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Abstract: A simple numerical method of simulating amplified spontaneous emission (ASE) in erbium doped fibers is presented along with an example case involving a 1 m fiber with 10dB of gain. Simulation results reveal an average noise output power of 1.24W.

INTRODUCTION

Erbium-doped fiber amplifiers (EDFAs) serve a critical role in providing increased signal-to-noise (SNR) ratio for applications centered around 1550 nm. In previous works, such as the work done by Lemons et al., erbium-doped fibers were successfully demonstrated to aid in further reducing phase noise to as low as 3.5 mrad when integrated into a feed forward system to drive an acousto-optic frequency shifter (AOFS) [1].

However, as with any other real-world system, the benefits of EDFAs do not come for free. Particularly, it is well known that EDFAs are susceptible to amplified spontaneous emission (ASE), a phenomenon whereby electrons in the upper state spontaneously radiate photons prior to being stimulated by a signal photon [2]. These spontaneously emitted photons then go on to stimulate other upper state electrons to emit more photons that are not correlated with the signal [3]. While intensity strength of ASE is typically small in reference to the signal, for certain applications, ASE may not be small enough to be considered insignificant. In the case of the aforementioned work by Lemons et al., the discussion of ASE was wholly absent, namely because the focus was on the carrier envelope phase (CEP) noise rather than the integrity of the signal within the carrier envelope. Thus, this work is targeted toward investigating whether the inclusion of an erbium-doped fiber has introduced significant noise to the system.

METHODS

In this investigation, a simple method of simulating the intensity of ASE at the output of an EFDA is introduced. All simulations were conducted on MATLAB with some of the code being sourced from Nguyen [3]. The aim of this study is to provide insight into predicting the expected noise contribution from ASE, which is crucial considering the use of erbium fibers for applications such as attosecond pulse generations and gravitational wave sensing where noise levels need to be minimized and carefully characterized to ensure proper functionality [4-5].

For the purposes of simplicity, ASE noise was modeled as point sources distributed at equal distances along the fiber. Furthermore, each point source was treated as independent of the other sources and its corresponding noise signal was allowed to propagate from location of the point source to the output end of the fiber. The superimposed power output of each of the point sources was then used to estimate the net ASE intensity at the output.

The first step was to estimate the power output from each noise source along the fiber. From theory, the general equation for spontaneous emission power density is given by [6]:

$$\hat{P} = \frac{h\nu}{\tau_{sp}} \cdot \frac{\sigma_a N_t + g}{\sigma_e + \sigma_a} \tag{1}$$

where h is Planck's constant, v is the operating frequency, τ_{sp} is the spontaneous emission lifetime, g is the optical gain, N_t is the total population of electrons, and finally σ_a and σ_e are the cross sections of the lower and upper level, respectively. Note that $\hat{P}$ is in units of $\frac{W}{m^3}$.

Given that erbium doped fibers are three level systems, σ_a and σ_e are known to be comparable in terms of magnitude, (1) can be approximated as:

$$\hat{P} \approx \frac{h\nu}{\tau_{sp}} \cdot \frac{\sigma_e N_t + g}{2\sigma_e} \tag{2}$$

where τ_{sp} and σ_e are known from tabulated values to be 10 ms and 6.0×10^{-25} m^2, respectively [6-7].

From here, N_t was taken to be 3.45×10^{26} m^{-3} based on an assumed Erbium doping concentration of 3.45×10^8μm^{-3}. The frequency was set to $\frac{c}{n\lambda}$, where λ is 1550 nm and n is 1.44, the index of refraction of silica glass at λ. Finally, g was set to 43.43 m^{-1} assuming a total gain of 10dB over 1 m of fiber. Using these aforementioned values, the spontaneous power density was estimated to be 3.221 $\frac{GW}{m^3}$, which for a core diameter of 16 μm and a cable length of 1m, amounts to 37.34 mW. Thus, for computational convenience, each noise source was modeled as a normally distributed signal with a peak amplitude of 37.34 mW centered at 1550 nm.

RESULTS AND INTERPRETATION

For an erbium fiber of length 1m and total gain of 10dB, the simulated ASE power had a mean value of 1.24 W and a root mean square value of 1.2505 W$^{1/2}$. In short, even with no mode-locked laser attached, one could still expect over 1 W of power at the output of a 1 m fiber with 10dB of gain so long as the pump is on. Considering that the max output power of the ORIGAMI-15 laser used by Lemons et al. has a max output power of 15 kW, the noise power is expected to be around three to four orders of magnitude lower than the signal.

However, the main concern is with regards to the effect of the ASE on the carrier envelope phase. On this matter, one must first draw the distinction that the method discussed in this paper is strictly for estimating the amplitude noise due to ASE. CEP noise, on the other hand, is a form of phase noise, meaning the amplitude results discussed here do not have any effect on the CEP. This fact, however, does not imply that ASE noise is irrelevant to phase noise altogether. Instead, prior work by Liao et al. have shown that for a similar f-2f setup on a Yb:fiber with a 200 fs pulse time and center wavelength of 1060 nm, the CEP noise due to ASE was less than a milliradian using analytical methods introduced by Haus et al. [8-9]. Given the similarity between the setups in [1] and [8], one could surmise that Lemons' group saw similar noise levels. For a measured phase noise of 3.5 mrad, 1 mrad of noise from ASE would be about 28% of the total phase noise.

CONCLUSIONS

A simple numerical method for approximating the ASE power in EDFAs was presented in which the ASE power was shown to be roughly three to four orders of magnitude lower than the output of commercial lasers. Further investigation into past literature produced an estimated ASE-induced phase noise in the sub-milliradian regime, meaning that ASE could be contributing up to 28% of the reported CEP jitter. Thus, while including a fiber amplification stage before the f-2f interferometer can result in ultra-low phase jitter, the fiber ultimately imposes a phase noise floor that may pose a challenge to further improving the stabilization.

Currently, future directions include factoring in the effects of backward ASE propagation using numerical methods capable of handling two-boundary conditions [2-3].

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