta.

➤ This AI-based model could be also used to foresee the impact of SRS on the fiber span of a S+C+L-band system and to design the distributed RAs to compensate for this effect.

References

- [1] Song Y, et al., Commun. Eng., 2024, 3(1): 109.
- [2] Zhang L, et al., CLEO: Science and Innovations, 2024, STh3J.5.
- [3] Kidorf H, et al., IEEE Photonics Technol. Lett., 1999, 11(5): 530-532.

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