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Loss prediction of three-level amplified spontaneous emission sources in radiation environment

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A model of three-level amplified spontaneous emission (ASE) sources, considering radiation effect, is proposed to predict radiation induced loss of output power in radiation environment. Radiation absorption parameters of ASE sources model are obtained by the fitting of color centers generation and recovery process of gain loss data at lower dose rate. Gain loss data at higher dose is applied for self-validating. This model takes both the influence of erbium ions absorption and photon bleaching effect into consideration, which makes the prediction of different dose and dose rate more accurate and flexible. The fitness value between ASE model and gain loss data is 99.98%, which also satisfies the extrapolation at the low dose rate. The method and model may serve as a valuable tool to predict ASE performance in harsh environment.

Keywords: amplified spontaneous emission (ASE) sources, irradiation effects, model extrapolation, performance prediction

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1. Introduction

Amplified spontaneous emission (ASE) sources exhibit excellent properties such as high output power, low thermal sensitivity and broadband spectrum, showing particular advantages on application of high precision fiber-optic gyroscopes (FOGs) and optical fiber sensing systems.[1,2] However, application of ASE sources in space will inevitably suffer from radiation environment.[3,4] These ionizing radiations cause degradation of gain and signal transmission in erbium doped fibers (EDFs), consequently degradation of ASE sources.[5,6] Generally, it is believed that the degradation mainly caused by the creation of color centers (CCs) that are responsible for a so-called radiation-induced attenuation (RIA).[7,8] And there coexist two combined effects: a) pump absorption by CCs which indirectly causes reduction of gain, and b) gain absorption by CCs. Besides, pump-induced bleaching in EDFs should also be in consideration.

A large body of researches have contributed to predict performance of EDFs in harsh environment, either in ASE source or in Er-doped fiber amplifiers (EDFAs).[9] Nevertheless, as suggested earlier the simple passive measurement of RIAs for loss prediction is insufficient, for a big deviation between calculation and measured loss occurred when extrapolating to low dose rate.[10,11] On one hand, RIA difference among the gain band should be taken into consideration for the gain bandwidth of ASE sources is about 40 nm, which means the experiment will be more complicated. On the other hand, passive measurements of RIA are not always adequate for gain prediction of three-level pump system as a result of photon bleaching effects at 980 nm. Then some other approaches were adopted for loss prediction of EDFs. Authors in Refs. [12,13] used RIA at 1310 nm to extrapolate RIA at other wavelengths with a simplified Lorentz tail absorption formula. This method avoids the measurement deviation of RIA induced by photon bleaching of 980 nm. Unfortunately, extrapolation of RIA from 1310 nm to 980 nm may introduce a huge error as color-center absorption coefficient at 1310 nm is three times smaller compared with absorption at 980 nm.

Therefore, we present an active measurement method to evaluate radiation induced power loss at 980 nm and gain band based on three-level ASE sources. It is well known that the RIA is a consequence of the generation and decay of CCs whose absorption bands generally located in the ultraviolet (UV) region. The kinetic response to irradiation dose for a given interrogating wavelength is usually the sum of different contributions from the underlying absorption bands kinetics. It can be described by saturating exponential model, which is powerful for its scalability, flexibility and effectiveness on modeling the dose and dose rate influence on attenuation.[14] A model based on spectrum dependency of RIA is introduced to obtain the spectrum response, reducing the extrapolation error from long wavelength. Then it is possible to predict the losses at pump and signal wavelengths. Besides, there is no report on modeling the radiation induced gain degradation of three-level ASE sources. This paper firstly models the radiation induced loss of gain for three-level ASE sources with the new measurement method.

2. Theory

Radiation creates numbers of CCs in the EDF, which increases the absorption of 980 nm pump and 1550 nm signal. The loss prediction model of three-level ASE sources under

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irradiation environment can be derived by substituting $\alpha(\nu,t)$ into the original three-level ASE sources output model[15]

$$\frac{\mathrm{d}P_{\mathrm{p}}(z,\nu_{\mathrm{p}})}{\mathrm{d}z} = -[\gamma_{\mathrm{p}}(z,\nu_{\mathrm{p}})+\alpha(\nu_{\mathrm{p}},t)]P_{\mathrm{p}}(z,\nu_{\mathrm{p}}), \quad (1)$$

$$\frac{\mathrm{d}P^{\pm}_{\mathrm{ASE}}(z,\nu_i)}{\mathrm{d}z} = \pm[\gamma_{\mathrm{s}}(z)-\alpha(\nu_i,t)]P^{\pm}_{\mathrm{ASE}}(z,\nu_i) \pm 2h\nu_i\gamma_{\mathrm{es}}(z,\nu_i)\frac{\Delta\nu}{n}, \quad (2)$$

where h is the Planck constant, $\Delta\nu$ is the gain band of EDF and evenly divided into n sections, $P_{\mathrm{p}}(z,\nu_{\mathrm{p}})$ and $P^{\pm}_{\mathrm{ASE}}(z,\nu_i)$ are the optical power of pump and signal at position z, respectively. "+" and "−" indicate the transmission direction of light. $\gamma_{\mathrm{p}}(z,\nu_{\mathrm{p}})$, $\gamma_{\mathrm{s}}(z)$, and $\gamma_{\mathrm{es}}(z)$ are the pump gain coefficient, signal stimulated emission coefficient, and signal spontaneous emission coefficient, respectively. $\alpha(\nu_i,t)$ and $\alpha(\nu_{\mathrm{p}},t)$ are the signal absorption loss and pump absorption loss of all CCs at radiation duration t, respectively.

The transmission loss $\alpha(\nu,t)$ can be described by a sum of different CCs[16]

$$\alpha(\nu,t) = \sum \alpha_k(\nu,t), \quad (3)$$

where k is the type of CCs and can be obtained by the decomposition of RIA spectrum.

A mixed Gaussian–Lorentz absorption profile is applied to describe the spectrum dependency of CCs

$$\alpha_k(\nu) = \Gamma_k\left\{\frac{\Delta\nu_k}{2\pi[(\nu-\nu_k)^2+(\Delta\nu_k/2)^2]} + \left(\frac{4\ln 2}{\pi}\right)^{\frac{1}{2}}\frac{1}{\Delta\nu_k}\exp\left[-\frac{4\ln 2(\nu-\nu_k)^2}{(\Delta\nu_k/2)^2}\right]\right\}, \quad (4)$$

where ν_k and $\Delta\nu_k$ are the characteristic parameters, representing the peak position and full width at half-maximum (FWHW) of the kth color center, respectively, and Γ_k is the number of the kth color center.

Under irradiation, CCs concentration can be described by differential equation, which takes into account both generation and annealing. Similarly, the kth color center induced absorption α_k can be described by the following differential equation:[17]

$$\frac{\mathrm{d}\alpha_k(\nu)}{\mathrm{d}t} = g_k f\left(\dot{D}\right) - \frac{\beta_k t^{\beta_k-1}}{\tau_k^{\beta}}\alpha_k^m(\nu), \quad (5)$$

where $g_k f\left(\dot{D}\right)$ represents defects generated over unit time, which is the function of dose rate. $\frac{\beta_k t^{\beta_k-1}}{\tau_k^{\beta}}\alpha_k^m$ describes annealing process, β_k is a constant between 0 and 1, and m is the order of the kinetic model. τ_k is a time constant describing the recovery process of CCs. In the research of Williams,[18] the fitting is the best with a dynamic order $m=2$.

After irradiation, α_k represents the annealing process, which is proportional to the number of CCs recovery. Therefore, the number of kth color center recovery can be expressed as

$$\Delta n_k(t) = n_{k0}\left(1-\frac{1}{(t/\tau_k)^{\beta_k}+1}\right), \quad (6)$$

where n_{k0} and Δn_k are the quantity of the kth color center at initial time and time t, respectively. These values of β_k and τ_k can be acquired by the fitting of the color center recovery process of the EDF.

Hence, ASE source loss prediction model can be obtained by solving types of CCs in Eq. (3) and every color center generation and annealing parameters in Eq. (5).

3. Experiment

The EDF used in the experiment is doped with aluminum (Al) to avoid concentration quenching due to clustering of the erbium ions, and the main parameters is given in Table 1.

The experiment setup used to measure the loss of gain is shown in Fig. 1. All the testing devices are positioned outside the ^{60}Co chamber except for EDF under test, between

Table 1. The fabricated parameters of EDF.

Fiber	Mode field diameter (μm)	Attenuation (dB/m)	Numerical aperture	Length (m)
M-12	3.7@980 nm 6.2@1550 nm	11–13@980 nm 18@1530 nm	0.21–0.23	3

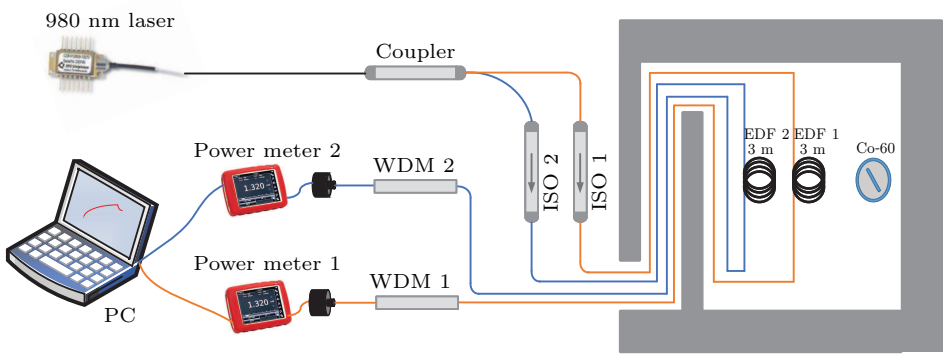


Fig. 1. Experimental setup designed for online measurements of the RIA at gain band in EDFs.

which are 16 m single mode (SM) fiber connected by fusion splice. Two groups of the same EDF with a length of 3 m are tested and named as EDF 1 and EDF 2, respectively. The EDF was concentrically spooled into a flat annular geometry with diameter of $\sim$ 20 cm and mounted to a sheet of cardboard, which was placed inside the ^{60}Co chamber. EDF 1 was with a dose rate of 30 Gy/min to total dose of 220 Gy. Due to EDF 2 far away from radiation source, it was with a dose rate of 0.8 Gy/min to total dose of 120 Gy.

The 980 nm laser with a pump power of 50 mW is equally split into two paths by coupler to pump EDF 1 and EDF 2. Isolators (ISO) are used to prevent backward signal light for enhancing the stability of 980 nm laser. Wavelength division multiplexers (WDM) are used to separate the pump and signal. Two power meters connected to computer simultaneously record the power at gain band. EDF 1 is used for modeling. EDF 2 is used for predicting.

4. Results and discussion

4.1. Resolve of radiation induced absorption spectrum

Post-irradiation spectrums of EDF are continuously recorded for seven hours and the measured spectrum is illustrated in Fig. 2 and marked by red circles. RIA spectrum and recovery spectrum are decomposed into different components to confirm the species of CCs. Researches have investigated the kind of CCs in EDF, indicating that Al- and Si-related CCs are responsible for RIA in Er–Al doped fibers.[19] And the profile of CCs are assumed to be Gaussian shapes. The fitting result with Gaussian shape shows a good consistence with measurement absorption at high energy band but lager errors do exist in low energy bands such as NIR and IR. In this paper, a solution combining the Gaussian and Lorentzian line shapes are acquired to resolve RIA and recovery spectrum.

And then the RIA spectrum is well reproduced by three kinds of CCs. The results and fitted parameters of CCs are shown in Fig. 2 and Table 2, respectively.

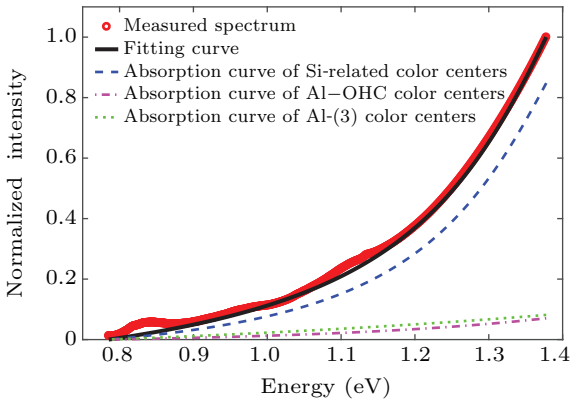


Fig. 2. The Gaussian and Lorentz reproduction of RIA absorption bands of EDF at the dose rate of 30 Gy/min in the near-infrared region.

As the peak position parameters v_k and FWHW Δv_k of CCs had been determined, the spectrum dependency parameter $a_k(v)$ of CCs could be figured out by Eq. (4). The gain band (1520–1570 nm) is divided into 11 intervals and the values of $a_k(v)$ relative to 980 nm are given in Table 3.

It seems the difference over the gain band is not remarkable, and this RIA difference is no more than 0.3 dB in the experiment.

Table 2. Kinds of CCs resolved from RIA spectrum.

Center (eV)	Width (eV)	Source
1.5	0.37	related to Si[a]
2.25	0.8	Al–OHC[b,c]
3.1	1.5	Al(3)[d]

[a]Ref. [20]. [b,c]Refs. [21,22]. [d]Ref. [23].

Table 3. The absorption ration between gain band and pump wavelength of Si-related, Al–OHC and Al-(3) CCs.

Wavelength (nm)	Si-related	Al–OHC	Al-(3)
1520	0.176503601	0.373164	0.679086187
1525	0.175220289	0.371365	0.677649808
1530	0.173958842	0.369590	0.676227163
1535	0.172718734	0.367838	0.674818060
1540	0.171499454	0.366110	0.673422308
1545	0.170300509	0.364405	0.672039723
1550	0.169121417	0.362721	0.670670120
1555	0.167961715	0.361060	0.669313321
1560	0.166820950	0.359420	0.667969149
1565	0.165698685	0.357801	0.666637432
1570	0.164594494	0.356203	0.665317999

4.2. The model of recovery processes

Measurements of recovery spectrums are recorded for seven hours after irradiation and given in Fig. 3.

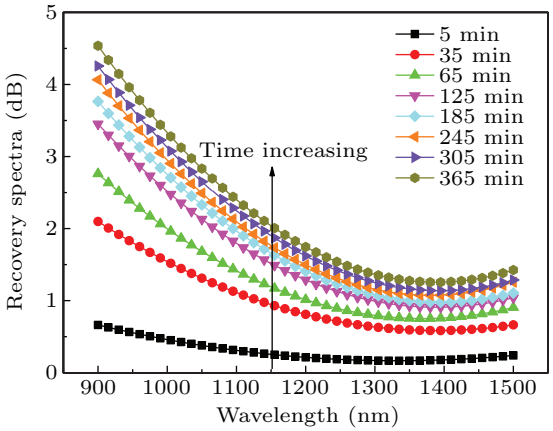


Fig. 3. Continuous spectrum measurements between 900–1500 nm in seven hours.

Then recovery spectrums at different time are resolved respectively, from which recovery process of three kinds CCs are obtained. Then, τ_k is figured out by fitting the recovery processes of the kth color center with Eq. (6). For comparison, the recovery of CCs is normalized. But the recovery process of Al-(3) color center is failed to model due to its large time constant (τ is greater than 10^9 min). And the fitting results of the Si-related and Al–OHC CCs are shown in Fig. 4.

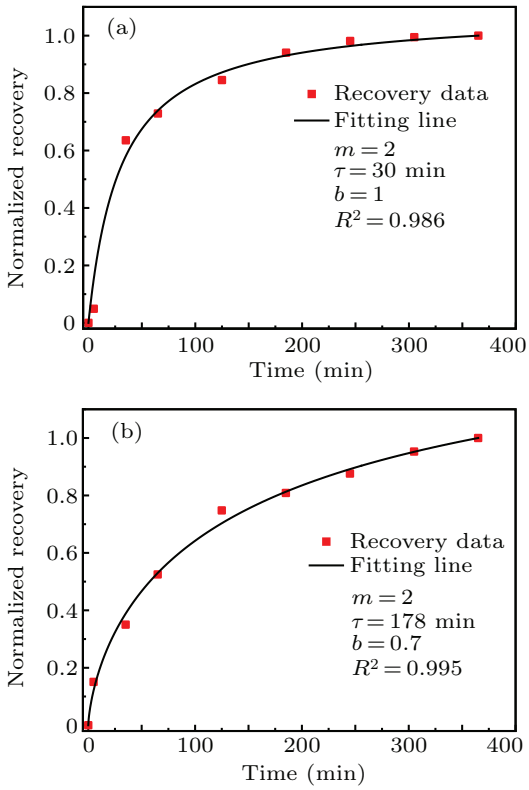


Fig. 4. Fitted recovery processes of CCs with the second-order kinetics model: (a) Si-related CCs (b) Al–OHC CCs.

The fitted parameters related to recovery process of Si-related and Al-OHC CCs are 30 min and 178 min, respectively.

4.3. Calculation of RIA at 980 nm with CCs model

RIA of different CCs is given in Eq. (5). While time constant τ_k is determined in section 4.2, $g_k f(\dot{D})$ for Si-related, Al–OHC and Al-(3) CCs are still uncertain. They can be computed by fitting RIA at any wavelength. However, the measured loss at 980 nm in our experiment are the total effects of RIA and pump absorption. So the actual RIA at 980 nm is determined by developed three-level ASE model (Eqs. (1) and (2)) with measured loss at 980 nm. However, before calculating the RIA at 980 nm, the accuracy of three-level ASE source model is confirmed and it is shown in Fig. 5.

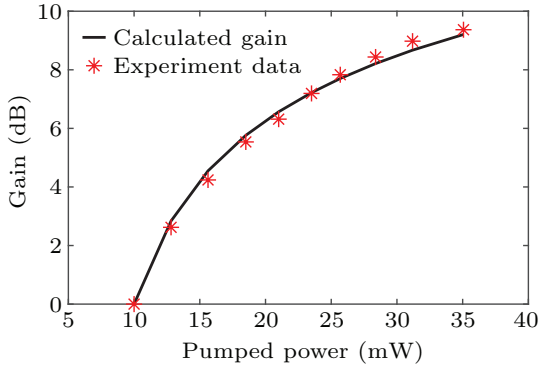


Fig. 5. Calculated and measured gain at 980 nm with different pump power.

4.4. The prediction of ASE degradation

All these results above can be used in Eqs. (1) and (2), and once solved, these equations give the gain evolution as a function of irradiation dose and dose rate. The loss prediction model is established by using the gain loss at the dose rate of 30 Gy/min with the dose range from 0 to 155 Gy. By solving Eqs. (1) and (2) by using parameters in Tables 3 and 4, all the model parameters can be obtained. The gain loss with the dose range from 155 Gy to 220 Gy is used for self-validating. Then, we use this model extrapolating to high dose with the same dose rate of 30 Gy/min. And Fig. 6 gives the self-validating result.

The color center generation only relates to the fiber material and radiation dose rate. The greater the dose rate, the faster the color center is produced. In the experiment, the same kind of EDF was used at different dose rate. Therefore, when extrapolating to low dose rate as low as 0.8 Gy/min, the only thing need to do is dividing these dose rate related parameters $g_k f(\dot{D})$ with a constant, which is about 40.1. Figure 7 displayed the extrapolation result and experiment data, and it fits well.

Table 4. Parameters used for ASE model calculation.

Parameters	Value
Erbium ion density	1.75×10^{25}/m^3
Pump light area	10.75×10^{-12}/m^2
Gain light area	30.2×10^{-12}/m^2
Fiber core area	8.14×10^{-12}/m^2
Absorption coefficient @980 nm	13 dB/m
Fluorescent lifetime	10.2×10^{-3}s

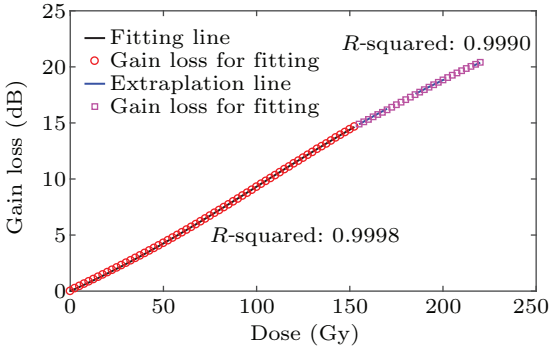


Fig. 6. Fitting of gain loss and self-validation.

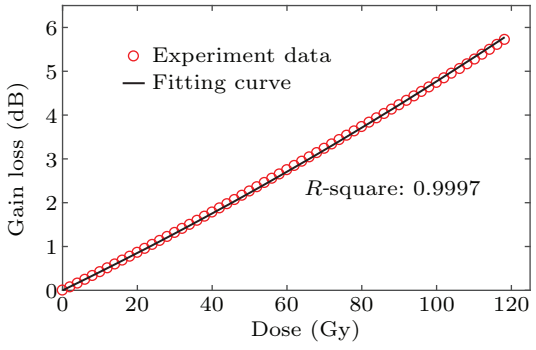


Fig. 7. Gain loss extrapolation to low dose rate.

5. Conclusion

This paper has modeled the three-level ASE sources degradation when exposed to radiation. Combing RIA spectrum response based on CCs and saturating exponential model, a good fitting result of measured gain degradation data is achieved by a simple measurement method. It means the method is accurate enough in ASE degradation prediction. What's more, the new model shows great advantages, as the measurement processes are simple. In addition, the color center model is flexible and powerful when considering the photon bleaching effect. And extrapolating to other dose and dose rate is also satisfied. The result shows that the model makes it possible to evaluate the performance of ASE source under lower dose rate and different service life of satellite in space environment. This research will contribute to the applications of ASE source in radiation environments.

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